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Palaeomagnetism of Metadolerite Dykes and Sills from Proterozoic Shillong Basin, NE India: Implications Related to the Age and Magmatism

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Abstract: The basement gneiss of the Shillong plateau and the overlying rocks of the Shillong basin have been dissected by a number of mafic dyke swarms represented by older Proterozoic dolerite dykes and sills named as Khasi greenstone and the younger set of Cretaceous dykes. The older dolerite~~s~~ dykes of Shillong basin are partly metamorphosed and have undergone low-grade metamorphism compared to the fresh unmetamorphosed Cretaceous dykes dominantly exposed in the BGC of West Garo hills region. The Khasi greenstones are tholeiitic in composition and range from basalt to basaltic andesite. Most of the metamorphosed mafic dykes indicate continental nature with some amount of overlapping oceanic tectonic setting. Palaeomagnetic study of the metadolerite dykes show a direction of magnetization of Dm=29, Im=38 (α_{95} = 28.84; k = 48.33; N = 2) with a palaeolatitude of 21.3° N to the Indian sub-continent that clearly support the Proterozoic dyke/dyke swarm emplacement in the region. The magnetic carrier as inferred from IRM studies is magnetite in the range of psuedosingle to multi domain (MD) states with minor contribution from hematite.

Keywords: Paleomagnetism, Proterozoic Shillong basin, Dykes and Sills, Meghalaya.

INTRODUCTION

The Shillong plateau of NE India plays a vital role in the Precambrian history of the Indian lithospheric plate. This geodynamically restless and seismically very sensitive plateau is a detached part of the Indian shield (Evans, 1964), and probably an extension of the Chotanagpur Gneissic Complex (Desikachar, 1974) or Eastern Ghat Proterozoic mobile belt (Crawford, 1969, 1974) and the detached zone is marked by Garo-Rajmahal tectonic graben (Eremenco et al., 1969). We have made an attempt in this study to find out the emplacement age of the metadolerite dykes and their relation to the tectonics of the region locally. The Shillong plateau comprises of varied rock types from Precambrian to Cenozoic period excluding rocks of Paleozoic and lower Mesozoic. Sylhet trap and a few alkaline complexes are the only members of Mesozoic period (Jurassic to Cretaceous). The basement of the Shillong plateau consist of metamorphites including sillimanite bearing paragneiss, quartzofeldspathic gneisses, amphibolites, granulites, calc-silicate rocks, banded iron formation (BIF), mafic and felsic intrusive, pegmatite and they can be grouped into Basement Gneissic Group (BGG). The plateau is criss crossed by numerous lineaments in NE-SW, N-S and E-W directions (Chattopadhyay and Hashmi, 1984). It is bounded to the north by Brahmaputra lineament, to the south by E-W trending Dauki fault, to the east by Indo Myanmar Mobile Belt (IMMB) and N-S trending Dhubri-Yamuna lineament to the west. These N-S and E-W trending faults were formed by the Kergulen plume related domal up-arching during the Mesozoic time (Gupta and Sen, 1988). The uplift of the Shillong plateau is related to collision of Indian and Tibetan plates during the Cenozoic period (Johnson and Alam, 1991; Bilham and England, 2001). Mesozoic fragmentation and subsequent northward migration associated with intraplate hot spot mechanism might have relation with the upwelling of mantle materials and the deep seated faults which act as the channel ways for the magma in subsequent period (Harijan et al., 2003). The Dauki fault separates the Shillong plateau from the plains of Bangladesh (Kailasam, 1979; Sarma and Dey, 1996). Further, a NW-SE tectonic lineament (Kopili lineament) dissects the Shillong plateau into two massifs namely Meghalaya massif and Mikir massif (renamed as Karbi Anglong massif by Sarma and Dey, 1996). In Neoproterozoic-Cambrian paleomagnetic reconstructions of the Rodinia supercontinent, the plateau was close to the Australia-Antarctic block and it constitutes the leading edge of the Indian plate during its supposed oblique collision with the Australo-Antarctic plate at ca. 500-650 Ma (Chatterjee et al., 2006). They have further stated that Prydz bay suture with a northward extension through the Shillong Meghalaya Gneissic Complex (erstwhile Shillong plateau) along the western boundary of the suture is located between Garo-Goalpara hills and Sonapahar areas.

Figure 1 shows the geological map of Shillong basin along with the location sites of the mafic sills and dykes of the study area. The Shillong plateau covers approx. 47,614 km^2 area having length and breadth of 192 and 64 km along E-W and N-S directions respectively. Geochronological evidences are scanty in the Shillong plateau. Basement gneissic rocks are dated at 1714±44 Ma from Patharkhang area of West Khasi hills districts of Meghalaya (Ghosh et al., 1994). Chatterjee et al. (2006) present monazite dates from Goalpara hills and Garo hills around Sonapahar area as 1596±15 Ma and 500±14 Ma respectively. Bidyananda and Deomurari (2007) present zircon age date from a few basement gneissic rocks (ranging 1.5 to 2.6 Ga), metasedimentary quartzite of Shillong Group (1.4 to 1.9 Ga) and also charnockite (1.0 to 1.3 Ga) from Shillong plateau, which proves the signature of Archean basement. They have suggested a possible common petrogenetic process correlating Shillong plateau with Eastern Ghat belt.

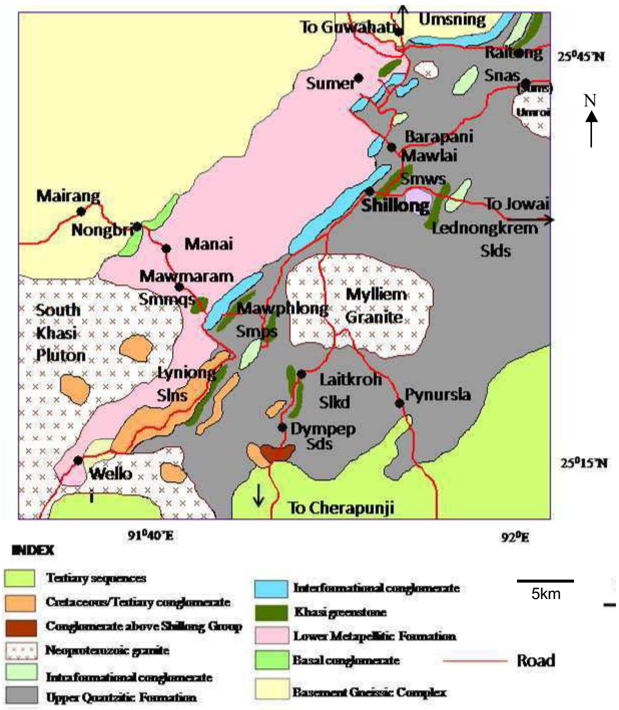

Fig.1. Geological map of the Shillong basin showing locations of sample sites of mafic dykes and sills (modified after Devi and Sarma, 2010).

In the central and eastern part of the plateau a NE-SW trending depression was probably initiated during Mesoproterozoic time and this intracratonic depression covering an area of 2500 sq km is named as Shillong basin (one of the Purana basins of Indian Peninsula). In this basin the meta-volcano sedimentary rock associations display multiple deformations and metamorphism under greenschist – amphibolite transitional facies (Mitra, 1998; Devi and Sarma, 2010). Metapelite-quartzite sequences along with conglomerates and metadolerite dykes and sills form the notable components of Shillong Group (Shillong series of Medlicott, 1869). The rocks are placed under two formations namely lower Metapelitic Formation (LMF) and upper Quartzitic Formation (UQF). The former is named as "Mawphlang Formation" (Bhattacharjee and Rahman, 1985) or Shillong Formation (Ahmed, 1981: Barooah and Goswami, 1972) whereas, LMF is known as Manai Formation by Bhattacharjee and Rahman, (1985) or Tyrsad Formation by Barooah and Goswami (1972), Barapani Formation by Ahmed (1981). The LMF of the overlying Shillong Group comprises of phyllite, quartz-mica schist, quartz-sericite schist, garnetiferous mica schist and biotite schist. The UQF of the basin is dominantly marked by massive quartzites and are partly intercalated with thinly bedded metapelites. They show evidences of primary structures. Occasionally, very thin bands of BIF are seen. Both upper and lower formations of the Shillong Group are transected by mafic dykes and sills (Khasi greenstone). Andalusite bearing hornfelsic rocks are observed along the aureols of Neoproterozoic granite plutons. The mafic dykes and sills of doleritic composition were emplaced into the sedimentovolcanic association of Shillong basin and partially metamorphosed under greenschist facies. Such mafic bodies are conventionally designated as Khasi greenstone since the days of Medlicott (1869) who proposed the term after Khasi (a local tribe) hills of the then undivided Assam. In fact, they are dolerites partially metamorphosed to a green coloured rock. For discussion, the name metadolerite will be retained henceforth. The covered Shillong Group of metasediments has been dated at 1530-1550 Ma (Mitra, 1998). During Neoproterozoic period granites intruded the Shillong basin in the form of plutons (e.g. Mylliem pluton, Kyrdem pluton and South Khasi pluton), which have been dated at 607±10 Ma (Crawford, 1969); 885-480 Ma (Ghosh et al. 1991, 1994; Bhattacharyya and Ray Barman, 1998) and they form another Formation named as "Mylliem Formation" (GSI, 1971). Sharp contact between basement gneisses and covered Shillong Group is exposed near Nongkhya, Nayabunglow of RiBhoi district and Nongbri of West Khasi hills district of Meghalaya (Devi and Sarma, 2006, 2010). A number of conglomerates set the lower and upper limit of the Shilllong basin and they are highly deformed along with other litho-association (Devi and Sarma, 2006, 2010). It is understood from the past studies that the metamorphic event in the Shillong plateau is widespread and occurs at about 1500 Ma which supports the tentative age of these dykes. We tried to test and confirm this metamorphic age by subjecting the dyke rocks to palaeomagnetism. Metamorphism will affect the magnetic signatures if the rocks have completely undergone high grade metamorphism, whereas, in Shillong basin the Proterozoic dykes show low grade metamorphism. Investigations on these dykes will not affect the magnetization. In this communication, the least studied paleomagnetic aspects of metadolerite of Shillong basin is dealt with.

Distribution of Metadolerites and their Field Association

In order to map the mafic dykes and sills of the basin different traverses were taken along the following roads namely (a) Nongpoh - Umsning (along GS road), (b) Umsning - Ritong, (c) Umsning - Shillong (along GS road), (d) Shillong – Sohrarim, (e) Shillong – Kyrdemkulai (f) Barapani – Bhailungbum – Umroi (g) Shillong – Mawngap – Manai (h) Sohiong – Mawngap – Tyrsad and (i) Shillong – Jowai road. The mafic bodies occur as dykes and sills of variable thickness and sometimes as isolated linear to curvilinear bodies within the Shillong Group.

Paleomagnetic investigation on rocks of Indian sub-continent is carried out by several workers and accordingly Apparent Polar Wandering Path (APWP) for rocks from Permo-Carboniferous to recent is established in Indian sub-continent but in case of Precambrian rocks, APWP is not well defined or established (Mahanty, 2006). The apparent polar wandering path (APWP) of the Proterozoic rocks of India shows five ''hairpin bends". The curve is represented by a number of poles determined from the lower Gwalior traps and ends up near the poles of Karimnagar and Kolar dykes at the margin of the Cuddapah basin. The second is represented by the samples from the upper Gwalior Group and the Cuddapah Supergroup. The APWP curve is found between the pole of Srisailam quartzite in the Cuddapah basin and the poles obtained from the Gangau tilloid. The poles were identified within the time frames between 2000 and 1900 Ma and 1900 Ma and 1800 Ma, possibly suggesting crustal-scale tectonic events in the Indian continent during this time period. The third bend in the APWP is estimated at ~1500 Ma age is interpreted in relation with a major collisional event. Therefore, Proterozoic tectonic set up is poorly understood and needs intensive study.

SAMPLING AND LABORATORY MEASUREMENTS

Mafic dykes and sills act like a black box where geomagnetic field direction and intensity of the earth through geologic past are recorded. They are the potential source of paleopole data. The study of such mafic dykes helps in ascertaining the nature of stress field and its tectonic evolution. Magnetic minerals in rocks align themselves along the direction of the earth's magnetic field and this alignment is retained even after consolidation throughout the geologic times. This would serve as a record of the geomagnetic field that can be made use of in correlation of the rocks formed at a particular period of time in their history as well as in understanding the tectonics of the region (Irving, 1964; McElhinny, 1968, 1973). Paleomagnetic study is an excellent technique and proved to be very useful.

NRM MEASUREMENT

Twenty one oriented block samples from 9 locations were collected for the palaeomagnetic study. The samples were oriented using Solar, Silva and Brunton compasses in *in situ* position. In the laboratory, the block samples were cored and cut into cylindrical specimens of standard dimension (2.5 cm diameter and 2.2 cm height). A few core samples were collected from field by portable hand-held drilling machine with proper care. Magnetic susceptibility was measured in the field using kappameter (kT-6). Natural Remanent Magnetization (NRM) and intensity of magnetization (Jn) of all the specimens were measured using JR-6A Spinner Magnetometer (Czechoslovakia make). NRM vectors were plotted on a stereographic plot to see the NRM distribution and grouping. Specimens were selected systematically for a pilot study to remove the secondary magnetization and to evaluate the Characteristic Remanent Magnetic (ChRM) directions using AF and thermal demagnetization techniques. Results of these pilot studies were made use of for blanket treatment of the remaining specimens to recover the remanent signature in these mafic dyke specimens using the above techniques. Laboratory results were analyzed using statistical (Fisher, 1953) and principal component analysis (PCA) methods (Kirschvink,

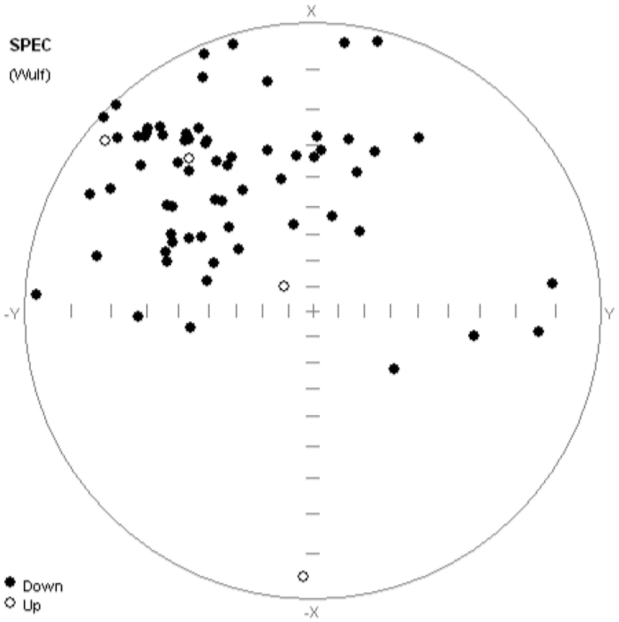

Fig.2. Specimen NRM directions of Shillong Proterozoic dykes.

1980) and dyke mean ChRM directions were evaluated. Virtual Geomagnetic Poles (VGPs) corresponding to various ChRM components of magnetization were computed. These VGPs and other parameters were then used in plotting the APWP vis-a-vis to understand the tectonics of the region.

The NRM directions of the dykes (3, 4, 5 and 8) show good grouping with NW pointed declinations and shallow to intermediate downward pointing inclinations whereas specimens from two dykes (2 and 9) reveal scattered directions. NRM directions of these dykes are shown in Fig.2. Remanent intensity of the specimens varies between 1.04 and 2.92 A/m. Magnetic susceptibility of these Khasi greenstone dykes indicate values between 83 and 5230 x10^{-6} SI units. Q ratio (Koenigsberger ratio = NRM intensity / kH where k is magnetic susceptibility and H is the inducing field i.e. 0.5 Oe) values are calculated from the measured NRM and the susceptibility values. The observed Q-ratio is greater than 1 in most of the specimens.

DEMAGNETIZATION

Two specimens from each dyke were selected and subjected to stepwise demagnetization on pilot basis using AF and thermal demagnetization techniques for ascertaining their magnetic history. The specimens were demagnetized at intervals of 2.5 to 20 mT up to a peak field of 100 mT in AF demagnetization and measured for their remanent direction after each step of demagnetization. Peak fields from 15mT – 35mT were selected for blanket demagnetization to recover the ChRM vectors in these dyke samples. Figure 3 shows the response of typical specimens to AF pilot study. In case of dykes 1 and 7 the ChRM direction is in northeast quadrant with moderate downward pointing inclinations whereas in case of dykes 3, 4, 5 and 8 the ChRM directions are in northwest with moderate downward dipping inclinations. Dykes 2, 6 and 9 are showing ChRM directions in northwest with shallow to moderate upward inclinations and which are quite different. The specimens exhibit extreme stability in their magnetic direction to AF fields with mdf values around 15 mT and at higher fields the specimens lose the remanent intensity very rapidly. Vector end point diagrams show that the vectors are passing the origin smoothly in case of Slns and Sds samples, whereas, in Smmqs samples the vectors are migrating at higher fields. In thermal demagnetization another two specimens from each dyke were heated in steps of 100, 200, 300, 400, 450, 500, 540 and 580, 600, 640, 680, 700°C and measured their remanent direction after cooling to room temperature. In thermal demagnetization study also the specimens maintain their remanent vector up to blocking temperature of the carrier mineral magnetite with 580°C and showing drop in remanent intensity at temperature above 500° C in one set of specimens. In another set of specimens the blocking temperature is at 680°C and in few cases 700°C. Vector end point diagrams show the vectors are passing the origin smoothly in case of Sds samples, whereas, in Slkd samples the vectors are migrating at higher temperatures. Typical demagnetization characteristics of these dykes to laboratory pilot thermal demagnetization are shown in Fig.4. Samples mean ChRM direction of the mafic dykes are shown in Fig.5. Two of the meta dolerite dykes (1, 7) reveal a mean ChRM of Dm =29, Im=+38 (N=2, α_{95}=28.84, k=48.33) and its corresponding VGP at λp=62.8°N, Lp= (-) 184.03°E with a palaeolatitude (λm) of 21.3°N to the Indian subcontinent. The ChRM directions and the corresponding VGPs obtained from the dolerite dykes of Shillong basin are listed in Table 1.

Table 1. Palaeomagnetic data for Shillong dykes, Shillong plateau, Meghalaya

Site No.	Location	Sp. Id	N	Dm	Im	K	α_{95}	λp°N	Lp°E
1	Dympep	Sds	4	16	37	25.31	12.23	75	197
2	Lednongkrem	Slds	4	321	-18	32.45	9.87	39	324
3	Leitkroh	Slkd	3	320	33	14.28	25.18	52	359
4	Lyniong	Slns	3	298	11	33.12	9.08	28	354
5	Mawphlong	Smps	3	274	41	42.35	8.61	13	22
6	Mawlai	smws	1	280	-33	225.6	3.22	1	341
7	Raitong	Snas	1	43	38	130.79	6.72	50	179
8	Mawmaram	Smmqs	2	323	32	71.02	30.09	54	356
9	Umroi bridge	Sums	2	336	-20	7.78	25.63	47	308
	Mean of (1 and 7)			**29**	**38**	**48.33**	**28.84**	**-63**	**4**

Dm = Mean Declination, Im = Mean Inclination, K = Precision Parameter, α_{95} = Radius of Circle of Confidence at 95% level and probability, λp = Latitude of VGP, Lp = Longitude of VGP.

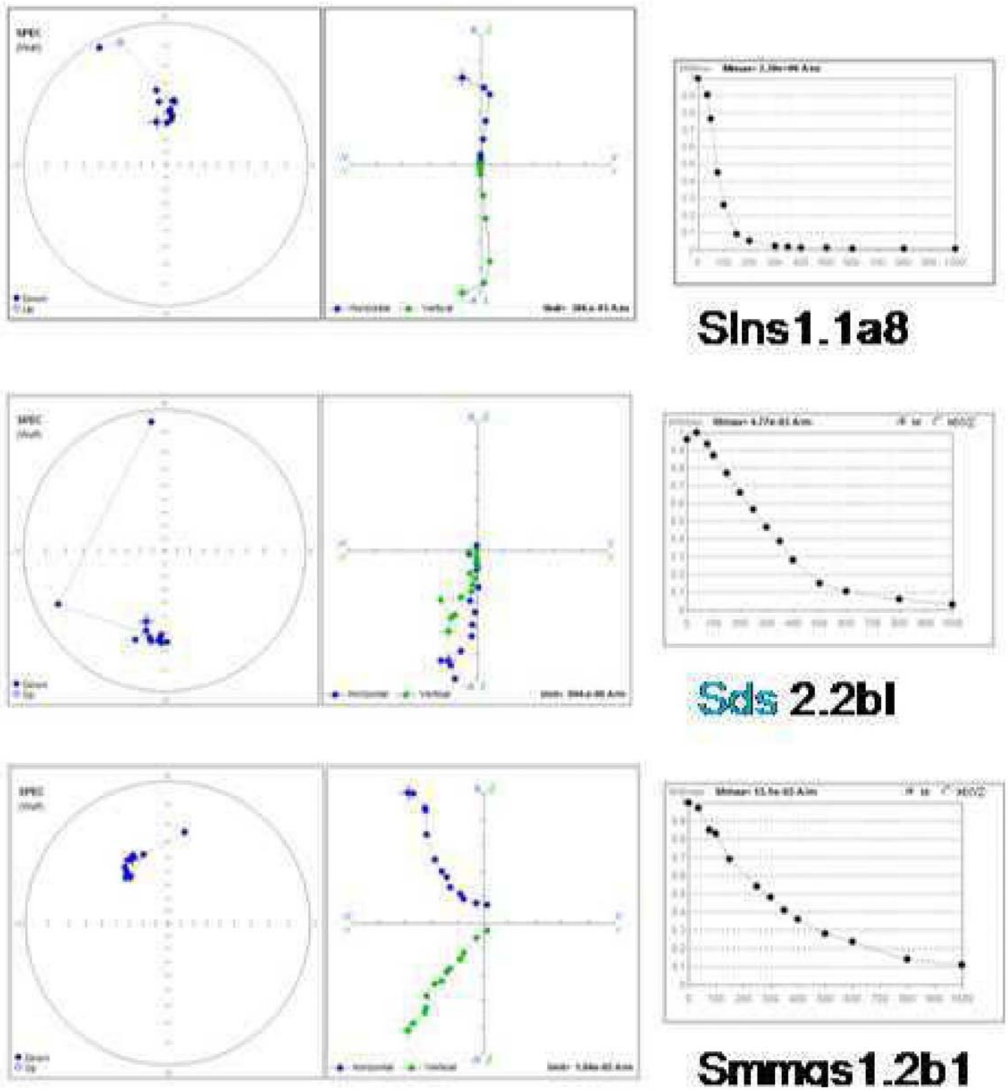

Fig.3. Shillong metadolerite dykes/sills behaviour during AF demagnetization.

The other mafic bodies (3, 4, 5 and 8) and (2, 6 and 9) of Shillong basin reveal different ChRMs with NW and SW pointed declinations with shallow to moderate upward and downward pointing inclinations respectively. Since, these ChRM does not group well with other dykes, they are not considered here for the present discussion of magmatic activity in the region.

IRM Study

For inference on domain state of the magnetic remanence carrier in these mafic dykes, several specimens were subjected to isothermal remanent magnetization (IRM) studies. Figure 6 shows the IRM curves. The IRM curves indicate that these dykes are having multiphase magnetic minerals in them. Few of the dykes show a saturation of magnetization between 160-200 mT indicating that magnetite is the remanence carrier and in other dykes the saturation does not occur even after treating to 300 mT indicating that haematite may be the remanence carrier. The back field study depicting the coercivity spectrum shows coercivity value < 50 mT indicating that the dykes are having single to Psuedosingle domain nature (15 – 45 mT) which is a good property to carry out palaeomagnetic investigations on these dykes.

DISCUSSION

The basement gneissic complex of the Shillong plateau and overlying Shillong basin rocks are intruded by two suites of mafic dykes of Proterozoic and Cretaceous periods. The geochemical and palaeomagnetic signatures of mafic bodies of both basement and covered rocks are distinctly different.

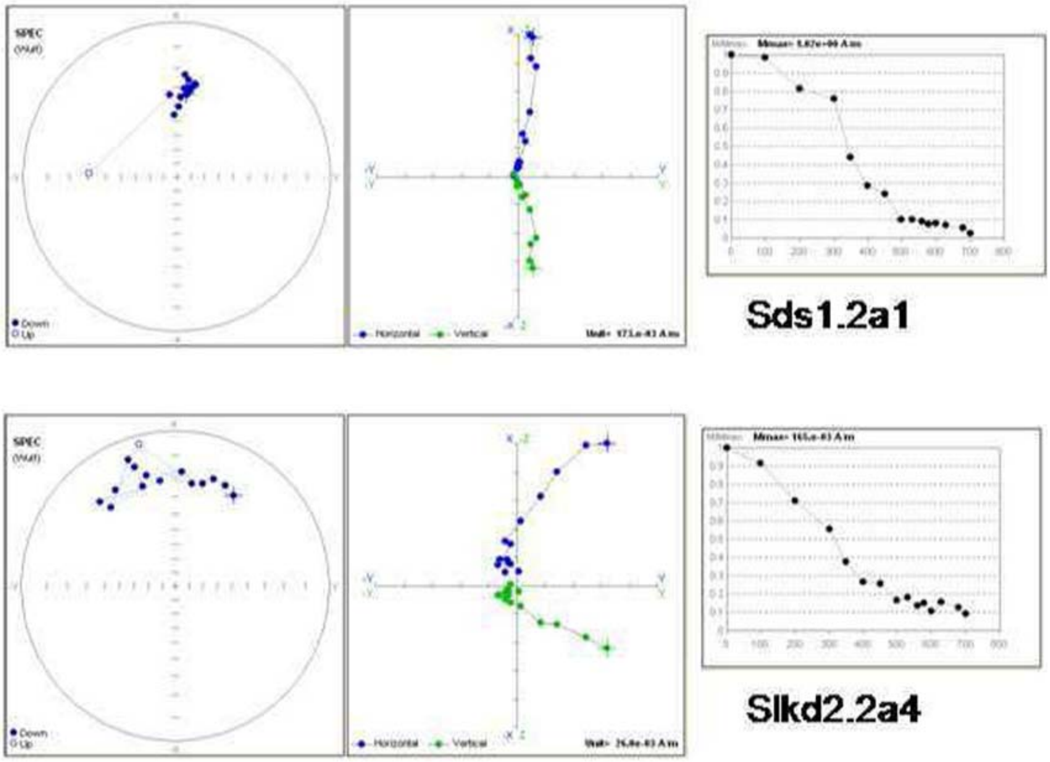

Fig.4. Metadolerite dykes/sill specimens behaviour during thermal demagnetization.

Mafic dykes and sills of Cretaceous period (syngenetic to Sylhet Trap) of Meghalaya are more abundant in Garo hills region of western part of Shillong plateau while they are infrequently observed in the intracratonic Shillong basin and east and west Khasi hills region. The metamorphic event in the Shillong Group is widespread and occurs at about 1500 Ma which support the tentative age of these dykes from palaeomagnetic study.

The Shillong plateau has been considered as continuation of the northeast India and detached from the rest of Indian sub-continent due to large scale right-lateral displacement

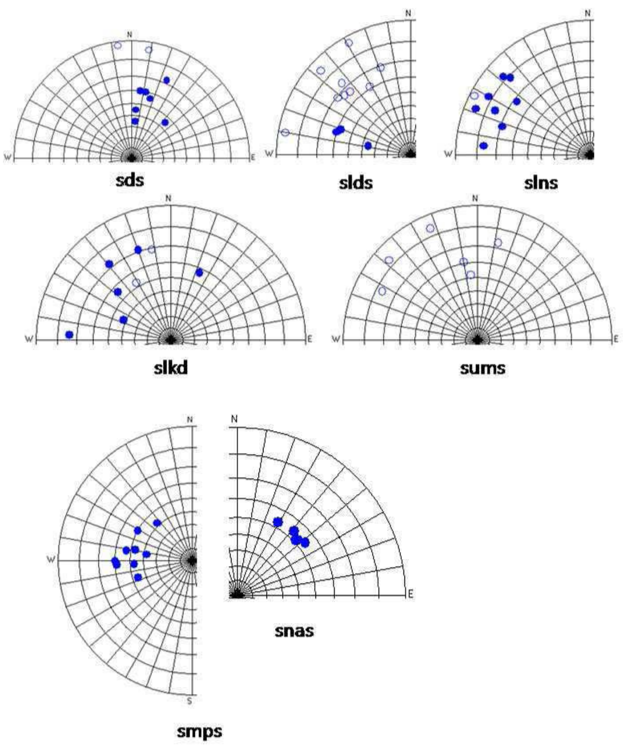

Fig.5. Stereoplot of sample mean Characteristic remanent magnetic directions of the dykes/sills from Shillong basin.

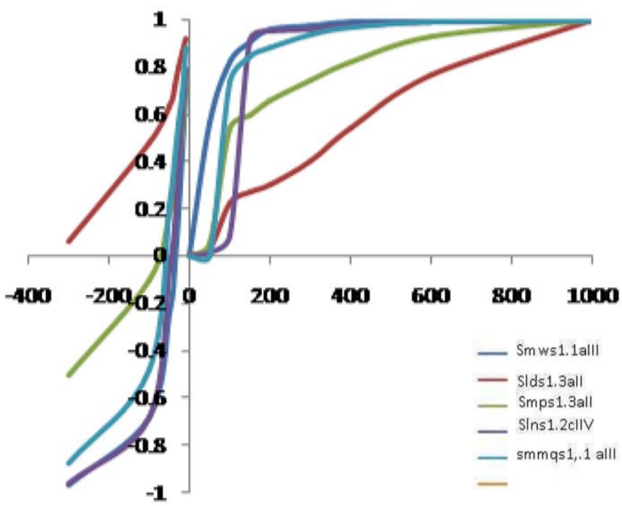

Fig.6. Isothermal remanent magnetization curves for Shillong dyke samples.

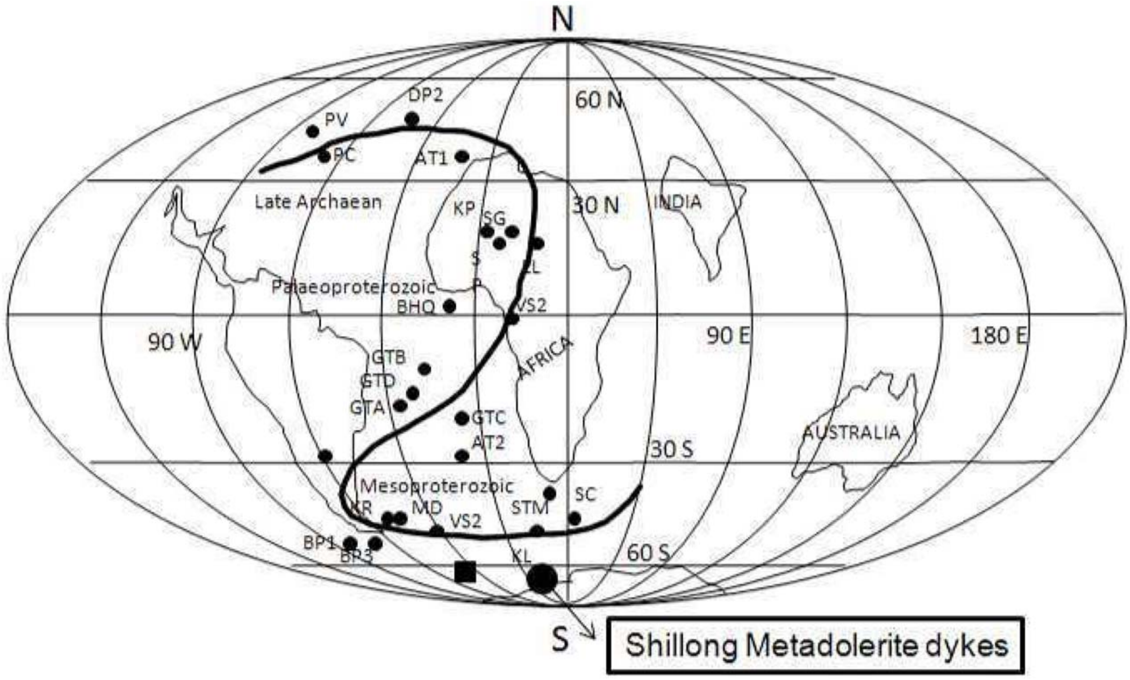

Fig.7. APWP for Indian subcontinent during palaeo and Meso-Proterozoic time. The VGPs plotted referred to available Proterozoic palaeomagnetic data referred in Poornachandra Rao and Mallikarjuna Rao (2006). • VGP of Khasi greenstone of the present study. VGP of Khasi Greenstones after Mallikarjuna Rao et al. (2009).

along the E -W trending Dauki fault (Evans, 1964). It has experienced Kerguelen hotspot related magmatism in its southern and western parts coeval with the Rajmahal traps in northeast India during middle-late Cretaceous. Therefore, it is likely that the Shilling plateau, Bengal basin and northeast India may constitute a micro-plate (Desikachar, 1974 and Evans, 1964). The widespread igneous activity has affected the rheology of crust-lithospheric region under the plateau (White and Lovell, 1997) and experienced great earthquakes (Bilham and Gaur, 2001). There is spur of ancient basement rocks extending from Shillong plateau through Mikir hills up to the eastern syntaxis. The northeastern part of the plateau got separated from the Mikir massif by rift-related Kopili depression. In the south, it is separated from the Surma valley by south dipping monoclinal Dauki fault system. These are all related phenomena of Mesozoic fragmentation and tectonic transportation along horizontal and vertical axes. Therefore, the magmatic activity represented by the dyke swarms of the West Garo hills region is considered as second suite of mafic magmatic activity during Cretaceous period. Geochemical and palaeomagnetic signatures of these mafic swarm of second set is documented by Mallikharjuna Rao et al. (2004); Mallikharjuna Rao and Poornachandra Rao, (2008). The present study is related to palaeomagnetism of Proterozoic metadolerite dykes (early dyke set) from Shillong basin and throws light on the existence of Mesoproterozoic magmatism. The obtained pole positions from two well grouped dykes indicate that these belongs to Mesoproterozoic and can be compared very well along with the available published data on mafic dykes from intracratonic Shillong basin (Mallikharjuna Rao et al., 2009).

A few mafic intrusives were studied by Mallikharjuna Rao et al., (2009) and suggested that they are tholeiitic in composition ranging from basalt to basaltic andesite with olivine or quartz normative character, both derived from picrites that subsequently undergone low pressure fractionation. Palaeomagnetic study reveals that the mafic dolerites dykes show a direction of magnetization of Dm=17, Im= +57 (α_{95}=22.34, k=31.5; N=24) with corresponding pole position at λp = 71.2°N, Lp = 137.6°E with a paleolatitude of 29.70°N to the Indian subcontinent that clearly support the Proterozoic dyke swarm emplacement in the region (Mallikharjuna Rao et al., 2009).

CONCLUSION

Present study of metadolerite dykes gives a pole position at λp= 62.8ºN, Lp= 184.03ºE which supports the results of Mallikharjuna Rao et al. (2009) very well in this part of the region. However, out of nine dykes, only two dykes are showing the Mesoproterozoic signatures. Similar behavior was observed by Mallikharjuna Rao et al. (2009) where only three out of 5 dykes have recorded the Mesoproterozoic signatures. The VGPs of the mafic dykes clearly suggest that they are of Proterozoic in age and older than the Cretaceous dykes of West Garo hills in the western part of the Shillong plateau when plotted on the Apparent Polar Wander Path (APWP) of the Indian subcontinent as shown in Fig.7. Palaeomagnetic investigations on a volcanic tuff of Shillong plateau by Venkateshwarlu et al. (2012) reveal that this acidic body belongs to Cretaceous age as evidenced from palaeomagnetic and petrological study and the results are similar with Dicheng Zhu et al. (2007). In fact, we also presume that there could be some Cretaceous magmatic event which might have occurred in this part of Shillong basin but our findings are not correlating with the results from Rajmahal and Sylhet trap events.

Yin et al. (2010) have discussed the structure and tectonic evolution of the Shillong plateau and suggested that prior to the deposition of Shillong Group, the northeastern craton experienced two episodes of magmatism at 1750-1600 Ma and 1150-950 Ma. The former is related to Proto-Indian continental arc magmatic event and the latter is related to Eastern Ghat orogenic belt during collision between India-Antarctica-Australia-South Tibet at the time of formation of Rodinia and Antarctica. Shillong Group was deposited in a passive continental margin during late Proterozoic as claimed by Yin et al. (2010). The third tectonic event is related to amalgamation of Eastern Gondwana. Upliftment of the Shillong plateau during Cenozoic (early Miocene around 20-23 Ma) is an independent issue but age of the Shillong Group tentatively fixed as younger than 900 Ma is somewhat confusing. Mafic dykes and sills intruded into metasedimentary and metavolcanic lithounits of the Shillong Group. The metamorphic signatures of the mafic bodies and their occurrences as enclaves within the Neoproterozoic granitic plutons like Mylleim granite, south Khasi pluton and Umroi granite are some of the aspects which need rethinking relating to the age of the Shillong Group.

Most of the mafic bodies of the Shillong basin occur as sills in the NE-SW directions parallel to the strike and trend of the country rock and that too, they are roughly parallel to the eastern and western margins of the Shillong basin. Initiation of the basin due to vertical tectonics in the NE-SW directions and subsequent deposition of the basinal sediments during Mesoproterozoic time followed by emplacement of mafic bodies in the trans-tensional mode in the NE-SW direction may be considered as evidence of Mesoproterozoic event. Palaeomagnetic signatures also indicates similar period of mafic igneous activity around 1500 Ma. More detailed sampling of the dykes and sills and their critical analyses are essential to discriminate between Proterozoic and Cretaceous evolution of the mafic bodies of the intracratonic Shillong basin of the NE India.

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