Characteristic seismic signals associated with ice sheet and glacier dynamics, Eastern Dronning Maud Land, East Antarctica

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Summary Several kinds of natural signals were recorded by a seismic experiment on the continental ice sheet in Eastern Dronning Maud Land during the 2002 austral summer. They include not only tectonic earthquakes, but also ice related phenomena possibly involving recent global climate change. The recorded signals are classified into (1) a teleseismic event, (2) local ice-quakes and (3) an unidentified event (X-phases). Interestingly, the frequency content at 2.0 Hz is small in the waveforms recorded by stations in middle part of the seismic profile. On the other hand, 5.0 Hz and 1.5 Hz components are large at these stations which are above a valley in topography at the interface between the ice sheet and topmost crust. The abrupt change of topography in the valley might cause both the anomalous frequency content and travel times. The estimated origin of the unidentified event might be an intraplate earthquake or possibly a large ice-quake around East Antarctica.

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Introduction

It was generally understood by a majority of seismologists in the IGY era that no extreme earthquakes occurred in the Antarctic. Though the Antarctic was known as an aseismic region, some significant earthquakes have occurred both on the Antarctic continent and in the surrounding oceans. Although the seismic stations in Antarctica have been operated as a part of the global network, no detailed studies of local events have been made until recently (e.g., Kaminuma, 2000; Reading, 2002). Several kinds of natural seismic signals, moreover, are recorded involving ice-related phenomena. These 'ice-quakes' are frequently generated by glacially related ice-mass movements from ice-sheets, sea-ice, tide-cracks and icebergs, etc. Sometimes, we can hardly distinguish between the waveforms generated by local tectonic earthquakes and those of ice-related phenomena. These ice-related phenomena seem to have been enhanced by recent global climate change.

Seismic observations were performed by the Japanese Antarctic Research Expedition (JARE) on Mizuho Plateau, Eastern Dronning Maud Land, during the 2002 austral summer. The experiment recorded chiefly the artificial waveforms originated by seven large explosions with 161 temporary stations (Miyamachi et al., 2003). They determined P-velocity structure of the crust and overlying ice sheet by travel time methods. An interesting feature of the obtained structure is complex topography of the boundary between the ice-sheet and crystalline crust. This topography represents a significant valley structure of about 10 km width beneath the middle part of the seismic profile, which is also identified by radio echo sounding (Takada et al., 2003). The P velocities beneath these strange indents were estimated to be slower (5.9-6.0 km/s) than those of the other area (6.1-6.2 km/s) (Miyamachi et al., 2003). A plausible possibility is the presence of water infilling the valley (Mae, 1978), just as sub-glacial lakes are reported elsewhere in the Antarctic continent (e.g. Kapitsa et al., 1996; Siegert et al., 2001).

Several characteristic seismic waves caused by natural sources (regional and teleseismic events and local ice-quakes) were well-recorded in the experimental data, in spite of recording time lengths limited to only several minutes a day during the experiment, which lasted about a month. In this paper, several remarkable features of the anomalies' travel times, amplitudes, and frequency contents are demonstrated in three examples of the recorded waveforms from several natural sources. We then discuss the origin of these characteristic waves to determine if they are associated with ice-related phenomena, any changes in climate, and/or micro-seismic activity around the Antarctic.

Data and Analysis

Characteristic seismic waves from natural sources recorded in exploration experiments on the Mizuho Plateau were evaluated with the following process. These waves have a high signal-to-noise ratio in spite of the small magnitudes the events. These waves were classified into the following three categories: (1) teleseismic events; e.g., those occurring in the Kermadec Is. region, (2) local ice-quakes around the Lützow-Holm Bay Region, near the Mizuho Plateau and (3) an unidentified event with an Antarctic origin (here we call these, X-phases).

We have performed two major analyses by means of stacking and running spectra. First, we use the phase-weighted stacking (PWS; Shimmel and Paulssen, 1997) method, instead of the usual linear staking. The PWS is a kind of non-linear stacking, which uses the sum of the phase components of traces as a weighting factor applied to the sum of the amplitude components of the traces. Thus a signal that is coherent throughout a seismic network can be constructively stacked across all traces, while an incoherent signal, which may be resolved on some traces but not all, results in a stacked signal with small amplitude. Second, the running spectra are taken by using an FFT applied to 2 s window waveform with a time interval of 1 s. Before taking the spectrum, instrumental response is deconvolved from the original waveform.

Using these methods, we find discordances in both the frequency content and the arrival times of waveforms in the traces. The following anomalous features are seen in the waveforms of the stations just above the valley structure of the boundary between the ice sheet and the upper crust: (1) The frequency components at 1.5, 3.0 and 5.0 Hz are large compared with those in other stations and those at 2.0 Hz are small. (2) A difference in the response generated from the valley structure below might exist depending on the type of waves that are incident on the structure. For example, P-wave incidence on this valley structure might result in the normal arrival, while the S-wave arrival might be delayed.

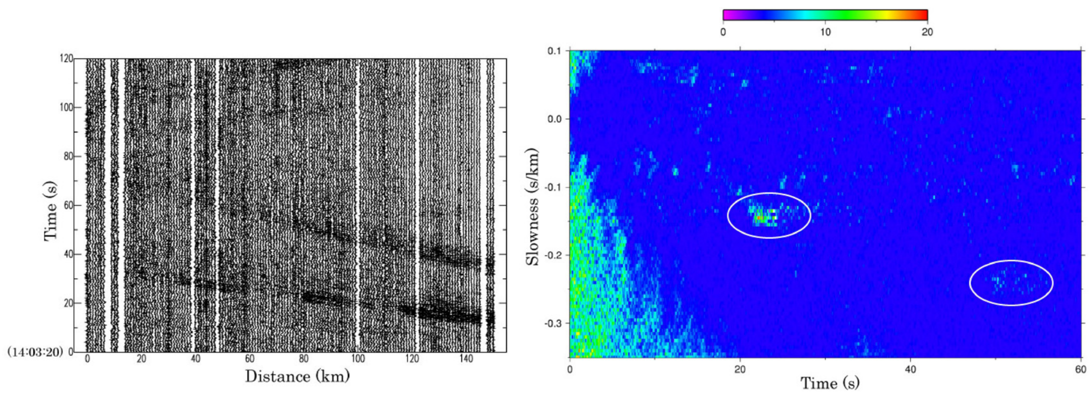

Figure 1. (left) Record section showing seismic waves of ice-quakes. Vertical axis starts from Jan. 14, 2002, 14:03:20 (UTC). (right) Contour map of PWS applied to ice-quakes.

Discussion

A significant feature of the X-phases is that successive arrivals of waveform energy have almost zero slowness for about 100 s after the onset. A candidate event might be the Rat Is. (Aleutians) earthquake. However, we show here that it could not be the event that produced the X-phases. The epicentral distance from the event to the center of the observation line is about 152º. Since this event has a small magnitude (4.8 m_b), it is uncertain that such a small earthquake could be recorded by seismographs at a large epicentral distance.

Another reason why the X-phases may not be in the PKP family comes from a comparison of the waveforms with the Kermadec Is. event. If we consider the X-phases to be the waves from the Rat Is. event, the back azimuth from the center of the observation line is 107.4º and the incident angle to the boundary between the ice sheet and the topmost crust ranges from 4.6º (PKPdf) to 13.4º (PKPab); they are 143.3º and 18.0º, respectively, for the direct P of the Kermadec Is. event. In addition, if we consider the raypaths of the PKPs of the Rat Is. event and the direct P of the Kermadec Is. event to a station on the observation line, the piercing points of these waves to the boundary differ horizontally only a few hundred meters. This distance is much smaller than the horizontal length of the valley structure, which is about 10 km.

Therefore, we cannot expect that different waveforms would both be generated by the complex topography of the boundary for the Rat Is. event and the Kermdec Is. event. However, there is a difference between the waves of the X-phases and the Kermadec Is. event. The gap of 2.0 Hz in the middle part of seismic line is found in both two cases. However, the peak of 1.5 Hz (delayed about a second after the gap) is seen only in the X-phases and the peak of 3.0 Hz (which is not time delayed) is seen only in the Kermadec Is. event. Thus, this difference may lead to a conclusion that the X-phases would not be the waves of the Rat Is. event.

The features of the X-phases are clearly different from those of the local ice-quakes. A possibility for the origin of the X-phases may be regional intra-plate earthquakes. Such regional events around Antarctica from 1900 to 1999 are compiled by Reading (2002). East Antarctica from 90ºE to 180ºE, particularly the areas of Wilkes Land, the Transantarctic Mountains, and the Ross Sea, is the region showing the highest seismicity in the Antarctic. From the comparison with the arrival data at Syowa Station (SYO), the maximum amplitudes of seismic phases appear to arrive at

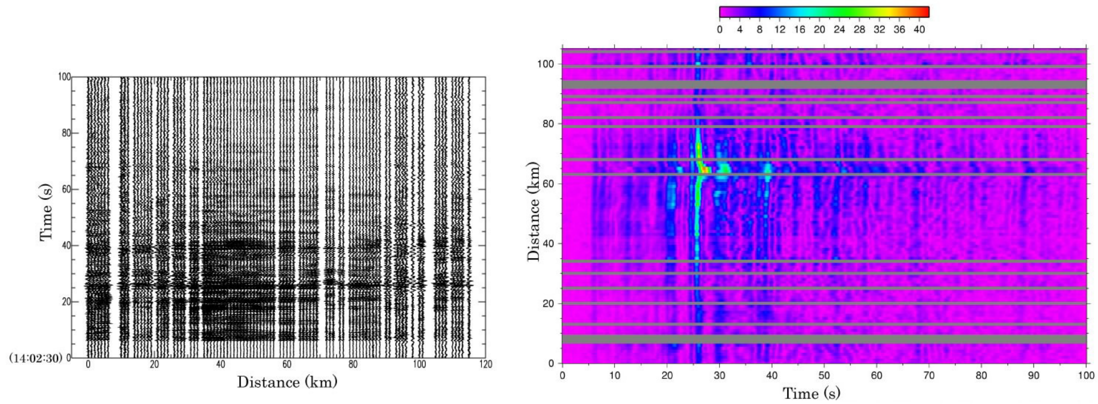

Figure 2. (left) Record section showing seismic waves of X-phases. Vertical axis starts from Jan. 27, 2002, 14:02:30 (UTC). (right) Contour map showing envelope amplitudes of band-pass (1.0-2.0 Hz) filtered traces.

SYO with the delay of several seconds. Therefore, the X-phases could possibly travel to the seismic observation line and then SYO from the relatively active, intraplate seismogenic region in Wilkes Land – Ross Sea area.

It should also be pointed out that several small to middle magnitude natural seismic events could not be located accurately, since they have ambiguous arrivals in the waveforms recorded by the present global network, particularly around Antarctica.

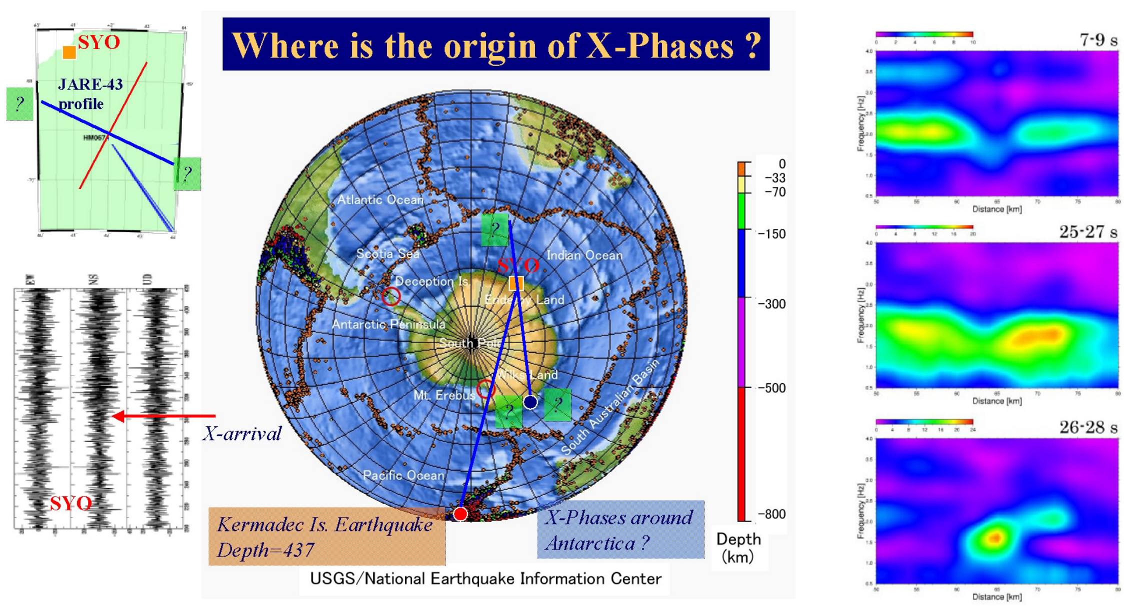

Figure 3. (left) Estimated location of the X-Phases and background seismicity around Antarctica. (right) Contour maps showing amplitudes of seismic energies plotted in the frequency-distance domain for the X-phases. Top and middle panels show the 'frequency gap' of 2.0 Hz at around 65 km and the bottom panel shows the 'frequency peak' of 1.5 Hz just a second after the time window of 'frequency gap' of the middle panel. These features may be due to the significant valley structure beneath the seismic profile.

Conclusion

The seismic records from natural sources obtained from seismic exploration show interesting features of the wavefield around Antarctica. Anomalous behavior of the waves characterized by the focusing/defocusing effects is possibly caused by a valley structure just beneath the stations located at the middle of the seismic profile.

Two characteristics were identified by detailed spectra analysis. (1) A frequency dependence of this focusing/defocusing effect is clear, with focusing at frequencies of 1.5, 3.0 and 5.0 Hz and defocusing at 2.0 Hz. (2) A difference of the response generated from the valley structure might exist for different kinds of incident waves: i.e. P-wave incidence on this valley structure results in the 'frequency gap', while on the other hand, S-wave incidence produces both the ‘gap’ and the ‘peak’ with a sufficient delay of the arrival time. Though the origin of the X-phases is not accurately identified, but the most plausible candidates are an intra-plate earthquake or a large ice-quake in the Antarctic.

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