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The results of magnetic surveys at Mt. Riiser-Larsen, Amundsen Bay, Enderby Land, East Antarctica, by the 42nd Japanese Antarctic Research Expedition

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Abstract: The summer party of the 42nd Japanese Antarctic Research Expedition (2000-2001) carried out magnetic surveys in the Mt Riiser-Larsen region the Napier Complex, Enderby Land, East Antarctica We found strong magnetic anomalies of magnitude 7000 nT resulting from a metamorphosed banded iron formation (meta-BIF) running in felsic gneiss of the representative formation The geological structure of the strike, fault and dolerite dyke under the moraine, lake and ice sheet are inferred from the lineation and discontinuity of the anomalies The meta-BIF irradiates the strong magnetic field it is useful to clarify the geological structure of the Napier Complex under the Antarctic ice sheet

key words magnetic anomaly, meta-BIF Mt Riiser-Larsen, Antarctica

1. Introduction

The summer party of the 42nd Japanese Antarctic Research Expedition (JARE-42, 2000-2001) conducted geophysical research in the Mt Riiser-Larsen region (66°45 7′S, 50°38 9′E), Amundsen Bay, Enderby Land, East Antarctica This region belonging to the Napier Complex, consists mainly of gneissose rocks characterized by ultrahigh temperature to 1000°C (*e g*, Sheraton *et al*, 1987) and high pressure to 11 kPa (Harley and Hensen, 1990) metamorphism The complex has been known as one of the oldest crusts in the world and has been dated to 3930±10 Ma (Black *et al*, 1986)

The region consists of post-glacial topography as represented by moraine, lakes, and steep ridges and cliffs, as shown in Fig 1 Outcrops of the basement rocks occur within mountain ridges and steep cliffs A geological map published by Ishikawa *et al* (2000) is shown in Fig 1 The continental glacier lies northward from the main ridges of Mt Riiser-Larsen Richardson Lake and an unnamed lake (called East Lake in this paper)

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*Ceased September 11, 2001

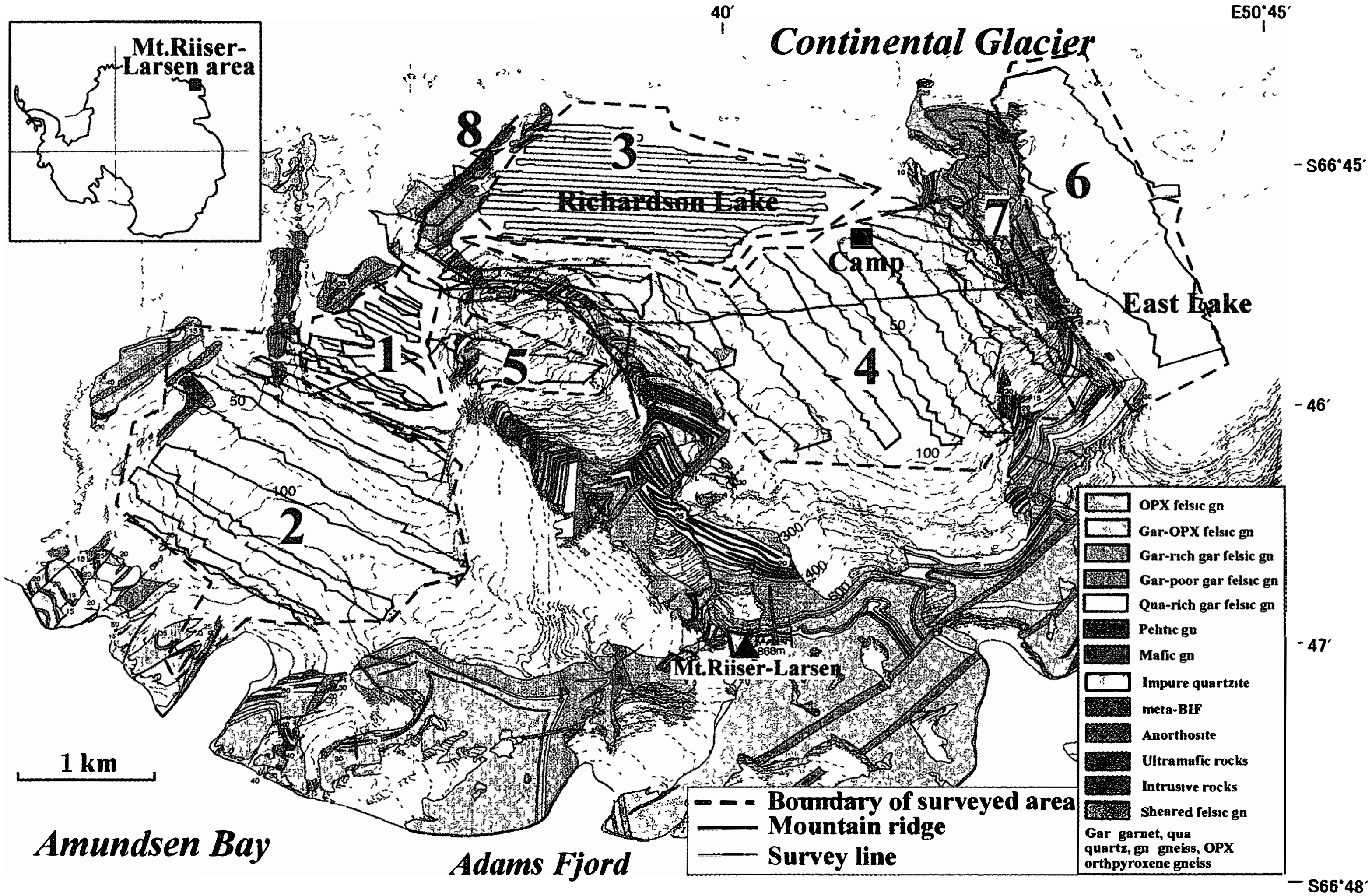

Fig 1 *Topographical and geological map of the Mt Riiser-Larsen region, Amundsen Bay, Enderby Land Magnetic survey areas (1 to 8) and surveyed lines are described in this paper*

lie between the glacier and the main ridge Magnetic surveys were planned to estimate the geological structures under moraine, lake and ice sheet, because magnetite layers have been reported in this region (*e g.*, Ishikawa *et al* , 2000) Mt Riiser-Larsen (686 m) lies not far from the north coastline of Adams Fjord in Amundsen Bay, as shown in Fig 1

2. Geological outline

The Mt Riiser-Larsen region consists of metamorphic rocks and unmetamorphosed dolerite intrusions as summarized by Ishizuka *et al* (1998) and Ishikawa *et al* (2000) The metamorphic rocks are divided into a layered gneiss series, occurring in the central to northwestern part of this region, and a massive gneiss series in the southern to southeastern part of this region (Fig 1) The layered gneiss is characterized by a layering structure composed of garnet pelitic and mafic gneiss, impure quartzite, and metamorphosed banded iron formation (meta-BIF) The massive gneiss consists mainly of massive orthopyroxene felsic gneiss Metamorphic foliation strikes NE-SW to E-W and dips at 20–40° to the south or southeast in this region Dolerite dykes intrude throughout the region striking N-S and NE-SW

Meta-BIF is widespread It is a minor formation in this region, occurring as layers and sometimes blocks within the garnet felsic gneiss and rarely orthopyroxene felsic gneiss The thickness of the meta-BIF layers ranges from several centimeters to several tens of centimeters, but it is rarely more than a few meters However, Funaki *et al* (2001) reported the meta-BIF characterized by the changeable thickness of 1 to 6 layers of meta-BIF within 30 m thick felsic gneiss in the layered gneiss series

Magnetic and mineralogical studies were carried out for meta-BIF in the Mt Riiser-Larsen region (Funaki, 1984, 1988, Funaki *et al* , 2001) The results indicated that the pseudosingle-domain (PSD)/multi-domain (MD) structures of magnetite carry strong natural remanent magnetization (NRM) and susceptibility (χ) Magnetite (Fe_3O_4) and quartz (SiO_2) are the principal components of meta-BIF

3. Magnetic surveys

Magnetic surveys were carried out from Dec 24, 2000 to Feb 2, 2001 in a region 3 km×7 km, as shown in Fig 1, by using the proton magnetometers of G856 (Geometrics Inc , USA), EDA (EDA Instruments Inc , Canada) and PM-53 (Tierra Tecnica Inc , Japan) 2 5 m above the surface The G856 and PM-53 were calibrated at Kakioka Magnetic Observatory, Japan, and that of EDA was performed to refer to the G856 data at the camp The difference of field intensity among the magnetometers was up to 1 0 nT We used the PM-53 for registration of magnetic variation in the camp, and G856 and EDA were employed for the magnetic surveys by walking and sledge All magnetic field data were registered in the magnetometer, but the positions obtained by GPS were recorded in the notebook, the horizontal accuracy of the GPS is 9 m (according to the GPS manual) Consequently, a total of *ca* 5600 data were obtained along a total of about 150 km of profile lines The surveyed region was divided into 8 areas (area-1 to -8) due to difference of the topography and survey methods, as shown in Table 1 and Fig 1 As the lake-ice condition worsened gradually over time, the surveys were planned in the order of area-1 to

Table 1 Characteristics of the magnetic surveys in the respective areas

Area	Location	Topography/surface	Survey method
1	Richardson lake	flat, ice	walk
2	moraine	convex slope	walk
3	Richardson lake	flat, ice	sledge
4	moraine	almost flat, small hills	walk
5	moraine	concave, valley	walk
6	East lake, ice sheet	almost flat, small hills, ice, glacier	walk
7	mountain ridges	mountain ridges, outcrops, moraine	walk
8	mountain ridges and peninsula	mountain ridges, outcrops, moraine	walk

-8 In this order, the surveys and transportation of cargos were safely done on Richardson Lake The continuous magnetic field was measured every minute by the PM-53 2 5 m above the ground at the south corner of the camp When the magnetic field changed rapidly by several nT/minute due to sub-storms etc, we did not use the data measured during those durations The magnetic field in this region has intensity 45079 nT, declination −56 17° and inclination −64 98° calculated from IGRF 2000* (Mandea and Macmillan, 2000) The profile lines were planned in the NW-SE direction in many cases, but the E-W direction was employed in area-3 of Richardson Lake As area-7 and -8 were set on ridges and a peninsula, profile lines were regulated by the topography

3.1 Walking surveys

Magnetic surveys by walking were carried out by one and/or two persons The magnetometer sensor was fixed to an observer's backpack or a load carrier made of aluminum poles The magnetic field data were registered in the magnetometer in manual mode The profile direction was maintained using a small magnetic compass and the distances were measured in paces The magnetic noise resulting from the equipment was estimated to be very small in the range of 1 to 5 nT

Areas-1 and -3 were covered by almost flat frozen lake ice with puddles along the coast In area-2, it was difficult to set parallel and constant interval profile lines because of the convex moraine field topography Area-4 consisted of a gentle depression covered by a moraine overall, but there were small hills in the southern and eastern parts and a brook canyon under steep cliffs in the southeastern part Area-5 was a steep and deep valley covered by moraines Area-6 had only 2 profile lines, because this area was the most dangerous for walking surveys due to many puddles and cracks in the lake and hidden crevasses in the ice sheet

3.2. Sledge surveys

A 4-wheel motorcycle pulling two sledges in tandem by 6 m ropes was employed for the magnetic surveys on Richardson Lake (area-3) An operator rode on the first sledge, made of fiberglass loaded with a magnetometer (G856), GPS system and batteries The magnetometer sensor was set up on an aluminum pole at 2 5 m height on the second sledge

*(IGRF model is based on work by IAGA Working Group V-8, Mioara Mandea, Institute Physique Globe de Paris)

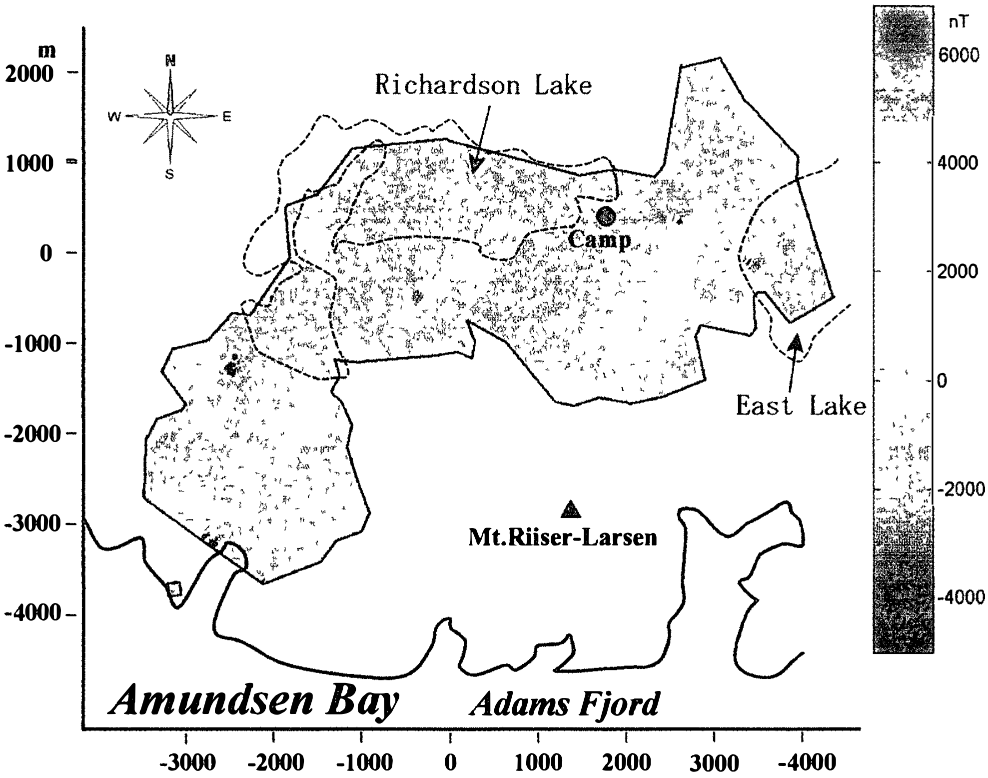

Fig 2 Magnetic anomaly map displayed in the range of −5000 nT to 7000 nT

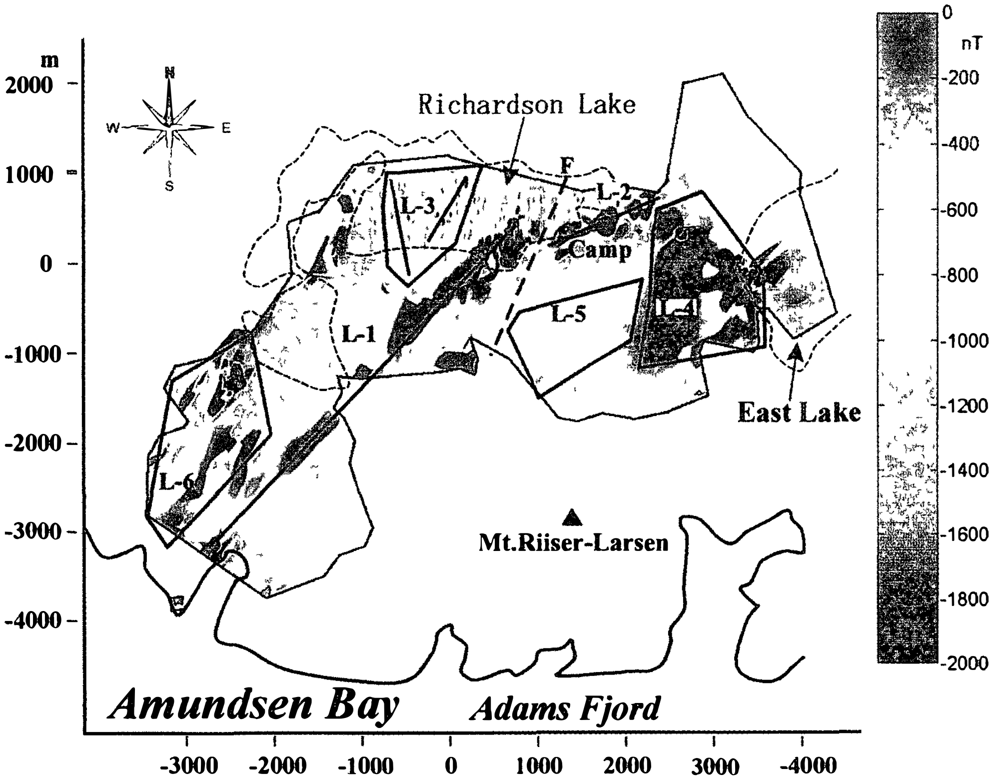

Fig 3 Lineation of the magnetic anomalies or clusters (L-1 to L-6) and surveyed area (area-1-8,) are denoted by solid lines One of the possible faults is denoted by the broken line 'F' Anomaly map in the range of −2000 nT to 0 nT

which was made of wood and plastic The magnetometer and a small chemical heater were wrapped in blankets to absorb shocks and vibrations and for thermal insulation The magnetic noise level resulting from the sledges and motorcycle was less than 10 nT by experimental tests The survey courses were planned in the E-W direction and were monitored by GPS The speed of the motorcycle during measurements was kept by the driver between 8 and 12 km/h The magnetic field was continuously measured every 10 s in automatic mode of the magnetometer Although the low precision mark was printed on the data during the sledge surveys, we adopted these data for analysis of the anomalies, because the mark came on even though the precision improved to 0 1 or 0 5 nT, which is extremely small compared with the observed magnetic field intensity

4. Results

The data measured by the walking surveys included some low grade data, which showed only extremely strong magnetic gradients around the meta-BIF layers So, we did not use these data for analyses of the magnetic anomaly When the prominent magnetic fields were measured at only one site without any relation to that of surrounding data, the data were also discarded Every GPS position was converted to a rectangular coordinate system based on geographic coordinates centered at latitude 66°45 7′S and longitude 50°38 9′E in WGS 84, subsequently the magnetometer sensor position was corrected to that of the GPS antenna (6 m deviation) The magnetic anomaly data were calculated by subtracting the continuous data measured at the base from the surveyed data, and then they were converted to 10×10 m rectangular grid data using finite element structural analysis

Consequently, we obtained an extremely strong magnetic anomaly pattern in this region having a range of −5000 nT to 7000 nT, as shown in Fig 2 The anomalies appeared along several straight lines throughout the region As the weaker anomalies cannot be seen due to low resolution in the wide range shown in Fig 2, a narrower scope, between −2000 and 0 nT, was extracted, it was plotted in Fig 3 A more precise anomaly pattern appears in the moraine fields, Richardson Lake, East Lake and mountain ridges in this figure

5. Discussion

The representative lineation and clusters of small lineations of the magnetic anomalies are denoted by solid lines (L-1 to L-6) in Fig 3 Along lineation L-1, several strong and sharp anomalies are distributed, passing through the moraine fields (area-2, -5 and -4), ridge (area-8) and Richardson Lake (area-3) with the strike N45E The lineation characterized by several discontinuous lines was aligned straight with different anomaly intensities Such structure may reflect the geometry of the source of the magnetic anomaly, discontinuity, variable scale and straight alignment The same strike is shown by L-6, while a short lineation appeared Lineation L-2, having the strike N65E, showed a similar characteristic to L-1 These lineations are parallel to the strike of felsic gneiss, but differ from the strike of the dyke (N-S and NE-SW) The lineations of L-4 and -5 were parallel to the lineation L-2 Namely, there is a discontinuity between L-1 and L-2, suggesting the presence of a fault 'F' with the rough strike N35E, as shown in Fig 3 The lineations L-1 and L-2 were possibly the same layer extending more than 7 km from Adams Fjord to the inland of the continent In the area-3 of Richardson Lake 2 lineations of weak anomaly with the strikes N35E and N15W can be seen The anomaly with the former strike was parallel to the strike of dolerite dykes described in the geological map (Ishikawa *et al*, 2000) We confirmed the other dolerite dyke 20 m thick parallel to the latter strike at the junction between the lineation and the ridge (area-8) Therefore, the sources of these anomalies are concluded to be the dolerite dyke In area-3 there are small and weak anomalies, shown by dots in Fig 3, which seem to be noise caused by vibrations of the magnetometer on the sledge, because these noises only occurred during moving of the sledges

The strike of the metamorphic foliation in this region is NE-SW to E-W, it dips at 20–40° to the south or southeast (Ishizuka *et al*, 1998, Ishikawa *et al*, 2000) These directions are essentially consistent with the magnetic anomalies in this region Meta-BIF is widespread, but it is a minor formation in this region according to the geological map (Ishikawa *et al*, 2000) However, the magnetic anomaly strongly suggests that the magnetic survey is a powerful method to estimate the geological structure under lakes, moraines and ice sheets According to Funaki *et al* (2001), meta-BIF layers are frequently found in this region with thicknesses of 0 5 to 2 m, occasionally 6 m, inferring the source of the magnetic anomaly in this region Meta-BIFs of 1 to 9 layers run in felsic gneisses up to 30 m thick, but the thickness and number of layers varied frequently in this region These appearances seem to resemble the anomaly patterns Meta-BIF consists mainly of magnetite and quartz Large amounts of PSD magnetite grians and MD magnetite grains are included in it, suggesting not only very strong χ but also strong NRM, the average values of 9 samples are reported as the NRM intensity (R)=66 2 (A/m), χ=1 54 (SI) and Q ratio ($R/(\chi \cdot h)$)=1 24 (Funaki *et al*, 2001) In contrast, felsic gneiss should have very low susceptibility and remanence because it includes poor magnetic minerals Namely, a strong magnetic anomaly resulting from the meta-BIF layers is inferred in this region From these viewpoints, we strongly suggest that the lineation of the magnetic anomaly results from the meta-BIF layers included in felsic gneiss, but the weak anomaly of L-3 is due to the dolerite dyke in the Mt Riiser-Larsen region

The depth of Richardson Lake is 53 m but the thickness of the sediment is unknown The peak anomaly appeared to be more than 2000 nT in area-3 and around −700 nT in area-4 If the magnetic properties and the geometry of the meta-BIF layers among areas-2, -3 and -4 are not so different, the thickness of the moraine can be roughly estimated based on the anomaly of Richardson Lake As the anomalies are of almost the same order for area-2 but much weaker for area-4, the thicknesses of moraines may be of the same order and much deeper than the depth of Richardson Lake, assuming shallow sediment in the lake If the lake sediment is much thicker, the moraines of both areas are thickener than the above estimation Since the topographies of area-2 and area-4 can be estimated to be a basin and a dome respectively from Fig 1 the moraine in area-4 may be estimated to be thicker than that in area-2

Golinsky *et al* (1996) summarized the magnetic anomaly measured by aeromagnetic surveys above 2000–4000 m in altitude One of their results was a moderate negative anomaly of about −300 nT above the Mt Riiser-Larsen region, with strong positive anomalies about 1000 nT offshore of the Napier complex This pattern can be seen also in the ADMAP-magnetic anomaly map of the Antarctic (Morris and Frense, 2001) Probably knowledge of the magnetic anomaly resulting from the meta-BIF layers directs us to estimate the source of the magnetic anomalies observed by the aeromagnetic surveys

We introduced the fundamental magnetic anomaly pattern of the Mt Riiser-Larsen region in this paper, although many problems still remain, such as compensation for topographic and depth effects In a more precise study, the relationship among anomalies, NRM, χ, and thickness of the meta-BIF layers must be studied This may contribute to elucidate the precise geological aspects of the oldest crust underlaying moraine, lake and Antarctic ice sheet If we can estimate the scale of meta-BIF layers in the Napier Complex by magnetic surveys, it will contribute to clarify the origin of meta-BIF as Algoma type (small scale of iron deposit compared with Superior type) or Superior type (large amount of iron deposit) which are sedimentary iron ores characterized by Archean and Proterozoic crusts, respectively

6. Conclusions

Magnetic surveys in the Mt Riiser-Larsen region found strong magnetic anomalies to 7000 nT not only on outcrops but also on the moraine field and lakes The anomalies align straight with the strike N45E or N65E, but the lineation is discontinuous with variable intensity of anomalies As the direction of lineation is concordant to the structure of felsic gneiss, the meta-BIF layers sandwiched in felsic gneiss are concluded to be the source of the strong magnetic anomaly A dyke and a fault in Richardson Lake are inferred from the directions of the anomaly and discontinuous lineation The meta-BIF may not be the main formation in this region, but the magnetic surveys are able to estimate geological structures under the Antarctic ice sheet because of irradiation of the strong magnetic field from the meta-BIF layers These magnetic surveys may elucidate more precise geological structures after compensation for the effects of topography, magnetic properties of meta-BIF and depth of the magnetic source

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