Geoscience Frontiers 6 (2015) 665–677

Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research paper

Seismicity, structure and tectonics in the Arctic region

Masaki Kanao [a,*], Vladimir D. Suvorov [b], Shigeru Toda [c], Seiji Tsuboi [d]

[a] National Institute of Polar Research, Research Organization of Information and Systems, 10-3, Midori-cho, Tachikawa-shi, Tokyo 190-8518, Japan
[b] Trofimuk Institute of Petroleum Geology and Geophysics of Siberian Branch, Russian Academy of Sciences, Koptyg ave. 3, Novosibirsk 630090, Russia
[c] Department of Earth Sciences, Faculty of Education, Aichi University of Education, Kariya, Aichi 448-8542, Japan
[d] Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology, Showa-machi 3175-25, Kanazawa-ku, Yokohama 236-0001, Japan

ARTICLE INFO

Article history:
Received 15 July 2014
Received in revised form
26 September 2014
Accepted 14 November 2014
Available online 29 November 2014

Keywords:
Arctic region
Seismicity
Tectonics
Earth's structure
Global network
Glacial earthquakes

ABSTRACT

The "Arctic" region, where the North Pole occupies the center of the Arctic Ocean, has been affecting the environmental variation of the Earth from geological time to the present. However, the seismic activities in the area are not adequately monitored. Therefore, by conducting long term monitoring of seismic phenomenon as sustainable parameters, our understanding of both the tectonic evolution of the Earth and the dynamic interaction between the cryosphere and geosphere in surface layers of the Earth will increase. In this paper, the association of the seismicity and structure of the Arctic region, particularly focused on Eurasian continent and surrounding oceans, and its relationship with regional evolution during the Earth's history is studied. The target areas cover representative tectonic provinces in the Eurasian Arctic, such as the wide area of Siberia, Baikal Rift Zone, Far East Russia, Arctic Ocean together with Greenland and Northern Canada. Based on discussion including characteristics of seismicity, heterogeneous structure of the crust and upper mantle, tectonic history and recent dynamic features of the Earth's surface in the Arctic are summarized.

1. Introduction

The "Arctic" region, where the Arctic Ocean surrounds the North Pole, has been affected by environmental variation of the Earth in both short and long terms of time scale. As an example of the short term variation, the global warming currently in progress is the most significant phenomena to influence a rapid change in the cryosphere (sea ice, ice sheet, ice shelves, ice caps, glaciers) in the Arctic (IPCC, 2007). In contrast, a long term environmental variation during the Earth's history has been affecting the deformation of solid Earth underneath the cryosphere. The different variations of the surface environments in space and time can be measured and investigated using seismological and geological approaches. However, the seismological phenomenon attributed by seismicity, structure of the Earth and its dynamics in the Arctic have not fully revealed during last few decades. Therefore, when monitoring these parameters for long terms with a sustainable procedure, an understanding of both the tectonic evolution of the Earth and the dynamic interaction among the cryosphere–geosphere system is expected to be revealed.

Regarding seismicity and structure in the Arctic, the largest continent of the Earth; the "Eurasia" is the most significant factor involving global tectonics during Earth's history in terms of amalgamation and disposal of super-continents (Fig. 1). The continent is characterized by a complex composition with various crustal provinces in ages from the Archean to Phanerozoic (Maruyama et al., 2007; Pisarevsky et al., 2008). These tectonic terrains have grown their areas with mutual interaction, evolving from several nucleuses of the Precambrian cratons, followed by adjacent mobile belts, recent subductions, the rift systems and other tectonic active areas. An increase of knowledge on seismicity and tectonics in the Arctic region could give rise to a better understanding of the evolutional process of the Earth, viewed from high northern latitude. Identification of the growth process, formation mechanism of the super-continents and super-plumes have significance in the effort to learn more about the structure and dynamics of deep interior, as well as the interaction between the mantle-core system and the surface layers of the Earth.

* Corresponding author.
E-mail addresses: kanao@nipr.ac.jp (M. Kanao), SuvorovVD@ipgg.nsc.ru (V.D. Suvorov), shigeru@auecc.aichi-edu.ac.jp (S. Toda), tsuboi@jamstec.go.jp (S. Tsuboi).
Peer-review under responsibility of China University of Geosciences (Beijing).

http://dx.doi.org/10.1016/j.gsf.2014.11.002

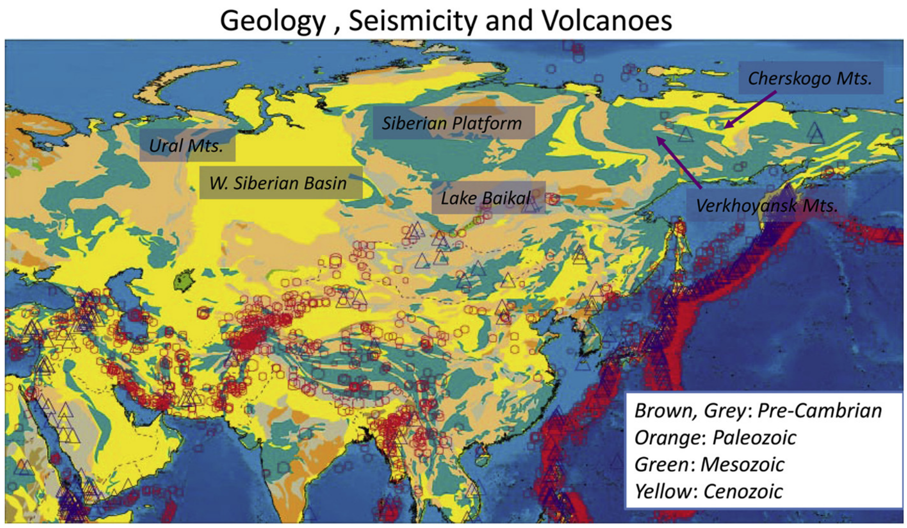

Figure 1. Distribution of tectonic provinces, seismicity and volcanoes in Eurasian continent and surrounding regions (after database of Cornell University; the world geology map, seismicity is after the International Seismological Centre (ISC), 2011). Tectonic provinces are classified as follows: Pre-Cambrian (brown; Archaean, gray; Proterozoic), Paleozoic (orange), Mesozoic (green), Cenozoic (yellow).

A justification of the development of seismic networks in the Arctic with respect to both the unique aspects of seismology in a polar region 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 global environmental change (sea level, climate); the scale and nature of rifting as a process that has shaped a continent and dominated its evolution; the role of Antarctica as the keystone in the supercontinent formation and break-up throughout Earth's history; how the tectonic and thermal structure of the Antarctic lithosphere affect 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, mantle, and core.

The International Polar Year (2007–2008) was a great opportunity to fulfill the Arctic seismic deployment in an attempt to achieve these targets (Rapley et al., 2004). During the IPY, many internationally collaborating geo-scientific projects were conducted in the polar regions, such as the Polar Earth Observing Network (POLENET) and the Antarctica's Gamburtsev Province (AGAP) (Wilson and Bell, 2011). These inter-disciplinary projects aimed to monitor the present status of environmental variations of the Earth, as viewed from polar regions, and simulating future activities of human beings. In the Arctic and Antarctic, development of seismic networks was achieved to study the interior of the Earth, dynamics and seismicity in polar regions.

In this paper, the seismicity and structure of the Arctic region, in particular focused on the largest continent of the Earth; the Eurasia and surrounding oceans, are demonstrated associated with the relationship to their regional evolution during Earth's history. The target areas cover several tectonic provinces of the Eurasian Arctic, such as the broad areas of Siberia, Baikal Rift Zone, Far East Russia, Arctic Ocean as well as Greenland and northern Canada. Seismic evidence is summarized with regard to the characteristics of seismicity, heterogeneous structure of the crust and upper mantle, tectonic history and recent dynamic features of the Earth's surface in the Arctic. The paper aims to demonstrate and reevaluate the relationship between the causes and effects in terms of seismicity and geodynamic processes in the Arctic, as well as how these investigations may fruitfully are influencing on the present surface ongoing dynamics of the Earth among global environmental variability.

2. Eurasian Arctic

The present structure and past evolution of the lithosphere in the Eurasian Arctic, where the majority of areas belong to Russian Federation, provide unique information on the process of amalgamation and separation of the past super-continents (Maruyama et al., 2007). The current status on lithospheric environment, moreover, gives rise to a unique aspect on the formation process of super-continent in future. The largest continental block on the present Earth, Eurasia, has been formed by assembly of several sub-continental blocks including Asia, India and Europe. The continent is also considered to be the nucleus of a future super-continent, which is expected to be formed about 250 myr after the present (Rosen, 2003; Maruyama et al., 2007; Pisarevsky et al., 2008). In this Chapter, several topics on lithospheric structure and evolution are demonstrated on the basis of recent studies of northern Eurasia, in particular focused on Siberia in the Russian Arctic.

Characteristic features of the Eurasian continent are attributed by the existence of various tectonic provinces over time from the Archean to Phanerozoic (Fig. 1). These tectonic terrains have been evolved from the nucleus of Precambrian cratons (Pisarevsky et al., 2008), followed by interaction with adjacent Proterozoic mobile belts (orogens), Mesozoic and Cenozoic terrains, the recent subduction, rifts and lithospheric deformed areas (Nokleberg et al., 2001). A remarkable growth processes in some terrains was revealed. For example, crustal structure of the Ural Mountains represents the frozen architecture of the paleo conversion tectonics inside the present lithosphere (Suvorov et al., 1997, 2002; Brown et al., 2006; Rybalka et al., 2007). Nikishin et al. (2010) discussed about the tectonic evolution of the Siberian Platform during the Vendian and Phanerozoic, to the present time evolution of the Siberian paleo-continent with the Siberian Craton making up its nucleus. They showed that the paleo-continent underwent significant intra-plate compression deformations with vertical movements and formation of inversion structural features within broad areas.

Seismicity of northern Eurasia and the surrounding area is found to be concentrated along the subduction zones in Western Pacific Ocean, with connection towards the inland high mountains such as the Himalaya (Figs. 1 and 2). The other tectonic regions hold relatively low seismicity, in distribution across large areas of the inland

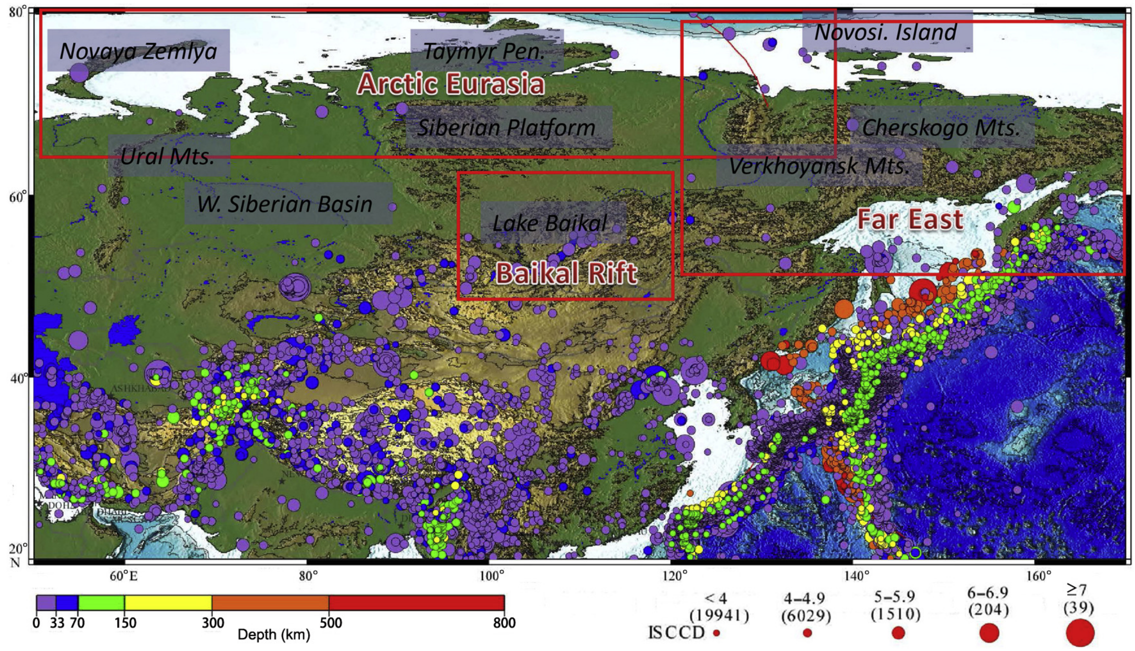

Figure 2. Regions in the Eurasian continent treated in this paper: Arctic Eurasia (Chapter 2), Baikal Rift (Chapter 3), Far East (Chapter 4), respectively. Seismicity information is taken by ISC (1964–2002).

plateau, in particular at the Baikal Rift Zone, Tibetan Plateau and northeastern China. The volcanic activities also indicate small volumes over the whole Eurasian continent, at similar locations with seismicity in wide areas inland near the Baikal Lake and central mountains such as Altai, Tianshan and Kunlun. Surface wave tomography images show a cross-section of the upper mantle over a whole continent, with clear contrast between cold mantle regions such as the Siberian cratons and relatively hot mantle areas at the subduction zones in the western Pacific (Ritzwoller and Levshin, 1998; Yanovskaya and Kozhevnikov, 2003).

The northern part of the Eurasian Plate, with its center in the great "Siberia", connects with adjacent plates at the eastern edge; North American Plate which also contains the Far East of Russia, Okhotsk micro-Plate including Kamchatka Peninsula (Fujita, 1978; Parfenov and Natal'in, 1986; Fujita et al., 1990; Nokleberg et al., 2001, Fig. 2). At the plate boundary, which continues from the Arctic Ocean between the Eurasian and the North American plates, there is micro-seismicity associated with extensional stress between the two plates mentioned above. In contrast, the Okhotsk micro-Plate is characterized by high seismicity and intra-plate deformation involving compression stress by both the Eurasia and North American plates (Imaev et al., 2000). Moreover, high seismic regions are identified along the plate boundary between the Amur micro-Plate and Eurasian Plate (Siberian Craton), which is occupied by Stanovoy and Yablonovy Mountains, and extends to the Baikal Lake having relative E–W movement between the two plates (Mackey et al., 2010). Lake Baikal is characterized by a striking rift zone, in spite of its location exactly in the middle of huge Eurasian continent. A detailed explanation of the existence of the Baikal Rift is given in next Chapter.

Specific seismic and volcanic activities are identified within the Arctic of the Eurasia. The recent development of field surveys, laboratory measurements for supra-crustal rocks, satellite geodetic measurements such as GPS, together with the remarkable advance in computer sciences have greatly improved the knowledge of ongoing lithospheric activity and deformation processes. The dynamics and strength of the continental lithosphere are compiled based on the data from seismic anisotropy, gravity studies, geological drillings and modeling simulation (Sherman and Lunina, 2001). The stress distribution compiled in elastic lithosphere indicates the complex features of a combination of the compression, shearing and extension regimes of each tectonic province.

In central and southern parts of Eurasia, the predominant direction in N–S compression is identified. Conversely, the northern part of the Eurasia including the Siberian craton and the western Siberian Basin is tectonically stable attributed by small stress distribution. Moreover, E–W compression is found at the Ural Mountains which is located between two adjacent Pre-Cambrian cratons (Brown et al., 2006). In the area from Baikal Rift to Tibetan Plateau, sporadic distribution of shearing, an extension stress field is recognized inside the wider area of compression field. The feature is explained by the local deformation inside the Eurasian continent associated with relative motion against the Amur micro-Plate. Heterogeneous structure of temperature within the upper mantle might be involved. In order to explain the local concentration of extensional stress in the inland continent, two ideas are presented (Logatchev et al., 1983): one is the far-field passive force involving the collision between India and Asia (Petit et al., 1997), in contrast, the second is the active force mechanism involved in the upwelling of hot plumes from the upper mantle beneath Baikal Rift (Gao et al., 1994).

Remarkable features in deeper parts of the crust and topmost mantle are identified beneath the northern Siberian craton, Yakutia region, by deep seismic surveys with active sources (Suvorov et al., 1997, 1999). The depth and velocity variations are found in the inner crustal structural boundaries (basement topography, the Conrad discontinuity), characterized by high correlation between these boundaries. The Moho discontinuity, moreover, has large velocity variations in 7.7–9.0 km/s, with thickened crust particularly found in the kimberlite province, Western Yakutia (Suvorov et al., 1999). Such velocity changes may be due to the variations in the material composition of the upper mantle rocks or anisotropy (Kobussen et al., 2006). The remarkable crustal structure in ages from Paleozoic to Mesozoic in northeastern Yakutia region (Kolyma-Omolon super-terrain) is quite different from other Pre-Cambrian terrains distributed globally. They are connected with subduction and accretion between Asia and Kolyma-Omolon terrains (Layer et al., 2001).

Regarding the deeper part of the upper mantle, in addition, many long-range seismic profiles were carried out in the mainland of Russian by using Peaceful Nuclear Explosion (PNE). Heterogeneous structure of the upper mantle beneath a large area of Siberia was obtained, with identification of major mantle seismic discontinuities at depths of 410, 520 and 680 km, respectively (Thybo and Perchuc, 1997; Pavlenkova, 2007). The QUARTZ profile, some 3850 km in length, demonstrates the existence of failed rift systems, and the delaminated "tectosphere" in the upper mantle beneath the West Siberian Basin, involving thermal disturbance at 410 km discontinuity (Morozova et al., 1999). However, in models with lateral heterogeneities, priority over the layering is identified as a connection between velocity anomalies in the upper mantle and large basement structures (Suvorov et al., 2010, 2013). A thermal fluctuation beneath the Siberian platform has also been revealed by deep sounding using PNE sources. Partially molten and delaminated lithosphere was identified beneath the western Siberian Basin, and a depression of 410 km seismic discontinuity was detected and associated with high geotherms on the surface of the Basin (Cherepanova et al., 2013; Kuskov et al., 2014).

3. Baikal Rift Zone

The Baikal Rift Zone (BRZ), located in southern part of Siberian craton, is adjacent to large orogenic mobile belts (Sharyzhalgay, Sayan-Baikal, and Mongol-Okhotsk sutures) of Paleozoic–Mesozoic ages, together with the Mongolia–North China craton to the south (Gordienko, 2006). The BRZ is situated almost central portion of the Eurasia continent, where is far from subduction zones in western Pacific, along with Tibet-Himalaya orogenic belts (Fig. 2). The BRZ has tectonic characteristics of typical rift systems under extensional regime with higher heat flows compared with surrounding areas (Golubev, 2000; Poort and Klerkx, 2004). These tectonic features are considered to be involved in the Cenozoic volcanic activities and also the currently observable seismicity in vicinity of BRZ (Sherman and Gladkov, 1999; Radziminovich et al., 2013, Fig. 3).

The BRZ has been considered to be formed in Cenozoic ages by both the source factors of active and passive origins. A crustal extension regime associated with underlying mantle plumes was suggested as the active origin (Zorin et al., 1989; Gao et al., 1994). On the contrary, extensional stress related with the India-Eurasia continental collision was supposed to be the candidate for tectonic passive source (Petit et al., 1997). A formation scheme of the BRZ, as pointed out by Zorin et al. (2003), can be controlled by three factors: that is, (1) mantle plumes, (2) older (pre-rift) linear lithosphere structures positioned relative to the plumes, and (3) favorable orientation of far-field forces.

Crustal thickness beneath BRZ was investigated down to 40–43 km in depths from active source surveys (Puzirev et al., 1979; Song et al., 1996; Suvorov et al., 2002) and only in the south-western flank (beneath Tunka depression) the Moho drops to 45–47 km (Suvorov et al., 2002). The result is almost contradictory to the thin-skinned crustal structure generally understood to form rift systems. Why has the thick crust been created? The receiver function analysis by Gao et al. (2004) determined the Moho depth about 35 km, however, only beneath one of the temporary stations, located in central Lake Baikal. Thybo and Nielsen (2009) found a magmatic intrusion in the lower crust, which could compensate the Moho uplift, but it is contrary to the distribution of the heat flow (Poort and Klerkx, 2004; Golubev, 2009). The thick crust in BRZ is also supported by a combined interpretation of the crustal section derived from both geophysical and

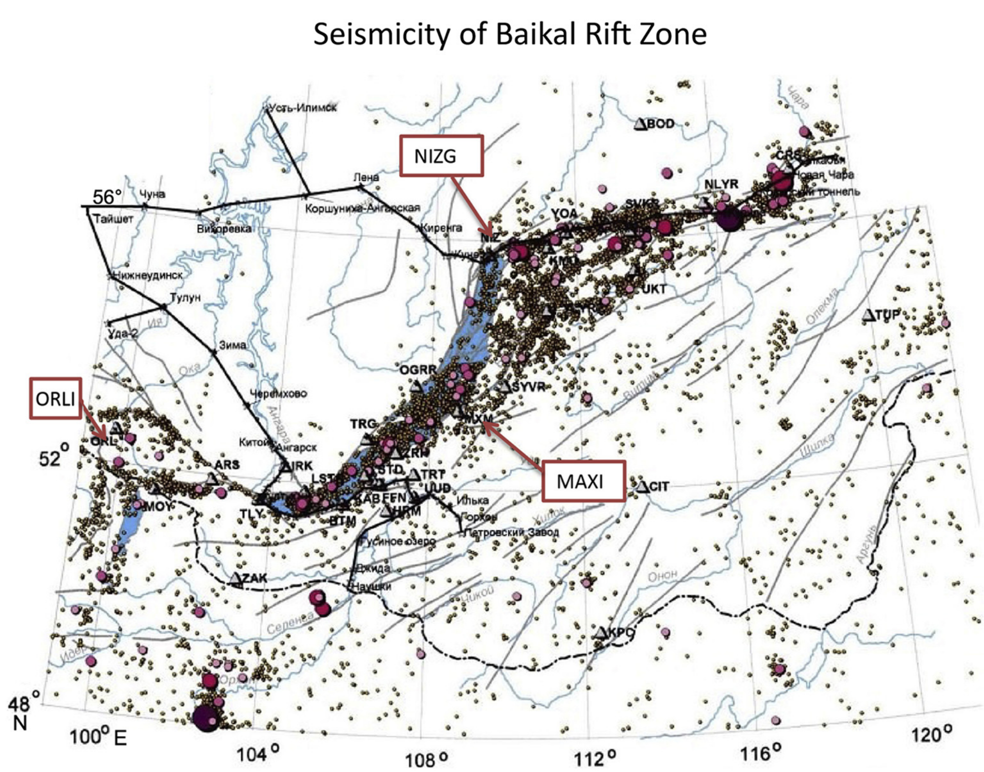

Figure 3. Seismicity of the Baikal Rift Zone (BRZ). Hypocenters are determined by the regional network of the Russian Academy of Science (RAS). Station names are: "Maksimikha (MAXI)" in the middle, "Orlik (ORLI)" in East Sayan and "Nizhneangarsk (NIZG)" in the north of BRZ.

geological information (Zorin et al., 2002). However, the uppermost mantle of BRZ was discovered to be a layer with abnormally low velocities of 7.6–7.9 km/s and a thickness almost 20 km (Puzirev et al., 1979; Song et al., 1996), where north-western boundary of this layer was determined along the northwest shore of Lake Baikal. In addition, observations of bottom stations in the northern part of Lake Baikal, such an anomaly beneath the Moho (at the depth 40 km) was not detected (ten Brink and Taylor, 2002). Several large tectonic sutures and pre-Cenozoic thrusts are believed to be the result of past collision processes between Siberian Platform and Mongolia–North China continent (Sharyzhalgay, Sayan-Baikal, and Mongol-Okhotsk sutures) (Gordienko, 2006).

Rayleigh waves' tomography and gravity anomalies image that the top of mantle plumes exist in the upper mantle beneath BRZ (Zorin et al., 2003). The teleseismic shear wave splitting analysis demonstrates a disturbance of anisotropy in the upper mantle, suggesting effects from hot mantle plumes (Gao et al., 1994). On the basis of depth variations in crustal thickness derived by deep seismic surveys, only 40% isostatic equivalence can be compensated. The resultant 60% isostasy has to be considered the effect from heterogeneity of density in wider areas of the upper mantle. In order to investigate the deep structure of BRZ, several tectonic factors should be taken into account; these are, the shapes of mantle plume, cratonic crustal structure before the formation of the rift, distance from the mantle plume, and an orientation of far-field forces against the collision direction between Indian - Himalaya continental blocks (Zorin et al., 2003).

By utilizing teleseismic waveforms recorded at temporary and permanent stations, velocity structure in the crust and uppermost mantle beneath BRZ was obtained from the analysis of receiver functions and shear wave splitting (Gao et al., 1994; Kanao et al., 2005; Zhao et al., 2006; Ananyin et al., 2009). In next few sentences, major results from receiver functions (Ananyin et al., 2009) are summarized. Velocity models down to the depth of 65 km are imaged based on the records collections while two years in 2004–2006 from the broadband seismic station "Maksimikha (MAXI)" in the middle of BRZ, at "Orlik (ORLI)" in East Sayan region and at "Nizhneangarsk (NIZG)" on north of BRZ, respectively (Fig. 3). The velocity structure has been inversely modeled by a reliable receiver function P-to-S method which efficiently uses the most informative S-waves in the code of the P-waves.

Due to the different conditions in the formation of deep structure beneath the stations, all the models differ considerably from each other. The models, which enable to design the seismic velocities beneath the northern and central parts of BRZ, are the most interesting. The models of the crust and the upper mantle obtained from ORLI are rather complex: the high-velocity layers alternate with those of low-velocity that is expected for the zone where the ancient Siberian platform and the Central Asian folded belt meet. Deployments of broadband observations around BRZ enable us to obtain more accurate velocity models of the lithosphere beneath the center and flanks of the zone. Long-term observations are most valuable because a large quantity of the seismic events, from all parts of the Earth, allow us to investigate the velocity structure in the different directions from the stations, which is important for such tectonically complex regions as the BRZ.

4. Far East Asia

The characteristic tectonic features of the crust and upper mantle around the Magadan-Kolyma region, Far East Asia, in the Russia Federation, are summarized in this Chapter by the data from deep seismic explorations and seismicity in the area (Fig. 2). The continental crust of the Far East, located further eastward from the great "Siberia" in the middle of Eurasia, was formed by the amalgamation process in the Mesozoic period by a number of small continental blocks. The eastern edge of Eurasian Plate, including the Siberian craton and the Kolyma-Verkhoyansk folded belt, is mainly connected to two plates: the first is the North American Plate, containing Chukotsk Peninsula, Kolyma Platform and Chersky Mountains; the second is the Okhotsk micro-Plate, including Magadan region, Okhotsk Sea and Kamchatka Peninsula, respectively (Fig. 4).

The plate tectonics of the area from the Verkhoyansk ranges to the Chukotsk Mountains represent a complex feature. At the plate boundary between the Eurasian (Asian) and North American plates (that contains Chukotsk Peninsula), seismicity associated with compression stress toward the south (into the Okhotsk micro-Plate) between the two plates is recorded (Fujita, 1978; Fujita et al., 1990; Mackey et al., 1998; Imaev et al., 2000). In contrast, the coastal area of the Far East, along the Arctic Ocean, is characterized by the occurrence of high seismicity involving NE–SW extension stress at the boundary between the Eurasian and North American plates. The plate boundary and high seismic area continue into the Arctic Ocean and is as a result of a high heat flow. Moreover, from seismic travel-time inversion analysis, the crustal thickness is determined as 20–30 km (Mackey et al., 1998). The thickness is smaller than the adjacent area, therefore, the plate boundary appears to have the features of a rift-like structure. Towards the southern and inland direction from the Far East into the Eurasia continent, highly seismic regions are located along the plate boundary between the Amur micro-Plate and Eurasian Plate (Siberian Craton). The boundary continues to the Stanovoy and Yablonovy Mountains, and then extends to BRZ. The seismic activity might associate with the EW relative movement between the above two plates.

Deep seismic explorations around the Magadan-Kolyma region started in the 2001 summer season to investigate the detailed crustal structure and the relationship with conversion tectonics of Kolyma Platform–Chukotsk Peninsula (Ronin and Lebedkin, 2007; Surkov et al., 2007). The total seismic profiles are approximately 2000 km in length, dividing into several short profiles conducted within a few years of summer seasons. The southern end of the profile starts at the margin of Okhotsk Sea (Magadan), extending into Kolyma Platform, Chukotsk Mountains, Chukotsk Sea, and terminate at Wrangel Island. The profile crossed the plate boundary between Okhotsk Plate (to the south) and North America Plate (to the north). The scientific purpose of the exploration was to define the present crustal velocity structure in order to get a better understanding of the formation of Kolyma Platform-Chukotsk Peninsula region which were formed chiefly in Mesozoic age. One of the main targets was to find the 'crustal roots' of the complicated system in these geological terrains and micro-continents. In the area, Mesozoic collision structures (not only in mountain area) are disposed. The near-vertical reflection data obtained represent the clear difference between the fragments of older platforms and younger fold belts of the Far East.

In western part of Chukotsk Peninsula, there is a triple junction between the Eurasia Plate and the other two plates as mentioned already. In the southern part of the seismic profiles, the Okhotsk Plate has been in undergoing deformation as a result of the convergence tectonics between North American and Eurasian plates. On the other hand, the northern part of the boundary between the North American and Eurasian plates has an extensional regime caused by the Moma rift system, as well as the Kolyma River basin. From the regional seismic network of the Russian Academy of Science (RAS), high seismicity was observed around the southern part of the profile (Chersky seismic belt) in the Okhotsk micro-Plate. A lithospheric deformation and compression have formed a

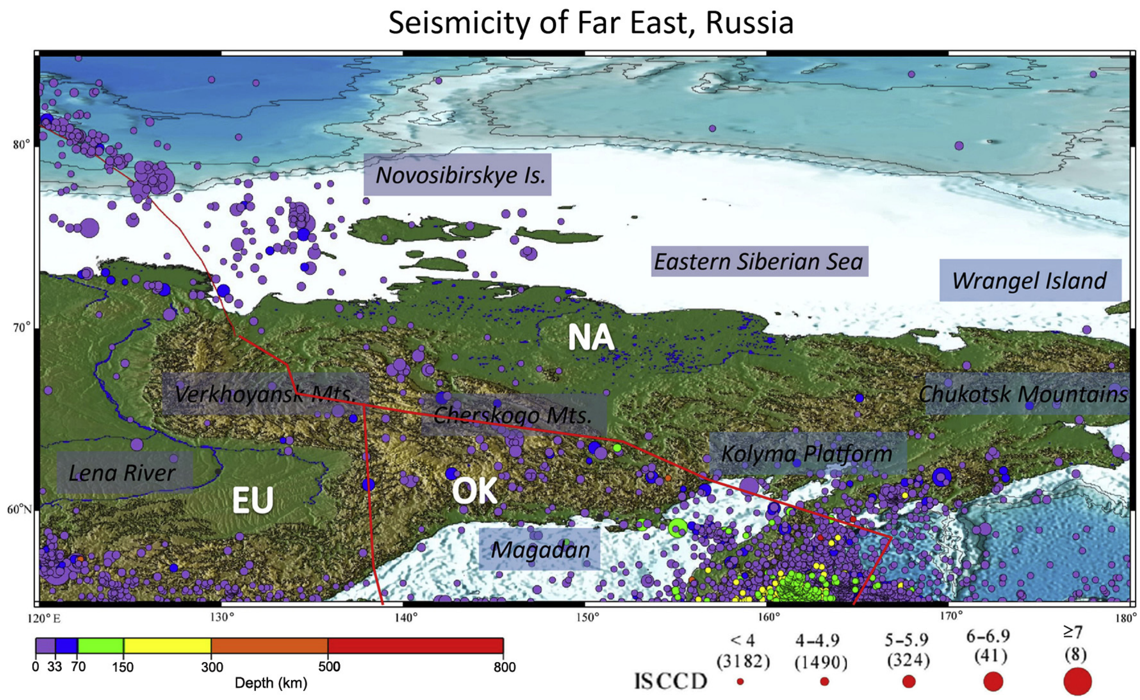

Figure 4. Seismicity of Far East, Russia. Seismicity information is taken by ISC (1964–2002). The red lines indicate the plate boundaries between North American Plate (NA), Okhotsk micro-Plate (OK) and Eurasian Plate (EU).

convergence of North American and Eurasian plates, and from which the relatively high seismicity originates (Fig. 4). Crustal thickness derived from travel-time inversion by using local seismic events represents a variation in 36–40 km in southern half of the profile (Mackey et al., 1998). Accordingly, it is significant to define the precise crustal structure of the Chukotsk area, involving the hypocentral distribution and an origin of local seismicity. A majority of strike-slip mechanisms for the seismic events occurring along the active faults were affected by the compression stress inside the Okhotsk micro-Plate (Riegel et al., 1993). A seismic occurrence ratio in a day inside the plate could become 65% in maximum (Mackey et al., 2003) and is higher than that of the subduction zone beneath the Kamchatka Peninsula (35–65%) when disregarding the event magnitude.

If the assumption that the Bering Sea is just a single micro-Plate, zonal seismicity with E–W trending could be explained in wide areas from Chukotsk Mountains to Kamchatka Peninsula by an effect from subducting oceanic plates westward beneath the Chukotsk Peninsula. The seismic occurrence mechanisms, moreover, are dominated by the reverse faults involving the subduction of Bering Plate (Oceanic Slab) (Mackey et al., 1997; Imaev et al., 2000). A remarkable study of the upper mantle beneath the Far East was conducted at the subduction zone of the Pacific Oceanic Plate, analogous to the continent-continent collision tectonics such as the India-Himalaya-Tibet. In the upper mantle beneath the Chukotsk Peninsula, in contrast, remnant subducted slabs of the ancient Kula Plate (northern past plate adjacent to Pacific Plate) are supposed to exist by local seismic tomography (Gorbatov et al., 1999, 2000). Moreover, the upper mantle structure of the marginal sea and subduction zones in northeastern Eurasia was also clearly imaged from Rayleigh wave regional tomography (Bourova et al., 2011).

From the above evidence, as a whole, the Far East region has evolved as a result from accumulation of many small continental blocks after the Mesozoic age in Earth's history (Parfenov et al., 2009). The boundary regions between these small terrains are considered to hold the remains of the evolutional process such as the evidence of "crustal root" and "suture zones" in deep crustal level (Ronin and Lebedkin, 2007; Surkov et al., 2007). An understanding of the structure and tectonics of the wide areas from Siberia to Far East is expected to reveal the dynamic history process of the surface layer in Eurasian Arctic, as well as the other tasks for earthquake prediction and disaster prevention in East Asia, including Japanese island.

5. Arctic Ocean

Tectonic features of the Arctic Ocean and surrounding areas are summarized in this Chapter. The mid-ocean ridges in the Arctic Ocean, which are continued from the North Atlantic Ocean, are the boundary between Eurasia and the North American plates. The mid-Arctic ridges connect eastward to the Laptev Sea, Far East Asia, after passing through the eastern Siberian continent. The plate boundaries are generally known to be tectonically stable and low seismic activities. The Gakkel Ridge in the middle of Arctic Ocean is defined by its ultra-low spreading speed with less than 1 cm/y, together with the existence of small volcanic activities at the spreading sea-floor (Edwards et al., 2001). A ship-based marine seismic survey combining reflection and refraction methods revealed the fine crustal structure across the Mendeleev Ridge from the Podvodnikov Basin to the Mendeleev Basin (Lebedeva-Ivanova et al., 2006). An evidence of continental crust was identified beneath the Mendeleev Ridge, which has been altered during the development of Arctic Basin and associated magmatism by comparison with information from ocean bottom sampling.

An integrated mapping of crustal thickness for entire areas in the Arctic Ocean was demonstrated by gravity inversion (Alvey et al., 2008), by linking interpretation between plate reconstructions model of the high Arctic. The tectonic evolution of the Arctic since Pangea breakup is summarized by Shephard et al.

(2013), with integrating constraints from surface geology and geophysics with mantle structure. The tectonic evolution of the circum-Arctic, including the northern Pacific, Siberian and North American margins, since the Jurassic has been punctuated by the opening and closing of ocean basins, the accretion of autochthonous and allochthonous terranes and associated deformation. Tectonic setting, structure and petroleum geology of the Siberian Arctic offshore sedimentary basins are reported by Drachev (2011) and Saltus et al. (2011). They summarizes the results of geological and geophysical studies of the Siberian Arctic Shelf (Laptev, East Siberian and Chukchi seas), which is one of the largest continental shelves on Earth. The region consists of more than 20 significant sedimentary basins of variable age and genesis which are expected to bear significant undiscovered volumes of hydrocarbons.

Seismicity in the Arctic Ocean is discussed on the basis of hypocentral distribution by a newly developed "International Seismological Centre (ISC) location algorithm" (Bondár and Storchak, 2011; International Seismological Centre, 2011) (Fig. 5). Hypocenters are more concentrated along the plate boundaries such as the mid-Atlantic Ridge to the Gakkel Ridge in the Arctic Ocean. The clustering seismicity, on the contrary, is identified at several spots inside both continents and oceans. Recently small earthquake activities at mid-oceanic ridges and transform faults in deep oceans were investigated by using the local network of hydrophone arrays (Dziak et al., 2009). The seismic events have not been detected by conventionally deployed onshore stations globally distributed. At the bottom of the Gakkel Ridge, moreover, small earthquakes are newly identified by combining recently developed local onshore networks installed by cooperation between Norway and Russia (Antonovskaya et al., 2014).

Currently progressing global warming in particular striking in the Arctic has been enhancing the speed by which the sea-ice spreading area in the Arctic Ocean is diminished, followed by the advance of international trading cooperation as well as other economic activities in the surrounding areas of the Arctic. However, new international conflict, such as an investigation of the sea-floor embedded resources in the Arctic Ocean and surrounding continental margins. It is expected in future that the continuous monitoring of seismic activities occurring in the bottom of Arctic oceans could be developed by making accurate detection of arrival times and waveforms of seismic phases recorded by hydrophone data. The micro-seismic and volcanic activities, together with details of the crustal structure in deep oceans, would be made clearer using such data. It also encouraged the development of international collaborative initiatives in observing networks which aim to monitor the environmental variations in the Arctic Oceans. It is recommended to establish a tight connection with existing global networks such as the Arctic Ocean Observing System (AOOS) in the Global Ocean Observing System (GOOS); the Sustaining Arctic Observing Networks (SAON) involving the International Arctic Science Committee (IASC) of the International Council of Science (ICSU).

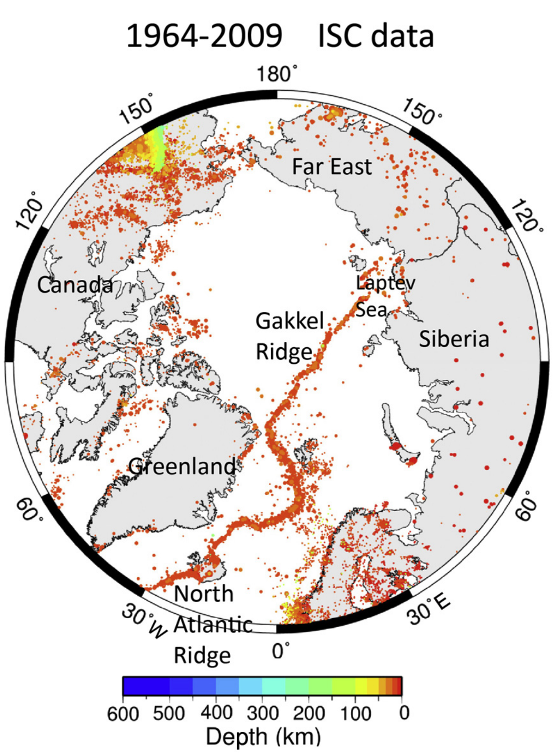

Figure 5. Seismicity of the Arctic Ocean and surrounding regions in 1964–2009. Hypocenters are determined by a new ISC location algorithm (Bondár and Storchak, 2011).

6. Greenland and Northern Canada

Although Greenland is the largest island in the world with its land area in 2,180,000 km^2, the majority of the island is covered by ice sheet at most 3000 m in thickness. Greenland is dominated by crystalline crustal rocks of the Precambrian shield, formed during a succession of Archean and early Proterozoic orogenic events which stabilized as a part of the Laurentian shield about 1600 Ma (Brooks, 2008; Henriksen, 2008). These outcrops are limited to coastal areas, therefore, current tectonic activities such as the occurrence of earthquakes and volcanoes are very few compared with other tectonically active regions. The marginal part of Greenland has been considered to be under extensional tectonic stress between the adjacent areas after mid-Mesozoic age. The crustal structure of southeast Greenland margin was derived from a joint seismic tomography by using refraction and reflection data (Korenaga et al., 2000), giving the typical appearance of a passive margin. Recently, in addition, a detailed crustal structure of the Greenland-Iceland Ridge was inferred from wide-angle seismic investigation (Reiche et al., 2011). A transitional continent-ocean structure was clearly obtained at the passive margins as well.

The crustal structure of Ellesmere Island, which is westward adjacent to Greenland, is imaged by broadband seismic deployments, giving a detailed extensional signature and geological evolution history (Stephenson et al., 2013). Another active source surveys in the sedimentary basin and underlying crust have been carried out at the Ellesmere Island and the Greenland continental shelf towards the Lomonosov Ridge, in the Arctic Ocean (Jackson et al., 2010). A regional variation in crustal thickness in Amerasia Basin and High Arctic was demonstrated by using seismic wave propagation of Lg and Sn phases (Chiu and Snyder, 2014). A large variation in crustal thickness was revealed over the entire basins and ridges in the Arctic Ocean. From these surveys, consequently, regional structure and tectonic history of several low seismicity areas in the Arctic were defined. Precious datasets have been accumulating to explain the formation process of the Arctic Ocean as well as the surface environmental variations.

The structure of the crust and lithospheric mantle in the majority of parts of the tectonic terrains in Canada (Harrison et al., 2011) have been investigated by the deep seismic surveys of LITHOPROBE program (Clowes et al., 1999; Percival et al., 2012). In the last few decades, many interesting features of the continental growth process, such as the delaminated lower crust and its subduction regimes into the mantle lithosphere, have been identified in Archean and Proterozoic terrains of the Canadian Shield (Cook et al., 1999; Gabriela et al., 2005; Lynn et al., 2005). A continental growth process of the North American continent with its nuclei at the Hudson Bay region has been gradually delineated by the active source deep surveys by the LITHOPROBE.

From the compiled data of Natural Resources Canada (Fig. 6), stationary seismicity from northern to eastern part of Canada is described as follows. North to Eastern Canada is occupied by a stable continent inside the North American Plate and, as a consequence, presents relatively low earthquake activity. Lately, approximately 350 earthquakes in northern Canada have occurred each year. Of this number, perhaps 4 exceed magnitude 4, 30 exceed magnitude 3, and about 25 events are reported felt. The seismographic network of earthquakes Canada can detect all events exceeding magnitude 3 in eastern Canada and all events magnitude 2.5 or greater in densely populated areas. The causes of earthquakes in northern–eastern Canada are not well understood. Unlike plate boundary regions where the rate and size of seismic activity is directly correlated with plate interaction, the region is a part of the stable interior of the North American Plate. Seismic activity in areas like these seems to be related to the regional stress fields such as the deglaciation as mentioned the details in next paragraph, attributed by the earthquakes concentrating on the spots in crustal weakness.

Several specified regions in the Arctic, such as at the margins of Greenland, northern Canada (Fig. 6) surrounding the Hudson Bay, as well as the rims of Baltic shield (Fennoscandia), have been identified as the places where the thick ice sheet covered in the northern hemisphere. In these areas, seismicity involving “Post Glacial Rebound” has been reported after deglaciation (Anderson, 1986; Chung, 2002; Wilson and Bell, 2011; Kozlovskaaya, 2013). The earthquake events relating to deglaciation are known to be generated at the continental margins where the thick ice sheet was overlaid. Moreover, ice-quakes involving the calving of glaciers and ice sheet dynamics occur at similar places in marginal parts of ice covered continents. This kind of ice related events are known to be connected to recent global warming and is particularly evident in the Arctic.

One remarkable example is the strong earthquake reaching 6.1 on Richter scale that hit the Svalbard Island on 21 February 2008 (Pirli et al., 2010). The epicenter was located in Storfjorden area, 10 km under the sea bed and 136 km from Longyearbyen city. Several smaller shakes were also registered both before and after the main event took place. There had been no damage caused in Longyearbyen before the occurrence of the earthquake. The earthquake was recorded by all regional seismometers as well as by many other stations around the world. The previous strong earthquake took place on 18th January 1976 and had a magnitude of 5.5. The hypocenter of this event was located on the margin of the European continental crust, and therefore, the events are plausibly associated with the crustal uplift after deglaciation. Alternatively, these large events could relate to the ice-mass movement or calving of glaciers in the vicinity of Svalbard, however, the mechanisms consistent with a double-couple, in which case the glacier motion seems less likely.

The Greenland ice-sheet and its response to climate change has potentially a great impact upon mankind, both through sea-level rise and modulation of fresh water input to the oceans. Monitoring the dynamic response of the Greenland ice-sheet to climate change is a fundamental component of long-term observations in global Earth science. In Greenland, the largest outlet glaciers draining the northern hemisphere’s major ice cap have suffered rapid and dramatic changes during the last decade. They have lost kilometers of ice at their calving fronts, thinned by 15% or more in

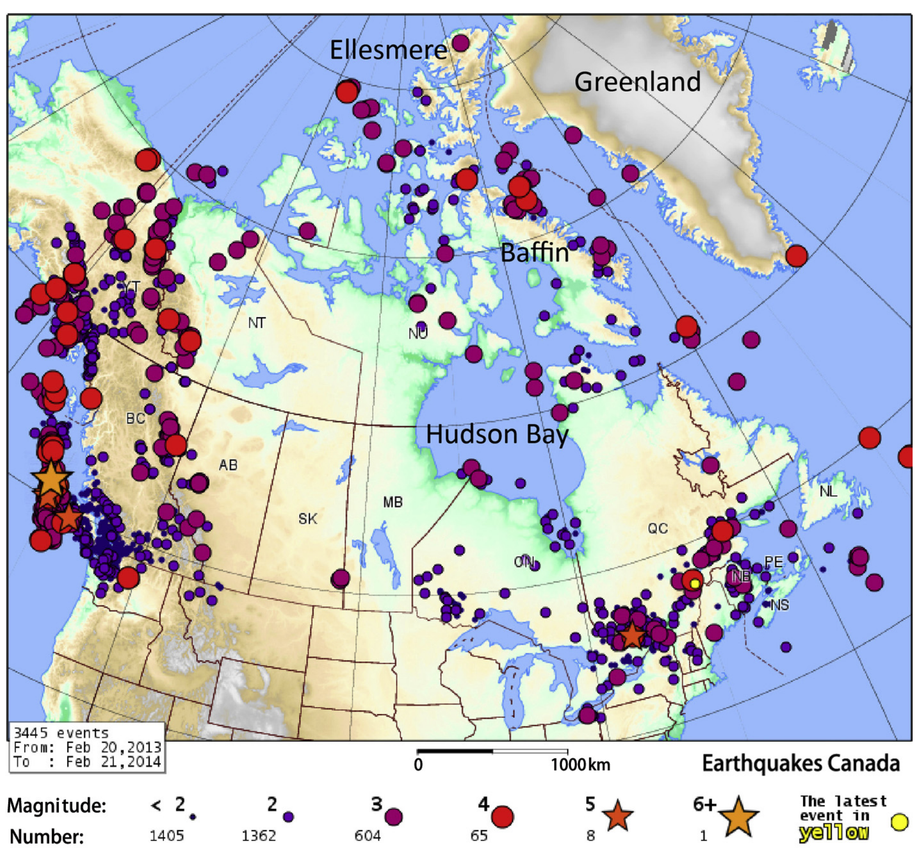

Figure 6. Seismicity in Canada and surrounding areas in the Arctic for the last one year from present in 2014 February, based on the compiled data at Natural Resources Canada.

their lower reaches, accelerated by factors of 1.5 (Howat et al., 2005; Rignot and Kanagaratnam, 2006), and generated increasing numbers of glacial earthquakes (Ekström et al., 2003, 2006; Nettles and Ekström, 2010). The "Glacial earthquakes" have been observed along the continental margins of Greenland (Fig. 7) with strong seasonality and increasing frequency in this 21st century by the data from Global Seismographic Network (GSN; Butler and Anderson, 2008). During the period of 1993–2006, more than 200 glacial earthquakes were detected, and 95% have occurred at Greenland, with the remaining events in Alaska and Antarctica (Dahl-Jensen et al., 2010).

Although the glacial earthquakes in Greenland are considered to be closely associated with major outlet glaciers at the margins of the continental ice-sheet, tectonic earthquakes are rare, and in some extent explain the paucity of permanent seismic instrumentation in Greenland. Examples of such changes are the increase in frequency of glacial earthquakes in 2001–2005, and spatial variation in glacial earthquake activity, including the recent initiation of glacial earthquake activity at high latitudes on the west coast of Greenland (Ekström et al., 2006; Veitch and Nettles, 2012). The seasonal patterns of glacial events are positively correlated with hydrologic variations, significantly increased flow speeds, calving-front retreat, and thinning at many outlet glaciers. These long-period surface waves generated by glacial earthquakes are incompatible with standard earthquake models for tectonic stress release, but the amplitude and phase of the radiated waves can be explained by a landslide source model.

Seismicity around Greenland including tectonic or volcanic events was investigated by applying a statistical model to the globally accumulated data. Calculated b values, the Magnitude-frequency-dependence parameter, indicate a slight increase from 0.7 to 0.8 in 1968–2007, implying that the seismicity including glacial events around Greenland have become slightly higher during the last four decades (Kanao et al., 2012). The detection, enumeration, and identification of smaller glacial earthquakes are limited by the propagation distance to globally distributed stations of GSN. Glacial earthquakes have been observed at stations within Greenland, but the coverage has been very sparse. In order to define the fine structure and detailed mechanisms of glacial earthquakes, a broadband, real-time network needs to be established throughout the ice-sheet and its perimeter.

7. Deep interiors and global networks

From a timeline of the number of seismic stations reporting to the International Seismological Centre (ISC) in the Arctic during the last fifty years, more than 17,000 stations have been operated over the whole globe, including more than 1000 stations in the Arctic. The number of stations in the Arctic has increased with time over the last half century by almost ten times compared with the number in 50 years ago. In 2010, 6711 stations worldwide including 461 in the Arctic were reporting. Existing permanent seismic stations allows resolution of the structure beneath the Arctic is sufficient to detect fundamental differences in the lithosphere beneath continents and oceans, however, cannot clearly define the structure within each tectonic terrain. In addition, seismicity around the Arctic is limited by the sparse station distribution and the detection level for earthquakes and remains

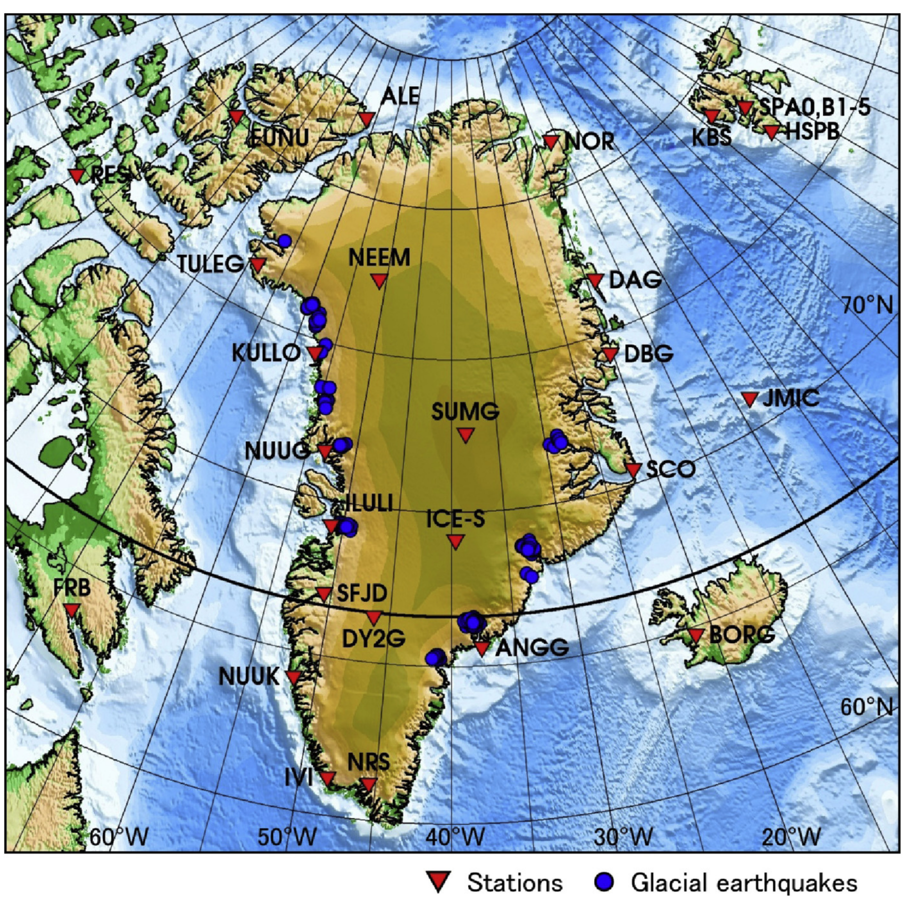

Figure 7. Distribution of glacial earthquakes around Greenland and vicinity in 1993–2008 (Blue circles). Seismic stations including both permanent and temporal are shown by red triangles. Hypocenters are taken from Nettles and Ekström (2010). Figure is modified after Kanao et al. (2012).

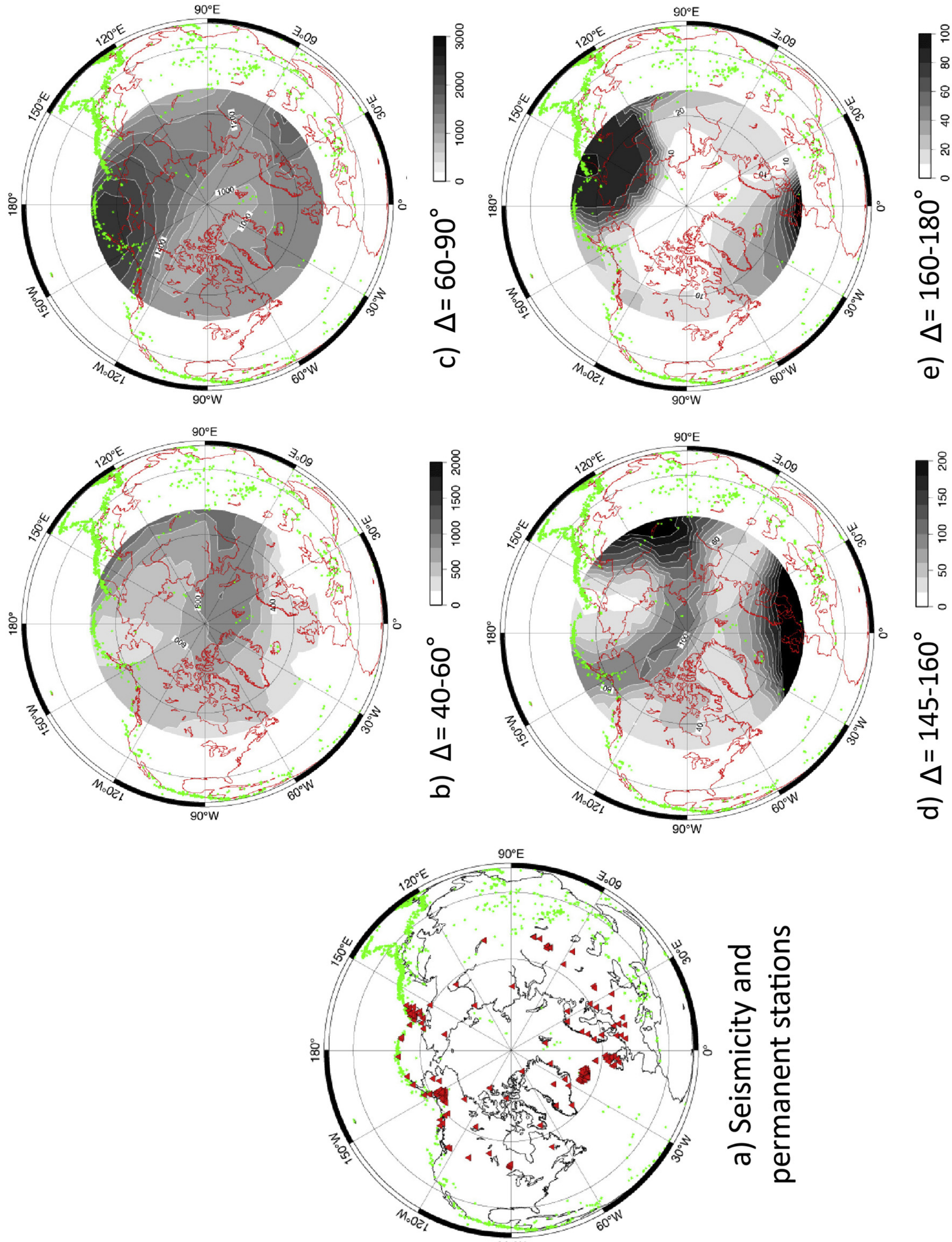

Figure 8. (a) A distribution map of the permanent GSN stations in the Arctic region (red color; data compiled from IRIS/DMS and PASSCAL). Distribution of teleseismic event numbers at each location in the Arctic counted from a list including earthquakes with magnitude greater than or equal to 5.5 in the period of 1990–2004, for the different hypocenter distance ranges (indicated by green color). (b) 40°–60°, (c) 60°–90°, (d) 145°–160° and (e) 160°–180°, respectively. Gray contour scales indicate the accumulated earthquake numbers that are counted at each location using an earthquake list for the period in 1990–2004.

inadequate for full evaluation of tectonic relating seismic activity. Therefore, an enhancement of the deployments of permanent stations in the Arctic could provide an opportunity for contribution to global Earth science, not only for local or regional research. The obtained data are eventually sent to global data systems such as GSN. Deep seismic studies by active sources would lead to detailed achievements for the target areas.

The presently revealed crustal architecture and formation mechanism of super-continents and their relationship to the development of super-plumes are also related to our knowledge of the structure, and dynamics of deep interior of the Earth. Any scales of heterogeneity, anisotropy at the Core-Mantle Boundary (CMB) and the overlying D″ layer helps us to accumulate the knowledge of the chemical and physical interactions between the Core-Mantle boundary and deeper interiors of the Core. The up- and down-welling processes of super-plumes in the mantle beneath Arctic, in particular for the Eurasia continent, has a great deal of significance to obtain clear information on mantle dynamics and the development of super-continents. By using the accumulated data from bi-polar regions, it is expected that further achievements in the study of the Earth's deep interior, the shallow part of the Earth, as well as the physical interaction between solid Earth and overlying multi-spheres (cryosphere, ocean, and atmosphere).

An open collaboration creates a foundation welcoming other international interest and participation, not only for seismological monitoring at the Greenland's ice sheet, but also for other observations using the infrastructure being developed. The International Polar Year (IPY 2007–2008) was a great opportunity to initiate the new program by international collaboration. Continuous digital records from GSN and their precursor networks extend back more than 40 years, and hence open up the possibility of using seismic data to investigate climate change. A new monitoring network such as in Greenland (the Greenland Ice Sheet Monitoring Network (GLISN); Dahl-Jensen et al., 2010; Clinton et al., 2014) significantly increases coverage in the surroundings of the Arctic. The GLISN has also a principle role in the Sustaining Arctic Observing Network (SAON) of the International Arctic Scientific Committee (IASC) under the International Council for Science (ICSU). Additionally, another large IPY-endorsed program was the 'Polar Earth Observing Network' (POLENET; Wilson and Bell, 2011) which aimed to establish a geophysical network to cover a whole Antarctic continent as well as Greenland, and Lapland as the Arctic domain.

The seismic data compiled in POLENET are being used to clarify the heterogeneous structure of the Earth, particularly in the Antarctic region, by studying the crust and upper mantle and the Earth's deep interiors. Fig. 8a represents a distribution of the permanent GSN stations in the Arctic together with hypocenters in the northern hemisphere. These data are compiled from IRIS/DMS and PASSCAL and hypocentral data are collected in 1990–2004. Fig. 8b,e demonstrates the distribution of teleseismic event numbers at each location in the Arctic counted from a list including earthquakes with magnitude greater than or equal to 5.5 in the period of 1990–2004, for the different hypocenter distance ranges. For example, the hypocentral 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. The longer hypocentral distances over 145°, moreover, would be appropriate for the observation of the core diffracted phases of Pdiff, and Sdiff, and the core phase of SKS. Mapping of observable seismicity for the individual epicenter distance groups has a merit to figure out the sufficient coverage to utilize the regional and teleseismic events for the study on deep interiors of the Earth. In addition to conventional seismological research targets (structures of the crust, mantle and core), the seismic stations developed at the IPY can be utilized for monitoring geographical variations in climate indicators, as the legacy of IPY and beyond.

8. Conclusion

In this paper, an overview of the structure and tectonics of the Arctic is demonstrated by incorporating recently deployed seismic approaches and detailed seismicity of the region. The relationship between seismicity and geodynamic processes in the Arctic are summarized, as well as how these investigations are fruitfully influencing on the surface ongoing dynamics of the Earth among global environmental variability. In particular, the Eurasian continent is largely focused in wide areas of Siberian Arctic, Baikal Rift Zone and the Far East. Though the majority areas of the Arctic are occupied by relatively stable continents, the tectonic history reveals distinct variations during the formation of the present landscapes and crustal structure. A variety of tectonic settings are present in the Arctic such as the collision zones at the plate boundary, deformed areas inside the continents, mantle plumes, rift systems, and so on. On the other hand, one of the remarkable founding is the glacial earthquake activities nearby the Greenland involving global warming. In addition, micro-seismic and volcanic monitoring has now been carried out including at the bottom of the Arctic Ocean. A continuous accumulation of the Arctic data from global networks could definitely contribute to the development of high space resolution analysis, the understanding of the deformation and uplift mechanism involving seismicity, the formation processes of the super-continents, and the bedrock topography and geological structure underneath the ice-sheet, in many parts of the polar region. A complete view of global tectonics could be achieved by advancing inter-disciplinary research in the Arctic, in particular at the Eurasian continent and Greenland. The Arctic is, without doubt, one of the frontiers that remain at present to human beings, and also the place which has a crucial role to clarify the tectonic history and currently ongoing variations on the Earth's surface.

Acknowledgments

We would like to express our sincere appreciation to many collaborators in the studies of Arctic regions, particular about field operations and researches of Siberia, Greenland and Arctic Ocean. We also express our appreciation for involved members of the IPY projects (POLENET; Prof. Terry Wilson of the Ohio State University, Prof. Douglas Wiens of Washington University, and other members), the post-IPY project of the Greenland Ice Sheet Monitoring Network (GLISN; Prof. Meredith Nettles of the Columbia University, Prof. Kent Anderson of the Incorporated Research Institutions for Seismology, and others). The authors also express their sincere appreciation to Dr. Istvan Bondar, Emily Delahaye and Dr. Dmitry Storchak, the Director of ISC, for providing seismicity data in the Arctic. We would also like to express sincere appreciation to the referees for critical readings and useful comments, as well as Prof. M. Santosh and Prof. X. X. Mo of China University of Geosciences (Beijing), Prof. T. Tsunogae of Tsukuba University for their sincere efforts to editorial matters for publishing this article to "Geoscience Frontiers". This work was supported by JSPS KAKENHI Grant Number 26241010 (P.I. by Dr. Masaki Kanao).

References

Alvey, A., Gaina, C., Kusznir, N.J., Torsvik, T.H., 2008. Integrated crustal thickness mapping and plate reconstructions for the high Arctic. Earth and Planetary Science Letters 274, 310–321.

Ananyin, L.V., Mordvinova, V.V., Gots, M.F., Kanao, M., Suvorov, V.D., Tatkov, G.I., Thubanov, T.A., 2009. 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 428, 1067–1071.

Anderson, J.G., 1986. Seismic strain rates in the central and eastern United States. Bulletin of the Seismological Society of America 76, 273–290.

Antonovskaya, G., Konechnaya, Y., Kremenetskaya, E.O., Asming, V., Kværna, T., Schweitzer, J., Pirli, M., Ringdal, F., 2014. Seismological research related to geophysical processes in the European arctic. Polar Science. http://dx.doi.org/10.1016/j.polar.2014.08.003 (in press).

Bondár, I., Storchak, D., 2011. Improved location procedure at the International Seismological Centre. Geophysical Journal International 186, 1220–1244.

Bourova, E., Yoshizawa, K., Yomogida, K., 2011. Upper mantle structure of marginal seas and subduction zones in northeastern Eurasia from Rayleigh wave tomography. Physics of the Earth and Planetary Interiors 183, 20–32.

Brooks, K., 2008. The new geological map of East Greenland. Geology Today 24, 28–32.

Brown, D., Juhlin, C., Tryggvason, A., Friberg, M., Rybalka, A., Puchkov, V., Petrov, G., 2006. Structural architecture of the southern and middle Urals foreland from reflection seismic profiles. Tectonics 25, TC1002.

Butler, R., Anderson, K., 2008. Global Seismographic Network (GSN), IRIS Annual Report, pp. 6–7.

Cherepanova, Yu, Artemieva, I.M., Thybo, H., Chemia, Z., 2013. Crustal structure of the Siberian craton and the West Siberian basin: an appraisal of existing seismic data. Tectonophysics 609, 154–183.

Chiu, K., Snyder, D.B., 2015. Regional seismic wave propagation (Lg & Sn phases) in the Amerasia Basin and high Arctic. Polar Science 9, 130–145.

Chung, W.-Y., 2002. Earthquakes along the passive margin of Greenland: evidence for postglacial rebound control. Pure and Applied Geophysics 159, 2526–2584.

Clinton, J.F., Nettles, M., Walter, F., Anderson, K., Dahl-Jensen, T., Giardini, D., Govoni, A., Hanka, W., Lasocki, S., Lee, W.S., McCormack, D., Mykkelveit, S., Stutzmann, E., Tsuboi, S., 2014. Real-time geophysical data enhance Earth system monitoring in Greenland. Eos, Transactions, American Geophysical Union 95, 13–24.

Clowes, R.M., Cook, F.A., Hajnal, Z., Hall, J., Lewry, J., Lucas, S., Wardle, R., 1999. Canada's LITHOPROBE Project (collaborative multidisciplinary geoscience research leads to new understanding of continental evolution). Episodes 22, 3–20.

Cook, F.A., Velden, A.J., Hall, K.W., 1999. Frozen subduction in Canada's Northwest Territories: lihoprobe deep lithospheric reflection profiling of the western Canadian Shield. Tectonics 18, 1–24.

Dahl-Jensen, T., Larsen, T.B., Voss, P.H., the GLISN Group, 2010. Greenland Ice Sheet Monitoring Network (GLISN): A Seismological Approach. GEUS Report of Survey Activities (ROSA) for 2009, pp. 55–58.

Drachev, S.S., 2011. Tectonic setting, structure and petroleum geology of the Siberian Arctic offshore sedimentary basins. In: Spencer, A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V., Ørensen, K. (Eds.), Arctic Petroleum Geology, Memoir 35. Geological Society, London, pp. 369–394.

Dziak, R.P., Parlk, M., Lee, W.S., Matsumoto, H., Bohnenstiehl, D.R., Haxel, J.H., 2009. Tectono-magmatic activity and ice dynamics in the Bransfield Strait back-arc basin, Antarctica, Proc. 16th Inter. Sympo. Polar Science 59–68.

Edwards, M.H., Kurras, G.J., Tolstoy, M., Bohnenstiehl, D.R., Coakley, B.J., Cochran, J.R., 2001. Evidence of recent volcanic activity on the ultraslow-spreading Gakkel ridge. Nature 409, 808–812.

Ekström, G., Nettles, M., Abers, G.A., 2003. Glacial earthquakes. Science 302, 622–624.

Ekström, G., Nettles, M., Tsai, V.C., 2006. Seasonality and increasing frequency of Greenland glacial earthquakes. Science 311, 1756–1758.

Fujita, K., 1978. Pre-Cenozoic tectonic evolution of northeast Siberia. Journal of Geology 86, 159–172.

Fujita, K., Cook, D., Hasegawa, H., Forsyth, D., Wetmiller, R., 1990. Seismicity and focal mechanism of the Arctic region and North American plate boundary in Asia. In: The Geology of North America. Boulder, (Colo.), Vol. L.. The Arctic Ocean Region, 77–110.

Gabriela, F., Clowes, R., Welford, J., 2005. Constraints on the composition of the crust and uppermost mantle in northwestern Canada: Vp/Vs variations along the Lithoprobe's SNORCLE transect. Canadian Journal of Earth Sciences 42, 1205–1222.

Gao, Sh, Davis, P.M., Liu, H., Slack, P.D., Zorin, Yu. A., Mordvinova, V.V., Kozhevnikov, V.M., Meyer, R.P., 1994. Seismic anisotropy and mantle flow beneath the Baikal Rift Zone. Nature 371, 149–151.

Gao, S., Liu, K.H., Chen, C., 2004. Significant crustal thinning beneath the Baikal Rift Zone: new constraints from receiver function analysis. Geophysical Research Letters 31, L20610. http://dx.doi.org/10.1029/2004GL020813.

Golubev, V.A., 2000. Conductive and convective heat flow in the bottom of Lake Baikal and in the surrounding mountains. Bulletin du Centre de Recherches Elf Exploration Production 22, 323–340.

Golubev, V.A., 2009. Geophysical data confirming lack of Late Cenozoic mantle intrusions in the Earth's crust under the Baikal depression. Doklady Earth Sciences 426, 623–627.

Gorbatov, A., Domínguez, J., Suárez, G., Kostoglodov, V., Zhao, D., Gordeev, E., 1999. Tomographic imaging of the P-wave velocity structure beneath the Kamchatka peninsula. Geophysical Journal International 137, 269–279.

Gorbatov, A., Widiyantoro, S., Fukao, Y., Gordeev, E., 2000. Signature of remnant slabs in the North Pacific from P-wave tomography. Geophysical Journal International 142, 27–36.

Gordienko, I.V., 2006. Geodynamic evolution of late baikalides and paleozoids in the folded periphery of the Siberian craton. Russian Geology and Geophysics 47, 53–70.

Harrison, J.C., St-Onge, M.R., Petrov, O.V., Strelnikov, S.I., Lopatin, B.G., Wilson, F.H., Tella, S., Paul, D., Lynds, T., Shokalsky, S.P., Hults, C.K., Bergman, S., Jepsen, H.F., Solli, A., 2011. Geological map of the arctic. Geological Survey of Canada. http://dx.doi.org/10.4095/287868. "A" Series Map 2159A, 2011; 9 sheets.

Henriksen, N., 2008. Geological History of Greenland – four billion years of earth evolution. Geological Survey of Denmark and Greenland (GEUS). ISBN: 978-87-7871-211-0, 270 pages.

Howat, I.M., Joughin, I., Tulaczyk, S., Gogineni, S., 2005. Rapid retreat and acceleration of Helheim Glacier, East Greenland. Geophysical Research Letters 32, L22502.

Imaev, V.S., Imaeva, L.P., Kozmin, B.M., Mackey, K., Fujita, K., 2000. Seismotectonic processes along boundary of lithospheric plates of Northeast Asia and Alaska. Geology of the Pacific Ocean 15, 211–232.

Intergovernmental Panel on Climate Change (IPCC), 2007. Climate Change 2007: The Physical Science Basis. Contributions of Working Group1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 996 pp.

International Seismological Centre, 2011. On-line Bulletin, http://www.isc.ac.uk. (International Seismological Centre, Thatcham, United Kingdom).

Jackson, H.R., Dahl-Jensen, T., Chian, D., Shimeld, J., Funck, T., Marcussen, C., Asudeh, I., Snyder, D., 2010. Sedimentary and crustal structure from the Ellesmere Island and Greenland shelves onto the Lomonosov Ridge, Arctic Ocean. Geophysical Journal International 182, 11–35.

Kanao, M., Suvorov, V.D., Tatkov, G.I., Toubanov, T.A., 2005. Deep structure and tectonics around the Baikal Rift Zone, Russia, from temporary broadband seismic observations. In: Proc. II Inter. Workshop on "Active Geophysical Monitoring of the Earth lithosphere", pp. 218–222.

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., 2012. Greenland ice sheet dynamics and glacial earthquake activities. In: Müller, J., Koch, L. (Eds.), Ice Sheets: Dynamics, Formation and Environmental Concerns. Nova Science Publishers, Inc., Hauppauge, NY. Chap. 4, 93–120.

Kobussen, A.F., Christensen, N.I., Thybo, H., 2006. Constraints on seismic velocity anomalies beneath the Siberian craton from xenoliths and petrophysics. Tectonophysics 425, 123–135.

Korenaga, J., Holbrook, W.S., Kent, G.M., Kelemen, P.B., Detrick, R.S., Larsens, H.C., Hoppesr, J.R., Dahl-Jenssen, T., 2000. Crustal structure of the southeast Greenland margin from joint refraction and reflection seismic tomography. Journal of Geophysical Research 105 (B9), 21591–21614.

Kozlovskaaya, E., 2013. Monitoring of Slow Seismic Events from Arctics Using the Data of the POLENET/LAPNET Broadband Temporary Array, IAHS-IASPO-IASPEI.IUGG Joint Assembly, S105S2.03, Gothenburg, Sweden, 22–26 July.

Kuskov, O.L., Kronrod, V.A., Prokofyev, A.A., Pavlenkova, N.I., 2014. Thermo-chemical structure of the lithospheric mantle underneath the Siberian craton inferred from long-range seismic profiles. Tectonophysics 615–616, 154–166.

Layer, P.W., Newberry, R., Fujita, K., Parfenov, L., Trunilina, V., Bakharev, A., 2001. Tectonic setting of the plutonic belts of Yakutia, northern Russia, based on 40AR/39Ar geochronology and trace element geochemistry. Geology 29, 167–170.

Lebedeva-Ivanova, N.N., Zamansky, Y.Y., Langinen, A.E., Sorokin, M.Y., 2006. Seismic profiling across the Mendeleev Ridge at 82°N: evidence of continental crust. Geophysical Journal International 165, 527–544.

Logatchev, N.A., Zorin, Y.A., Rogozhina, V.A., 1983. Baikal rift: active or passive? – comparison of the Baikal and Kenya rift zones. Tectonophysics 94 (1–4), 223–240.

Lynn, C., Cook, F., Hall, K., 2005. Tectonic significance of potential-field anomalies in western Canada: results from the Lithoprobe's SNORCLE transect. Canadian Journal of Earth Sciences 42, 1239–1255.

Mackey, K.G., Fujita, K., Gunbina, L.V., Kovalev, V.N., Imaev, V.S., Koz'min, B.M., Imaeva, L.P., 1997. Seismicity of the Bering Strait region: evidence for a Bering block. Geology 25, 979–982.

Mackey, K.G., Fujita, K., Ruff, L.J., 1998. Crustal thickness of northeast Russia. Tectonophysics 284, 283–297.

Mackey, K.G., Fujita, K., Gounbina, L.V., Koz'min, B.M., Imaev, V.S., Imaev, L.P., Sedov, B.M., 2003. Explosion contamination of the Northeast Shiberian Seismicity Catalog: implications for natural earthquake distributions and the location of the Tanlu Fault in Russia. Bulletin of the Seismological Society of America 93, 737–746.

Mackey, K.H., Fujita, K., Hartse, H.E., Stead, R.J., Steck, L.K., Gunbina, L.V., Leyshuk, N., Shibaev, S.V., Koz'min, B.M., Imaev, V.S., Gordeev, E.I., Chebrov, V.N., 2010. Seismicity map of Eastern Russia, 1960–2010. Seismological Research Letters 81, 761–768.

Maruyama, S., Santosh, M., Zhao, D., 2007. Superplume, supercontinent, and post-perovskite: mantle dynamics and anti-plate tectonics on the Core-Mantle Boundary. Gondwana Research 11, 7–37.

Morozova, E.A., Morozov, I.B., Smithson, S.B., Solodilov, L.N., 1999. Heterogeneity of the uppermost mantle beneath Russian Eurasia from the ultra-long-range profile QUARTZ. Journal of Geophysical Research 104. http://dx.doi.org/10.1029/1999JB900142.

Nettles, M., Ekström, G., 2010. Glacial earthquakes in Greenland and Antarctica. Annual Review of Earth and Planetary Sciences 38, 467–491.

Nikishin, A.M., Sobornov, K.O., Prokopiev, A.V., Frolov, S.V., 2010. Tectonic Evolution of the Siberian Platform During the Vendian and Phanerozoic. Moscow University Geology Bulletin 65, pp. 1–16.

Nokleberg, W.J., Parfenov, L.M., Monger, J.W.H., Norton, I.O., Khanchuk, A.I., Stone, D.B., Scotese, C.R., Scholl, D.W., Fujita, K., 2001. Phanerozoic Tectonic Evolution of the Circum-North Pacific, U.S. Geological Survey, Professional Paper 1626, p. 133.

Parfenov, L.M., Natal'in, B.A., 1986. Mesosoic tectonic evolution of Northeastern Asia. Tectonophysics 127, 291–304.

Parfenov, L.M., Badarch, G., Berzin, N.A., Khanchuk, A.I., Kuzmin, M.I., Nokleberg, W.J., Prokopiev, A.V., Ogasawara, M., Yan, H., 2009. Summary of Northeast Asia geodynamics and tectonics. Stephan Mueller Special Publication 4, 11–33.

Pavlenkova, N.I., 2007. Results of seismic profiling with peace nuclear explosions in Russia. In: Papers of the Inter. Symp. "Model of the Earth's Crust and Upper Mantle by Deep Seismic Profiling", pp. 142–146.

Percival, J.A., Cook, F.A., Clowes, R.M., 2012. Tectonic Styles in Canada: the LITHOPROBE Perspective. Geological Association of Canada, p. 498. Special Paper No. 49, 2012.
Petit, C., Burov, E.V., Devepshere, J., 1997. On the structure and mechanical behavior of the extending lithosphere in the Baikal Rift Zone. Earth and Planetary Science Letters 149, 29–42.
Pirli, M., Schweitzer, J., Ottemöller, L., Raeesi, M., Mjelde, R., Atakan, K., Guterch, A., Gibbons, S.J., Paulsen, B., Dębski, W., Wiejacz, P., Kværna, T., 2010. Preliminary analysis of the 21 February 2008 Svalbard (Norway) seismic sequence. Seismological Research Letters 81, 63–75.
Pisarevsky, S.A., Natapov, L.M., Donskaya, T.V., Gladkochub, D.P., Vernikovsky, V.A., 2008. Proterozoic Siberia: a promontory of Rodinia,. Precambrian Research 160, 66–76.
Poort, J., Klerkx, J., 2004. Absence of regional surface thermal high in the Baikal rift; new insights from detailed contouring of heat flow anomalies. Tectonophysics 383, 217–241.
Puzirev, N.N., Mandelbaum, M.M., Krylov, S.V., Mishenkin, B.P., Mishenkina, Z.R., Petrick, U.V., Seleznev, V., 1979. New data from explosion seismology in the Baikalian Rift zone. Tectonophysics 56, 128.
Radziminovich, N.A., Gileva, N.A., Melnikova, V.I., Ochkovskaya, M.G., 2013. Seismicity of the Baikal Rift system from regional network observations. Journal of Asian Earth Sciences 62, 146–161.
Rapley, C., Bell, R., Allison, I., Bindschadler, P., Casassa, G., Chown, S., Duhaime, G., Kotlyakov, V., Kuhn, M., Orheim, O., Pandey, P.C., Petersen, H., Schalke, H., Janoschek, W., Sarukhanian, E., Zhang, Z., 2004. A Framework for the International Polar Year 2007–2008. ICSU IPY 2007–2008 Planning Group. ICSU, Paris, p. 57.
Reiche, S., Ian Reid, I., Thybo, H., 2011. Crustal structure of the Greenland-Iceland Ridge inferred from wide-angle seismic data. Geophysical Research Abstracts 13, 11623.
Riegel, S.A., Fujita, K., Koz'min, B.M., Imaev, V.S., Cook, D.B., 1993. Extrusion tectonics of the Okhotsk Plate, northeast Asia. Geophysical Research Letters 20, 607–610.
Rignot, E., Kanagaratnam, P., 2006. Changes in the velocity structure of the Greenland ice sheet. Science 311, 986–990.
Ritzwoller, M.H., Levshin, A.L., 1998. Eurasian surface wave tomography: group velocities. Journal of Geophysical Research 103, 4839–4878.
Ronin, A.L., Lebedkin, P.A., 2007. Consolidated crustal structure of old platforms and young fold areas: results of statistic-dynamic analysis (SDA) of CDP deep investigation data. In: Papers of the Inter. Symp. "Model of the Earth's Crust and Upper Mantle by Deep Seismic Profiling", pp. 168–172.
Rosen, O.M., 2003. The Siberian Craton: tectonic zonation and stages of evolution. Geotectonics 37, 175–192.
Rybalka, A.V., Kashubina, T.V., Petrov, G.A., Kashubin, S.N., 2007. The middle-Urals transect: new data on the deep structure of the Urals. In: Papers of the Inter. Symp. "Model of the Earth's Crust and Upper Mantle by Deep Seismic Profiling", pp. 186–191.
Saltus, R.W., Miller, E.L., Gaina, C., Brown, P.J., 2011. Regional magnetic domains of the circum-Arctic – a framework for geodynamic interpretation,. In: Spencer, A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V., Ørensen, K. (Eds.), Arctic Petroleum Geology, Memoir 35. Geological Society, London, pp. 49–60.
Shephard, G.E., Müller, R.D., Seton, M., 2013. The tectonic evolution of the Arctic since Pangea breakup: Integrating constraints from surface geology and geophysics with mantle structure. Earth-Science Reviews 124, 148–183.
Sherman, S.I., Gladkov, A.S., 1999. Fractals in studies of faulting and seismicity in the Baikal Rift Zone. Tectonophysics 308, 133–142.
Sherman, S.L., Lunina, O.V., 2001. The map of the state of stress of the elastic lithosphere. Doklady Akademii Nauk 378, 672–674.
Song, Y., Krylov, S.V., Yang, B., Cai, L., Dong, S., Liang, T., Li, J., Xu, X., Mishen'kina, Z.R., Petrik, G.V., 1996. Deep seismic sounding of the lithosphere of the Baikal-Northeastern China International Transect. Russian Geology and Geophysics 37, 1–13.
Stephenson, R., Oakey, G.N., Schiffer, C., Jacobsen, B.H., 2013. Ellesmere island lithosphere Experiment (ELLITE): Eurekan basin inversion and mountain building, ellesmere island, Nunavut. Geological Survey of Canada. http://dx.doi.org/10.4095/292859. Current Research (Online) no. 2013-21, 12 pages.
Surkov, V.S., Salnikov, A.S., Kuznetsov, V.L., Seleznev, V.S., Yemanov, A.F., Solovyov, V.M., 2007. The structure of Earth's crust abutment profile 2 DV (Nord-East of Russia) bases on dates of new technology of deep seismic sounding. In: Papers of the Inter. Symp. "Model of the Earth's Crust and Upper Mantle by Deep Seismic Profiling", pp. 233–236.
Suvorov, V.D., Yurin Yu, A., Timurshin, K.V., Krylov, S.V., Parasotka, B.S., Cherny, S.D., Seleznev, V.S., Soloviev, V.M., Matveev, V.D., 1997. Structure and evolution of the crust and uppermost mantle beneath the kimberlite province of Yakutia based on seismic evidence. Geologiya i Geofizika (Russian Geology and Geophysics) 38, 518–527.
Suvorov, V.D., Parasotka, B.S., Chernyi, S.D., 1999. Deep seismic sounding studies in Yakutia. Physics of the Solid Earth 35, 612–629.
Suvorov, V.D., Mishenkina, Z.M., Petrick, G.V., Sheludko, I.F., Seleznev, V.S., Solovyov, V.M., 2002. Structure of the crust in the Baikal Rift Zone and adjacent areas from Deep Seismic Sounding data. Tectonophysics 351, 61–74.
Suvorov, V.D., Mishen'kina, Z.R., Melnik, E.A., 2010. Upper mantle roots of Siberian craton basement structures along the Rift DSS profile. Russian Geology and Geophysics 51, 885–897.
Suvorov, V.D., Mel'nik, E.A., Mishen'kina, Z.R., Pavlov, E.V., Kochnev, V.A., 2013. Seismic inhomogeneities in the upper mantle beneath the Siberian craton (Meteorite profile). Russian Geology and Geophysics 54, 1108–1120.
ten Brink, U.S., Taylor, M.H., 2002. Crustal structure of central Lake Baikal: insights into intracontinental rifting. Journal of Geophysical Research 107. B7, ETG 2-1; 2–15.
Thybo, H., Perchuc, E., 1997. The seismic 8°discontinuity and partial melting in continental mantle. Science 275, 1626–1629.
Thybo, H., Nielsen, C.A., 2009. Magma-compensated crustal thinning in continental rift zones. Nature 457, 873–876.
Veitch, S.A., Nettles, M., 2012. Spatial and temporal variations in Greenland glacialearthquake activity, 1993–2010. Journal of Geophysical Research 117, F04007. http://dx.doi.org/10.1029/2012JF002412.
Wilson, T., Bell, R., 2011. Earth Structure and Geodynamics at the Poles. Understanding Earth's Polar Challenges: International Polar Year 2007–2008, pp. 273–292.
Yanovskaya, T.B., Kozhevnikov, V.M., 2003. 3D S-wave velocity pattern in the upper mantle beneath the continent of Asia from Rayleigh wave data. Physics of the Earth and Planetary Interiors 138, 263–278.
Zhao, D., Lei, J., Inoue, T., Yamada, A., Gao, S.S., 2006. Deep structure and origin of the Baikal Rift Zone. Earth and Planetary Science Letters 243, 681–691.
Zorin, Y.A., Kozhevnikov, V.M., Novoselova, M.R., Turutaov, E.K., 1989. Thickness of the lithosphere beneath the Baikal Rift Zone and adjacent regions. Tectonophysics 168, 327–337.
Zorin, Yu A., Mordvinova, V.V., Turutanov, E.Kh, Belichenko, B.G., Artemyev, A.A., Kosarev, G.L., Gao, S.S., 2002. Low seismic velocity layers in the Earth's crust beneath Eastern Siberia (Russia) and Central Mongolia: receiver function data and their possible geological implication. Tectonophysics 359, 307–327.
Zorin, Yu A., Turutanov, E.Kh, Mordvinova, V.V., Kozhevnikov, V.M., Yanovskaya, T.B., Treussov, A.V., 2003. The Baikal Rift Zone: the effect of mantle plumes on older structure. Tectonophysics 371, 153–173.