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Origins of the lower crustal reflectivity in the Lützow-Holm Complex, Enderby Land, East Antarctica

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The combination of rock velocities with a seismic signature has been used as a clue to understanding the structure and evolution of the continental lithosphere. The lower crustal reflectivity beneath part of the Pan-African orogeny, the Lützow-Holm Complex (LHC), Western Enderby Land, East Antarctica, has been imaged on single-fold seismic reflection profiles using active seismic studies on the continental ice sheet. The set of velocity layers at middle to lower crustal depths were obtained by modeling the later phases of teleseismic receiver functions observed at Syowa Station (39°E, 69°S), in the LHC. The later phases around 10–16 s from P onset in radial components are explained by assuming a layered lower crustal model with velocity changes of 0.3 km/s in shear waves for 0.5–1.0 km thick layers. The origin of lower crustal reflectivity is discussed in terms of high-pressure laboratory measurements on metamorphic rocks from Western Enderby Land. Lower crustal velocities of 6.9 km/s derived by seismic refraction surveys can be explained by a major composition of mafic pyroxene granulite, as occurs in the Archean Napier Complex. A tectonic model involving collision between the paleo East and West Gondwana blocks during the last stage of Pan-African orogeny is presented to explain the high velocities and reflectivity in the lower crust underlying the LHC. The Napier Complex is considered to have descended eastward under part of the Pan-African belt (LHC), generating a higher-pressure mafic granulite composition. The reflectivity of the lower crust of the LHC may have been enhanced subsequently by extensional stress during the breakup process.

Key words: crustal reflectivity, receiver functions, metamorphic rock velocities, Lützow-Holm Complex, Pan-African orogeny.

1. Introduction

Deep crustal structure has been derived from the variations in geophysical characteristics such as seismic velocities, seismic reflectivity, gravity and electromagnetic fields, and heat flow in many regions of the continental terrain. Among these interesting techniques, seismic reflectivity gives the best representation for bringing out the detailed architecture and tectonic evolution of any targeted lithosphere (e.g., Brown, 1990; Brown *et al*., 1996). In NW Canada (SNORCLE transect), for instance, a delaminated crustal structure has been found by tracing the continuity of the reflective layers in the lower crust and the uppermost mantle. The delamination was considered to be generated by collision tectonics of several continental blocks during the early-Proterozoic ages (e.g., Cook *et al*., 1999; Eaton *et al*., 1999). As such, the reflection image of a terrain is a result of the various tectonic processes experienced during continental evolution.

The principal question is "What is the origin of the seismic reflectivity in the deeper part of the crust?" What are the significant geophysical and/or geochemical parameters that will cause such strong reflections, particularly in the deeper crust? The majority of studies to understand crustal reflectivity are, in general, concerned with tectonic extensional regimes such as rifts, basin and ranges (e.g., Le Gall, 1990; Gans, 1987; Warner, 1990). An extensional stress will be able to enhance lithologically layered structures by ductile stretching. In addition, several studies of continental island arcs have found evidence of lower crustal reflectivity that is assumed to be associated with the existence of several kinds of fluid (water, magmas, etc.) (e.g., Ito, 1993; Ogawa, 1992). On the other hand, some recent seismic reflection studies of Precambrian terrain have demonstrated the presence of strong lower crustal reflectivity (e.g., Clowes *et al*., 1999; Diaconescu *et al*., 1998; Goleby *et al*., 1998). Then, why are these reflective signatures identified beneath Precambrian terrain? The source of the reflectivity in the continental terrain can be explained by several multi-genetic features such as lithologic and metamorphic layering, igneous intrusions, mylonite zones, shear zones and seismic anisotropy (e.g., Hyndman and Shearer, 1989; Smithson and Johnson, 1989; Warner, 1990).

There are many reports on the crustal reflectivity of global distributed geological terrains; however, there have not been so many multidisciplinary studies including passive/active seismic sources, geological/geophysical signatures and laboratory measurements, in a target area. When we can combine the seismological and geological approaches, we will get much better information on the composition of the deeper part of the crust. East Antarctica, that once had been part

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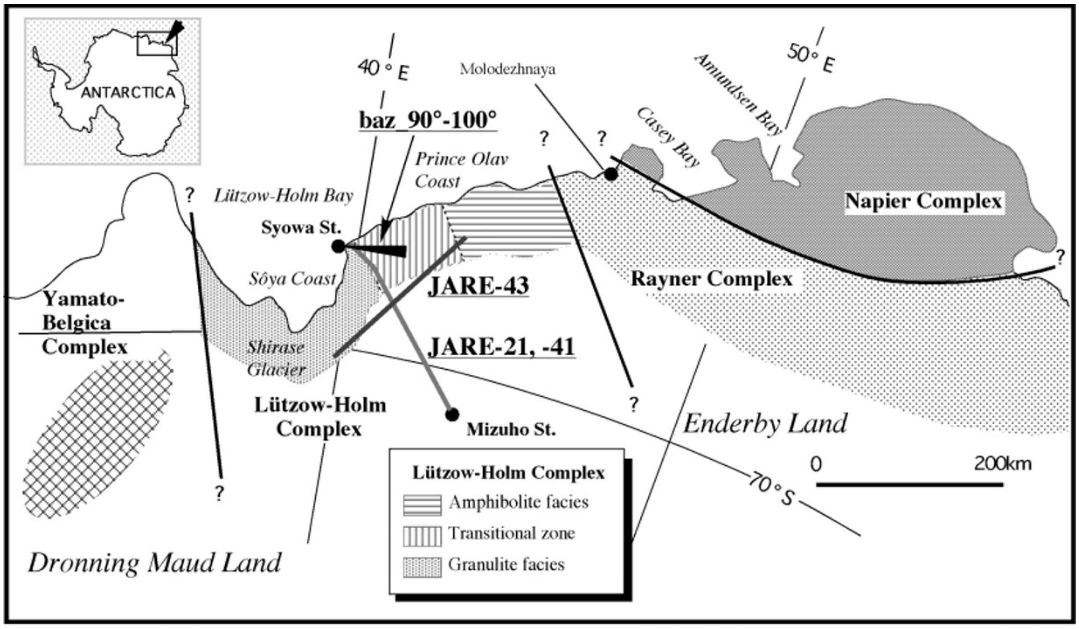

Fig. 1. Geological setting in Eastern Dronning Maud Land and Western Enderby Land, East Antarctica, showing the distribution of the four distinct metamorphic complexes: Napier Complex (Archean), Rayner Complex (late-Proterozoic/early-Paleozoic), Lützow-Holm Complex and Yamato-Belgica Complex (early-Paleozoic) (modified after Motoyoshi *et al.*, 1989). Metamorphic grade in the Lützow-Holm Complex increases progressively along the Prince Olav Coast to the Shirase Glacier. Refraction/wide-angle reflection seismic survey lines by SEAL-2000 (JARE-41) and SEAL-2002 (JARE-43) are indicated by bold solid lines. A solid triangle area of its center at Syowa Station (SYO) indicates the analyzed region by receiver function inversion analysis in 90°–100° back-azimuth.

of the continental block of the supercontinent Gondawa (e.g, Lawver *et al.*, 1998), consists of several areas of Precambrian terrain including major Archean cratons. The deeper parts of the crust beneath the thick continental ice sheet has gradually come to be understood in some parts of West Antarctica and the Antarctic Peninsula (e.g., King and Bell, 1997; Sroda *et al.*, 1997; Della Vedova *et al.*, 1997). However, because of the difficulty of logistic support in remote places, the deeper crust of East Antarctica has not yet been completely revealed and remains the last continental frontier.

In this paper, we present seismological evidence on lower crustal reflectivity in the Lützow-Holm Complex (LHC), Western Enderby Land, East Antarctica, and then evaluate the validity of lower crustal model of laminated layers with different seismic velocities by simulation of waveform inversion and also by forward synthetic modeling. Next, we discuss the origin of the lower crustal reflectivity using high-pressure laboratory measurements of the physical properties of metamorphic rocks of Western Enderby Land. The area is considered to be part of the Pan-African orogenic belts between Enderby Land and Dronning Maud Land (e.g., Lawver *et al.*, 1998; Harley and Hensen, 1990), and was connected with South India and Sri Lanka before the breakup of Gondwana in the mid-Mesozoic. After identifying the crustal composition by the above multidisciplinary interpretation, we present a tectonic evolution model of the LHC from the Pan-African orogeny until the present.

2. Geological Background

Western Enderby Land and Eastern Dronning Maud Land include several crustal blocks with different geological history. From east to west, there are the Napier Complex (Archean), the Rayner Complex (late-Proterozoic/early-Paleozoic), the LHC (early-Paleozoic) and the Yamato-Belgica Complex (early-Paleozoic) (Fig. 1). The Archean Napier Complex is known to be the oldest craton affected by ultra-high temperature (UHT) metamorphism (e.g., Black *et al.*, 1987, Osanai *et al.*, 1999). Cambrian and perhaps more recent fault systems are believed to have resulted in sufficient thickening to cause later exposure of this complex through erosion. The adjacent Rayner Complex was once believed to have late-Proterozoic ages of 700–800 Ma (e.g., Sheraton *et al.*, 1987); however, Shiraishi *et al.* (1997) re-investigated the metamorphic rock ages by zircon dating (SHRIMP) and determined the western part of the Rayner Complex as Pan-African (530–550 Ma) age.

The Lützow-Holm Complex (LHC) experienced regional metamorphism in the early- Paleozoic ages, part of the Pan-African orogeny (e.g., Shiraishi *et al.*, 1994). The metamorphic grade increases progressively from the Prince Olav Coast area (eastern part of the LHC) to the Sôya Coast area (western part of the LHC); and the maximum thermal axis lies in southern Lützow-Holm Bay with a NNW-SSE orientation (Hiroi *et al.*, 1991; Motoyoshi *et al.*, 1989) (Fig. 1). The transitional zone between amphibolite facies and granulite facies along the western part of the Prince Olav Coast is defined by the first appearance of orthopyroxene in ordinary basic to intermediate gneisses, through various reactions. The LHC was deformed under compression stress perpendicular to the thermal axis during this Pan-African metamorphism around 500 Ma.

The Gondwana supercontinent started to break up, associated with the Antarctica/Australia-India rifting, around 150 Ma (e.g., Anderson, 1994; Storey, 1995) when LHC was in

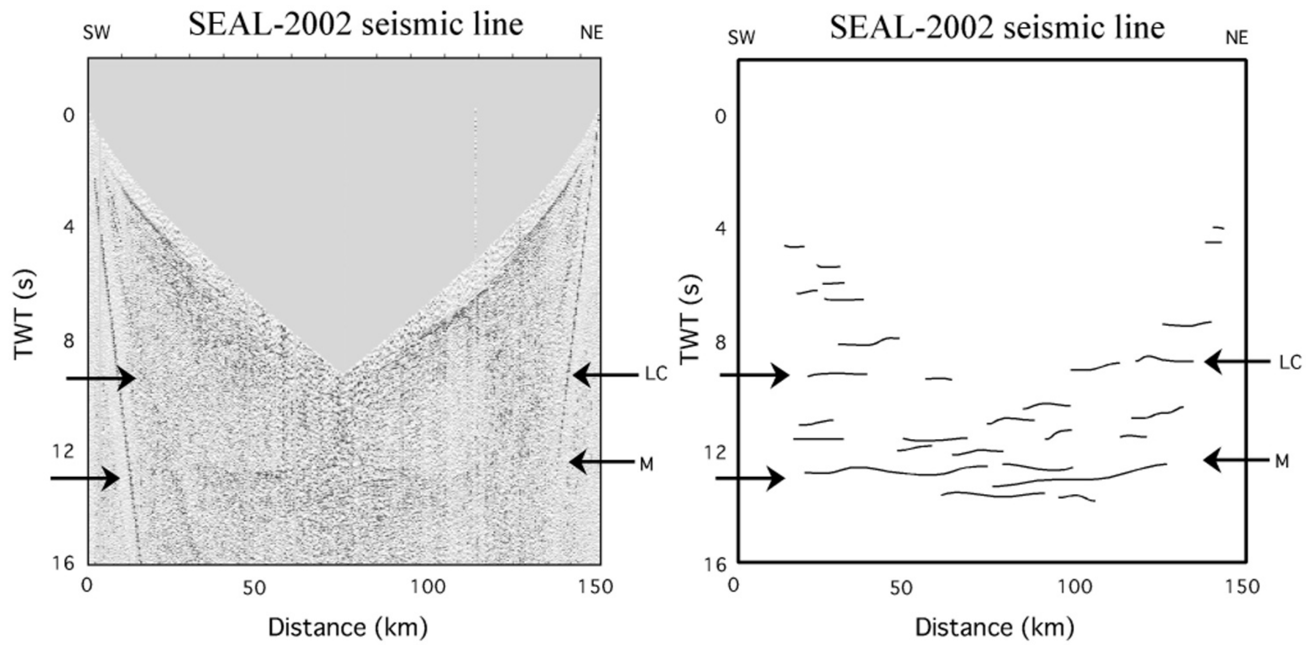

Fig. 2. A single-fold reflection profile produced by combining the NMO corrected records from shots at either ends of the seismic line in the SEAL-2002 (JARE-43) exploration (after Yamashita *et al*., 2003). Interpreted continuous reflectors are illustrated by the solid curves. The Two-Way-Traveltime (TWT) of the reflections from the Moho discontinuity are marked by 'M', the TWT for the reflections from the boundary between the middle and the lower crust is marked by 'LC'.

a condition of extensional stress that induced the uplift of mantle material and underplating. The seafloor spreading direction in Enderby Basin, which is located north of the LHC, is NNE-SSW, as deduced from magnetic anomaly and fracture zone trends (e.g., Nogi *et al*., 1992).

3. Seismic Reflections from Active Source Studies

Details of crustal seismic reflectivity were revealed by active source studies in the LHC. A geoscience research program named "Structure and Evolution of the East Antarctic Lithosphere (SEAL)" has been carried out since the 1996–1997 austral summer season, by the Japanese Antarctic Research Expedition (JARE). In the austral summer of 2000, deep seismic refraction/wide-angle reflection probing was conducted by JARE-41 on the continental ice sheet of the northern Mizuho Plateau in the LHC as the SEAL-2000 experiment (Fig. 1). Seven shots, using a total of 3300 kg of dynamite, along the Mizuho traverse routes generated enough seismic energy to obtain information on the deep velocity structure and reflectivity beneath the LHC (Miyamachi *et al*., 2001, Tsutsui *et al*., 2001a, b). The SEAL-2002 survey was carried out parallel to the coast (NE-SW) on the northern Mizuho Plateau, during the 2002 austral summer by JARE-43 (Miyamachi *et al*., 2003). The seismic profile was located perpendicular to that of JARE-41, in order to obtain an image of the difference in the subsurface structure between granulite and amphibolite metamorphic facies phases as seen in outcrops from the Sôya Coast to the Prince Olav Coast (Fig. 1).

The presence of good reflections in the LHC was first detected by Normal Move-Out (NMO) analysis for the data recorded in 1979–1981 by pre-SEAL surveys (Ito and Kanao, 1996). More detailed images of crustal reflections were subsequently obtained from the recent SEAL surveys. From both the surveys of JARE-41 and -43, we can recognize the clear reflected phases (PmP) from the crust/mantle boundary (Moho discontinuity). The crustal seismic reflectivity along the seismic line was obtained by single-fold reflection profiles. Large seismic wave energies are observed around the PmP phases; this suggests the existence of strong heterogeneity around the lower crust-uppermost mantle boundary. Inland dipping Moho reflections were recognized along the Mizuho traverse routes by the SEAL-2000 surveys (Tsutsui *et al*., 2001b). On the other hand, fairly flat lying reflections around the Moho and at lower crustal depths were found by the SEAL-2002 survey (Yamashita *et al*., 2003; Kanao *et al*., 2004; Fig. 2). Reflections from the Moho discontinuity were identified at a Two-Way-Traveltime (TWT) of 13 s; and, reflections from the boundary between the middle and the lower crust at around 9 s of TWT. In addition, several reflections can be found at the middle and the lower crustal depths.

4. Teleseismic Receiver Functions

Crustal reflectivity can be caused by laminated layers having different seismic velocities. To test this hypothesis, we present an example of simulation in time domain waveform inversion and forward synthetic modeling of the teleseismic receiver functions in the LHC.

First, a shear velocity model of the crust and the uppermost mantle was obtained by time domain inversion of the receiver functions. Since the receiver functions are sensitive to P-to-S conversions through the interfaces beneath a recording station, the inversion result gives information on the shear velocity structure (e.g., Owens *et al*., 1984). A time domain inversion was applied to the stacked radial receiver

Table 1. A list of teleseismic earthquakes used in the receiver function inversion analysis for the backazimuth of 90°–100° around the Syowa Station. The total number of traces used in this study was 11. Mb denotes the body-wave magnitude determined by the United States Geological Survey.

Date	Lat. deg.	Lon. deg.	Depth km	Mb	Distance deg.	Backazimuth deg.	Incident angle deg.
May 25, 1990	2.871S	130.338E	15	5.8	87.666	91.725	19.53
July 18, 1990	6.820S	130.601E	97	5.7	84.100	93.393	20.80
Dec. 05, 1990	5.264S	131.370E	75	5.9	85.818	93.548	20.29
May 31, 1991	6.048S	130.599E	33	6.0	84.815	93.112	20.64
Aug. 11, 1991	3.141S	130.320E	33	5.7	87.409	91.805	19.66
Aug. 24, 1991	6.065S	130.368E	149	5.6	84.716	92.903	20.54
Oct. 15, 1991	6.494S	130.043E	137	5.9	84.202	92.755	20.72
Oct. 18, 1992	6.279S	130.214E	119	5.8	84.462	92.837	20.66
Nov. 17, 1992	5.822S	130.616E	33	5.9	85.030	93.046	20.57
Dec. 23, 1992	6.541S	130.417E	102	6.1	84.292	93.121	20.73
Jan. 20, 1993	7.205S	128.566E	33	6.2	82.908	91.637	21.30

functions up to 30 s after P-arrival to determine the velocity model for a back-azimuth of 90°–100° centered at Syowa Station (SYO; 69°S, 39°E, Fig. 1). The back-azimuth area covers the continental crust that mainly belongs to the transitional zone between the amphibolite facies and the granulite facies metamorphic phases on the surface geology.

Observed receiver functions are obtained by the following parameter setting and analytical procedures. First, noise in frequencies longer than 0.10–0.20 Hz is suppressed by high-pass-filtering. Then the vertical component is deconvolved from the radial component by a spectral division, applying the water level parameter which controls the smallest spectral amplitude allowable for the vertical component. The parameter is expressed as a fraction of the maximum spectral amplitude. A Gaussian high-cut filter of 1 Hz is also applied to suppress high frequency noises. The water level parameter is also varied depending on the signal-to-noise ratio of each trace. A total of 11 teleseismic events with Tangential-to-Radial (T/R) ratios smaller than 0.40 were used to obtain the observed receiver functions (Table 1). Hypocentral distances were selected within 70°–90° that produce a similar incident angle of about 20° for the direct P-arrivals. The data length of receiver functions is set to 30 s from the P-arrival, in order to eliminate contamination of the other large phases such as PP, which have different slowness from that of direct P-waves.

A smoothness constraint in the inversion was implemented by minimizing the roughness norm of the velocity model (Ammon *et al.*, 1990). The necessary number of iterations, up to 30, were conducted in the inversion procedures in order to reduce the waveform-fit residuals to the allowable extent for the optimum solution. The most stable solutions of global minimum values for waveform-fit residuals were adopted as the final models. In the inversion procedure, the P-wave velocity model determined by the refraction experiments in the northern Mizuho Plateau of the LHC in 1979–1981 (Ikami *et al.*, 1984) was adopted as a starting velocity model. The Vp/Vs values of the crust and the uppermost mantle were assumed to be 1.73 and 1.80, respectively. Qp and Qs were derived from the 2 Hz attenuation model for S-coda waves of local earthquakes around the Lützow-Holm Bay region (Kanao, 1997). The shear wave velocity models derived consist of 32 layers with thickness of either 1 or 2 km, depending on the expected large velocity discontinuity in the starting model after Ikami *et al.* (1984). That is, we have set the thickness of 1 km for the topmost surface layer and the middle-lower crust discontinuity. The lower- and upper-limits for shear wave velocities in each layer were introduced by the least square method, with linear inequality constraints (Lawson and Hanson, 1974). The initial model parameters in the inversion procedure are shown in Table 2.

The shear velocity model derived from inversion is shown in the upper left of Fig. 3a. The observed radial receiver function after stacking the 11 events, and a synthetic receiver function obtained by assuming the inverted velocity model, are shown in the upper two traces of Fig. 3b. The shear velocity model obtained by inversion has greater fluctuations in velocities with depth than the initial model. A fairly clear Moho discontinuity can be identified around 38 km in depth. The velocity fluctuation with depth in the continental back-azimuth 90°–100° around SYO might partially be associated with the past metamorphism in the Pan-African age. Low velocity layers within the crust derived by the inverted shear velocity modeling may be composed of felsic metamorphic rocks beneath the granulite and amphibolite facies phases along the coast. Metamorphic rock composition is discussed in the next Chapter.

Next, we tried an evaluation of the existence of laminated velocity layers in the crust using forward synthetic modeling. Synthetic radial receiver functions for a back-azimuth of 90°–100° were produced using thin layers of different seismic velocities at the middle-lower crustal depths. In this simulation study, the velocity model obtained by us was adopted as the initial model. The laminated layers are assumed to exist over the middle and lower crustal depth range of 23–34 km with 2.0, 1.0, 0.5, 0.25, and 0.0 (no laminated model) km thickness for the layering intervals (Fig. 3a). The velocity jumps in the laminated layers are selected to be 0.3 km/s in shear wave velocities, after taking into consideration the typical metamorphic rock velocities of the felsic and the mafic compositions (after Christensen and Mooney, 1995). We can generate the maximum amplitudes on later phases around

Table 2. A list of model parameters in the time domain receiver function inversion. The initial velocity models for Vp and Vs, constraints of upper- and lower-limit of the inversion (L-limit Vs and U-limit Vs), assumed ratio of P- to S-wave velocities (Vp/Vs) and the attenuation factor for P- and S-waves (Qp, Qs) were presented in the 32 layers. The initial Vp model was referred from refraction surveys after Ito and Ikami (1984). Qp and Qs were referred in the case of 2 Hz attenuation model by S-coda waves of the local earthquakes around the Lützow-Holm Bay region after Kanao (1997).

Layer No.	Thickness km	Initial Vp km/s	Initial Vs km/s	L-limit Vs km/s	U-limit Vs km/s	Vp/Vs	Qp	Qs
1	1.00	6.00	3.47	2.50	3.80	1.73	60	25
2	2.00	6.10	3.53	3.00	3.80	1.73	120	50
3	2.00	6.20	3.58	3.00	3.80	1.73	145	60
4	2.00	6.20	3.58	3.00	3.80	1.73	157	65
5	2.00	6.25	3.61	3.00	3.80	1.73	194	80
6	2.00	6.30	3.64	3.00	3.80	1.73	206	85
7	2.00	6.30	3.64	3.00	3.80	1.73	206	85
8	2.00	6.40	3.70	3.10	4.10	1.73	290	120
9	2.00	6.40	3.70	3.10	4.10	1.73	290	120
10	2.00	6.40	3.70	3.10	4.10	1.73	290	120
11	2.00	6.40	3.70	3.10	4.10	1.73	290	120
12	2.00	6.40	3.70	3.10	4.10	1.73	290	120
13	2.00	6.40	3.70	3.10	4.10	1.73	290	120
14	2.00	6.40	3.70	3.10	4.10	1.73	290	120
15	2.00	6.40	3.70	3.10	4.10	1.73	290	120
16	1.00	6.40	3.70	3.10	4.10	1.73	290	120
17	1.00	6.65	3.84	3.50	4.50	1.73	411	170
18	1.00	6.80	3.93	3.50	4.50	1.73	508	210
19	2.00	6.95	4.02	3.50	4.50	1.73	726	300
20	2.00	6.95	4.02	3.50	4.50	1.73	847	350
21	2.00	6.95	4.02	3.50	4.50	1.73	847	350
22	2.00	6.95	4.02	3.50	4.50	1.73	847	350
23	2.00	7.95	4.41	4.10	4.80	1.80	1360	600
24	2.00	7.95	4.41	4.10	4.80	1.80	1360	600
25	2.00	7.95	4.41	4.10	4.80	1.80	1360	600
26	2.00	7.95	4.41	4.10	4.80	1.80	1360	600
27	2.00	8.05	4.47	4.10	4.80	1.80	1360	600
28	2.00	8.05	4.47	4.10	4.80	1.80	1360	600
29	2.00	8.05	4.47	4.10	4.80	1.80	1360	600
30	2.00	8.05	4.47	4.10	4.80	1.80	1360	600
31	2.00	8.05	4.47	4.10	4.80	1.80	1360	600
32	2.00	8.05	4.47	4.10	4.80	1.80	1360	600

10–16 s in the radial receiver functions by assuming velocity lamination zones with 1.0 km thick intervals (Fig. 3b). These later phases cannot be enhanced enough in the synthetic receiver function computed from the final model of the inversion (second upper trace in Fig. 3b). Consequently, we can deduce the existence of velocity lamination zones in the lower crustal depth from these large later phases in the receiver functions.

Sandmeier and Wenzel (1990) derived the crustal reflectivity in the Black Forest region, Germany, by use of the reflectivity method (Fuchs and Müller, 1971). They obtained strong reflectivity using laminated velocity layers at lower crustal depths with an average thickness of 120 m. The thickness of laminated layers in the Black Forest region is thinner than those obtained by receiver function forward modeling in the LHC. Since seismic frequencies around 1–2 Hz are predominant in the teleseismic waves, the thickness of around 1.0 km would be the most responsible for the reflections, by assuming the quarter-wavelength is the most dominant frequency.

5. Velocities of the Metamorphic Rocks

The seismic velocities of the crust and the uppermost mantle can be determined by using arrival times of the observed seismic phases; such as first-arrival phases; later wide-angle reflected phases, and refracted waves along the velocity boundaries. A velocity model inferred from the receiver function inversion, however, has larger fluctuations in the depth-velocity variation, as seen in the previous Chapter, and does not give the actual velocity distribution within the crust as precisely, because three dimensional heterogeneities within the crust would influence the receiver func-

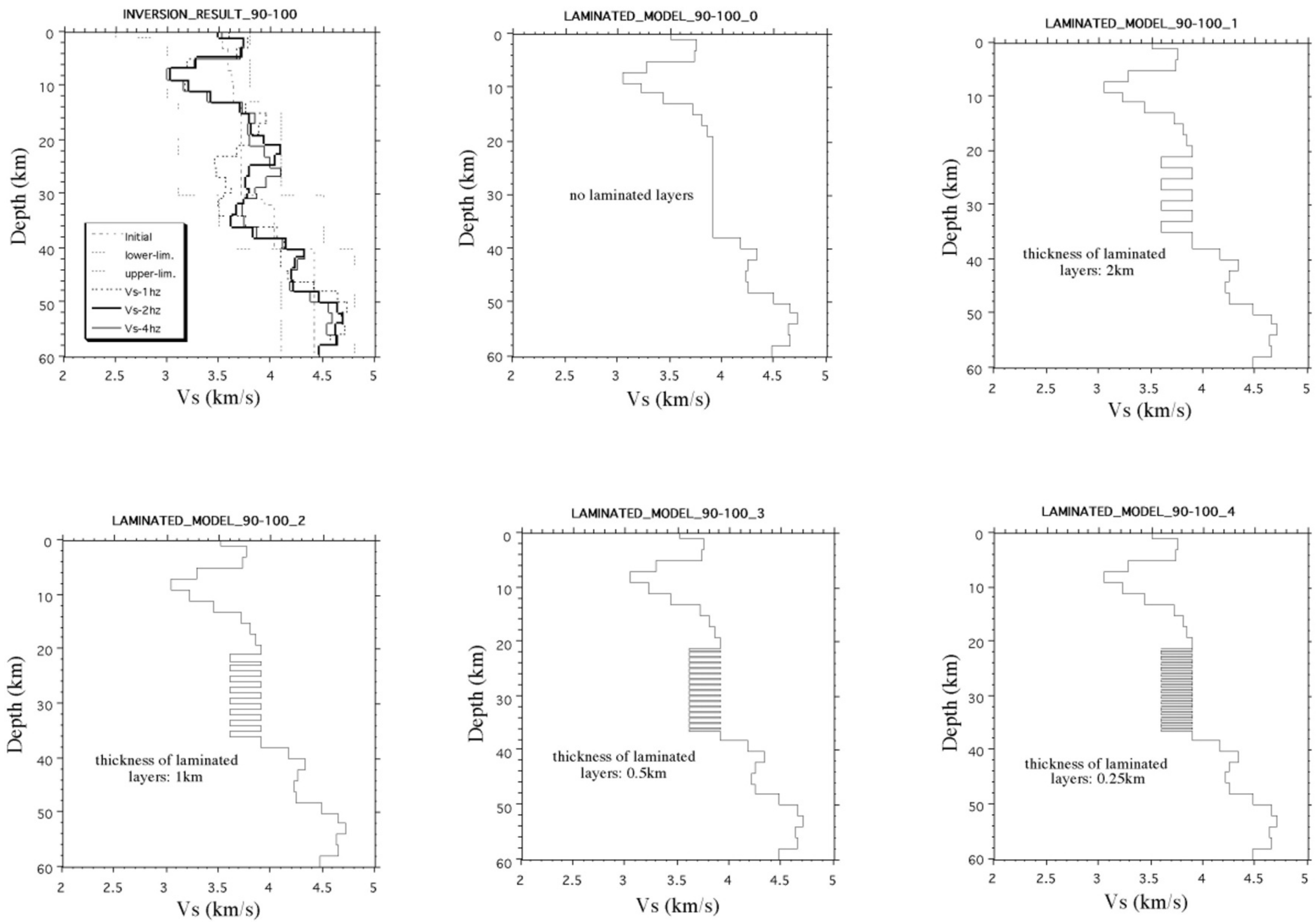

Fig. 3(a). (upper left): Shear velocity models derived from a linearized time domain receiver function inversion for the 90°–100° back-azimuth around the Syowa Station (SYO). The initial P-wave velocity model for the inversion was adopted from the refraction results of Ikami and Ito (1984). The lower- and the upper-limits in determining shear velocities during the inversion were represented by two broken lines (L-limit Vs and U-limit Vs in Table 2), respectively. (the other five figures): Velocity laminated models in the forward simulation to produce the synthetic receiver functions as shown in Fig. 3b. Laminated layers are assumed in the middle and the lower crustal depth with 2.0, 1.0, 0.5, 0.25, and 0.0 (no laminated model) km thickness.

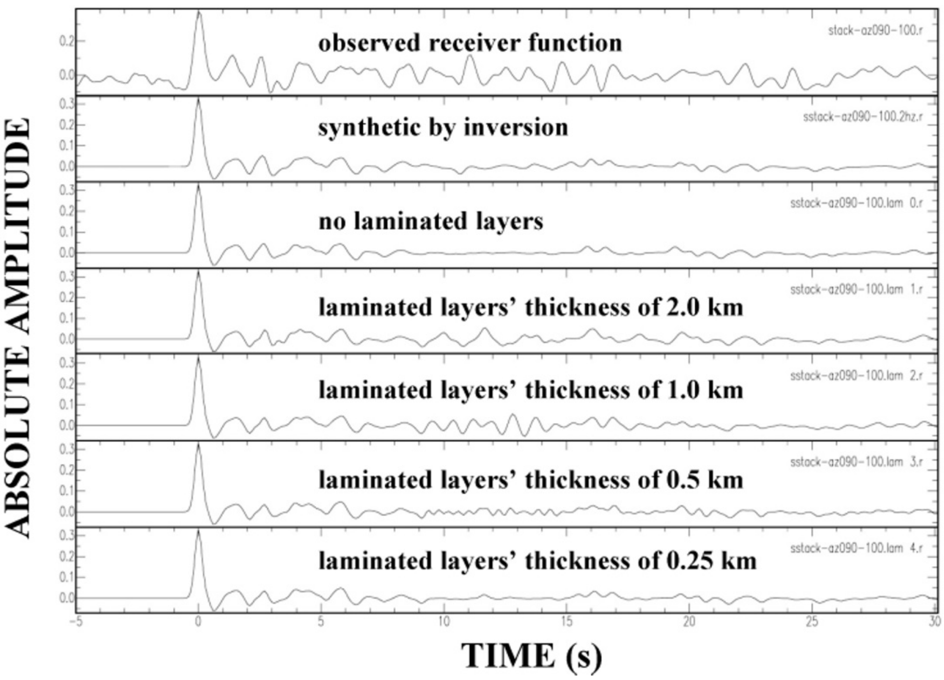

Fig. 3(b). (from the upper to the lower traces) Observed radial receiver function after stacking, synthetic receiver function computed using the 2 Hz attenuation factor model, together with five synthetic receiver functions by assuming various depth-intervals of the laminated layers within the middle and the lower crust as shown in Fig. 3a.

tion waveforms. Therefore in the subsequent discussion, we will chiefly consider the velocity models derived from active source travel-time analysis.

Seismic P-velocity variations of the shallow crust in the LHC have been reported in several papers on active source surveys. From the preliminary analysis of the first arrival phases detected by the SEAL-2000 surveys, velocities in the uppermost crust were determined as 6.2 km/s in approximately the entire region along the survey line (Tsutsui *et al.*, 2001a). The uppermost crustal velocities for the SEAL-2002 seismic line were found to be 5.9 to 6.2 km/s (Miyamachi *et al.*, 2003) increasing from NE to SW associated with the metamorphic grade from the amphibolite-granulite transitional zone to the granulite facies zone. The P-wave seismic velocities in the deeper part of the crust obtained by the pre-SEAL refraction/wide-angle reflection studies on the Mizuho Plateau (Ikami *et al.*, 1984; Ito and Ikami, 1984; Ikami and Ito, 1986), were approximately 6.4 and 6.9 km/s, with a thin transition zone between the middle and the lower crust at about 30–34 km depth.

Recent high-pressure laboratory measurements (e.g., Christensen and Mooney, 1995; Rudnick and Fountain, 1995) have obtained seismic velocities at pressures corresponding to the lower crust by using ultrasonic elastic waves that propagate within metamorphic rock samples. A comparison of the crustal P-velocities from seismic travel-time analyses and from metamorphic rock measurements is used to construct an actual compositional model beneath the studied region. Rock velocities measured at pressures of up to 1 GPa are equivalent to the crustal depth of approximately 35 km. The low geotherm gradient of the shields and the platforms was assumed.

Figure 4 shows ultrasonic compressional-wave velocities (Vp) of felsic gneiss and pyroxene granulite from the Archean Napier Complex as a function of pressure between 0.1 to 1.0 GPa (Shingai *et al.*, 2001; Ishikawa *et al.*, 2001). Vp was determined for various temperatures at about 100°C intervals between 25°C and 400°C. By assuming a typical continental geotherm of shields and platforms (Turcotte and Schubert, 1982; left part of Fig. 5), Vp from laboratory data can be related to the calculated seismic velocities from the field experiment data. Geotherms for shield area are assumed since the surface heat flow in the LHC is fairly low, of about 42 mW/m^2 (Pollack and Chapman, 1977). However, no consideration has been made of any anisotropy in the high-grade metamorphic rock velocities.

Seismic velocities of 5.9–6.2 km/s for the uppermost crust beneath the LHC, for instance, are only observed on the ultrasonic velocities of the felsic gneiss samples in Fig. 4. Lower velocity values than 5.9–6.2 km/s would be achieved in the lower pressure ranges below 0.2 GPa, because of the opening of micro-cracks under these pressure ranges. P-velocities also generally decrease with increasing SiO2 for high-grade metamorphic rocks (Fountain *et al.*, 1990), as seen also in Fig. 4. This implies that a variation in seismic velocities of the uppermost crust along the SEAL-2002 seismic line could be related to the increase of metamorphic grade from the NE-SW direction.

The seismic P-velocities of the middle part of the crust in the LHC (6.4 km/s) (Ikami *et al.*, 1984) would be comparable to velocities of a mixture of mafic (pyroxene) granulite (20%) and felsic gneiss (80%) as shown in Fig. 5 (Shingai *et al.*, 2001; Ishikawa *et al.*, 2001), while the lower crustal velocities of approximately 6.9 km/s (Ikami *et al.*, 1984) could be explained by the mafic (pyroxene) granulite. This suggests that the lower crustal composition, if it is assumed to

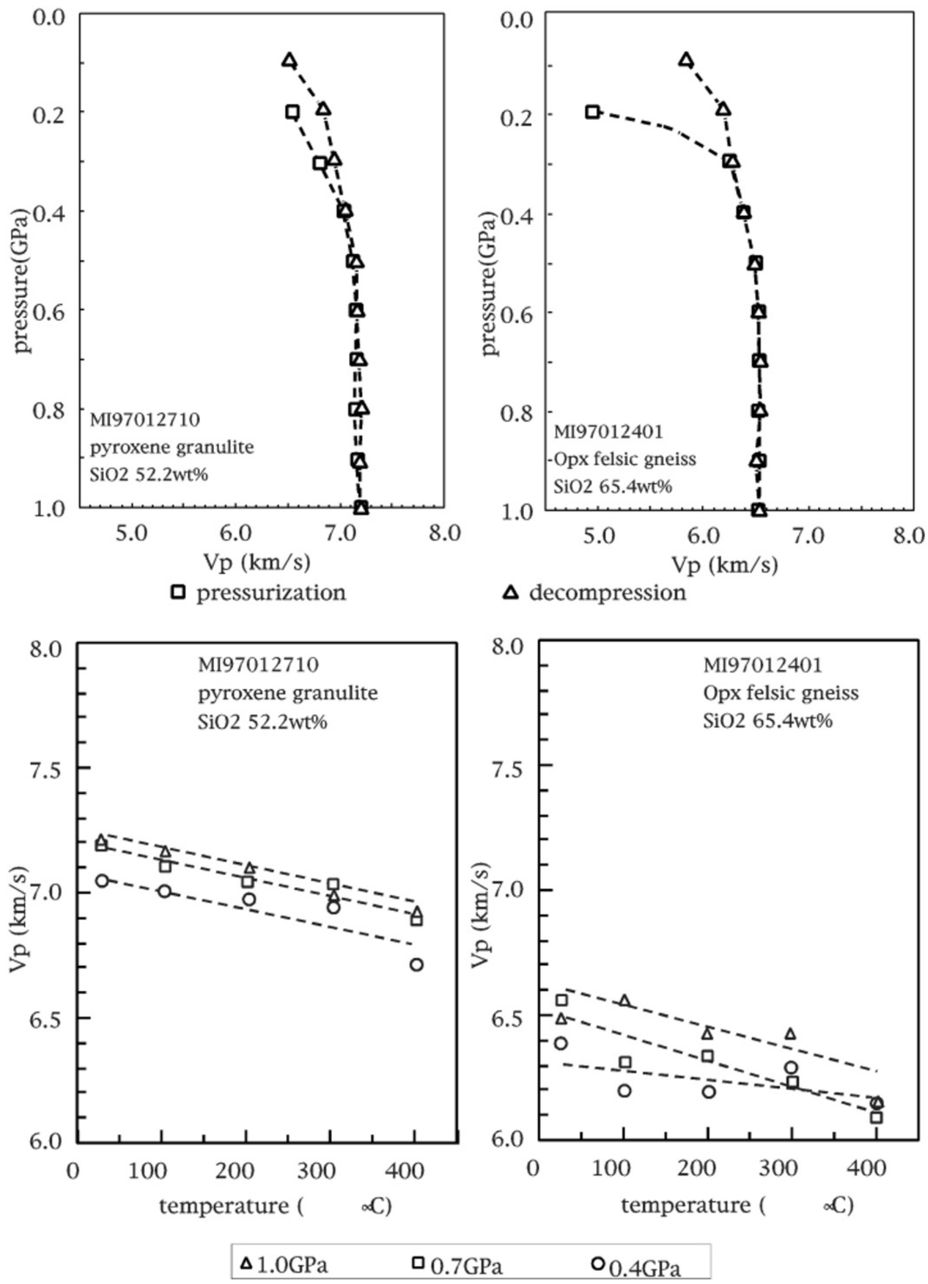

Fig. 4. (upper two) Ultrasonic compressional-wave velocity (Vp) of felsic gneiss and pyroxene granulite as a function of pressure (Shingai *et al*., 2001; Ishikawa *et al*., 2001). Vp was determined from the zero-pressure core length and the measured travel time of the pulse under various pressures at 0.1 GPa interval during pressurization (open squares) and decompression (open circles) between 0.1 GPa to 1.0 GPa. (lower two) Ultrasonic compressional-wave velocity (Vp) of felsic gneiss and pyroxene granulite as a function of temperature at 0.4 GPa (open circles), 0.7 GPa (open squares) and 1.0 GPa (open triagles) (Shingai *et al*., 2001; Ishikawa *et al*., 2001). Vp was determined under various temperatures at about 100°C intervals between 25°C and 400°C.

be pyroxene granulite from Napier Complex, may have been overlain by the LHC. From the rock velocity information after Shingai *et al*. (2001), there is a possibility of some inclusion of pyroxenite at the crust-mantle boundary in order to produce the uppermost mantle velocities (7.9 km/s). There is also the possibility of the inclusion of mafic eclogite facies and other ultramafic rocks to produce the high (7.9 km/s) velocities.

6. Discussion

Crustal reflections in general have been considered to have multi-genetic sources; such as igneous intrusions, lithologic and metamorphic layering, mylonite zones, anastomosing shear zones, seismic anisotropy and fluid layers (e.g., Hyndman and Shearer, 1989; Smithson and Johnson, 1989; Warner, 1990). Metamorphic layering is considered to be the principal cause in case of the LHC. Strong reflectivity might be expected from a deep crust characterized by layered sequences of mafic and felsic rocks (Goff *et al*., 1994). It is generated where mafic rocks are interlayered with upper amphibolite and lower granulite facies metapelites. Reflectivity is weaker where mafic rocks are interlayered with high-grade metapelites (Burke and Fountain, 1990; Holliger *et al*., 1993).

Christensen and Mooney (1995) modeled the petrology of the average continental crust based on a selection of

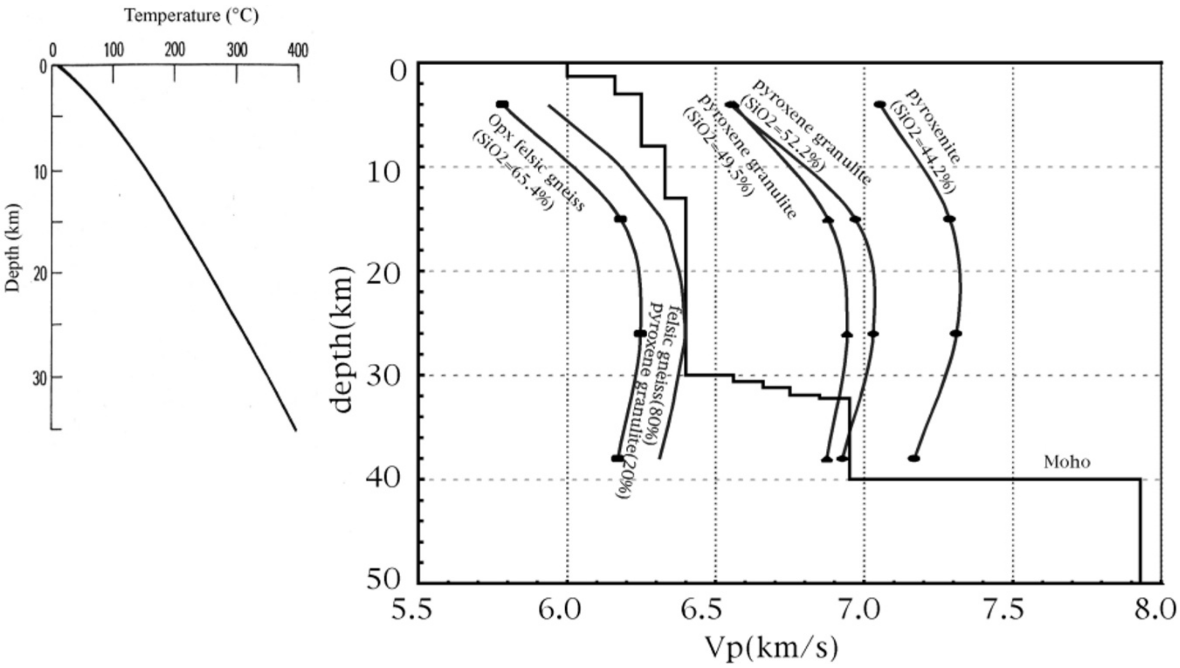

Fig. 5. Ultrasonic compressional-wave velocity for felsic gneiss, pyroxene granulites, pyroxenite and mixture of felsic gneiss (80 vol.%) and pyroxene granulite (20%) assuming cold geotherm of Turcotte and Schubert (1982). Seismic refraction/wide-angle reflection P-wave profile beneath the Mizuho Plateau (Ikami *et al.*, 1984) was also shown for comparison.

rock assemblages which are commonly observed in exposures of crustal sections, that is, an association of granitic gneiss, tonalitic gneiss, amphibolite, mafic granulite and mafic garnet granulite. They derived a weighted-average crustal velocity-depth curve based on the above metamorphic rocks and the observed average crustal model giving a petrological and velocity model. The causes of major reflectors at midcrustal depths are large contrasts in the acoustic impedance of amphibolite with granitic gneiss and tonalitic gneiss. In the deeper crust, garnet-rich layers, with high densities and velocities, are likely to generate significant reflections. This model can be applied to the LHC as an initial explanation of the high velocity zones at the lower crustal depth and crustal reflective layers. We infer a gradual increase of volume percentages of mafic rocks with depth and the lamination of several metamorphic rocks in the lower crust. If we assume that the lower crust is made up of the Napier Complex pyroxene granulite, the crustal composition model beneath the LHC would be as shown in Fig. 6. The composition ratio of the mafic (pyroxene) granulite is similar to that of meta-mafic sills in the Archaean Napier Complex, which are probably related to mafic magma underplating during the Archaean. The single-fold reflection cross-section from the SEAL-2002 surveys (Yamashita *et al.*, 2003) and the model calculation of the acoustic impedance presented earlier imply the existence of middle and lower crustal laminations of various compositions. These factors suggest that rocks of the Napier Complex lie under the Pan-African orogenic belt of the LHC. Variations in the seismic signature of the crust are considered to be related to past regional tectonic events, such as the metamorphism in the late-Proterozoic to Paleozoic (e.g., Hiroi *et al.*, 1991; Motoyoshi *et al.*, 1989). As West Gondwana is considered to have been thrust eastward under the Pan-African belt, including beneath the LHC (e.g., Lawver *et al.*, 1998; Grunow *et al.*, 1996), the amalgamation of Gondwana can be regarded as due to collision tectonics where late Proterozoic island arcs and ophiolites were thrust over both East and West Gondwana.

In some regions, the above primary causes of crustal reflectivity are enhanced by ductile stretching during a subsequent tectonic extension. Strong reflected layers in the lower crust, in particular, have been found in thin-skinned tectonic areas (e.g., Le Gall, 1990; Gans, 1987; Warner, 1990). The reflectivity of the lower crust in the LHC, as revealed by the SEAL profiles, may have been enhanced under the extensional conditions during the breakup of Gondwana, of Australia and India from Antarctica, at about 150 Ma. The breakup process might also have created heterogeneity by the thinning process at the continental margins. Subsequent injection of uppermost mantle materials, such as gabbro, into the crust under extensional stress might have taken place along with the non-volcanic breakup process of the continental margins of East Antarctica (e.g., Anderson, 1994; Storey, 1995).

7. Conclusions

Single-fold seismic reflection studies on the Mizuho Plateau have shown evidence of significant reflectivity in the lower crust and around the Moho discontinuity in the LHC of Western Enderby Land. Forward modeling simulations of the teleseismic receiver functions have shown the existence of laminated layers in the lower crust. The later phases around 10–16 s from P wave onset in radial receiver functions can be well explained by assuming velocity gaps of 0.3 km/s for shear waves with 0.5–1.0 km thick lamination layers at crustal depths of 23–34 km.

High-pressure laboratory measurement on metamorphic rocks from Western Enderby Land help constrain the crustal

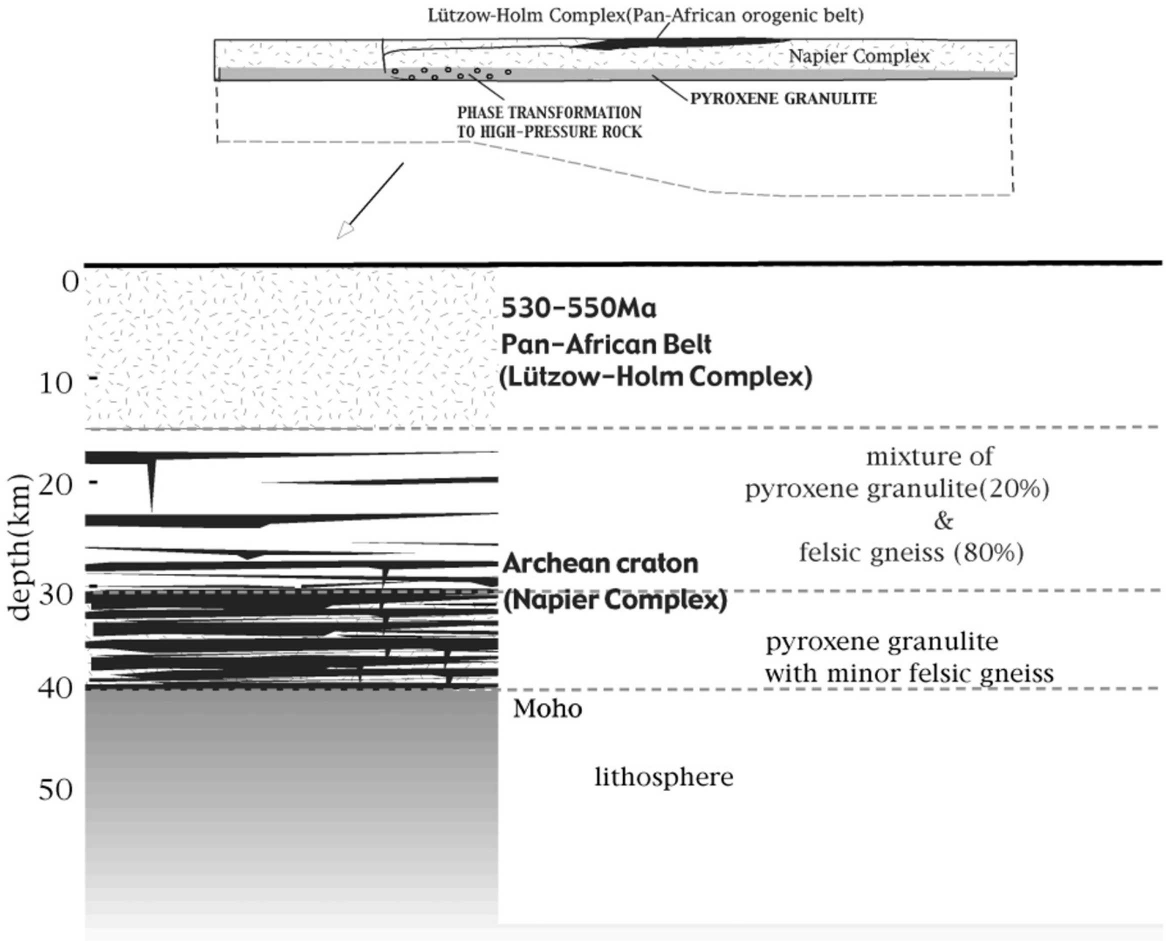

Fig. 6. (lower): Crustal composition model of the Lützow-Holm Complex derived from a comparison of the laboratory rock velocity measurements with seismic studies. Lützow-Holm Complex occupies only the upper crust of the Lützow-Holm Complex. The middle and lower crusts are interpreted to consist of the Archean crust: felsic gneiss (including metasedimentary quartzofeldspathic rocks) together with pyroxene granulite (middle crust), and pyroxene granulite with minor amounts of felsic rocks (lower crust). (upper): Proposed tectonic evolution model during the Pan-African orogeny. After a collision of East Gondwana (Archean Napier craton), the Lützow-Holm Complex was exhumed by wedge extrusion and extruded onto the Napier Complex. Then the Lützow-Holm Complex was deeper exposed due to surface erosion.

rock types and the origin of lower crustal reflectivity. The lower crustal velocities measured by seismic refraction surveys can be explained by the major composition of pyroxene granulite from the Archean Napier Complex, that is considered to be overlain by the LHC including higher-pressure granulite.

A tectonic model of the LHC during the Pan-African orogeny and the succeeding continental break-up has been derived. It is proposed that the West Gondwana block, including the Napier Complex, has descended eastward under the Pan-African belt, including the LHC, and that rocks of the paleo Napier Complex form the lower crust. Subsequently, the reflectivity of the lower crust under the LHC may have been enhanced by the extensional tectonics of the continental margin during the breakup of Gondwana.

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References

Ammon, C. J., G. E. Randall, and G. Zandt, On nonuniqueness of receiver function inversion, *J. Geophys. Res.*, **95**, 15303–15318, 1990.

Anderson, D. L., Superplumes or supercontinents?, *Geology,* **22**, 39–42, 1994.

Black, L., S. L. Harley, S. S. Sun, and M. T. McCulloch, The Rayner complex of East Antarctica: complex isotopic systematics within a Proterozoic mobile belt, *Jour. Metamor. Geol.*, **5**, 1–26, 1987.

Brown, L. D., COCORP, crustal structure and hydrocarbon exploration in The Potential of Deep Seismic Profiling for Hydrocarbon Exploration, *Technip*, 135–139, 1990.

Brown, L. D., W. Zhao, K. D. Nelson, M. Hauck, D. Alsdorf, A. Ross, M. Cogan, M. Clark, Z. Liu, and J. Che, Bright spots, structure, and magmatism in southern Tibet from INDEPTH seismic reflection profiling, *Science*, **274**, 1688–1690, 1996.

Burke, M. M. and D. M. Fountain, Seismic anisotropy of metapelites from the Ivrea-Verbano zone and Serie dei Laghi (northern Italy), *Phys. Earth Planet. Inter.*, **78**, 301–317, 1990.

Christensen, N. I. and W. D. Mooney, Seismic velocity structure and composition of the continental crust: A global view, *J. Geophys. Res.*, **100**, 9761–9788, 1995.

Clowes, R. M., F. A. Cook, Z. Hajnal, J. Hall, J. Lewry, S. Lucas, and R. Wardle, Canada's LITHOPROBE Project (Collaborative multidisciplinary geoscience reseach leads to new understanding of continental evolution), *Episodes,* **22**, 3–20, 1999.

Cook, F. A., A. J. Velden, and K. W. Hall, Frozen subduction in Canada's Northwest Territories: Lihoprobe deep lithospheric reflection profiling of the western Canadian Shield, *Tectonics,* **18**, 1–24, 1999.

Della Vedova, B., G. Pellis, H. Trey, J. Zhang, A. K. Cooper, J. Makris, and the ACRUP Working Group, Crustal structure of the transantarctic mountains, western Ross Sea, in *The Antarctic Region: Geological Evolution and Processes,* edited by C. A. Ricci, pp. 609–618, 1997.

Diaconescu, C. C., J. H. Knapp, L. D. Brown, D. N. Steer, and M. Stiller, Precambrian Moho offset and tectonic stability of the East European platform from the URSEIS deep seismic profile, *Geology,* **26**, 211–214, 1998.

Eaton, D. W., G. M. Ross, and R. M. Clowes, Seismic-reflection and potential-field studies of the Vulcan structure, western Canada: A Paleoproterozoic Pyrenees?, *J. Geophys. Res.*, **104**, 23255–23269, 1999.

Fountain, D. M., M. H. Salisbury, and J. Percival, Seismic structure of the continental crust based on rock velocity measurements from the Kapuskasing uplift, *J. Geophys. Res.*, **95**, 1167–1186, 1990.

Fuchs, K. and G. Müller, Computation of synthetic seismograms with the reflectivity method and comparison with observations, *Geophys. J. R. Astron. Soc.*, **23**, 417–433, 1971.

Gans, P. G., An open-system, two-layer crustal stretching model for the eastern Great Basin, *Tectonics,* **6**, 1–12, 1987.

Goff, J. A., K. Holliger, and A. Levander, Modal fields: A new method for characterization of random velocity heterogeneity, *Geophys. Res. Lett.*, **21**, 493–496, 1994.

Goleby, B. R., T. MacCready, B. J. Drummond, and A. Goncharov, The Mount Isa geodynamic transect-crustal implications, structure and evolution of the Australian Continent, *Geodynamics,* **26**, 109–117, 1998.

Grunow, A., R. Hanson, and T. Wilson, Were aspects of Pan-African deformation linked to Iapetus opening?, *Geology*, **24**, 1063–1066, 1996.

Harley, S. and B. J. Hensen, Archean and Proterozoic high-grade terranes of East Antarctica (40°–80°E): a case study of diversity in granulite facies, in *High Temperature Metamorphism and Crustal Anatexis,* edited by J. R. Ashworth and M. Brown, pp. 320–370, 1990.

Hiroi, Y., K. Shiraishi, and Y. Motoyoshi, Late Proterozoic paired metamorphic complexes in East Antarctica, with special reference to the tectonic significance of ultramafic rocks, in *Geological Evolution of Antarctica,* edited by M. R. A. Thomson, J. A. Crame, and J. W. Thomson, pp. 83–87, 1991.

Holliger, K., A. R. Levander, and J. A. Goff, Stochastic modeling of the reflective lower crust: Petrophysical and geological evidence from the Ivrea zone (northern Italy), *J. Geophys. Res.*, **98**, 11967–11980, 1993.

Hyndman, R. D. and P. M. Shearer, Water in the lower continental crust: modelling magnetotelluric and seismic reflection results, *Geophys. J.*, **98**, 343–365, 1989.

Ikami, A. and K. Ito, Crustal structure in the Mizuho Plateau, East Antarctica, by a Two-Dimensional Ray Approximation, *Jour. Geod.*, **6**, 271–283, 1986.

Ikami, A., K. Ito, K. Shibuya, and K. Kaminuma, Deep crustal structure along the profile between Syowa and Mizuho Stations, East Antarctica, *Mem. Natl. Inst. Polar Res., Ser. C (Earth Sci.),* **15**, 19–28, 1984.

Ishikawa, M., E. Shingai, and M. Arima, Archean continental crust under the Pan-African orogenic belt, East Antarctica, *Eos, Trans.*, **82**, 1182, 2001.

Ito, K., Cut-off depth of seismicity and large earthquakes near active volcanoes in Japan, *Tectonophysics,* **217**, 11–21, 1993.

Ito, K. and A. Ikami, Upper crustal structure of the Prince Olav Coast, East Antarctica, *Mem. Nat. Inst. Polar Res., Ser. C (Earth Sci.),* **15**, 13–18, 1984.

Ito, K. and M. Kanao, Detection of reflected waves from the lower crust on Mizuho Plateau, East Antarctica, *Antarct. Rec.*, **39**, 233–242, 1996.

Kanao, M., Variations in the crust structure of the Lützow-Holm Bay region, East Antarctica using shear wave velocity, *Tectonophysics,* **270**, 43–72, 1997.

Kanao, M., M. Ishikawa, M. Yamashita, K. Kaminuma, and L. D. Brown, Structure and evolution of the East Antarctic lithosphere: Tectonic implications for the development and dispersal of Gondwana, *Gondwana Research,* **7**, 31–41, 2004.

King, E. C. and A. C. Bell, Seismic reflection investigation of George VI Sound, Antarctic Peninsula, in *The Antarctic Region: Geological Evolution and Processes,* edited by C. A. Ricci, pp. 697–703, 1997.

Lawson, C. L. and R. J. Hanson, Solving least squares problems, Englewood Cliffs, NJ, Prentice-Hall Inc., 158–173, 1974.

Lawver, L. A., L. M. Gahagan, and I. W. D. Dalziel, A tight fit-early Mesozoic Gondwana, a plate reconstruction perspective, *Mem. Natl. Inst. Polar Res., Spec. Issue,* **53**, 214–229, 1998.

Le Gall, B., Evidence of an imbricate crustal thrust belt in the southern British Variscides: Contributions of Southwestern Approaches Traverse (SWAT) deep seismic reflection profiling recorded through the English Channel and the Celtic Sea, *Tectonics,* **9**, 283–302, 1990.

Miyamachi, H., H. Murakami, T. Tsutsui, S. Toda, T. Minta, and M. Yanagisawa, A seismic refraction experiment in 2000 on the Mizuho Plateau, East Antarctica, *Antarct. Rec.*, **45**, 101–147, 2001 (in Japanese with English abstract).

Miyamachi, H., S. Toda, T. Matsushima, M. Takada, Y. Takahashi, D. Kamiya, A. Watanabe, M. Yamashita, and M. Yanagisawa, A seismic refraction and wide-angle reflection exploration in 2002 on the Mizuho Plateau, East Antarctica, *Antarct. Rec.*, **47**, 32–71, 2003 (in Japanese with English abstract).

Motoyoshi, Y., S. Matsubara, and H. Matsueda, P-T evolution of the granulite-facies of the Lützow-Holm Bay region, East Antarctica, Evolution of Metamorphic belts, *Geol. Soc. Spec. Iss.*, **43**, 325–329, 1989.

Nogi, Y., N. Seama, and N. Isezaki, The directions of magnetic anomaly lineations in Enderby Basin, off Antarctica, in *Recent Progress in Antarctic Earth Science,* edited by Y. Yoshida, K. Kaminuma, and K. Shiraishi, pp. 649–654, 1992.

Ogawa, Y., Deep crustal resistivity structure revealed by wideband magnetotellurics—Tohoku and Hokkaido region, Ph.D thesis, the University of Tokyo, 1992.

Osanai, Y., T. Toyoshima, M. Owada, T. Tsunogae, T. Hokada, and W. A. Crowe, Geology of ultrahigh-temperature metamorphic rocks from Tonagh Island in the Napier Complex, East Antarctica, *Polar Geosci.*, **12**, 1–28, 1999.

Owens, T. J., G. Zandt, and S. R. Taylor, Seismic evidence for an ancient rift beneath the Cumberland Plateau, Tennessee: A detailed analysis of broadband teleseismic P waveforms, *J. Geophys. Res.*, **89**, 7783–7795, 1984.

Pollack, H. N. and D. S. Chapman, Mantle heat flow, *Earth Planet. Sci. Lett.*, **34**, 174–184, 1977.

Rudnick, R. L. and D. M. Fountain, Nature and composition of the continental crust: a lower crustal perspective, *Rev. Geophys.*, **33**, 267–309, 1995.

Sandmeier, K. J. and F. Wenzel, Lower crustal petrology from wide-angle P- and S-wave measurements in the Black Forest, *Tectonophysics,* **173**, 495–505, 1990.

Sheraton, J. W, R. J. Tingey, L. P. Black, L. A. Offe, and D. J. Ellis, Geology of Enderby Land and western Kemp Land, Antarctica, *Bulletin, Bureau of Mineral Resources, Australia,* **223**, 51, 1987.

Shingai, E., M. Ishikawa, and M. Arima, P-wave velocity in ultrahigh temperature granulites from the Archean Napier Complex, East Antarctica, *Polar Geoscience,* **14**, 165–179, 2001.

Shiraishi, K., D. J. Ellis, Y. Hiroi, C. M. Fanning, Y. Motoyoshi, and Y. Nakai, Cambrian orogenic belt in East Antarctica and Sri Lanka: implication for Gondwana assembly, *J. Geol.*, **102**, 47–65, 1994.

Shiraishi, K., D. J. Ellis, C. M. Fanning, Y. Hiroi, H. Kagami, and Y. Motoyoshi, Re-examination of the metamorphic and protolith ages of the Rayner Complex, Antarctica: evidence for the Cambrian (Pan-African) regional metamorphic event, in *The Antarctic Region: Geological Evolution and Processes,* edited by C. A. Ricci, pp. 79–88, 1997.

Smithson, S. B. and R. A. Johnson, Crustal structure of the western U. S. based on reflection seismology. Geophysical Framework of the Continental Unites States, *Geol. Soc. Am. Mem.*, **172**, 577–612, 1989.

Sroda, P., M. Grad, and A. Guterch, Seismic models of the Earth's crustal structure between the South Pacific and the Antarctic Peninsula, in *The Antarctic Region: Geological Evolution and Processes,* edited by C. A. Ricci, pp. 685–689, 1997.

Storey, B. C., The role of mantle plumes in continental breakup: case histories from Gondwanaland, *Nature,* **377**, 301–308, 1995.

Tsutsui, T., H. Murakami, H. Miyamachi, S. Toda, and M. Kanao, P-wave velocity structure of the ice sheet and the shallow crust beneath the Mizuho traverse route, East Antarctica, from seismic refraction analysis, *Polar Geosci*., **14**, 195–211, 2001a.

Tsutsui, T., M. Yamashita, H. Murakami, H. Miyamachi, S. Toda, and M. Kanao, Reflection profiling and velocity structure beneath Mizuho traverse route, East Antarctica, *Polar Geosci*., **14**, 212–225, 2001b.

Turcotte, D. L. and G. Schubert, Geodynamics applications of continuum physics to geological problem, 1–450, 1982.

Warner, M., Basalts, water, or shear zones in the lower continental crust?, *Tectonophysics,* **173**, 163–174, 1990.

Yamashita, M., H. Miyamachi, T. Matsushima, S. Toda, M. Takada, A. Watanabe, and M. Kanao, Deep crustal structure beneath the Mizuho Plateau, East Antarctica from seismic exploration, XXIII General Assembly of the International Union of Geodesy and Geophysics, SW03/10A/D-004, 2003.

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