# Deep seismic reflection imaging of the Pan-African mobile belt, the Lützow-Holm Complex, East Antarctica

M. Kanao,[1] A. Fujiwara,[2] H. Miyamachi,[3] K. Ito,[4] and T. Ikawa[2]

[1]National Institute of Polar Research, Research Organization of Information and Systems, 1-9-10 Kaga, Itabashi-ku, Tokyo, 173-8515, Japan (kanao@nipr.ac.jp)
[2]GEOSYS Inc., 1-5-18, Otsuka, Bunkyo-ku, Tokyo 112-0012, Japan (fujiwara@geosys.co.jp, ikawa@geosys.co.jp)
[3]Faculty of Science, Kagoshima University, Kourimoto 1-21-35, Kagoshima 890-0065, Japan (miya@sci.kagoshima-u.ac.jp)
[4]Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto, 611-0011, Japan (ito@recp.dpri.kyoto-u.ac.jp)

**Summary**    The deep structure and evolution of the crust and upper mantle were demonstrated by Deep Seismic Surveys (DSS) in Pan-African terrain of the Lützow-Holm Complex (LHC), Dronning Maud Land, East Antarctica. DSS were conducted on the continental ice-sheet of the LHC in the austral summers of 2000 and 2002, by the "Structure and Evolution of the East Antarctic Lithosphere (SEAL)" program.  Detailed processing, based on NMO corrections and CDP stacking, of the DSS data extracted clearer images of reflections of the crust-mantle boundary, together with several crustal reflections.  A layered structure at the crust-mantle boundary was clarified by coherency enhancement processing after NMO correction to very far offset data.  Crustal structure of the LHC imaged by seismic reflections suggests the tectonic influence of compression stress in a NE-SW orientation during the Pan-African, during the last stage of formation of broad mobile belt between East and West Gondwana super-terrains.

## Introduction

Lithospheric evolution and deep structure of the Precambrian Shield of East Antarctica are of relevance to Earth evolution and continental growth processes. Surface geological features of East Antarctica have been attributed to several crustal terrains associated with amalgamation and break-up of the Gondwana and Rodinia super-continents. In the broad area of Enderby Land - Dronning Maud Land, there are several distinct geological blocks from Archean to the present.  Late Proterozoic structures were interpreted to have caused initial uplift and succeeding exhumation in the Archaean Napier Complex (Black et al., 1987; Harley and Hensen, 1990).  Cambrian and more recent fault systems are believed to have resulted in sufficient crustal thickening to cause later exposure through erosion.  Based on surface wave tomography, Enderby Land is known to have high seismic velocities with maxima around the Napier Complex, compared with the other adjacent terrains (e.g, Ritzwoller et al., 2001).

The Lützow-Holm Complex (LHC), Eastern Dronning Maud Land, is located 500 km west of the Napier Complex.   The LHC experienced regional metamorphism in early- Paleozoic times (Shiraishi et al., 1994). Metamorphic grade increases progressively from amphibolite facies (eastern part of the LHC) to high-grade granulite facies (western part); the maximum thermal axis lies in the  southernmost part of the LHC in a NNW-SSE direction (Hiroi et al., 1991).  A transitional zone between amphibolite and granulite facies is located in the central part of the LHC; which was defined by a first appearance of orthopyroxene in basic to intermediate gneisses (Motoyoshi, et al., 1989).  The LHC was deformed under compressional stress perpendicular to the thermal axis (almost parallel to the coast) during the Pan-African metamorphic event.  From the magnetic anomaly data of  Golynsky et al., 1996, we can identify a clear boundary between the LHC and adjacent crustal terrains.  Within LHC, magnetic anomalies vary in according to the metamorphic grade of the surface geology from amphibolite to granulite facies.

In this study, the deep structure and lithospheric evolution of the LHC were investigated by recently completed Deep Seismic Surveys (DSS).  Detailed processing of the DSS data was conducted to extract a clearer image of seismic reflections in the crust and uppermost mantle, based on the NMO correction and CDP (CMP) Stacking method. A tectonic evolution model of the LHC involving Gondwana amalgamation and break-up processesis demonstrated on the basis of obtained reflection profiles.

## Deep Seismic Surveys

DSS were carried out on the continental ice-sheet of the LHC during expeditions in 1978-80, 2000 and 2002 austral summers, respectively.  The latter two surveys were carried out as a program of the "Structure and Evolution of the East Antarctic Lithosphere (SEAL)" by the Japanese Antarctic Research Expedition (JARE) (Kanao et al., 2004). In both surveys (SEAL-2000, and -2002), about 160 plant-type 2 Hz geophones were installed on the ice-sheet in an array more than 150 km in length (Fig. 1, Table 1).  A total of 8,300kg dynamite charges at the fifteen sites on the ice-sheet gave sufficient information concerning the deep structure of continental margin in East Antarctica.

Before starting this study, crustal velocity models and basement topography were already known from the profiles in 2000 and 2002.  From this work, wide-angle travel-time analyses revealed the crustal thickness as ranging

in 38-42 km along the profiles, with the averaged P- velocities of the upper crust, the middle crust, the lower crust and the uppermost mantle, as 6.2, 6.4, 6.5 and 8.0 km/s, respectively (Miyamachi et al., 2003, Yoshii et al., 2004). As for the shallow crystalline crust for the SEAL-2002 profile, velocities in the topmost layer have variations for 5.9-6.2 km/s for P-waves (Miyamachi et al., 2003), which appear to correspond with metamorphic grade from amphibolite to granulite facies of the surface geology along the coast.

| Items | SEAL-2000 | SEAL-2002 |
|---|---|---|
| Line length | 180km | 150km |
| Average receiver interval | 1.1km | 1.0km(0.5km between loc.57 to 77) |
| Total receiver locations | 160 | 160 |
| Total shot points | 7 | 8 |
| Standard charge size | 610kg(S-1:250kg, S-7:25kg) | 710kg(S-8:20kg) |
| Average shot interval | 36km | 25km |
| Recording system | LS8000SH | LS8000SH |
| Amplifier gain | 59.1db(900 power) | 49.5db (300 power) |
| A/D converter | 16bits | 16bits |
| Filter, Low pass | 60Hz | 30Hz |
| Sample interval | 5ms | 5ms |
| Record length | 60sec | 60sec |
| Geophone, | L22D | L22D |
| Geophone frequency | 2.2Hz | 2.2Hz |
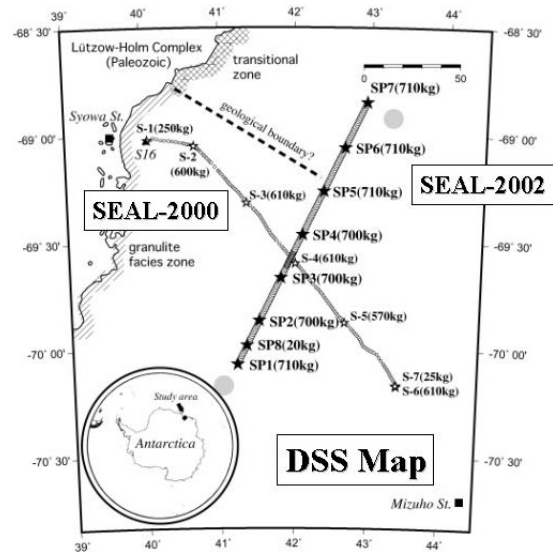
**Figure 1.** (left) Field parameters. (right) Map showing the study area. Solid and open stars are shot locations; large and small circles indicate the stations in SEAL-2002 and -2000, respectively. A numeral in kg in each shot is a weight of dynamite used.

## Data Processing

Processing of the DSS data was undertaken to extract a clearer image of reflections above the crust-mantle boundary (Moho) based on NMO correction and CDP (CMP) stacking method. The parameters of field data and the basic data processing flow chart are shown in Table 1.

At first, a geometry table for CDP stacking was created from the surveyed data and the interval of CDP traces was defined at 500m. Simple refraction analyses of first break based on Time-term method was performed by assuming two layers model of the ice-sheet and the crystalline basement rock. On the assumption of P-velocities within the ice-sheet as 3.8km/s, the top layer of crystalline rocks was analyzed to have values of 6.1-6.4km/s in velocity (Fig. 2). These resultant velocity values are almost similar with those obtained by previous wide-angle analyses (Miyamachi et al., 2003, Yoshii et al., 2004). There is no significant improvement was recognized, however, in spite of the static time correction of the ice-sheet was tested; then it was not applied for the CDP stacking process.

In succession, the velocity analyses based on CDP stacking were tried. The CDP profile by far offset data in which the Moho reflections are detectable only on very far offset traces. Therefore, velocity scan was tried for these far offset data and found 6.6 km/s RMS velocity is optimum for the Moho reflections. The resultant velocity function combining the above analyses was determined. The CMP stacking was not so effective due to the following reasons; 1) The interval of the receiver points is sparse (1.0km); 2) Shot point interval is also sparse (30km); 3) PmP reflection appears only on the very far offset data (more than 50km). It was considered, however, that very promising for the reflection data processing associated with refraction method, if shorter interval of the receiver points, i.e., less than 200m, is adopted in future. The maximum stacking fold was six near the center of each seismic profile.

## Reflection imaging

The single coverage CDP section by far offset shots and the CDP stack section with limited offset for the SEAL-2002, and -2000 DSS are in Fig. 3. Distance for the limited offset traces was decided not to apply stacking on the basis of test processing.

Referring to the reflection images obtained from processing the SEAL-2000 and -2002 DSS data, we can identify several characteristic features as follows. 1) Velocity structure was determined with reasonable accuracy based on refraction analysis and velocity scan of the reflection data. 2) Reflections from the bottom of ice-sheet (bed rocks) was clearly determined both by refraction and reflection analyses. 3) Moho reflection can be traced only on very far

offset traces more than 60 km and conventional CDP stacking is not so effective to enhance the Moho reflection. However, CDP processing of the single coverage section by far offset data revealed the clear reflection from the Moho discontinuities.

A crustal structure revealed by SEAL DSS beneath the LHC has been attributed to have lateral and vertical variations. The clear reflections from the Moho, together with several inner crustal reflections observed on the CDP sections; which imply the existence of horizontal heterogeneity on the crust-mantle boundary beneath the Paleozoic orogenic belt of the LHC. The similar reflective pattern, in spite of relatively weak signals, was already pointed out by the previous single hold reflection study only for the SEAL-2002 DSS data (Yamashita et al., 2005). Laminated layered structure around the crust-mantle boundary, moreover, was identified by the spectral ratio analyses for the PmP waves (Yamashita et al., 2002).
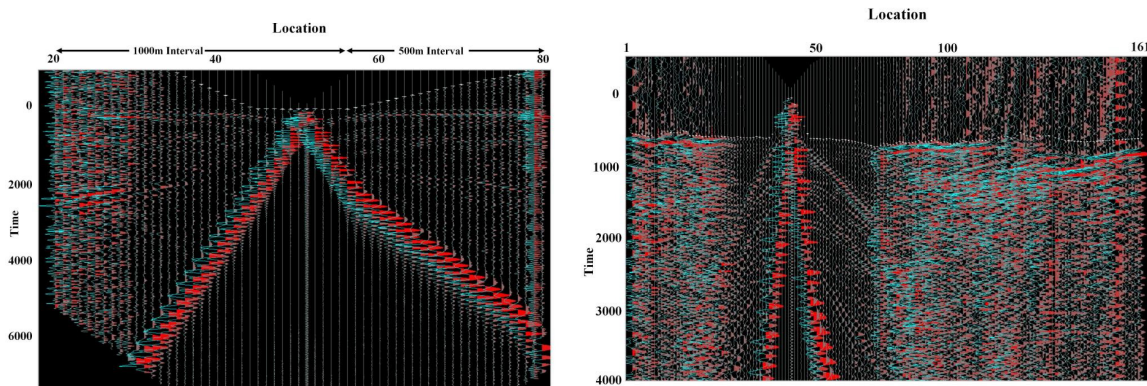


**Figure 2.** Picked and reduced first break with 3.8 km/s (upper) and with 6.1 km/s (lower) in P-velocities, for SEAL-2002, Shot Point 3. The waveforms are horizontally ordered in equi-space pot by location.

## Tectonic interpretation

A gently dipping Moho (38-42 km) along the SEAL-2000 profile by refraction / wide-angle reflection survey (Yoshii et al., 2004) can be correlated with past regional tectonics, such as metamorphism and orogenic activity in the early-Paleozoic. Based on geological papameters during the Pan-African period, the LHC was under compressive stress in a NEE-SWW direction, perpendicular to the thermal axis in the southern part of the LHC. Repetitive (wedge shaped ?) crustal structures characterized in the reflection section by SEAL-2002 (Fig. 3a) might indicate the influence of compressive stress along the profile in NE-SW direction during the Pan-African period; during the last stage of deformation in mobile belt between the East- and West-Gondwana supra terrains.

Furthermore, the relatively high magnetic anomalies of the LHC compared with surrounding terrains (Golynsky et al., 1996) indicate the LHC lies in one of the major sutures of the Pan-African mobile belt. These have been identified by recent geochronological and structural studies between East Africa and Dronning Maud Land. The proposed major sutures appear to continue from the LHC to the Shackleton Range of West Antarctica (e.g., Lawver and Scotese, 1987, Fitzsimons, 2000).

We suggest that during the Gondwana breakup between Antarctica / Australia-India (Anderson, 1994) at ~150 Ma the LHC experienced extensional stress that caused the thinning process at the continental margins of East Antarctica. Marine magnetic anomalies and fracture zone trends north of the LHC at this age were WNW-ESE and NNE-SSW (Nogi et al., 1992). The flat lying reflectors identified by the SEAL-2000 DSS suggest the effect of the extensional stress in NW-SE direction presumably involving the breakup of Gondwana. These reflective layers around the crust-mantle boundary might have been enhanced under the extensional conditions during the last stage of breakup.

## Conclusion

The DSS deployed in the LHC has revealed characteristic features of lithospheric evolution in the Pan-African mobile belt in Dronning Maud Land. After completing NMO corrections and CDP stacking for far offset data, reflection imaging of the crust and uppermost mantle were well achieved. Layered structure around the crust-mantle boundary were obtained by the coherency enhancement processing after NMO. Deep structure of the LHC, as imaged by both reflection profiles in 2000, and 2002, and combined with the other geophysical / geological information, suggests the accumulated influence of tectonic stress after the Pan-African event. Collision processes between East and West Gondwana supra terrains are supposed to have generate the resultant reflection signatures beneath the LHC.
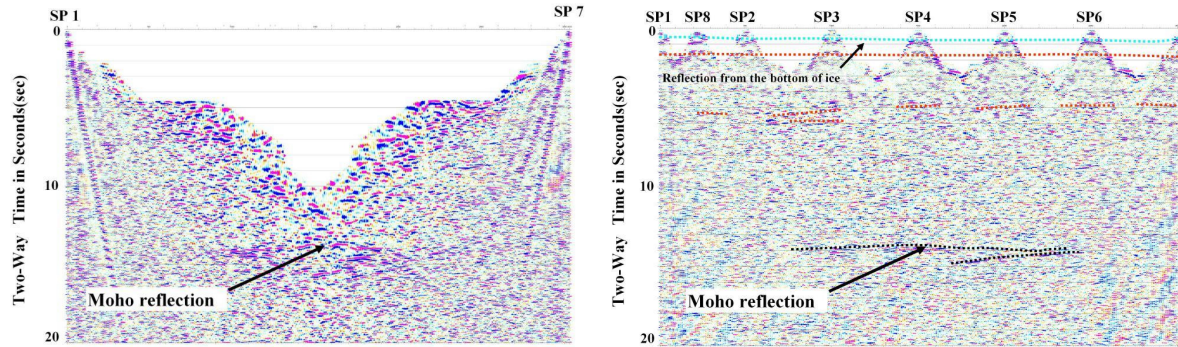
**Figure 3.** Single coverage CDP section by far offset shots for SP1, SP7 (upper) and the CDP stack section with limited offset within 120km (lower) for the SEAL-2002 DSS.

## References

Anderson, D. L. (1994), Superplumes or supercontinents ?, Geology, 22, 39-42.

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

Fitzsimons, I. C. W. (2000), A review of tectonic events in the East Antarctic Shield and their implications for Gondwana and earlier supercontinents, J. Afri. Earth Sci., 31, 3-23.

Golynsky, A. V., V. N. Masolov, Y. Nogi, K. Shibuya, C. Tarlowsky and P. Wellman (1996), Magnetic anomalies of Precambrian terranes of the East Antarctic shield coastal region (20E-50E), Polar Geosci., 9, 24-39.

Harley, S. and B. J. Hensen (1990), Archean and Proterozoic high-grade terranes of East Antarctica (40- 80E): a case study of diversity in granulite facies, In: Ashworth, J. R. and Brown, M. (Eds.), High Temperature metamorphism and crustal Anatexis, 320-370.

Hiroi, Y., K. Shiraishi and Y. Motoyoshi (1991), Late Proterozoic paired metamorphic complexes in East Antarctica, with special reference to the tectonic significance of ultramafic rocks, In: Thomson, M. R. A., Crame, J. A. and Thomson, J. W. (Eds.), Geological evolution of Antarctica, 83-87.

Kanao, M., M. Ishikawa, M. Yamashita, K. Kaminuma and L. D. Brown (2004), Structure and Evolution of the East Antarctic Lithosphere: Tectonic Implications for the Development and Dispersal of Gondwana, Gondwana Research, 7, 31-41.

Lawver, L. A. and C. R. Scotese (1987), A revised reconstruction of Gondwanaland, In: G. D. McKenzie (Ed.), Gondwana Six: Structure, Tectonics abd Geophysics, Am. Geophys. Union Geophys. Mon., 17-23.

Miyamachi, H., S. Toda, T. Matsushima, M. Takada, A. Watanabe, M. Yamashita and M. Kanao (2003), Seismic refraction and wide-angle reflection exploration by JARE-43 on Mizuho Plateau, East Antarctica, Polar Geosci., 16, 1-21.

Motoyoshi, Y., S. Matsubara and H. Matsueda (1989), P-T evolution of the granulite facies rocks of the Lützow-Holm Bay region, East Antarctica, In: J. S. Daly et al., (Eds), Evolution of Metamorphic Belts Oxford, Blackwell, 325-329.

Nogi, Y., N. Seama and N. Isezaki (1992), The directions of magnetic anomaly lineations in Enderby Basin, off Antarctica, In: Yoshida, Y., Kaminuma, K. and Shiraishi, K. (Eds.), Recent Progress in Antarctic Earth Science, Tokyo, Terra Sci. Publ., 649-654.

Ritzwoller, M. H., N. M. Shapino, A. L. Levshin and G. M. Leahy (2001), Crustal and upper mantle structure beneath Antarctica and surrounding oceans, J. Geophys. Res., 106, 30645-30670.

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

Yamashita, M., M. Kanao and T. Tsutsui (2002), Characteristics of the Moho as revealed from explosion seismic reflections beneath the Mizuho Plateau, East Antarctica, Polar Geosci.,15, 89-103.

Yamashita, M., H. Miyamachi, M. Kanao, T. Matsushima, S. Toda, M. Takada and A. Watanabe (2005), Deep Reflection Imaging beneath the Mizuho Plateau, East Antarctica, by SEAL-2002 Seismic Experiment, Futterer D.K., Damaske D., Kleinschmidt G., Miller H., Tessensohn F. (eds) Antarctica: Contributions to global earth sciences, Springer-Verlag, Berlin Heidelberg New York, 147-154.

Yoshii, K., K. Ito, H. Miyamachi and M. Kanao (2004), Crustal structure derived from refractions and wide-angle reflections in the Mizuho Plateau, East Antarctica, Polar Geosci., 17, 112-138.