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PALEOMAGNETIC STUDY OF RAJMAHAL TRAP IN INDIA —DISCUSSION OF GEOMAGNETIC DIPOLE MOMENT AND RECONSTRUCTION OF GONDWANALAND—

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Abstract: A paleomagnetic study was conducted on the Rajmahal trap in northeastern India. The age of the trap was determined by $^{40}Ar/^{39}Ar$ dating as 125 to 130 Ma (H. SAKAI *et al.*, J. Geol. Soc. Jpn., **103**, 192, 1997). The VGP (vitual geomagnetic pole) of the Rajmahal trap was studied and compared with the APWP (apparent polar wander path) of India (J.E. BESSE and V. COURTILLOT, J. Geophys, Res., **96**, 4029, 1991). The VGP is situated slightly apart from the position of 120Ma in Indian APWP, which suggests that the Rajmahal trap is older than 120 Ma. That is, paleomagnetic study supports the $^{40}Ar/^{39}Ar$ age of 125–130 Ma. This result suggests that the Rajmahal trap was formed around the age of rifting of India from Antarctica.

Thelliers' paleointensity experiment was applied to the Rajmahal basalt and the paleointensity of $31.4 \pm 5.8\ \mu T$ was determined. The geomagnetic dipole moment in Mesozoic was summarized using formerly reported paleointensities and data in this study. We can identify that the dipole moment from 180 Ma to 125 Ma before the period of Cretaceous quiet zone, oscillates between 30% and 70% of the present moment.

key words: Rajmahal trap, VGP, APWP of India, paleointensity, Cretaceous quiet zone

1. Introduction

The breakup history between India and Antarctica related to Gondwanaland has not been elucidated clearly. Recently, several studies such as BESSE and COURTILLOT (1991), STOREY (1995) proposed that the rifting of India is connected with the extensive magmatism on the Kerguelen Plateau. The Rajmahal trap in northeastern India is suggested to have been formed with this Kerguelen hotspot. The age of the trap has been estimated as 100 to 114 Ma (K-Ar age; MACDOUGALL and MCELHINNY, 1970) and recently the $^{40}Ar/^{39}Ar$ age of 110–117 Ma was studied by BAKSI (1995).

SAKAI *et al.* (1997) did a paleomagnetic study with $^{40}Ar/^{39}Ar$ dating of the Rajmahal trap. They reported the $^{40}Ar/^{39}Ar$ age of 125 to 130 Ma (details are now in preparation by TAKIGAMI *et al.*). The VGP of Rajmahal trap showed the concordant data with the $^{40}Ar/^{39}Ar$ age. This means that the Rajmahal trap was formed around the time of the breakup between India and Antarctica.

In this study, the paleointensity (geomagnetic field intensity) is examined using the Rajmahal trap. The paleointensity in the Mesozoic, in particular in the mid-Cretaceous, has recently become an important subject in relation to the Cretaceous magnetic quiet zone (CQZ). The CQZ, a period of long normal polarity with less polarity reversal, began around 125 Ma. Paleointensity study of the Rajmahal trap is important for the discussion of the geomagnetic dipole moment and core activity around the period of the CQZ.

We will give a brief summary of paleomagnetic direction (SAKAI *et al.*, 1997), then discuss paleointensity data from the Rajmahal trap.

2. Materials and Methods

Samples were collected from the basaltic rock of the Rajmahal trap in the northeast of India (Fig. 1). The volcanic activity of the Rajmahal trap in the studied area is divided into three stages (1st, 2nd, 3rd), which were studied by the Geological Survey of India. The sampling was done at five sites from three stages (Table 1). Paleomagnetic samples were mainly collected as oriented cores using gasoline powered drills. At each site, 11 to 23 cores were obtained. Several block samples with orientation were also collected at the same site, which were drilled into core samples at the laboratory. One or two core specimens were prepared from each core sample, and were used in magnetic measurement.

Reliability of the remanent magnetization was studied by demagnetization experi-

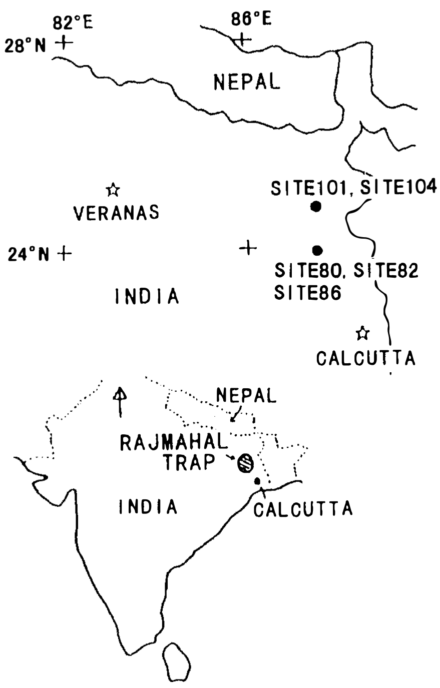


Fig. 1. Sampling location at Rajmahal trap. Solid circles show the sampling locarity.

ments (alternating magnetic field: AF and thermal treatment). Also, thermomagnetic analysis and magnetic hysteresis analysis were studied. Thermomagnetic analysis was made by VSM (vibration sampling magnetometer, BHV-50) of the National Institute of Polar Research. Magnetic hysteresis parameters were measured by the MPMS (Magnetic Property Measurement System, Quantum Design) of Toyama University.

Paleointensity was studied by Thelliers' method (THELLIER and THELLIER, 1959). The heating experiment was done in an atmosphere of nitrogen to avoid the alteration of magnetic minerals during the heating.

Remanent magnetization was measured by a spinner magnetometer (Natsuhara SMM-85) and cryogenic magnetometer (CCL-GM401, ScT-C110).

3. Thermomagnetic Analysis and Domain Structure Study by Magnetic Hysteresis Measurement

Thermomagnetic analysis was applied to the four samples (Fig. 2). A heating experiment was done at 10^{-4} Pa and a magnetic field of 1T was used. The reversible curve was obtained between heating and cooling cycles from each sample. Microscopic study shows that the titanomagnetite in the sample is consistent with distribution of Curie temperature shown by the thermomagnetic curve. The reversible thermomagnetic curve indicates that the effect of low temperature oxidization is slight in the studied samples.

The magnetic domain structure of four samples from each site was investigated by

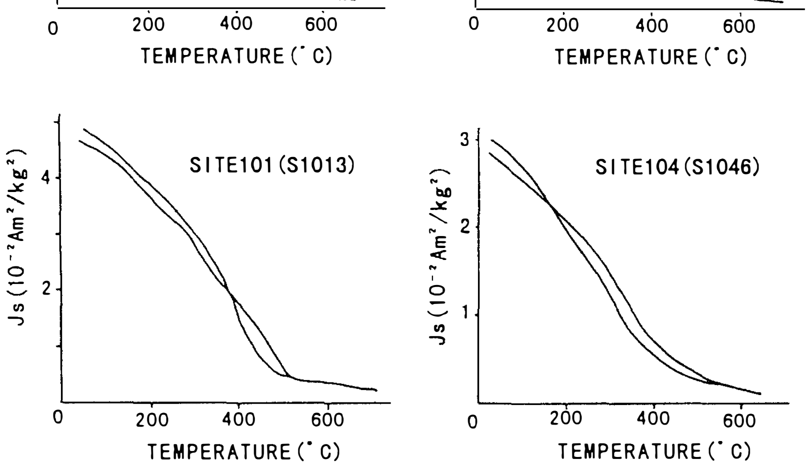


Fig. 2. Thermomagnetic curve of the four samples from Rajmahal trap.

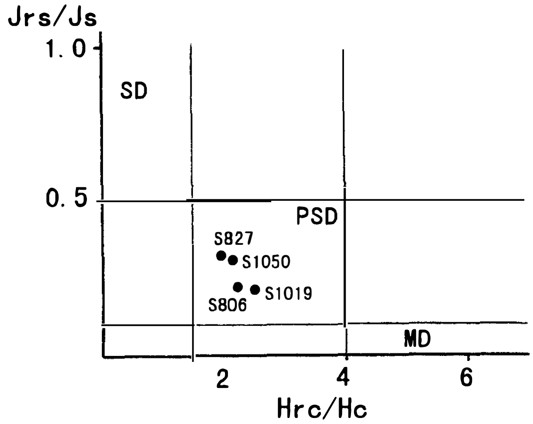


Fig. 3. Hysteresis parameter and the domain structure (DAY et al., 1977). Js: saturation magnetization, Jr: saturation remanence, Hc: coercive force, Hrc: remanent coercivity, SD: single domain, PSD: pseudo-single domain, MD: multi domain.

the method of DAY *et al.* (1977). This method uses the magnetic hysteresis parameters and is applicapable to the titanomagnetite grains. MPMS was applied to measure the hysteresis parameters of *Js* (saturation magnetization), *Jr* (saturation remanence), *Hc* (coercive force) and *Hrc* (remanent coercivity). Then, the parameter *Jrs*/*Js* and *Hrc*/*Hc* of each sample were plotted on the diagram (Fig. 3) and the domain structure was examined. The result indicates that the magnetic grains of studied samples have the pseudo-single domain structure. Generally, the sample of pseudo-single domain magnetic grain is appropriate in Thelliers' experiment.

4. Paleomagnetic Direction Study

4.1. Paleomagnetic direction of Rajmahal trap

A stepwise demagnetization experiment was made on the pilot specimens to examine the characteristic magnetization for each site. AF demagnetization was applied to four pilot specimens, and thermal demagnetization was done on another four specimens for each site. The stability of magnetization was examined by the Zijderveld diagram (ZIJDERVELD, 1967). In most of the specimens except for those of site 86, the unstable magnetization component was eliminated by demagnetization level at 150°C and/or 10 mT and the characteristic magnetization was elucidated. The samples of site 86 showed the complicated magnetization in Zijderveld diagram.

After the stepwise demagnetization experiment on pilot specimens, other specimens were subjected to demagnetization in the following several steps. For sites 80, 82, 86 and 101, the AF demagnetizations at 15, 20, 25 and 30 mT were carried out. For site 104, thermal demagnetizations at 250°C, 300°C and 350°C were applied. Then, the site-mean direction and radius of circle of confidence (α_{95}; FISHER, 1953) were calculated for the data set of each demagnetization level. And the site-mean direction with minimum α_{95} was selected as the paleomagnetic direction for each site. Table 1 shows the site-

Table 1. Paleomagnetic direction data of Rajmahal trap.

Site	Stage	No. of samples	Demag	Inc(°)	Dec(°)	α_{95}(°)	Int(Am^2/kg)
80	3rd	25	25 mT	–63.6	294.5	2.2	2.4×10^{-3}
82	2nd	27	20 mT	–65.0	319.5	1.6	8.7×10^{-4}
86	1st	13	200°C	–53.7	342.3	12.6	3.8×10^{-4}
101	1st	17	20 mT	–63.5	288.0	2.3	2.1×10^{-3}
104	2nd	11	300°C	–64.8	301.4	3.1	1.3×10^{-3}
	(Average of four sites)			–64.7	300.5	6.7	
				–65	316	3	PIPER (1990)
	(Average of five data sets)			–65	304	6	

VGP N-pole (PLat; 3°N, PLong; 303°)
VGP S-pole (PLat; 66°S, PLong; 191°): after rotation by the model of SMITH and HALLAM (1970).

Site: sampling site, stage: stage of volcanic activity (1st, 2nd, 3rd), Demag: demagnetization level where the site-mean magnetization is calculated, Inc(°): mean inclination, Dec(°): mean declination, α_{95}(°): radius of circle of confidence, Int (Am^2/kg): mean intensity of remanent magnetization, PLat: paleolatitude, PLong: paleolongitude.

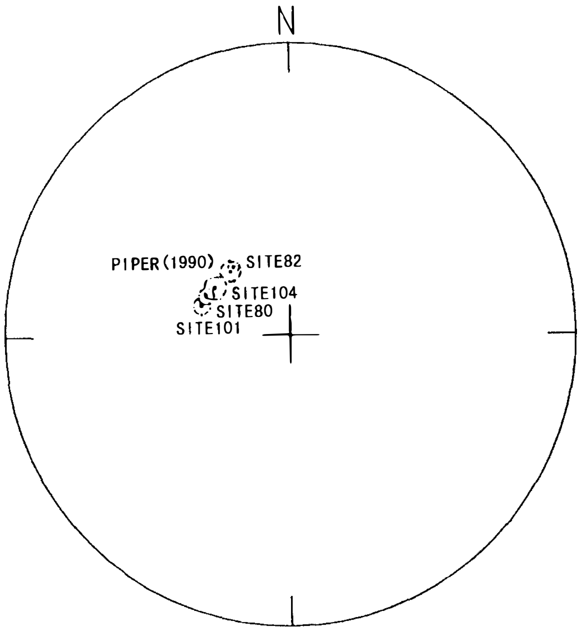


Fig. 4. Site-mean paleomagnetic directions of four sites and the direction of Rajmahal trap summarized by PIPER (1990).

mean direction data (SAKAI *et al.*, 1997). As we cannot obtain the reliable magnetic component from site 86, this site is not used for the discussion.

In Fig. 4, site-mean paleomagnetic directions of four sites (sites 80, 82, 101 and 104) are shown. The data of PIPER (1990) who summarized the formerly reported paleomagnetic data for Rajmahal (KLOOTWIJK, 1971; etc.) are also shown. We can identify the concordant directions in the westward declination with inclination of about –65°. Mean direction of Rajmahal trap is calculated as declination of 304° and inclination of –65°, which corresponds to the VGP of paleolongitude of 303° and paleolatitude of 3°N.

4.2. VGP of Rajmahal trap and APWP of India

BESSE and COURTILLOT (1991) obtained the APWP of India from 120 Ma to the present by analysis of the magnetic lineation of the Indian Ocean. In Fig. 5, the VGP of the Rajmahal trap in Table 1 is compared with the Indian APWP. The VGP of Rajmahal trap is situated slightly apart from the position of 120 Ma in the Indian APWP, which suggests that the age of the Rajmahal trap is older than 120 Ma and supports the $^{40}Ar/^{39}Ar$ age of 125 to 130 Ma (SAKAI *et al.*, 1997).

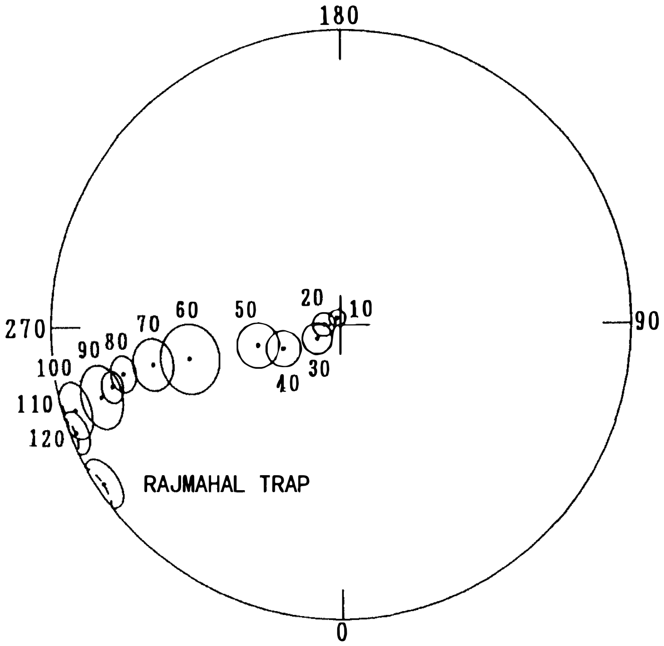


Fig. 5. VGP of Rajmahal trap plotted by equal-area net projection and APWP of India by BESSE and COURTILLOT (1991).

4.3. Rajmahal trap and Kerguelen Plateau

Previous studies (BESSE and COURTILLOT, 1991; STOREY, 1995) indicate that the Kerguelen Plateau, situated between India and Antarctica, was formed during 100–115 Ma. Paleomagnetism of Kerguelen Plateau was investigated at ODP Leg 119 and 120 cruises (SAKAI *et al.*, 1990; INOKUCHI and HEIDER, 1992). The age of the Kerguelen Plateau was examined by the paleoposition of the Plateau. In Fig. 6, solid squares show the VGPs (S-pole) of India (referred from Table 1 and BESSE and COURTILLOT, 1991). VGPs are those after rotation to Antarctica's frame (East Gondwanaland) using the reconstruction model of SMITH and HALLAM (1970). Circles around the VGPs are drawn using the angle (paleolatitude) of Kerguelen Plateau studied by INOKUCHI and HEIDER (1992).

Figure 6 shows that the Kerguelen Plateau corresponds not only to the paleolatitude of 110 Ma and 120 Ma, it also conforms to the paleolatitude of 125–130 Ma. That is, the paleolatitude of Plateau corresponds to the period between 110–130 Ma suggesting the possibility that the Rajmahal trap and Kerguelen Plateau were formed around 125–130

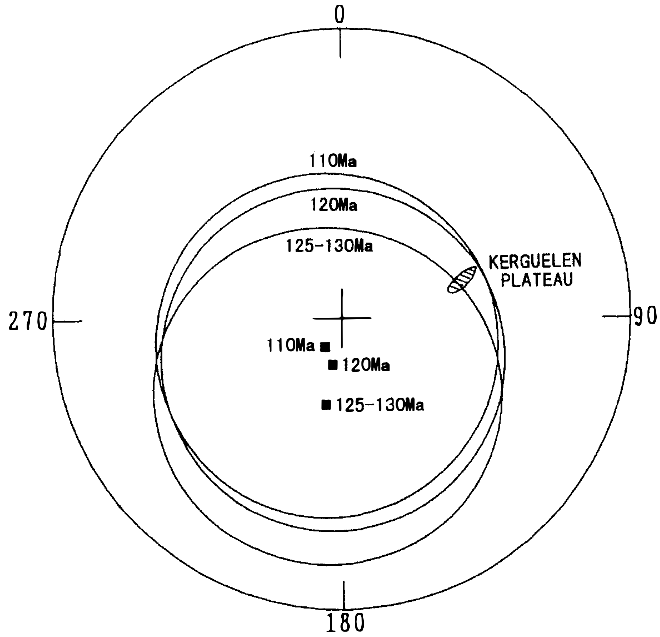


Fig. 6. Paleoposition of Kerguelen Plateau examined by the VGPs (S-pole) of India. VGPs are those after rotation to Antarctica's frame using the model of SMITH and HALLAM (1970). Solid squares show the VGPs for the ages of 110 Ma, 120 Ma, 125–130 Ma. Circles around them are drawn using the angle (paleolatitude) of Kerguelen Plateau studied by INOKUCHI and HEIDER (1992).

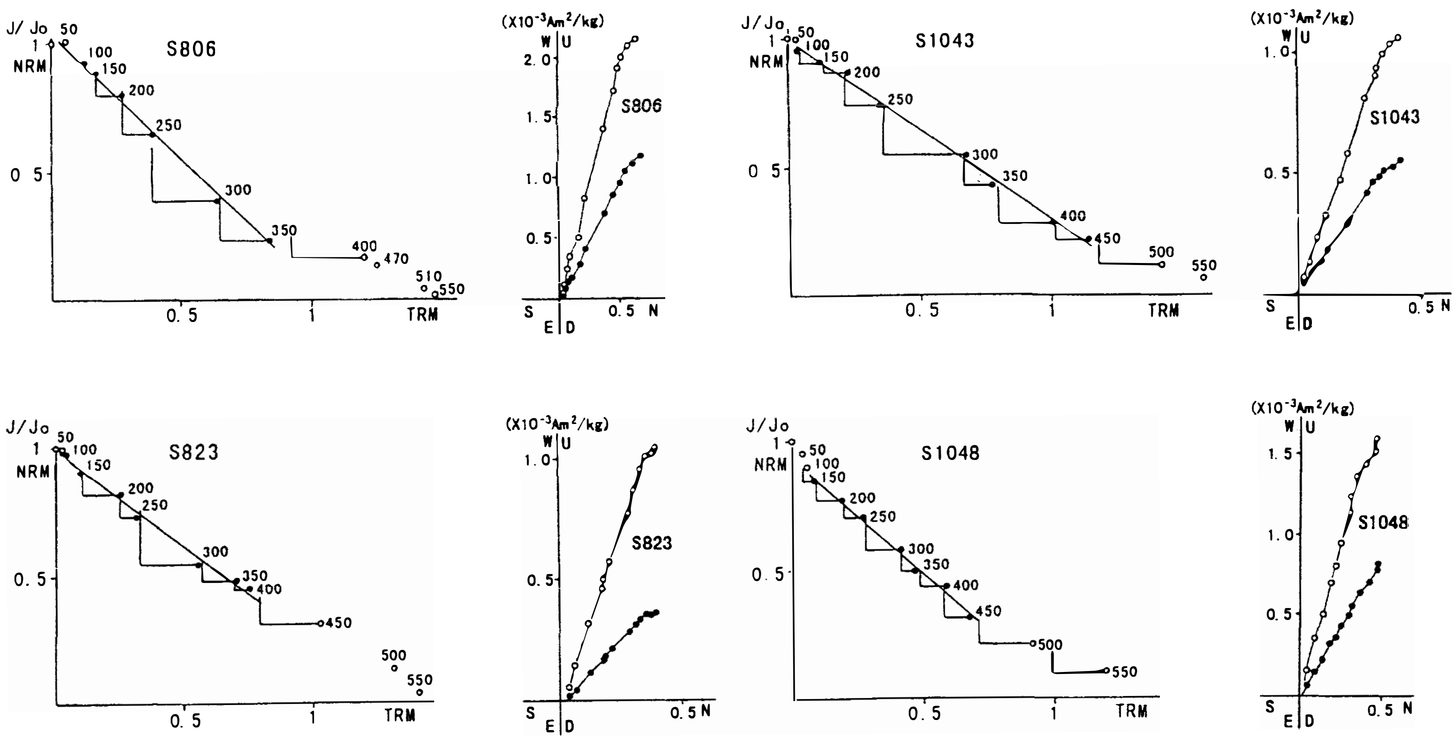
Ma, relating to the break up of East Gondwanaland.

5. Paleointensity from Rajmahal Trap

5.1. Result of Thelliers' method

Paleointensity study was made by Thelliers' double heating method. The magnetic field of 40 μT was used to induce the artificial TRM (thermo remanent magnetization). For the study, we selected and used samples whose demagnetization experiment showed that the unstable magnetization component was eliminated before the demagnetization step of 150°C and/or 10 mT.

Sixteen specimens were subjected to the experiment. Figure 7 shows the NRM-TRM diagrams of five specimens. The reliability of the data was examined by the linearity of points on the NRM-TRM diagram, PTRM (partial TRM) acquisition test and Zijderveld diagram showing directional change of magnetization by thermal demagnetization. We used the following reliability criteria for the linearity of the points on the NRM-TRM diagram. That is, data with over 6 points on the linear relation whose correlation coefficient is over 0.99 were counted as reliable data. When an unstable component remains, the data points at that temperature are not used in the above selection criteria. The data of Thelliers' experiment are summarized in Table 2, where ten specimens with the mark Y show the selected data. The average paleointensity is calculated from ten specimens as 31.4±5.8 μT. This geomagnetic field intensity corresponds to virtual geomagnetic dipole moment (VDM) of $5.1\pm0.9\times10^{22}$ Am^2.



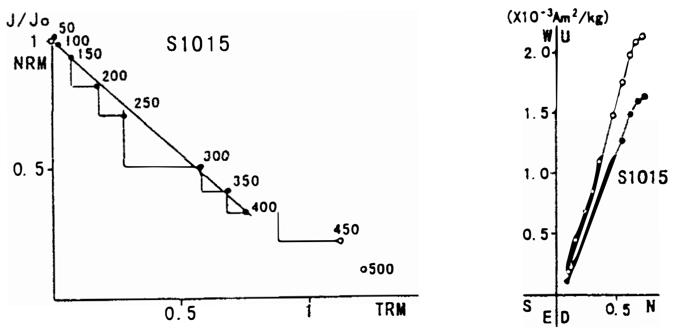


Fig. 7. NRM-TRM diagrams of Thelliers' experiment obtained from five samples of Rajmahal trap, with the Zijderveld diagram during the progressive thermal demagnetization. In the Zijderveld diagram, the solid circle shows the projection of the magnetization on the horizontal plane (NS-EW) and open circle shows that on the vertical plane (NS-UD).

Table 2. Results of Thelliers' method from Rajmahal trap.

Sample	Paleointensity (μT)	T1–T2 (°C)	n	c.c.	
S802	35.2±2.9	100–360	5	0.988	N
S806	40.8±3.1	100–350	6	0.992	Y
S809	50.3±4.6	150–350	5	0.978	N
S810	38.2±2.3	100–450	8	0.992	Y
S821	31.6±2.5	50–300	6	0.990	Y
S823	30.1±1.9	100–400	7	0.993	Y
S827	28.7±3.5	100–350	6	0.984	N
S829	42.3±4.2	100–300	6	0.981	N
S833	24.4±1.6	100–400	7	0.991	Y
S1012	35.5±2.1	150–400	6	0.994	Y
S1014	33.1±5.1	150–300	4	0.975	N
S1015	30.7±1.7	50-400	8	0.994	Y
S1019	22.6±1.4	100–400	7	0.991	Y
S1020	24.7±3.9	50–250	5	0.984	N
S1043	27.6±1.7	100–450	8	0.992	Y
S1048	33.5±2.2	150–450	7	0.990	Y
Mean paleointensity		31.4±5.8 (μT)			
Virtual dipole moment		5.1±0.9 (× 10^{25} Am^2)			

T1–T2 : Temperature range used in the paleointensity estimate.
n : The number of points between T1–T2.
c.c. : Correlation coefficient of the points.
Y : Paleointensity used for discussion.
N : Data not used for discussion.

SHERWOOD *et al.* (1993) have reported paleointensities from the Rajmahal trap. Their obtained paleointensities are almost consistent with the data in this study. They suggested the possibility of low temperature oxidization in their studied samples from the thermomagnetic analysis.

Thermomagnetic analysis in this study (Fig. 2) showed the reversible curve between heating and cooling cycle. Therefore, the effect of low temperature oxidization effect is slight in the studied samples. We consider that the reliability of paleointensities in this study is not distorted by low temperature oxidization.

5.2. *Paleointensity in the Mesozoic*

Figure 8 summarizes the variation of VDMs during the Mesozoic using the data of this study, SAKAI and FUNAKI (1988), SHERWOOD *et al.* (1993) and PREVOT *et al.* (1990). The data of SHERWOOD *et al.* (1993) using the Rajmahal trap are plotted at the age of 125-130 Ma. Data by SAKAI and FUNAKI (1988) were obtained from Beacon sandstone in Antarctica which acquired TRM at the intrusion of Ferrar dolerite in the Jurassic. PREVOT *et al.* (1990) suggested that the VDM from 185 to 125 Ma is constantly low, around 30% of the present dipole moment (8×10^{22} Am^2). In Fig. 8, we can identify that the dipole moment during this period is weak; however, the moment is not constant and oscillates. That is, the geomagnetic dipole moment from 185 Ma to 125 Ma, before CQZ in Mesozoic, is generally low and varies between 30% and 70% of the present moment.

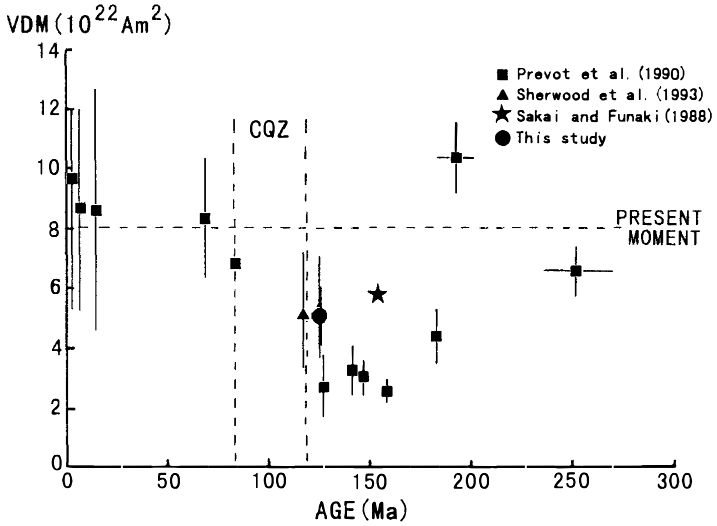


Fig. 8. Variation of VDM during Mesozoic.

6. Summary

A paleomagnetic study was conducted on the Rajmahal trap of India. The age of the trap was determined by $^{40}Ar/^{39}Ar$ dating as 125 to 130 Ma.

The VGP of trap is compared with APWP of India analyzed from the magnetic lineation pattern of the Indian Ocean. The comparison supports the $^{40}Ar/^{39}Ar$ age of the Rajmahal trap. Thelliers' paleointensity experiment was applied to the trap and the paleointensity of 31.4±5.8 μT was obtained. The summary of the geomagnetic dipole moment in Mesozoic shows that the dipole moment from 185 Ma to 125 Ma, before the period of CQZ, varies between 30% and 70% of the present moment.

References

Baksi, A.K. (1995): Petrogenesis and timing of volcanism in the Rajmahal flood basalt province, northeastern India. Chem. Geol., **121**, 73–90.

Besse, J.E. and Courtillot, V. (1991): Revised and synthetic polar wander paths of the African, Eurasian, North American and Indian plates, and true polar wander since 200 Ma. J. Geophys. Res., **96**, 4029–4050.

Day, R., Fuller, M. and Schmidt, V.A. (1977): Hysteresis properties of titanomagnetites: Grain size and composition dependence. Phys. Earth Planet. Inter., **13**, 260–266.

Fisher, R.A. (1953): Dispersion on a sphere. Proc. R. Soc. London, **A217**, 295–305.

Inokuchi, H. and Heider, F. (1992): Paleolatitude of the southern Kerguelen Plateau inferred from the paleomagnetic study of upper Cretaceous basalts. Proc. ODP, Sci. Pap., **120**, 89–96.

Klootwijk, C.T. (1971): Paleomagnetism of the upper Gondwana Rajmahal traps, northeast India. Tectonophysics, **12**, 449–467.

MacDougall, I. and McElhinny, M.N. (1970): The Rajmahal traps of India—K-Ar ages and paleomagnetism. Earth Planet. Sci. Lett., **9**, 371–378.

Piper, J.D.A. (1990): Paleomagnetic Database. Open University Press, 264p.

Prevot, M., Derder, M.E., McWilliams, M. and Thompson, J. (1990): Intensity of Earth's magnetic field: Evidence for a Mesozoic dipole low. Earth Planet. Sci. Lett., **97**, 129–139.

Sakai, H. and Funaki, M. (1988): Paleomagnetic study of the beacon supergroup in antarctica : Remagnetization in the Jurassic time. Proc. NIPR Symp. Antarct. Geosci., **2**, 46–54.

SAKAI, H., FUNAKI, M., KEATING, B.H. and ODP Leg 119 shipboard scientific party (1990): Paleomagnetism of ODP Leg 119- Kerguelen Plateau and Prydz Bay. Proc. NIPR Symp. Antarct. Geosci., **4**, 201–212.

SAKAI, H., FUNAKI, M., SATO, T., TAKIGAMI, Y., SAKAI, H. and HIROOKA, K. (1997): Paleomagnetic study with $^{40}Ar/^{39}Ar$ dating of Rajmahal hills and Mahanadi graben in India-reconstruction of Gondwanaland-. J. Geol. Soc. Jpn., **103**, 192–202 (in Japanese with English abstract).

SHERWOOD, G., SHOW, J., BAER, G. and MALLIK, S.B. (1993): The strength of the geomagnetic field during the Cretaceous Quiet Zone: Paleointensity results from Israeli and Indian Lavas. J. Geomagn. Geoelectr., **45**, 339–360.

SMITH, A.G. and HALLAM, A. (1970): The fit of the southern continents. Nature, **225**, 139–144.

STOREY, B.C. (1995): The role of mantle plumes in continental breakup: Case histories from Gondwanaland. Nature, **377**, 301–308.

THELLIER, E. and THELLIER, O. (1959): Sur l'intensité du champ magnétique terrestre dans le passé historique et géologique. Ann. Geophys., **15**, 285–376.

ZIJDERVELD, J.D.A. (1967): A.C. demagnetization of rocks: Analysis of results. Methods in Paleomagnetism, ed. by D.W. COLLINSON *et al.* Amsterdam, Elsevier, 254-286.

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