its chemical affinity to organic phases[12] present in large amounts in the atmosphere in this region (the so-called Asian Brown Cloud)[13], in addition to its anthropogenic emission.

The PM_{10} dust samples studied have an average of 6000 and 15,000 ppm Cu concentration in the summer and winter respectively. These values, nearly 1.5% Cu in the aerosols, suggest that they are better than Cu ores in terms of Cu content (any rock containing > 0.5% Cu is a potential Cu ore today). The economics of Cu recovery from the aerosols needs to be understood. Similarly, environmental and health impacts of such high Cu concentration in the air need to be investigated. Although Cu is an essential nutrient required by plants and animals in small amounts, the observed levels of Cu concentration in the respirable fraction of aerosols, i.e. PM_{10} could cause gastrointestinal disturbances, including nausea, vomiting, and liver or kidney damage depending on exposure time. We need to generate sound scientific knowledge about the causes and consequences of heavy-metal concentration in the aerosols at a local, regional and global level for better policy options on development and the environment.

1. Sikka, D. R., *Curr. Sci.*, 1997, **72**, 35–46.
2. Tripathi, J. K. and Rajamani, V., *Chem. Geol.*, 1998, **155**, 265–278.
3. Taylor, S. R., McLennan, S. M. and McCullah, M. T., *Geochim. Cosmochim. Acta*, 1983, **47**, 1897–1905.
4. Al-Rajhi, M. A., Al-Shayeb, S. M., Seoward, M. R. D. and Edwards, H. G. M., *Atmos. Environ.*, 1996, **30**, 145.
5. Padamnabha, Murty B., *Mausam*, 1984, **35**, 237–239.
6. Sharma, V. P., Arora, H. C. and Gupta, R. K., *Atmos. Environ.*, 1983, **17**, 1307–1314.
7. Negi, B. S., Sadasivan, S. and Mishra, U. C., *ibid*, 1987, **21**, 1259–1266.
8. Sadasivan, S. and Negi, B. S., *Sci. Total Environ.*, 1990, **96**, 269–279.
9. Kulshrestha, U. C., Saxena, A., Kumar, N., Kumari, K. M. and Srivastava, S. S., *Indian J. Environ. Protect.*, 1994, **14**, 685–687.
10. Romo-Kroger, C. M., Morales, J. R., Dinator, M. I., Llona, F. and Eaton, L. C., *Atmos. Environ.*, 1994, **28**, 705–711.
11. Nriagu, J. O. and Pacyna, J. M., *Nature*, 1988, **320**, 735–738.
12. Fergusson, Jack E. and Kim, Nicholas, D., *Sources Speciation*, 1991, **100**, 125–150.
13. Srinivasan, J. and Gadgil, Sulochana, *Curr. Sci.*, 2002, **83**, 586–592.

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Palaeomagnetism of palaeoliquefaction: An aid to palaeoseismology

Palaeoseismology has emerged as a valuable tool in earthquake hazard assessment, since it provides the recurrence period of large/great earthquakes from geological records[1–6]. This study involves evaluation of the timing of earthquakes generally obtained by dating organic material associated with deformed structures such as faulted strata, change in sedimentation pattern in lakes, liquefaction, etc. Liquefaction is the transformation of granular material from solid to liquid state as a consequence of increase in pore water pressure due to seismic shaking. Geological features formed due to liquefaction are accepted as evidence for palaeoearthquake[7–8], and the liquefaction phenomenon is generally associated with large/great earthquakes. The timing of the palaeoearthquake generally obtained by radiocarbon dating is bracketed between lower-bound (maximum age) and upper-bound (minimum age), except for rare cases where the coeval timing of the earthquake is obtained by dating of large-scale extinction of trees (e.g. the Cascadia earthquake[9]). This necessitates developing direct methods of dating an earthquake especially in the case where it yields large-scale liquefaction. This communication is an attempt to demonstrate that liquefaction features can acquire natural remanent magnetism (NRM) different from the host strata and thus, in principle, this phenomenon can aid in providing the time constraint to palaeoseismic events. Here, we demonstrate that the liquefaction features which were quite widespread in the Shillong Plateau area during the Great 1897 Assam Earthquake[10] have been emplaced at different times than the host strata, using Virtual Geomagnetic Pole (VGP) positions. Salyards *et al.*[11] have used the palaeomagnetic data from Pallet Creek across the San Andres Fault to study the non-brittle deformation expressed as rotation within the fault zone, with the amount of clockwise rotation of 30° or less in beds deposited immediately after the great earthquake in 1480 AD. No work on palaeomagnetism of liquefaction features has been reported so far, except that of Salyards[12,13], that sand eruption on the surface during the 1811–1812 New Madrid events has remanent magnetic direction in conformity with the magnetic field direction recorded at nearby St. Louis in 1819.

Sukhija *et al.*[4–6] have undertaken palaeoseismological studies in Shillong Plateau, the area most affected by the 1897 earthquake, and dated three more palaeoearthquakes that occurred 500, 1000 and 1500 yr BP, thus suggesting a recurrence period of 500 years for great earthquakes in the region. All these earthquakes were identified using palaeoliquefaction as geological evidence, and time constraint was obtained from radiocarbon dating of organic samples located in deformed and undeformed strata. In order to explore whether palaeomagnetic studies can aid in obtaining a time constraint on palaeoliquefaction, remanent magnetic studies on sand dykes and the host clay and silt strata in the Shillong Plateau were carried out. Results from this study are presented here.

The study area is located south of the eastern Himalaya in Shillong Plateau, northeast India (Figure 1). It is bound by several tectonic features such as Dauki fault in the south, Brahmaputra river in the north and west, and Indo-Burma range in the east. The study sites are located close to the Chedrang fault (Figure 1) where a slip of 9 m was reported within the meizoseismal zone of the 1897 earthquake in Shillong Plateau[9]. In the study area (Figure 1) along the Krishnai river, a tributary of Brahmaputra, several sand dykes rising from their sand reservoir have been reported by Sukhija *et al.*[4–6]. In the Beltaghat location, the sand dykes are about 1–2 m high and 10–20 cm wide with clear roots in the sand reservoir, and have intruded into clay (< 1 m) overlain by silt (2–3 m). One such typical sand dyke is shown in Figure 2. Near Bedabari (Figure 1) we noticed tilted and deformed brown and white sand with angular unconformity as palaeoseismic feature. At Jira (Figure1) prominent liquefaction features in the form of dykes of 2 m height with white and brown sand were noticed below an overburden of 1.5 m.

Samples for remanent magnetic studies were collected from three locations at Beltaghat, Bedabari and Jira along the Krishnai river bank where several sand dykes have been identified (Figure 1). At each location, two sand dykes separated by 15–50 m were selected and vertical section of the sand dyke and the surrounding host strata was well exposed by trenching. At each site, five samples each from the sand dyke and host silt were collected into plastic cubes by pushing the cube horizontally into the sand. The N-S orientation mark was drawn on top of the plastic container. The plastic container was sealed tightly so that field *in situ* arrangement of the sand particles was not disturbed. Depending on the size of the sand dykes, the sampling interval varied from 10 to 15 cm for both the dyke and the host strata. A total of 58 samples from the three locations was collected to carry out remanent magnetic studies in the laboratory. The samples were labelled as BG from Beltaghat, BB from Bedabari and JR from Jira. The C-series samples indicate country (host) rock and the D-series refer to sand dyke samples.

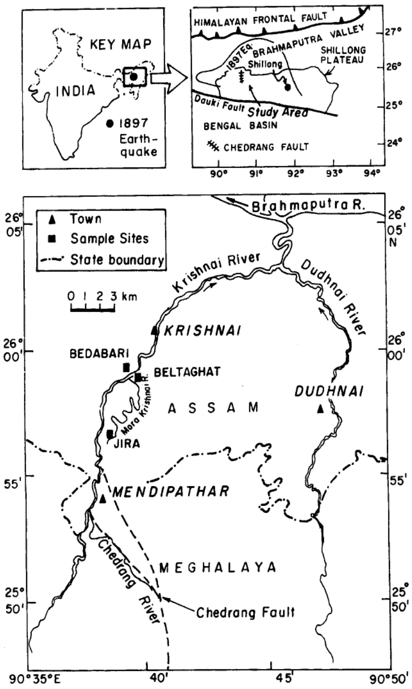

Figure 1. Map showing sample locations for palaeomagnetic studies at liquefaction sites in Shillong Plateau, the meizoseismal area of the Great 1897 Assam Earthquake, close to Chedrang Fault which experienced extensive liquefaction along Krishnai and Dudhnai rivers.

NRM direction and intensity of the samples were measured on a spinner magnetometer (Model DSM-2 Schonstedt, USA). Magnetic volume susceptibility was measured on a hysteresis and susceptibility apparatus[14]. AF demagnetization was carried out on an apparatus similar to that described by Creer[15]. NRM directions of samples from all the sites show very high scatter (except those from one site at Beltaghat) which reveals acquisition of viscous magnetization in the present field. The remanent intensity (Jn) varies between 5.3 and 29.5 mA/m, and the volume susceptibility (K) between 0.12 and 1.16×10^{-3} SI units. Site mean Jn and K values listed in Table 1 are uniform and are well within those of sedimentary rocks.

Characteristic component of magnetization (ChRM) in the samples was established by subjecting them to AF demagnetization. At least one sample from each site of sand dyke and host rock has been subjected to AF demagnetization in progressively increasing alternating magnetic fields in steps up to 50 mT on a pilot basis. In case of the Bedabari location, two samples each were investigated. The samples behave well to this test, with the remanent magnetic vector moving closer to the mean direction of magnetization. There is varying amount of intensity (30–75%) leftover at 50 mT peak field. The viscous effects are removed at 10 mT. Typical demagnetization behaviour of a sand dyke and host silt exhibiting continuous decay of intensity with increasing AF fields is shown in Figure 3. The remaining samples from all the sites of sand dyke and host strata were blanket demagnetized to recover the ChRM vector in these samples by nullifying the viscous effects acquired in the present earth's field. The sample remanent magnetic directions from each site were averaged to get site mean remanent magnetic direction (Table 1) for all the sites using Fisher's[16] statistical methods. Samples of sand dyke and host silt from one site each at Beltaghat and Jira showed reverse magnetic directions with downward inclination, whereas samples from the rest of the sites showed normal magnetic directions with downward inclinations. In studies of this nature, observation of opposite polarities (reverse magnetism) is not uncommon; similar data were reported from a sand blow at New Madrid Seismic Zone[12].

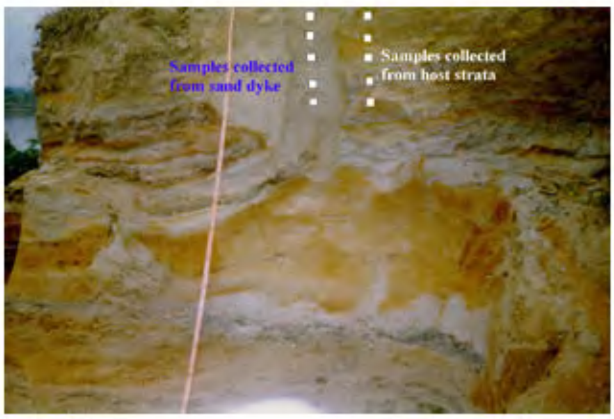

Figure 2. Intrusion of about 1.5 m height sand dyke into overlying silt and silty clay layers due to seismic shaking at Beltaghat. Palaeomagnetic samples were collected from sand dyke and host strata at an interval of 10–15 cm from a vertical section.

Table 1. Remanent magnetic data on liquefaction sites in Shillong Plateau

				Remanent magnetic direction				VGP	
Site no.	No. of samples	*Jn* mA/m	$K10^{-3}$ SI	*Dm*	*Im*	*k*	α_{95}	λp°N	*Lp*°E
BG-C1	5	26.8	0.68	136.8	+ 18.4	9.10	26.80	35°06′	326°12′
BG-D1	5	10.5	0.85	141.5	+ 23.5	77.52	11.24	36°30′	319°48′
BG-C2	5	17.7	0.33	279.1	+ 29.1	11.55	20.60	14°42′	011°18′
BG-D2	5	22.4	1.16	341.2	+ 24.7	8.80	23.60	68°00′	327°48′
BB-C1	5	29.5	0.68	012.2	+ 15.1	20.52	15.45	68°18′	236°06′
BB-D1	5	05.3	0.21	357.4	+ 30.3	6.24	32.36	80°00′	285°12′
BB-C2	5	29.5	0.50	360.0	+ 35.2	6.82	23.98	83°24′	270°06′
BB-D2	5	09.8	0.12	329.6	+ 48.6	7.25	23.26	62°54′	015°12′
JR-C1	3	11.6	0.97	198.7	+ 30.9	10.27	25.48	70°18′	205°00′
JR-D1	5	17.3	1.04	184.7	+ 08.2	5.60	41.84	67°42′	258°12′
JR-D2	5	14.6	1.13	311.2	+ 32.0	6.17	32.53	44°06′	000°06′
JR-D3	5	16.7	0.74	351.0	+ 39.1	13.23	22.22	80°56′	337°30′

BG, Beltaghat; BB, Bedabari; JR, Jira; C1, C2, Country (host) strata at each site; D1, D2, Sand dyke at each site; *Jn*, and *K*, Remanent magnetic intensity and susceptibility; *k*, Precision parameter; α_{95}, Radius of circle of confidence; *Dm*, *Im*, Mean declination and inclination; λp, *Lp*, Latitude and longitude of the Virtual Geomagnetic Pole.

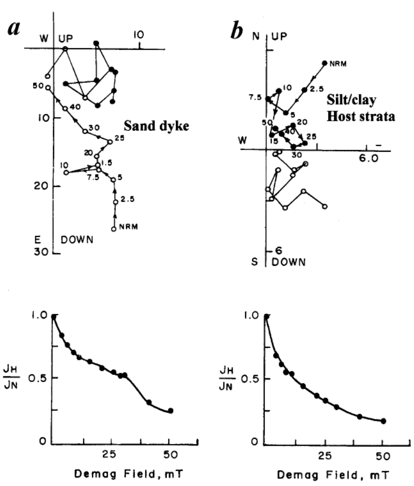

Figure 3. AF demagnetization characteristics of pilot specimens investigated from (***a***) sand dyke and (***b***) host strata (silt/clay) from palaeoliquefaction site at Bedabari in Shillong Plateau. Diagrams are Zijderveldt plots showing intensity and vector variation pattern with increasing peak fields. Solid circles are projection of the resultant vector on an E–W horizontal plane and open circles are projection of the resultant vector along the N–S vertical plane. Intensity variation with increasing peak demagnetizing fields is shown below in each case. Numbers refer to the peak fields in mT, and intensities are in units of mA/m.

VGP positions corresponding to ChRM vectors at each site were computed to compare the emplacement periods of both sand dyke and host strata from all the three locations. VGP positions, ChRM directions and other precision parameters are listed in Table 1.

Two approaches generally considered in palaeomagnetism to obtain ages of unknown rocks are (i) magnetostratigraphy based on the reversal of the earth's magnetic field and (ii) secular variation of geomagnetic field which makes use of short period changes in magnetic directions. The common limitation in both the approaches is the repetition of magnetic field in its position. Thus additional constraints are necessary to resolve this ambiguity. The magnetic field record would be of normal polarity as the directing field is normal in the Brunhes Normal chron which started at 0.73 Ma ago[17]. Here we consider the second approach in which the secular variation of geomagnetic field of short duration is taken into account. The present study comprises the samples taken from the sand dykes which are emplaced at the time of seismic events and those from the host sedimentary strata. The mechanism of acquisition of magnetism in the case of sand dykes is most probably by virtue of detrital remanent magnetism due to liquefaction which is also referred to as LRM[18]. In our view, this is due to fine-grained hematite particles which have comparatively hard behaviour to AF demagnetization. Further, remanent magnetism acquired at the time of genesis of sand dykes most probably gets locked in the material of sand dykes which are sufficiently dewatered and consolidated. According to Collinson[19], a very short time of 15 s is enough for sediments to align magnetically. However, future work will throw more light on this aspect.

To date the historical earthquakes, various properties of remanent magnetic signatures were used by Salyards *et al.*[11] and Salyards[12,13]. At Reelfoot Trench in the New Madrid seismic zone, Salyards[13] constrained the liquefaction period using palaeomagnetic record and secular variation magnetostratigraphy in two sand bodies showing good agreement with the magnetic field directions in 1812 AD at St. Louis which date the Great Earthquakes of 1811–12.

In our investigation, though the difference in the VGP positions is interpreted in terms of time of emplacement of sand dyke caused due to seismic events, re-liquefaction and reworking of the material in the sand dyke cannot be ruled out completely. In the absence of availability of secular magnetic field variation record, we have used the method of agreement and disagreement of observed site mean ChRM and VGP data of earthquake-generated sand dykes and that of the host strata at the selected sites. Since we are dealing with very young sediments and emplacement of dykes are due to seismic events that have taken place in the last 1500 years (lower-bound age obtained by radiocarbon dating[4–6]), VGP positions of these sites are expected to be located in very high latitudes and hence VGP positions with latitudes of more than 60° only are considered here. The host strata samples from both sites at Beltaghat and one site at Jira along with the sand dyke sample from Beltaghat revealed VGP positions with low latitudes between 14°42′ and 44°06′N, and hence they are not considered further in this discussion. To compare their VGP positions, only three sites, i.e. two sites from Bedabari and one site from Jira, are considered in the present discussion. VGP positions of the sand dyke and host strata from these sites are plotted in Figure 4. It is evident

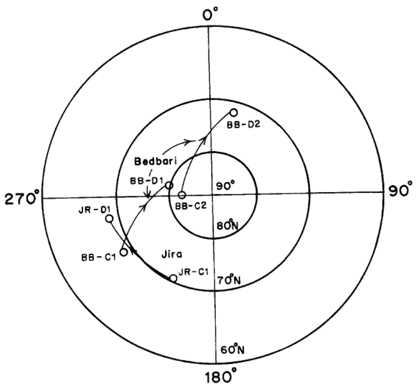

Figure 4. Virtual Geomagnetic Pole (VGP) position of samples investigated for palaeoseismology from Shillong Plateau. Arrows denote changes in VGP positions of the host strata (C) and sand dykes (D) for liquefaction sites at Bedabari (BB) and Jira (JR).

from Figure 4 that there is a considerable difference in the VGP positions of the dyke of seismic origin *vis-à-vis* host strata which can be attributed to differences in emplacement timings of the dykes and host strata. Figure 4 shows cases of Bedabari D1 and D2, and Jira D1, wherein the VGP positions have moved clockwise in comparison to those of the host strata (Bedabari C1 and C2, and Jira C1). However, neither the emplacement time of the sand dyke nor that of the host strata can be assigned at present due to lack of secular variation curve of geomagnetic field of the study area for this period. However, the potential of remanent magnetic studies is demonstrated here to obtain the timing of emplacement of the palaeoliquefaction features as a result of earthquake occurrences belonging to historical or pre-historical past.

1. Sieh, K. E., *J. Geophys. Res.*, 1978, **83**, 3907–3938.
2. Yeats, R. S., Sieh, K. and Allen, C. R., *The Geology of Earthquakes*, Oxford University Press, New York, 1997, p. 568.
3. McCalpin, J. P. (ed.), *Paleoseismology*, Academic Press, London, 1996, p. 583.
4. Sukhija, B. S., Rao, M. N., Reddy, D. V., Nagabhushanam, P., Hussain, S., Chadha, R. K. and Gupta, H. K., *Earth Planet. Sci. Lett.*, 1999, **167**, 269–282.
5. Sukhija, B. S., Rao, M. N., Reddy, D. V., Nagabhushanam, P., Hussain, S., Chadha, R. K. and Gupta, H. K., *Tectonophysics*, 1999, **308**, 53–65.
6. Sukhija, B. S., Rao, M. N., Reddy, D. V., Nagabhushanam, P., Hussain, S., Chadha, R. K. and Gupta, H. K., *Himalayan Geol.*, 1999, **20**, 105–112.
7. Obermeier, S. F., see ref. 3, pp. 331–396.
8. Tuttle, M. P. and Schweig, E. S., *J. Geophys. Res.*, 1996, **101**, 6171–6178.
9. Adams, J., *Tectonics*, 1990, **9**, 569–583.
10. Oldham, R. D., *Mem. Geol. Surv. India*, 1899, **29**, 309.
11. Salyards, S. L., Sieh, K. E. and Kirschvink, J. L., *J. Geophys. Res.*, 1992, **97**, 12,457–12,470.
12. Salyards, S. L., *Seismol. Res. Lett.*, 1992, **63**, 367–373.
13. Salyards, S. L., *Quaternary Geochronology: Methods and Applications*, AGU Reference Shelf 4, 2000, pp. 557–562.
14. Likhite, S. D. and Radhakrishnamurty, C., *Bull. Natl. Geophys. Res. Inst.*, 1965, **3**, 1–8.
15. Creer, K. M., *Geophys. J. R. Astron. Soc.*, 1959, **2**, 262–275.
16. Fisher, R. A., *Proc. R. Soc.* (*London*), *Ser. A*, 1953, **217**, 295–305.
17. Mankinen, E. A. and Dalrymple, G. B., *J. Geophys. Res.*, 1979, **84**, 615–626.
18. Salyards, S. L. and Kirchvink, J. L., *EOS*, 1985, **66**, 868.
19. Collinson, D. W., *J. Geophys. Res.*, 1965, **70**, 4663–4668.

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Reproductive mode in the shrub frog *Philautus glandulosus* (Jerdon, 1853) (Anura: Rhacophoridae)

The diversity of reproductive modes is much greater in amphibians than in other groups of vertebrates, especially the amniotes[1]. Mode of reproduction is a combination of oviposition site and type of egg development[2].

Among the 33 genera of anurans reported from India[3,4], *Philautus* is the only genus having direct development (all development occurs within the egg membranes, and there is no free-swimming tadpole stage). The Asian genus *Philautus* consists of 84 nominal species belonging to the family/subfamily Rhacophoridae/nae[4]. The highest diversity in this genus is found in the Western Ghats of India and in Sri Lanka; many of these species are awaiting scientific description[5,6]. But taxonomy and systematics of this group are, however, in a preliminary stage[4]. Courtship and mode of reproduction of this group in India have virtually not been studied, except in *P.* '*variabilis*'[7], *P. tinniens*[4] and *P. bombayensis*[8]. This communication reports the mode of reproduction of a fourth species – *Philautus glandulosus* (Jerdon, 1853) from Kalpatta in the Western Ghats. This species has direct development.

This small-sized (SVL 20.4–22.9 mm male; 24.5–26.0 mm female) shrub frogs usually have a light leaf-green dorsum without marking. During the breeding season, however, the leaf-green colour of the female turns light yellowish-green with small brownish specks, and males turn uniform brownish-green.

The study was conducted in a coffee plantation near the moist secondary forests in Kalpatta, Wayanad (11°38′N, 76° 08′E). During the late evening (18.00 h) of 28 June 1997, a pair of *P. glandulosus* in amplexus was observed sitting on a coffee leaf about 1 m above the ground. Many calling males were observed on the same plant (Figure 1), but no other female was located nearby. By night, two sources of light were used to take