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Seismicity in the Antarctic and surrounding ocean

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ABSTRACT
Seismicity in the Antarctic and surrounding ocean is evaluated based on the data compiled by the International Seismological Centre for the period 1964 - 2002. The Antarctic continent and surrounding ocean were believed to be one of the aseismic regions of the Earth for many decades. However, after the development of Global Seismic Networks and local seismic arrays, a number of tectonic earthquakes have been detected in and around the Antarctic Continent.

Antarctica and the surrounding ocean has been divided into a total of 13 seismic areas, 3 for the continental region and another 10 for the oceanic region. Wilks Land is the most active area in the Antarctic Continent; where several small earthquakes were detected and located. In the ocean surrounding Antarctica, the seismic activity in 120°-60°W sector is three times lager than the other oceanic areas. This is probably due to stress concentration towards the Easter Island Triple Junction among Antarctic Plate, Pacific Plate and Nazuca micro-Plate. Three volcanic areas, namely the Deception Island, Mt. Erebus and Mt. Melbourn, are seismically active.

INTRODUCTION

The Antarctic Plate, surrounded almost completely by divergent margins and very short portions by convergent and/or transform margin has an unique tectonic setting. The divergent margin is characterized by the circum Antarctic seismic zone and covers about 92% of the Antarctic Plate boundary. The convergent margin is located in the northwest side of the South Shetland Islands and accounts for less than 2% of the plate boundary. While the transform margin along the Scotia micro-Plate covers less than 7 % of the plate boundary (Fig. 1).

At the beginning of the International Geophysical Year (IGY) in 1957, the Antarctic seismicity was known to be associated with active volcanoes like Mount Erebus, and Deception Island. Although the seismic activity of Deception Island was known since the 19th century, no seismic station operated there. (Gutenberg and Richter, 1954; Richter, 1953, Fig. 1).

During the IGY, about ten seismic stations were established in the Antarctic. Phase readings of the events recorded at the Antarctic stations were reported to the USCGS (United States Coastal Geological Survey). The USCGS had published "Antarctic Seismological Bulletin" on the basis of the phase readings received telegraphically from the Antarctic seismological stations. In the bulletins published, no earthquakes were reported from Antarctic for almost 15 years since the installation of stations during 1957.

In the later years, as the number of seismic stations in the Antarctic increased, low magnitude earthquakes were detected in the Antarctic Continent, (e.g. Kaminuma and Ishida, 1971; Adams et al., 1972; Adams 1982). An earthquake with magnitude around 4 occurred once every few years in the Antarctic Continent.

Johnstone (1987) explained the lack of seismic activity due to pressure produced by the continental ice sheet.

With the global increase in the number of seismic stations, several tectonic earthquakes were detected in the Antarctic. The intraplate seismicity in the Southern Ocean is very low. However, one great earthquake with Ms 8.0 struck the Balleny Islands region on March 25,1998. This intraplate earthquake is the largest one ever recorded in the Antarctic Plate.

Kaminuma (1994a) summarized the seismicity in and around the Antarctic Continent and also made a mention of icequakes.

Later, Kaminuma (2000) evaluated the seismicity of Antarctica from the seismotectonics and/or neotectonics view.

Reading (2002) presented a hypocentral map of Antarctic intraplate earthquakes for the period of 1900-99 using the data from all seismic stations.

Seismicity of the Antarctic Continent

A seismicity map of the Antarctic Plate and its surroundings is shown in Fig. 1. The Antarctic Continent is divided into two zones; East Antarctica

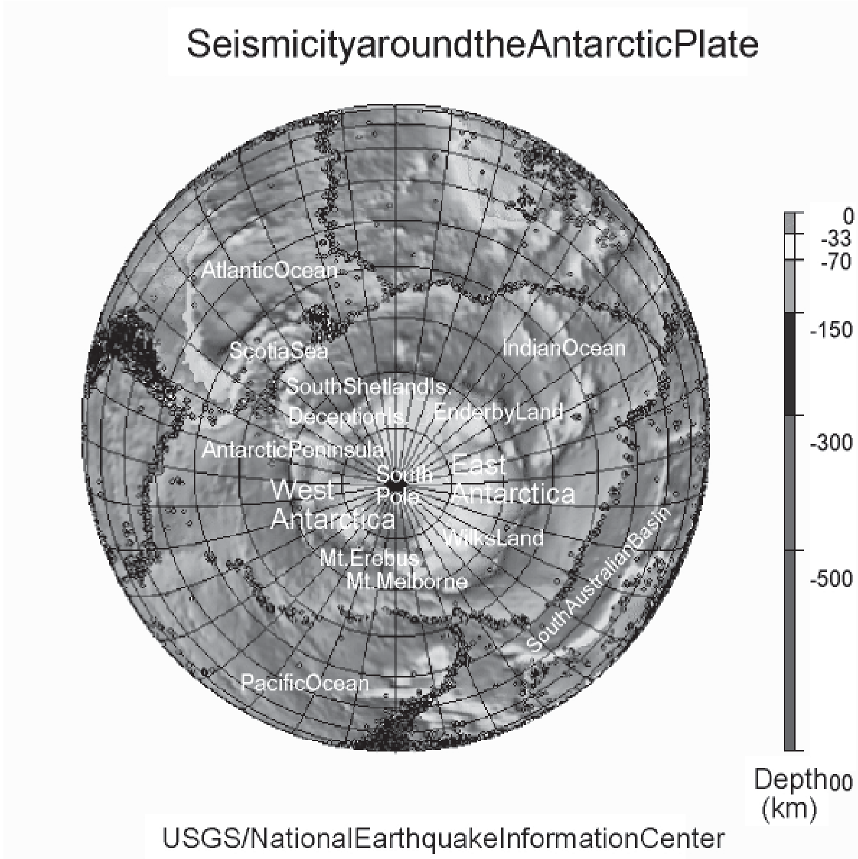

Figure 1. Seismotectonic regions discussed in this paper. Earthquake distribution in and around the Antarctic plate was compiled by NEIC (National Earthquake Information Center) of USGS. Three volcanoes and South Shetland Islands are also shown by solid triangles.

Table 1. Kaminuma and Kanao

Block	LAT	LON	Event number	Comment
A	0°-60°E	20°-80°S	33	Ocean
B	60°-120°E	20°-80°S	58	Ocean, Kerguelen Plateau
C	60°-120°E	20°-80°S	26	Ocean
D	60°-120°E	20°-80°S	5	Continent
E	120°-180°E	20°-80°S	33	Ocean
F	120°-180°E	20°-80°S	26	Ocean
G	120°-180°E	20°-80°S	23	Continent, Wilks Land
H	180°-120°W	20°-80°S	22	Ocean
I	120°-60°W	20°-80°S	19	Ocean, Easter Is. Triple Junct.
J	120°-60°W	20°-80°S	20	Ocean
K	120°-60°W	20°-80°S	17	Ocean
L	60°-0°W	20°-80°S	33	Ocean
M		80°-90°S	8	Continent, South Pole

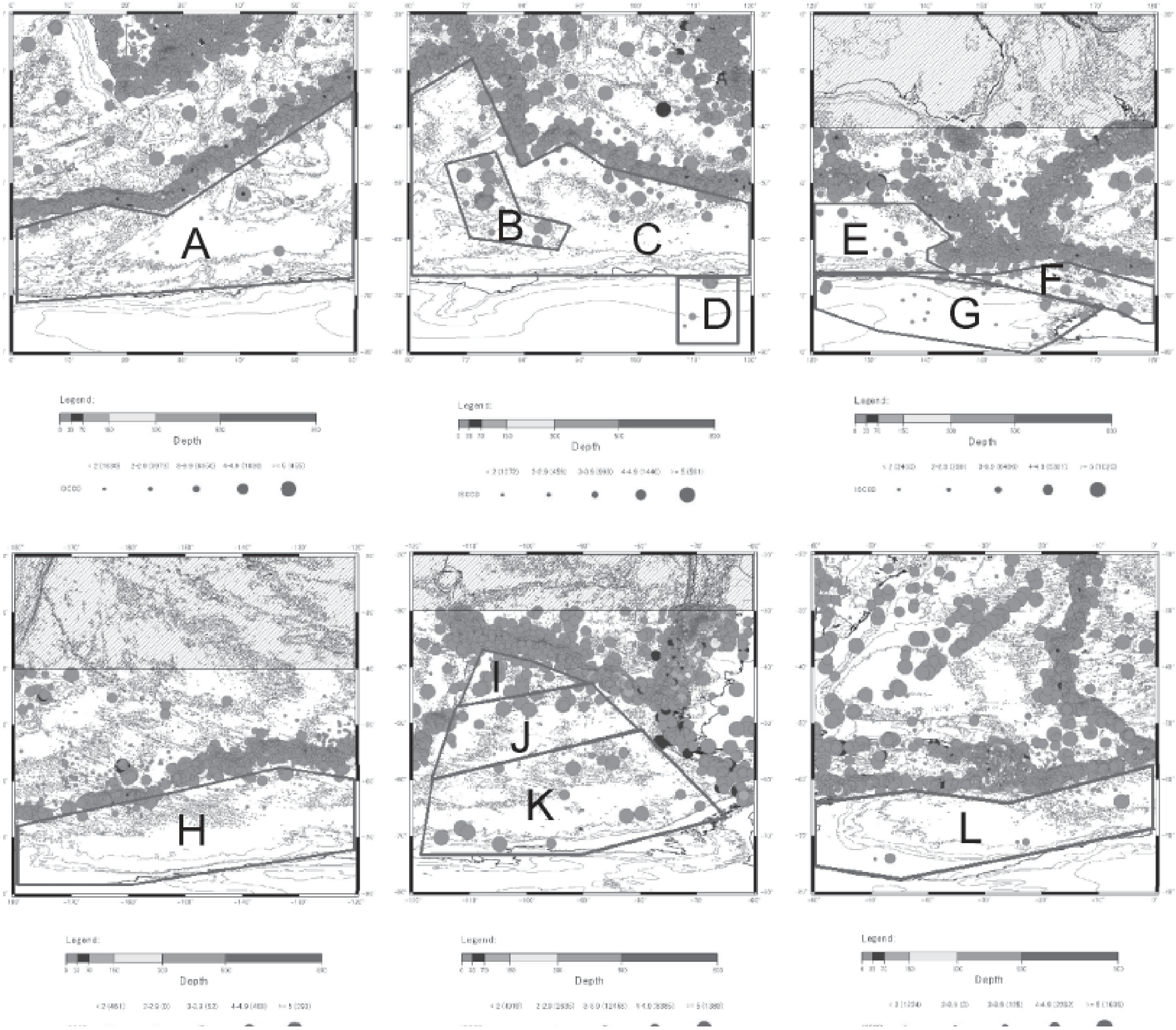

Figure 2. Earthquake locations determined by ISC in 20°-80°S and every 60° of longitude. Surrounded areas by solid lines indicate individual blocks (A-L) discussing seismicity in this paper. These areas were classified into Antarctic continent (D and G) and oceanic region within Antarctic Plate (other regions). Numbers in the brackets correspond to the number of events included for each 60° longitude sector.

(eastern hemisphere side of the Transantarctic Mountains) and West Antarctica. East Antarctica is characterized by a fragment of Gondwana super-Continent, together with the adjacent Pre-Cambrian terrains in the southern hemisphere (South America, Africa, India and Australia, as shown in Fig.1). West Antarctica, on the contrary, is a chain of Islands beneath the ice sheet of Cenozoic era attributed to active volcanoes.

For the Pre-IGY era, only one significant earthquake has been reported for the Antarctic continent (Adams et al.; 1985).

On June 26, 1968 an event of magnitude 4.3 with epicentre at 20° W, 80° S was located in Coats Land using the initial phase readings of five seismic stations on the Antarctic Continent (Kaminuma and Ishida; 1971). The magnitude of the event was estimated using wave form amplitude of a three-component seismograph at South Pole Station. This was the first earthquake located instrumentally in the continent using the data of seismic stations in Antarctica only. However, this event was not listed in the ISC data catalog. Kaminuma

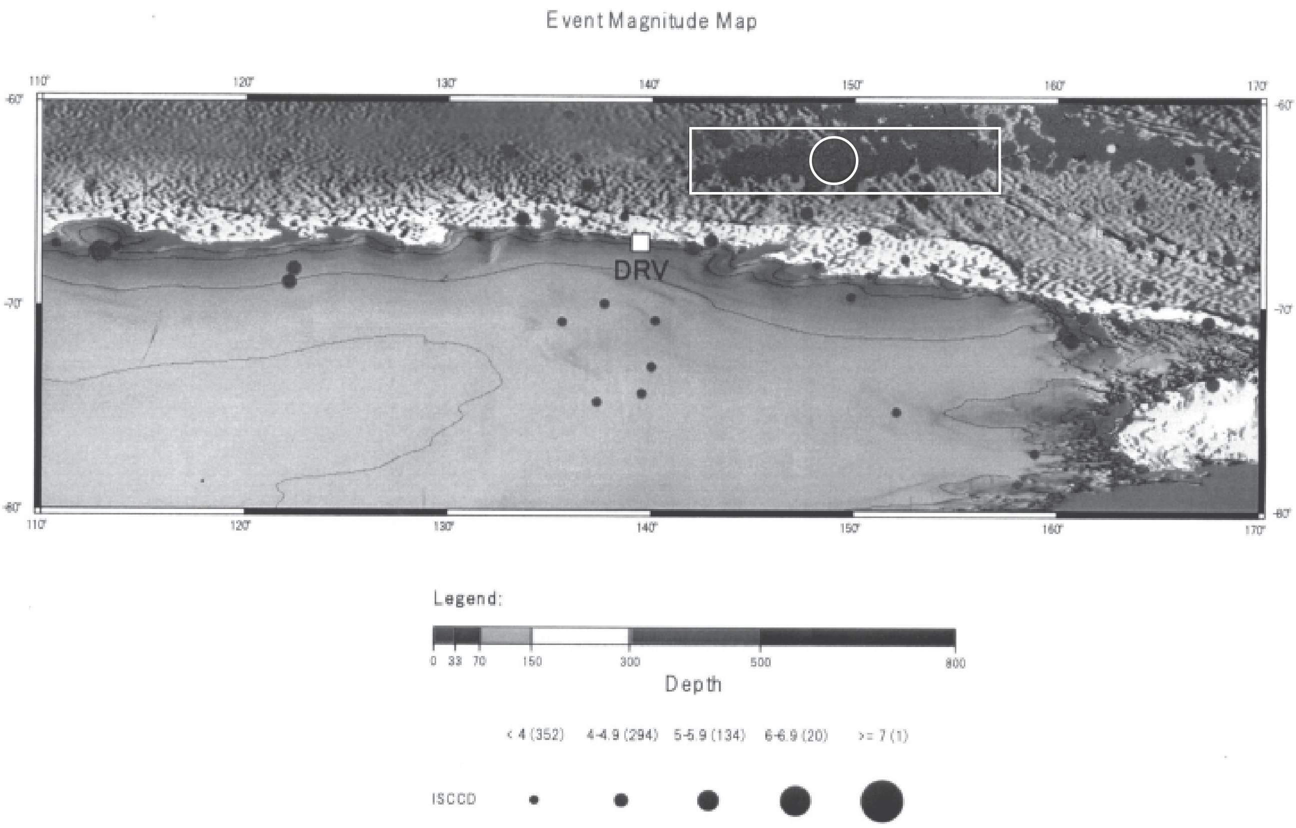

Figure 3. Earthquake locations in 60°-80°S and 110°-170°E, including both the Wilks Land and after shock area of the March 25, 1998 Balleny Island earthquake (Mw=8.1). Numbers in the brackets correspond to the number of events included.

and Ishida (1971) determined the focal depth of the earthquake to be 1 km beneath the sea level and hence its being an icequake was ruled out.

Adams (1982) reported an earthquake of magnitude 5 near the coast of Oates Land at 70.5°S and 161.3°E on October 15, 1974. He concluded that the event might be an icequake associated with ice movement or cracking. This event was the only shock to be located on the Antarctic Continent by international agency till 1982.

As pointed out by Kaminuma (2000), the seismic activity in Wilks Land is about ten times more than around Syowa Stations. Seven earthquakes with Mb 4.0~4.9 were located in the area bounded by 100°~170°E and 66°^ÿ82°S during the 33 years period, 1964~1996. Another nine earthquakes in the inland area and two offshore were located. The magnitudes of these eleven earthquakes were not accurately determined. Micro-seismic activity as well as small earthquake activity in Wilks Land and surrounding coasts is higher than other areas in Antarctica. The subglacial topography in Wilks Land is characterized by a subglacial basin 1000 m below sea level (Drewry; 1983). The maximum thickness of the ice sheet in the area is over 4000 m, the surface elevation being mostly over 2000 m.

Seismicity in the southern ocean

Figure 2 represents the epicenters determined by ISC in the area bounded by 20°- 80° S and every 60° of longitude. Among the individual 60° longitude sectors and South Pole area in 80°-90°S, the earthquake activity regions are divided into 13 regions (from A to M, Table 1). Since the seismic activities are extremely high along the plate boundaries around the Antarctic Plate between the surrounding plates, the intra-plate areas have been selected very carefully, not to include the events associated with plate boundaries.

Moreover, the region corresponding to the after shock areas of the March 25, 1998 Balleny Island earthquake, was excluded, because the region contain a huge number of aftershock events associated with the occurrence of the Balleny main shock. Since the recent seismic activities after the Balleny event could be related with the nucleation of the new plate

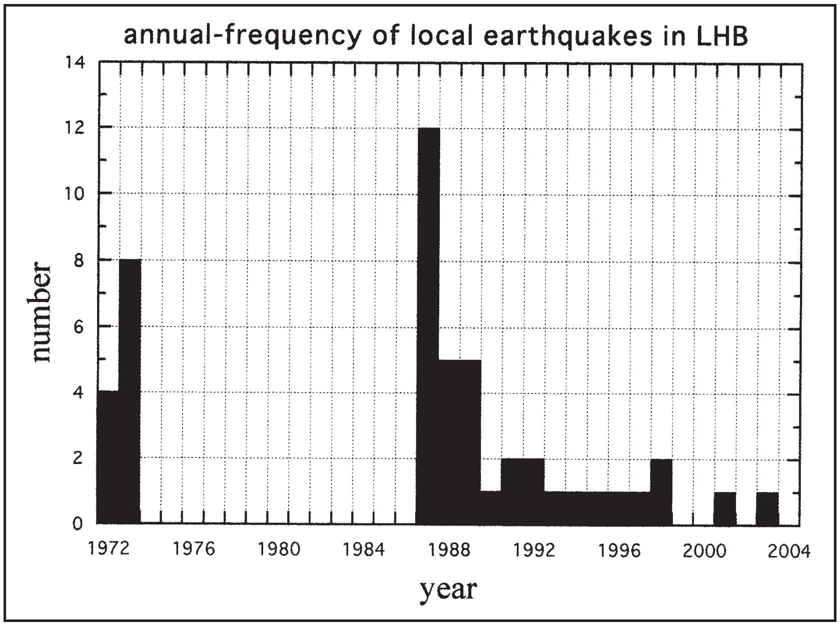

Figure 4. Annual frequency of local earthquakes during the period of 1972-2003 around Lützow-Holm Bay, East Antarctica recorded at Syowa Station.

boundaries (Tsuboi, 2000), it is better not to include it in the intra Antarctic Plate seismicity discussed here.

The total 13 seismicity areas were simply classified into the Antarctic continent (D, G and M) and oceanic region within Antarctic Plate (the other 10 areas). Regarding the areas corresponding among the Antarctic oceanic plate, generally, seismicity has been about the same level among all the areas, with a number of 20-30 events during 1964-2002. This indicates that the stress distribution among the oceanic area of the Antarctic Plate is almost averaged in longitude distribution.

However, the most particular area is Kerguelen Plateau (B), which has relatively high seismicity compared with the surrounding Indian oceans. The hot spot activity with high heat flow around the area (Anderson, 1994; Storey, 1995) is probably responsible for high seismicity.

Continental Margin

Reading (2002) pointed out the considerable number of intra-plate earthquakes in the 90°-180°E quadrant and divided the earthquakes into two groups as poorly and well located ones.

Among the continental areas in Antarctica, there were very few earthquakes in D, G and L areas (Fig. 2).

As Kaminuma (2000) already pointed out, the poorly located earthquakes were lined from north to south along the 140°E longitude. There is a possibility that the poorly located earthquakes were icequakes, because the thick ice sheet and complicated subglacial topography can cause iceshocks.

Generally the edge of the continent, the coast area, is aseismic. However, once a denser seismic network was established, small/micro earthquakes began to be located. The area around Japanese Syowa Station (69.0° S, 39.0° E) is one among the areas where seismic activity has been well studied since 1980s (e.g. Kaminuma and Akamatsu; 1992).

Area around the Neumayer Station (08°W, 71°S) is another region where seismic activity has been well studied (Müller and Eckstaller, 2003). A seismic array has been operated for more than one decade at Neumayer Station. Since the deployment of the seismic network/array, some local events could be detected. Two seismically active regions were discovered on land and offshore of the continent.

Bannister and Kennett (2002) studied the seismicity around the SBA (Scott Base, 167°E, 78°S) and VNDA (Wright Valley, 162°E, 78°S) area using a temporary broadband seismic network. They found several interesting features about the location of local events; that is, a majority of the events were located along the coast, particularly in the vicinity of large glaciers. They have suggested several reasons for the occurrence of these events: basal sliding of the continental ice sheet, movement of ice streams associated with several scales of glaciers, movement of sea-ice, and tectonic earthquakes. In order to

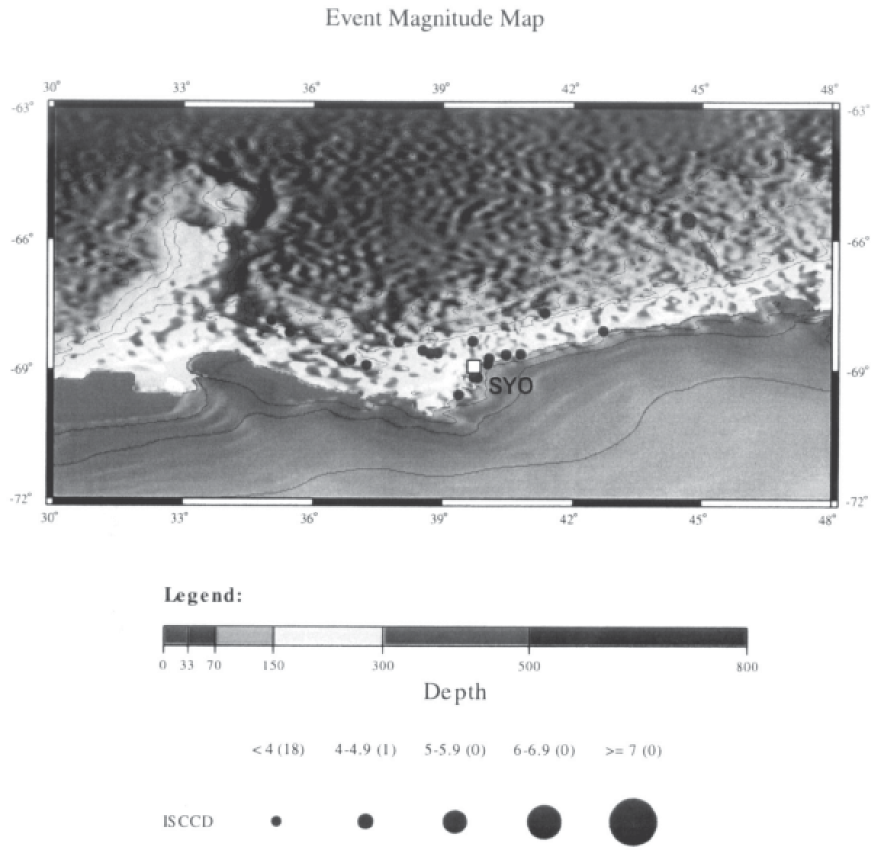

Figure 5. Earthquake locations in and around Lützow-Holm Bay, East Antarctica detected at Syowa Station. A total of 19 events were located. Numbers in the brackets correspond to the number of events included.

distinguish the actual origins of these events, they underlined the importance of determining the earthquake mechanism together with the depths of hypocenters.

Recently a broadband seismic network was deployed in a large region between Mawson and Casey stations and inland as far as 75° S by Australia (Reading, 2003). The aim to establish this seismic network was to discover the" seismic structure of the continent under Antarctica (SSCUA)". Characteristics of seismic activities will be detected by the network in the near future.

India has also carried out the seismic observations at Maitri Station (12°E, 71°S) since 1997. The seismic data were already contributed to earthquake locations by ISC. India also has published "Seismological Bulletin of Maitri Station, Antarctica" (Chander et al., 2003).

Seismicity around Syowa Station

A tripartite seismic network has been operated since 1987, in and around Syowa Station, at Lützow-Holm Bay, East Antarctica (Kaminuma and Akamatsu; 1992). Several micro earthquake have been recorded. Annual frequency of the detected local earthquakes is shown in Fig. 4 and hypocenters are given in Fig. 5. A total of 18 local earthquakes were located during the 15 years from 1987 through 2003 (Kanao and Kaminuma, 2005).

Characteristic features in time variations of seismic activity were found as follows: Seismicity during 1987-1989: A three-station seismic network was operated around the Syowa Station. Epicenters of ten local earthquakes were located during these three years. Many different types of earthquakes, such as a mainshock-aftershock, twin earthquake, earthquake swarms, etc., were detected and identified at that time. The seismic activity during this period was higher than that of the following decade. Earthquake locations were concentrated along the coast and the central part of Lützow-Holm Bay.

In 1990-1996, nine local earthquakes were recorded with many different types of events. The seismic activity during this period was very low and the magnitudes of the earthquakes ranged from -0.5 to 1.4.

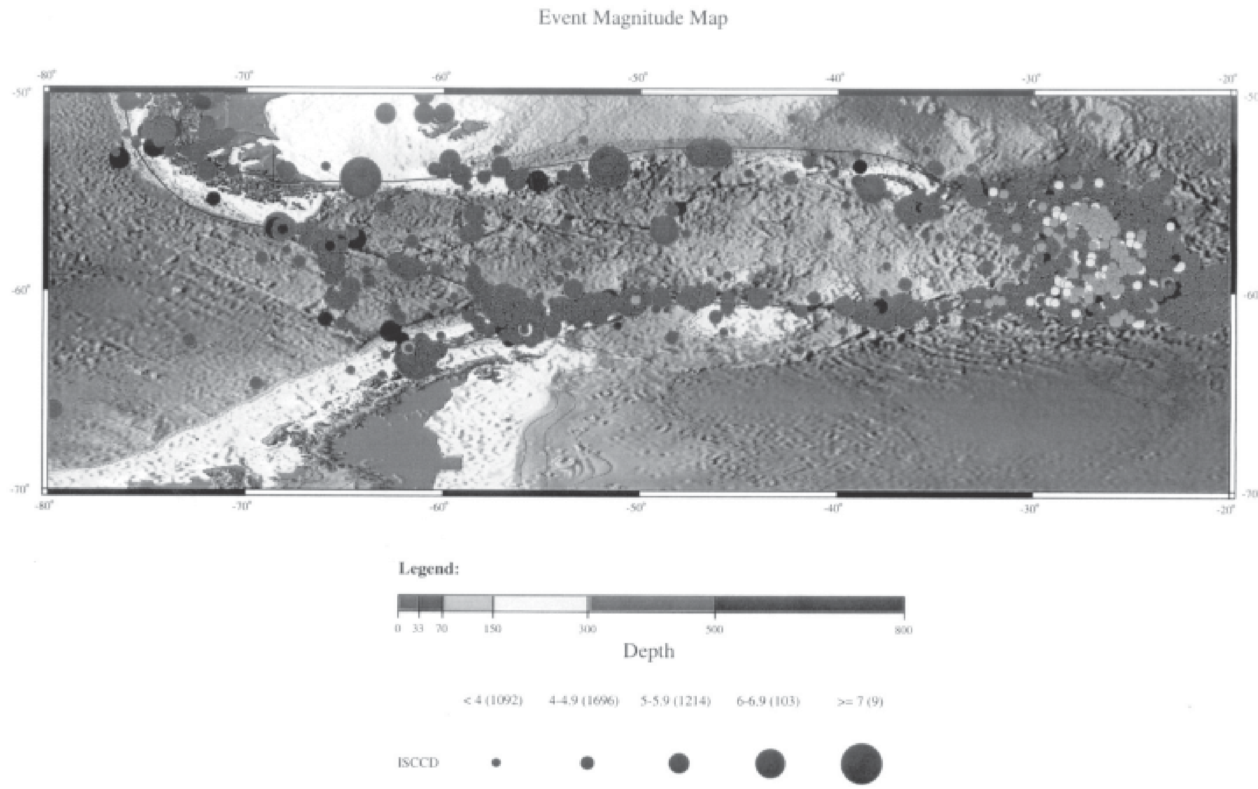

Figure 6. Earthquake locations around Antarctic Peninsula. Numbers in the brackets correspond to the number of events included.

One local event was detected in 1997, two events in 1998 and one event in 2001 and 2003, respectively. The low seismic activity continues to the present day in 2004.

Local earthquakes in and around Syowa Station were presumably caused by tectonic stress accumulated with crustal uplift after deglaciation (e.g. Kaminuma and Kanao; 1999). The effect of ice sheet changes may have caused phenomena such as crustal deformation, earthquake occurrence, faulting system, etc. in the shallow part of the lithosphere beneath Antarctica (e.g., Bannister and Kennett, 2002).

The high seismic region around the Antarctic Peninsula

The epicenters in the Antarctic Peninsula region bound by 20°- 80° W, 50°-70° S are shown in Fig. 6 (ISC catalog during the 1964-2002 period). The earthquake activity in this region is the highest in Antarctica including active volcanic areas in Deception Island, and the subduction zone in the Bransfield Strait. The focal depths of the earthquakes are mostly shallower than 40 km. During 1971-1989, only four earthquakes occurred with focal depths between 40 and 100 km (Kaminuma, 2000). One big event (mb6.3, Ms 7.0) occurred on Feb. 8, 1971. This is only Ms 7.0 earthquake known to have occurred in Antarctica. This is also the first tectonic earthquake to be felt in Antarctic, at Farady Station (65° S, 64°W) of UK (Kaminuma, 1995).

According to the report of seismic events recorded at King Sejoung Station (60°S, 59° W) of South Korea, King George Island of the South Shetland Islands, a few earthquake swarms occurred around Bridgeman Island (Jin et al., 1998). The earthquake swarms seemed to have typical volcanic earthquake waveforms (Kaminuma 2001). The earthquake swarm may have occurred around ORCA Sea Mount about 20 km southeast of King Sejoung Station.

Robertson et al. (2002) deployed seven continuously recording broadband seismometers in the South Shetland Islands region during 1997 and 1998. High level of local seismicity was identified in the first 15 months. About 90 earthquakes with magnitude mb 2~4 were located. Many earthquakes with 10~30 km depth are located in the fore arc region extending from the South Shetland Trench axis toward and beneath the South Shetland Islands. The earthquake locations suggest active convergence along the South Shetland subduction zone, however, there is no significant subduction zone extending into mantle.

Many earthquakes are located in the back-arc, either on large submarine volcanoes or rifting region along the center of the Bransfield Strait. Earthquakes concentrated around ORCA Sea Mount and Bridgeman Island. These earthquake locations indicate that the seismicity is associated with active volcanic rifting, non active subduction etc.

Volcanic regions

Seismic observations in volcanic regions have been carried out only at three volcanoes as shown in Fig. 1. Eruptions were recognized at Deception Island (63°S, 61°W) and Mount Erebus (78°S, 167°E, 3974 m). However, no eruption has been recognized at Mount Melbourne (74°S, 165°E, 2732 m).

The first felt shock in the Antarctic was the magnitude 4.7, December 4, 1967 earthquake accompanied by the volcanic eruption at Deception Island (Kaminuma, 1995). This eruption was the first recognized explosion of Deception Island by humankind. The buildings of the stations on Deception Island were destroyed by the eruptions. However, all members at the stations of Argentina, Chile and the UK evacuated safely after the eruption. All the stations at Deception Island have been since decommissioned.

Spain established a summer stations at Deception Island in 1980's and started geophysical research on Deception Volcano. Vila et al. (1992) have carried out seismic observations with five stations during the austral summer since 1987, and observed approximately 1000 local events per month. Earthquake locations seem to be concentrated along the NE-SW direction crossing the central part of the island.

In the 1991-92 survey, the seismic activity was found to be high with more than 700 events recorded. The seismic activity extended to areas of fumaroles and geothermal anomalies. The seismic activity was low in 1992-93 and 1993-94 surveys, and no other volcanic anomalies were observed. In the 1994-95 survey, a new increase of seismic activity was recorded with more than 800 seismic events (Ortiz et al., 1997).

Seismic observations by radio-telemetry continued in the summit area and on the slope of Erebus Volcano on Ross Island by the international cooperation among Japan, New Zealand and US during 1981-90 (Kaminuma and Dibble, 1990; Kaminuma, 1994b). Seismic activity around Mount Erebus became clear and a remarkable change of seismic activity were recognized before and after the new phase of volcanic activity started on September 13, 1984. It was characterized by larger and more frequent strombolian eruptions. Significant changes in seismicity within Ross Island and Mount Erebus were recognized both before and after the increased eruptive activity.

The seismic activity of Mount Erebus in 1980-1990 is divided into the following four stages: 1) normal high activity, 2) preceding the new phase, 3) new phase in volcanic activity and 4) low seismic activity. These stages suggest a general pattern of volcanic activity and give a fundamental information concerning production of volcanic eruption.

US scientists still continue the monitoring of seismic activity around Mount Erebus (Aster et al., 2004).

A research program on physical volcanology has been conducted around Mount Melbourne by Italian scientists since the end of the 1980's. Four seismic stations were installed on Mount Melbourne since 1990 and many local earthquakes have been reported together with other geophysical data (e.g. Privitera et al., 1992; Banaccorso et al., 1997a).

Local seismicity clustered along the eastern flank of Mount Melbourne, possibly in spatial association with the local north-south magnetic trend. One event occurred on December 10, 1990. This is the largest earthquake with magnitude 1.9 around Mount Melbourune (Armadillo et al., 2002).

DISCUSSION AND CONCLUSION

For many decades, the Antarctic Continent was believed to be an aseismic continent. Some earthquakes were located in the Antarctic Continent after IGY. It was known that there are small earthquake activities detected in the Antarctic Continent even though the activity itself is not so high as other continents. However, no event with magnitude larger than 5 is detected during the last four decades.

The number of tectonic earthquakes located in the Antarctic has increased with the development of Global Seismic Networks and local seismic arrays. Most of the tectonic earthquakes along the coast of the Antarctic Continent are caused by tectonic stress accumulated by crustal deformation after deglaciation. The micro-earthquake activity around Syowa Station as mentioned the previous section, may be a typical activity on the coastal area of the Antarctic Continent where crustal uplift after deglaciation is going on.

As seismological observations, like the local array deployment around Syowa Station, is promoted in the coastal area, more micro-earthquakes will be detected on the continental margin of Antarctica. If the other geophysical observations such as tide gauges, super conducting gravimeters etc., like at Syowa Station, are implemented at other stations in the coastal area, the relation between micro-earthquake activity and crustal movement will become clear.

Recently some intra-plate earthquakes were located in the southern ocean. As Negishi et al. (1998) pointed out, most intraplate earthquake in the surrounding ocean are not caused by stress after deglaciation. However, as Tsuboi et al. (2000) pointed out, there is a possibility that some earthquakes off of the Antarctic Plate are also caused by crustal deformation /tectonic stress involving deglaciation. It is strongly suggested that the effect of volume and shape change of ice sheet causes crustal uplift, earthquake occurrence, lithospheric deformation, etc.

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