Polar Geosci., **14**, 165–179, 2001

P-wave velocity in ultrahigh temperature granulites from the Archean Napier Complex, East Antarctica

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Abstract: *P*-wave velocities (*Vp*) in ultra-high temperature granulites (UHT) were measured up to 1.0 GPa from 25°C to 400°C with a piston-cylinder-type high-pressure apparatus. Rocks measured are meta-igneous UHT rocks collected from Mount Riiser-Larsen, Amundsen Bay, Napier Complex. Core rock samples 14 mm in diameter and 12 mm long were subjected to high-pressure experiments. All rocks show a rapid increase of *Vp* at low pressure up to 0.5 GPa and nearly constant *Vp* at higher pressures. The *Vp* values measured at 1.0 GPa and 400°C are 7.17 km/s for a meta-pyroxenite, 6.93 km/s, 6.88 km/s for mafic granulites and 6.17 km/s for an ortho-pyroxene felsic gneiss. A well-defined correlation exists between *Vp* and the SiO_2 content of the rocks, which is expressed as *Vp* (km/s)$=-0.051SiO_2+9.85$ at 1.0 GPa and 25°C. The *Vp* values measured for the Napier mafic granulites are comparable to those of the Mizuho lower crustal layer (6.95 km/s of *Vp* at depth from 33 to 40 km; A. Ikami *et al.*, Mem. Natl Inst. Polar Res., Ser. C, **15**, 69, 1984). The present results suggest that the lower crust in the Mizuho Plateau is probably composed of mafic granulites (garnet-free) rather than garnet-bearing rocks. The higher pressure in Lützow-Holm Complex overlie the lower pressure rocks (Napier Complex). The double-thickened crustal model in which peak metamorphic pressure increases with depth can't explain the inversion of metamorphic pressure across the crust. We suggest that the Lützow-Holm Complex was exhumed tectonically upon the Napier Complex after the Pan-African continental collision between the Napier Complex and Dronning Maud Land.

key words: *P*-wave velocity, granulite, Archean Napier Complex, Mizuho Plateau, crustal structures

1. Introduction

A linear correlation between *P*-wave velocity and whole rock composition of rock has been demonstrated from *P*-wave velocity measurements of rocks with various whole rock compositions, and lithological crustal models have been proposed by linking a velocity model to laboratory data (Christensen and Mooney, 1995; Rudnick and Fountain, 1995). The *P*-wave velocity in high-grade metamorphosed mafic rocks strongly depends on metamorphic grades and mineral paragenesis as well as whole rock composition. Garnet-bearing mafic rocks such as eclogite and garnet-granulite show higher *P*-wave velocity than amphibolite-facies rocks, although they have similar whole rock composition. Therefore, linking laboratory data of various metamorphic rocks to a seismic velocity model of metamorphic belts could be a useful tool to estimate the metamorphic grade of the lower parts of crust.

Seismologists have made great efforts to understand the crustal structure of the Lützow-Holm Bay region in East Antarctica (Ikami *et al.*, 1984; Ito and Ikami, 1984, 1986; Ito and Kanao, 1995; Kanao, 1997; Kanao *et al.*, 1997). In spite of these efforts, little progress has been made in laboratory measurements of elastic velocities of metamorphic rocks in East Antarctica. *P*-wave laboratory data are only available from metamorphic rocks of Ongul Island measured at pressures up to 440 MPa (Yukutake and Ito, 1984). Here we report *Vp* values of ultra-high temperature granulite-facies rocks from Mount Riiser-Larsen, Amundsen Bay, Archean Napier Complex.

The Napier Complex is characterized by ultra-high temperature granulite-facies metamorphism where metamorphic temperature reaches over 1000°C (Harley and Hensen, 1990). The Napier metamorphic rocks are also characterized by extremely "dry" nature, and it has been proposed that H_2O is released by dehydration of precursors or partial melting prior to UHT metamorphism. To the east of the Napier Complex, the Lützow-Holm and Rayner Complexes are widely distributed (Fig. 1), they are characterized by relatively higher abundances of hydrous minerals. Tectonic relationships among these three metamorphic complexes are not well understood. The Rayner Complex to the east of the Lützow-Holm Complex has been recognized as a ~1000 Ma high-grade metamorphic terrane overprinted by ~500 Ma lower grade metamorphism (Black *et al.*, 1987). However, Shiraishi *et al.* (1997) suggests that the eastern margin of the Rayner Complex is underwent high-grade metamorphism during the Cambrian and it is an eastward continuation of the ~500 Ma Lützow-Holm Complex. We consider a hypothesis that the Lützow-Holm and Rayner Complexes were exhumed tectonically upon the Napier Complex during and/or after the amalgamation of Gondwana continent. Combining the seismic structure presented by earlier studies (Ikami *et al.*, 1984; Ito and Ikami, 1984, 1986; Ito and Kanao, 1995; Kanao, 1997; Kanao *et al.*, 1997), we use the present *Vp* data to estimate the crustal structure of the Lützow-Holm Complex.

2. Samples

Rock samples used in this study were collected from Mount Riiser-Larsen, Amundsen Bay, in the Napier Complex (Ishizuka *et al.*, 1998; Ishikawa *et al.*, 2000). The sample locations are shown on the geological map (Fig. 1). Four samples with homogenous texture were used to measure *Vp*. They are pyroxenite (MI97012402), mafic granulites (MI97012710, MI96122602) and orthopyroxene felsic gneiss (MI97012401). The whole rock chemistry was analyzed by the X-ray fluorescence method (XRF) at the National Institute of Polar Research (NIPR). The chemical composition of rocks measured ranges from 44 to 66 wt% SiO_2 (Table 1). The modal compositions (vol%) are also given in Table 1.

2.1. Pyroxenite (MI97012402)

Pyroxenite (MI97012402) is a homogenous rock with granoblastic texture. It contains orthopyroxene (51.3 vol%) and clinopyroxene (31.3 vol%) with small amounts of plagioclase (4.0 vol%) and biotite (2.6 vol%). The rock is classified as websterite. The

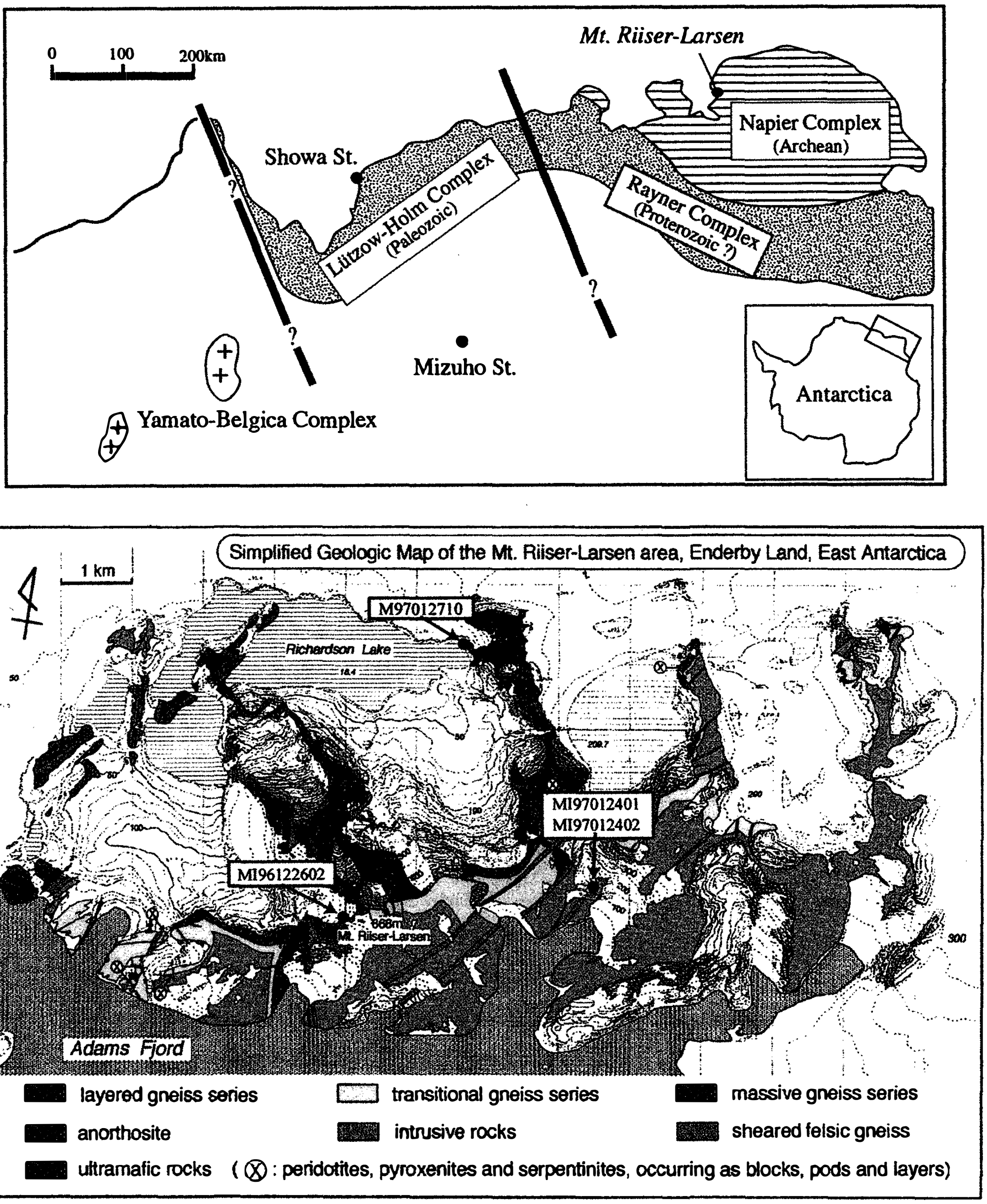


Fig. 1. Geological map of Mount Riiser-Larsen, Amundsen Bay, Enderby Land, East Antarctica (after Ishizuka et al., 1998), showing sample localities of four rocks used in this study.

bulk chemistry of pyroxenite shows basic composition with SiO_2 content of 44.18 wt%. Grain sizes of mineral constituents range from 0.8 to 1.0 mm.

2.2. *Orthopyroxene felsic gneiss (MI97012401)*

Orthopyroxene felsic gneiss is a homogeneous rock with medium grain size (1.0 mm). No foliation or lineation is noted. Pyroxenes and plagioclase are the predominant

Table 1. Chemical and physical properties of the rock samples.

Sample No. Run No. Rock type	M97012710 SH-01 mafic granulite	MI97012401 SH-02 Opx felsic gneiss	MI96122602 SH-03 mafic granulite	MI97012402 SH-04 pyroxenite
Bulk chemistry (wt%)				
SiO_2	52.23	65.42	49.50	44.18
TiO_2	1.17	0.44	0.72	1.69
Al_2O_3	13.52	15.96	14.20	5.25
Fe_2O_3	14.17	3.87	14.00	20.77
MnO	0.15	0.06	0.18	0.22
MgO	6.28	1.53	8.45	15.37
CaO	9.22	4.05	9.14	9.99
Na_2O	1.52	4.13	2.16	0.00
K_2O	0.34	1.90	0.33	1.03
P_2O_5	0.06	0.09	0.05	0.06
Total	98.67	97.46	98.74	98.48
Mode (vol%)				
Opx	24.6	6.5	17.0	51.3
Cpx	19.5	8.0	14.0	31.3
Pl	52.8	81.5	61.5	4.0
Qtz	–	2.5	–	–
Bt	0.4	–	1.0	2.6
Opq	2.7	1.5	6.5	5.8
Grain size (mm)				
Opx, Cpx	1.5	1.0	3.0	0.8–1.0
Pl	1.5	2.0	2.0	–
Sample length (mm)	12.22	12.05	11.38	11.93
Density (g/cm^3)	3.024	2.681	2.881	3.405

mineral constituents. This rock exhibits granoblastic polygonal texture. Bulk rock analysis of the gneiss shows SiO_2 content of 65.42 wt%.

2.3. Mafic granulite MI97012710 and MI96122602

The main mineral constituents are plagioclase (52.8 and 61.5 vol%), orthopyroxene (24.6 and 17.0 vol%) and clinopyroxene (19.5 and 14.0 vol%). They are homogeneous medium-to-coarse grained rocks (1.5–2.5 mm) with granoblastic texture.

3. Method

Measurements of *P*-wave velocity in four rocks were carried out up to 1.0 GPa and 400°C with a piston-cylinder-type apparatus. Rock samples were cut to form a 14 mm diameter core which was doubly polished to a length of 12 mm. The length was measured with a micrometer and the uncertainly is estimated to be about ±0.05 mm. The core samples were then oven-dried for 24-hours.

Figure 2 shows the high-pressure cell assembly and the ultrasonic attachment. The rock sample was loaded into a talc-pyrophyllite high-pressure cell. We used a cylinder with 34-mm borehole 80 mm in thickness. Piezoelectric $LiNbO_3$ transducers were located on both ends of the core sample. A graphite heater was used. The temperature was monitored by a Pt-Rh_{13} thermocouple on the top end of the core sample.

Vp was measured using the pulse transmission technique. We measured the travel

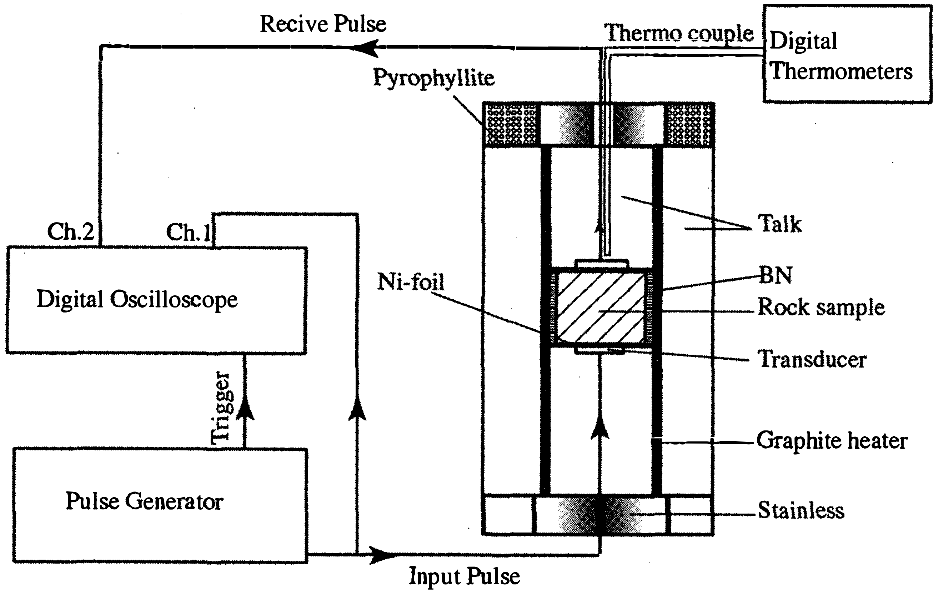


Fig. 2. High pressure cell assembly and the ultrasonic attachment.

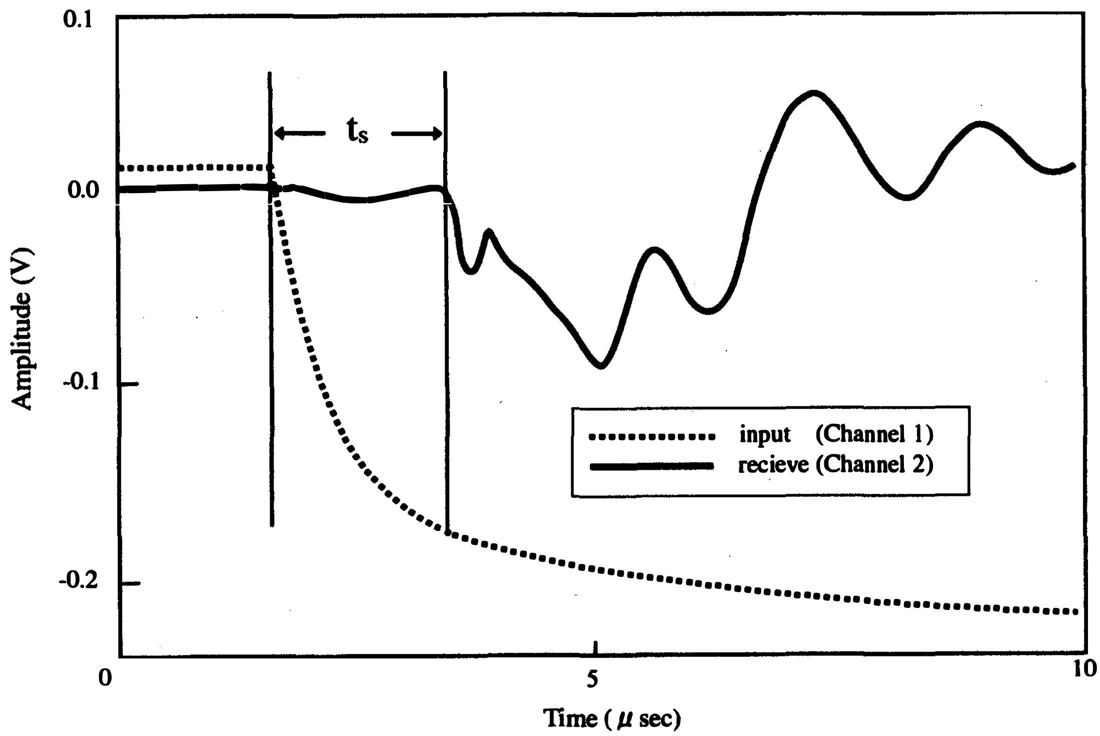


Fig. 3. Determination of travel times. The travel time t_s was determined by LSAR model. The t_s–t_0 value is true travel time; t_0 is the travel time when there is no sample.

time of an ultrasonic wave through a core sample of known length. The system setup is shown in Fig. 2. It consists of a high-voltage (235V) pulse generator and a 500 MHz sampling digital oscilloscope with sampling rate of 1.0–2.0$\times$10^{10} samples/s. The high voltage pulse was separated into two lines. One thousand reduced pulses were recorded.

Pulses were input to the $LiNbO_3$ transducers to produce compressional waves. Another transducer then received the compressional waves and the pulses were converted into electrical pulses. The raw data consisting of waveforms are stored on a hard disk of the digital oscilloscope for determination of travel times using the LSAR model (Kitagawa and Takanami, 1991). Because the travel time t_s monitored includes the time of transmission in lead lines and time to convert electric-mechanical signals, we measured travel time t_0 without the core rock sample, which has been subtracted from the t_s value (Fig. 3). The t_s–t_0 value is considered to be the true travel time throughout the rock sample. Electrical waveforms were measured 4096 times for each pressure-temperature condition, and *Vp* values reported in this study represent the average values. Errors of the present ultrasonic velocity measurements are estimated to be less than 0.1 km/s.

4. Results

Figure 4 shows a pressure-temperature path during one experimental run. We first measured *P*-wave velocity at room temperature under various pressures at 0.1 GPa intervals during pressurization from 0.1 GPa to 1.0 GPa. During decompression from 1.0 GPa to 0.1 GPa, we measured *P*-wave velocity under various temperatures (from room temperature to higher temperatures up to 400°C) at a constant pressure at 0.1 GPa intervals.

Figure 5 shows *P* wave velocity versus pressure relations for all runs at 25°C. The

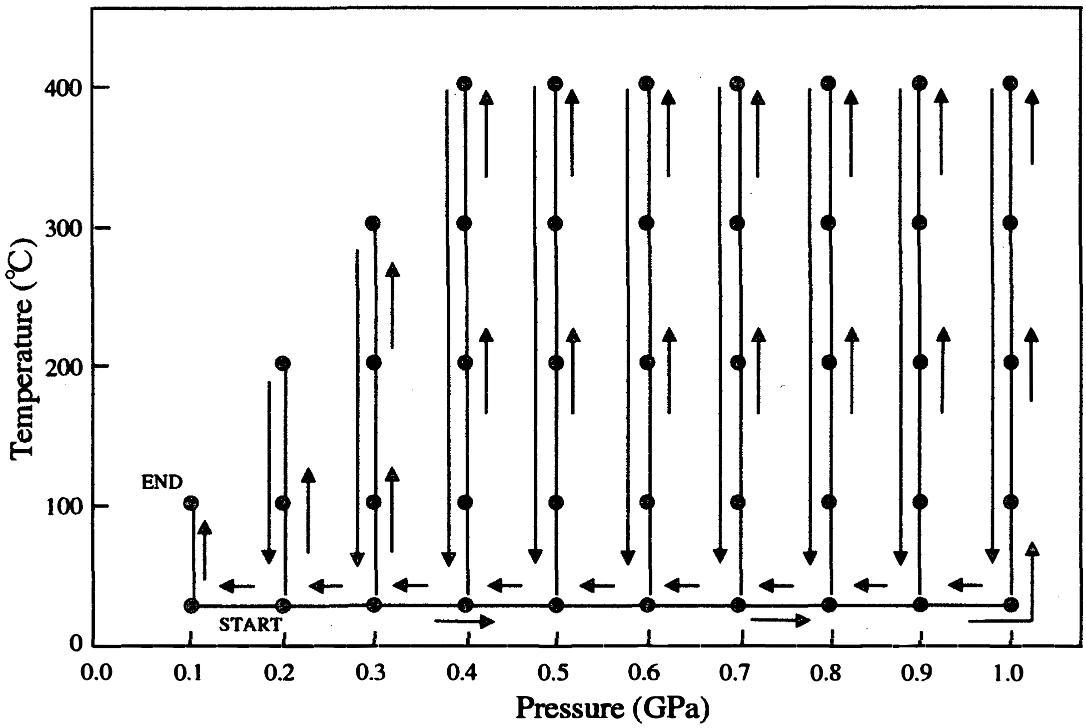


Fig. 4. Pressure-temperature path for a typical run. Vp was measured during pressurization from 0.1 GPa to 1.0 GPa at 0.1 GPa intervals, and subsequently was measured during decompression from 1.0 GPa to 0.1 GPa at 0.1 GPa interval and temperature from 25°C to 400°C.

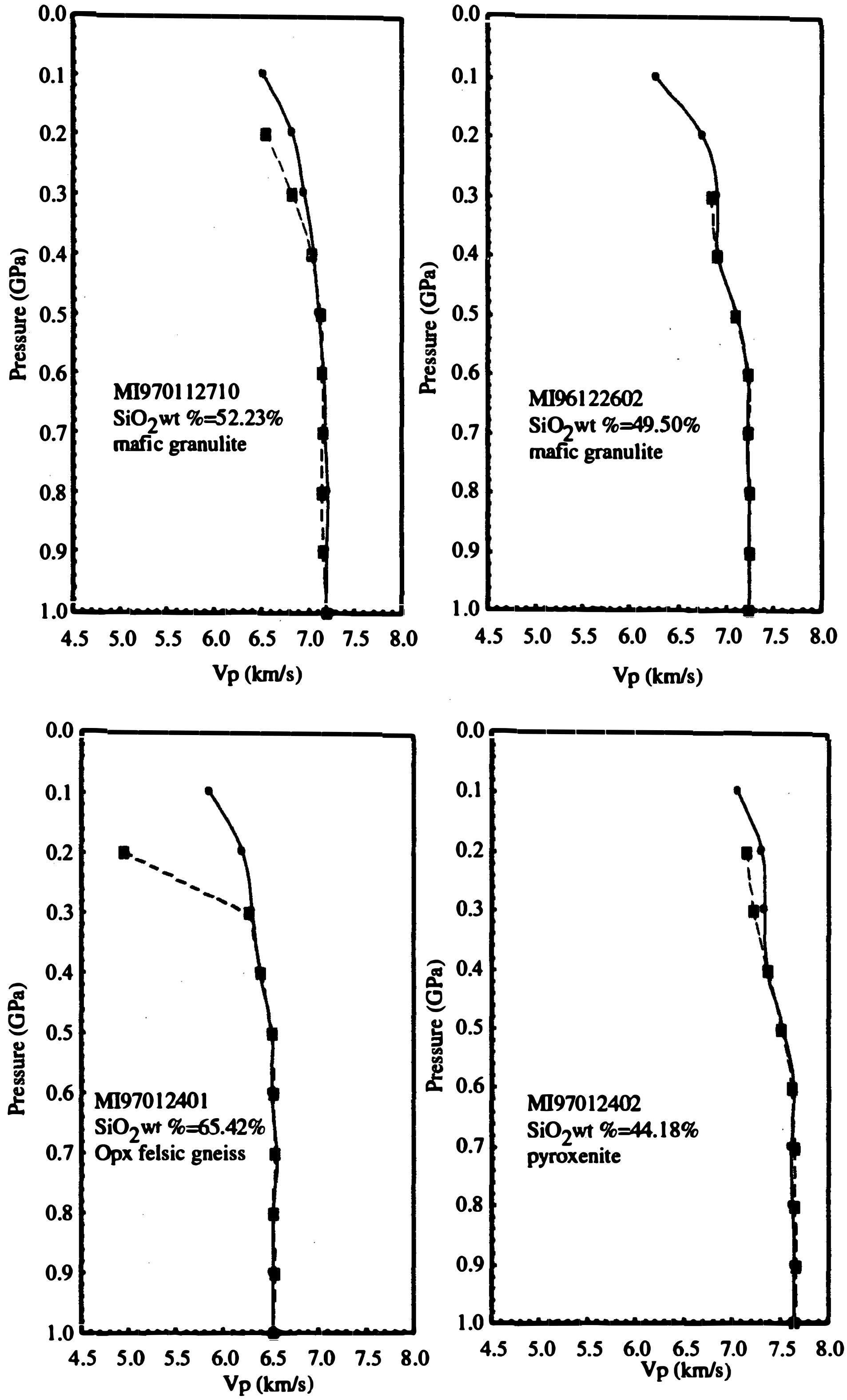


Fig. 5. P wave velocity versus pressure for all runs at 25°C. The broken line means Vp during pressurization and the solid line means during decompression.

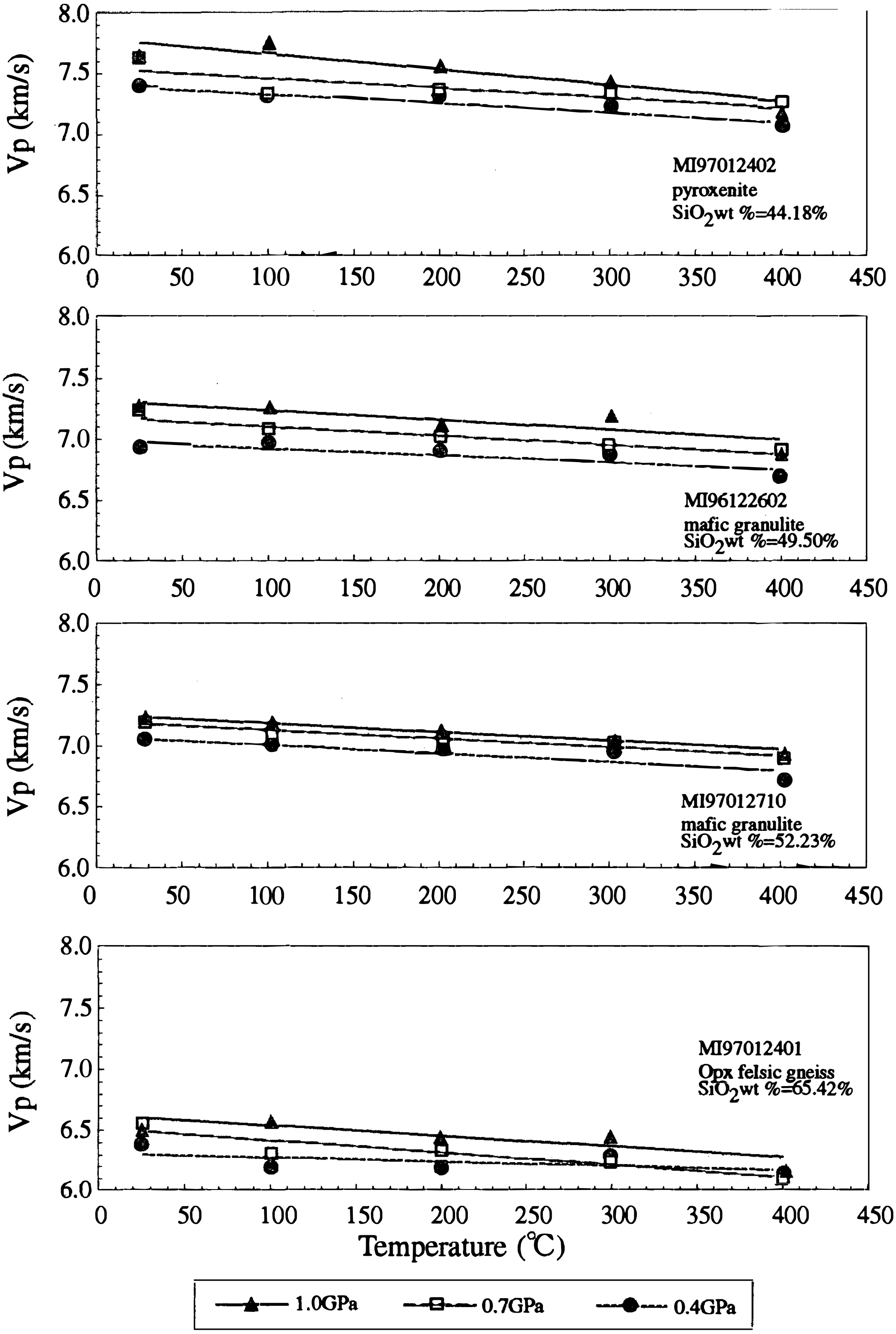


Fig. 6. Relation between P-wave velocities and run temperature. A solid triangle represents run temperature at 1.0 GPa; an open square represents run temperature at 0.7 GPa; and a solid circle represents run temperature at 0.4 GPa. Solid and broken lines are obtained by least square fitting.

P-wave velocities measured during pressurization are shown in this figure together with the velocities measured during decompression. The pressure dependence of velocity data (d*Vp*/d*P*) is much lower above 0.6 GPa than below 0.6 GPa. Strong pressure-dependence of velocity at relatively lower pressure conditions has been attributed to closure of micro-cracks and decreasing rock porosity (*e.g.* Nieslar and Jackson, 1989). The present data indicate that rock porosity is squeezed out continuously up to 0.6 GPa. The d*Vp*/d*P* values obtained below 0.6 GPa during decompression are much lower than those observed during pressurization, probably due to unopened micro-cracks which were once closed at higher pressures. At pressures from 0.6 to 1.0 GPa, *Vp* slightly increases or remains nearly constant. d*Vp*/d*P* ranges from 8.81×10^{-4} to 1.46×10^{-2} km/s GPa. *P* wave velocity at 1.0 GPa and 400°C is 7.17 km/s for pyroxenite, 6.93 km/s–6.88 km/s for mafic granulites and 6.17 km/s for orthopyroxene felsic gneiss, respectively.

The measured *P*-wave velocity decreases with increasing run-temperature in all rock samples (Fig. 6). The results show a well-defined linear positive correlation between *Vp* and rock density (*cf.* Birch, 1961). The calculated acoustic impedance ($\times 10^6$ kg/m^{-2}s^{-1}) of the pyroxenite, mafic granulites, and felsic gneiss are 26.0, 21.8, 20.8, 17.5, respectively (Fig. 7). The reflection coefficient between the mafic granulites and the felsic gneiss ranges from 0.011 to 0.086 at 1.0 GPa and 25°C.

Figure 8 shows the measured *Vp* values at 0.6 GPa and 25°C. The solid line is obtained by fitting the *Vp* value as a function of the SiO_2 composition of rocks using the least squares fitting method. We obtained a linear correlation expressed by *Vp* (km/s) = $-0.051SiO_2+9.85$. The regression line (dashed line) obtained from laboratory measure-

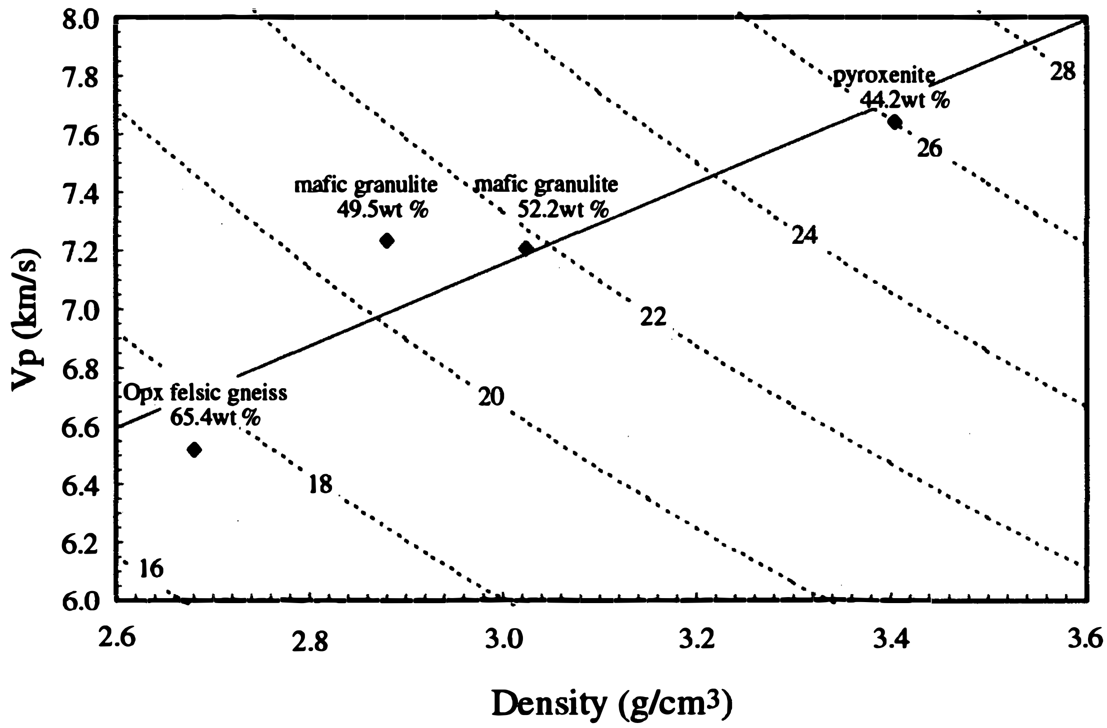


Fig. 7. Positive correlation between Vp and densities at 1.0 GPa and 25°C. Dotted lines shows constant acoustic impedance (×10^6 kg/m^{-2}s^{-1}).

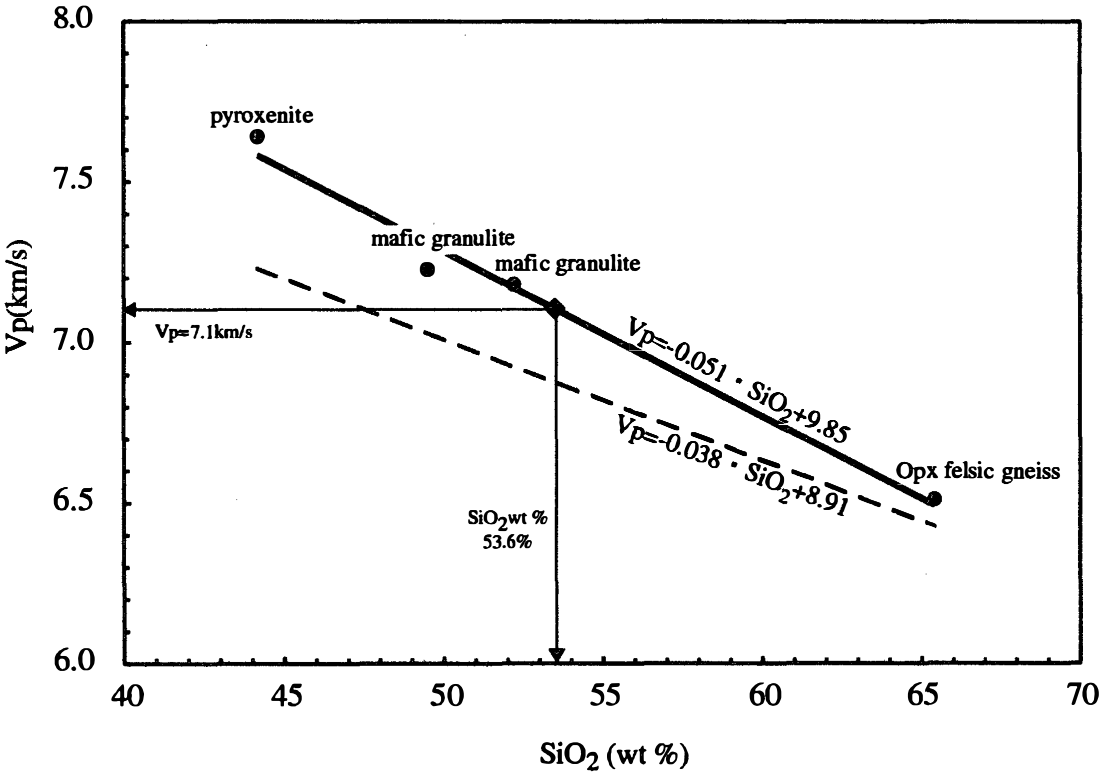


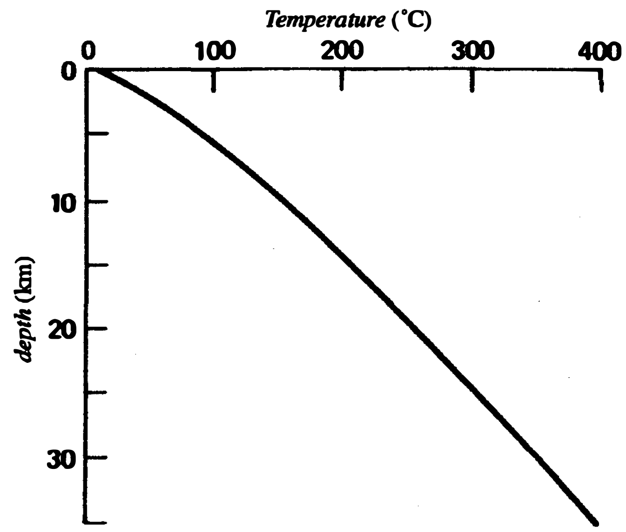
Fig. 8. P-wave velocities as a function of SiO_2 wt% at 0.6 GPa and 25°C. Solid circles are present data. The solid line ($Vp=-0.0513SiO_2+9.8469$) is a least square fitting. Broken line after Rudnick and Fountain (1995).

ments of granulite-facies rocks (Rudnick and Fountain, 1995) is also shown in this figure. The present *Vp* values are significantly higher than the regression line given by Rudnick and Fountain (1995). This difference could be attributed to the extremely "dry" nature of our samples. The samples measured in this study exhibit an extremely low abundance of hydrous minerals (less than 2.5 vol% biotite, no amphibole).

The present data indicate that *Vp* in the hornblende-free basic granulites is considerably higher than the mean *Vp* value (7.1 km/s) of the lower crust in the Archean/Proterozoic continental crust model (Rudnick and Fountain, 1995). The present results suggest that the lower crust of Archean/Proterozoic continental crust cratons is composed of anhydrous (dry) granulite with andesitic composition or alternatively it consists of hydrous rock (hornblende-bearing) with basaltic composition.

5. Tectonic implications

The Napier Complex is exposed in Enderby Land, East Antarctica, and regarded as a fragment of the Archean continent (Sheraton *et al.*, 1987). Zircon U-Pb dating of the felsic gneisses show a wide range of age data ranging from 3900 Ma to 2400 Ma, reflecting multiple growth history (Black *et al.*, 1986; Harley and Black, 1997). The Napier Complex is composed of metamorphosed igneous and sedimentary rocks; its main rock constituent is orthopyroxene felsic gneiss with chemical characteristics of the Archean TTG (Suzuki, 2000). Protoliths of meta-sedimentary rocks including magnetite-



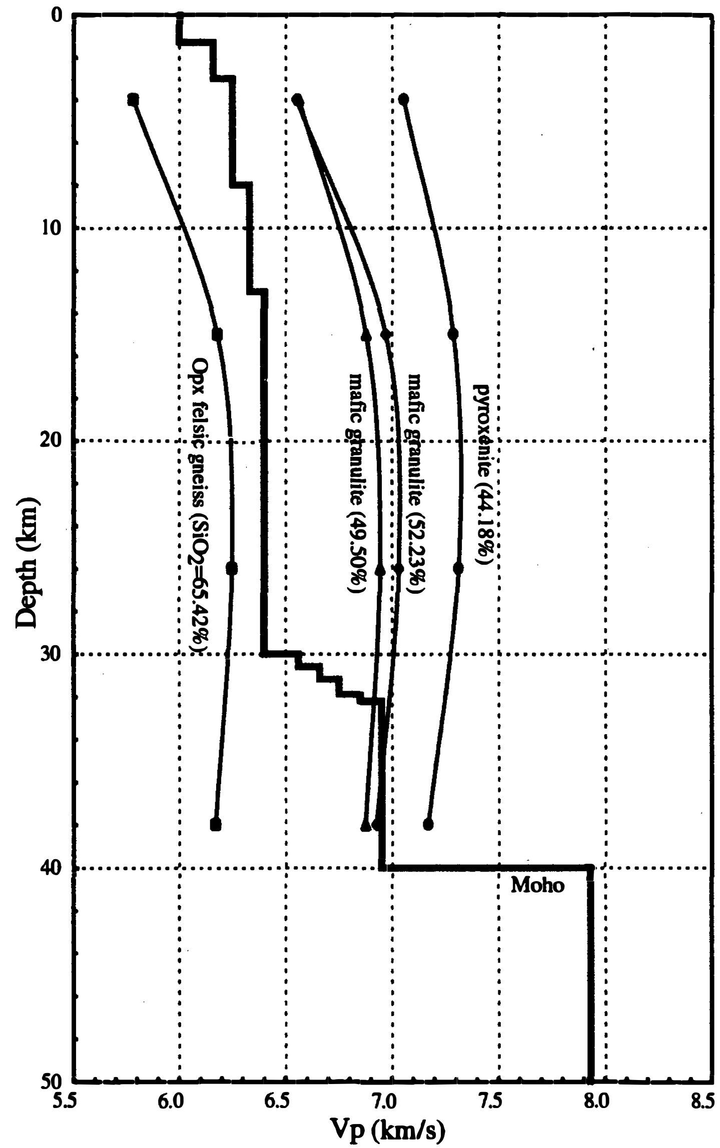


Fig. 9. Comparison of present data with the seismic velocity structure in Mizuho Plateau (right) (Ikami et al., 1984). The Vp are adjusted to values by assuming a typical continental geotherm, after Turcotte and Schubert (1982) (left).

quartz rock (banded iron formation), quartzite, garnet-quartz and garnet-sillimanite gneisses (psamitic-to-pelitic rocks) were probably formed by arc-amalgamation processes in the convergent tectonic environment. Thick mafic sills intruded into the orthopyroxene felsic gneisses and meta-sedimentary rocks (Ishikawa *et al.*, 2000), indicating extensive magmatic activities after the arc-amalgamation.

In contrast to the Napier Complex, the neighboring late Proterozoic Rayner Complex (Sheraton *et al.*, 1987) and early Paleozoic (550–530 Ma) Lützow-Holm Complex (Hiroi *et al.*, 1991; Shiraishi *et al.*, 1989a, b) are composed predominantly of amphibolite to granulite-facies rocks characterized by large amounts of hydrous minerals. The Lützow-Holm Complex is regarded as a Pan-African orogenic belt, representing one of the collision

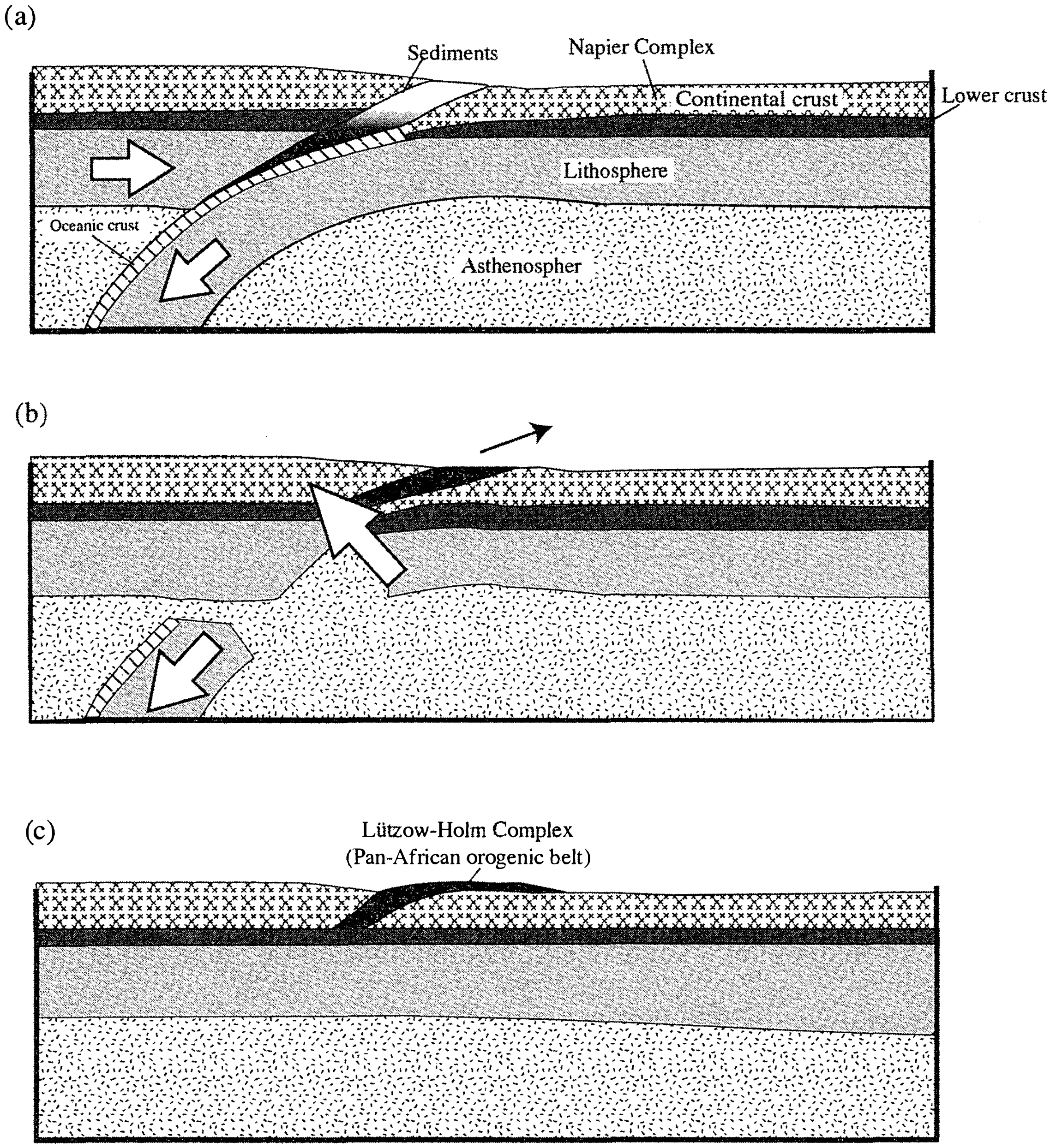


Fig. 10. Tectonic evolution model for Lützow-Holm Complex. (a) Continental collision stage. (b) Exhumation of Lützow-Holm Complex due to slab break-off. (c) Post collision stage.

zones during Gondwana amalgamation (Shiraishi *et al.*, 1994). Seismic experiments were carried out on the Mizuho Plateau, Lützow-Holm Complex in 1979–1981 (Ikami *et al.*, 1984). The *P*-wave arrival time data show the Moho discontinuity at 40 km depth, *Vp* of 6.95 km/s in the lower crust lies at depths from 33 to 40 km (Fig. 9). The measured *Vp* values for the Napier mafic orthopyroxene-clinopyroxene-plagioclase granulite samples are similar to the *P*-wave velocity reported for the lower crust.

Granulite-facies rocks with clockwise *P-T* path are widely exposed in orogenic belts formed during supercontinent amalgamation (*e.g.* Pan-African orogenic belt). A clockwise *P-T* path has been proposed for the Lützow-Holm Complex (*e.g.* Motoyoshi *et al.*, 1989; Motoyoshi and Ishikawa, 1997). England and Thompson (1984) attributed exhumation of granulite-facies rocks with clockwise *P-T* paths to extensive surface erosion of double-thickened crust in continental collision zones. The double-thickened crust model requires development of garnet-bearing high pressure rocks at a deeper level of the crust. It may be concluded that the Lützow-Holm Complex is an exposed deep level of a double-thickened crust which was exhumed statically, probably due to surface erosion.

Combining the present experimental results, however, our interpretation of the *P*-wave velocity structure of the Mizuho Plateau, Lützow-Holm Complex led to the suggestion that the lower crust is composed of mafic orthopyroxene-clinopyroxene-plagioclase granulites (garnet-free) rather than garnet-bearing rock. This means that the higher-pressure granulite-facies rocks (Lützow-Holm Complex) overlie lower pressure granulite-facies rocks (probably Napier Complex) (Fig. 10). The double-thickened crust model can't explain inversion of metamorphic pressure across the crust because peak metamorphic pressure increases with depth in the model. We suggest that the Lützow-Holm Complex was metamorphosed during the Pan-African continental collision between the Napier Complex and Dronning Maud Land and exhumed tectonically upon the Napier Complex after the collision. The exhumed tectonic slice, once metamorphosed at a deeper crustal level, overlies the Napier Complex, which now consists of the lowermost crustal layer of the Lützow-Holm Bay region.

6. Summary

We measured *P*-wave velocities in ultra-high temperature granulites collected from Mount Riiser-Larsen, Amundsen Bay, Napier Complex. The measurements were done with a piston-cylinder-type high-pressure apparatus up to 1.0 GPa from 25°C to 400°C. The *Vp* values measured at 1.0 GPa and 400°C are 7.17 km/s for a meta-pyroxenite, 6.93 km/s, 6.88 km/s for mafic granulites and 6.17 km/s for an orthopyroxene felsic gneiss. *Vp* and SiO_2 contents of the rocks exhibit well-defined linear correlation at 1.0 GPa and 25°C, which is formulated as $Vp=-0.051SiO_2+9.85$. The *Vp* values measured for the Napier mafic granulites are comparable to those of the Mizuho lower crust suggested by Ikami *et al.* (1984). The present results suggest that the lower crust in the Mizuho Plateau in probably composed of mafic granulites (garnet-free) rather than garnet-bearing rocks. We suggest that the Lützow-Holm Complex was exhumed tectonically upon the Napier Complex after the Pan-African continental collision between the Napier Complex and Dronning Maud Land.

Acknowledgments

We thank Prof. K. Shiraishi and Miss K. Seno for providing XRF facilities and helping with the bulk chemical analysis. This study was supported by Grants-in-Aid for Scientific Research from the Japanese Society for the Promotion of Science (10440151 and 12440147).

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(Received March 12, 2001; Revised manuscript accepted May 14, 2001)