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Comparison of stress azimuth data derived by geogenic electromagnetic radiation technique and from the analysis of exhumation joints

During the last decade, considerable progress has been made to understand the cause and nature of electromagnetic emission anomalies that precede major earthquakes[1,2]. Based on field measurements using a portable instrument, the preferred orientations of geogenic electromagnetic radiation (EMR), especially the principal directions of radiation have been proved to be reproducible and are related to the stress field of the lithosphere[3–6]. Thus, the geogenic electromagnetic emission could be an important precursor of active deformation of the earth's crust[7,8]. Although it is a fairly new technique in the geoscience arena, there are some examples where EMR was used to decipher crustal stress orientations. Using this technique, maximum principal horizontal stress azimuth of N103°E was measured in the Upper Rhine Graben near the Odenwald mountains in Germany[5]. In the Kachchh region of western India, EMR yielded a mean SH_{max} (maximum horizontal stress) azimuth of N60°E (ref. 6). This technique is also used for quantitative measurement of stresses inside a tunnel. The azimuth for the major principal horizontal stress was calculated to be N143°E around the Feuerberg tunnel in Germany[3]. The technique was also used to decipher the horizontal stress azimuth in the Lower Muschelkalk region of Northern Baden-Württemberg, Germany[4]. The mean SH_{max} azimuth was calculated to be N137°E, which tallies with the *in situ* stress measurements calculated using other techniques.

Exhumation joints have been classically used by geologists to decipher the direction of recent stresses and those during uplift[9]. Conjugate exhumation joints develop due to shear failure of a rock when it relaxes during its uplift or later in response to the recent stresses. Acute bisector of a conjugate joint set can indicate the direction of maximum stress. If the joints are observed on a horizontal bedding plane and the joint faces are vertical, the derived stress azimuth can indicate the direction of maximum horizontal stress (SH_{max}) or the direction of maximum compression.

In this study, we have derived SH_{max} azimuth in a geological site near Bhopal, India using both methods mentioned above, and compared the corresponding results. The similarities observed in the results corroborate for the accuracy of the EMR technique in such applications. As location-specific stress data are relatively scarce, the results should encourage scientists to adopt the EMR technique for recent surface stress estimation. The site was chosen because Bhopal is situated in the heart of stable continental Indian peninsula and away from any known active fault; hence the derived stress orientation should represent that of the regional stress and possibly have not been modified by pre-existing discontinuities. The exposed rocks around Bhopal are either Deccan basalt or sandstone equivalent to Rewa or Bhander group from the Vindhyan super group. The rocks are exposed as inliers and are geomorphically distributed in small hills in and around the city of Bhopal.

The emission of low-frequency electromagnetic signals associated with rock fracturing has been essentially attributed to the concept of the earth's crust acting as charging electric battery under increasing strain, analogous to the concept of piezoelectricity. The electric charges are released by activation of dormant charge carriers in the oxygen anion sublattice (peroxy bonds or positive hole pairs). The intermittent and erratic occurrences of EM signals are the results of increasing build-up of the charges in the earth's crust. They get released when crack networks percolate through the stressed rock volumes as a result of onset of nucleation[8]. The damage zone at the tip of an existing fracture consists of multiple microcracks with high stress concentrations oriented with respect to the fracture zone. Since nanocracks and microcracks are the sources of geogenic EMR emission, it is possible to determine the high stress regions or zones by measuring EMR being emitted much before any macroscopic failure[10]. EMR associated with microcracks was observed in all kinds of rocks as well as in glass, ceramics, metals and ice[11–14]. Since fracture propagation is always accompanied by microcrack formation, initiation of an active movement along a plane would produce anomalous EMR signals in contrast to the stable surroundings. The principal directions of emissions are well reproducible and seem to be geometrically related to the stress field of the lithosphere[3–5,15,16].

EMR was measured using ANGEL-M (VNIMI JSC, Russia), which is a portable measurement device that enables reception of radiation caused by processes of rock destruction. Its major components consist of a ferrite aerial, microprocessor-controlled receiver, analog–digital converter, digital logical circuit, interface card and RAM (Figure 1 *a*). The portable instrument can measure only a restricted frequency range from 5 to 150 kHz. The amplifier is capable of the amplification between frequencies 60 and 90 dB (decibels). The EMR signal received is converted into digital data by the analog–digital converter. During an individual measurement, all impulses higher than a distinction level are counted for a time interval of 10 sec. The data are stored in the RAM and transferred to a PC using the interface. The aerial is initially oriented towards the north using a compass, while its long axis is kept horizontal (Figure 1 *b*). It is then rotated clockwise, and at each 5° interval EMR amplitude is measured. The process continues until it completes a full circle. A complete horizontal measurement of total 360° rotation comprises 72 individual measurements. The horizontal measurements are analysed using polar diagrams (Figure 1 *c* and *d*).

Such EMR measurements were done at two nearby places which are located around 200 m away from each other. The site for measurement was chosen in such a way that any visible anthropogenic interfering source like high-voltage electric cable which affects the result, can be avoided. Figure 1 *c* and *d* shows the 360° distribution of normalized EMR amplitudes. The result clearly suggests that the distribution is sensitive to direction and the higher amplitudes are clearly oriented along ENE–WSW (70° and 75° respectively). As the principal direction of EMR emission is thought to be associated with the direction of maximum compression, SH_{max} azimuth of this area can be assigned as N70°–75°E.

This rock exposure located near the Bhopal central jail is made of massive Bhopal sandstone, which is equivalent to the Vindhyan super group. The exposure preserves a number of conjugate exhumation joints (Figure 2 *a*) which are consistently oriented geographically. Thirty-one joint azimuth data were collected and plotted in a rose diagram (Figure 2 *b*). The dominant joint set of the conjugate pair is oriented along N300°E and the other set is oriented along N40°E. The mean acute bisector of these conjugate joint sets should be oriented along N80°E. Hence the SH_{max} azimuth should also be the same.

The SH_{max} azimuths derived from both measurements are close to each other. Figure 2 *c* shows the stress azimuth distribution of Southeast Asia (Source: World Stress Map: http://www.world-stress-map.org/). Figure 2 *c* shows that there are no recorded stress data near Bhopal by any other methods like earthquake focal point mechanism, borehole break out, etc. The nearest data come from Jabalpur, Madhya Pradesh (NNW–SSE) and near Vadodara, Gujarat, Western India (NNE–SSW). The results derived from the EMR measurements seem to be consistent, although they could not be compared with data derived using other conventional methods from the same location.

Hence we compare EMR-derived stress orientation with the same calculated using different techniques in two other locations. The principal stress orientation obtained from focal plane solution at the epicentre of the Jabalpur earthquake (1997) shows an azimuth of N164°E. EMR reading has been taken at the same location yielding a stress azimuth of N155°E (Figure 2 *c*, right blow-up). We expect this slight deviation in the reading due to the fact that the depth from which the focal plane measurement is obtained is approximately 38 km, while the skin depth of EMR pulses is roughly 1 km. Gowd *et al.*[17] provide a list of stress azimuth measurements by *in situ* hydrofracture technique in the Mid-continental Stress Province of India. The measurements are from Hyderabad, Malanjhkhand (90 km northeast of Balaghat district in Madhya Pradesh), Tatanagar (or Jamshedpur in the state of Jharkhand), and Udaipur, and vary between N31°E and N73°E (ref. 17). These measurements represent shallow subsurface stresses (depth ranging from 150 to 345 m (ref. 17)). Geographically, these locations are at least 250 km away from Jabalpur, and hold significantly different geological and structural settings. Hence a difference in stress azimuth from EMR measurements at Jabalpur and the same from hydrofracture measurements at these locations is expected.

Previously, SH_{max} azimuth was calculated to be N60°E in the Kachchh region by EMR technique (Figure 2 *c*, left blow-up)[6]. The mean azimuths calculated from earthquake focal point solution as listed in the World Stress Map (http://www.worldstress-map.org/) and as described in previous publications[17] are oriented along north–south with few degrees of deviation on either side. The difference is attributed to the curving/rotation of principal stresses at depth from being

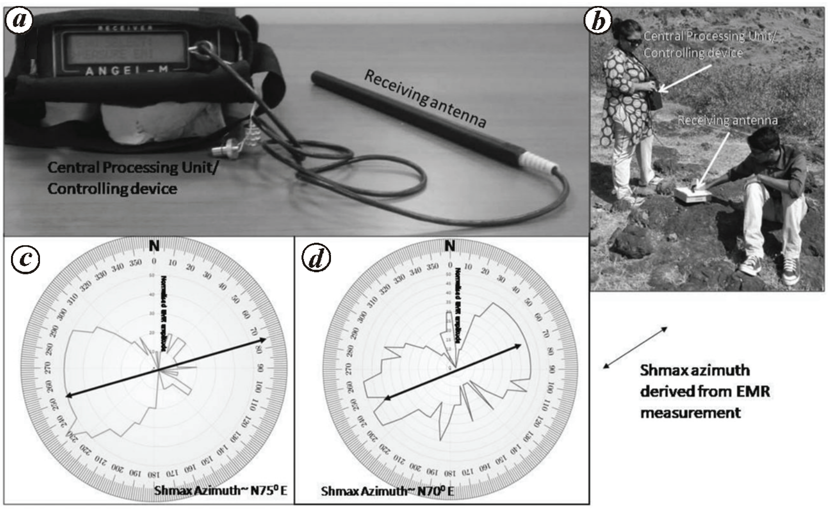

Figure 1. Electromagnetic radiation (EMR) measuring device, measurement process and results. ***a***, Portable EMR measurement device (ANGEL-M) and its different components. ***b***, Measurement of horizontal stress azimuth in the field. ***c***, ***d***, A 360 degree normalized EMR amplitude distribution in two locations.

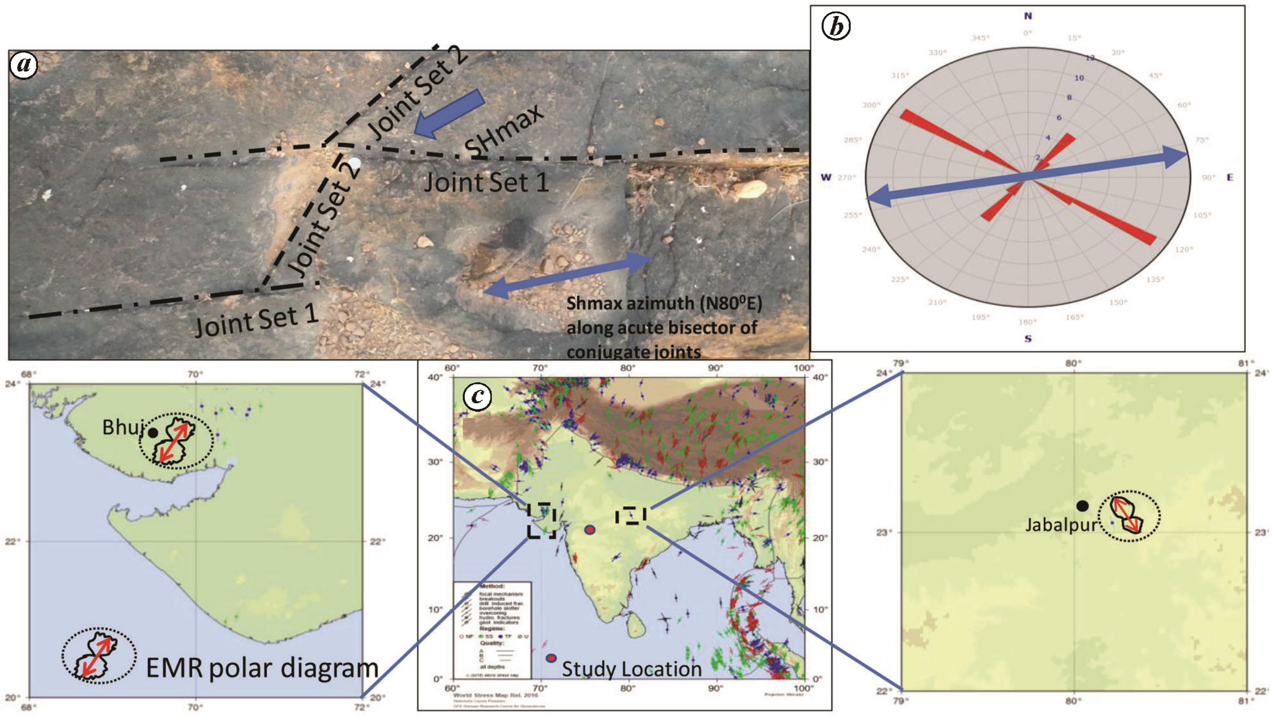

Figure 2. ***a***, Field photograph of conjugate exhumation joints. ***b***, Rose diagram showing angular distribution of joint strike direction. ***c***, Stress azimuth distribution in the Indian subcontinent. Blow-up to the right shows comparison of stress azimuth data near Jabalpur derived from EMR and earthquake focal point solution. Blow-up to the left shows comparison of stress azimuth data near Kachchh (Bhuj) derived from EMR and other techniques like earthquake focal point solution.

strictly vertical or horizontal due to additional shear stresses applied[6]. Also, earthquake focal point solution mostly provides stress orientation related to one fault responsible for the earthquake, whereas EMR technique provides regional stress orientations.

Although EMR technique is widely used in the mining industry, its application in geological studies is rather new. The primary aim of this note is to create awareness about this technique amongst geologists for such application. EMR is a quick and simple technique that can be used to decipher stress azimuth for a wider area in a limited period of time. The result is consistent with other conventional techniques.

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