Polar Geosci., 12, 183–191, 1999

AFTERSHOCK ACTIVITY OF THE GREAT 1998 EARTHQUAKE IN THE ANTARCTIC PLATE

Katsutada KAMINUMA, Reiji KOBAYASHI, Yoshifumi NOGI and Masaki KANAO

National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515

Abstract: On March 25, 1998, a great earthquake (M_S 8.0) struck the Balleny Islands region. This intraplate earthquake is the largest ever recorded in the Antarctic plate where the seismicity is very low. The aftershock activity of the Antarctic earthquake is investigated using the Weekly PDE (Preliminary Determination of Epicenters) seismicity catalog. Sixty seven aftershocks have been located during a period of 273 days. The distribution of the aftershocks may suggest that the fault plane trends E-W. The statistical parameters of the aftershock activity are determined. The *b*-value of the Gutenberg-Richter magnitude-frequency relation is 1.05. The large *b*-value indicates that many small aftershocks have occurred. The *p*-value of the modified Omori formula for aftershock activity is also determined as 1.14. In comparison with other great earthquakes, the *p*-value is relatively small, which may indicate that the aftershock activity continued for a long time.

key words: Antarctic earthquake, aftershock, *b*-value, *p*-value, intraplate earthquake

1. Introduction

Seismicity in the Antarctic plate is very low, except the high seismicity along the plate boundaries. The seismicity can be divided into the following five regions; 1) intraplate low seismic region, 2) high seismic region around the tip of the Antarctic Peninsula, 3) aseismic region of the Antarctic continent, 4) low seismic region of the coastal area at the continental edge, and 5) volcanic regions (KAMINUMA, 1994).

At least three previous felt shocks have been recorded since the International Geophysical Year (IGY) of 1957. The first one was the M4.7 earthquake accompanied by the volcanic eruptions of Deception Island (62°57′S, 60°38′W) on December 7, 1967. The huts of the stations on Deception Island were destroyed by the eruptions. All members in the stations evacuated safely after the eruptions.

The largest earthquake ever recorded in the Antarctic plate occurred in the South Shetland Islands on February 8, 1971. Its body-wave magnitude and surface-wave magnitude were determined by the US Geological Survey (USGS) National Earthquake Information Center (NEIC) to be 6.3 and 7.0, respectively. This is the only recorded earthquake of magnitude larger than 7.0 in the Antarctic. This earthquake was also felt at Faraday Station (65°14.8′S, 64°15.5′W) of the UK.

An eruption of Mount Erebus occurred on October 13, 1984; it was felt at McMurdo

Station (77°51′S, 166°40′E) of the US. All of these events were volcanic ones (KAMINUMA, 1994).

The seismic activity at the tip of the Antarctic Peninsula is the highest in the Antarctic. On the other hand, very few intraplate earthquakes have been located in the Southern Ocean, and the magnitudes are less than 6.

2. A Great Earthquake on March 25, 1998

A great earthquake with surface-wave magnitude 8.0 took place in the Balleny Islands region on March 25, 1998. Table 1 lists the source parameters determined by NEIC, except the best double-couple mechanism and moment magnitude (M_W) of the largest aftershock determined by the Harvard group. The earthquake was located about 500 km offshore from the Antarctic coast in the Antarctic plate. There have been other earthquakes with a magnutude larger than 5.5, but this earthquake is the largest oceanic intraplate earthquake ever recorded in the Antarctic plate (WIENS *et al.*, 1998).

The leader of Dumont d'Urville Station (66°40′S, 140°01′E) of France informed the leader of Syowa Station (69°00′S, 39°35′E) of Japan that all wintering members in the station felt a quake, and something on the shelf in the building fell down. The March 25, 1998, earthquake is the first event that has been felt on the Antarctic continent except volcanic earthquakes. The intensity at the station is estimated to be III (8.0–2.5 Gal) on the intensity scale of the Japan Meteorological Agency and V on the Medvedev-Sponheur-Karnik (MSK) intensity scale. Figure 1 shows the locations of the epicenter with the focal mechanism and of the two stations, and fracture zones.

The focal mechanism indicates the strike slip fault trending N-S or E-W. Some fracture zones are located near the epicentral region. It is clear in Fig. 1 that the fracture zones are perpendicular to the plate boundary between the Antarctic plate and the Australian plate, and trend NNW-SSE. However, the epicenter itself is not located on the fracture zone, and the strikes of the fracture zones differ from those of the nodal planes of the focal mechanism. The fault plane cannot be inferred from the tectonic background.

Aftershocks are important data in order to determine the fault plane. Thus the aftershock activity of the March 25, 1998, Antarctic earthquake is investigated, and the fault plane is determined by the aftershock distributions. The b-value and p-value are also determined. These values are statistical parameters of aftershock activity. The relation between the aftershock activity and the source process is also discussed.

Table 1. Source parameters of the main shock and largest aftershock.

	Main shock	Largest aftershock
Origin time (UTC)	1998/03/25 03:12:24.7	1998/03/25 12:17:22.7
Location	62.876°S, 149.712°E	63.578°S, 147.876°E
Depth	10 km	10 km
Magnitude	m_b 6.6, M_S 8.0, M_W 7.7	m_b 5.8, M_S 6.1, M_W 6.5
Best double-couple	(94°, 76°, –9°),	(277°, 67°, 21°),
(strike, dip, slip)	(187°, 81°, –165°)	(179°, 71°, 156°)

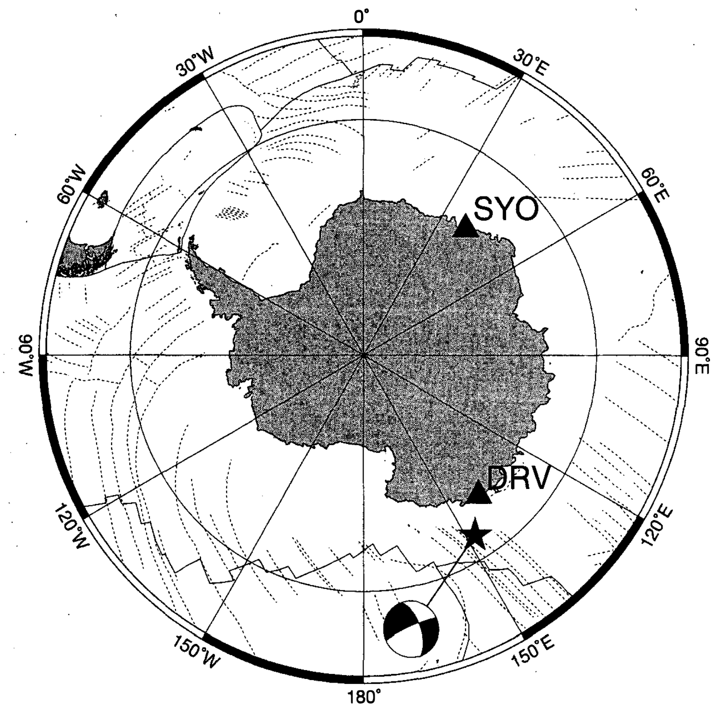

Fig. 1. Stereo projection showing the epicenter of the March 25, 1998, earthquake (star), and Syowa (SYO) and Dumont d'Urville (DRV) stations (triangles). Thin and dashed lines represent tectonic boundaries and fracture zones, respectively.

3. Aftershocks

According to the Weekly Preliminary Determination of Epicenters (PDE) of NEIC, 67 aftershocks occurred during 273 days from March 25 to December 23, 1998, as listed in Table 2. The epicenter distribution of the main shock and aftershocks are shown in Fig. 2, and the temporal distribution of the aftershocks with magnitude is shown in Fig. 3a. The fault plane of the main shock was taken as the E-W direction estimated from the aftershock distribution in Fig. 2. The epicenter of the main shock was located in the eastern part of the aftershock distribution, and indicates unilateral faulting.

The rupture length of the fault plane reached at least 300 km. However, the hypocenters of the aftershocks were located at 10 km depth except for two aftershocks located at 33 km depth. Since the focal region is near the Australian-Antarctic ridge, the shallow fault plane may be due to the young thin lithosphere.

Nine hours after the main shock, the largest aftershock with an M_S of 6.1 occurred. This event is located south of the fault plane with some concentration of aftershocks as shown in Fig. 2. The temporal variation of the concentrated aftershocks in the south is shown in Fig. 3b. The largest aftershock with one foreshock (m_b 4.5) and some aftershocks seem to be induced shocks by the main shock because the epicenters are distributed about 60–70 km south of the fault plane of the main shock. The best double-couple mechanism of the largest aftershock is very similar to that of the main shock. However, we cannot determine whether the N-S or E-W nodal plane is the fault plane, because the aftershocks concentrated near the largest aftershock do not lie on a line.

Table 2. Main shock and aftershocks from the Weekly PDE.

Date (YYYY/MM/DD)	Time (HH/MM/SS.S)	Lat. (°S)	Lon. (°E)	Depth (km)	M
1998/03/25	03:12:25.0	62.877	149.527	10.0	8.0Ms
1998/03/25	03:19:05.1	61.301	143.342	10.0	
1998/03/25	03:21:10.5	61.916	151.043	33.0	5.2mb
1998/03/25	03:34:08.4	62.306	149.614	10.0	4.3mb
1998/03/25	03:38:56.0	62.708	144.832	10.0	4.6mb
1998/03/25	04:01:32.5	62.659	147.684	10.0	4.1mb
1998/03/25	04:10:19.9	63.176	146.838	10.0	3.9mb
1998/03/25	04:14:25.8	63.718	148.129	10.0	4.5mb
1998/03/25	05:42:54.7	63.027	144.604	10.0	4.7mb
1998/03/25	06:00:27.8	62.625	149.345	10.0	4.5mb
1998/03/25	06:06:14.6	63.046	147.695	10.0	4.3mb
1998/03/25	07:12:17.3	62.869	145.389	10.0	4.3mb
1998/03/25	07:19:17.8	62.970	144.337	10.0	4.6mb
1998/03/25	07:32:00.1	62.892	145.643	10.0	4.8mb
1998/03/25	08:21:55.9	62.817	144.413	10.0	4.8mb
1998/03/25	08:28:12.1	61.857	142.432	10.0	4.0mb
1998/03/25	09:04:24.6	62.304	145.189	10.0	4.3mb
1998/03/25	11:45:12.7	62.848	150.178	10.0	4.9mb
1998/03/25	12:17:22.5	63.612	147.937	10.0	6.1Ms
1998/03/25	13:14:59.0	63.561	147.862	10.0	5.8Ms
1998/03/25	13:19:58.0	62.760	149.146	10.0	4.4mb
1998/03/25	14:21:08.4	63.613	147.956	10.0	4.7mb
1998/03/25	17:15:57.0	62.977	146.037	10.0	3.9mb
1998/03/25	18:06:54.8	63.137	151.490	10.0	3.7mb
1998/03/25	19:36:40.3	62.752	145.152	10.0	4.7mb
1998/03/26	00:59:18.6	62.866	148.570	10.0	4.5mb
1998/03/26	06:05:28.6	62.692	147.604	10.0	4.2mb
1998/03/26	08:53:53.4	63.189	150.386	10.0	4.5mb
1998/03/26	12:25:12.5	62.817	145.776	10.0	5.4mb
1998/03/26	14:51:08.1	62.654	146.032	10.0	4.3mb
1998/03/27	00:36:14.0	63.035	146.223	10.0	4.4mb
1998/03/27	01:19:55.8	62.616	145.989	10.0	4.6mb
1998/03/27	01:42:07.9	63.243	144.610	10.0	4.3mb
1998/03/27	08:57:01.3	62.890	148.467	10.0	3.7mb
1998/03/27	10:47:15.9	63.304	148.538	10.0	4.5mb
1998/03/27	13:41:34.6	61.275	148.748	10.0	3.9mb
1998/03/27	15:56:56.7	61.192	153.249	10.0	4.1mb
1998/03/28	06:34:50.2	63.528	148.212	10.0	4.8Ms
1998/03/28	13:22:31.2	62.996	147.289	10.0	4.4mb
1998/03/29	10:06:38.4	63.158	150.318	10.0	4.0mb
1998/03/29	11:41:33.3	62.900	145.466	10.0	4.6Ms
1998/03/30	17:19:59.7	62.545	149.586	10.0	4.0mb
1998/03/31	01:24:07.8	62.631	147.086	10.0	5.2mb
1998/03/31	01:43:53.1	62.658	147.395	10.0	4.5mb
1998/03/31	22:15:08.5	62.708	148.947	10.0	4.0mb
1998/04/01	10:12:34.3	62.953	147.928	10.0	4.1mb
1998/04/04	07:11:40.8	62.980	147.728	10.0	4.3mb
1998/04/04	22:10:38.3	63.023	148.236	10.0	4.2mb
1998/04/05	15:12:34.3	63.026	144.553	10.0	4.4mb
1998/04/06	03:53:21.6	62.885	150.442	10.0	3.9mb
1998/04/09	01:18:24.0	63.660	148.292	10.0	4.1mb
1998/04/10	10:10:41.9	62.885	149.450	10.0	4.1mb
1998/04/16	11:15:41.8	62.832	145.041	10.0	4.4mb
1998/04/18	10:04:21.7	63.470	147.673	10.0	5.3Ms
1998/04/19	02:31:15.6	62.935	147.749	10.0	4.4mb
1998/04/19	15:14:00.9	62.979	149.891	10.0	4.3mb
1998/04/30	03:40:48.6	63.186	149.697	10.0	
1998/05/16	18:30:17.8	62.814	149.510	10.0	4.4mb
1998/05/17	03:52:18.2	63.027	151.847	10.0	4.4mb
1998/05/26	19:51:50.0	62.927	144.503	10.0	4.8mb
1998/06/04	17:43:08.2	63.032	148.886	10.0	
1998/06/17	13:20:45.0	62.847	152.133	10.0	3.8mb
1998/06/17	13:30:57.4	62.958	148.670	10.0	4.0mb
1998/06/20	11:49:33.3	63.163	144.846	10.0	4.3mb
1998/07/06	10:58:49.0	62.838	150.964	33.0	3.8mb
1998/08/10	21:00:34.3	62.693	148.032	10.0	4.7mb
1998/08/14	13:21:24.7	63.607	147.488	10.0	5.3mb
1998/09/08	14:09:32.7	62.714	145.306	10.0	4.0mb

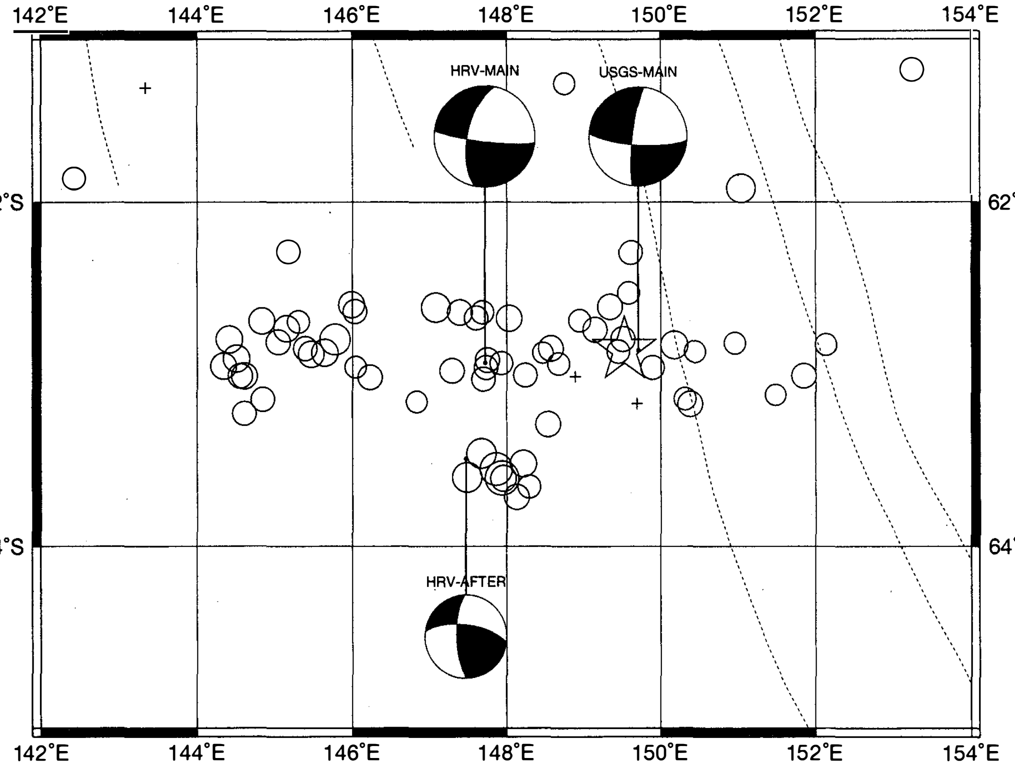

Fig. 2. Distribution of the main shock (star) and the aftershocks (circles). HRV-MAIN, USGS-MAIN, and HRV-AFTER denote the best double-couple of the main shock determined by USGS and the Harvard group, and of the largest aftershock by the Harvard group, respectively.

UTSU (1965) applied the maximum likelihood procedure to obtain the b-value of the Gutenberg-Richter magnitude-frequency relation for earthquakes (GUTENBERG and RICHTER, 1944), which is one of the important statistical laws in seismology. The relation is as follows.

$$\log n(M) = a - bM, \tag{1}$$

where n denotes the number of earthquakes as a function of magnitude M, and a and b are constants depending on the group of earthquakes considered. The b-value for M4.3–6.1 aftershocks determined using Utsu's method is 1.05 as shown in Fig. 4. The Gutenberg-Richter relation does not fit the aftershocks with a magnitude less than 4.3. This may suggest that the world wide seismological network used by USGS cannot detect earthquakes with magnitude less than 4.3 in this region.

The frequency of aftershocks with magnitude more than a given value decreases with increasing time as given by the following equation.

$$n(t) = \frac{K}{(t+c)^p} + B, \tag{2}$$

where $n(t)$ denotes the frequency of aftershocks occurring between time t and $t+\Delta t$, B denotes background seismicity, and, K, c, and p are positive constants. In this study, B

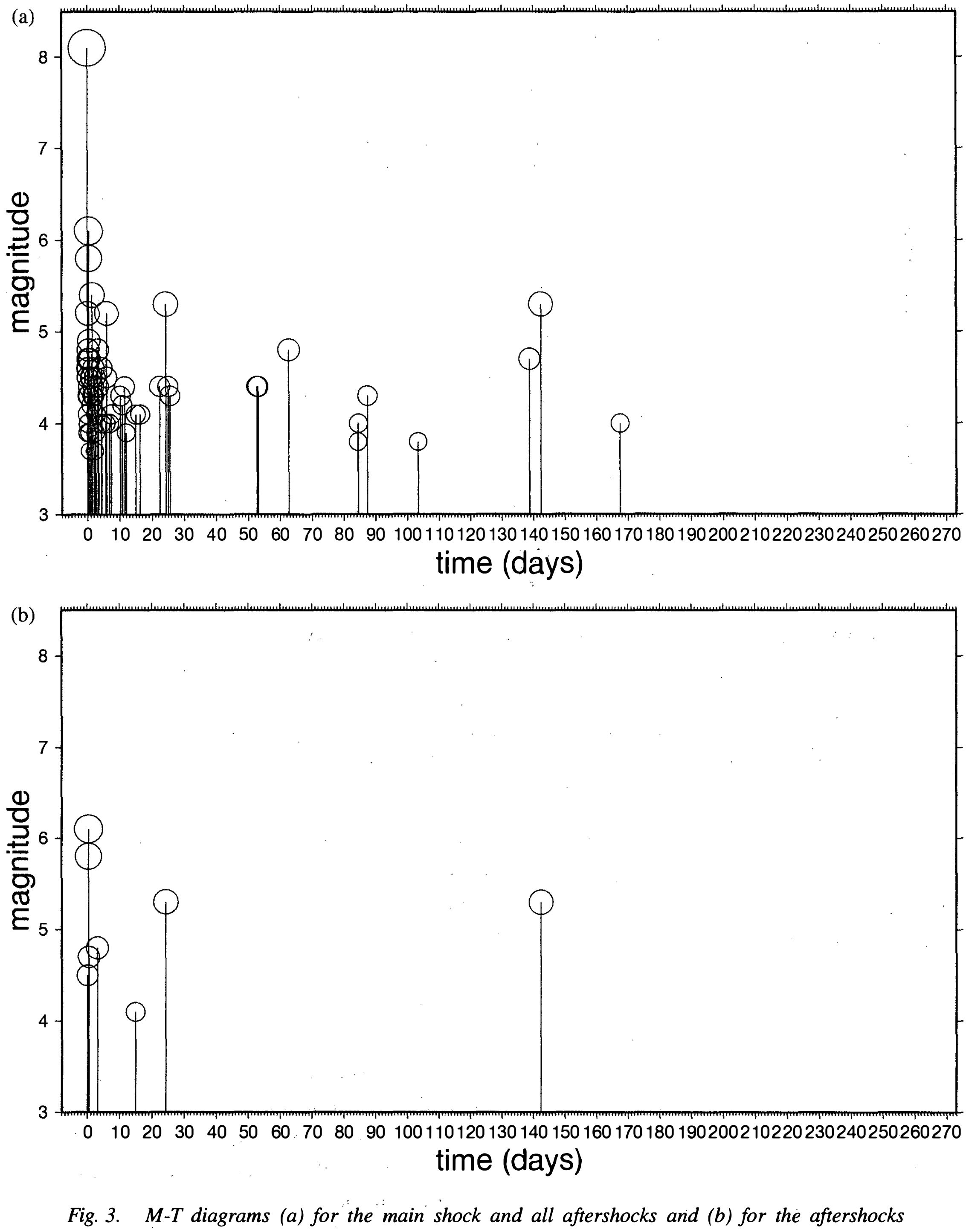

Fig. 3. M-T diagrams (a) for the main shock and all aftershocks and (b) for the aftershocks concentrated near the largest aftershock.

can be ignored because there was no seismicity in the focal region before the main shock occurred. When t is the number of days, the parameters were determined by using Ogata's method (OGATA, 1983) as follows. K=6.76, c=0.1, and p=1.14 (Fig. 5).

Table 3 lists the b- and p-values of aftershocks of six shallow great earthquakes in Japan obtained by UTSU (1961, 1969) to compare with those of the 1998 Antarctic earth-

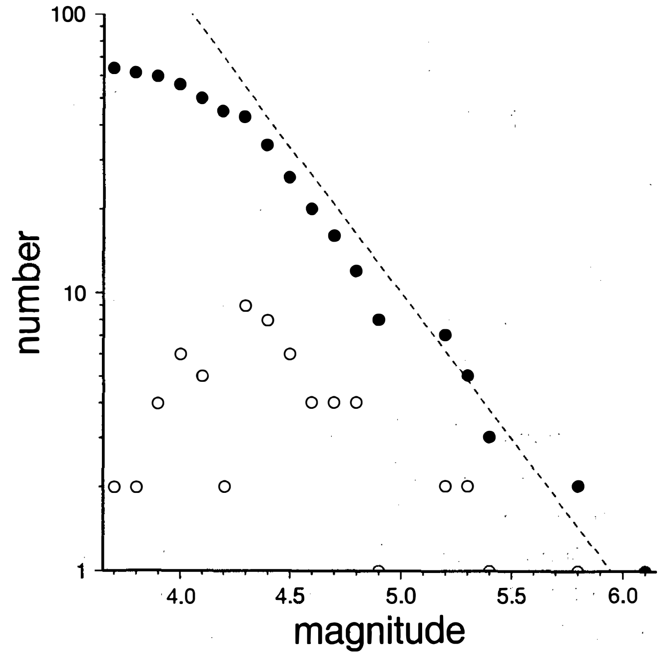

Fig. 4. *Number of aftershocks as a function of magnitude. Open circles represent the number of aftershocks with magnitude M. Filled circles represent the total number of aftershocks with magnitude more than M. The regression line is represented by log n (M)=6.259–1.05M.*

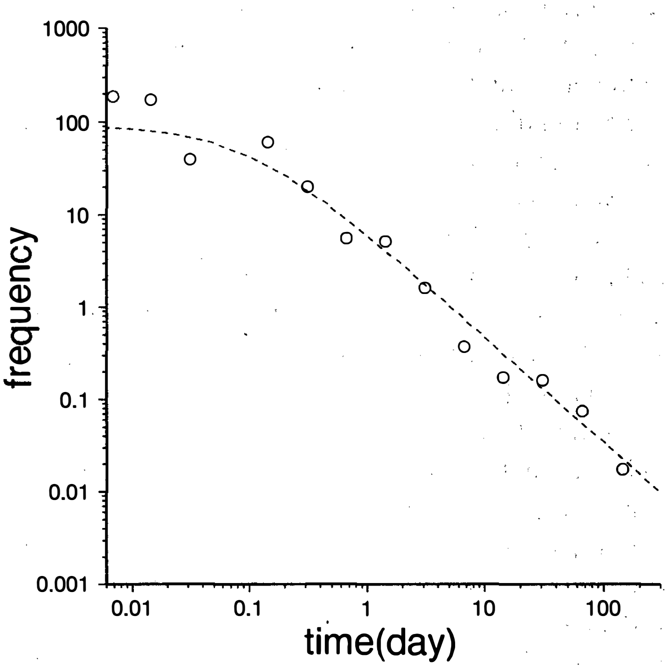

Fig. 5. *Frequency of aftershocks with magnitude more than 4.3. Open circles represent the numbers for each time interval of* $(10^{i+j/3}, 10^{i+(j+1)/3}$ *days with i=–3, –2, –1, 0, 1, 2, and j=0, 1, 2 divided by the time interval. The dashed line is represented by* $n(t)=6.76/((t+0.1)^{1.14})$.

Table 3. b- and p-values of aftershocks of great earthquakes in Japan.

Location	Year	M	*b*	*p*	Remarks
Kanto	1923	7.9		1.3	
Sanriku	1933	8.1	1.1	1.5	U1
To-nankai	1944	7.9	0.7	1.1	U2
Nankai	1946	8.0	0.7	1.0	U2
Tokachi-oki	1952	8.2	0.8	1.1	U1
Tokachi-oki	1968	7.9	0.9	1.0	U2
Antarctica	1998	8.0	1.05	1.14	

quake. U1 and U2 in "Remarks" denote UTSU (1961) and UTSU (1969), respectively.

The b-value is considered to be related to some tectonic condition or physical properties of crustal rock in the focal region. The b-values listed in the table range between 0.7 and 1.1. Therefore, the large b-value of 1.05 means that small earthquakes occurred frequently, and that the structure of the focal region may be inhomogeneous.

The p-values in the table range between 1.0 and 1.5. The p-value of 1.14 of the Antarctic earthquake is relatively small, compared with the listed great earthquakes. This means that the aftershocks continued for a long time, as the p-value is considered to represent the speed of decay of aftershock activity.

4. Discussion

The fault plane of the main shock determined from the aftershock distribution trends E-W. However, no tectonic lineation trending E-W in the focal region has been detected by using maps of bathymetry and gravity anomaly. Furthermore, the stress field inferred from the fracture zones trending NNW-SSE cannot explain the mechanism of the main shock indicating NW-SE compression.

The statistical parameters b and p of the aftershock activity indicate that many small aftershocks occurred, and that aftershocks continued for a long time. It is inferred that the parameters probably reflect the strong heterogeneity of the asperity or the fault plane divided into segments whose strikes trend in slightly different directions. The source process analysis using the teleseismic body waves shows that the focal mechanisms of the subevents of the main shock almost trend in the same directions (KIKUCHI and YAMANAKA, 1998). On the other hand, the large non-double-couple component (ε=−0.41, NETTLES *et al.*, 1998) cannot be explained by the source process determined from teleseismic body wave analysis. The large non-double-couple component could be caused by strong lateral heterogeneity in the seismic velocity structure, or by the complex source process related to the subevents, which have fault planes trending in different directions. A more detailed analysis is required to determine the cause of the large non-double-couple component.

5. Conclusion

Aftershock activity of the March 25, 1998, Antarctic earthquake is reported. The distribution of the aftershocks shows that the fault plane of the main shock trends E-W. However, no tectonic lineation trending E-W has been found in the maps of bathymetry and gravity anomaly, and the source mechanism cannot be interpreted by the tectonic condition in and around the focal region. The large b-value of 1.05 indicates that many small earthquakes occurred, and the small p-value of 1.14 indicates that the aftershock activity decayed slowly.

Acknowledgments

The aftershock data are taken from the IRIS Data Management Center. The authors thank Dr. R. MATSU'URA for the program "AFT12" for the Ogata's method. The authors thank Dr. F. TAJIMA of University of California at Berkeley and Dr. S. TSUBOI of the National Defense Academy for their critical reviews.

References

KAMINUMA, K. (1994): Seismic activity in and around Antarctic continent. Terra Antarct., **1**(2), 423–426.

KIKUCHI, M. and YAMANAKA, Y. (1998): Great earthquake near the Antarctic continent on March 25 (M_S 8.0). EIC Seismology Note, No. **41**, 3 p. (in Japanese).

GUTENBERG, B. and RICHTER, C.F. (1944): Frequency of earthquakes in California. Bull. Seismol. Soc. Am., **34**, 185–188.

OGATA, Y. (1983): Estimation of the parameters in the modified Omori formula for aftershock frequencies by the maximum likelihood procedure. J. Phys. Earth, **31**, 115–124.

NETTLES, M., WALLACE, T.C., BECK, S. and EKSTRÖM, G. (1998): The March 25, 1998 Antarctic plate earthquake (abstract). Eos; Trans., **79**, F662–F663.

UTSU, T. (1961): A statistical study on the occurrence of aftershocks. Geophys. Mag., **30**, 521–605.

UTSU, T. (1965): A method for determining the value of b in a formula log $n=a-bM$ showing the magnitude-frequency relation for earthquakes. Geophys. Bull. Hokkaido Univ., **13**, 99–103 (in Japanese with English abstract).

UTSU, T. (1969): Aftershocks and earthquake statistics (I). J. Fac. Sci., Hokkaido Univ., Ser VII, **3**, 129–195.

WIENS, D.A., WYSESSION, M.E. and LAWVER, L. (1998): Recent oceanic intraplate earthquake in Balleny Sea was largest ever detected. Eos; Trans., **79**, 353–354.

(Received February 15, 1999; Revised manuscript accepted April 12, 1999)