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A combined HLEM-TEM approach to well-siting in deeply-weathered granitic terrains in Piaui State, Brazil.

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ABSTRACT

The location of prolific fracture-zone aquifers under a thick (> 50m) weathered mantle is a major hydrogeological problem. This paper proposes the use of combined HLEM and TEM profiling techniques for improved mapping of concealed fracture-zones in basement areas affected by deep lateritic weathering. In 1997, the prefecture of São Raimundo Nonato in southern Piaui State of Brazil initiated a major groundwater development scheme in rural basement areas. The first phase of the project involved the use of geophysical methods to accurately locate drilling sites in several villages in the region. The weathered mantle is more than 50m thick in the dominantly granitic terrain and we jointly deployed the HLEM and TEM methods at all the sites and obtained concordant results. Several examples of the results of this borehole siting program are presented in which 100 percent success was achieved using the combined TEM-HLEM approach.

INTRODUCTION

Parts of Piaui State in northeast Brazil consist of crystalline rocks - mostly metasediments of low to intermediate metamorphic grade and some granitic rocks, all affected by faulting and fracturing. Rainfall is low in the region (<400mm per year and confined to the period November to March) but *in situ* chemical weathering has led to the formation of a weathered mantle (of variable thickness) over the crystalline basement rocks. Useable groundwater has been abstracted from the base of the weathered layer in parts of the crystalline terrain at shallow depths (<20 m) using large-bore wells dug by traditional means. However, these shallow aquifers in the weathered zone are often contaminated and have low yields especially during the dry season and the typical problem is how to identify deep-reaching fracture zones where significant quantities of good quality water can be found and cheaply abstracted.

Palacky, Ritsema and de Jong (1981) successfully applied frequency domain EM (HLEM and VLF) and dc resistivity profiling techniques in groundwater exploration programs in Precambrian crystalline basement terrains in Burkina Faso. Their results demonstrated that the cost-effective HLEM (and to some extent VLF) methods are well suited to the problem of finding vertical conductive features at depths that are easily accessible using low-cost drilling technology in such terrains. Most of the subsequent accounts of groundwater prospecting in crystalline basement terrains (e.g., Lindqvist, 1987; Beeson and Jones, 1988; Edet,1990) lean heavily on this landmark case study, and the more successful ones employed the combined approach involving dc resistivity and HLEM techniques. Lindqvist (1987) emphasized the special importance of the HLEM component in hard-rock terrains since it is capable of pin-pointing steep, narrow fracture-zones that may sometimes be missed by resistivity depth probing. Numerous field studies in mining environments (e.g., Fokin, 1971; Peters and de Angelis, 1987) have shown that the TEM method can pin-point the location of anomalous conductivity or geological contacts and we therefore decided to evaluate the utility of TEM profiling with small (10-25 m-sided) loops in fractured-rock hydrogeological settings. We envisaged that combining HLEM and TEM methods would improve our depth imaging capability and target identification. The results of intensive borehole siting campaigns in several villages underlain by granite are presented in this paper. These are landmark case studies since the boreholes previously sited using geological information and aerial photography were found to be dry, and we achieved 100 percent success using HLEM-TEM approach which proved to be a turning point in the history of drilling for groundwater in basement rocks in the area.

WELL-SITING USING COMBINED TEM-HLEM APPROACH

The HLEM method is well-established in fractured-rock hydrogeology. However, the potency of the conventional HLEM method decreases with increasing thickness of conductive overburden. The transient electromagnetic (TEM) method has better capability for probing beneath thick conductive overburden and has proved to be a powerful tool for detecting deeply-concealed targets in mining environments. Combining these two methods would lead to a more powerful approach to fracture-zone detection in areas with thick weathered mantle. The basement terrain south of São Raimundo Nonato (Fig 1) is deeply weathered (Meju and Fontes,1999) and since dc resistivity profiling will be time-consuming and difficult in this dry terrain (see Meju et al., 1999) with significant outcrops of granitic rocks, the HLEM and TEM methods were selected as the tools with the optimum potential for well-siting in the prospective areas (see Fig 1). Nine sites were investigated between July and September 1997 using the HLEM-TEM approach in the first phase of the campaign, and all the boreholes drilled at the recommended sites were successful. Sample surveys in some villages with previously unsuccessful boreholes (Calango, Moisés, Morro do Algodão, Firmeza) are described here. A Tx-Rx separation of 50 m was adopted in all the HLEM surveys and data were recorded for 8 frequencies (14080, 7040, 3520, 1760, 880, 440, 220 and 110 Hz) using the APEX Max-Min II equipment. Two Sirotem Mk3 equipment were available for the TEM surveys. The adopted approach for each site was to perform HLEM profiling and single-loop TEM soundings with 10m- or 20 m-sided loops, identify any anomalous features common to both methods, and then conduct TEM soundings with a larger-size loop to help constrain our estimates of depths to potential drilling targets. This means that the surveys sometimes took a few days to complete at some sites especially where there is a scarcity of anomalies and several line kilometers had to be surveyed to find a drillable target. Also, the high daytime temperatures (ca. 40^{o}C) during the field campaign period and the hostile vegetation limited the survey speed to some extent (clear paths sometimes had to be cut through the thorny bush for the survey lines).

Calango site

This is a small farm settlement (see Fig 1 for location) whose inhabitants depend on a small stream south of the survey site during the rainy season and on sources located several kilometres away in the long (6 months) dry season when the local stream is dry. The underlying geology is granitic but there is no hardrock outcrop at this site; it is covered by laterite except in the shallow stream channel where loose dry sands are found. A borehole drilled at the site in early 1997 did not encounter groundwater. There is no major linear feature running through the village in Fig 1. An aerial photograph of this locality was re-examined to help define possible minor structural trends near the site. A 500 m long line of HLEM and TEM soundings was surveyed in August 1997 across an inferred trend with a 10m station interval. Single-loop TEM soundings were carried out with a 20 m-sided Tx loop and short-offset soundings were made using a 10 m-sided Tx loop. The HLEM results for only the interesting 275 m segment of the survey line are summarised in Fig 2. The HLEM measurements yielded anomalies in both the inphase and quadrature components at all the frequencies (and the high background values suggest deep weathering at this site). There are anomalies at comparable locations in the TEM profiles. Two prospective anomalous zones at positions 100 m and 215 m were identified along the line and ranked for drilling (see A and B in Fig 2). The anomaly at position 100m was given top priority since it appeared more conductive than the other. Inversion of TEM data predicted the depth to the sought conductive target to be about 70 m. Drilling commenced at this site on September 24, 1997 but was temporarily halted after penetrating 65m of completely weathered granite and into partly weathered biotite granite without encountering groundwater. These authors persuaded the drillers (who also drilled the previous dry well only 40 m east of position 100m) to drill to the predicted depth of 70 m; groundwater aquifer was eventually encountered at a depth of 73 m and pump tests gave a water yield of 380 l/h (Table 1).

Moisés site

There are no granite outcrops at this Moisés site which is covered by laterite and the interpreted linear features (see Fig 1) are distant from the village. A north-south survey line consisting of a 350 m long southern segment and a 900 m long northern segment was recorded so as to delineate these possible linears. HLEM and single-loop TEM soundings (with a 10m-sided loop) were made at 10m intervals along the whole line. After these initial soundings, 3-component central-loop soundings were performed (with a 50 m-sided Tx loop since increased laterite cover was suspected) over the identified anomalous locations to constrain the depths to prospective aquiferous targets. The surveys at this particular site took 3 days to complete due to site difficulties (the TEM loops are wider than the dirt track that serves as the road to the village and local labour was required to clear some paths for the large loops). The HLEM data for the northern segment of the line are presented in Fig 3. The high negative values of HLEM responses suggest the presence of thick conductive overburden. There is an interesting anomaly in both the inphase and quadrature components of the measured data at position 625 m. A narrower and less conductive zone is also suggested around position 455 m. Two potential drilling sites (locations 455 and 625 m) were selected based on these results. The anomalous zone at position 625 m was given the highest priority based on TEM considerations and was drilled to a maximum depth of 64 m during October 6-8, 1997. A very prolific aquifer was found at this site and gave a water yield of 12000 l/h (see Table 1).

Morro do Algodão site

There are granitic outcrops in the vicinity of this site. Two NE-SW trending linear features appear to run close to the village in Fig 1. Initial examination of an aerial photograph also suggested the presence of a linear feature across the site. HLEM and TEM soundings were performed over a 500 m long line. The HLEM survey employed variable (10-20 m) spacings and the results are summarised in Fig 4. There are two prospective zones (A and B in the figure) located at 170 and 275 m. The TEM profile over HLEM anomaly A is shown in Fig 5. There is a notable band-limited early time (0.047 - 0.059 ms) anomaly at 170m coincident with the HLEM anomaly. There is also a persistent TEM anomaly at abot position 130 m but this has no significant HLEM (in particular, quadrature) expression and is therefore presumed to be deep-lying and with possibly reduced potential for surface recharge. Positions 180 and 270 m were selected as the two drilling sites. One of the locations (site A in Fig 4) was given the highest priority since it has a more notable early time TEM anomaly. A new borehole drilled in September 28th 1997 was successful. The borehole gave a yield of 2000 l/h (see Table 1).

Firmeza site

According to the regional geological map, Firmeza village (Fig 1) is underlain by granitic rocks. The presence of a major NE-SW linear in the area is suggested in Fig 1 but the analysis of aerial photographs did not produce any convincing structural patterns and several long reconnaissance lines had to be surveyed in different places using the HLEM method at only three frequencies (14080, 7040 and 3520 Hz). The HLEM data from the seventh transect looked the most attractive and the results are summarised in Fig 6. Three potential anomalous zones are visible in the profiles (around positions 70, 380 and 560 m) and the high background values suggest deep weathering at this site. A follow-up TEM survey was carried out along this line. Single-loop TEM soundings were completed over a 450 m segment of the HLEM profile using contiguous 20 m-sided loops. The TEM profiles for some delay times are shown in Fig 7 togetther with a pseudo-section based on the simple Bostick transformation. Note the distinct anomaly centered around position 75 m at delay times of 0.11 to 0.293 ms and the smaller amplitude anomaly at position 395m. The two positions with coincident HLEM and TEM conductivity anomalies and another one at position 565 m (based only on HLEM data) were selected as the drilling points. The drilling target at position 70 m was given the highest priority and was drilled to a maximum depth of 54m during October 2-4, 1997. The borehole encountered groundwater and pump tests gave a yield of 2000 l/h (see Table 1).

CONCLUSION

Groundwater occurs in fracture-zones in basement rocks and remote sensing and HLEM/dc resistivity techniques have been used in the past to locate aquiferous targets. When the basement rocks are covered by thick (>60m) thick weathred layer, the search problem is froth with difficulties and uncertainties. In this problematic situation, we suggest that a combined HLEM-TEM approach has the best potential for successful mapping of prolific fracture-zone aquifers. Several examples of successful application of the combined TEM-HLEM methods in borehole-siting over deeply-weathered granites in Piaui State of northeast Brazil have been presented to support our exploration model and to demonstrate the potency of the joint EM approach.

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REFERENCES

Beeson, S. and Jones, C.R.C., 1988, The combined EMT/VES geophysical method for siting boreholes: Groundwater, 26, 54-63.

Edet, A.E., 1990, Application of photogeologic and electromagnetic techniques to groundwater exploration in northwestern Nigeria: Journ. African Earth Sciences, ***11****, 321-328.*

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

Fontes, S.L., Meju, M.A., Lima, J.P.R., Carvalho, R.M., La Terra, E.F., Germano, C.R. and Metelo, M., 1997, Geophysical investigation of major structural controls on groundwater distribution, north of São Raimundo Nonato, Piaui State: 5th Internat. Congr. Brazil. Geophys. Soc., Expanded Abstracts , 766-769.

Lindqvist, J.G., 1987, Use of electromagnetic techniques for groundwater exploration in Africa: Geophysics, ***52****, 456-458.*

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

Meju, M.A., Fontes, S.L., Oliveira, M.F.B., Lima, J.P.R., Ulugergerli, E.U., and Carrasquilla, A.A.,1999, Regional aquifer mapping using combined VES-TEM- AMT/EMAP methods in the semi-arid eastern margin of Parnaiba Basin, Brazil: Geophysics, ***64****, no. 2, 337-356.*

Palacky, G.J., Ritsema, I.L. and De Jong, S.J., 1981, Electromagnetic prospecting for groundwater in Precambrian terrains in the Republic of Upper Volta: Geophys. Prosp., ***29****, 932-955.*

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.*

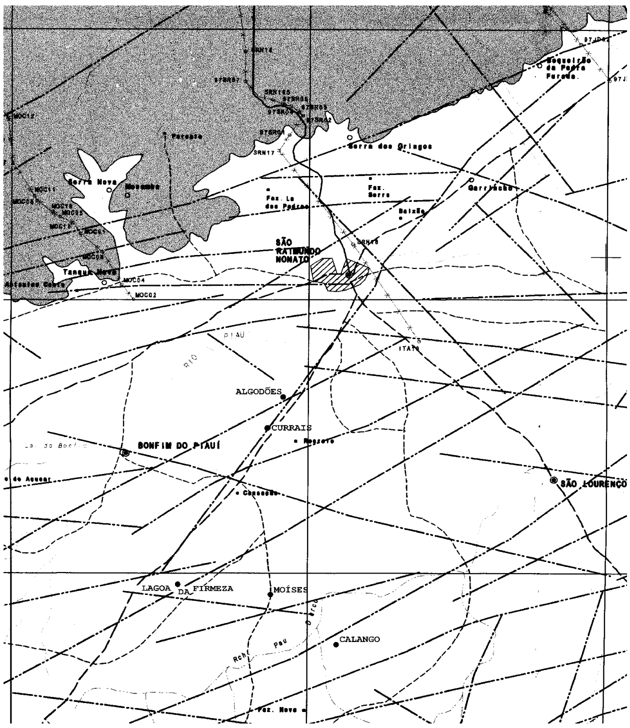

FIG.1. Map showing site locations and the main linear structural features evinced from aerial photography and the aeromagnetic map of the region south of SRN (modified from Fontes et al., 1997).

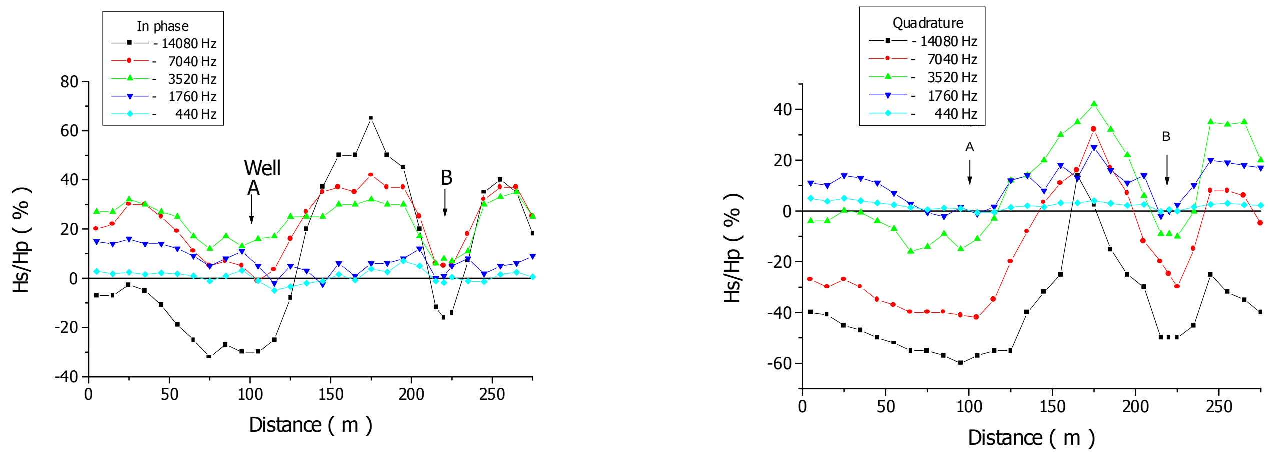

FIG. 2. HLEM profiles for Calango (Tx –Rx = 50m)

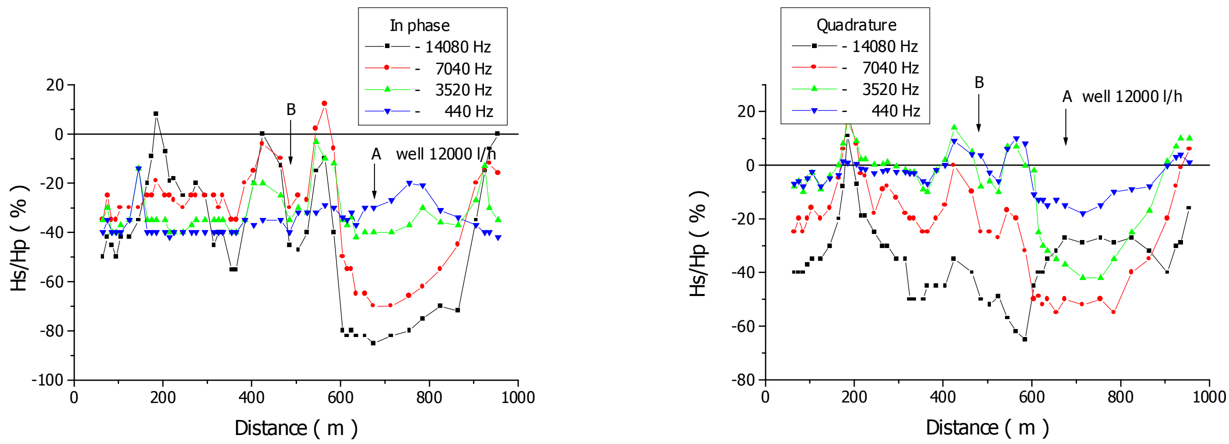

FIG.3. HLEM profiles for the northern segment of a long profile at Moises site

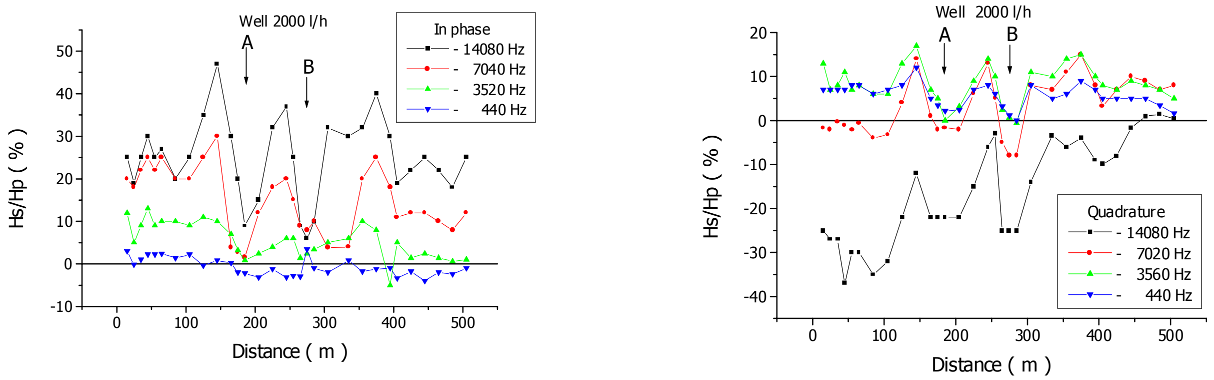

FIG. 4. HLEM profiles from Morro do Algodão site.

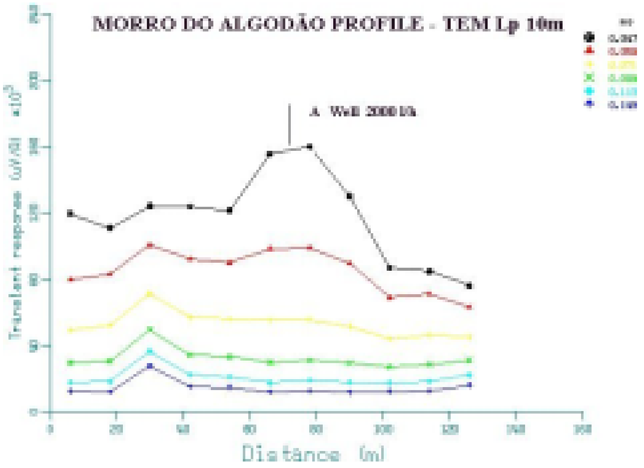

FIG. 5. TEM profiles from Morro do Algodão site

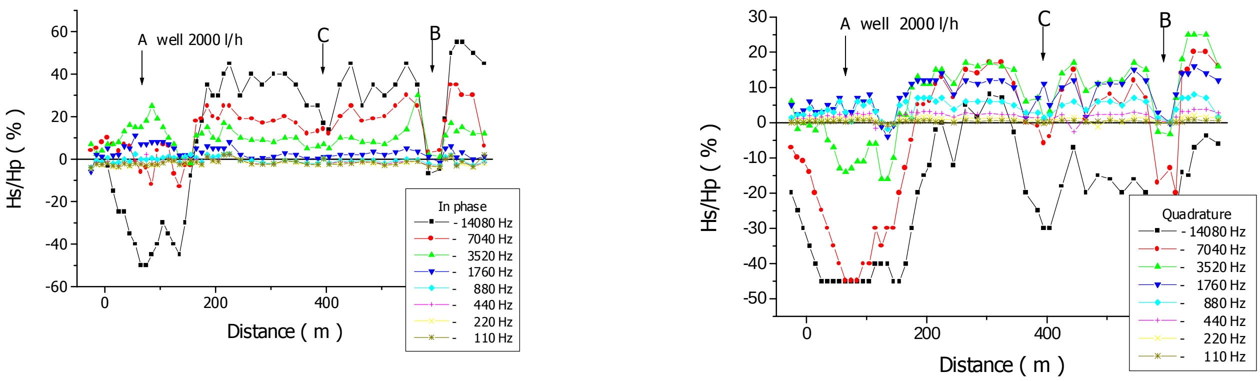

FIG. 6. HLEM profiles obtained at Firmeza

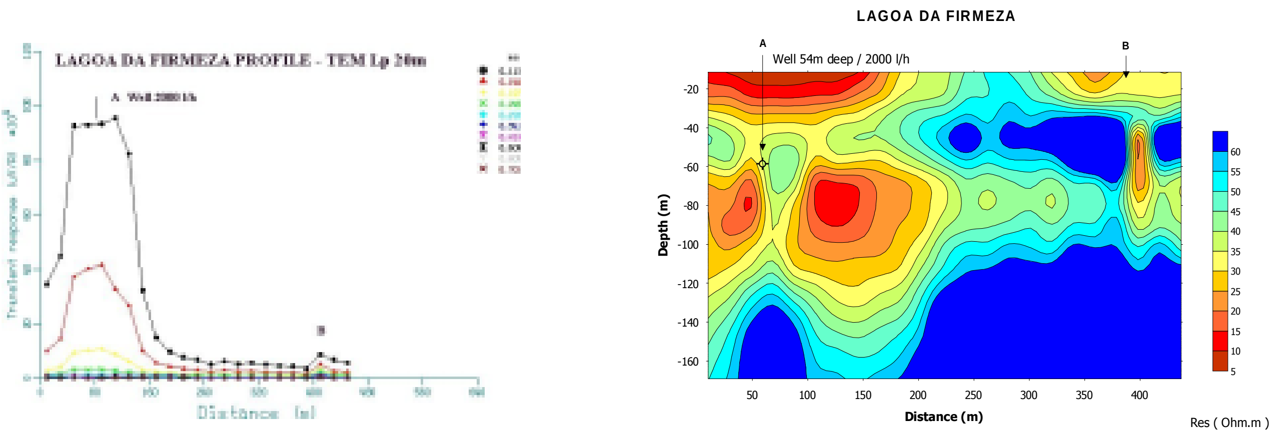

FIG. 7. TEM profiles and the Bostick pseudo-section obtained at Firmeza

Site	Terminal depth (m)	Water yield (l/h)	Static level(m)	Dynamic level(m)
Morro do Algodão	60	2000	21	43
Calango	77	380	-	-
Firmeza	54	2000	12.5	40
Moisés	64	12000	18	46

Table 1: Summary of total drilled depth, water yield and water levels at some locations in granitic basement south of São Raimundo Nonato.