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A revaluation of the seismicity in the Antarctic

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Abstract: The Antarctic Peninsula region and some volcanic regions in the Antarctic plate are regions of which the tectonic evolution has been well studied Occurences of tectonic and volcanic earthquakes in the region have been discussed from the point of view of seismotectonics

As the number of seismic stations in the world has increased, so has the number of tectonic earthquakes detected in the Antarctic The seismic activity in the following three regions can be discussed from the point of view of seismotectonics or neotectonics 1) the great earthquakes in the intraplate low seismic region, 2) microseismic activity at the edge of the continent and 3) seismic activity in Wilkes Land Some tectonic earthquakes in these regions are caused by tectonic stress accumulated by crustal deformation after deglaciation The effect of ice sheet change in Antarctica has caused such phenomena as crustal deformation, earthquake occurrence etc in the crust and upper mantle

key words seismicity, seismotectonics, crustal uplift, icequake, ice sheet

1. Introduction

It was general knowledge before 1957, when the International Geophysical Year (IGY) started, that the Antarctic Continent was an aseismic one and only minor seismicity in the vicinity of the active volcano, Mount Erebus, was to be expected (Gutenberg and Richter, 1954; Richter, 1958). About ten seismic stations were established in the Antarctic during the IGY As the number of seismic stations in the Antarctic increased, earthquakes came to be detected on the Antarctic Continent, even though its seismicity was very low (*e.g* Kaminuma and Ishida, 1971, Adams, 1972). The notion that there are no tectonic earthquakes in Antarctica seemed to be abondoned by the 1980's It became clear that an earthquake with magnitude 4 occurred every few years However no earthquakes with magnitude larger than 5 have occurred during the last three decades This requires discussion Johnstone (1987) proposed an explanation for the lack of seismic activity in terms of pressure effects produced by the continental ice sheet

Seismic activities in some volcanic regions have become clear by local seismic networks which were established around Mount Erebus and Mount Melborne of the McMurdo Volcanic Group, and on Deception Island in the South Shetland Islands, since the 1980's (Kaminuma, 1994b, Priveitera *et al* , 1992, Banaccorso *et al* , 1997a, b; Vila *et al* , 1992) The seismic network in the world became dense in the 1980's and the network of digital seismographs was established in the 1990's As the numbers of seismic data and seismic surveys in the ocean has increased, the studies of seismicity in the Antarctic have now become studies of seismotectonics in the Antarctic

Especially on the Antarctic Peninsula and in the South Shetland Islands region, the tectonics and seismicity have been discussed by many researchers Larter and Barker (1991) discussed forces on a subducting plate along the South Shetland Trench This subduction is only one subducting zone around the Antarctic Plate Tectonic deformations in the South Shetland Trench are discussed by Lodolo *et al* (1993) and by Kim *et al* (1995), and the results of seismic surveys in Bransfield Strait have been reported by Jin *et al* (1996), Tanahashi *et al* (1998) Evolution, tectonics and volcanics in Bransfield Strait have been discussed by González-Ferrán (1985, 1991), Barker and Austin (1994), Birkenmajer (1992) Lee *et al* (1998) located earthquake epicenters around King George Island in the South Shetland Islands, and Jin *et al* (1998) reported earthquake swarm activities recorded at King Sejon Station on King George Island

Negishi *et al* (1998) discussed the relation between tectonics and mechanism of an intraplate earthquake with body wave magnitude (m_b) 4 6 which occurred off of the Prince Olav Coast, East Antarctica on September 25, 1996 Tsuboi *et al* (2000), and Kreemer and Holt (2000) discussed possible driving forces behind the occurrence of the 1998 great intraplate earthquake with surface wave magnitude (Ms) 8 0 near the Balleny Island region In this paper, the cause of earthquakes in the Antarctic will be reviewed and discussed from the point of view of seismotectonics

2. Seismicity in the Antarctic

Figure 1 shows epicenter locations of earthquakes south of 45°S, including the Antarctic, which were compiled by the International Seismological Centre (ISC) for the 1964–1996 period The seismic activity in the Antarctic plate was divided into the following five regions as shown in Fig 1 A) an intraplate low seismic region, B) the high seismic region around the Antarctic Peninsula, C) the Antarctic Continent aseismic region, D) low seismic regions at the edge of mostly East Antarctica, and E) volcanic regions (Kaminuma, 1994a) The details of each region are as follows

2.1 An intraplate low seismic region

As is clear in Fig 1, the earthquake activity along the plate boundary is very high, however the seismicity in the Southern Ocean, the intraplate seismic activity, is very low Very few earthquakes of magnitude larger than 6 0 were recorded One great earthquake with Ms 8 0 struck the Balleny Islands region on March 25, 1998 This intraplate earthquake is the largest ever recorded in the Antarctic plate

2 2 The high seismic region around the Antarctic Peninsula

The epicenter locations in the Antarctic Peninsula region of 30°–80°W and 50°–70°S are shown in Fig 2, according to the ISC, during the 1964–1996 period

The focal depths of the earthquakes are mostly shallower than 40 km During two decades, from 1971 to 1989, only four earthquakes occurred with focal depths between 40 and 100 km and only one event for which m_b and Ms were determined to be 6 3 and 7 0 respectively (Kaminuma, 1995) This earthquake, which occurred on February 8, 1971, is

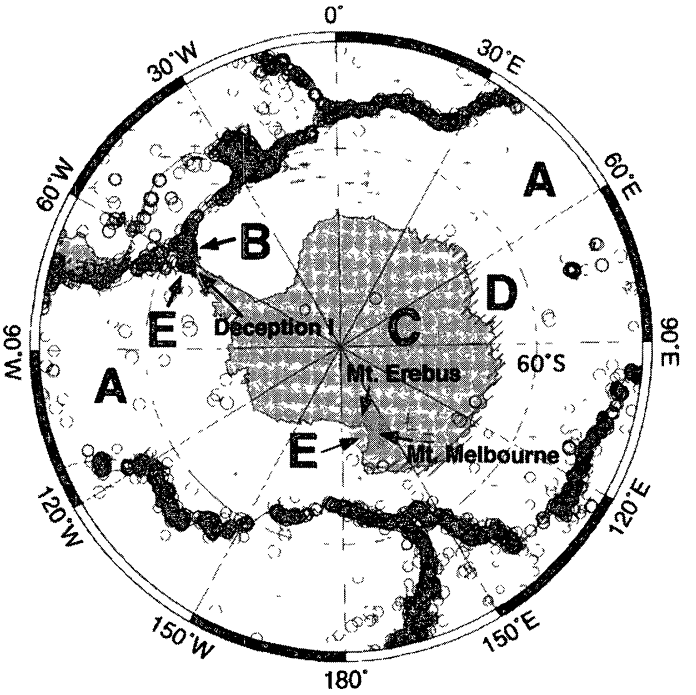

Fig 1 Earthquake locations in the Antarctic Plate in 1964-1996 and seismotectonics regions The data were compiled by the International Seismological Centre Seismotectonic regions in Antarctica A) intraplate low seismic regions, B) high seismic region around the Antarctic Peninsula, C) the Antarctic Continent aseismic region, D) low seismic region at the edge of the continent (hatched area) and E) volcanic regions The symbols are the same as in Fig 2

the largest ever recorded in the region This is the only recorded earthquake of magnitude larger than 7 0 in the Antarctic This earthquake was felt at Faraday Station (65°14 8′S, 64°15 5′W) of the UK and was the first tectonic earthquake to be felt in the Antarctic

2.3. *The Antarctic Continent aseismic region*

Adams *et al* (1985) reported that four earthquakes were held in the ISC files for continental Antarctica from an early stage of Antarctic research. However, except for only one event, no significant earthquakes were located in the Antarctic Continent before the IGY, because neither their locations nor their magnitudes were determined

One event which occurred on June 26, 1968 was located in Coats Land, near 20°W, 80°S using the initial phase readings of five seismic stations on the Antarctic Continent (Kaminuma and Ishida, 1971) The magnitude of the event was 4 3 This was the first earthquake located instrumentally in the Continent using seismic data only on the Antarctic Continent

2.4. *Low seismic regions at the edge of the Continent*

A tripartite seismic array with three-component seismographs was operated around Syowa Station (69°S, 39°E) in 1987-1989 to study the local seismicity around Syowa Station and the propagation characteristics of seismic waves under the east Antarctic shield area Only ten local events were located by the network during the 27 months from June

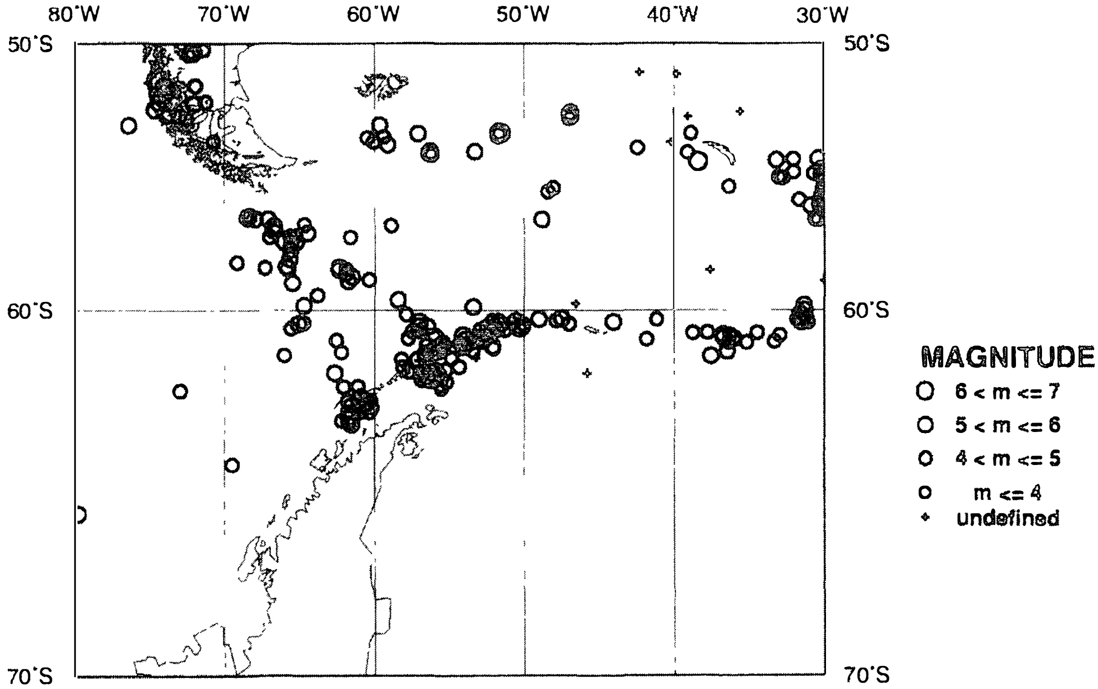

Fig 2 Earthquake locations around the Antarctic Peninsula in 1964–1996

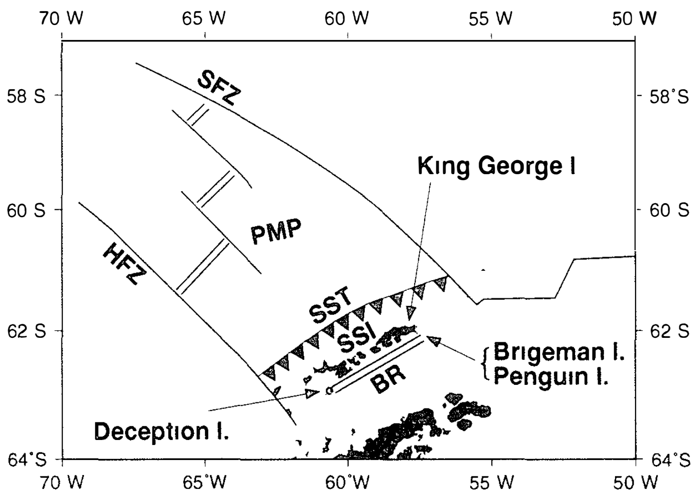

Fig 3 Tectonics around the Antarctic Peninsula The abbreviations are as follows PMP (Phoenix Micro Plate), SFZ (Shackleton Fracture Zone), HFZ (Hero Fracture Zone), SSI (South Shetland Islands), SST (South Shetland Trench) and BR (Bransfield Rift)

1987 to October 1989 (Akamatsu *et al* , 1988, 1989, 1990, Kaminuma and Akamatsu, 1992) Even though the seismic activity was very low, there were various types of earthquake occurrences, such as a swarm type, a main shock-after shock type, twin earthquakes etc which is very similar seismic activity with that in the Japanese Islands where the seismicity is the highest in the world

All of the earthquakes were located in the geological and geomophological structure

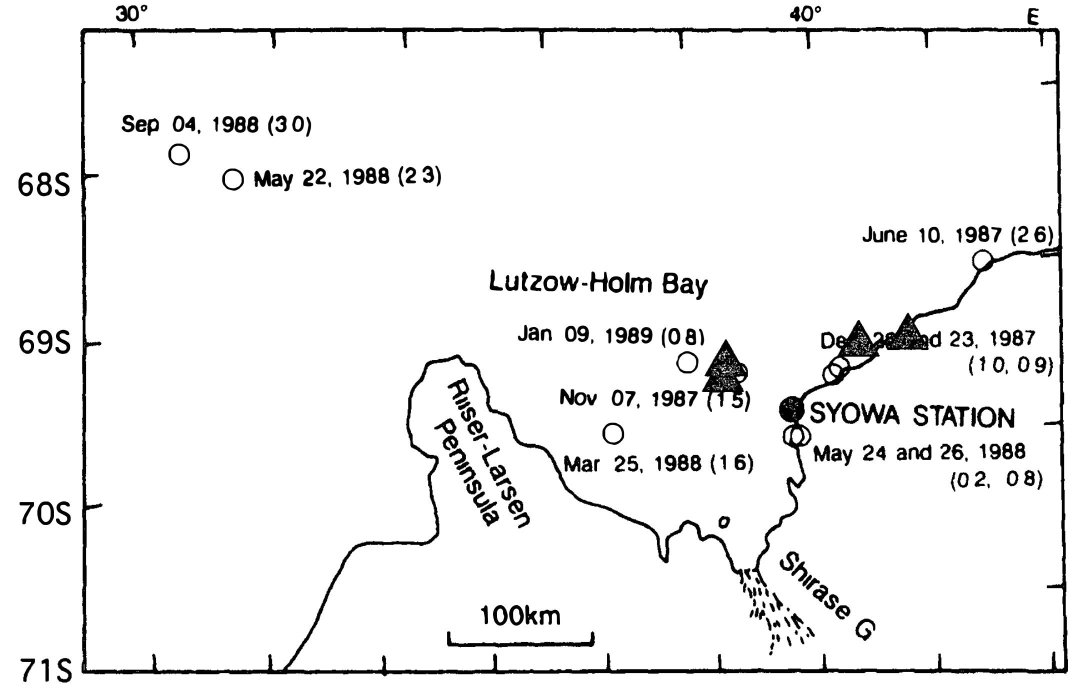

Fig 4 Earthquake locations around Syowa Station Data were compiled by Kaminuma and Kanao (1999) Open circles show the epicenters determined by the tripartite network and solid triangles show those determined by the single station method

boundaries of the coastal area of the Antarctic Continent and offshore, no earthquakes were located in the inland area, as shown in Fig 4 (Kaminuma *et al*, 1998) There is considerable geomophological evidence of crustal uplift in the snow free area along Lützow-Holm Bay around Syowa Station, the crustal uplift is believed to have been caused after deglaciation (*e.g* Yoshida and Moriwaki, 1979). Therefore it seems that the local earthquakes around Syowa Station are caused by the tectonic stress, which is accumulated as a result of slow-moving crustal uplift (Kaminuma and Kanao, 1999)

2.5. *Volcanic regions*

Seismic observations in volcanic regions have been carried out at only three volcanoes, as shown in Fig 1, Deception Island (63 0°S, 60 6°W), Mount Erebus (77 6°S, 167 1°E, 3794 m) and Mount Melbourne (74 4°S, 164 7°E, 2732 m)

The first felt shock in the Antarctic was the M 4 7 earthquake accompanied by the volcanic eruptions of Deception Island on December 4, 1967 The buildings of the stations on Deception Island were destroyed by the eruptions and all members in the stations of Argentina, Chile and the UK evacuated safely after the eruption. All of the stations have been closed since that time

Seismic activity on Deception Island was studied by Vila *et al* (1992) They 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 E-W direction crossing the central part of the island

Seismic observations by radio-telemetry continued in the summit area and on the slope of Erebus Volcano on Ross Island, Antarctica, during 1981–1990 (Kaminuma and

Dibble, 1990, Kaminuma, 1994b) Remarkable changes of seismic activity were recognized before and after the new phase of volcanic activity in September 1984 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

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, many local seismic events have been reported together with other geophysical data (*e g* Privitera *et al* , 1992, Banaccorso *et al* , 1997a)

3. Seismotectonics

As the seismicity in the Antarctic has become clear, the seismic activity in some regions can be discussed from the point of view of seismotectonics or neotectonics The seismicity in the Antarctic Peninsula region has been discussed from the point of view of seismotectonics since the early 1990's as described in the Introduction of this paper As described in 2–5, the seismicity in the volcanic region is well known with some geophysical and geological data and views Only a few earthquakes were determined to be on the Antarctic Continent except Wilkes Land The seismotectonics in the following regions is discussed in this paper 1) The great earthquake in the intraplate low seismic region in relation to crustal deformation after deglaciation, 2) Microseismic activity at the edge of the continent in relation to the crustal uplift after deglaciation, and 3) Seismic activity in Wilkes Land

3.1 The great earthquake in the intraplate low seismic region

A great earthquake with Ms 8 0 took place in the Balleny Islands region (62 9°S, 149 7°E, 10 km in depth) on March 25, 1998 This intraplate earthquake is the largest ever recorded in the Antarctic Plate where the seismicity is very low The earthquake was located about 500 km off the Antarctic coast There have been other earthquakes with magnitudes larger than 5 5, but that earthquake is the largest oceanic intraplate earthquake ever recorded in the Antarctic Plate (Wiens *et al* , 1998, Tono and Kaminuma, 1998)

The wintering members in Dumont d'Urville Station (66°00′S, 39°35′E) felt a quake, and something on the shelf in the building fell down (Tono and Kaminuma 1998, Kaminuma *et al* , 1999) The intensity at the station is estimated to be III (8 0–25 Gal) on the intensity scale of the Japan Meteorological Agency The March 25, 1998 earthquake is the first event that has been felt on the Antarctic Continent except for volcanic earthquakes

The hypocenter parameters and focal mechanism of the event are given by the National Earthquake Information Service (NEIS) of the US Geological Survey (USGS) and the Harvard Centroid Moment Tensor (CMT) solution The focal mechanism indicates the strike slip fault trending N-S or E-W The fault plane of the main shock determined by the aftershock distribution trends E-W and 300 km long The aftershock activity has been well studied by Kobayashi *et al* (1999) Most of the aftershocks are about 10 km in depth A swarm activity of induced earthquakes is recognized in the aftershock activity with three large earthquakes whose magnitude is larger than 5 The induced earthquakes are located about 60–70 km south from the fault planes

However the focal mechanism has not only a (strike slip) double couple component but also a non-double couple A significant non-double couple component in the moment tensor solution was proposed by Kuge *et al* (1999) from the analysis of long-period surface waves

James and Ivins (1998) presented a possibility of crustal deformation in the sea floor of the southern ocean around the Antarctic Continent caused by deglaciation Tsuboi *et al* (2000) presented a paper to show that the great earthquake was caused by the accumulated stress of the crustal deformation after deglaciation Those studies show a possibility that the earthquakes in the southern ocean occur by the effect of crustal deformation after deglaciation

On the other hand, Kreemer and Holt (2000) found that the mechanism of the great earthquake is inconsistent with strain orientations inferred from kinematic modeling of a diffuse zone of deformation within the triple junction region among the Australia, Pacific and Antarctic plates This means that stress perturbations associated with deglaciation cannot be ruled out as a triggering mechanism for the event

As Negishi *et al* (1998) showed for one event, all other intraplate events in this region seemed to be caused by tectonic stress accumulated along the pre-existing lineament inside the Antarctic Plate

3.2. *Microseismic activity at the edge of the continent*

When seismic observations were made by a tripartite network around Syowa Station in 1987–1990, microseismic activity was reported (Kaminuma and Akamatsu, 1992) Crustal movements around Syowa Station are summarized as follows based on local earthquake activities, oceanic tide, elevated beaches and leveling survey (*e.g* Kaminuma and Akamatsu, 1992; Kaminuma and Kanao, 1999).

1) The elevated beaches around Syowa Station show that the crustal uplift after deglaciation is still going on at present

2) A trend of sea level falling at a rate of 4 5 mm/y was obtained from the oceanic tide data during the 18 years in 1975–1992, and a falling rate of 9.5 mm/y was also obtained from the oceanic tide data during the seven years in 1981–1987. These two falling rates indicate that the falling is an intermittent phenomenon, it is estimated from earthquake occurrence

3) As the locations of microearthquake epicenters are in the coastal and offshore areas, local earthquakes are inferred to be caused by tectonic stress accumulated by crustal uplift after deglaciation The occurrence pattern of local earthquakes is intermittent

4) The crustal uplift occurs only for a few years during one decade/more, because the occurrence of earthquakes corresponds with the intermittent crustal uplift.

5) As there was no significant height change of leveling during the 15 years in 1982–1997, the crustal uplift is not a tilt trend movement

6) Estimating from all data mentioned above, the crustal uplift in the Ongul Islands is a block movement

Evidence of past glaciation is observed in the coastal area of the Antarctic continent Erratic boulders, glacial scour and various glacial deposits etc can be found in the snow free area Elevated beaches and emergent marine deposits represent important clues for estımatıng vertıcal movement, sea level change, ıce advance and retreat, and hence envıronmental change ın the polar regıons (*e.g* Yoshıda and Morıwakı, 1976)

Syowa Statıon ıs the only statıon ın the coastal area of the Antarctıc contınent where tıdal observatıons have been contınued for more than 30 years Normally tıdal observatıons are dısturbed by sea ıce and tıde gauges are not ınstalled at most of the coastal statıons ın the Antarctıc A fallıng trend ın sea level was obtaıned by Odamakı *et al* (1991) and Mıchıda *et al* (1995) The sea level fallıng ıs consıdered to be crustal uplıft after deglacıatıon

Monıtorıng of gravıty change and GPS observatıons are also done at Syowa Statıon Therefore ıt ıs one of the best sıtes to dıscuss seısmotectonıcs usıng those data together wıth mıcroseısmıcıty around Syowa Statıon

3 3 Seısmıc activity in Wılkes Land

It ıs clear ın Fıg 1 that the earthquake actıvıty ın Wılkes Land ıs relatıvely hıgh Mıcroseısmıc actıvıty ın thıs regıon was reported by Browne-Cooper *et al* (1967) The number of mıcroearthquakes counted ın 1965 was more than 190 Thıs ıs about ten tımes larger than the actıvıty around Syowa Statıon where Kamınuma *et al* (1998) reported the actıvıty

Seven earthquakes wıth m_b 4 0–4 9 were located ın the area of 100°-170°E and 66°-82° S durıng the 33 years 1964-1996 as shown ın Fıg 5 Another nıne earthquakes were located ın the ınland area and two were offshore as shown wıth the cross symbol ın Fıg 5 The magnıtudes of these eleven earthquakes were not determıned Not only the mıcroseısmıc actıvıty but the small earthquake actıvıty ın Wılkes Land ıs hıgher than that ın other areas on the Antarctıc Contınent

Drewry (1983) edıted "Antarctıca Glacıologıcal and Geophysıcal Folıo" whıch presented many features of the Antarctıc Contınent such as the surface of the Antarctıc Ice Sheet, the bedrock surface of Antarctıca, Antarctıc Ice Sheet thıckness, etc The subglacıal topography ın Wılkes Land ıs characterızed by a subglacıal basın called the Wılkes

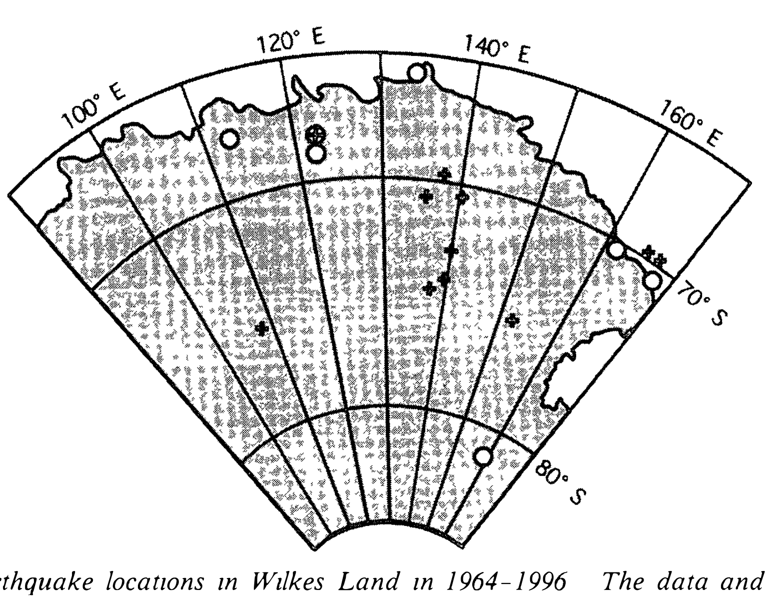

Fıg 5 Earthquake locatıons ın Wılkes Land ın 1964-1996 The data and symbols are the same as ın Fıg 1

subglacial basin The minimum elevation of the bed rock is deeper than 1000 m below sea level. The maximum thickness of the ice sheet in the area is over 4000 m The surface elevation of the ice sheet in the area is mostly over 2000 m The highest point is 3200 m The point is called Dome Circe (Dome C) around 75°S, 125°E The maximum isostatic uplift of about 1000 m is estimated in the area

Six earthquakes out of nine with undefined magnitudes inland were located from north to south along the 140° longitude line Subglacial topography in the epicenter area is complicated. Resolution subglacial highland, Adventure subglacial Trench and Belgica subglacial highland are located along the longitudinal direction from east to west (Drewry, 1983) There is a possibility that the six events were icequakes, because the thick ice sheet and complicated subglacial topography must cause iceshocks

The earthquakes in the edge of the continent in Wilks Land might be also caused by tectonic stress accumulated by the crustal deformation after deglaciation

4. Discussion and conclusion

The Antarctic Plate, the Antarctic Peninsula region and some volcanic regions are regions of which the tectonic evolution has been well studied (*e.g* Barker, 1982, Birkenmajer, 1992). The Pacific margin of the Antarctic Peninsula seems to be an active margin since the breakup of Gondwana (Pankhurst, 1982) The Phoenix Micro Plate (PMP) is a tectonic block bounded by the Shackleton Fracture Zone (SFZ) on the northeast side, the Hero Fracture Zone (HFZ) on the southwest and the South Shetland Islands (SSI) on the southeast. The South Shetland Trench (SST) located northwest of the SSI is a unique trench around the Antarctic Plate. The SST was formed by subduction of the PMP.

However, the subduction of the PMP stopped at about 4 Ma (*e.g*. Barker, 1982; Larter and Barker, 1991; Kim *et al*, 1995) No significant seismic activity is recognized along the subducting zone (Kaminuma, 1995)

The existence of a rift along the southeast of the SSI in Bransfield Strait has been proposed by various authors on the basis of both geophysical and geological data (*e.g* Barker, 1976, Birkenmajer *et al*, 1981, Thomson *et al*, 1983) A block diagram of the Bransfield Rift (BR) and its volcanic ridge were proposed by González-Ferrán (1991) The axis of the volcanic ridge is defined with volcanoes of Deception, Penguin and Bridgeman Islands, and some submarine volcanoes, as shown in Fig 3

As shown in Fig 2, earthquakes in this region are located mostly along the two fracture zones and the SST, and concentrated around the three active volcanoes Deception, Penguin and Bridgeman Islands Many volcanic earthquake activities on Deception Island have been reported by Spanish scientists (*e.g* Ortiz *et al*, 1997) Some earthquake activities around Bransfield Strait have been reported by Korean scientists using the seismic observation data at King Sejong Station Lee *et al* (1998) located some earthquakes on the north-west and east parts of King George Island Jin *et al* (1998) reported some microearthquake swarm activities around Bridgeman Island. The seismic activity along the BR is still active at present

The tectonics of Mount Erebus have also been well studied and published (edited by Kyle, 1994) As mentioned before, the tectonics of Mount Melbourne have been studied by Italian scientists The seismotectonics of active Antarctic volcanoes are becoming increasingly clear at present

The tectonic earthquakes along the coast of the Antarctic Continent and in Wilkes Land are caused by tectonic stress accumulated by crustal deformation after deglaciation The microearthquake activity around Syowa Station mentioned in Section 3 2 might be typical of activity on the coast of the Antarctic Continent where crustal uplift after deglaciation is occurring If geophysical and seismological observations like the ones at Syowa Station are carried out in the coast, the microseismic activity will be detected on every coast and its relation to crustal movement will become clear

There might be no doubt that the three events on the coast shown by open circles in Fig 5 were caused by tectonic stress accumulated by crustal uplift after deglaciation However, the occurrence of four other events inland has no relation to crustal deformation because their epicenter area is covered by a huge ice sheet and no isostatic crustal uplift is expected As described in Section 3 3, earthquakes on the continent tend to be concentrated in Wilkes Land It is speculated that the existence of a thick ice sheet in Wilkes Land is the cause of occurrence of earthquakes and/or icequakes, even though the mechanism is not clear at present To solve this, more earthquake data, and measurements of ice sheet movements and changes, are necessary

As Negishi *et al* (1998) pointed out, most intraplate earthquakes 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 Continent are also caused by crustal deformation/tectonic stress after deglaciation It is suggested strongly that the effect of ice sheet change causes some phenomena in the crust and upper mantle such as crustal uplift, earthquake occurrence, etc

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