—研究ノート—
Scientific Note

Detection of Reflected Waves from the Lower Crust on Mizuho Plateau, East Antarctica

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人工地震データの再解析によるみずほ高原の下部地殻反射波の検出

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要旨：下部地殻からの反射はさまざまな造山帯，特に顕生代の拡大テクトニクス場において報告されているが，南極大陸においてはこれまで反射法による地殻深部探査は行われていない．本研究では，第21次日本南極地域観測隊（JARE-21）で行われた屈折法探査データを再解析し，その結果みずほ高原において下部地殻からの反射波を検出した．リュツォ・ホルム湾内の海中発破（薬量3トン）により，みずほルート上の約300kmに及ぶ測線上27観測点で記録が得られたが，このデータに8-15Hzのバンドパス・フィルターをかけた後，速度を6.3km/sとしてnormal-moveout補正を行うと，往復走時で8-16秒の範囲に顕著な反射波がみられた．これは下部地殻からの広角反射に対応し，その深さは18-48kmであることがわかった．この反射層の深さ分布は，過去の内陸トラバース旅行で得られた重力異常，特にブーゲ異常と良く対応しており，リュツォ・ホルム岩体の進化を研究する上でも重要である．

Abstract: 'A reflective lower crust' has been found in some regions of Phanerozoic orogens. In Antarctica it has not been surveyed and is an important target for explosion experiments. Seismic refraction data from the explosion experiments during the 21st Japanese Antarctic Research Expedition (JARE-21) in 1981 were re-analyzed to detect reflected waves from the lower crust. An explosion in Lützow-Holm Bay with 3000 kg of explosive gave well-recorded seismic waves at 27 stations along a 300 km profile on the northern Mizuho Plateau, East Antarctica. A band-pass filtered record section with a normal-moveout velocity of 6.3 km/s shows clear phases of large amplitudes in a range of 8-16 s of two-way travel time; these phases can be considered as wide-angle reflected waves from the lower crust. The reflection depths correspond to about 18-48 km. The depth patterns of reflective layers on the Mizuho Plateau can be related to the Bouguer gravity anomalies and are useful for studying the evolution of the Lützow-Holm Complex.

1. Introduction

'A reflective lower crust' has been found in some regions of the Phanerozoic crust in Europe and Northern America by reflection explosion experiments (TRAPPE *et al*.,

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1988; MATTHEWS and the BIRPS GROUP, 1987; ALLMENDINGER *et al.*, 1987a). The predominant reflected layers in the lower crust, in particular, are found in the thin-skinned tectonic areas under extentional stress. The origin of lower crustal reflectivity is considered as multi-genetic from both geologic and geophysical data. The possible origins of lower crustal reflections are as follows: igneous intrusions, lithologic and metamorphic layering, mylonite zones, anastromosing shear zones, seismic anisotropy and fluid layers (*e.g.*, HYNDMAN and SHEARER, 1989; SMITHSON, 1989; WARNER, 1990). These "primary" causes mentioned above are enhanced by ductile stretching during the extension process. The tectonic history of the crust is strongly correlated with the observed reflectivity patterns. The shapes and characteristic features of the reflection layers have been interpreted with different geological terranes (*e.g.*, ALLMENDINGER *et al.*, 1987b).

Early seismic reflection profiles in Precambrian crust have indicated a generally structureless lower crust; however, recent reflection studies have revealed pronounced structural features of steeply dipping zones of reflections deeper than 15 km from the lower crust and Moho (*e.g.*, SMITHSON and JOHNSON, 1989; GOLEBY *et al.*, 1990; BABEL WORKING GROUP, 1990; GREEN *et al.*, 1989). These observed structures indicate the existence of ancient continental collisions and/or rifting which are different from the present plate motions. These Precambrian structures have persisted through time with long-term thermal and tectonic stability (GIBBS, 1986). Since most Precambrian data collected to date are from Preterozoic terranes, the deep reflection profiling of Archean crust remains a scientific frontier. Evidence of the lower crustal reflectivity in an island arc area, for example in Japan, has been also reported and the origins of the reflected layers have been investigated in relation to the volcanic activity and the Conrad discontinuity (*e.g.*, MIZOUE *et al.*, 1982).

The crustal velocity structures on the Antarctic continent have been investigated by use of refraction explosion experiments conducted mainly by the U.S.A., U.S.S.R. (present Russia) and Japan (reviewed by BENTLEY, 1983; KADMINA *et al.*, 1983; ITO and IKAMI, 1984). The reflection pattern in the crust is information as useful as the velocity structure for the study of evolution of the Antarctic continent. Although the results of coincident seismic reflection/refraction studies of the continental crust have been compiled (MOONEY and BROCHER, 1987), reflections from the lower crust in Antarctica have not been surveyed yet. East Antarctica, particularly, is an important target for explosion experiments as a typical Precambrian shield, since there are ancient orogens of continental crust from Archean to Phanerozoic ages in Enderby Land.

In this paper, the seismic refraction data obtained by the Japanese Antarctic Research Expeditions (JARE-20, -21 and -22; 1979–1981) (IKAMI *et al.*, 1984; ITO and IKAMI, 1984) are re-analyzed to detect reflected waves from the lower crust of the Mizuho Plateau. Syowa Station is located in the Lützow-Holm Complex, western part of Enderby Land, where two regional metamorphisms are known in the late-Preterozoic and Paleozoic age (HIROI *et al.*, 1991; SHIRAISHI *et al.*, 1992). This study is aimed at obtaining a preparatory image of reflection of the crust from the late-Preterozoic to Paleozoic ages where seismic reflection and refraction studies are planned in the near future by JARE.

2. Data and Method

The velocity structure of the crust and the uppermost mantle along the 300 km

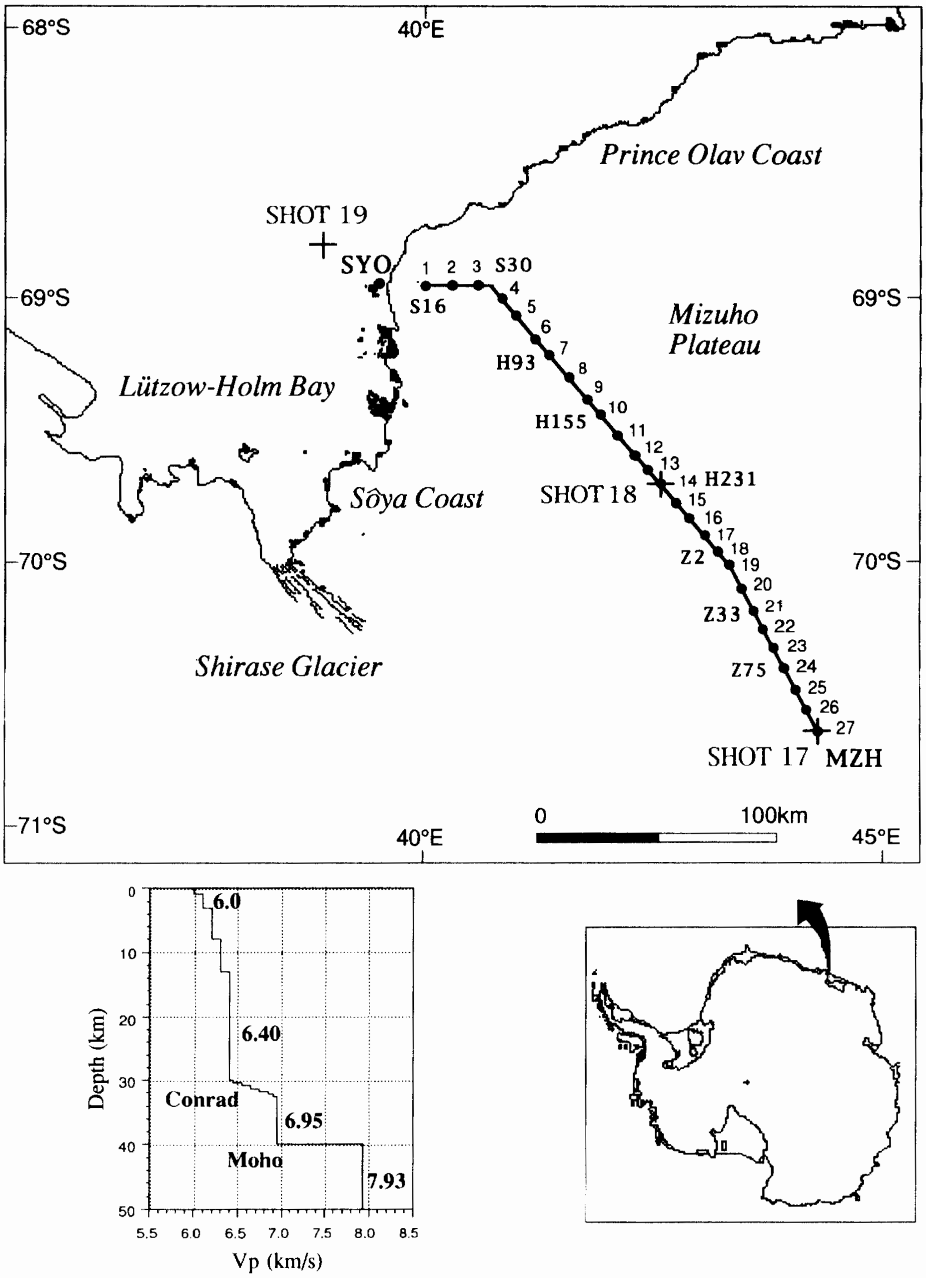

Fig. 1. Locations of shot points (SHOT) and observation stations (solid circles) conducted in the refraction experiments in 1981 (upper figure). All stations are located along the traverse routes between two stations, Syowa (SYO) and Mizuho (MZH). Seismic P-wave velocity-depth relation obtained by the refraction experiments (lower figure) (after Ikami et al., 1984).

long seismic profile between Syowa and Mizuho Stations was derived from analyses of the travel-time data and from comparison of observed seismograms with synthetic ones. This investigation revealed that the Moho depth was about 40 km, and the obtained velocities of the surface layer, middle crust, lower crust and uppermost mantle were 6.0, 6.4, 6.9 and 7.9 km/s, respectively (IKAMI *et al.*, 1984; see the lower part of Fig. 1).

Locations of shot points and observation stations are shown in Fig. 1. Shot 19 in Lützow-Holm Bay (Fig. 1) with 3000 kg of explosive gave well-recorded seismic waves at all 27 stations along the above profile in Fig. 1. The record section with a reduction velocity of 6.0 km/s is redrawn in Fig. 2 after IKAMI *et al.* (1984). Clear later phases, which are thought to be reflected waves, can be traced at distances from 100 to 200 km (see Fig. 2).

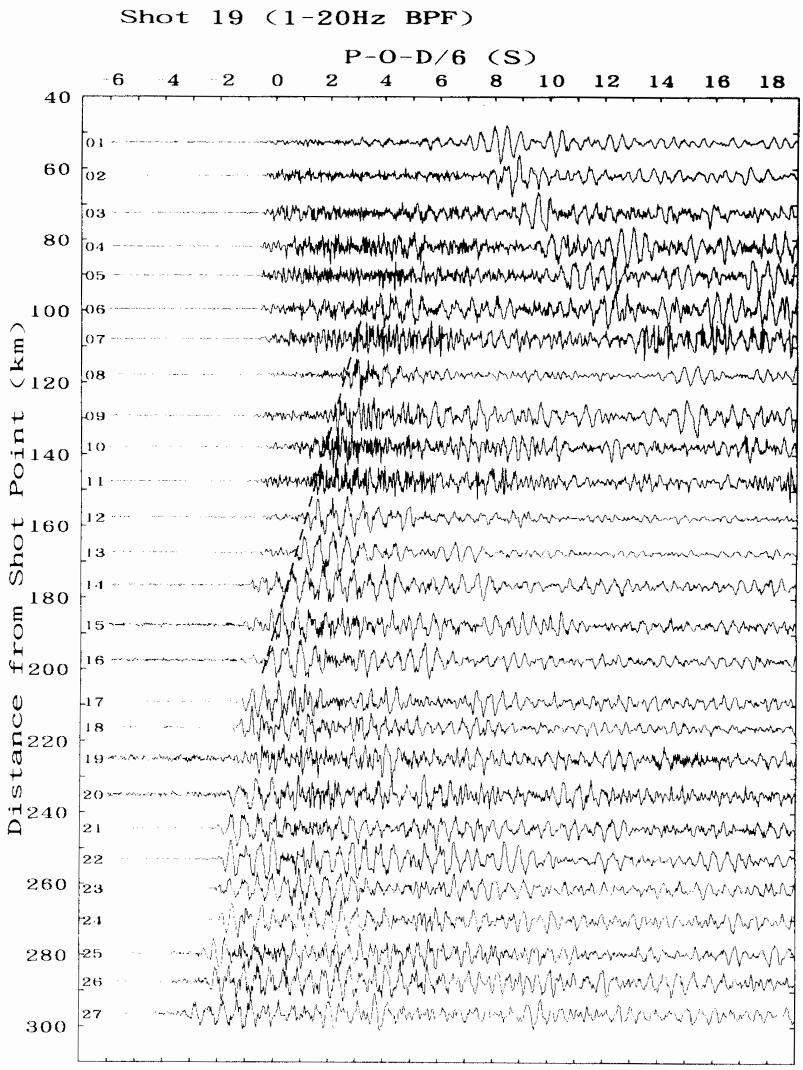

Fig. 2. Original record section of Shot 19 with a reduction velocity of 6 km/s. Clear later phases thought to be reflected waves can be traced at a distance of 100–200 km (after IKAMI *et al., 1984).*

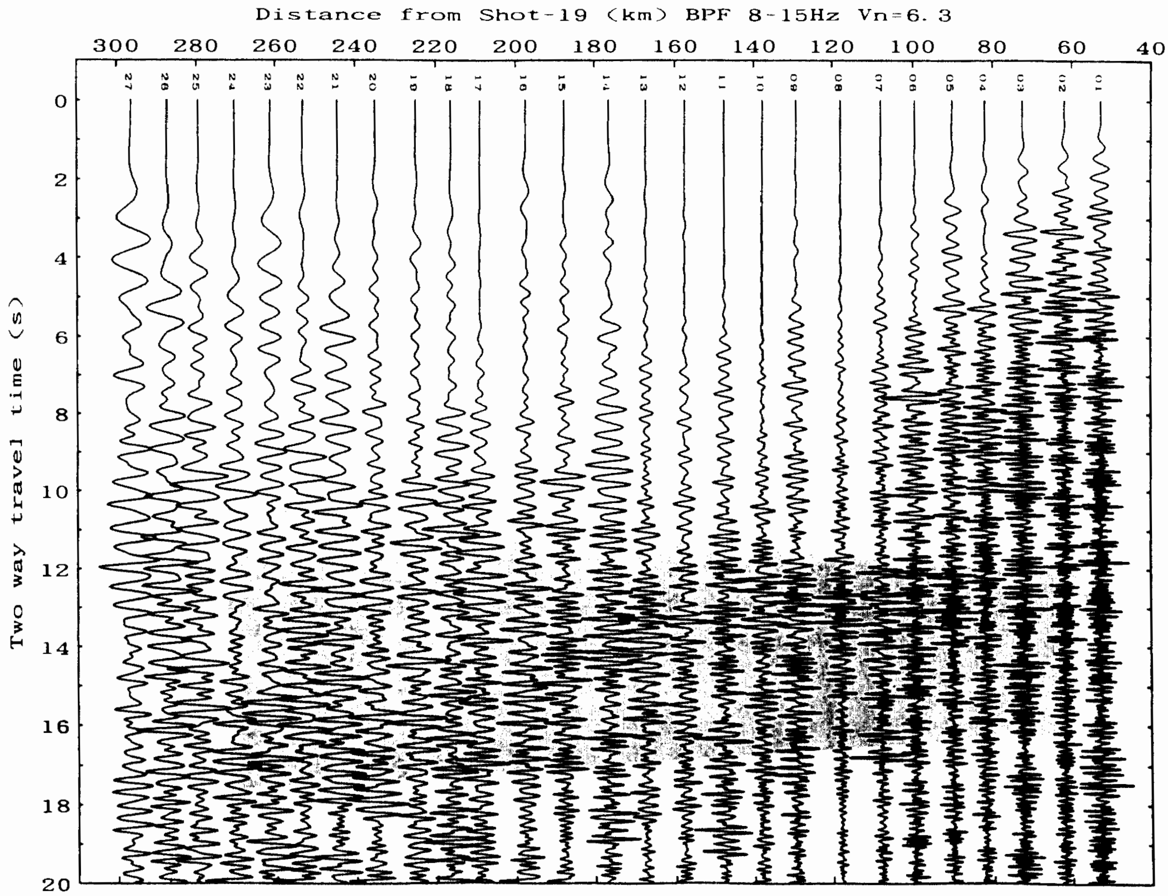

Fig. 3. A reflected record section of Shot 19 with the band-pass filter of 10–20 Hz after normal-moveout correction. There are clear phases of large amplitude in a range of 8–16 s of two-way travel time (TWT). The shadowed area shows the reflective zones corresponding to the lower crust.

These data were processed by filtering and normal-moveout correction to enhance the reflected waves and to reveal the depth range of the reflected waves with large amplitude. In the horizontally layered velocity structure, two-way-travel time, hereafter denoted as TWT (t'), is derived from travel time t as follows:

$$t' = \sqrt{t^2 - (\frac{\Delta}{v})^2}, \qquad (1)$$

where Δ and v are the epicentral distance and velocity of the upper crust, respectively. Normally, a band-pass filter is applied to the original waveform to detect clear reflected waves before normal-moveout correction. An example of a record section after band-pass filtering at 8–15 Hz using a normal-moveout velocity of 6.3 km/s is shown in Fig. 3. Sometimes first break mute and gain recovery corrections are applied to waveform data to suppress the large first wave and to enhance the reflected wave amplitudes. However, these corrections were not used in the analyses since the reflected waves are large enough to be detected in Fig. 3 only after normal-moveout correction. This record section approximately corresponds to the structure about 150 km inland from the coast, where its interpretation will be described in detail in Section 3.

The later phases 10 s behind the TWT for the stations near shot 19 do not have enough quality of signal-to-noise ratios, partly because the experiments were concentrated on detecting the first arrival phases, and partly because the analog recording systems had the dynamic range of only 40 dB. The amplitudes at distant stations from the shot point were over-magnified, where the time span was elongated by normal-moveout correction for an adequate interpretation for the reflection section. Nevertheless, we can detect predominant reflected waves in the distance range of 80–200 km at 8–16 s of TWT. The rough image of the reflected lower crust can be obtained by use of these reflected phases.

3. Results and Discussion

The composite seismograms which were band-pass filtered at 8–15 Hz (Fig. 3) show several interesting features. As a whole, phases of large amplitudes were identified in the range 8 to 17 s of TWT. Clear phases around 12 s of TWT at stations 07 and 08 can be considered as reflected from the top of the lower crust (6.8–6.9 km/s *P*-wave velocity) at about 33 km depth, while those in the range of 8–15 s of TWT at stations 09–15 indicate the existence of the reflective lower crust in the corresponding depth range of 24–30 km.

Since the above large amplitude phases seem to appear within a certain time, the reflective lower crust is limited within a certain depth range. The large amplitudes appear faster, according as those large amplitudes disappear later toward the inland area. Therefore, TWT has larger values in the coastal area than in the inland area and the corresponding reflected layer becomes thicker toward the inland area. A schematic illustration of the assumed depth of reflected layers is shown in the lower part of Fig. 4, together with the *P*-wave velocity model from the refraction experiments along the profile. Typical reflective layering is shown as dashed lines in the figure.

Surface elevation, free-air and Bouguer gravity anomalies along the routes (SHIMIZU *et al.*, 1972; YOSHIDA and YOSHIMURA, 1972; ABE, 1975; KAMIYAMA *et al.*, 1994) are plotted in the upper part of Fig. 4. The downward dipping of the reflected zones along the routes must have a correlation with the variations of Bouguer gravity anomalies. When the lower crustal reflective layer thickens in the inland area, the associated Bouguer gravity anomalies must become low. The thickness variations of the reflective layers are related to the density variation, thus to the gravity variations. The density model along the Mizuho routes was obtained by fitting the calculated Bouguer anomalies with the observed ones (ITO and IKAMI, 1986); the dipping Moho toward the inland area (see dashed lines of the bottom of reflective layers in Fig. 4) was found to be associated with the thinning crustal structure toward the continental margin. The main reason to have lower Bouguer gravity anomalies toward the inland area may come from the dipping Moho rather from the dipping Conrad discontinuity, since the density gap between the lower crust and the uppermost mantle is larger than that between the upper and the lower crust.

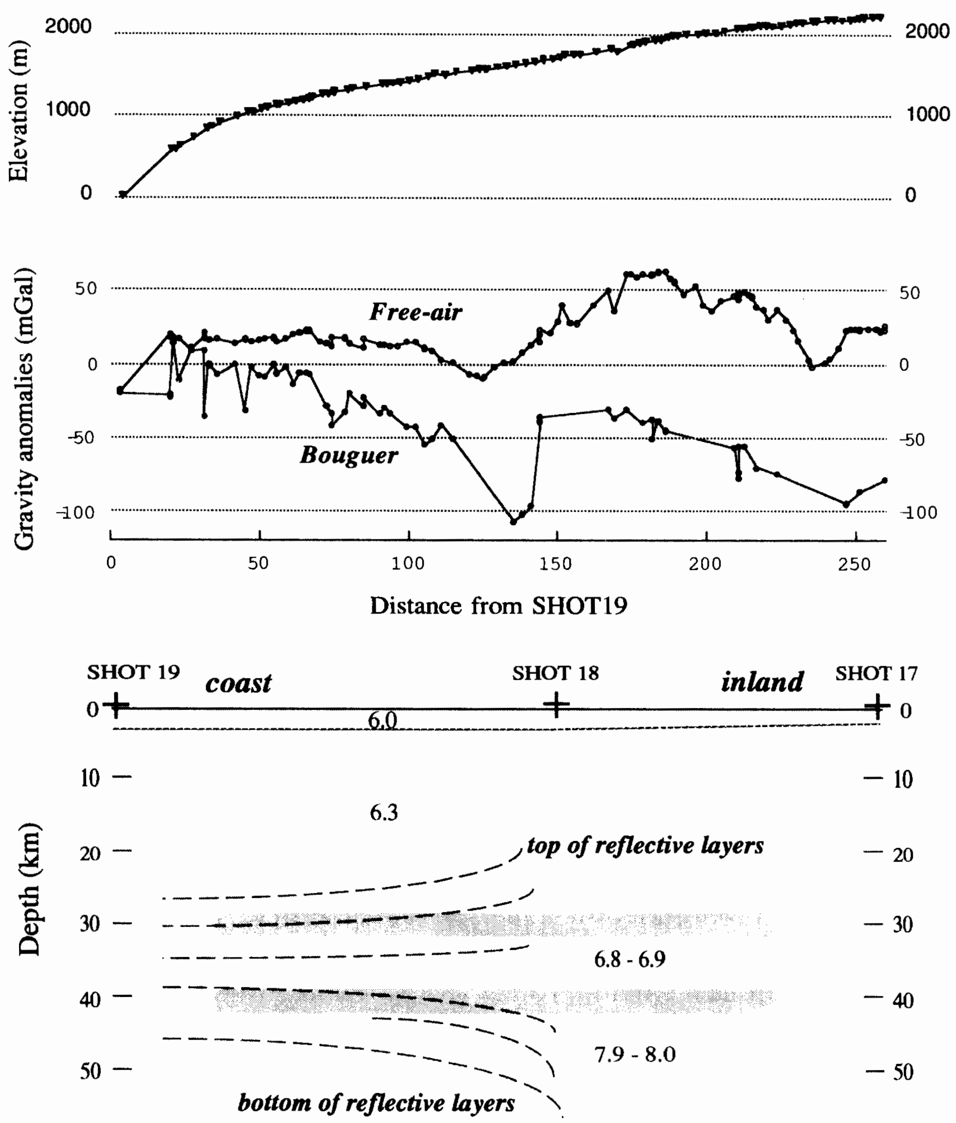

Fig 4. Schematic illustration of the estimated depth of the representative reflected layers (dashed lines in the lower figure) plotted on the P-wave velocity model by the refraction experiments along the Mizuho route. Numerals in layers indicate P-wave velocities in km/s. Surface elevation, free-air and Bouguer gravity anomalies along the routes are after SHIMIZU *et al. (1972),* YOSHIDA *and* YOSHIMURA *(1972),* ABE *(1975) and* KAMIYAMA *et al. (1994).*

An inversely proportional relationship between the depth to the top of the lower crustal reflective layers and the surface heat flow data has been pointed out in different geological terranes (KLEMPERER and the BIRPS GROUP, 1987; Fig. 5). The low heat flow value of 42 mW/m^2 around Syowa Station, Lützow-Holm Complex (POLLACK and CHAPMAN, 1977) is consistent with the thick reflective layers to a depth of 25 km. The evidence of deep reflective layers in relation to the relatively low heat flow suggests that these are has not been in the orogenic stress after the last metamorphism in this region. These deep dipping zones of the reflective lower crust

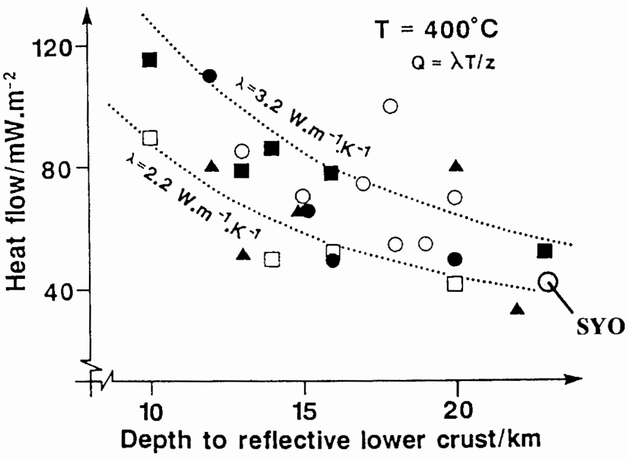

Fig 5. Worldwide compilation of the relationship between the depth to the top of the lower crustal reflective layer and the surface heat flow; with data around Syowa Station (SYO) added to data of KLEMPERER et al. (1987): Solid squares; data from COCORP 40°N Transect, open squares; other North America data, open and solid circles; European data, triangles; Australian data. Curves are isotherms for constant thermal conductivity λ.

indicate that the structures formed during the late-Preterozoic and Paleozoic ages have persisted through time with thermal and tectonic stability.

The reflected waves in the crust of Mizuho Plateau are large enough to be detected without gain-recovery. On the other hand, the shear wave crustal structure derived from the receiver function analyses of teleseismic waveforms recorded at Syowa Station indicates a velocity increase in the uppermost layer of the lower crust in the SE backazimuth near Mizuho routes (KANAO and SHIBUTANI, 1995). Thus, the uppermost layer of the reflective lower crust might correspond to the velocity gap between the middle and the lower crust.

The spacing of observation stations, however, was too sparse to provide a clear image of reflection in the lower crust. Planning of reflection experiments with more dense spacing of shots and observation stations will be necessary in the future to obtain more detailed information on the lower crust in East Antarctica.

4. Conclusions

The reflective lower crust of the Mizuho Plateau, East Antarctica was investigated by re-analyses of seismic refraction data of explosion seismic experiments in 1979-1981. A record section after normal-moveout correction along the 300 km long Mizuho route showed evidence of lower crustal reflectivity. A band-pass filtered (8-15 Hz frequency) record section with a normal-moveout velocity of 6.3 km/s showed clear phases of large amplitude in the range of 8-16 s TWT. These phases can be considered as reflected from the lower crust at depths from 18 to 48 km. The thickness of the reflective layer becomes larger toward the inland area from the Sôya Coast.

The thickness of the reflective lower crust on the Mizuho Plateau has an inverse correlation with the Bouguer gravity anomalies, which in turn are correlated with downward dipping of the Moho discontinuity. The evidence of large depth to the top of the lower crustal reflective layers corresponds to the low surface heat flow attributed to the ancient orogens from the late-Preterozoic to Paleozoic metamorphic ages.

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