ANNALS OF GEOPHYSICS, 57, 3, 2014, SS0322; doi:10.4401/ag-6379

Special section: Geophysical monitorings at the Earth's polar regions

Broadband seismic deployments in East Antarctica: IPY contribution to monitoring the Earth's interiors

Masaki Kanao[1,*], Douglas A. Wiens[2], Satoru Tanaka[3], Andrew A. Nyblade[4], Genti Toyokuni[1], Patrick J. Shore[2], Seiji Tsuboi[3], David S. Heeszel[5], Yusuke Usui[6], Timothy Parker[7]

[1] National Institute of Polar Research (NIPR), Tokyo, Japan
[2] Washington University, Department of Earth and Planetary Sciences, St. Louis, MO, USA
[3] Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokohama, Japan
[4] Pennsylvania State University, Department of Geosciences, University Park, PA, USA
[5] US Nuclear Regulatory Commission, Washington, DC, USA
[6] Geodynamics Research Center, Ehime University, Matsuyama, Ehime, Japan
[7] Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL), Incorporated Research Institutions for Seismology (IRIS)

Article history
Received June 30, 2013; accepted January 16, 2014.
Subject classification:
Broadband seismology, International Polar Year, East Antarctica, Global network, Deep interiors.

ABSTRACT

"Deployment of broadband seismic stations on the Antarctica continent" is an ambitious project to improve the spatial resolution of seismic data across the Antarctic Plate and surrounding regions. Several international collaborative programs for the purpose of geomonitoring were conducted in Antarctica during the International Polar Year (IPY) 2007-2008. The Antarctica's GAmburtsev Province (AGAP; IPY #147), the GAmburtsev Mountain SEISmic experiment (GAMSEIS), a part of AGAP, and the Polar Earth Observing Network (POLENET; IPY #185) were major contributions in establishing a geophysical network in Antarctica. The AGAP/GAMSEIS project was an internationally coordinated deployment of more than 30 broadband seismographs over the crest of the Gambursev Mountains (Dome-A), Dome-C and Dome-F area. The investigations provide detailed information on crustal thickness and mantle structure; provide 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. From GAMSEIS and POLENET data obtained, local and regional seismic signals associated with ice movements, oceanic loading, and local meteorological variations were recorded together with a significant number of teleseismic events. In this chapter, in addition to the Earth's interiors, we will demonstrate some of the remarkable seismic signals detected during IPY that illustrate the capabilities of broadband seismometers to study the sub-glacial environment, particularly at the margins of Antarctica. Additionally, the AGAP and POLENET stations have an important role in the Federation of Digital Seismographic Network (FDSN) in southern high latitude.

1. Introduction

Existing permanent seismic stations belonging to the Federation of Digital Seismographic Network (FDSN) allows resolution of the structure beneath Antarctica at a horizontal scale of ~1000 km, which is sufficient to detect fundamental differences in the lithosphere beneath East-West Antarctica, but not to clearly define the structure within each sector. Observation of seismicity around the Antarctic is limited by the sparse station distribution and the detection level for earthquakes remains inadequate for full evaluation of tectonic activity [Reading 2002, 2006]. A strategy of attaining a sufficient density of seismic stations on the Antarctic continent will allow for optimal ray path coverage across Antarctica and improvement of seismic tomography resolution [Roult et al. 1994, Ritzwoller et al. 2001, Kobayashi and Zhao 2004]. In addition to these lithospheric studies, the observed teleseismic data have advantages in investigating the deeper part of Earth's interior such as lower mantle, D" layers, the core-mantle boundary (CMB) and the inner core as they are effectively a large span array located in the southern high latitude.

The justification for developing broadband arrays addresses both the unique aspects of seismology in Antarctica and general issues that would be common to global Earth sciences; for example: - lithospheric dynamics in an ice-covered environment; - how lithospheric processes drive and may be driven by the global environmental changes (sea level, climate); - the scale and nature of rifting as a process that has shaped the continent and dominated its evolution; - the role of Antarctica as the keystone in the super-continent formation and breakup throughout Earth's history; - how the tectonic and thermal structure of the Antarctic lithosphere affected current ice sheet dynamics; - age, growth, and evolution of the continent and processes that have shaped the lithosphere; - the effect of improved seismic coverage on global models of the lithosphere, together with deep interior of the Earth. The International Polar Year (IPY) 2007-2008 provided an excellent opportunity to make significant advances in seismic array deployment to achieve these science targets.

Following the model of the successful TransAntarctic Mountain SEISmic experiment (TAMSEIS; Lawrence et al. [2006], Wiens et al. [2008]) deployment in 2000-2002, several big geo-science projects were conducted to study the interior of Antarctic continent and surrounding region. The Antarctica's GAmburtsev Province (AGAP; http://www.ldeo.columbia.edu/~mstuding/AGAP, IPY #147), the GAmburtsev Mountain SEISmic experiment (GAMSEIS; http://epsc.wustl.edu/seismology/GAMSEIS/) as a part of AGAP, and the Polar Earth Observing Network (POLENET; http://www.polenet.org, IPY #185) were the largest contributions in establishing a broadband seismic network to monitor Antarctica during the IPY. Moreover, the broadband deployment around Eastern Dronning Maud Land - Enderby Land by the Japanese Antarctic Research Expedition (JARE; http://polaris.nipr.ac.jp/~pseis/garnet/; Kanao et al. [2011a]) significantly contributed as a part of both the POLENET and the AGAP in East Antarctica.

From GAMSEIS and POLENET data obtained, local and regional seismic signals associated with ice movements, oceanic loading and local meteorological variations were recorded together with a significant number of teleseismic events. In this Chapter, the project history, field operations during the IPY and the initial data retrieved from AGAP/GAMSEIS and POLENET are demonstrated. In addition to reviewing the conventional seismological approaches for the shallow part of the Earth, we put the significance on monitoring the Earth's deep interiors, as viewed from Antarctica as a large aperture of seismic arrays in southern high latitude.

2. Project development history

"Deployment of broadband seismic stations on the Antarctica continent" was an ambitious goal to improve the spatial resolution of seismic data across the Antarctic Plate at the end of the last century. Several temporary broadband experiments had been carried out in the past decades around several regions within the continental margins of Antarctica [Bannister and Kennett 2002, Kanao et al. 2002, Robertson et al. 2002, Müller and Eckstaller 2003]. Discussions at the working group of the Antarctic Neotectonics program (ANTEC) under the Science Committee on Antarctic Research (SCAR; Siena, Italy, 2001) and the workshop on the "Structure and Evolution of the Antarctic Plate" (SEAP; Boulder, Colorado, 2003) have led to Antarctic seismic array deployments (http://www.antarcticarrays.org). The principal ideas of the Antarctic arrays were derived from components of the Regional Leapfrogging Arrays (RLA) and the Program Oriented Experiments (POE). The strategy of attaining a sufficient density of stations (20-30) in symmetrically disposed sectors of the continent allows optimal ray path coverage across Antarctica and improves tomographic resolution [Ritzwoller et al. 2001].

The Antarctic seismic arrays were modified according to logistical and financial concerns, but remained strongly supported by many nations involved in Antarctic observations, including Japan. The resultant seismic stations in Antarctica were put together for initiating several international programs (POLENET, AGAP/GAMSEIS; Wilson and Bell [2011]) during the IPY. Targeting the vast central region of East Antarctica, the AGAP/GAMSEIS project was an internationally coordinated deployment of few tens of broadband seismographs over the crest of the Gambursev Subglacial Mountains (Dome-A), Dome-C and Dome-F area [Wiens 2007]. The investigations provided detailed information on crustal thickness and mantle structure and provide key constraints on the origin of the GSM [Hansen et al. 2010], and more broadly on the structure and evolution of the East Antarctic craton and subglacial environment. The broadband arrays in the Lüzow-Holm Bay (LHB) region [Kanao et al. 2011a], moreover, made a significant contribution not only to the permanent global network of FDSN, but also to such projects as the Global Alliance of Regional Networks (GARNET), RLA, POE, POLENET and IPY.

It was clear that the deployment strategy could only be achieved through strong international cooperation. Nations with winter-over bases (existing or planned) and with logistical capabilities in a particular sector could firmly contribute to the deployment of permanent stations in the backbone network (FDSN) and/or portable instruments in the evolving regional arrays (RLA and POE). More than twenty cooperative researchers from Japanese and international institutions had specific tasks to carry out in these projects. Several members deployed field stations so as to record the data during the IPY period: others engaged in analyses of specific topics by use of the observed data sets combined with regional and global data. After the assembly of the results from national participants, several international workshops were conducted to integrate these results with international collaborators. There have been a number of opportunities for the researchers in the project to meet and discuss the progress of the project deployments and results and future plan. For educational activities, additionally, some members made efficient lectures for a wide range of school children about the research of the project and its results, together with an introduction to IPY activities. We sincerely had an obligation to teach the younger generation for the advancement of future polar sciences.

3. Field operations at the IPY

Targeting the underlying structure, dynamics and evolution of the broader part of East Antarctica, the AGAP project was an internationally coordinated program including sub-groups of air-borne geophysics, seismics and ice-core drilling (Figure 1; Wilson and Bell [2011]). Multi-national collaboration both for science investigation and field operational logistics by many nations from USA, Japan, China, France, Italy and Australia was a significant factor in the success of the project. Two field camps were established at AGAP-N and AGAP–S, which were located on opposite sides of the Chinese camp at Dome-A. At these camps, there was support for the flight operations of both the air-borne geophysics and seismic deployment research teams. Moreover, Chinese ground traverses had been conducted along the routes from Zhong Shan Station to Dome-A.

Four fundamental questions drove research at AGAP: 1) What role does topography play in the nucleation of continental ice sheets? (a map of the ice surface topography of the target area is shown in Figure 2); 2) How are major elevated continental massifs formed within intra-plate settings but without a straightforward plate tectonic mechanism? (high elevations under the GSM are initially identified by gravity anomalies from GRACE satellite); 3) How do tectonic processes control the formation, distribution, and stability of subglacial lakes?; 4) Where is the oldest climate record in the Antarctic ice sheet?

Some of these questions have been studied and partially answered previously. Buried beneath the thick ice sheet, the GSM was characterized by peak elevations of more than ~3000 m above sea level [Bell et al. 2011]. The new data from GAMSEIS has also allowed for more detailed investigation of the crustal structure beneath the

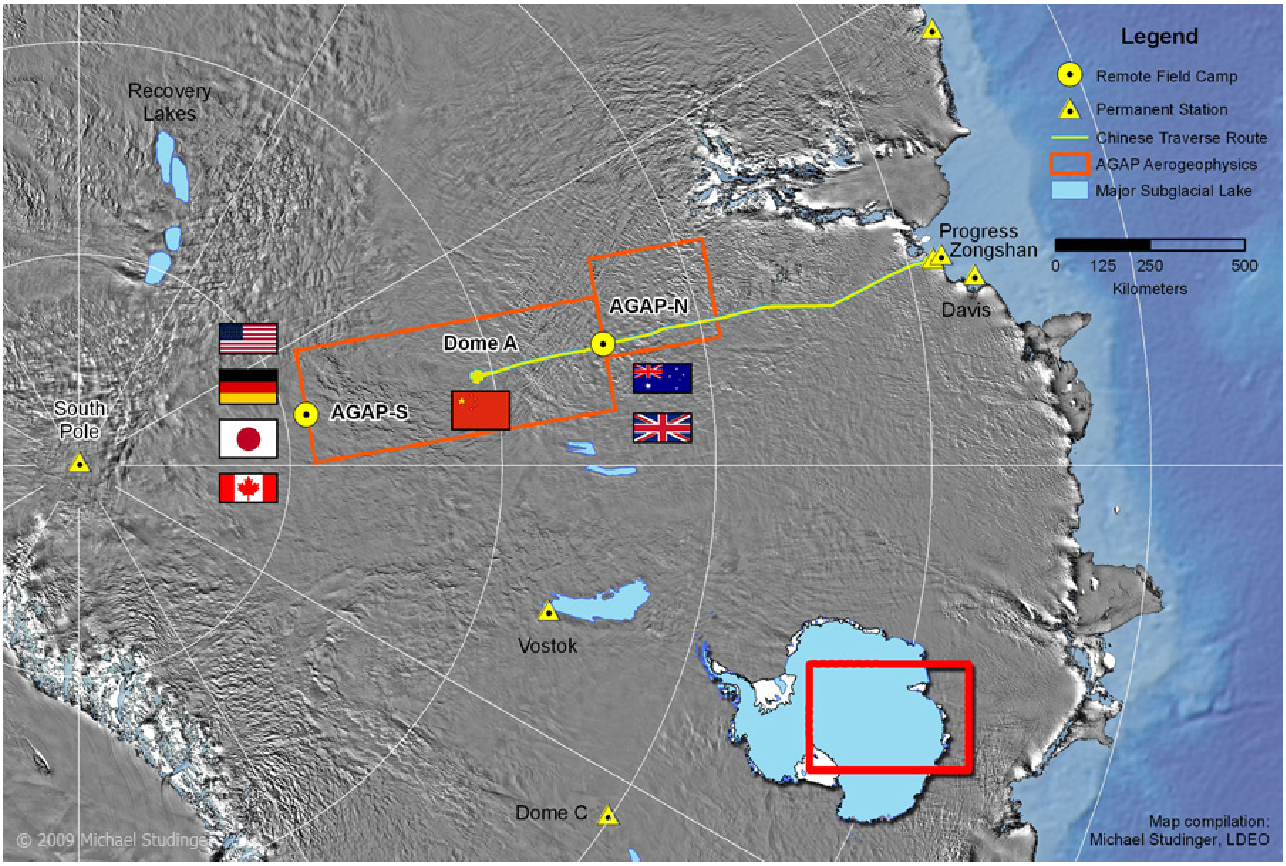

Figure 1. Location map of the field camps utilized during the AGAP which occurred during the IPY. The two camps for AGAP-N and -S had been operated for supporting flight operations of the air-bone geophysics and seismic deployments in wide area of the East Antarctic ice sheet. The Chinese ground traverse route from Zhong Shan Station to Dome-A is illustrated by the solid yellow line.

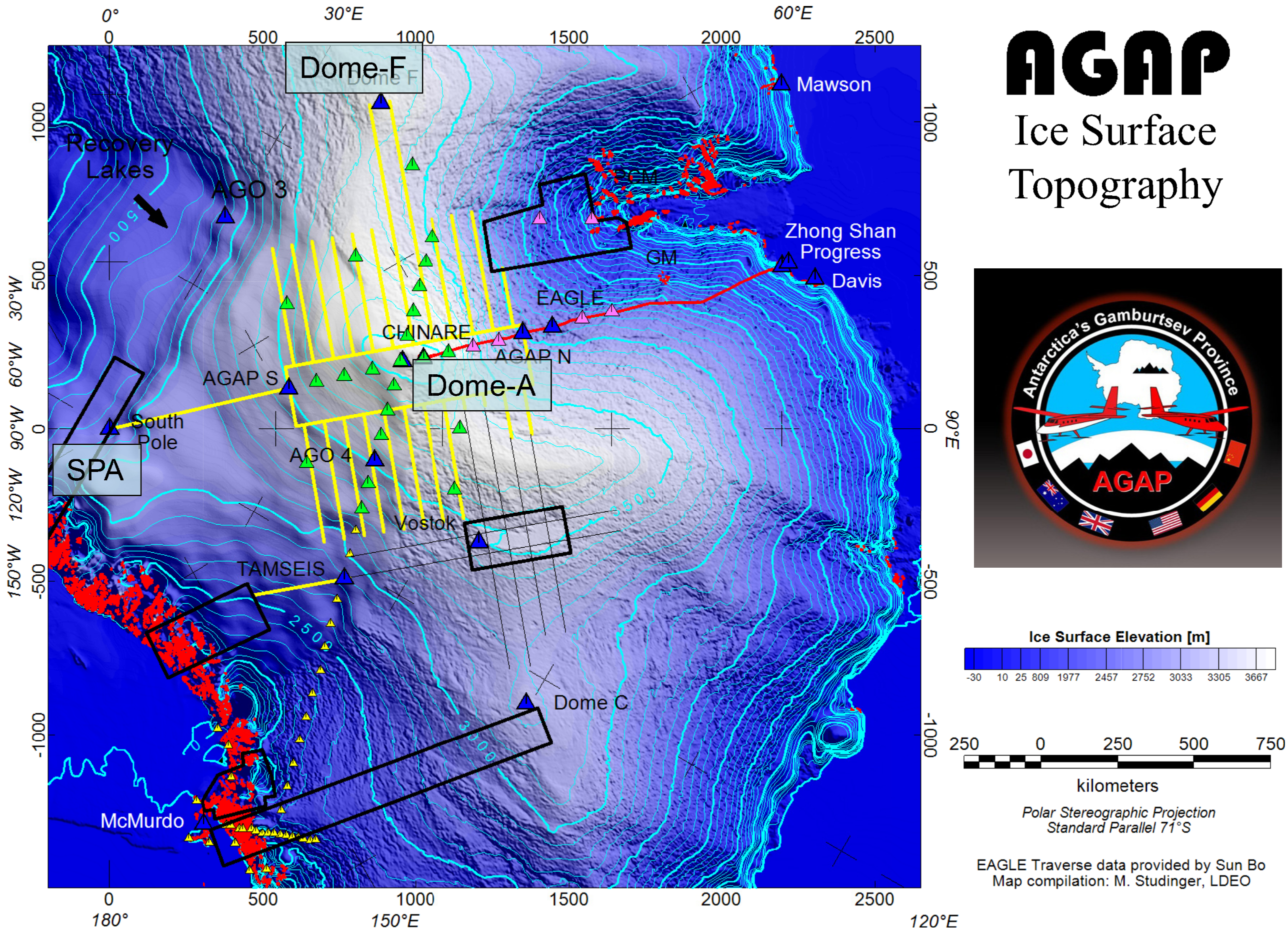

Figure 2. Map of the broadband seismic stations (green triangles) and geophysical airborne surveys (yellow lines) in AGAP/GAMSEIS project conducted during the IPY 2007-2008 (Courtesy of R. Bell and M. Studinger; http://www.ldeo.columbia.edu/~mstuding/AGAP/). The red line represents the Chinese ground traverse route from Zhong Shan Station to Dome-A. The red colored areas are the outcrops around the coast.

GSM and the surrounding regions [Hansen et al. 2010].

Among the whole AGAP program, the sub-group for the seismic portion named GAMSEIS deployed few tens of broadband seismographs over a wide area of the continental ice sheet from the GSM, Lake Vostok, and in the vicinity of Dome-F. Although we do not mention the details in logistics here, a significant number of flights have been conducted by Twin-Otter aircraft in order to install the stations on ice sheet. The most distant station was Japanese station located at Dome-F (GM07), nearly 1000 km from the base camp at AGAP-S. Additionally, significant fuel caches were prepared at several locations approximately at 500 km from the AGAP-S in the event of emergency.

The seismic instrumentation utilized for GAMSEIS and POLENET were provided by the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) of the Incorporated Research Institutions for Seismology (IRIS). A review of the field operations at remote sites in the polar region, both for Antarctica and Greenland, are summarized by Anderson and Parker [2009]. The PASSCAL polar instruments were developed with input from the community of Antarctic seismologists and the main specifications are as follows [Anderson et al. 2007]. Seismometer; Guralp CMG-3T in a special configuration to operate at –55°C, Data logger; Quanterra Q-330 with flash memory (operates to –55°C), Enclosures; insulated vacuum keep at ~15°C above ambient without additional heating, Solar panels and AGM batteries for summer power, Lithium batteries for winter power, and these instruments were optimized for ease of deployment from Twin-Otter aircraft.

In addition to the PASSCAL observation system, original coordinated systems were developed by Japan (at Dome-F (GM07) and GM06 stations), and also by the other research groups in China and France. Regarding the Japanese instrument system, the same sensor and data logger as used by US/PASSCAL were utilized, but the electric power supply system and enclosures were developed independently with technical advice from PASSCAL staff. Data were recorded in MiniSEED format, a commonly accepted international standard, to ease analysis. Logistical and staff support were provided by the US researchers and staff at AGAP-S camp in the installation of the Japanese stations GM06 and GM07.

Outside the AGAP/GAMSEIS deployed area of the continental margins of East Antarctica, several broadband seismic stations have been deployed in LHB, between the Enderby Land and Dronning Maud Land. These observations have been carried out from 1996 until present and serve as a major contribution to POLENET, FDSN, and GARNET. The stations were established on rock outcrops and ice sheet around the continental margins of LHB. A significant number of global earthquakes, local earthquakes, and ice-related events within close proximity to the stations have been recorded during the array's operation. During the IPY period, seven stations were continuously operated. The observation systems consisted of a portable broadband seismometer and a data-recorder (Japanese original), combined with AGM and solar batteries. Guralp Systems CMG-40T seismometers were used. Detailed information for the GARNET stations in LHB and operational information are available from the web-site of NIPR (http://polaris.nipr.ac.jp/~pseis/garnet/).

4. Initial data and science targets

During the observation periods of the IPY, a significant number of teleseismic events, as well as many local and regional seismic signals were recorded by AGAP/GAMSEIS and POELNET stations. An example of teleseismic waveforms recorded at several GAMSEIS stations are presented in Figure 2. These traces record the large Sichuan earthquake, in China (May 12, 2008, Mb 7.9). Both the body waves and surface waves were clearly recorded for each waveform trace. These teleseismic data obtained by GAMSEIS and POLENET provide detailed information on crustal thickness and mantle temperatures in East Antarctica through their use in regional receiver function and tomography studies.

Data collected by AGAP/GAMSEIS are capable of providing key constraints on the origin of GSM as a crustal root associated with ancient orogenic events [Hansen et al. 2010], and more broadly on the structure and evolution of the entire East Antarctic craton [An et al. 2011, Heeszel et al. 2013, Lloyd et al. 2013]. Understanding the origin of the GSM and the structure of the East Antarctic craton could also be vitally linked to other first-order problems, such as the geologic history of Antarctica, the role of its topography and heat flow on Earth's climate and glacial history, and the geophysical and geologic controls on subglacial lakes [Bell et al. 2011]. Crustal thickness beneath the GSM shows large values, over 55 km, which imply that an ancient mountain range may have been supported by thick, buoyant crust [Hansen et al. 2010, Heeszel et al. 2013]. These newly obtained images of the crust and upper mantle in the middle part of East Antarctica aid in understanding the evolution of the Gondwanan super-continent during the Earth's history.

Several kinds of natural seismic signals connected to the atmosphere–ocean–cryosphere system can be detected in polar regions. The movement of ice is capable of causing small magnitude earthquakes, generally labeled 'ice-quakes' (or 'ice-shocks') for their relationship to glacial dynamics [Tsuboi et al. 2000, Anandakrishnan et al. 2003, Kanao and Kaminuma 2006, Kanao et al. 2011b]. Such cryoseismic sources include the movement of ice sheets, sea-ice, oceanic tide-cracks, oceanic gravity waves, icebergs and the calving fronts of ice caps. At times, it can be hard to distinguish between the waveforms generated by local tectonic earthquakes and those of ice-related phenomena. Cryoseismic sources are likely to be influenced by environmental conditions, and the study of their temporal variation may provide indirect evidence of climate change.

In addition to the ice motion signals, almost all seismic stations deployed on the Earth's surface can record ubiquitous signals at periods between 4 and 25 s, commonly referred to as 'microseisms'. Microseisms are considered to be dominated by Rayleigh waves that arise from gravity waves in the ocean that are forced by surface winds. The period ranges of microseisms are dictated by the physics of gravity wave generation, and are constrained by the speed and extent of Earth's surface winds [Aster et al. 2008, Aster 2009, Bromiriski 2009]. On a global scale, microseism amplitudes are generally highest during local winter, because nearby oceans are stormier in winter than in summer [Stutzmann et al. 2009]. In contrast, we observe the opposite in polar regions: microseism amplitude is attenuated during local winter for both primary and secondary microseisms [Grob et al. 2011]. This observation can be explained by the sea-ice extent impeding both the direct ocean-to-continent coupling and the coastal reflection. Microseism studies of Antarctica using both GAMSEIS and POLENET have recently been undertaken [Wiens et al. 2011].

5. Monitoring Earth's deep interior

In addition to the bedrock, crust and upper mantle which underlie the Antarctic ice sheet, the teleseismic data observed by the AGAP/GAMSEIS and POLENET hold a great advantage for investigating the heterogeneous structure and dynamics of the deep part of Earth's interior. The target depth areas are, for instance, the lowermost layer of the mantle (D" region) and in the core-mantle boundary (CMB) [Usui et al. 2008], together with the inner core [Isse and Nakanishi 2001]. The heterogeneous and anisotropic structure of these depth ranges could be investigated by using the teleseismic data retrieved at both polar regions by these studies, as a large aperture array located in the southern high latitude.

Figure 3 demonstrates the distribution of teleseismic event numbers at each location in the Antarctic counted from a list including earthquakes with magnitude greater than or equal to 5.5 in the period of 1990-2004, for the different epicenter distance ranges. The epicentral distance range from 60° to 90° would be especially suitable for the observation of the D" reflected phases, SdS as well as the core reflected phases of ScS and PcP. That from 90° to 130° would be appropriate for the observation of the core diffracted phases of Pdiff, and Sdiff, and a the core phase of SKS. So far we have only a few regions in the southern hemisphere where the deep mantle structure has been examined in detail.

By using the observed teleseismic waveforms detected by GAMSEIS and POLENET, the synthetic seismograms calculated by spherical 2.5-D finite-difference methods were compared to identify the lateral heterogeneity in realistic Earth's structure [Toyokuni et al. 2012]. Although it is required to improve the more realistic structural model a more detailed seismic velocity model will utimately be required, the agreement in the compared waveforms indicated potential of the spherical 2.5-D finite-difference model as a tool to reveal the deep inner structure of the Earth. The seismic station distribution by of GAMSEIS and POLENET, moreover, was found to be a sufficient number to fulfill the special spatial and back-azimuth coverage over the globe in the requirements for global wavefield modeling.

As mentioned above, the Antarctic seismic stations play an important tools for probing the Earth's deep structures, such as D" and the CMB. Here, we demonstrated the efficiency to detect interesting structure around the D" layer, by using the stations as large aperture arrays across the Antarctica. Broadband seismic arrays are composed of AGAP and POLENET (Figure 4a). Three hypocentral areas that are appropriate for the study of D" structure are considered (Figure 4b). Here, we show synthetic seismograms of the SH com-

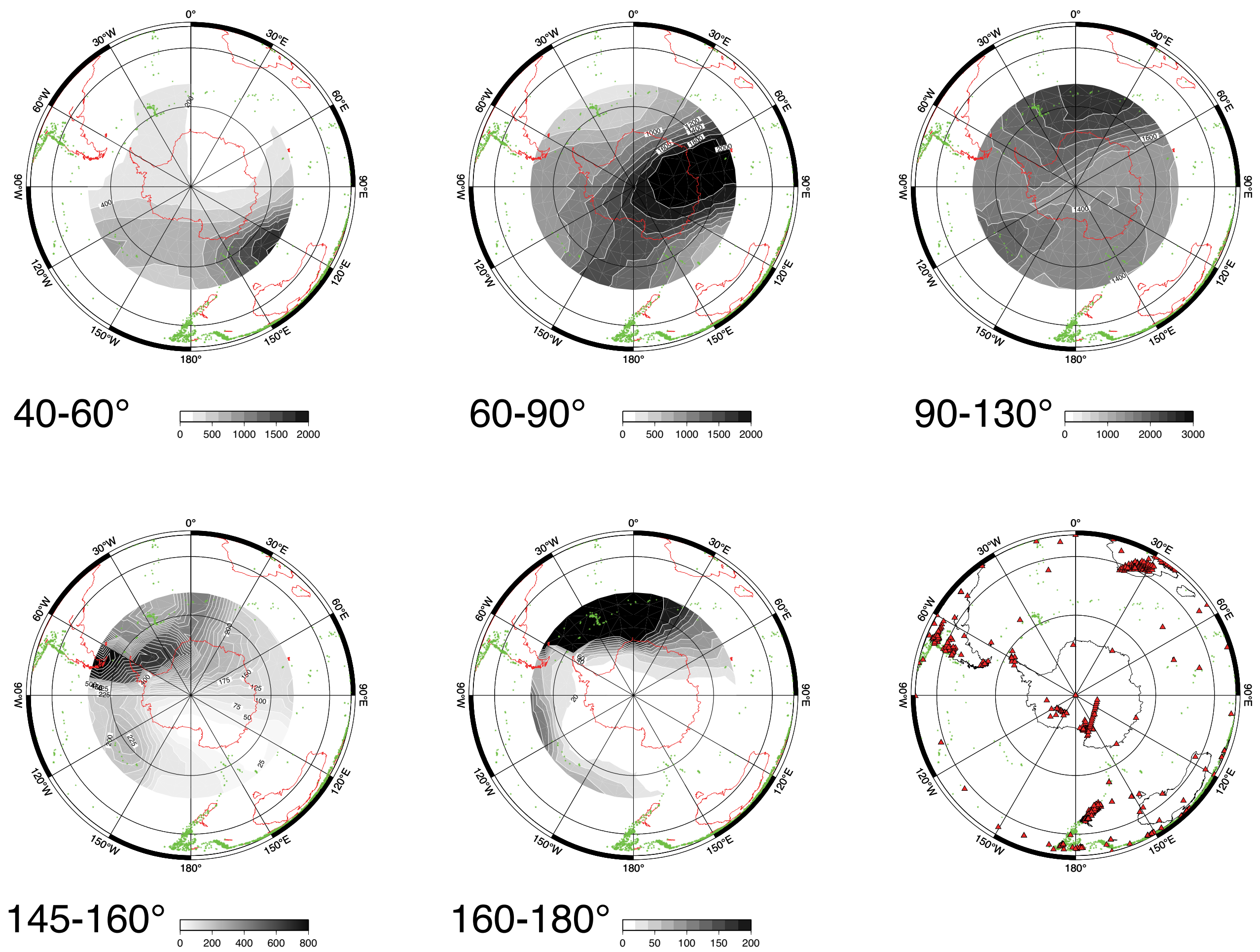

Figure 3. Geographical distribution of teleseismic event numbers (gray horizontal scales) observed at each location in the Antarctic for epicentral distances of 40-60°, 60-90° and 90-130° (from left to right in upper row), 140-160° and 160-180° (in lower row), respectively. A list including global distributed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

ponent calculated by the reflectivity method [Müller 1985] for a Fiji event of which hypocenter is assumed to be (20° S, VS at the point of geographic co-ordinate 20° S, 179° W with a focal depth of 500 km). The CMT solution of the event 2005/03/19 is adopted (Figure 5d). A positive shear-wave velocity jump of 3% at 300 km above the CMB is assumed (Figure 5e), which results in a D" reflected phase SdS as shown in Figure 5c. Figure 5a and b shows the synthetic record sections of AGAP and POLENET, respectively. The travel times are reduced to emphasized the section from S to ScS phases. Interestingly, the D" reflected phase SdS is clearly identified in the both two record sections. Furthermore, the record sections of AGAP and POLENET can be useful for a detailed observation for convergence of three phases (Figure 5a) and SdS appearance (Figure 5b), respectively. In summary, the continental scale broadband seismic arrays of AGAP and POLENET have the high-potential to precisely explore the D" regions beneath many areas in the southern hemisphere where nobody has accessed before.

Seismic data from inland Antarctica is expected to bring images of the Earth's deep interiors with enhanced resolution due to the high signal-to-noise ratio and wide extent of this region, as well as rarity of their sampling PKIKP paths along the rotation axis of the Earth as mentioned by Isse and Nakanishi [2001].

6. Data management and future direction

The broadband seismic data accumulated by AGAP/GAMSEIS and POLENET during the IPY were initially stored and available for all the related polar seismological community from the data library system of the Data Management System, in the Incorporated Research Institute of Seismology (DMS/IRIS). The GARNET/JARE data, in contrast, were initially stored and accessible to cooperative researchers via the data library server of NIPR (POLARIS; http://polaris.nipr.ac.jp/~pseis/garnet/). After a defined period for two years, the data are made available to world data centers of seismology, such as the DMS/IRIS, FDSN/ Global Seismological Network (GSN), PACIFIC21center of Japan, and the others. The data-management issues in Antarctica are strongly connected with the Standing Committee on Antarctic Data Management (SCADM) under SCAR, as well as the Antarctic Master Directory (AMD) in the Global Change Master Directory (GCMD) of NASA.

By carrying out broadband deployments over the whole of Antarctica, a more detailed understanding of the continents tectonics and upper mantle structure can be obtained. Additionally, these arrays are capable of providing insight into the heterogeneous characteristics of Earths' deep interior. After combining the numerous IPY related projects in seismology and geophysics,

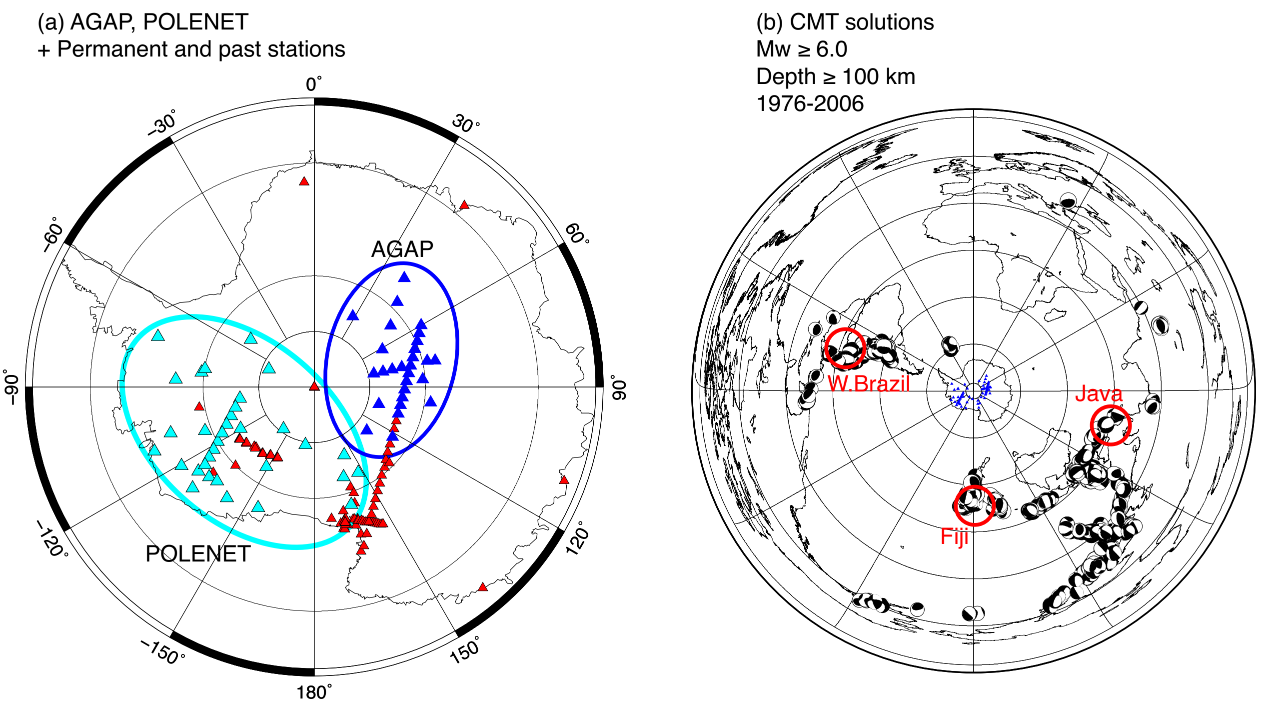

Figure 4. (a) Geographical distribution of the broadband seismic arrays of AGAP (blue triangles) and POLENET (light blue triangles). Stereographic projection is used. Permanent stations and those for the past experiments, such as TAMSEIS are also plotted by red triangles. (b) Geographical distribution of CMT solutions of deep earthquakes (Mw ≥ 6.0, depth ≥ 100 km) in the period of 1976-2006. Equidistant projection is used. The hypocentral areas marked by red circles are discussed here (for Fiji, Java, western Brazil seismic events).

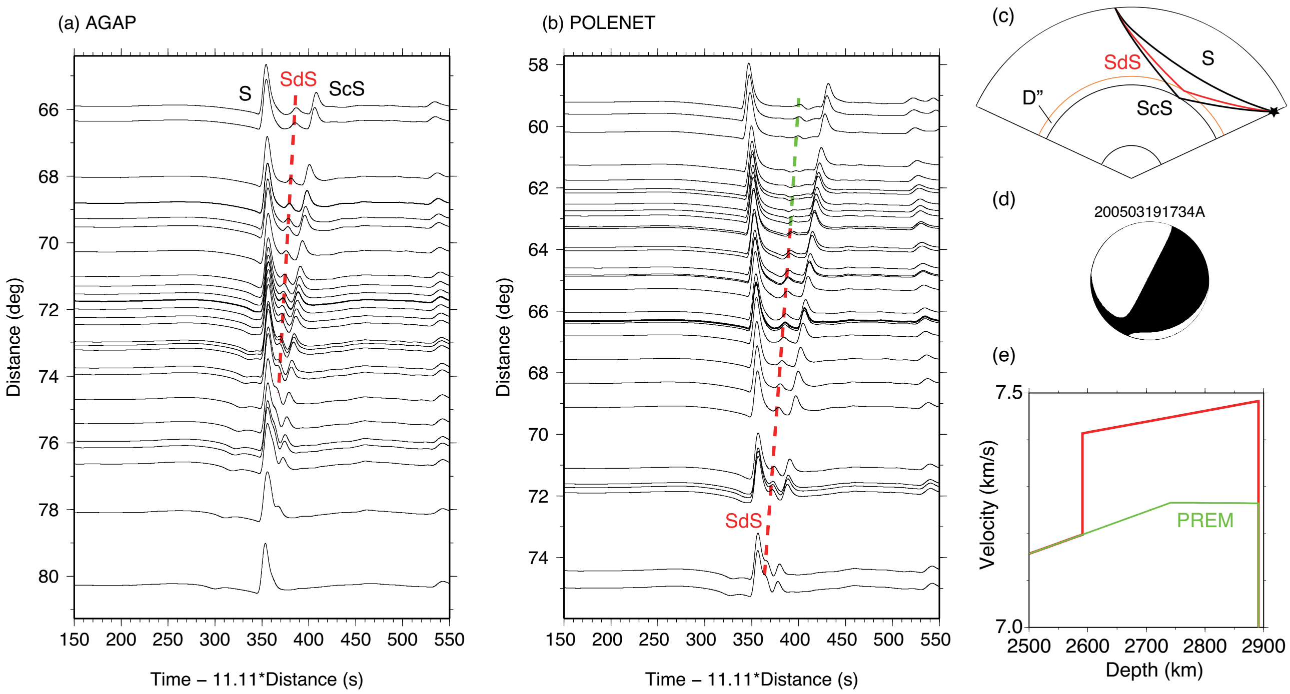

Figure 5. Seismograms of the SH component synthesized by reflectivity method for a typical deep Fiji event to the (a) AGAP and (b) POLENET stations. Clear arrivals of SdS are marked with a red broken line in (a) and (b). Predicted arrival of SdS with no clear and coherent signal is marked by a green line in (b). The reduced velocity of 11.11°/s is adopted to emphasize S, SdS and ScS phases. (c) Ray paths of S, SdS and ScS on a vertical cross-section. (d) A focal mechanism solution of a typical deep Fiji event (the CMT solution of the event 2005/03/19) that is used in the calculation. (e) A red line is a velocity profile in D" region that is used in the calculation. PREM [Dziewonski and Anderson 1981] is drawn by a green line for comparison.

specifically the AGAP/GAMSEIS and POLENET projects including the GARNET deployment at LHB in East Antarctica, we are able to provide constraints on the origin of the GSM and the broader structure of Precambrian craton as well as the subglacial environment. Detection of seismic signals from basal sliding of the ice sheet and ice streams [Anandakrishnan et al. 2003, Wiens et al. 2008, Winberry 2010] would be expected from the future study, as well as the detection of outburst floods from the sub-glacial lakes underlying the East Antarctic ice sheet.

The northern part of the Eastern Dronning Maud Land, particularly from the coastal region of LHB to Dome-F, would be the most plausible place with enough logistical support by JARE to conduct a deployment of portable seismic stations in the future. The temporary seismic monitoring stations along the inland traverse routes on the continental ice-sheet on the plateau could be installed using snow terrain vehicles with support from aircraft. These field observation stations on the Antarctic ice sheet, which are composed of long-term operating batteries and large capacity digital data-loggers, may also be utilized for the other science purposes, such as geophysical, meteorological, glaciological and biological studies, these latter only at the coastal stations. Multi-purpose inland data collection sites on the Antarctic continent could be utilized by many nations involved in Antarctic research in order to advance their monitoring of long-term variations in the polar environment.

In the broader context of global seismic monitoring, together with seismic networks such as FDSN/GSN, additional permanent stations in the Antarctic could also contribute to both the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) and the Pan-Antarctic Observations System (PAntOS) under SCAR. The combination of seismic, infrasound and hydro-acoustic observations would be required to understand, in more detail, the atmosphere–ocean–cryosphere–geosphere system and its role in long-term environmental variability. By combining and amalgamating data retrieved by several global networks as mentioned above, we advance our ability to conduct multidisciplinary science and identify future global monitoring targets. New scientific knowledge and understanding as viewed from Earth's polar regions will continue to play a critical role in our understanding of the Earth's system. New international collaborations will help us make rapid advances in the progress of such research activities.

7. Summary

The IPY 2007-2008 provided an excellent opportunity to make significant advances in geophysical monitoring of both polar regions. These advances serve as an important addition to the permanent global network of FDSN and such projects as GARNET, RLA, POE, POLENET and other geomonitoring science bodies and communities. Accumulated high quality seismic data in Antarctica from both the POLENET and AGAP/GAMSEIS projects could be efficiently utilized to clarify the dynamic seismicity and heterogeneous structure of the Earth, particularly around the Antarctic region. Seismic deployments can efficiently study the crust and upper mantle, as well as the Earth's deep interior, including features such as the CMB and the lowermost mantle layer (the D" region). These studies also provide significant insight into the characterisitics of seismicity associated with global environmental change. Teleseismic waveforms observed by the GAMSEIS and POLENET stations have an advantage for investigating the interior of the Earth. The epicentral distance in 60-90° was especially suitable for the observation of D" reflected phases as well as the core reflected ones of ScS and PcP. The events from 90-130° were appropriate for observation of the core diffracted phases of Pdiff, Sdiff, and a core phase of SKS. Additionally, we confirm the validity of the GAMSEIS and POLENET for a deep mantle study throughR reflectivity waveform synthetics, in which we demonstrate the detectability of a D" reflected phase SdS from events in Fiji, by assuming the D" discontinuity. From the AGAP/GAMSEIS data obtained in the IPY, local and regional seismic signals associated with 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 could be expected from detailed analyses. The project history, the field operations at the IPY and the initial data retrieved from GAMSEIS and POLENET were described. In addition to reviewing the conventional seismological approaches for the shallow part of the Earth, we place significant emphasis on these arrays' ability to monitor the Earth's deep interior, as viewed from Antarctica, as a single, large aperture array in the southern high latitude.

Acknowledgements. The authors would like to express our special appreciation to the many collaborators in the IPY projects for AGAP (Prof. R. Bell and Dr. M. Studinger of Lamont-Doherty Earth Observatory of Columbia University and others), GAMSEIS and POLENET (Prof. T. Wilson and Dr. S. Konfal of the Ohio State University, and others). The authors would like to express sincere thanks to Profs. K. Shiraishi, K. Shibuya, Y. Motoyoshi, K. Doi, Y. Nogi, T. Hokada, Y. Aoyama and the other staff of NIPR for their useful discussions about the geoscience studies on East Antarctica. They would like to express their sincere thankfulness for Prof. F. Davey of the Institute of Geological and Nuclear Sciences Ltd, New Zealand, and Prof. A. K. Cooper of the Department of Geological and Environmental Sciences, Stanford University, for their criticalreviews and useful comments. The authors would like to express appreciation for Prof. D. Di Mauro for his arrangement on publishing the special section on Annals of Geophysics.

References

An, M., D.A. Wiens, Y. Zhao, M. Feng, A.A. Nyblade, M. Kanao, Y. Li, A. Maggi and J.J. Lévêque (2011). 3D Lithosphereœ Model of Antarctica from Surface Wave Observations, 11th International Symposium on Antarctic Earth Sciences (Edinburgh, Scotland, July 10-16, 2011), PS18.9.

Anandakrishnan, S., D.E. Voigt, R.B. Alley and M.A. King (2003). Ice stream D flow speed is strongly modulated by the tide beneath the Ross Ice Shelf, Geophys. Res. Lett., 30; doi:10.1029/2002GL016329.

Anderson, K., B. Beudoin and T. Parker (2007). IRIS/PASSCAL Polar Power/ Comms MRI Year 1 Midseaon Report, 14 pp.

Anderson, K., and T. Parker (2009). Polar Operations, IRIS 2009 Annual Report - twenty five years of IRIS, 26-27.

Aster, R., D. McNamara and P. Bromirski (2008). Multidecadal climate-induced variability in microseisms, Seismol. Res. Lett., 79, 194-202; doi:10.1785/gssrl.79.2.194.

Aster, R. (2009). Studying Earth's ocean wave climate using microseisms, IRIS Annual Report, 8-9.

Bannister, S., and B.L.N. Kennett (2002). Seismic Activity in the Transantarctic Mountains - Results from a Broadband Array Deployment, Terra Antarctica, 9, 41-46.

Bell, R.E., F. Ferraccioli, T.T. Creyts, D. Braaten, H. Corr, I. Das, D. Damaske, N. Frearson, T. Jordan, K. Rose, M. Studinger and M. Wolovick (2011). Widespread Persistent Thickening of the East Antarctic Ice Sheet by Freezing from the Base, Science Xpress Report; doi:10.1126/science.1200109; www.sciencexpress.org.

Bromirski, P.D. (2009). Earth vibrations. Science, 324, 1026-1027.

Dziewonski, A.M., and D.L. Anderson (1981). Preliminary reference Earth model, Phys. Earth Planet. In., 25, 297-356.

Grob, M., A. Maggi and E. Stutzmann (2011). Observations of the seasonality of the Antarctic microseismic signal, and its association to sea ice variability, Geophys. Res. Lett., 38, L11302; doi:10.1029/2011GL047525.

Hansen, S.E., A.A. Nyblade, D.S. Heeszel, D.A. Wiens, P. Shore and M. Kanao (2010). Crustal Structure of the Gamburtsev Mountains, East Antarctica, from S-wave Receiver Functions and Rayleigh Wave Phase Velocities, Earth Planet. Sci. Lett., 300, 395-401; doi:10.1016/j.epsl.2010.10.022.

Heeszel, D.S., D.A. Wiens, A.A. Nyblade, S.E. Hansen,

M. Kanao, M. An and Y. Zhao (2013). Rayleigh wave constraints on the structure and tectonic history of the Gamburtsev Subglacial Mountains, East Antarctica, J. Geophys. Res., 118 (5), 2138-2153; doi:10.1002/jgrb.50171.

Isse, T., and I. Nakanishi (2001). Inner-Core anisotropy beneath Australia and differential rotation, Geophys. J. Int., 151, 255-263.

Kanao, M., A. Kubo, T. Shibutani, H. Negishi and Y. Tono (2002). Crustal structure around the Antarctic margin by teleseismic receiver function analyses, In: J.A. Gamble, D.N.B. Skinner and S. Henrys (eds.), Antarctica at the close of a millennium, Royal Society of New Zealand Bulletin, 35, 485-491.

Kanao, M., and K. Kaminuma (2006). Seismic activity associated with surface environmental changes of the Earth system, East Antarctica, In: D.K. Futterer, D. Damaske, G. Kleinschmidt, H. Miller and F. Tessensohn (eds.), Antarctica: Contributions to global Earth sciences, Springer-Verlag, Berlin/Heidelberg/New York, 361-368.

Kanao, M., Y. Usui, T. Inoue and A. Yamada (2011a). Broadband seismic deployments for imaging the upper mantle structure in the Lützow-Holm Bay region, East Antarctica, Inter. J. Geophys., 2011, 1-15; doi:10.1155/2011/272646.

Kanao, M., A. Maggi, Y. Ishihara, M.-Y. Yamamoto, K. Nawa, A. Yamada, T. Wilson, T. Himeno, G. Toyokuni, S. Tsuboi, Y. Tono and K. Anderson (2011b). Interaction on Seismic Waves between Atmosphere–Ocean–Cryosphere and Geosphere in Polar Region, Seismic Waves - Research and Analysis, InTech. Publisher, 1-20; doi:10.5772/1400.

Kobayashi, R., and Z. Zhao (2004). Rayleigh-wave group velocity distribution in the Antarctic region, Phys. Earth Planet. In., 141, 167-181.

Lawrence, J.F., D.A. Wiens, A.A. Nyblade, S. Anandakrishan, P.J. Shore and D. Voigt (2006). Upper mantle thermal variations beneath the Transantarctic Mountains inferred from teleseismic S-wave attenuation, Geophys. Res. Lett., 33, L03303; doi:10.1029/2005GL024516.

Lloyd, A.J., A.A. Nyblade, D.A. Wiens, P.J. Shore, M. Kanao, S.E. Hansen and D. Zhao (2013). Upper mantle seismic structure beneath the East Antarctic shield from body wave tomography: Implications for the origin of the Gamburtsev Subglacial Mountains, G-Cubed, Geochem. Geophys. Geosyst., 14 (4), 902-920; doi:10.1002/ggge.20098.

Müller, G. (1985). The reflectivity method: A tutorial, J. Geophys., 58, 153-174.

Müller, C., and A. Eckstaller (2003). Local seismicity detected by the Neumayer seismological network, Dronning Maud Land, Antarctica: tectonic earthquakes and ice-related seismic phenomena, IX International Symposium on Antarctic Earth Science Programme and Abstracts, Potsdam, p. 236.

Reading, A.M. (2002). Antarctic seismicity and neotectonics, In: J.A. Gamble, D.N.B. Skinner and S. Henrys (eds.), Antarctica at the close of a millennium, Royal Society of New Zealand Bulletin, 35, 479-484.

Reading, A.M. (2006). On seismic Strain-Release within the Antarctic Plate, In: D.K. Futter, D. Damaske, G. Kleinschmidt, H. Miller and F. Tessensohn (eds.), Antarctica: Contributions to global Earth sciences, Springer-Verlag, New York, 351-356.

Ritzwoller, M.H., N.M. Shapino, A.L. Levshin and G.M. Leahy (2001). Crustal and upper mantle structure beneath Antarctica and surrounding oceans, J. Geophys. Res., 106, 30645-30670.

Robertson, S.D., D.A. Wiens , P.J. Shore, G.P. Smith and E.Vera (2002). Seismicity and tectonics of the South Shetland Islands and Bransfield Strait from the SEPA broadband seismograph deployment, In: J.A. Gamble, D.N.B. Skinner and S. Henrys (eds.), Antarctica at the close of a millennium, Royal Society of New Zealand Bulletin, 35, 549-554.

Roult, G., D. Rouland and J.P. Montagner (1994). Antarctica II: Upper-mantle structure from velocities and anisotropy, Phys. Earth Planet. In., 84, 33-57.

Stutzmann, E., M. Schimmel, G. Patau and A. Maggi (2009). Global climate imprint on seismic noise, Geochem. Geophys. Geosyst., 10, Q11004; doi:10.1029/2009GC002619.

Toyokuni, G., H. Takenaka, M. Kanao, D.A. Wiens and A.A. Nyblade (2012). 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 Sci., 6, 155-164.

Tsuboi, S., M. Kikuchi, Y. Yamanaka and M. Kanao (2000). The March 25, 1998 Antarctic Earthquake: caused by postglacial rebound, Earth Planets Space, 52, 133-136.

Usui, Y., Y. Hiramatsu, M. Furumoto and M. Kanao (2008). Evidence of seismic anisotropy and a lower temperature condition in the D" layer beneath Pacific Antarctic Ridge in the Antarctic Ocean, Phys. Earth Planet. In.; doi:10.1016/j.pepi.2008.04.006.

Wiens, D.A. (2007). Broadband Seismology in Antarctica: recent progress and plans for the international polar year, In: Proceedings of the International Symposium Asian Collaboration in International Polar Year National Committee (Tokyo, Japan, March 2007), 21-24.

Wiens, D.A., S. Anandakrishnan, J.P. Winberry and

M.A. King (2008). Simultaneous teleseismic and geodetic observations of the stick-slip motion of an Antarctic ice stream, Nature, 453, 770-774.
Wiens, D.A., F. Koch, G. Euler, A. Nyblade, S. Anandakrishnan, A. Huerta, R. Aster, M. Kanao and T. Wilson (2011). Seasonal and Directional Variation of Microseismic Noise - Tracking Sea Ice Cover with Seismology, 11th International Symposium on Antarctic Earth Sciences (Edinburgh, Scotland, July 10-16, 2011), PS15.11.
Wilson, T., and R. Bell (2011). Earth Structure and Geodynamics at the Poles. Understanding Earth's Polar Challenges: International Polar Year 2007-2008, 273-292.
Winberry, J.P. (2010). Stick-Slip Motion of Antarctic Ice Streams: Observations from the Meter Scale and the Hundred-Kilometer Scale, International Workshop on Geophysics of Interior Antarctica (Beijing, China, October 22-24, 2010), Abstracts, 20.

*Corresponding author: Masaki Kanao,
National Institute of Polar Research (NIPR), Tokyo, Japan;
email: kanao@nipr.ac.jp.