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Chapter 6

A Decade of Advances in Cryoseismology

Masaki Kanao

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Abstract

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

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

1. Introduction

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

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terminologies of cryoseismic signals. We use these terminologies depending on the context of individual sentences.

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

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

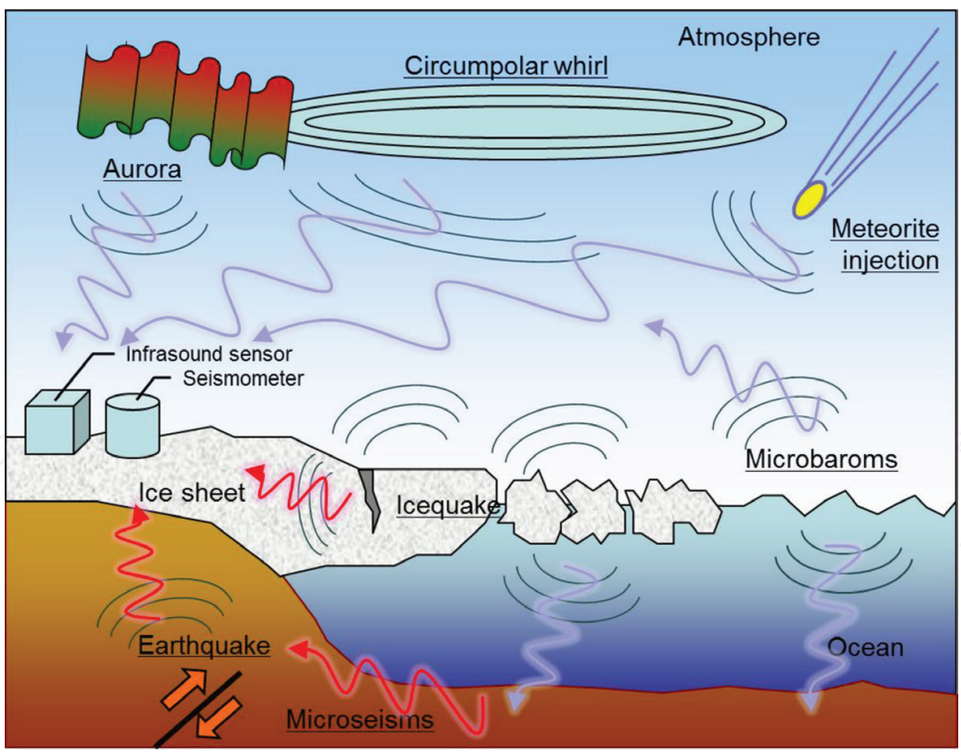


Figure 1. Schematic illustration of the excitation of atmospheric pressure changes and seismic waves in polar regions. Physical interaction among the solid Earth, atmosphere, ocean, and cryosphere systems can be detected by using infrasonic waves, which are generated by several sources around the coast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

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2. Antarctic region

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

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

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

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

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

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

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

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

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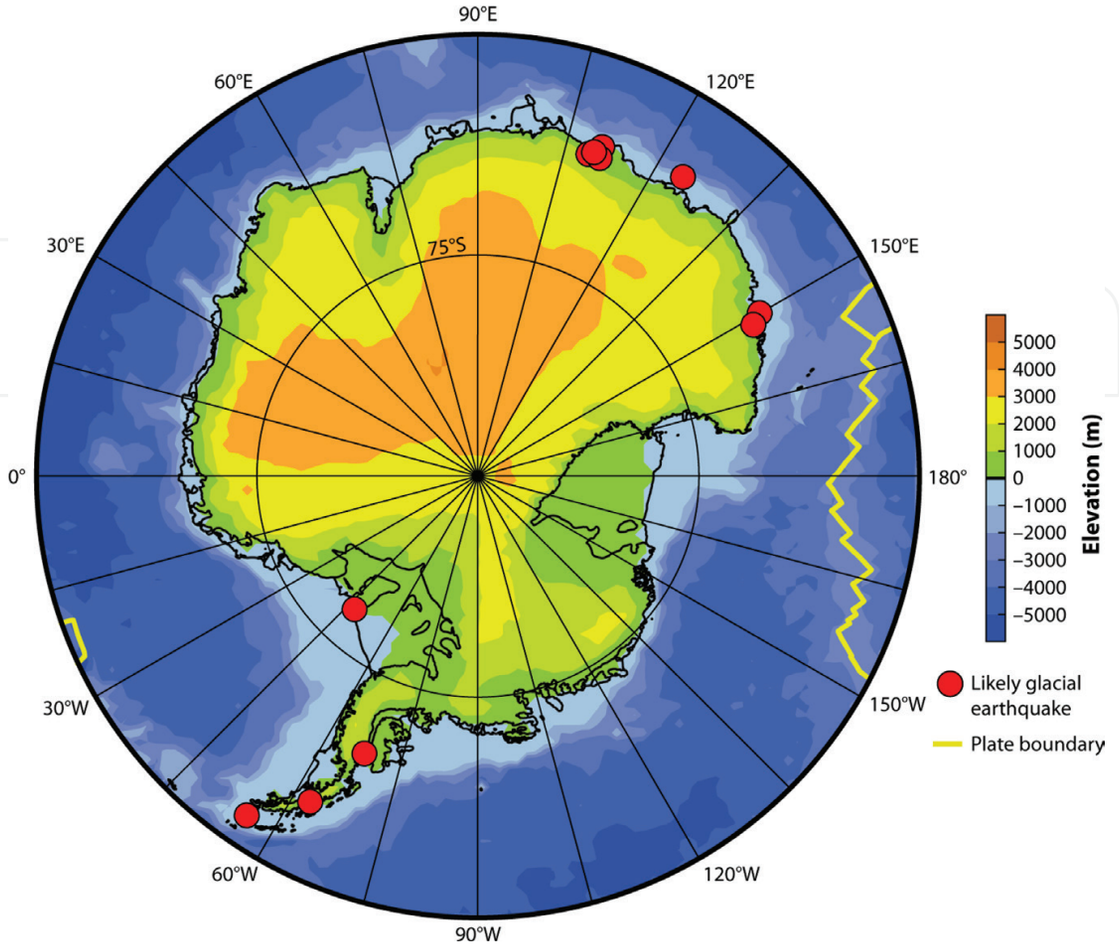


Figure 2. Hypocenters for the detected events that are likely to correspond to glacial earthquakes around Antarctica during 1993–2008 (red circles) (modified after [4]). Copyright Clearance Center (CCC, http://www.copyright.com/). License number: 4280640194100, license date: February 02, 2018.

3. Arctic region

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

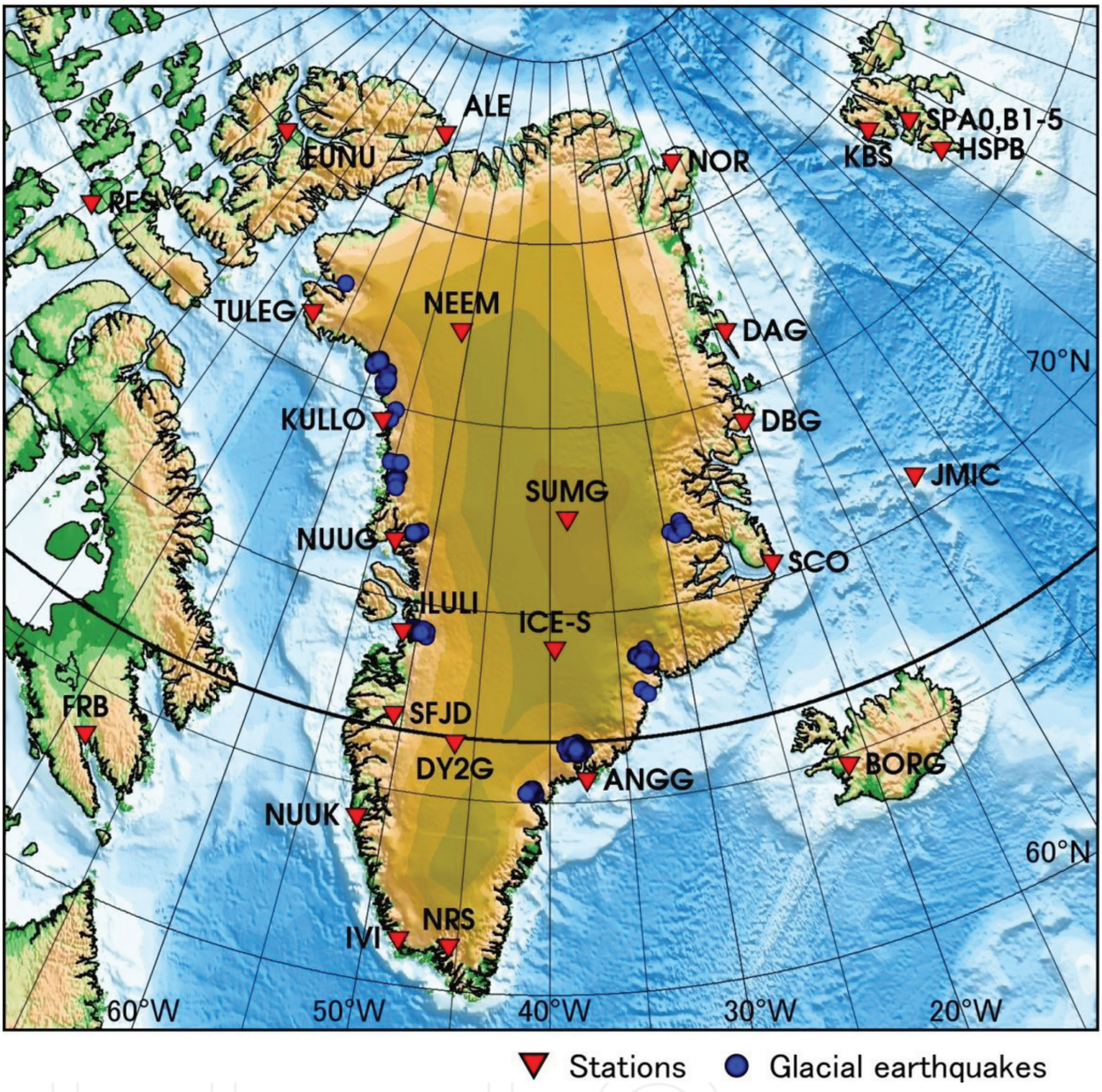


Figure 3. Distribution of glacial earthquakes around Greenland and the surrounding area during 1993–2008 (blue circles). Seismic stations including both permanent and temporal are shown by red triangles. Hypocenters are taken from [4] (figure is after [33]). Open Access Journal (CC BY 3.0) (first author is M. Kanao).

In order to monitor the dynamics of the Greenland ice sheet, more than one decade ago, an international program "the GreenLand Ice Sheet monitoring Network (GLISN)" was initiated after the IPY by 14 countries involved in the Arctic research, including the USA, Denmark, and Japan [27, 28]. By collaborating with existing global seismic networks (FDSN), a relationship between the occurrence mechanism of glacial earthquakes and the shrinking ice sheet caused by global warming can be revealed. Moreover, it is expected that the correlation between the cryosphere dynamics and the sea-level change, as well as an understanding of the amplification process of global warming in the Arctic, could be clarified. The significance of seismic

activities of glacial earthquakes in Greenland and Antarctica, for example, could be determined by using the statistical methods for estimating the temporal-spatial distribution of the aftershocks such as the epidemic type aftershock sequence (ETAS) model. Statistical analysis of both the tectonic and glacial earthquakes regarding plate movement and volcanic activities around Greenland has been reported [29]. Seismically active regions of glacial earthquakes were found to be expanding from the southeast to the northwest part of Greenland since 2005. The evidence corresponded to the ice mass loss distribution obtained by the satellite data from the Gravity Recovery and Climate Experiment (GRACE) [25].

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

4. Summary

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

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