SBGf31199

Three-component TEM method for improved location of fracture-zone aquifers in deeply-weathered basement terrains: First field test in northeast Brazil.

Maxwell A. Meju* and Sergio L. Fontes+

*University of Leicester, Leicester, England / +Observatório Nacional, Rio de Janeiro, Brazil.

ABSTRACT

The transient electromagnetic (TEM) method has capability for probing great depths but is not widely used in fractured hard-rock hydrogeological investigations and so far, only the vertical component of the transient response is used in routine studies of clastic aquifers. At a granitic test site where the weathered mantle is more than 60m thick across a known prolific (21000 l/hr) fracture-zone aquifer, three-component central-loop and short-offset TEM recordings are found to enable accurate location of the steep conductive target. The fracture-zone anomaly is band-limited in the horizontal and vertical component data. The across-strike voltage response (V_x) is found to be most diagnostic of concealed contacts, and so are the associated V_x/V_z ratios. The vertical component (V_z) response is less diagnostic of the fracture-zone but the response profiles show discernible patterns at some delay times. We recommend that horizontal component TEM data should be recorded in routine investigations of fractured crystalline terrains.

INTRODUCTION

The transient electromagnetic (TEM) method is now widely used in hydrogeological, environmental and mining investigations. The transient response may be the secondary magnetic field (H) or the voltage (V) response to inductive energization of the ground. The vertical voltage response is measured in the field using a receiver (Rx) which may be a small multi-turn coil or a larger wire-loop in routine hydrogeological investigations. The use of horizontal component TEM data is not common in hydrogeological studies of fractured crystalline rocks. Interestingly, numerous field studies in complex mining environments (e.g., Fokin, 1971; Fouques et al., 1986; Peters and de Angelis, 1987) and numerical and physical-scale modeling studies (e.g., Newman et al., 1987; Wilt and Williams, 1989) have shown that the horizontal components of the TEM response can pin-point the location of anomalous conductivity or geological contacts. Measurements across elongate steeply-dipping conductors may show anomalous signatures in the vertical component (V_z) and across-strike horizontal component (V_x) of the transient response enabling the location of concealed target bodies. The along-strike horizontal component (V_y) of the transient response is typically subdued but may become prominent where there are other off-line conductors oriented at oblique angles to the TEM survey line. Using central-loop soundings across an outcropping contact in a physical-scale model, Wilt and Williams (1989) showed that the horizontal magnetic fields in the centre of the loop are diagnostic of contact effect (in the form of a peaked anomaly located near, or centered over, the contact especially at early times). For a concealed 3-D conductive target in a layered medium, the horizontal fields may show characteristic sign reversals with peak amplitudes near the flanks of the target body where there is maximum concentration of induced vortex current (Newman et al., 1987); the ratios of the horizontal to vertical fields in the middle of the transmitter (Tx) loop would also exhibit such characteristic variations (see Spies, 1988, Fig. 9). Newman et al. (1987) also showed that when the transmitter (Tx) loop is positioned directly over the conductor's center, the central-loop horizontal response is several orders of magnitude smaller than at other Tx locations.

From geological considerations, it can be expected that the intensively dissected upper parts of a fracture-zone in a crystalline rock mass will be more susceptible to weathering than the surrounding relatively solid rock. A weathered fracture-zone in a basement terrain may thus be characterised by the presence of tabular or elongate preferentially weathered surficial zones (consisting of leached or mottled upper zone and underlying highly conductive saprolite zone) and a discordant transition zone of partial weathering above fresh bedrock (Meju and Fontes, 1999). For the horizontal component profiles over such a structure, we expect the across-strike transient response to peak on the flanks of the conductive fracture-zone and be depressed over its center such that a prospective target may be defined by a weak response flanked by two large responses of opposite polarity in dual-loop measurements (cf. Newman et al., 1987). For single-loop vertical component measurements across fracture-zones, twin-peak anomalies would be expected over near-vertical conductive structures and a single peak anomaly over flat 3-D surficial weathered structures as known from mining applications.

Efficient three-component TEM receivers are now available and it will be interesting to gauge the importance of horizontal component TEM recordings in a fractured-rock hydrogeological setting. With state-of-the-art highly portable TEM equipment (e.g., Geonics Protem47, Sirotem Mk3, Zonge NanoTEM and Bison TDEM-2000), it is possible to image deep basement features of hydrogeological significance even in areas with very thick (>60m) conductive overburden. In this paper, we examine the detection characteristics of three-component TEM responses obtained using small-loop profiling techniques across a known aquiferous fracture-zone in a granitic basement terrain in Piaui State in northeast Brazil. The fracture-zone is covered by about 60m thick weathered materials.

CURRAIS TEST SURVEY

The village of Currais is located south of the city of Sao Raimundo Nonato in southeast Piaui State. The site map is shown in Figure 1. On aerial photographs, there appears to be a NE-SW linear feature in the vicinity of the village. A 62 m deep borehole, located with the aid of dc resistivity profiling across the photolineament by a geophysical company (Geofisica - Geological Services Ltd, Fortaleza, 1997), found water in the weathered (fractured?) zone and gave a yield of 21000 l/h. The Currais site is underlain by strongly foliated granite which outcrops in a dry stream valley near the borehole site (Figure 1). The granite outcrop is lenticular in shape with a sharp, steeply-dipping (~80^0) southeastern flank between the borehole site and the stream channel. There is a thick lateritic cover especially over the southeastern part of the site.

Three-component TEM measurements

In September 1997, we recorded three-component TEM data across the borehole site using the Sirotem Mk3 equipment with contiguous 20 m-sided Tx loops. Operationally, for each Tx loop position, data are first acquired in the central-loop configuration and then with the receiver (Rx) coil positioned outside the Tx loop at 20 m offset (i.e. at the next Tx loop centre along the line and thus sampling the intermediate position between contiguous Tx loops); the time taken to complete this sequence of operations - including Tx loop layout - ranged from about 8 to 20 minutes at this site. However, only 128 samples were stacked for each time-window to achieve these recording times. The Sirotem receiver (model RVR-3X) was used for the measurements. This receiver simultaneously measures the vertical and two orthogonal horizontal components of the induced-voltage response (V_z, V_x and V_y); the output of each axis is provided independently from 3 separate amplifiers in a central enclosure and each sensor coil has an effective area of 10^4 m^2. Every effort was made during system set-up to accurately position the Rx coil, and the Sirotem Mk3 equipment has facility for sferic rejection (i.e., for minimization of natural EM noise). The 180m long survey line is offset to the east of, and approximately centered on, the existing borehole (based on the trace of the lineament, the projected position of the well is around position 100 m on the TEM survey line).

The central-loop V_z profiles are complex at delay times earlier than 0.197 ms. The profiles for delay times of 0.245 to 1.133 ms are shown in Figure 2 and are characterised by a broad zone of low amplitude response centered on the borehole location (position 100 m) with bordering zones of somewhat larger size responses. The V_z profiles for the short-offset TEM (SOTEM) technique are of negative polarity at delay times earlier than 0.197 ms. Sample profiles (0.245 to 1.133 ms) are presented in Figure 3 and show marked peak migration of anomaly. At delay times of 0.197 to 0.293 ms, the largest amplitudes occur at locations 30 to 50 m and at location 170 m; these are probably undesirable overburden signatures. The later time profiles show a potentially prospective trend and peak migration. At delay times of 0.341 to over 1 ms, the largest amplitude is seen at location 90 m and we interpret this as the signature of the concealed steep fracture-zone.

Sample across-strike horizontal component (V_x) profile data (0.245 to 1.133 ms) from the 3-component recordings are shown in Figures 4 and 5 for the central-loop and SOTEM configurations respectively. For both techniques, we found that the V_x values are largest near the inferred position of the prolific fracture-zone and there are consistent sign reversals possibly over the middle of the fracture-zone in the time bandwidth 0.245 to 1.133 ms for the SOTEM arrangement and 0.245 to 0.5 ms in the central-loop case. The observed response patterns are in accord with those known from numerical and physical-scale modeling studies (Newman et al., 1987; Wilt and Williams, 1989). Thus, horizontal TEM recordings may be used independently to locate the target fracture-zone at this site. Although not presented here, the profiles of the V_x/V_z ratios also showed diagnostic sign reversals and large amplitudes at the flanks of the known target-zone. The along-strike horizontal component (V_y) response is of very small magnitude within the zone of anomalous V_x response as expected from geometrical considerations; a large amplitude response occurs at positions 30 to 50 m at early times (see Figure 6) possibly suggesting the presence of a cross-cutting surficial feature in that locality.

COMPARISON OF LOOP-COIL AND SINGLE-LOOP V_z PROFILES

Single-loop V_z data were recorded using the same Tx loops employed for the central-loop and SOTEM profiling along the test survey line for comparison. The single-loop induced-voltage profiles for some delay times (0.059 to 0.605 ms) are presented in Figure 7. Note the anomalous zone stretching from position 80 to 120 m in this figure. There is a single-peak anomaly at early delay times. This particular band-limited V_z anomaly suggests the presence of a flat surficial conductor across the borehole location. At later times the borehole location is characterised by a low amplitude response with flanking zones of high amplitude response; this prominent twin-peak anomaly is indicative of the presence of a steep conductive feature at the borehole site. The observed single-loop early and late time response patterns are thus in accord with what would be expected over a steep conductive zone capped by a preferentially weathered, conductive overburden. It is of exploration interest that the response pattern seems to suggest that the position of the steep target zone may be more confidently identified using single-loop V_z measurements (at sufficiently early times) than is the case for the central-loop and SOTEM configurations.

CONCLUSION

We have demonstrated that three-component dual-loop TEM techniques can be successfully adapted to the search for an aquiferous fracture-zone at a granitic test site with about 60m weathered overburden. Using central-loop and short-offset TEM configurations, we found that the horizontal component data can pin-point the location of the deeply concealed steep fracture-zone much more accurately than the vertical component data. The vertical component data recorded with the Sirotem Mk3 field equipment in the single-loop configuration was more diagnostic than those obtained using dual-loop geometries at this particular test site. We recommend that early-time 3-component TEM surveys should be incorporated in routine fracture-zone mapping in the crystalline basement terrains of northeast Brazil. Although we have successfully detected diagnostic fracture-zone anomalies using 20 m station intervals, we recommend the use of smaller station intervals (not more than 10m) in such surveys so as to resolve any possible short-wavelength anomalies.

Sixth International Congress of the Brazilian Geophysical Society

REFERENCES

Fokin, A.F., 1971, Method perekhodnikh protsessov pri poickakh mestorozdeniy sulfidnikh rud: Nedra, Leningrad.

Fouques, J.P., Fowler, M., Knipping, H.D. and Schimann, K., 1986, The Cigar Lake Uranium deposit: discovery and general characteristics, Can. Inst. Min. Metallurgy Bull.,79 (886), 70-86.

Meju, M.A. and Fontes, S.L.,1999, The use of TEM, HLEM and dc resistivity methods to locate fracture-zone aquifers in lateritized deeply-weathered crystalline basement terrains in Piaui State, northeast Brazil: Geophysics.

Newman, G.A., Hohmann, G.W. and Anderson, W.L., 1986, Transient electromagnetic response of a three-dimensional body in a layerered-earth: Geophysics, 51, 1608-1627.

Newman, G.A., Anderson, W.L., and Hohmann, G.W., 1987, Interpretation of transient electromagnetic soundings over three-dimensional structures for the central-loop configuration: Geophys. J. R. Astr. Soc., 89, 889-914.

Peters, W.S. and de Angelis, M., 1987, The Radio Hill Ni-Cu massive sulphide deposit: a geophysical case history: Explor. Geophys., 18, 160-166.

Spies, B.R., 1988, Local noise prediction filtering for central induction transient electromagnetic sounding: Geophysics, 53,1068-1080.

Wilt, M.J., Becker, A. and Morrison, H.F., 1986, Effects of vertical contacts on time domain electromagnetic sounding: Extended Abstracts, SEG annual meeting, Houston, Texas 177-180.

Wilt, M.J. and Williams, J.P., 1989, Layered model inversion of central-loop EM soundings near a geological contact: Explor. Geophys., 20(1/2), 71-73.

ACKNOWLEDGMENTS

The authors thank CAPES, The British Council in Rio de Janeiro and the mayor of Sao Raimundo Nonato for financial support. Logistical support from CPRM (Residência Teresina) and IBAMA (Superintendência Piauí) is also acknowledged. We are grateful to Emin Ulugergerli, Carlos R. Germano, Emanuele F. La Terra and Ronaldo M. Carvalho for field assistance.

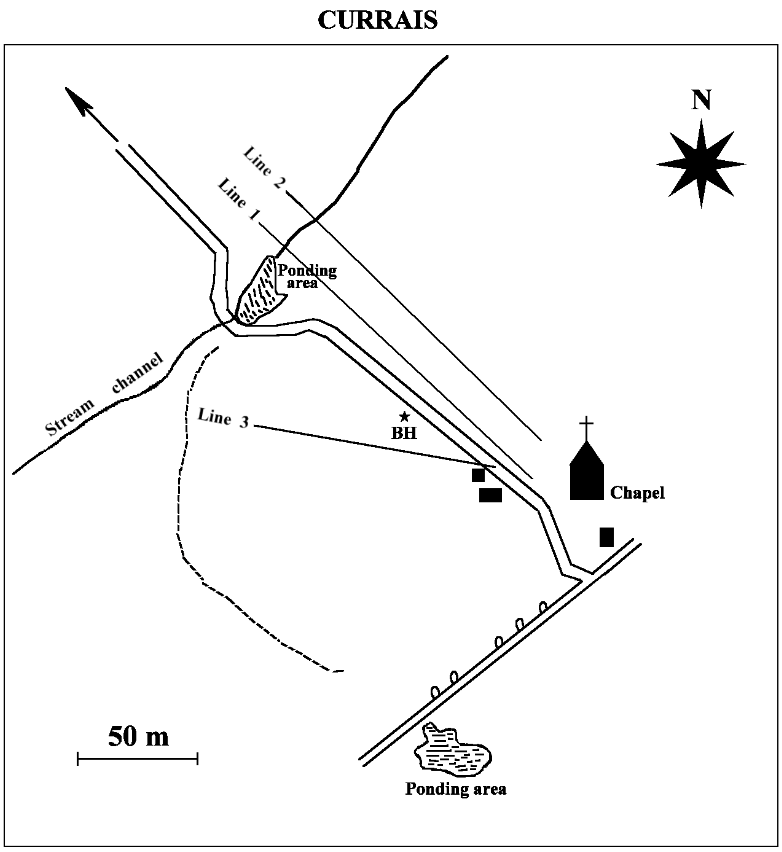

FIG. 1. Currais site plan. The locations of the borehole and the geophysical survey line are indicated.

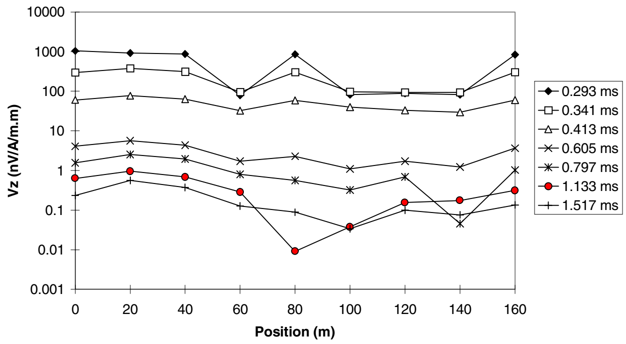

FIG. 2. Sample central-loop vertical component TEM data from Currais. The Tx loops are 20 m on a side.

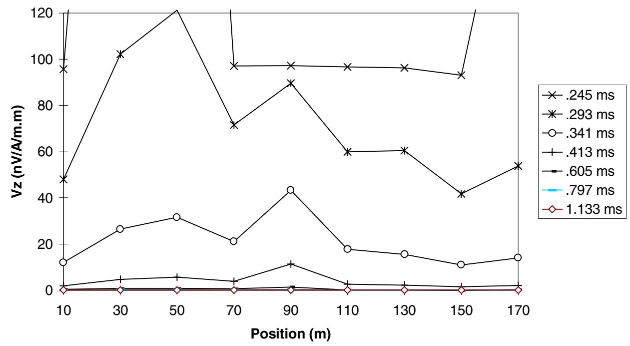

FIG. 3. Examples of SOTEM vertical-component data. from Currais.

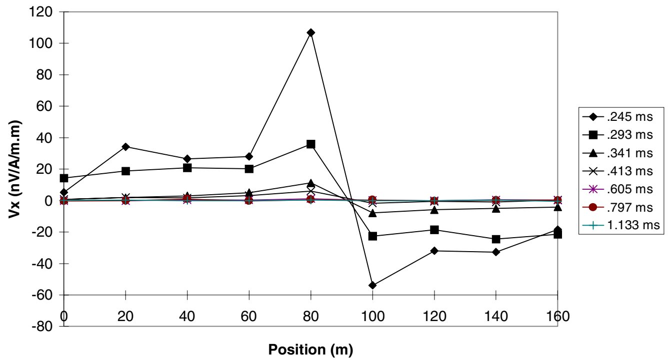

FIG. 4. Central-loop across-strike horizontal-component data.

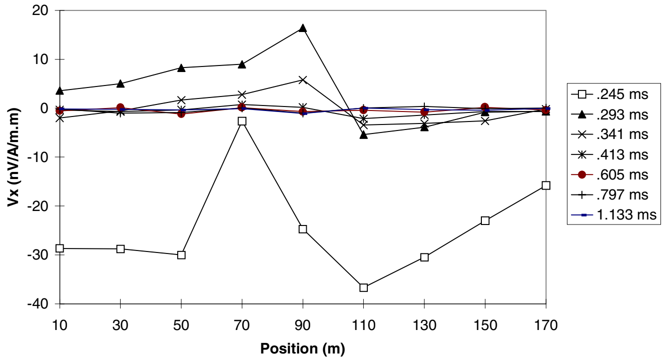

FIG. 5. SOTEM across-strike horizontal-component data.

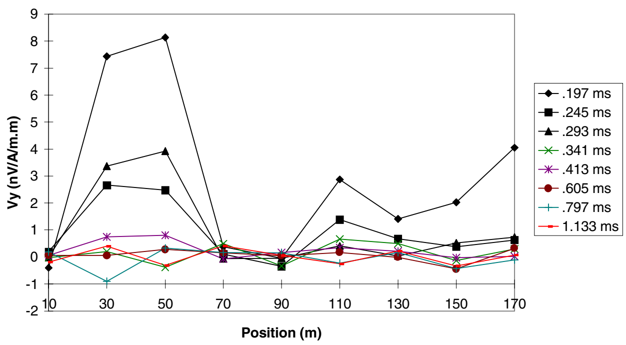

FIG. 6. SOTEM along-strike horizontal-component data.

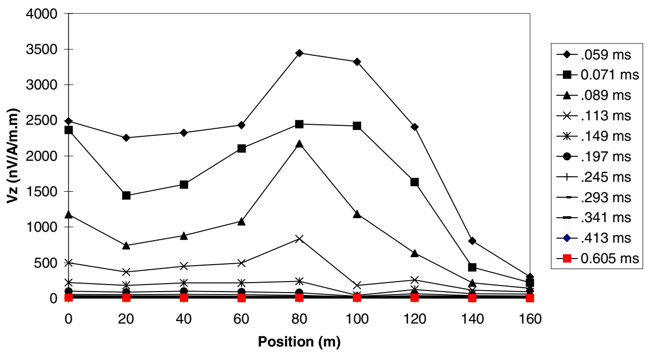

FIG. 7. Sample vertical component data from 20m-sided single-loop profiling.

Sixth International Congress of the Brazilian Geophysical Society