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Spacial distribution and time variation in seismicity around the Antarctic Plate–Indian Ocean region

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Abstract: Spacial distribution and time variations in seismicity around the Antarctic Plate–Indian Ocean (0–160°E, 20–80°S) is evaluated based on the data compiled at the global seismological centers since 1964. Seismicity in the oceanic area of the Antarctic plate, along with ridges/transform faults between the Indian–Australian Plate, represents characteristic features before and after large earthquakes, such as the Balleny Earthquake on March 25, 1998. Seismicity in the aseismic ridges immediately east of the Australia–Antarctic Discordance (AAD) increased the year before occurrence of the Balleny Earthquake. Long period variations in seismicity during more than 30 years imply several characteristic time periods of increase in cumulative seismicity, associated with dynamic distribution of tectonic stress in space and time between adjacent plates. Time variations in seismicity around the Balleny Earthquake region, in particular, drastically changed before and after the main shock in March 1998. The recent distribution of hypocenters in this area appears to extend toward Wilks Land, followed by the excitation of local events beneath the continental ice sheet of Antarctica. Seismic activities of these areas might reflect far-field tectonic stress in the lithosphere around the region.

key words: seismicity, Antarctic-Plate, Indian Ocean, AAD, Balleny Earthquake

1. Introduction

A large earthquake (Mw = 9.0, 3.30 N, 95.96 E, depth = 30 km) occurred Off the West Coast of Northern Sumatra, on December 26, 2004. This is the fourth largest earthquake in the world since 1900 and the largest since the 1964 Alaska earthquake. In total, more than 300,000 people were killed, and about 1,000,000 were displaced by the earthquake and subsequent tsunami waves in South Asia. The tsunami caused more casualties than any other in recorded history and was observed on tide gauges in the Indian, Pacific and Atlantic Oceans including the coastal area of East Antarctica (*e.g.*, Titov *et al.*, 2005; Merrifield *et al.*, 2005).

The Sumatra earthquake occurred as thrust-faulting on the interface of the India and the Burma Plates. In a period of minutes, the faulting released elastic strains that had accumulated for centuries from ongoing subduction of the India Plate beneath the overriding Burma Plate. Currently available models of the main-shock fault displacement differ in details, but are consistent in that fault-rupture propagated to the northwest from the epicenter and substantial fault-rupture occurred hundreds of kilometers northwest of the epicenter. The source parameters obtained by teleseismic body-wave inversion (for instance, Yamanaka, 2006) are: centroid depth = 32 km, (strike, dip, rake) = (340, 8, 112), seismic moment $Mo = 3.5 \times 10^{22}$ Nm (Mw = 9.0), length L = 850 km, and max slip Dmax = 8.9 m.

Another large earthquake occurred Off the North Coast of the Antarctic continent near Balleny Island on March 25, 1998 (Mw = 8.1, 62.88 S, 149.71 E, depth = 10 km). This event was the largest intra-plate earthquake ever recorded in the Antarctic Plate. The source parameters obtained by teleseismic body-wave inversion (Tsuboi *et al.*, 2000) are: centroid depth = 20 km, (strike, dip, rake) = (282, 83, −1), seismic moment $Mo = 1.6 \times 10^{21}$ Nm (Mw = 8.1), length L = 200 km, and average slip Dave = 4.4 m.

This Balleny Island earthquake occurred in the mid-plate but there have been no reports of such large earthquakes in this region. Furthermore, the source mechanism cannot be related to the plate motion inferred from the nearby transform faults. Therefore this earthquake is not a usual tectonic event. It is argued that the sub-events aligned along the nodal plane with trending east-west direction, which indicates that the main shock occurred along this east-west, left-lateral, strike-slip fault (*e.g.*, Wiens *et al.*, 1998; Nettles *et al.*, 1999).

The Antarctic continent and surrounding ocean were once believed to be one of the aseismic regions of the Earth (*e.g.* Kaminuma, 2000; Reading, 2002). However, occurrence of these large earthquakes around the Indian Ocean sector of the Antarctic Plate in recent years implies dynamic features in the oceanic lithosphere of the surrounding region encompassing the Indian, Pacific and Antarctic Plates. Seismicity of the crust and uppermost mantle among the Antarctic Plates and boundaries between adjacent Plates is one of the geophysical features that represent ongoing Coulomb stress accumulating in the lithosphere.

In this study, spacial distribution and time variations in seismicity around the Antarctic Plate–Indian Ocean (here, we define the area as 0–160°E, 20–80°S) is evaluated involving the occurrence of these large earthquakes, chiefly based on data compiled in the International Seismological Centre (ISC) since 1964. The recent hypocentral data from 2003 are sourced from the National Earthquake Information Center of the United States Geological Survey (NEIC/USGS). In addition to the analysis of variations in seismicity for the decade 1994–2004, fluctuations of seismicity of period more than 30 years are investigated relating the distribution of tectonic stress of the lithosphere in space and time. A detailed study of seismic activities around the Antarctic Plate–Indian Ocean region would reveal the transportation process of the far-field forces associated with the occurrence of various scales of earthquake events.

2. Distribution of huge earthquakes

The Antarctic continent and surrounding ocean were believed to be one of the aseismic regions of the Earth for many decades (*e.g.* Kaminuma and Ishida, 1971;

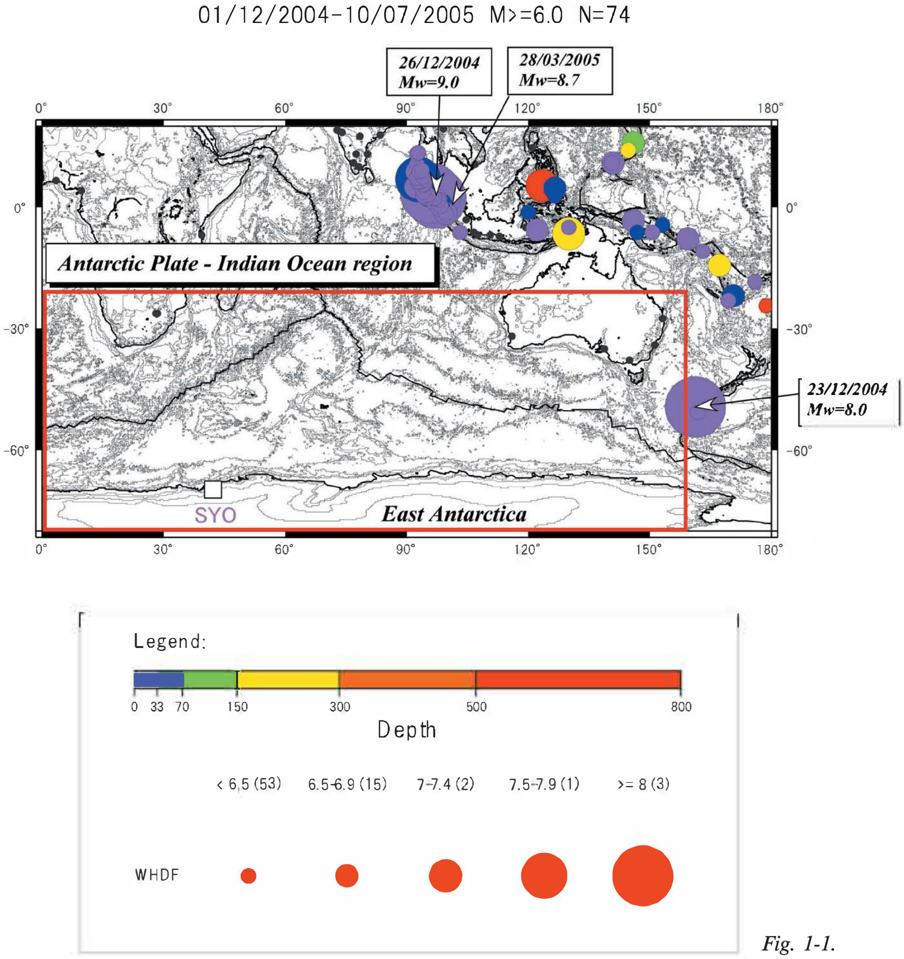

Fig. 1-1.

Fig. 1. Seismicity around the Antarctic Plate–Indian Ocean region (0–160°E, 20–80°S; inside red square area) with Magnitude more than 6.0, ten months after (Fig. 1-1) and ten years before (Fig. 1-2) the Sumatra Earthquake of December, 2004. Four large earthquakes were observed around the Antarctic Plate-Indian Ocean region during the total period. 1) Balleny Islands Region (Mw=8.1, March 25, 1998), 2) North of Macquarie Island (Mw=8.1, December 23, 2004), 3) Off West Coast of Northern Sumatra (Mw=9.0, December 26, 2004) and 4) Near Nias Island, Northern Sumatra (Mw=8.7, March 28, 2005). Hypocentral data catalog are as follows: ISCCD; Bulletin of the International Seismological Centre, MHDF; monthly hypocenter data file from the National Earthquake Information Center of the United States Geological Survey (NEIC/USGS), WHDF; weekly hypocenter data file from NEIC/USGS.

Adams *et al*., 1985). However, the following significant earthquakes with Magnitude 8.0 and greater have been observed since 1990 around the Antarctic Plate–Indian Ocean region (Fig. 1). 1) Balleny Islands Region (Mw=8.1, March 25, 1998), 2) North of Macquarie Island (Mw=8.1, December 23, 2004), 3) Off West Coast of Northern Sumatra (Mw=9.0, December 26, 2004) and 4) Near Nias Island, Northern Sumatra

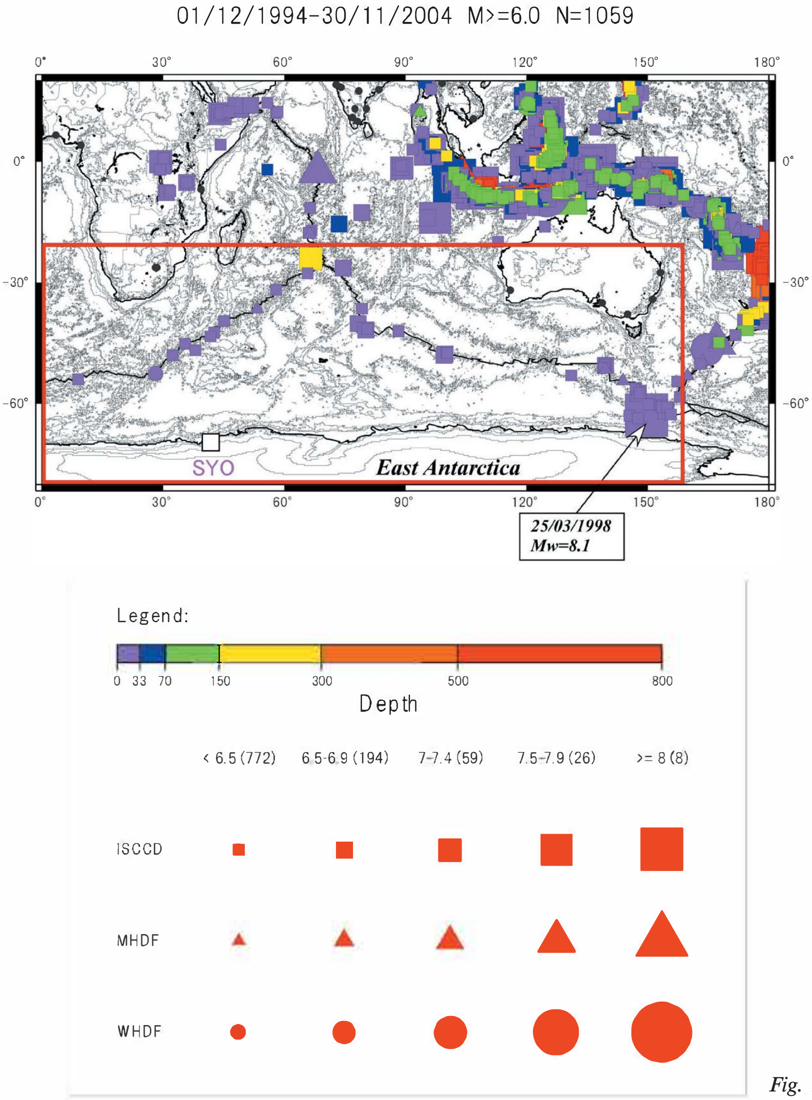

Fig. 1-2.

(Mw=8.7, March 28, 2005). Details of the source mechanism and tectonic interpretation for events 1) and 3) have been mentioned in Section 1. Here, we describe those for event 2) and 4).

The New Zealand area is part of a largely submerged micro-continent straddling the boundary between the Pacific and Australian Plates and is undergoing gradual elongation and compression, due to the continuous 4 cm/year northeastward motion of the Australian Plate relative to the Pacific Plate. In the New Zealand region, the plate boundary consists of a transform fault system connecting two subduction zones of opposing convergent directions that lie to the north and south of South Island. The Australian-Pacific plate boundary continues for 1500 km from the south of New Zealand to the triple junction with the Antarctic Plate.

The earthquake on December 23, 2004 (event 2) occurred in North of the Macquarie Ridge region. Macquarie Ridge is a continuous bathymetric high with a north-south trend that extends from the Puysegar trench in the north to the Hjort trench in the south. Macquarie Ridge forms part of the Pacific-Australian Plate boundary and is a predominantly right-lateral, strike-slip transform fault with a component of convergence that connects two subduction zones to the north and south. It is a narrow active plate boundary less than 5 km wide, although deformation occurs to a lesser degree in a broad area on either side of the ridge.

The source parameters obtained by USGS/NEIC Moment Tensor Solution for the Macquarie Island event 2) are: centroid depth $=35$ km, (strike, dip, rake) $=(261, 75, 174)$, seismic moment $Mo=1.0\times10^{21}$ Nm ($Mw=8.1$), respectively. Generally, along with other major strike slip faults, the Macquarie Ridge region includes many subsidiary faults. Although the earthquake North of Macquarie Island (event 2) occurred just three days before the Northern Sumatra event (3), there is no clear evidence for a relationship between the two events.

The earthquake on March 28, 2005 (event 4) occurred principally on the interface of the Australia Plate and Sunda Plate and was caused by the release of stresses that develop as the Australia Plate subducts beneath the overriding Sunda Plate. The Australia Plate begins its descent into the mantle at the Sunda trench, which lies to the southwest of the earthquake's epicenter. At this latitude, the trench is the surface expression of the plate interface between the Australia Plate and the Sunda Plate.

In the region of earthquake 4), the Australia Plate moves toward the northeast at a rate of about 5 cm/year relative to the Sunda Plate. This results in oblique convergence at the Sunda trench. The oblique motion is partitioned into thrust-faulting, which occurs on the plate-interface and which involves slip directed perpendicular to the trench, and strike-slip faulting, which occurs several hundred kilometers northeast of the trench and involves slip directed parallel to the trench. Event 4) occurred as a result of thrust faulting.

The source parameters obtained by teleseismic body-wave inversion for event 4) are: centroid depth $=27$ km, (strike, dip, rake) $=(320, 12, 104)$, seismic moment $Mo=1.3\times10^{22}$ Nm ($Mw=8.7$), length $L=250$ km, and max slip $Dmax=12$ m (Yamanaka, 2006). This earthquake was likely triggered by stress changes caused by the December 26, 2004 earthquake (event 3). However, it occurred on a segment of the fault 160 km southeast of the rupture zone of event 3).

Although a total 12 huge earthquakes with Magnitude 8.0 and greater have been recorded since 1990 in the world, the occurrence of the above four huge earthquakes within a limited time interval of seven years (from the Balleny Earthquake in March 1998 to the Sumatra Earthquake in December 2004) imply recent anomalous dynamics of the oceanic lithosphere in the region surrounding the Antarctic Plate.

3. A decade of variations in seismicity of the Antarctic Plate–Indian Ocean

3.1. *Large earthquake distribution*

When we discuss a restricted area of Antarctic Plate–Indian Ocean region (0–160°E, 20–80°S), in contrast, ten years of hypocentral data from ISC and NEIC/USGS from December 1994 until November 2004 indicate no significant events of Magnitude 7.0 or greater inside the Antarctic Plate itself and surrounding oceanic ridges/transform faults (Fig. 1-1, within red squared area).

Moreover, fewer than 30 earthquakes of Magnitude 6.0 or greater were observed in the same region during these ten years. Consequently, the seismicity of the Antarctic Plate–Indian Ocean region has been relatively low compared with that of other Plate boundaries such as subduction zones. No seismic events occurred in this region with Magnitude 6.0 and greater in the ten months after the Sumatra Earthquake of December, 2004 (Fig. 1-2).

3.2. *Total seismcity before and after large events*

In order to clarify the relationship between the occurrence of large earthquakes and variations of regional tectonic stress, annual seismicity for ten years (from December 1994 until November 2004) has been investigated around the Antarctic Plate–Indian Ocean region (Fig. 2-1, 2-2). Spacial distribution and time variations in seismicity around the oceanic ridges between the Antarctic Plate and Indian–Australian Plate represent characteristic features before and after the large earthquakes.

Figure 3-1 shows annual variations in seismicity before and after the Balleny Earthquake in 1998. The figure treats the same period as classified in Fig. 2-1; however, a more detailed explanation is given. The seismicity of the aseismic ridges immediately eastern of the Australia–Antarctic Discordance (AAD) (area (b)) increased in the year before occurrence of the Balleny Earthquake. Seismicity of the oceanic ridge around 90°E (area (c)), moreover, has a little bit excitation in activity associated with the occurrence of large events.

The area near the oceanic ridge around 90° E is known as the Kerguelen Plateau, which has relatively high seismicity compared with the adjacent Indian Ocean. The Kerguelen Plateau is the second largest Large Igneous Province (LIP) on Earth, and is thought to have been formed through mafic magmatism in Cretaceous time. It is subdivided into several segments according to structural differences and temporal evolution (*e.g*., Coffin and Eldholm, 1994). Large intraplate asthenospheric flow near the Kerguelen region could explain excitation of seismicity around the Plateau (*e.g*, Okal, 1981, 1983).

Additionally, seismicity along the 80–85°E fracture zone on the Antarctic Plate between the Kerguelen Plateau and the Amsterdam–Saint Paul Plateau has been interpreted as thermal and bending stresses in the lithosphere overlying a thermal anomaly resulting from channelled flow between the Kerguelen hotspot and the Southeast Indian Ridge (SEIR) axis, as pointed out by Bergman *et al*. (1984).

Regarding the periods before and after the Sumatra Earthquake 2004, seismicity of the aseismic ridges immediately east of the AAD (area (b) in Fig. 3-2) appeared to increase in the year before the occurrence of the Sumarta Earthquake. The oceanic ridge around 90°E, in contrast, does not have similar increase of seismic activity corresponding to the occurrence of the Sumatra Earthquake.

Fig. 2-1.

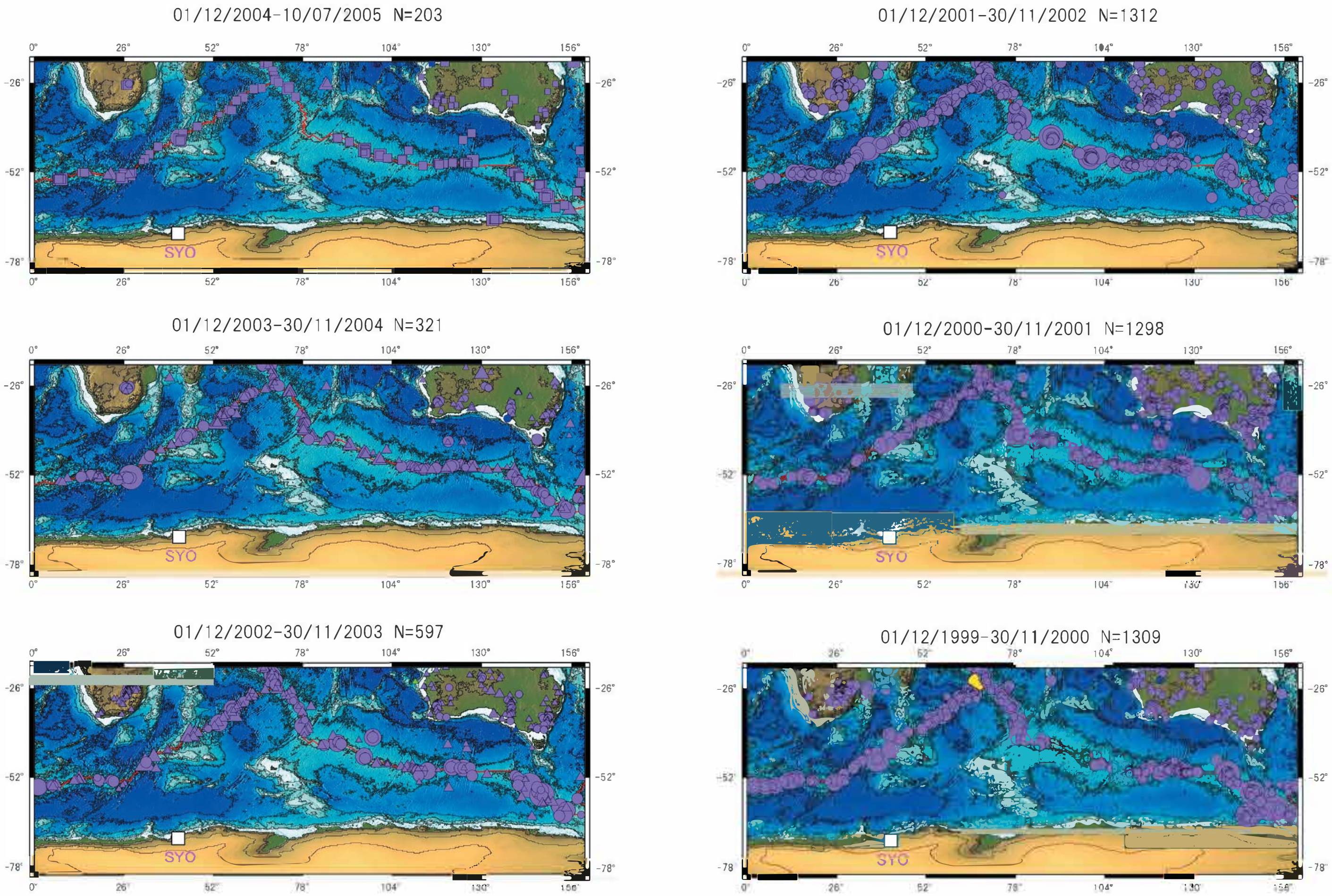
01/12/2004-10/07/2005 N=203
01/12/2001-30/11/2002 N=1312
01/12/2003-30/11/2004 N=321
01/12/2000-30/11/2001 N=1298
01/12/2002-30/11/2003 N=597
01/12/1999-30/11/2000 N=1309
0°
26°
52°
78°
104°
130°
156°
-26°
-52°
-78°
SYO

Fig. 2-2.

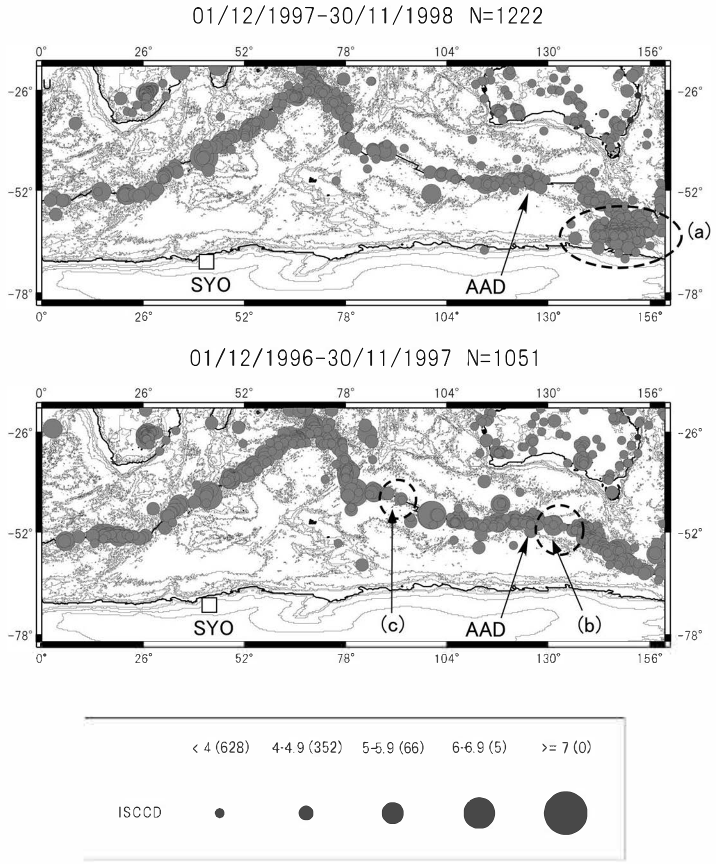

Fig. 3-1. Seismicity before and after the Balleny Earthquake 1998, around the Antarctic Plate–Indian Ocean region (0–160°E, 20–80°S). Aftershock regions of the Balleny Earthquake are shown as the area (a). Seismicity of the aseismic ridges immediately east of the Australia-Antarctic Discordance (AAD) (area (b)) increased in the year before occurrence of the Balleny Earthquake. Seismicity of the oceanic ridge around 90°E (area (c)), moreover, has similar activity associated with the occurrence of large events.

3.3. Australia–Antarctic Discordance (AAD)

In this section, we focus on the seismicity around the AAD. The AAD is known as an anomalously deep and rugged zone of the SEIR in 120–128°E. It is also defined by the intersection of the SEIR and Australian–Antarctic Depression, associated with a V-shaped trend of residual depth of anomalies (*e.g.* Marks *et al.*, 1990). The anomalously large depths characterized by high seismicity at the AAD are interpreted as a result of unusually cold underlying mantle which yields low melt supplying to the spreading plate boundary with 74 mm/y separation rate (*e.g.* West *et al.*, 1994). The anomalously low seismic velocities of the upper mantle beneath the ADD are identified from several seismic tomographic models (*e.g.*, Ritzwoller, *et al.*, 2001; Kobayashi and Zhao, 2004).

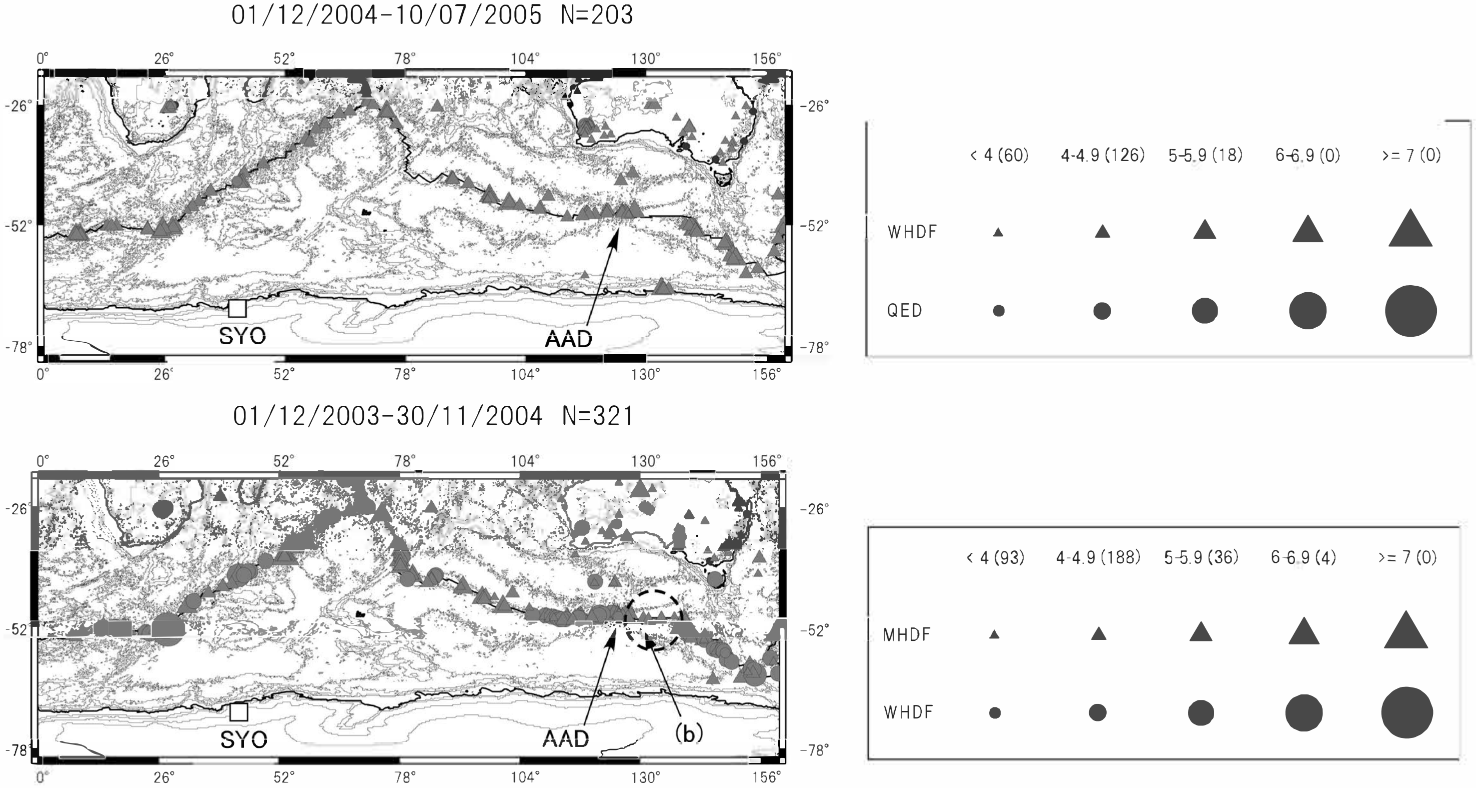

Fig. 3-2. Seismicity before and after the Sumatra Earthquake 2004, around the Antarctic Plate–Indian Ocean region (0–160°E, 20–80°S). Seismicity of the aseismic ridges immediately east of the AAD (area (b)) appears to have increased in the year before occurrence of the Sumarta Earthquake. Hypocentral data catalogs are as follows: MHDF; monthly hypocenter data file, WHDF; weekly hypocenter data file, QED; Quick Epicenter Determinations file by NEIC/USGS.

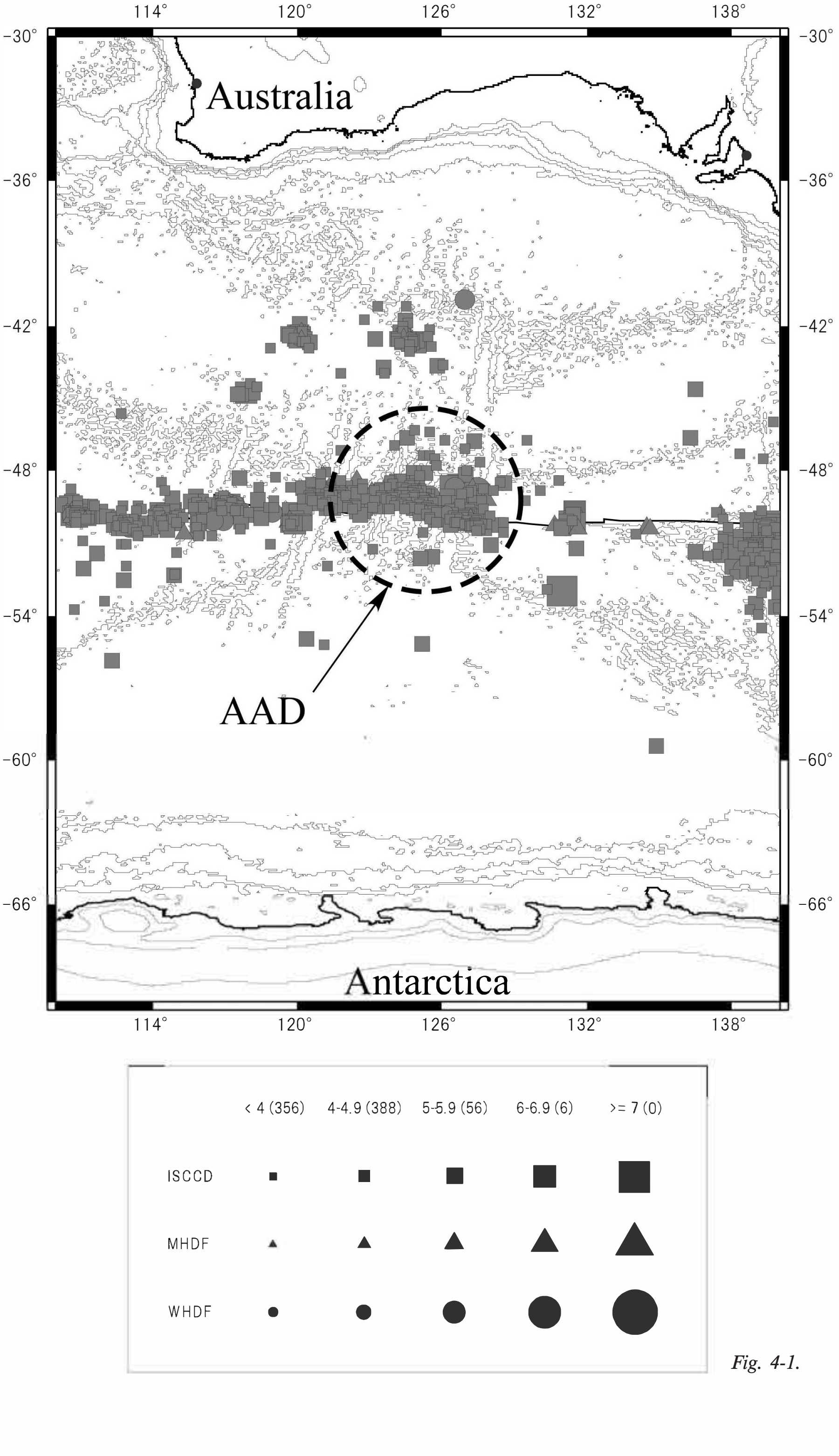
114°
120°
126°
132°
138°
-30°
-36°
-42°
-48°
-54°
-60°
-66°
Australia
AAD
Antarctica
< 4 (356)
4-4.9 (388)
5-5.9 (56)
6-6.9 (6)
>= 7 (0)
ISCCD
MHDF
WHDF

Fig. 4-1.

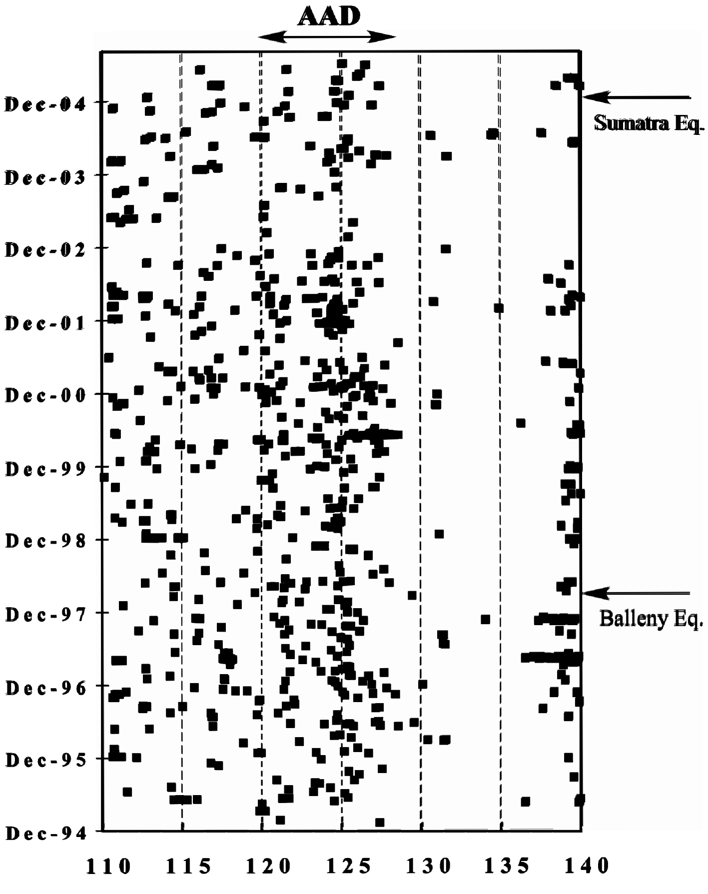

Fig. 4-2.

Figs. 4-1, 4-2. Seismicity around the Australia-Antarctic Discordance (AAD) from December 1994 to July 2005. Seismcity in the AAD was relatively high compared with the surrounding oceanic ridges. Seismicity of the aseismic ridges immediately east (135–140°E) of the AAD increased twice in the year before occurrence of the Balleny Islands earthquake in March 1998. Hypocentral data catalogs are as follows: ISCCD; Bulletin of the International Seismological Centre, MHDF; monthly hypocenter data file, WHDF; weekly hypocenter data file by NEIC/USGS.

Ten years of seismicity (from December 1994 until July 2005) around the AAD are examined in detail (Fig. 4). Seismicity of the exact location within the AAD is relatively high throughout the decade compared with that of surrounding oceanic ridges. The seismicity of the aseismic ridges immediately east (135–140°E) of the AAD increased twice significantly in the year before occurrence of the Balleny Earthquake in March 1998 (Fig. 4-2). Although several earthquakes were observed immediately east of the AAD, we cannot deduce relationship between the regional seismic activity and occurrence of the Sumatra Earthquake in December 2004, as was observed before the Balleny Earthquake.

4. Long term variations in seismicity of the Antarctic Plate–Indian Ocean

4.1. Cumulative number

In order to determine long-term variations in seismicity around the Antarctic Plate–Indian Ocean region, the cumulative number of earthquakes with Magnitude greater than 2.0 is investigated during more than 30 years, from the beginning of 1964 until the end of 1998 (Fig. 5). The increase ratio of the cumulative number per year has several increments during these three decades. For instance, there is a big increase in the last 1960 (arrow (a)), which can be considered due to the influence of the development of a world wide seismic network. Global seismic activities, however, are generally observed as relatively high in the period 1950–1970 (*e.g.*, Kanamori, 1977), particularly at high latitude (*e.g.*, Mogi, 1979). Then it is plausible that seismicity around the Antarctic Plate–Indian Ocean region was also high at the last 1960'th.

It also identified successive increases of a ratio in the cumulative number per year both in the middle of 1980'th (arrow (b)) and the middle of 1990'th (arrow (c)), res-

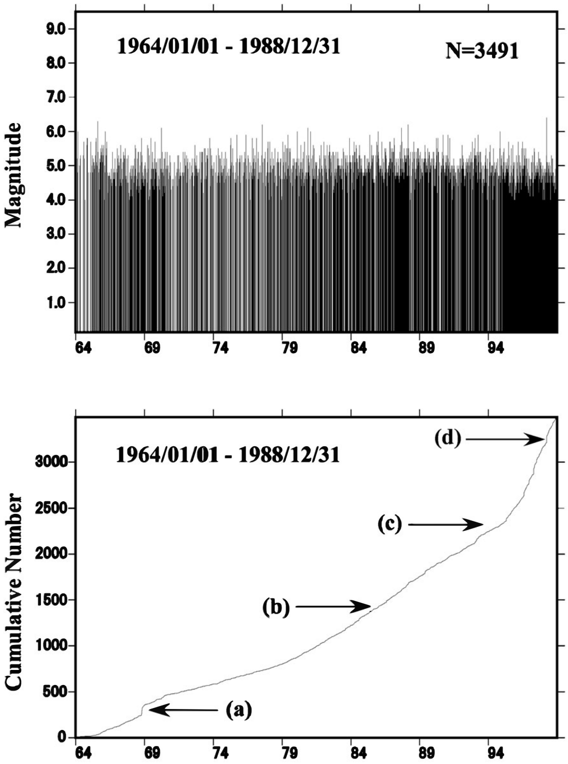

Fig. 5. Time variations in seismicity (Magunitude greater than 2.0 with their cumulative number) around the Antarctic Plate–Indian Ocean region (0–160°E, 20–80°S) during more than 30 years (from the beginning of 1964 until the end of 1998). The cumulative number increased several times: at the end of 1960'th (a), in the middle of 1980'th (b), and in the middle of 1990'th (c), followed by the last increase after the occurrence of the Balleny Earthquake in 1998 (d).

pectively. Since the ratio of the two increases has a gradual slope, instead of stepwise increments, the two time periods could be influenced by deployment of digital seismographs and local/regional networks, respectively. Local seismic networks have been developed during two decades in various regions around Antarctica (*e.g.*, Kaminuma and Kanao, 1999; Kanao and Kaminuma, 2006; Muller and Eckstaller, 2003; Reading, 2003; Jin *et al*., 1998; Bannister and Kennett, 2002; Robertson *et al*., 2002).

The last small increase (arrow (d)) in cumulative number occurred after the Balleny Earthquake in 1998. This last increment is affected by the aftershocks accumulated around the Balleny region.

4.2. Balleny Earthquake region and Wilkes Land

As we cannot identify time-space variations in seismicity around the Balleny Earthquake region and Wilkes Land in Fig. 2, long-term seimisity of the same region is examined in detail (Fig. 6). In the hypocentral distribution during a total period of more than 40 years, we cannot clearly distinguish the time variations before and after the main shock in 1998. Therefore, we divided the total data period into the following individual periods: 1) before the Balleny Earthquake, from January 1964 to March 1998 (Fig. 6-1), 2) after 500 days from the occurrence of the main event (*i.e*., from March 1998 to August 1999; Fig. 6-2), 3) from September 1999 to the end of 2002 (Fig. 6-3) and 4) from January 2003 to February 2005 (Fig. 6-4), respectively. On the basis of variations in seismicity as illustrated in Fig. 6, we attempted to apply a tectonic interpretation to the time variations in seismicity.

Before the main shock in 1998, the aseismic region (area (a) in Fig. 6-1) is clearly identified in the time period since 1964. In contrast, during the 500 days after occurrence of the main shock (from March 1998 to August 1999; Fig. 6-2), aftershocks were distributed around the main earthquake fault systems (area (b)). It has been argued by various authors that the sub-events of the Balleny Earthquake aligned along the nodal plane trending east-west, which indicates that the earthquake occurred along this east-west, left-lateral, strike-slip fault. Kobayashi *et al*. (1999) examined the magnitude dependence of the aftershock activity for the same period as covered in Fig. 6-2 (500 days after the main shock). They determined statistical parameters of the aftershocks as relatively large for b-values (Gutenberg-Richter Magnitude-frequency parameter) compared with those obtained in active continental areas. The resultant larger b-values correlate with those typically obtained in the oceanic plate.

Recent distribution of the hypocenters around this area (September 1999–Decem-

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Fig. 6. (next page) Time variations in seismicity with tectonic implication around the Balleny Earthquake region and Wilkes Land, East Antarctica; before the Balleny Earthquake from January 1964 to March 1998 (6-1; (a) aseismic area), after 500 days from the occurrence of the event from March 1998 to August 1999 (6-2; (b) aftershock area), after September 1999 until December 2002 (6-3; (c) spreading of seismicity), after January 2003 until February 2005 (6-4; (d) local seismicty around continental margin). Note that a large earthquake (Mw = 8.0, Depth = 35 km) occurred North of the Macquarie Islands on December 23, 2004. Hypocentral data catalogs are as follows: ISCCD; Bulletin of the International Seismological Centre, MHDF; monthly hypocenter data file, WHDF; weekly hypocenter data file by NEIC/USGS.

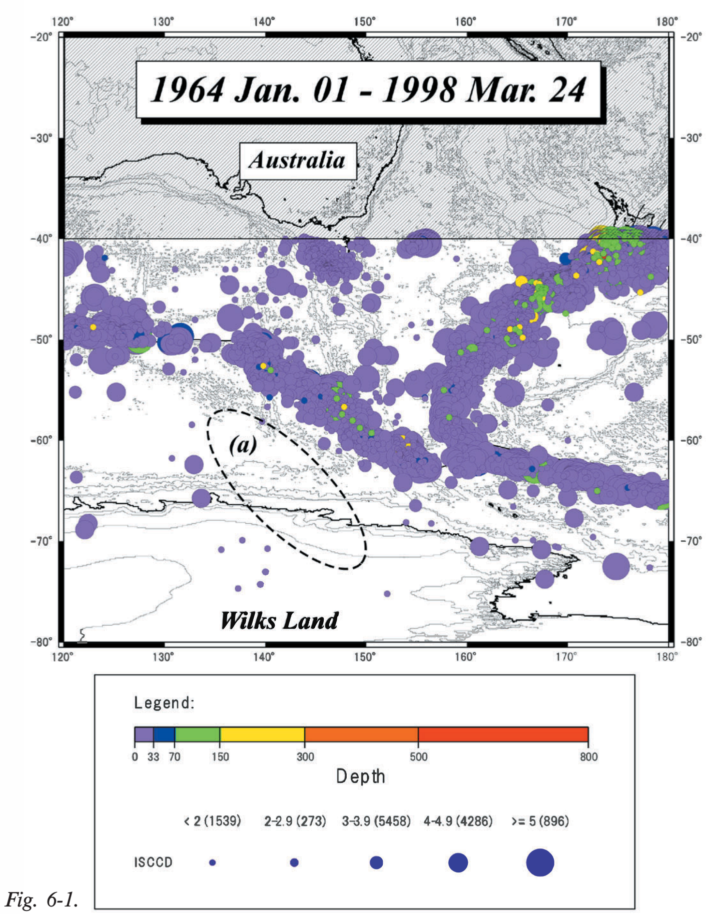
1964 Jan. 01 - 1998 Mar. 24
Australia
Wilks Land
(a)
120° 130° 140° 150° 160° 170° 180°
-20° -30° -40° -50° -60° -70° -80°
Legend:
0 33 70 150 300 500 800
Depth
< 2 (1539) 2-2.9 (273) 3-3.9 (5458) 4-4.9 (4286) >= 5 (896)
ISCCD

Fig. 6-1.

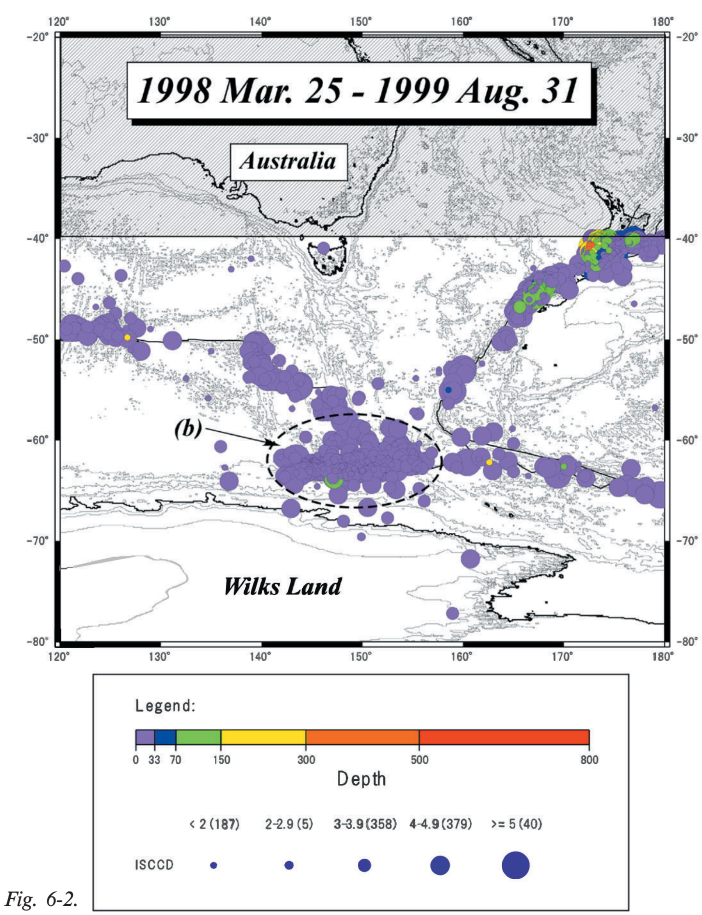
1998 Mar. 25 - 1999 Aug. 31
Australia
Wilks Land
(b)
120° 130° 140° 150° 160° 170° 180°
-20° -30° -40° -50° -60° -70° -80°
Legend:
0 33 70 150 300 500 800
Depth
< 2 (187) 2-2.9 (5) 3-3.9 (358) 4-4.9 (379) >= 5 (40)
ISCCD

Fig. 6-2.

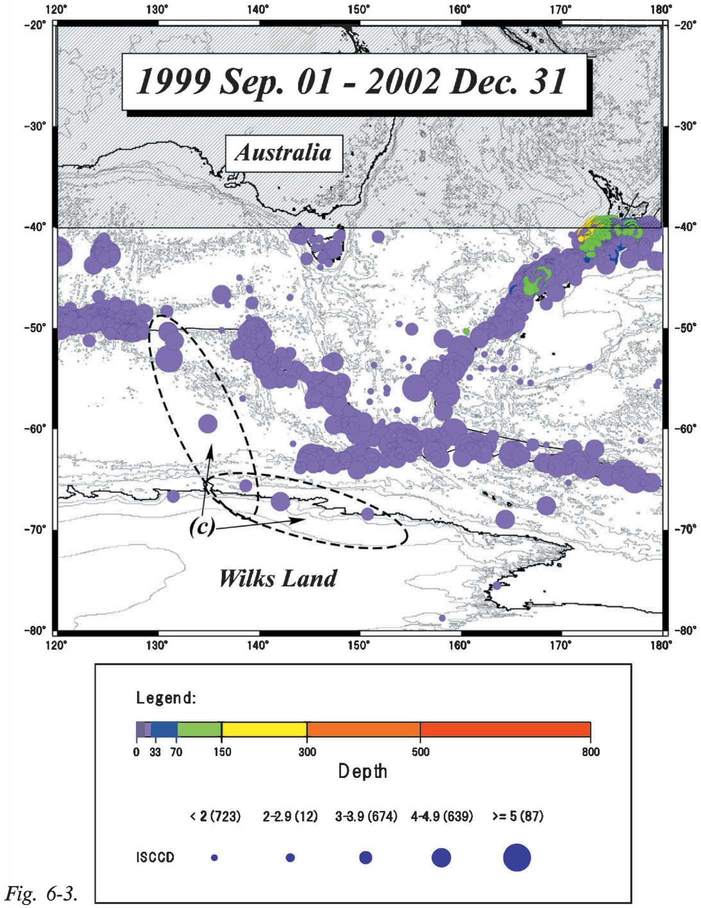
1999 Sep. 01 - 2002 Dec. 31
Australia
(c)
Wilks Land
120°
130°
140°
150°
160°
170°
180°
-20°
-30°
-40°
-50°
-60°
-70°
-80°
Legend:
0
33
70
150
300
500
800
Depth
< 2 (723)
2-2.9 (12)
3-3.9 (674)
4-4.9 (639)
>= 5 (87)
ISCCD

Fig. 6-3.

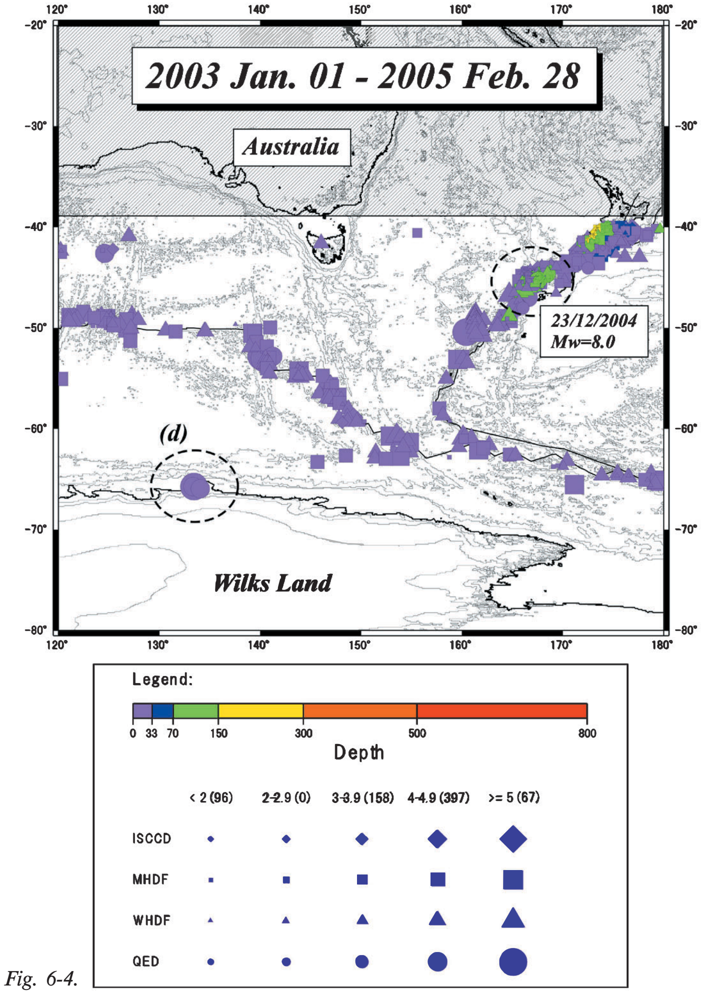
2003 Jan. 01 - 2005 Feb. 28
Australia
(d)
23/12/2004
Mw=8.0
Wilks Land
120°
130°
140°
150°
160°
170°
180°
-20°
-30°
-40°
-50°
-60°
-70°
-80°
Legend:
0
33
70
150
300
500
800
Depth
< 2 (96)
2-2.9 (0)
3-3.9 (158)
4-4.9 (397)
>= 5 (67)
ISCCD
MHDF
WHDF
QED

Fig. 6-4.

ber 2002; Fig. 6-3) additionally seem to be extended toward the continental margin of Wilkes Land, followed by the excitation of local events beneath the continental ice sheet of Antarctica (area (c) in Fig. 6-3). Thus, time variations in seismicity around the Balleny region drastically changed before and after the main shock in March 1998.

During the most recent time period after January 2003 (Fig. 6-4), a large earthquake ($\mathrm{Mw}=8.0$, Depth = 35 km) occurred in North of the Macquarie Islands, on December 23, 2004. This event occurred just three days before the Sumatra Earthquake. We cannot find evidence of any relationship between these two large events; however, seismic activity between the Antarctic and the Indian–Australian Plates has increased in the last few years. Moreover, local seismic activities are observed at the continental margin of Wilkes Land in the same period after January 2003 (area (d) in Fig. 6-4). Consequently, the greater Balleny region has given rise to a number of larger earthquakes, supporting the suggestion (Choy and McGarr, 2002) that the lithosphere in this area is capable of sustaining a remarkably high level of tectonic stress.

Around continental areas of East Antarctica, in general, seismicitiy was low. Wilkes Land, on the other hand, has been identified as the most active region in the Antarctic. Earthquakes in Wilkes Land are aligned from north to south along 140°E longitude, crossing several sub-glacial highlands such as the Resolution, the Adventure and the Belgica (*e.g.*, Browne-Cooper *et al.*, 1967; Kaminuma, 2000). The poorly located hypocenters, in contrast, could be large ice-quakes, because complicated subglacial topography with overlying ice-sheet in this area can efficiently cause ice related seismic phenomena.

5. Discussion

Intra-plate seismic activity is known to be very low in the Antarctic (Kaminuma, 1994, 2000); there have not been any significant earthquakes reported in the last century around the Balleny region. Although the centroid of this earthquake is located on the extension of nearby transform faults, the east-west strike of the fault plane of this earthquake does not coincide with the strike of the adjacent transform faults. In addition, the northeast-southwest compression stress in the hypocenter area is opposite to the stress orientation of the earthquakes that occurred along the transform faults. Thus it is not plausible to relate the fault mechanism of this earthquake to the plate motion of nearby transform faults. Then, it is difficult to interpret of the source mechanism in terms of plate tectonics. One possible mechanism for generation of large earthquakes is thermal stress of the young lithosphere, associated with unusual deformation at the Macquarie triple junction (*e.g.*, Wiens *et al.*, 1998; Nettles *et al.*, 1999). On the other hand, as Tsuboi *et al.* (2000) pointed out, there is a possibility that several earthquakes outside of the polar regions have been caused by crustal deformation/tectonic stress involving deglaciation.

It has been shown that the large scale surface lineament in northern Fennoscandia is a postglacial fault formed by an $\mathrm{Mw}=8$ earthquake which occurred shortly after local deglaciation 9000 years ago (Arvidsson, 1996; Johnston, 1987, 1996). Hunt and Malin (1998) have also suggested that a similar postglacial earthquake occurred in northern Canada. Thus removal of the ice sheet at the end of the last glaciation may have caused

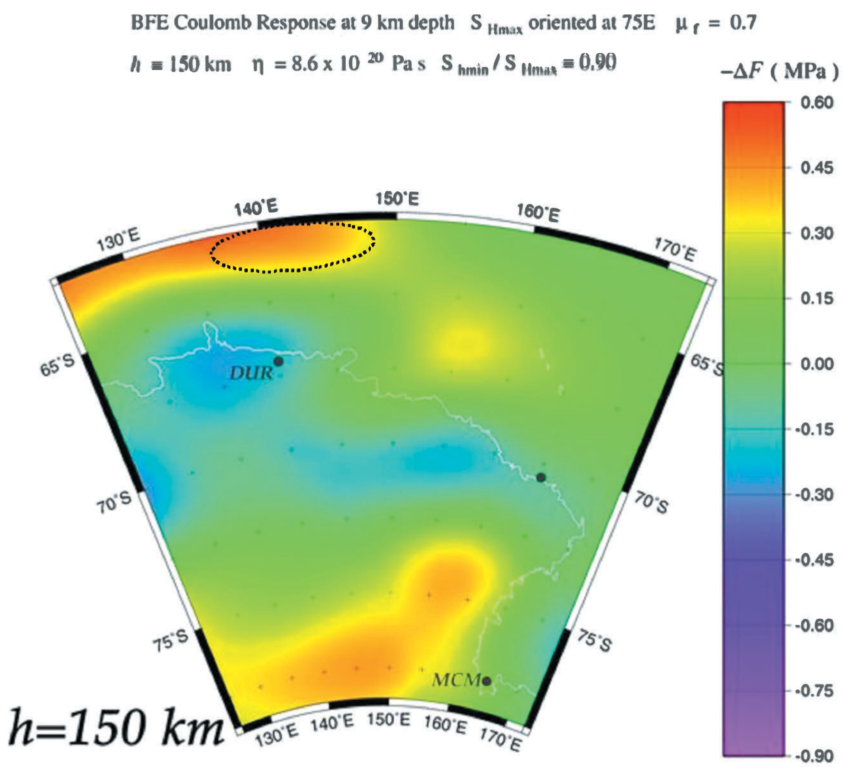

Fig. 7. Effective Coulomb Stress around the Balleny Earthquake region. Distribution of the effective Coulomb stress: ΔF, calculated from the stress change caused by the ice mass change (after Ivins et al., 2003). The viscosity of 10^{21} *Pa s, and 150 km thickness of the elastic lithosphere, are assumed. The Coulomb stress change becomes significantly negative (promoting seismicity) around the 1998 Balleny Earthquake region (circled by dashed line).*

non-isostatic compressive stresses and triggered large earthquakes. The postglacial rebound in the Antarctic is difficult to measure since most of the continent is still covered by ice. Only very limited observation is available for the crustal motion around Antarctica (*e.g.*, Kaminuma and Kanao, 1999). Currently, model calculation is performed to predict crustal response caused by deglaciation of the Antarctic ice sheet (James and Ivins, 1995, 1998; Wahr *et al.*, 1995).

In connection with the Balleny Earthquake, it is possible that the fault mechanism of the Balleny event was consistent with lithospheric deformation of the Antarctic Plate derived from the Earth's response to present-day and past ice mass changes in the Antarctic. James and Ivins (1998) computed both vertical and horizontal crustal responses assuming past and present-day ice mass changes in Antarctica. They incorporated a visco-elastic response as well as an elastic response of the spherically symmetric Earth model. The direction of the horizontal crustal motion around the Balleny region coincides with the compression axis of the fault mechanism of this earthquake. They assume at the plate boundary that either the displacement of the horizontal crustal motion is zero or there exists a slight ridge push. Thus, 5000 years of horizontal crustal motion with constant rate of 1 mm/yr may result in deformation of about 5 m around the hypocenter area. This is comparable with the dislocation obtained for this earthquake, as pointed out by Tsuboi *et al.* (2000).

Ivins *et al.* (2003) also quantitatively examined the regional earthquake potential associated with postglacial rebound of the Antarctic lithosphere (Fig. 7). They calculated the stress changes caused by ice mass variations with viscosity 10^{20} Pa s, and a 150 km thick elastic lithosphere. Then the change in the effective Coulomb stress was calculated. This is similar to the procedure adopted by modelers of earthquake stress transfer adapted to lithospheric rebound. The stress changes occur in a background tectonic stress orientation along 75° East. Their results show that the Coulomb stress change becomes significantly negative (promoting seismicity) around the 1998 Balleny Earthquake region, which indicates that the ice mass change can be a possible cause of the earthquake. The results also imply that the thickness of the lithosphere can be an important parameter for quantification of the stress change caused by the ice mass change.

Recently, 'Global High Seismic Active Periods (HSAP)' has been proposed by Dyad'kov *et al.* (2000), on the basis of an inverse relationship from both regional seismic activities and tectonic stress distribution between two separated areas around East Asia; that is, subduction zones of the Western Pacific region and the Baikal Rift Zone, central Eurasia. It has also been reported that the high seismicity regions move from one area to another within a few years, as reported for the Western Pacific region (Yoshida, 2002). Then it is possible that a high seismic activity area could migrate from one place to other over a long distance, depending on the concentration/relaxation process of tectonic stress in the lithosphere. Thus re-distribution of the stress field is one possible mechanism for triggering a generation of intra- and inter-Plate seismic activity in a high stress concentration area, such as the Balleny Earthquake source region spanning the Antarctic Plate and Indian Ocean.

5. Concluding remarks

Spacial distribution and time variations in seismicity around the Antarctic Plate–Indian Ocean region are evaluated associated with the occurrence of large earthquakes, such as the Balleny Earthquake in 1998, on the basis of data compiled at global seismological centers since 1964. In contrast, there is no clear relationship in seismicity involving the occurrence of the 2004 Sumatra Earthquake. Detailed investigation of the seismic activities may clarify the concentration/relaxation process of far-field tectonic stress around the regions. The wider regions of the oceanic lithosphere that surround Antarctica are capable of supporting high levels of stress and may buffer the Antarctic continent from lateral forces due to spreading ridges (Reading, 2006).

Time variations in seismicity around the Balleny Earthquake region have drastically changed before/after the main shock in March 1998. The recent distribution of the hypocenters around this area seems to extend inland of Wilkes Land, followed by the excitation of local events beneath the continental ice sheet. Seismicity around the oceanic ridges between the Antarctic Plate and the Indian–Australian Plate, in contrast, represent characteristic features before and after large earthquakes. Seismicity of the aseismic ridges east of the AAD increased, particularly in the year before occurrence of the Balleny Earthquake. Although not detected by Global Seismic Networks (GSN) and local seismic arrays, there is a possibility that several small earthquake events occurred around the aseismic ridges involving non-volcanic extension along the oceanic plate boundaries. Seismic activities in these usually aseismic regions might reflect far-field tectonic stress around the Antarctic Plate–Indian Ocean region.

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