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NATURAL REMANENT MAGNETIZATION OF SOME ROCKS FROM SOUTHERN SRI LANKA

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Abstract: The first detailed paleomagnetic studies were performed for the samples from southern Sri Lanka. The stable NRM components were recognized in the Tonigala granite, pink granite, Gallodai dolerite and some gneisses. The reliable NRMs were obtained by the AF demagnetization 30 or 35 mT from the Tonigala granite, pink granite and Gallodai dolerite. The VGP positions were elucidated as the latitude (Lat)=6.1°S, longitude (Lon)=28.0°E, α_{95}=6.2°, Lat=27.1°N, Lon=38.5°E, α_{95}=11.0° and Lat=8.5°N, Lon=152.9°E, α_{95}=6.4° respectively.

Sri Lanka is rotated around a pole position (Lat=5.3°S, Lon=23.8°E, with −100.5° of counterclockwise angle) which was decided by adjusting the VGPs of both Cambro-Ordovician and the latest Jurassic periods from the Tonigala granite, Gallodai dolerite of Sri Lanka and the previous results from East Antarctica. Thus, the location of Sri Lanka is settled in Gondwana in the offing of eastern Queen Maud Land. A model of juxtaposition of Sri Lanka with Lützow-Holm Bay was shown, taking into account the conformity of declinations of Cambro-Ordovician NRMs of the two areas.

1. Introduction

Geological and geochronological knowledge of Sri Lanka has recently been accumulated and the juxtaposition of Sri Lanka with East Antarctica has come to be focused. The general reconstruction model has been proposed that Sri Lanka was situated in Gondwana in the offing of Lützow-Holm Bay connected with the east Gunners Bank in Enderby Land, East Antarctica (*e.g.* COLLERSON and SHERATON, 1986: YOSHIDA *et al.*, 1987). Structural, petrological and metamorphic characteristics are comparable between the Highland Group of Sri Lanka and the granulite facies portion of the Lützow-Holm Complex and between the eastern Vijayan Complex of Sri Lanka and the Yamato Belgica Complex of eastern Queen Maud Land (YOSHIDA *et al.*, 1987). This model is also consistent with the geochronological evidences (*e.g.* GREW and MANTON, 1979).

However, very little paleomagnetic study has been done for Sri Lanka up to now. FUNAKI *et al.* (1990) carried out paleomagnetic reconnaissance of Precambrian and Jurassic rocks of Sri Lanka using the samples collected for geological studies. The results indicated that the dominant NRM directions of the Highland Group form two clusters at inclination (I)=61.2°, declination (D)=260.4°, circle of the 95% probability (α_{95})=5.8° (cluster A) and I=68.7°, D=349.0° and α_{95}=6.9° (cluster B). Many samples of the Vijayan Complex showed relatively low inclinations with an indistinct cluster around the present geomagnetic field direction of Sri Lanka. The Jurassic dolerite dyke rock showed the mean NRM direction of I=24.6°, D=67.5° and α_{95}=24.6° (cluster C), although the number of samples was only 2. The VGP positions obtained from cluster A (latitude (Lat)=2.3°N, longitude (Lon)=34.1°E and cluster C (Lat=24.0°N, Lon=159.5°) are consistent with those of Cambro-Ordovician and Jurassic VGPs from East Antarctica after rotation of Sri Lanka based on the model proposed by BARRON *et al.* (1978). This paper is the first detailed paleomagnetic study of Sri Lanka, supplementing preliminary works, and giving definite data for the location of Sri Lanka in Gondwana.

2. Samples

In the present study, we collected a total of 95 rock samples for paleomagnetic analyses from southern Sri Lanka, as shown in Fig. 1. The rock types are granite (Tonigala granite) and granitic rock from the Tonigala region, dolerite, biotite gneiss and pegmatite from the Gallodai region, granite (pink granite) and migmatite from the Kandy region, charnockite from the Mahiyangana region and gneissose granite and hornblende gneiss from the Ambarangoda region. The samples of the biotite gneiss from Gallodai were collected systematically taking the distance from the dolerite dyke into consideration.

3. Basic Magnetic Properties

Representative 3 samples from each group were selected for the AF demagnetization test up to 50 mT. The stable NRM components were recognized in the Tonigala granite, pink granite and Gallodai dolerite, as shwon in the Zijderveld projection of Fig. 2. The samples of the Tonigala granite had stable NRM components associated with the unstable ones which were demagnetized almost completely up to 30 mT. The Gallodai dolerite had also the stable and unstable NRM components, but the unstable ones were demagnetized almost completely up to 25 mT. Single component of stable one was recognized in the samples of pink granite. The samples of migmatite, gneissose granite, pegmatite and biotite gneiss had both stable and unstable NRM components. Their soft NRM components were demagnetized up to 30 mT. The samples of the hornblende gneiss had either stable or unstable NRM in a same group. However, only unstable NRM was recognized for the charnockite and granitic rock from the Tonigala region. From the results of the Zijderveld analyses, the optimum AF demagnetization field intensities were decided to be set as 30 mT for every group, except 35 mT for the pink granite.

The thermal demagnetization test was carried out in air for the samples having stable NRM components from room temperature to 630°C at intervals of 50°C. The samples were supplied after being AF demagnetized to the optimum field. Unblocking temperatures (TBs) of NRM were observed between 530°C and 580°C for the Tonigala and pink granites, as shown in Fig. 3, although a zigzag behavior of demagnetization

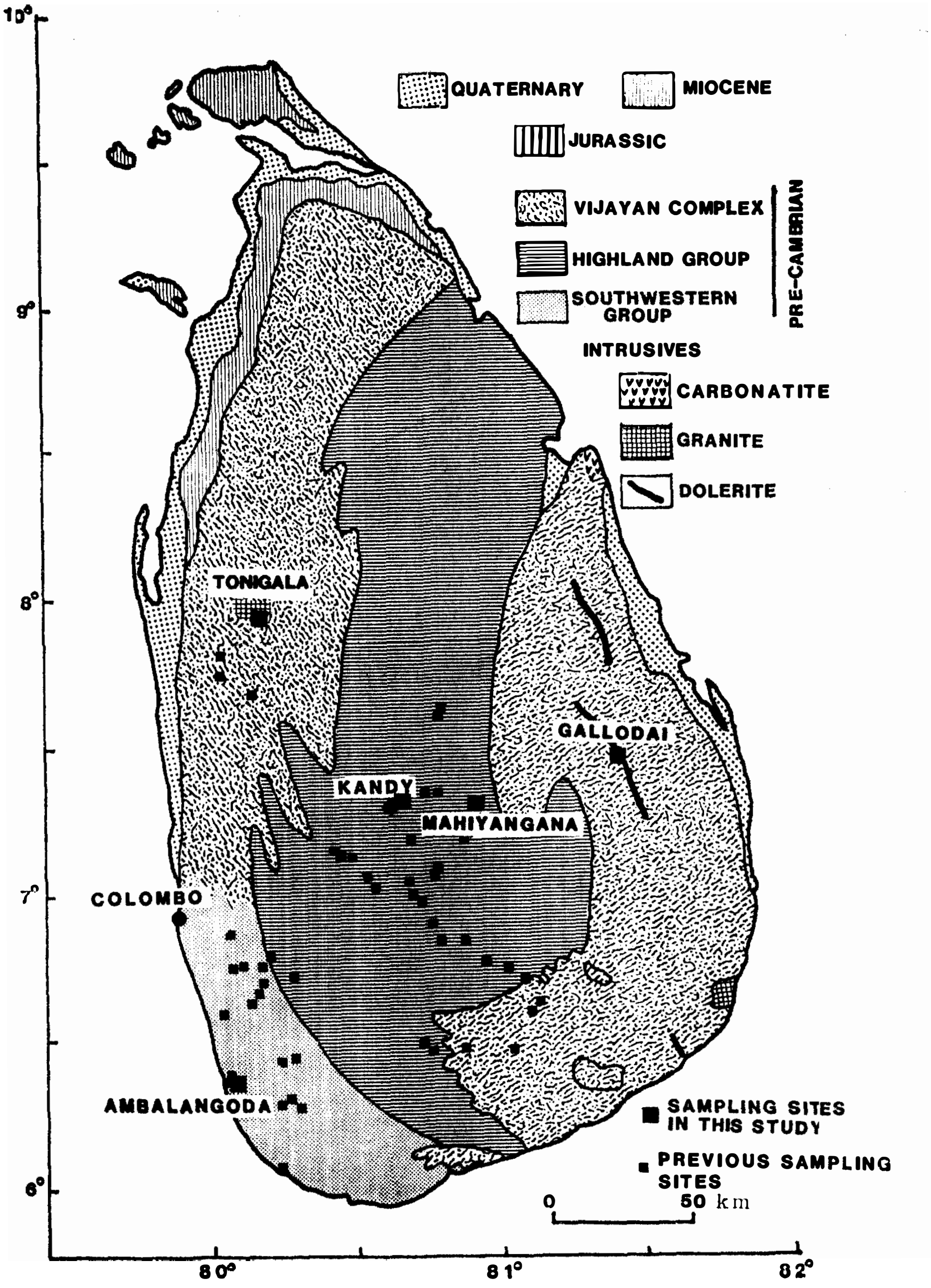

Fig. 1. Sampling sites in the previous and present studies and a geological map of Sri Lanka.

curves was recognized in comparison with the AF demagnetization curves. The unstable magnetization is ascribed to oxidation or reduction of magnetic minerals and breaking off of small parts of the samples during the heating procedure. The NRM of the Gallodai dolerite was demagnetized smoothly up to 530°C with a minor TB at 330°C. It was demagnetized steeply from 530° to 580°C which is the main TB for the Gallodai dolerite, as shown in Fig. 3. These TBs are only the hard NRM component, because the samples were already AF demagnetized to 30 or 35 mT. Significant directional changes of NRM were not obsreved in this thermal demagnetization. The TBs of

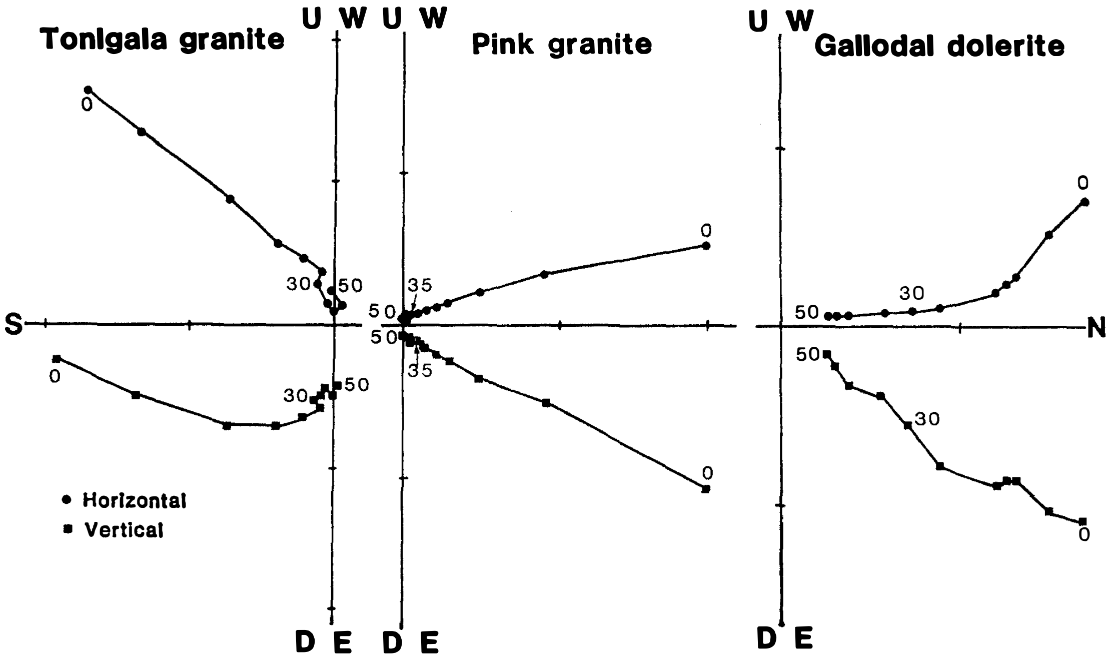

Fig. 2. AF demagnetization curves by the Zijderveld projection. U: up, D: down, N: north, S: south, E: east and W: west.

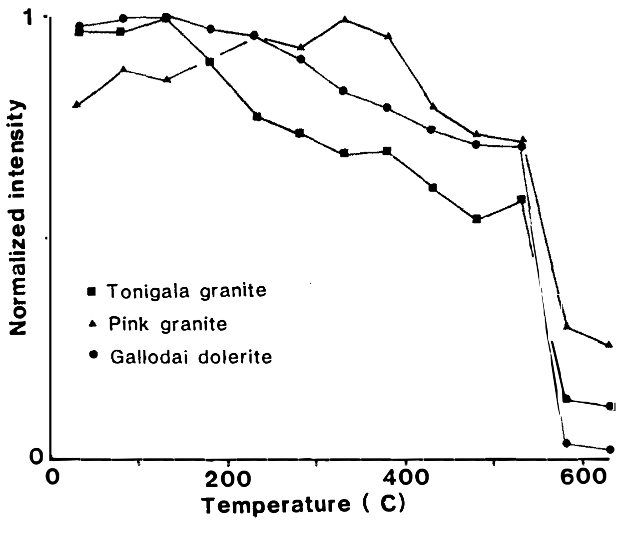

Fig. 3. Normalized intensity change curves against thermal demagnetization.

NRM for the gneisses and migmatites are distributed between 330° to 580°C, although they occasionally show different temperature in a same group.

Thermomagnetic (*Js-T*) curves of the 1st and the 2nd run cycles in Fig. 4 were obtained for the samples of the Tonigala granite, pink granite and Gallodai dolerite from the room temperature to 650°C by a magnetic balance under 0.4 T external magnetic field in 10^{-2} Pa atmosphere. The *Js-T* curves of the Tonigala granite were completely reversible with the Curie ponit at 580°C indicating the single phase of almost pure magnetite. By the microscopic observation, magnetite grains smaller than 200 μm in diameter were observed in the sample. The *Js-T* curves of the pink granite were ir-

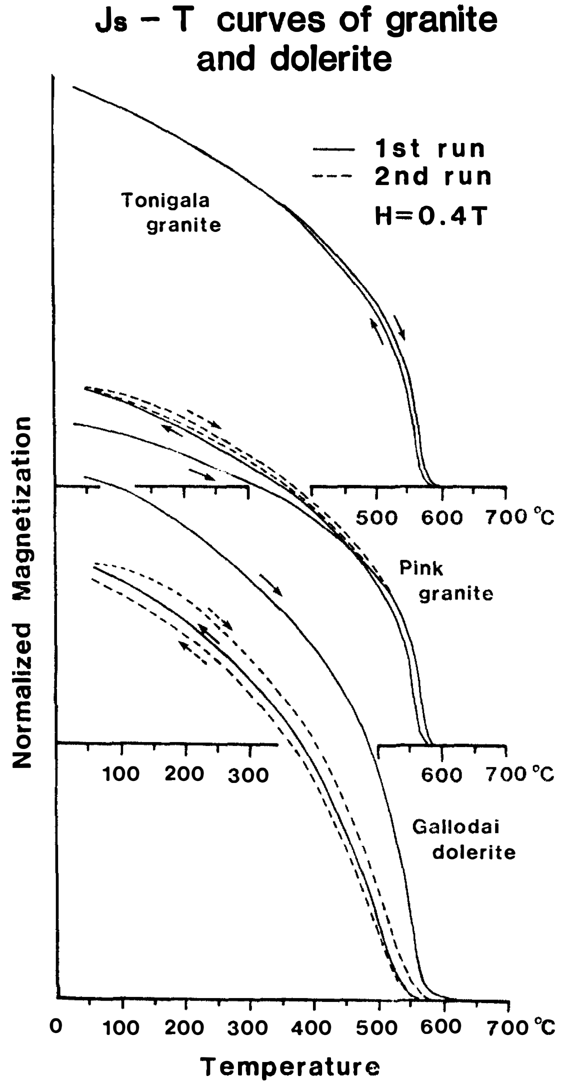

Fig. 4. Thermomagnetic curves of the 1st and 2nd run cycles for granite and dolerite.

reversible in the 1st run cycle; the magnetization increased after the cooling maintaining the same Curie point. This phenomenon suggests that a small amount of magnetite was produced by the heaitng. In this sample, magnetite grains smaller than 250 μm in diameter with ilmenite exolutions were observed under the microscope. A very small amount of hematite was observed along the grain boundary and cracks of the magnetite grains. The increased magnetization after the 1st run cycle is considered to be caused by the reduction of this hematite. Samples of the Gallodai dolerite showed irreversible *Js-T* curves having the Curie point at 575°C in the 1st run cycle. After the cycle the magnetization decreased about 83% compared with the original one. The 2nd run is reversible and consistent with the 1st run cooling curve, maintaining the same Curie point. Microscopic observations indicated that the magnetic grains smaller that 100 μm in diameter were heavily oxidized; maghemite and/or titanomaghemite veins spread into the magnetite grains.

4. NRM Direction

Every sample having stable NRM components was AF demagnetized at 3 steps with the respective optimum field and with both 5 mT lower and 5 mT higher than that field. When α_{95} showed the minimum value, mean NRM directions were adopted for representative NRM directions of their group. Reasonably good clusters were obtained from the Tonigala granite, pink granite and Gallodai dolerite. The mean NRM intensity (R), *I*, *D*, precision (K) and α_{95} are listed in Table 1 and NRM directions

Table 1. Paleomagnetic results of Sri Lanka and some previous results for East Antarctica.

No.	Site	Demag	N	*I*	*D*	K	α_{95}	Lat	Lon	Lat*	Lon*
1	Tonigala	0	13	31.6	230.3	10	18.5				
	granite	30		55.5	275.2	45	6.2	6.1°S	28.0°E	10.7°S	21.6°E
2	Pink	0	13	40.9	358.9	3	33.5				
	granite	35		63.8	301.9	15	11.0	27.1°N	28.5°E	23.2°S	55.5°E
3	Gallodai	0	17	31.2	74.7	7	14.5				
	dolerite	30		33.6	88.3	32	6.4	8.5°N	152.9°E	54.2°S	152.0°W
4	Ongul Islands	10	80	59.1	336.8	14	4.5	20.2°S	20.7°E		
5	Wright Valley	15	26	−69.4	237.6	137	2.4	45.3°S	112.0°W		

Demag: AF demagnetization field, N: number of samples, *I*(*D*): inclination (declination) of the mean NRM, K: precision parameter, α_{95}: confidence of 95% probability, Lat (Lon): latitude (longitude) of VGP, *: VGP position after rotation of Sri Lanka with respect to East Antarctica.

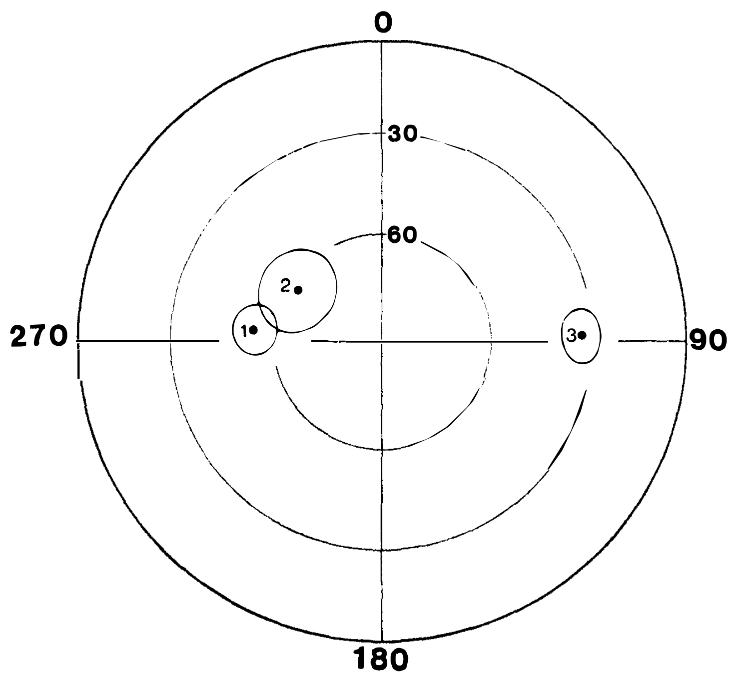

Fig. 5. Mean NRM directions after AF demagnetization at 30 or 35 mT and their α_{95} varlues for the Tonigala granite (1), pink granite (2) and Gallodai dolerite (3). Equal-area projection.

with α_{95} values are illustrated in Fig. 5. The NRM directions of the hornblende gneiss and the gneissose granite from Ambarangoda clustered unclearly around the present geomagnetic field direction of Sri Lanka. Probably the NRMs result mainly from the viscous remanent magnetization (VRM). The biotite gneiss and pegmatite from Gallodai within 10 m from the contact of the dolertie dyke showed almost parallel NRM directions to those of the dolerite dyke. It may suggest that the NRM directions of the country rocks were remagnetized by the heating of the dyke intrusion. However, the NRM directions of the migmatite from Kandy scatter widely throughout the both hemispheres, although individual samples have stable NRM components.

5. Discussion

The Tonigala granite has almost pure magnetite grains estimated from the *Js-T* curves and microscopic observations. Since its NRM is very stable against AF and thermal demagnetizations, the NRM is reliable paleomagnetically. The NRM of the pink granite is also stable, but the magnetite grains are partly oxidized to hematite. The hematite might have been produced by the recent weathering judging from its mode of formation. As the amount of the hematite is very small compared with magnetite, the original NRM may not be so disturbed by the hematite magnetization. On the other hand, a part of the NRM of the Gallodai dolerite is carried by the maghemite and/or titanomaghemite, associated with the magnetization resulting from magnetite. The biotite gneiss near the dolerite dyke is remagnetized evidently during the dolerite intrusion, showing the gradual change of NRM directions toward that of the Gallodai dolerite. It indicates that the NRM direction of the Gallodai dolerite was not disturbed by the formation of the maghemite and/or titanomaghemite. From these estimations, the NRMs of the Tonigala granite, pink granite and Gallodai dolerite are considered to be reliable.

Geochronological ages have been obtained from the Tonigala granite, for instance 986 ± 28 Ma of Rb/Sr whole rock isochron age (CRAWFORD and OLIVER, 1969) and 558 ± 14 Ma of U/Pb zircon age (HÖLZL and KÖHLER, 1989). These ages may indicate the times of the intrusion in middle Proterozoic and the metamorphism in Cambrian respectively. A Cambrian age (580 ± 7 Ma; U/Pb in zircon) has been reported from a pink granite around Kandy (HÖLZL and KÖHLER, 1989). Many data from 520 to 450 Ma (late Cambrian to middle Ordovician) of Rb/Sr ages have been reported from various Precambrian rocks throughout Sri Lanka. Since the age determined by the U/Pb method shows the older age than that by the Rb/Sr one generally, it can be understood that the Precambrian rocks of Sri Lanka were metamorphosed widely sometime during late Cambrian to middle Ordovician and that these rocks might have been magnetized or remagnetized at that time.

The NRM directions of the Tonigala and pink granites are consistent with each other taking their α_{95} values into consideration as shown in Fig. 5. In the paleomagnetic reconnaissance of Sri Lanka (FUNAKI *et al.*, 1990), the NRM directions of many granites and gneisses (cluster A) showed roughly the same directions as these granites of the present study. Therefore, it seems that they acquired NRM at almost the same time. The age of the Tonigala granite (HÖLZL and KÖHLER, 1989) was determined directly using the samples from the same outcrop where we collected samples for the present study. However, sampling localities of the pink granites were different between ours and HÖLZL and KÖHLER's. From the problem of age of the pink granite, the paleomagnetic data of the Tonigala granite are adopted for the representative data of the late Cambrian to middle Ordovician of Sri Lanka in this study.

Age of the Gallodai dolerite was reported as 152.6 ± 7.6 and 143.3 ± 7.2 Ma of the whole rock K/Ar age by YOSHIDA *et al.* (1989). It indicated that the dolerite was magnetized during the latest Jurassic or the earliest Cretaceous. The NRM direction $I=33.6°$, $D=88.3°$ and $\alpha_{95}=6.4°$ obtained in the present study is essentially consistent with the previous result on the Gallodai dolerite ($I=24.6°$, $D=67.5°$ and $\alpha_{95}=21.7°$) by FUNAKI *et al.* (1990).

FUNAKI and WASILEWSKI (1986) reported a VGP position of the hornblende gneiss, amphibolite and granite from Ongul Islands in Lützow-Holm Bay as Lat=20.2°S, Lon =20.7°E and $\alpha_{95}=4.5°$. These rocks were estimated to be remagnetized or intruded during Cambro-Ordovician. On the other hand, many Jurassic VGP positions have been reported from the Ferrar dolerite of the Transantarctic Mountains. One of them is Lat=45.3°S, Lon=152.0°W and $\alpha_{95}=2.4°$ for the Wright Valley (FUNAKI, 1983). Sri Lanka has been estimated to be a Gondwana fragment connected with Lützow-Holm Bay (*e.g.* BARRON *et al.*, 1978). Therefore, the juxtaposition of Sri Lanka with Lützow-Holm Bay is tested in the following, using the Cambrian to Ordovician VGP positions from the Tonigala granite and Ongul Islands, and Jurassic ones from the Gallodai dolerite and the Ferrar dolerite.

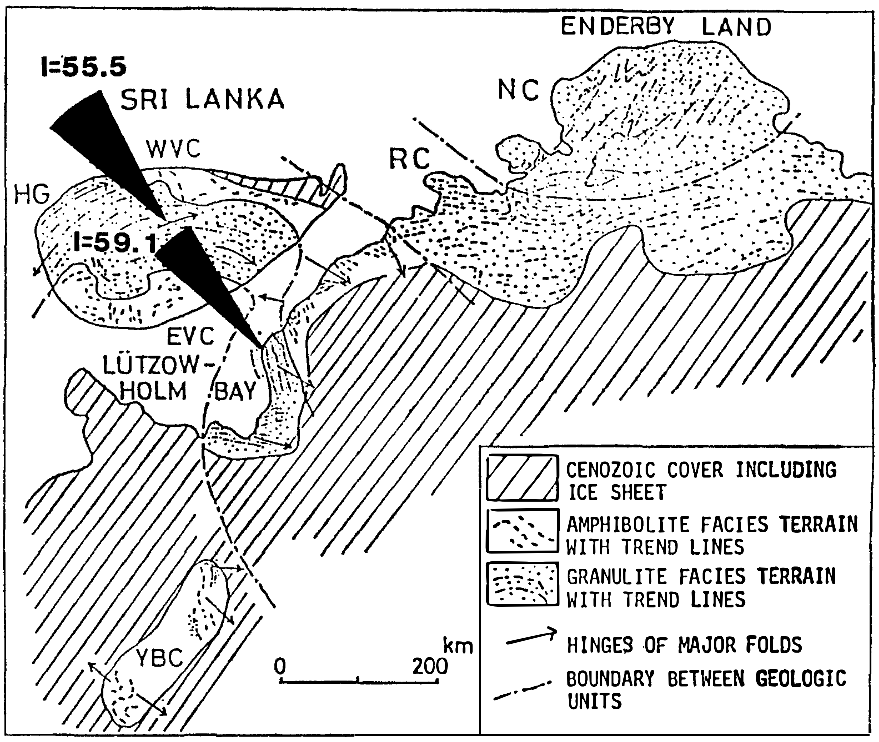

Fig. 6. Reconstruction of Sri Lanka and Lützow-Holm Bay by adjusting the declination of the Tonigala granite and the previous result of Ongul Island. Source of the geological relationships by YOSHIDA *et al. (1987).*

The VGP positions calculated from the Tonigala granite and the Gallodai dolerite were rotated with respect to East Antarctica referring to the rotation point Lat = 5.3°S, Lon = 23.8°E and an angle (ω) = − 100.5° (counterclockwise). The rotation point and ω were determined by fitting VGPs of the Tonigala granite and Ongul Islands and those of the Gallodai dolerite and the Ferrar dolerite. The latitude and longitude of the VGPs after the rotation are listed in Table 1. When Sri Lanka is rotated in this way, it is situated in the offing of eastern Queen Maud Land. This result supports the hypothesis that Sri Lanka was connected to the east Gunners Bank in Lützow-Holm Bay taking their α_{95} value into consideration. Figure 6 shows a plausible reconstruction model of Lützow-Holm Bay and Sri Lanka based on the declination of NRM and its 95% probability (δ_{95}) for the Tonigala granite and the result of Ongul Islands; Sri Lanka is rotated to Lützow-Holm Bay adjusting the declination of the Tonigala granite to that of Ongul Islands. The NRM inclinations of the Tonigala granite and Ongul Islands are consistent with each other, being $I = 56.8°$ ($\delta_{95} = 11.0°$) and $I = 59.1°$ ($\delta_{95} = 8.8°$) respectively, suggesting a higher possibility of this reconstruction model. This model has no discrepancy with the recent reconstruction models of YOSHIDA *et al.* (1987), which took geology, geochronology and 2000 m isobath into account.

6. Conclusion

The Tonigala granite and pink granite have stable NRMs carried by magnetite, and the stable NRMs are considered to have been magnetized during the latest Cambrian to middle Ordovician. The Gallodai dolerite was magnetized during late Jurassic to the earliest Cretaceous, although magnetic minerals (low titanium titanomagnetite) are partially oxidized. These results are consistent with our previous preliminary paleomagnetic study for Sri Lanka. The biotite gneiss near the Gallodai dolerite was remagnetized by the dolerite intrusion during the latest Jurassic to the earliest Cretaceous. However, other gneiss, migmatite and pegmatite do not make a significant cluster of NRM directions.

To obtain the location of Sri Lanka in the Gondwana reconstruction, Sri Lanka was rotated with regard to Antarctica referring VGPs of the Tonigala granite, Gallodai dolerite, Ongul Islands and the Ferrar dolerite. Consequently. Sri Lanka is situated in the offing of eastern Queen Maud Land including Lützow-Holm Bay. It is possible to obtain the most reliable reconstruction of Sri Lanka and Lützow-Holm Bay when the NRM directions are taken into consideration.

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