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Recent advance in polar seismology: Global impact of the International Polar Year

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The most exciting initiative for the recent polar studies was the International Polar Year (IPY) in 2007-2008. The IPY has witnessed a growing community of seismologists who have made considerable efforts to acquire high-quality data in polar regions. It also provided an excellent opportunity to make significant advances in seismic instrumentation of the polar regions to achieve scientific targets involving global issues. Taking these aspects into account, we organize and publish a special issue in Polar Science on the recent advance in polar seismology and cryoseismology as fruitful achievements of the IPY.

Long-term accumulation and improvements in seismic event data for the polar regions by the International Seismological Centre

Dmitry A. Storchak, Masaki Kanao, Emily Delahaye, James Harris

The International Seismological Centre (ISC) is a non-governmental non-profit making organization funded by 62 research and operational institutions around the world and charged with the production of the ISC Bulletin – the definitive summary of the global seismicity based on reports from over 130 agencies worldwide, including those active in Polar regions. Jointly with the National Earthquake Information Center (NEIC) of the United States Geological Survey (USGS), the ISC runs the International Seismic Station Registry. The ISC is also charged with maintaining the International Association of Seismology and Physics of the Earth Interior (IASPEI) Reference event List. The new ISC product, the ISC Event Bibliography allows users to obtain references to scientific articles describing specific seismic events, natural and anthropogenic. In this paper we demonstrate how these products and services are applicable to seismic events both in Arctic and Antarctic regions. We also give a summary of the ISC data in polar regions and provide credit to Institutions that report these data to the ISC.

Search for latitudinal variation of spectral peak frequencies of low-frequency eigenmodes excited by great earthquakes

Hironobu Shimizu, Yoshihiro Hiramatsu, Ichiro Kawasaki

Continuous waveform records of STS-1 seismometers of the Incorporated Research Institutions for Seismology (IRIS) and superconducting gravimeters of the Global Geodynamics Project (GGP) obtained during the 2004 Sumatra-Andaman, the 2010 Chile, and the 2011 off the Pacific coast of Tohoku earthquakes are examined to search for latitudinal variations of the spectral peak frequencies of 0S0, 1S0, and 0S2. No latitudinal variation is determined. The observed spectral peak frequencies are identical to those of the Preliminary Reference Earth Model (PREM).

A quantitative evaluation of the annual variation in teleseismic detection capability at Syowa Station, Antarctica

Takaki Iwata, Masaki Kanao

In this study, we evaluate the annual variation in teleseismic detection capability at Syowa Station (69.0° S, 39.6° E) located in East Antarctica, a variation that has been noted in previous studies. For the quantitative evaluation of the annual variation, we introduced a statistical model of a magnitude-frequency distribution of earthquakes covering the entire magnitude range. The annual variation in the model parameter that quantifies the detection capability was then estimated by using Bayesian analysis. In the estimation, we incorporated the annual variation in air temperature at the station and succeeded in clarifying the significant effect that the variation in temperature has on the teleseismic detection capability.

Infrasound array observations in the Lützow-Holm Bay region, East Antarctica

Takahiko Murayama, Masaki Kanao, Masa-Yuki Yamamoto, Yoshiaki Ishihara, Takeshi Matsushima, Yoshihiro Kakinami

The characteristic features of infrasound waves observed in Antarctica reveal a physical interaction involving surface environmental variations in the continent and the surrounding Southern Ocean. A single infrasound sensor has been making continuous recordings since 2008 at Syowa Station (SYO; 69.0S, 39.6E) in the Lützow-Holm Bay (LHB) of East Antarctica. The continuously recorded data clearly show the contamination of background oceanic signals (microbaroms) throughout all seasons. In austral summer 2013, several field stations with infrasound sensors were established along the coast of the LHB. Two infrasound arrays of different diameters were set up: one at SYO (with a 100-m spacing triangle) and one in the S16 area on the continental ice sheet (with a 1000-m spacing triangle). In addition to these arrays, isolated single stations were deployed at two outcrops in the LHB. These newly established arrays clearly detected the propagation direction and frequency content of microbaroms from the Southern Ocean. Microbarom measurements are a useful tool for characterizing ocean wave climates, complementing other oceanographic and geophysical data from the Antarctic. In addition to the microbaroms, several other remarkable infrasound signals were detected, including regional earthquakes, and airburst shock waves emanating from a meteoroid entering the atmosphere over the Russian Republic on 15 February 2013. Detailed and continuous measurements of infrasound waves in Antarctica could prove to be a new proxy for monitoring regional environmental change as well as temporal climate variations in high southern latitudes.

On-ice vibroseis and snowstreamer systems for geoscientific research

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We present implementations of vibroseis system configurations with a snowstreamer for over-ice long-distance seismic traverses (>100 km). The configurations have been evaluated in Antarctica on ice sheet and ice shelf areas in the period 2010-2014. We discuss results of two different vibroseis sources: Failing Y-1100 on skis with a peak force of 120 kN in the frequency range 10-110 Hz; IVI EnviroVibe with a nominal peak force of 66 kN in the nominal frequency range 10-300 Hz. All measurements used a well-established 60 channel 1.5 km snowstreamer for the recording. Employed forces during sweeps were limited to less than 80% of the peak force. Maximum sweep frequencies, with a typical duration of 10 s, were 100 and 250 Hz for the Failing and EnviroVibe, respectively. Three different concepts for source movement were employed: the Failing vibrator was mounted with wheels on skis and pulled by a Pistenbully snow tractor. The EnviroVibe was operated self-propelled on Mattracks on the Antarctic plateau. This lead to difficulties in soft snow. For later implementations the EnviroVibe with tracks was put on a polyethylene (PE) sled. The sled had a hole in the center to lower the vibrator baseplate directly onto the snow surface. With the latter setup, data production varied between 20 km/day for 6-fold and 40 km/day for single fold for 9 h/day of measurements. The combination of tracks with the PE-sled was especially advantageous on hard and rough surfaces because of the flexibility of each component and the relatively lose mounting. The systems presented here are suitable to obtain data of subglacial and sub-seabed sediment layers and englacial layering in comparable quality as obtained from marine geophysics and land-based explosive surveys. The large offset aperture of the streamer overcomes limitations of radar systems for imaging of steep along-track subglacial topography. With joint international scientific and logistic efforts, large-scale mapping of Antarctica's and Greenland's subglacial geology, ice-shelf cavity geometries and sea-bed strata, as well as englacial structures can be achieved.

Evidence of unfrozen liquids and seismic anisotropy at the base of the polar ice sheets

Gérard Wittlinger, Véronique Farra

We analyze seismic data from broadband stations located on the Antarctic and Greenland ice sheets to determine polar ice seismic velocities. P-to-S converted waves at the ice/rock interface and inside the ice sheets and their multiples (the P-receiver functions) are used to estimate in-situ P-wave velocity (Vp) and P-to-S

velocity ratio (Vp/Vs) of polar ice. We find that the polar ice sheets have a two-layer structure; an upper layer of variable thickness (about 2/3 of the total thickness) with seismic velocities close to the standard ice values, and a lower layer of approximately constant thickness with standard Vp but ~25% smaller Vs. The lower layer ceiling corresponds approximately to the −30 ° C isotherm. Synthetic modeling of P-receiver functions shows that strong seismic anisotropy and low vertical S velocity are needed in the lower layer. The seismic anisotropy results from the preferred orientation of ice crystal c-axes toward the vertical. The low vertical S velocity may be due to the presence of unfrozen liquids resulting from premelting at grain joints and/or melting of chemical solutions buried in the ice. The strongly preferred ice crystal orientation fabric and the unfrozen fluids may facilitate polar ice sheet basal flow.

Numerical modeling of seismic waves for estimating the influence of the Greenland ice sheet on observed seismograms

Genti Toyokuni, Hiroshi Takenaka, Masaki Kanao, Seiji Tsuboi, Yoko Tono

We calculate regional synthetic seismograms for a realistic structure model beneath Greenland, including surface topography and ice sheet thickness, for observations of the multinational GreenLand Ice Sheet monitoring Network (GLISN). The thick and heterogeneous Greenland ice sheet can cause distortion of the seismic waveforms observed at the GLISN stations on ice. We developed a numerical technique that calculates accurate regional seismic wavefields with low computational requirements. Here, we calculate the elastic wave propagation up to 2 Hz for four structural models of the Greenland ice sheet from a seismic source at various depths and with different mechanisms. Our computations for a realistic ice sheet model, the near-surface seismic source produced a very characteristic wave train with a group velocity smaller than the S-wavespeed in the ice, considered to be an ice-sheet guided S wave, developed by the superposition of post-critical reflections between the free surface and the ice bed. We named this wave "Le", analogous to the Lg wave, a crustally guided S wave. Furthermore, computation for a deeper seismic source resulted in reinforcement of the crustal Sg-coda wave with a group velocity range of ~3.1-2.6 km/s, which agrees with the characteristic waveform observed on the Greenland ice sheet.

Ice melting and earthquake suppression in Greenland

M. Olivieri, G. Spada

It has been suggested that the Greenland ice sheet is the cause of earthquake suppression in the region. With few exceptions, the observed seismicity extends only along the continental margins of Greenland, which almost coincide with the ice sheet margin. This pattern has been put forward as further validation of the earthquake suppression hypothesis. In this review, new evidence in terms of ice melting, post-glacial rebound and earthquake occurrence is gathered and discussed to re-evaluate the connection between ice mass unloading and earthquake suppression. In Greenland, the spatio-temporal distribution of earthquakes indicates that seismicity is mainly confined to regions where the thick layer of ice is absent and where significant ice melting is presently occurring. A clear correlation between seismic activity and ice melting in Greenland is not found. However, earthquake locations and corresponding depth distributions suggest two distinct governing mechanisms: post-glacial rebound promotes moderate-size crustal earthquakes at Greenland's regional scale, while current ice melting promotes shallow low magnitude seismicity locally.

Seismic explosion sources on an ice cap – Technical considerations

Alexey Shulgin, Hans Thybo

Controlled source seismic investigation of crustal structure below ice covers is an emerging technique. We have recently conducted an explosive refraction/wide-angle reflection seismic experiment on the ice cap in east-central Greenland. The data-quality is high for all shot points and a full crustal model can be modelled. A crucial challenge for applying the technique is to control the sources. Here, we present data that describe the efficiency of explosive sources in the ice cover. Analysis of the data shows, that the ice cap traps a significant amount of energy, which is observed as a strong ice wave. The ice cap leads to low transmission of energy into the crust such that charges need be larger than in conventional onshore experiments to obtain reliable seismic signals. The strong reflection coefficient at the base of the ice generates strong multiples which may mask for secondary phases. This effect may be crucial for acquisition of reflection seismic profiles on ice caps. Our experience shows that it is essential to use optimum depth for the charges and to seal the boreholes carefully.

Seismic and density heterogeneities of lithosphere beneath Siberia: Evidence from the Craton long-range seismic profile

E.A. Melnik, V.D. Suvorov, E.V. Pavlov, Z.R. Mishenkina

The estimate of seismic lithosphere thickness in Siberia remains controversial in spite of long-range controlled-source data available from peaceful nuclear explosions (PNE). Published models of layered upper mantle based on this evidence fail to unambiguously constrain the asthenospheric depth. The observed velocity changes may be due either to vertical layering or to lateral heterogeneity, which are difficult to discriminate because of large (1000 km) PNE spacing. Among the upper mantle models, obtained with reference to Moho velocities derived from higher-resolution chemical explosion data, we focus especially on lateral density heterogeneity. The model reveals three velocity layers, with velocities 8.0-8.5 km/s in Layer 1, 8.6-8.7 km/s in Layer 2, and ~8.5 km/s in Layer 3. Layers 2, which varies strongly in thickness, may consist of dense eclogite, judging by the high velocities. Its base may correspond to the base of the lithosphere underlain by the lower-velocity asthenospheric material of Layer 3. The lateral variations in velocity within Layer 1 and in thickness of Layer 2 correlate with major tectonic units: the West Siberian basin, the Tunguska basin with the Permian-Triassic continental flood basalts (the large igneous province of Siberian Traps), as well as the Vilyui basin and the Yakutian kimberlite province. Isostasy in the West Siberian and Vilyui basins results in thick sediments and thin crust, while the large depths of the basement and the intra-crustal discontinuity in the Tunguska basin isostatically compensate the elevated surface topography due to voluminous lavas. The magmatism left its imprint in the mantle as an attenuated "eclogitic layer" beneath the Tunguska basin. However, the available data are still insufficient to understand the exact causes of this attenuation, because mantle conditions may have changed during the elapsed 250 m.y. since then.

Regional seismic wave propagation (Lg & Sn phases) in the Amerasia Basin and High Arctic

Karen Chiu, David B. Snyder

Observation of Lg seismic waves at regional distances has long been considered indicative of continental crust that is 30-40 km thick. This study updates an earlier assessment of Lg propagation efficiency to characterize continental or non-continental crust and related structures across the Amerasia Basin and surrounding continental areas of the high Arctic. Recent refraction surveys and receiver function studies provide crustal thickness estimates of 18-41 km for comparison. Among 7000 candidate earthquake-station pairs considered, no classic Lg phases (0.14-2 Hz) are observed to cross the Amerasia Basin (Canada Basin, Alpha-Mendeleev Ridge) efficiently, but lower frequency (0.035-0.17 Hz) arrivals with group velocities intermediate between Lg and Sn (sometimes called early Lg) are observed along many ray paths crossing the basin. The characteristic frequencies of these observed arrivals match well with those of synthetic waves propagated within models with thinned or pinched continental crust, such as crust characteristic of the North Sea, and thus suggest that most parts of the Amerasia Basin have a crustal thickness intermediate between that typical of thin continental and oceanic crust.

Seismicity of the Arctic mid-ocean Ridge system

Vera Schlindwein, Andrea Demuth, Edith Korger, Christine Läderach, Florian Schmid

The Arctic mid-ocean ridge system constitutes the most active source of earthquakes in the north polar region. However, the characteristics of its earthquake activity at teleseismic and local scales are not well studied because of the remote location of the ridge. We present here a comprehensive seismicity analysis that compares the teleseismic earthquake record of 35 years drawn from the catalogue of the International Seismological Centre with reconnaissance-style local earthquake records at six locations along the ridge that were instrumented either with ocean bottom seismometers or with seismometers on drifting ice floes. The teleseismic earthquake activity varies along the ridge and reflects ultraslow spreading processes with more and larger earthquakes produced in magma-rich regions than in magma-starved areas. Large magnitude earthquakes M > 5.5 are common along this ultraslow spreading ridge. Locally recorded earthquakes are of small magnitude (M < 2) and probably reflect the formation of the pronounced topographic relief. Their size and event rate is not as variable along the ridge as that of teleseismic events. Locally recorded earthquakes in the upper mantle are generated at several locations. Their focal depths do not depend on spreading rate but reflect the thermal state of the lithosphere with very deep earthquakes indicating an exceptionally cold lithosphere.

Enhanced Earthquake Monitoring in the European Arctic

Galina Antonovskaya, Yana Konechnaya, Elena O. Kremenetskaya, Vladimir Asming, Tormod Kværna, Johannes Schweitzer, Frode Ringdal

This paper presents preliminary results from a cooperative initiative between the Norwegian Seismic Array (NORSAR) institution in Norway and seismological institutions in NW Russia (Arkhangelsk and Apatity). We show that the joint processing of data from the combined seismic networks of all these institutions leads to a considerable increase in the number of located seismic events in the European Arctic compared to standard seismic bulletins such as the NORSAR reviewed regional seismic bulletin and the Reviewed Event Bulletin (REB) issued by the International Data Centre (IDC) of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) organization. The increase is particularly pronounced along the Gakkel Ridge to the north of the Svalbard and Franz-Josef Land archipelagos. We also note that the vast majority of the events along the Gakkel Ridge have been located slightly to the south of the ridge. We interpret this as an effect of the lack of recording stations closer to and north of the Gakkel Ridge, and the use of a one-dimensional velocity model which is not fully representative for travel-times along observed propagation paths. We conclude that while the characteristics of earthquake activity in the European Arctic is currently poorly known, the knowledge can be expected to be significantly improved by establishing the appropriate cooperative seismic recording infrastructures.

Geophysical investigations of the area between the Mid-Atlantic Ridge and the Barents Sea: From water to the lithosphere-asthenosphere system

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As a part of the large international panel "IPY Plate Tectonics and Polar Gateways" within the "4th International Polar Year" framework, extensive geophysical studies were performed in the area of southern Svalbard, between the Mid-Atlantic Ridge and the Barents Sea. Seismic investigations were performed along three refraction and wide-angle reflection seismic lines. Integrated with gravity data the seismic data

were used to determine the structure of the oceanic crust, the transition between continent and ocean (COT), and the continental structures down to the lithosphere-asthenosphere system (LAB). We demonstrate how modeling of multiple water waves can be used to determine the sound velocity in oceanic water along a seismic refraction profile. Our 2D seismic and density models documents 4-9 km thick oceanic crust formed at the Knipovich Ridge, a distinct and narrow continent-ocean transition (COT), the Caledonian suture zone between Laurentia and Barentsia, and 30-35 km thick continental crust beneath the Barents Sea. The COT west of southern Spitsbergen expresses significant excess density (more than 0.1 g/cm3 in average), which is characteristic for mafic/ultramafic and high-grade metamorphic rocks. The results of the gravity modeling show relatively weak correlation of the density with seismic velocity in the upper mantle, which suggests that the horizontal differences between oceanic and continental mantle are dominated by mineralogical changes, although a thermal effect is also present. The seismic velocity change with depth suggests lherzolite composition of the uppermost oceanic mantle, and dunite composition beneath the continental crust.