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Proton Magnetic Resonance Technique in Weathered-Fractured Aquifers
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Proton Magnetic Resonance Technique in Weathered-Fractured Aquifers
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Synopsis

The region of Hyderabad (Andra Pradesh, India), with a geology essentially composed of Archean granite and its semi-arid climate, is representative of central and south India. In such a context, where the overexploitation of groundwater threatens the sustainability of agricultural development, NGRI and BRGM with the collaboration of IRD, UMR Sysiphe (Paris VI University) proposed a research project entitled “Proton Magnetic Resonance technique in weathered-fractured aquifers”, which was partly granted by the Indo-French Centre for The Promotion of Advanced Research (IFCPAR, project N°2700-W1), New-Delhi. This project aims at establishing a methodology based on the combined use of electrical and electromagnetic methods (Electrical Resistivity Tomography, ERT, Time Domain ElectroMagnetic, TDEM) for delineating subsurface water-bearing zones and Magnetic Resonance Sounding (MRS) for estimating the hydrodynamic characteristics of aquifers.

Field investigations were carried out on two hydrogeological watersheds in the Hyderabad region: the Maheshwaram and Wailpally watersheds, whose subsurfaces are composed of weathered granite. In such a hard rock context, several compartments, corresponding to various grade of weathering, constitute a composite aquifer. From the top to the base, it is composed of: saprolite, the Fissured Zone (FZ) and fresh unweathered rock. Following such a detailed aquifer schema, geophysical field data were carefully compared to borehole lithology and hydrogeological testing data. Associated with a numerical study of geophysical methods sensitivity, it has led to the following results.

Electrical and electromagnetic methods are able to qualitatively image the weathering profile and map the substratum elevation at reasonable cost. ERT is preferred to TDEM because the FZ is too resistive to be distinguished from the underlying unweathered rock by the latter technique. A reliable formation resistivity cannot be easily obtained and consequently the way to evaluating water content through Archie’s law or a similar empirical relationship is not obvious. This conclusion supports our choice of preferring MRS for this purpose.

During fieldwork, contrasted MRS responses were observed:

a) On KB Tanda rice fields (Maheshwaram watershed) in 1999 and 2003, while the water table had respectively deepened from 5 to 12 m below groundwater level (BGL);

b) In 2005, on two sites in the Wailpally watershed, where water levels are respectively at 9 m BGL in a non-irrigated area and 19 m BGL because of intense pumping.

These contrasted observations were modelled using geometrical constraints provided by detailed borehole lithology and demonstrate that MRS is able to assess the groundwater table depletion over time or spatially, in agreement with piezometric measurements and with local agricultural activities.
Working in a low water content environment, we often faced being at the detection limit of the MRS equipment. It was found that with the currently available instrumentation (NUMISPLUS), the groundwater assessment capability of the MRS method is limited. While the sensitivity of the instrument is sufficient for characterizing the water-saturated saprolite, in the FZ where the water content is much lower, the magnetic resonance signal is accordingly lower. The method sensitivity may then not be sufficient and this formation cannot be fully resolved. The MRS screening effect of the saprolite water layer on the underlying FZ is also discussed and the limit of the inversion schema of interpretation in this context is underlined.

From this analysis a geophysical model of the Hyderabad region weathered granite aquifer is proposed, where the different water-bearing zones can be distinguished by their MRS, electrical and magnetic characteristics. MRS water content estimation compared favourably with other MRS observations obtained in Burkina Faso granite, thus suggesting that these results could be extended to similar geological settings around the world.

The observed significant variations in magnetic susceptibility along the weathered profile are an indicator of potential magnetic field inhomogeneities that could significantly affect the MRS response, but it is not necessary to invoke them for interpreting the observed contrasted MRS responses since they are fully explained by water table variations.

Further development on the potential effect of magnetic field inhomogeneities and further MRS determination of FZ water content or hydraulic conductivity in this context will require a gain of at least one order of magnitude in the signal/noise (S/N) ratio. The well documented sites investigated in the Hyderabad region during this project could be the laboratory for such future experiments.
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1. Introduction

The region of Hyderabad, with its subsurface essentially composed of hard rock under a semi-arid climate, is representative of central and south India. The Green Revolution of the seventies has led to a complete inversion of the irrigation scenario with groundwater sustaining most irrigated land instead of the previously used surface water. Nowadays, the strain on groundwater resources due to the pumping of large quantities of water threatens the sustainability of agricultural development.

In such a context, NGRI and BRGM with the collaboration of IRD, UMR Sysiphe (Paris VI University) proposed a research project entitled “Proton Magnetic Resonance technique in weathered-fractured aquifers”, which was partly granted by the Indo-French Centre for The Promotion of Advanced Research (IFCPAR, project N°2700-W1). It aims at establishing an original geophysical methodology applied to groundwater evaluation in the weathered-fractured hard rock environment of the Hyderabad region.

The expected results of the project included a methodology for locating borewells on water-bearing structures/zones and evaluating water resources in hard rock terrain.

Because 2D/3D structures such as fractured or deeply weathered zones were supposed to be the target for groundwater exploration in hard rock terrain, objectives were focused on such structures using the Magnetic Resonance Sounding\(^1\) (MRS) method since it is currently the most promising and original method for this purpose. Other geophysical methods such as electrical, electromagnetic or magnetic methods can be combined with MRS and are also used and tested.

The principal tool to evaluate management scenarios for hydrosystems is groundwater modelling. One of the major prerequisites for establishing the reliability of such models is an accurate knowledge of the geometry and hydrodynamic properties of the aquifer. Borewell and pumping tests are time consuming and expensive. A reliable geophysical characterization of hard rock would indeed be a valuable tool as a complement to a hydrogeological investigation since it helps to extrapolate hydrogeological information between boreholes and makes it possible to reveal lateral variations at a reasonable cost. The proposed development would ideally effectively contribute, together with hydrogeological testing and modelling, to water resource management as well as the exploration of new resources.

Two different watersheds in the Hyderabad region (Maheshwaram and Wailpally) were investigated. They have the same geological settings composed of weathered granite.

\(^1\) The Magnetic Resonance Sounding (MRS) method is also known as the Proton Magnetic Resonance (PMR) or the Surface Nuclear Magnetic Resonance (SNMR) method.
The Maheshwaram watershed, located 30 km to the south of Hyderabad (Figure 1), was chosen as the main study area for experiments because it benefited from the experience and the large amount of data collected there by the "Indo-French Centre for Groundwater Research" (IFCGR) since 1999. The geophysical results of the present project can thus be compared to good quality hydrogeological data and also be used and built on by hydrogeologists in the framework of IFCGR activities. A preliminary geophysical investigation was previously carried out in 1999 within this watershed and demonstrated the feasibility of MRS combined with electrical and EM methods for characterizing the granitic weathered zone (Baltassat & Legtchenko 1999, Krishnamurthy et al. 2003, Descloitres M. and Robain H., 2000).

The Wailpally watershed is not as well known as the Maheshwaram watershed. The first scientific borewells and tests took place there, in September 2005, in the framework of this project in order to provide the necessary hydrogeological information for comparing and calibrating the geophysical results.

Based on the field evaluation and the numerical study of geophysical method sensitivity, this report attempts to answer the following questions:

- What are the domains and limits of application of the geophysical method in general and MRS in particular for the characterization of weathered granite aquifers?

- What is the reliability of the MRS estimation of the aquifer characteristics and how do they compare with the hydrodynamic properties?

The report would therefore like to contribute to a better geophysical characterization of the weathered granite aquifer of the Hyderabad region; such knowledge could be compared and extended to similar geological settings in central - south India and around the world.

This report is based on the analysis of selected results amongst the different field investigations conducted in the framework of the project and integrates some results from the previous 1999 geophysical survey. A more exhaustive compilation is given in three intermediary reports presented in Appendix 12, Appendix 13 and Appendix 14 on a compact disk enclosed.

The MRS 2D/3D model partly developed in the framework of this project is also presented and applied to the simulation of a surface water recharge in a paddy field.
Figure 1: Location of the Hyderabad region and test sites within the Maheshwaram watershed.
2. Hydrogeological setting

2.1. GENERAL OVERVIEW

The geological environment of the Hyderabad region is essentially composed of granite of Archean age. In such a crystalline basement, aquifers generally occupy the upper tens of metres of the subsurface profile (Detay et al. 1989), which can be divided according to a conventional conceptual model into several stratiform compartments that together constitute the aquifer, but which are characterized by distinct hydrogeological properties (Lachassagne et al., 2001, Wyns et al. 2004, Marechal et al. 2005, Dewandel et al. 2006).

These different compartments, illustrated in Figure 2, are:

- The upper compartment (alterite or saprolite) composed of weathered and decayed rocks of clayey-sandy composition. Their hydraulic conductivity is usually low, but their water-retention capacity can be significant and they play an essential storage role in the functioning of the aquifer.

- The intermediate fissured zone (FZ) is characterized by almost horizontal fractures that diminish in density with depth, and common vertical fractures and fissures that enhance flow relationships with the fractures in the bedrock. This zone is characterized by higher values of hydraulic conductivity, but also has a significant storage role.

- The underlying fresh unweathered rock is highly permeable locally, where affected by tectonic fracturing, and it has a very limited storativity.

The global geometry of this composite is mainly controlled by the weathering processes, which front are parallel to paleosurfaces and thus lead to a mainly sub-horizontal and stratiform structure (Wyns et al. 2004). However, geological features such as fault and dikes or contrasts in rock mineralogy can locally modify the characteristics of the weathering profile and lead to the development of 2D and 3D structures. These anomalies favour the development of topographic high, such as inselbergs, or topographic low at fault corridors location.

2.2. MAHESHWARAM WATERSHED

In the 55 km² Maheshwaram watershed, since 1985, the irrigated surface area has increased by a factor of 3, from 0.7 to 2 km² out of a total cultivated area of 18 km². The number of pumping wells has increased from 10 to almost 800 and the mean ground levels have deepened by about 8 m, drying out most of the upper capacitive part of the aquifer (saprolite, Figure 3). The general development of the village and the power supply network (also used for pumping) has followed the same trend.
The major part of the basin is composed of biotite granite but also leucogranite, which is mainly found in the south. These granites are intruded by quartz veins, pegmatite veins and dolerite dikes (Figure 4). A total of 34 boreholes drilled in the framework of IFCGR activities for scientific purposes (IFP wells) provide the most useful hydrogeological and hydrodynamic information. With a mean water level between 15 and 20 m depth, the aquifer mainly occurs in the FZ, the bottom of which generally is not deeper than 30 or 40 m. Based on numerous hydrodynamic testing and modelling at different scales (slug tests, flow metre measurements during injection tests and pumping tests), a comprehensive conceptual model of the hydrodynamic properties of the fissured aquifer in the Maheshwaram basin was proposed by Marechal et al. 2005 (Figure 5). Data shows that the FZ is the most conductive part of the aquifer, at depths ranging between 20 and 35 m, and particularly in its upper part where the density of sub-horizontal fissures is higher (Figure 5 right).

The absence of a confining layer and the storage values obtained by hydraulic tests suggest that the aquifer is unconfined (Marechal et al. 2004). An average specific yield, $S_y$ of $6.3 \times 10^{-3}$ is considered as representative of the total aquifer (matrix blocks and fissure saquifer), which is consistent with the value estimated at the watershed scale using a groundwater balance analysis ($S_y = 1.3 \times 10^{-2}$, Marechal et al. 2003).

All of these results are mainly based on the fissured zone characteristics, since most of the upper saprolite layer is generally unsaturated. Such detailed characteristics of the overlying saprolite is available for the permeability distribution (Dewandel et al. 2006) but its storativity is poorly described.

Five sites were selected, at the beginning of the project, within the Maheshwaram basin for their interesting hydrodynamic characteristics (high transmissivity, shallow water table depth and great aquifer thickness), which made them suitable for experimental purposes (Baltassat & Robain 2003, Appendix 12). Two of these five (IFP21 and IFP 16) are analysed here together with the KB Tanda site, which was initially investigated in 1999 (but also in 2003 and 2005) and the Recharge site, which was investigated in 2005.

### 2.2.1. KB Tanda site

The KB Tanda site is located in the western part of the watershed at the eastern foot of a small hill elongated northward and composed of outcropping granite boulders. Following the 1999 survey, six scientific borewells were drilled by NGRI on this site. A general map of the different geophysical investigations and borewells is given in Appendix 1.

The weathering profile in KB Tanda appears a little shorter than is usual in the Maheshwaram watershed and this should be considered with respect to the neighbouring boulder zone. The detail of lithological descriptions is not constant over the set of soundings. While OB1 and MW1, for example, were described in detail by IFCGR hydrogeologists, the simplified lithology of MW3 does not make it possible to identify a FZ that the resistivity log suggests is located at a depth of between 17 and 21
m. The saprolite thickness ranges from only 8 m on MW1 to 18 m on OB1 and the mean depth to the unweathered rock is about 25 m.

Figure 2: Conceptual model of weathered hard rock aquifer (from Wyns et al. 2004).

Figure 3: Groundwater depletion and increasing irrigation in the Maheshwaram basin.
Figure 4: Geological map of the Maheshwaram basin and location of IFP wells. (Extracted from the IFCGR GIS).
Figure 5: Conceptual hydrogeological model of the fissured zone of a hard rock aquifer based on Maheshwaram watershed observations (from Marechal et al. 2004).

Figure 6: Borewell lithology (courtesy of IFCGR) and associated resistivity data on the KB Tanda site.
The FZ located at around 50 m on MW1 should be considered as a local anomaly, perhaps associated with tectonic fractures and is not taken in consideration in the average calculation of the weathering profile geometry in Table 1.

MRS performed along a profile in 1999 (Figure 7) shows a main water-bearing layer extending from the surface or a few metres depth down to 10-15 m. It is characterized by a 1 to 7% water content and a maximum relaxation time constant, \( T_2^* \) of 200 ms. It is moreover interesting to notice that the base of the water-bearing layer as drawn by the 1% water content contour is closely delineated by the 200 ohm.m iso-resistivity contour (Krishnamurthy et al., 2003).

Figure 7: MRS and ERT cross-section on the KB Tanda site (1999 field survey data).

2.2.2. Recharge site

The Recharge site is where an experimental water recharge to the aquifer is conducted by NGRI and IFCGR through a dug well where runoff from a small local basin are concentrated. For the purpose of monitoring the underground recharge and hydrogeology characterization, seven boreholes were drilled on this site and carefully described by IFCGR hydrologeologists. This site presents a thicker weathering profile
than at KB Tanda, even if it is also close to boulders visible at the surface and that are intersected in IFP27/5 (Figure 8).

<table>
<thead>
<tr>
<th>Site</th>
<th>Borehole</th>
<th>Saprolite base depth (m)</th>
<th>Fresh rock depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KB Tanda</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MW1</td>
<td>8</td>
<td>21 (55)</td>
</tr>
<tr>
<td></td>
<td>OB2</td>
<td>12</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>OB3</td>
<td>15</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>OB1</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>MW3</td>
<td>17</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>14</td>
<td>24</td>
</tr>
<tr>
<td>IFP16</td>
<td>IFP16</td>
<td>18?</td>
<td>36</td>
</tr>
<tr>
<td>IFP21</td>
<td>IFP21</td>
<td>14?</td>
<td>18</td>
</tr>
<tr>
<td>Yalamakana</td>
<td>Y-1</td>
<td>27</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>Y-2</td>
<td>28</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>Y-3</td>
<td>30</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>28</td>
<td>46</td>
</tr>
<tr>
<td>Recharge site</td>
<td>IFP27</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IFP27/3</td>
<td>28</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>IFP27/4</td>
<td>21</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>IFP27/5</td>
<td>24</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>25</td>
<td>41</td>
</tr>
</tbody>
</table>

Table 1: Geometry of the weathering profile from the different sites' borewells.

2.2.3. IFP16

IFP16 was the best candidate among the five different sites selected for their most favourable hydrodynamic properties within a set of 24 scientific borewells (Baltassat & Robain 2003, Appendix 12). It is characterized by a high hydraulic transmissivity (about $10^{-3} \text{ m}^2/\text{s}$) and a high density of fissures between 14 and 28 m depth. Unfortunately no value of specific yield is available here.

The saprolite thickness is about 10 m and the fresh unweathered rock depth can be defined at 36 m on the basis of the drilling time log although this borehole lithology is not described in detail. The location map of geophysical investigation is given in Appendix 3.

2.2.4. IFP21

The IFP21 site was chosen for its interesting hydrodynamic characteristics and its proximity to the Mohabatnagar site where various geophysical investigations were performed in 1999 (see the location map in Appendix 4). This site is particular since the
The weathering profile is not well developed with a saprolite of 14 m thick and an unweathered rock at 18 m.

![Graph](image)

### Figure 8: Borewell lithology (courtesy of IFCGR) and associated resistivity data on the Recharge site.

#### 2.3. WAILPALLY WATERSHED

The Wailpally watershed is not as well known as the Maheshwaram watershed. The first scientific borewells were drilled there in September 2005, on the Yalamakana site, in the framework of this project. An attempt was also made to drill on the Kalvakuntala site but the area was flooded due to a late monsoon and the drilling machine was not able to reach the site of interest. The IFCGR hydrogeologist team provided their technical support for drilling supervision and pumping tests, whose corresponding data are presented in Dewandel 2005 (Appendix 15). The location of investigations at the
Kalvakuntala and Yalamakana sites, which are only 2 km apart within the Wailapaly watershed, are presented on the maps of Appendix 5 and Appendix 6.

### 2.3.1. Yalamakana site

The area is composed of orthogneissic biotite granite of Archean age. This is intruded by leucocratic granite, which is mainly observed at shallow depth above 15-20 m. A highly weathered and calcretized dolerite dike is observed at a distance of about 100 m from the scientific borewells. The saprolite base depth appears quite constant in the three borewells, while the FZ thickness is variable (from 12 to 23 m) with an average value of 18 m (Figure 9 and Table 1).

![Figure 9: Borewell lithology (courtesy of IFCGR) and associated resistivity and magnetic susceptibility data on the Yalamakana site.](image)

The main results of hydraulic tests are given by Dewandel, 2005 (Appendix 15). Slug tests and a long-duration (24 hours) pumping test revealed a hydraulic behaviour characterized by a double porosity functioning with a fissure permeability $K = 3.0 \times 10^{-6}$ m/s and a specific yield, $S$ ranging from $2.0$ to $4.0 \times 10^{-3}$. Sub-horizontal and vertical fissures induce a permeability anisotropy in the ratio $K_r/K_z = 5$ to 6.

These values are mean values corresponding to the total thickness of the aquifer, which is considered to be about 30 m taking into account a water table at about 16 m. However, it is probable that the top of the fissured layer and of the laminated layer (saprolite) are characterized by much higher specific yield. Usually the upper part of the
fissured layer is more densely fissured along its first few meters and contributes to a level higher than 50%, to the productivity of the aquifer.

2.3.2. Kalvakuntala site

Due to the lack of outcrop, an accurate description of the area’s geology is not possible. Orthogneissic biotite granite is observed at the only outcrop in the main stream in the village, while cuttings near recent farmer wells (Kal-1 and Kal-2) indicate a thick saprolite layer (more than 10 m) and that a dolerite dike crosses the site (on Kal-1, see Appendix 15).

Only limited hydraulic information is available on Kalvakuntala. Slug tests performed on the two farmer boreholes revealed a fairly good permeability of $6.0 \times 10^{-6}$ m/s, higher than on Yalamakana.
3. Geophysical methodology and results

The proposed methodology is based on the combined use of electric-electromagnetic methods that are used for delineating the subsurface structure and geometry and Magnetic Resonance Sounding (MRS) for defining the hydrodynamic characteristics of the aquifer. Electric-electromagnetic methods are first used as mapping methods for locating the main structures. Magnetic mapping was also used for this purpose, taking advantage of its high rate of measurement. Profiling methods such as EM-VLF were tested for this purpose, but considering the limited extent of the test sites, sounding methods such as TDEM (along profile) and ERT were preferred because they provide at the same time the structure location in depth. Once the main structures are spatially located, MRS is performed at the places of interest (potential fractured zones, bedrock deepening, etc.) in order to define aquifer parameters.

MRS is an efficient tool for characterizing the geometry of water-bearing structures (Legchenko et al. 2004, Boucher et al. 2005, Vouillamoz 2003) within the limits of its resolution and equivalence. It cannot, however, be used as a mapping method because of the too low rate of measurement with the currently available equipment (NUMISPLUS) under most actual noise conditions of measurement, even in rural environments. For example, in the conditions of the Maheshwaram basin, a maximum rate of only one sounding per day can be envisaged.

Magnetic mapping is also used to control the geomagnetic field variation and may reveal a high field gradient, highly magnetic rocks and remanent magnetization, which may seriously limit the applicability of the MRS method.

The detailed methodology used and the results obtained for each method are presented in the following paragraphs.

3.1. BOREHOLE GEOPHYSICS

Borehole geophysical measurements are used in order to contribute to a better definition of the different geophysical facies and to bring constraints to the inversion/modelling of surface geophysical measurements. Two types of borehole measurements were performed using a simple device implemented with the available means: resistivity logging using a normal (pole-pole) array and susceptibility measurement on cuttings from Yalamakana drillings using a pocket susceptibility-meter.

3.1.1. Resistivity logging

A normal (pole-pole) tool was manufactured by NGRI using a PVC pipe and two copper ring electrodes 1 m apart (Figure 10). Connected to a field resistivity meter (Syscal
Junior Switch 48 from Iris Instrument), it was used for logging the Y-3 borehole at Yalamakana.

Well logging previously performed on the KB Tanda site by Dr Prasad (NGRI, pers. comm.), in the framework of the Council of Scientific and Industrial Research (CSIR) Network project, was also used for correlation with the lithological descriptions and for comparison with the ERT inversion results.

“Mud effect” correction

Resistivity values measured in boreholes using electrical logging are different from true formation resistivity, $R_t$\(^2\). This difference may have various origins (Serra 2000):

- the effect of the column of fluid in the borehole. It is traditionally called the “Mud effect” but in our case, since all of the boreholes were drilled using a down-to-the-hole hammer technique and with air as a fluid, the hole fluid is groundwater. This water has closed characteristics to the formation fluid resistivity, $R_w$\(^2\);

- the effect of mud invasion in porous zones, which could be significant in weathered formations when mud and formation fluid have contrasted resistivities (which is not our case);

- the effect of lithology when the layers’ thickness is small in comparison to the probe spacing (which generally is not our case either).

We should consider the “mud effect”, even if there is no mud in our boreholes. With a ratio of apparent resistivity, $R_a$\(^2\) to fluid resistivity, $R_m$\(^2\) often greater than 20 (Table 2), the mud effect cannot be neglected and should be corrected. An attempt was made to correct the measured resistivity using the 1947 Schlumberger master curves (Serra 2000, Beck and Girardet 2002) and simplified chart derived from this one (see Appendix 7). The correction results are presented for OB1, OB2, OB3 boreholes on Figure 11. The correction does not always appear to be efficient since SN and LN resistivities sometimes diverge after correction (OB1 and OB3). In principle, the measured resistivities, $R_a$, should converge towards the formation resistivity, $R_t$ when the correction is applied. In the case of OB1 and OB3, SN and LN resistivities, $R_a$ are already close to each other and high: they probably are close to the formation resistivity. In these cases, the measured resistivities, instead of the corrected resistivities will be considered (cf. Table 2).

3.1.2. Magnetic susceptibility measurements

Magnetic susceptibility measurements are used as an indicator of potential magnetic field inhomogeneities that could significantly affect the MRS response. As significant variations in magnetic susceptibility were observed on rock outcrops within the

\[^{2}\text{Schlumberger nomenclature, see Appendix 7}\]
Maheshwaram basin (Baltassat et al. 2004), it appeared interesting to investigate variations in this parameter laterally on the different investigated sites and vertically along the weathered profile.

Table 2: Range of resistivities obtained from well logging measurements using Short Normal (SN), Long Normal (LN) and Normal Array with spacing AM=1 m; MW1, MW3, OB2: corrected resistivity; OB1, OB3: non corrected resistivity. The fluid resistivities used for correction are also given.

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Fluid resistivity (ohm.m)</th>
<th>Normal Array</th>
<th>Saprolite resistivity (ohm.m)</th>
<th>Fissured zone resistivity (ohm.m)</th>
<th>Fresh rock resistivity (ohm.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mean</td>
<td>Minimum</td>
</tr>
<tr>
<td>MW1</td>
<td>11</td>
<td>SN</td>
<td>120</td>
<td>40</td>
<td>270</td>
</tr>
<tr>
<td>OB2</td>
<td>10</td>
<td>SN</td>
<td>175</td>
<td>130</td>
<td>280</td>
</tr>
<tr>
<td>OB2</td>
<td>10</td>
<td>LN</td>
<td>435</td>
<td>200</td>
<td>600</td>
</tr>
<tr>
<td>OB3</td>
<td>9</td>
<td>SN</td>
<td>330</td>
<td>145</td>
<td>620</td>
</tr>
<tr>
<td>OB3</td>
<td>9</td>
<td>LN</td>
<td>785</td>
<td>125</td>
<td>1300</td>
</tr>
<tr>
<td>OB1</td>
<td>14</td>
<td>SN</td>
<td>320</td>
<td>135</td>
<td>475</td>
</tr>
<tr>
<td>OB1</td>
<td>14</td>
<td>LN</td>
<td>1150</td>
<td>980</td>
<td>1500</td>
</tr>
<tr>
<td>MW3</td>
<td>12</td>
<td>SN</td>
<td>175</td>
<td>140</td>
<td>210</td>
</tr>
<tr>
<td>Y-3</td>
<td>4</td>
<td>AM = 1 m</td>
<td>40</td>
<td>540</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 10: Normal probe manufactured by NGRI (right, a ring copper electrode is shown) and schema of the normal (pole-pole) array (left).
Magnetic susceptibility was thus measured using a pocket susceptibility-meter KT6 (from SatisGeo) on drill cuttings from borewells Y-1, Y-2 and Y-3 on the Yalamakana site and on various outcrops within the Maheshwaram watershed.

At Yalamakana, cuttings were collected while drilling every 3 ft (91.44 cm) and then packed in a polythene envelope to make a sample of a size not smaller than 15 cm x 15 cm x 6 cm. This amount was collected in order to provide a volume of sample in accordance with the investigation volume of the instrument (80% of the signal comes from a 20 mm layer below the face of the coil, which has a 6 cm diameter). This procedure is employed in the absence of a susceptibility logging tool and because coring was not possible. It has the following shortcomings:

- the cutting sample is not exactly representative of the formation rock, even if they have the same mineralogical content, since the rock was cut into small size particles by the drilling tool: for example, its density is lower than the actual formation’s density and its susceptibility should have decreased in the same ratio.
- cuttings sampled at the surface while drilling could be a mixture of the actual drilled formation at the moment of sampling and the overlying formation that is collected by the drilling fluid (here cuttings, compressed air and saturated water) going up-hole from the tool position toward the surface. Hydrogeologists indeed observed at Yalamakana that cuttings from the first ten metres of the FZ were polluted by the overlying saprolite.

It is assumed that the susceptibility measured following the above described procedure should be lower than the actual susceptibility and that the susceptibility of the upper FZ may be a combination of saprolite and FZ actual susceptibility.

Despite these limitations, the observed measurements show very convincing correlation with lithology (Figure 9). Susceptibility limits plotted at the sharp and major increase of the parameter are located at less than 2 m from the lithological determination of the saprolite depth and less than 3.5 m for the fresh rock depth (Table 3). On Y-3, peaks of susceptibility within the FZ also show a good correlation with peaks of resistivity at 30-35 m and 39-44 m (Figure 9).

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Saprolite base from susceptibility (m)</th>
<th>Difference with lithology (m)</th>
<th>Fissured zone base from susceptibility (m)</th>
<th>Difference with lithology (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-1</td>
<td>29</td>
<td>+ 2</td>
<td>43</td>
<td>+ 3.5</td>
</tr>
<tr>
<td>Y-2</td>
<td>27</td>
<td>- 1</td>
<td>48.5</td>
<td>+ 2.5</td>
</tr>
<tr>
<td>Y-3</td>
<td>30.5</td>
<td>0</td>
<td>46</td>
<td>+ 2</td>
</tr>
</tbody>
</table>

Table 3: Correlation of susceptibility limits with lithologs.

In the Maheshwaram watershed, one of the most interesting measurements was performed in a dug well where an operator descended into the well with the help of a rope end (Figure 12), carrying a pocket susceptibility-meter in his hand. The rapid increase with depth below 2 m is considered as an exception in comparison with other sites where values are always less than 0.6 \(10^{-3}\) s.i. within the first few metres (Girard et al. 2005). These shallow and high susceptibilities should be compared to the ERT resistivity increase observed at 2-3 m on this site and attributed to a less weathered granite or boulder such as observed in IFP27/5 (Figure 8).

The range of observed susceptibilities on outcrops or on cuttings is shown in Figure 13. The values on cuttings are well within the range of measurements on outcrops although, as expected, a little bit lower as shown by saprolite cuttings in comparison with the Recharge Site saprolite or unweathered rock cuttings in comparison with fresh granite on outcrops. The susceptibility increase with depth along the weathering profile also appears clearly.
This could be explained by the transformation and disappearance of the magnetic minerals (magnetite mainly) as a result of the weathering process. Théveniaut and Freyssinet (1999) attributed the mean decrease in susceptibility along a weathered leptynite profile studied in detail in French Guyana to the loss of inherited magnetite and paramagnetic minerals (amphibole and biotite).

As a result, magnetic susceptibility appears to be a good indicator of the weathering grade and the existence of a significant increase in magnetic susceptibility along the weathering profile should be kept in mind when interpreting MRS. These interesting observations nevertheless need to be confirmed because the procedure of measurement on cuttings has considerable shortcomings. A confirmation could be obtained from measurements on existing core samples of the weathered profile.

Figure 12: Susceptibility measurement in a dug well at the Recharge Site.
3.2. TIME DOMAIN ELECTROMAGNETISM (TDEM)

3.2.1. The TDEM method

The TDEM method is an electromagnetic method well suited to groundwater exploration for various hydrogeological problems like fresh-salt water interfaces or low resistivity zones. The basic principles can be found in detail in the publications of McNeill (1994) or Spies and Frischknescht (1991). To summarize, the TDEM method uses a cable laid out on the ground as a transmitter loop (Tx). A square current is generated inside the Tx loop. When the current is switched off, the variation in the primary magnetic field Bp induces a circulation of eddy currents in the ground. The eddy currents diffuse into the ground with a shape that can be imaged as “smoke rings”. They generate a secondary decaying magnetic field Bs measured at the surface by a receiver coil (Rx) when the current remains switched off. The variations in amplitude of Bs with time are linked to the changes of resistivity with depth. The TDEM is consequently a sounding method and is preferentially well suited to 1D layered earth (2 and 3-D cases are very seldom considered at the interpretation phase and only for simple cases such as spheres, round patches etc.). Figure 14 presents the principle of the method.
The main advantages are a good sensitivity to variations in conductivity, a good lateral resolution and a depth of penetration generally equal or superior to the length of the side of the Tx loop. In the field and particularly on dry ground, a significant advantage of electromagnetism in comparison with the DC electrical method resides in the fact that no electrodes are used for transmitting electrical current into the ground.

Figure 14: Principles of the TDEM method: example of a central loop acquisition (after Mc Neill, 1994).
The main disadvantages are a poor definition of resistive bodies and the high sensitivity to external electromagnetic noises (induced by fences, power lines, etc.). These disadvantages are major factors in the Maheshwaram basin, as described in this report.

3.2.2. TDEM equipment

The TDEM equipment used for this survey was a GEONICS Digital Protem system. In 1999, an EM47 transmitter was used. This transmitter makes it possible to cut off the current for periods as short as 1.8 µs for a 25x25 m² Tx loop and 2 A current. The measuring period starts from 6.816 µs after the end of the turn-off time and consists of 20 channels measurements of the secondary magnetic field. This transmitter is dedicated mainly to shallow investigations. The full technical specifications of the EM47 transmitter and Protem receiver are available from Geonics (Mississauga, Ontario, Canada).

In 2003, some tests were performed using a high moment transmitter from HGG Aarhus University (Denmark), in order to obtain more reliable results at late times. This transmitter allowed us to inject currents as high as 20 A, 10 times higher than the conventional Geonics TEM47. In addition, a low noise receiver coil Rx from HGG was also used.

3.2.3. Objectives assigned to TDEM sounding

The geological situation of Maheshwaram with a conductive “cover” (the saprolite) overlying a resistive bedrock (granite) through an intermediate medium resistivity zone (FZ) with some faults, dikes or lineaments as 2D structures is not favourable for the use of the TDEM method. This is because it is difficult or even impossible i) to accurately define the high resistivity of the bedrock and ii) to take into account 2D or 3D cases when interpreting the data. However, the method could help to define the resistivity and the thickness of the conductive first layer. Consequently, and as research objectives, a TDEM survey was carried out in order to be able to answer the following questions:

- Is it possible to characterize accurately (or not) the alterite resistivity and thickness with TDEM?

- Is it possible to use TDEM as an alternative to 1D-DC electrical soundings?

- What confidence can be placed in the TDEM results (interpreted with 1D assumption)? For this purpose, a comparison was made with 2D-DC electrical imaging.

- Is the TDEM method well suited to perform soundings with the same geometrical configuration as the PMR method and are the TDEM results useful for PMR interpretation?
3.2.4. Field methodology

In order to answer the questions “Is it possible to characterize accurately (or not) the alterite resistivity and thickness with TDEM?” and “Is it possible to use TDEM as an alternative to 1D-DC electrical soundings?”, it is necessary to test the method over varying conditions of resistivity and depth. Thus, TDEM sounding were performed along profiles crossing interesting structures or conditions using loops as small as possible to facilitate the survey and to maintain good lateral resolution.

Figure 15: Comparison between the 1D interpretations with 50x50 and 25x25 m² transmitter loop sizes on the Mohabatnagar site. GPS coordinates of the TDEM sounding: X: 2581006 Y: 711283 (Indian III A grid system).
a) Determination of the optimum transmitter loop size for TDEM profiling

Two transmitters of 50x50 m² and 25x25 m² loop size were implemented for testing in the vicinity of a borehole on the Mohabatnagar site (area to the NW of IFP21, investigated in 1999, see Appendix 4). The receiver coil Rx was located at the centre of the TX loop in the well-known “central loop” configuration. For this test as well as for all the soundings performed in the 1999 survey, a current of 2 A was used in the Tx loop. The turn-off time was 1.8 µs. An example of the information given by a TDEM sounding assuming a 1-D layered earth is given in Figure 15.

The interpretations of TDEM sounding curves were made assuming that the ground is horizontally layered (1D case). The inversions were performed using TEMIX Software (Interpex Ltd). For the best fit solution, equivalencies were calculated assuming a 1% rms variation from the best fit. The best fitting solutions from 50x50 and 25x25 m² were close together. The resistivity model showed a three layer solution:

- a resistive layer (100 ohm.m), with a thickness of 13 m;
- a conductive layer (50 ohm.m), with a thickness of 13 m,
- a resistive substratum (1000-2000 ohm.m).

From this comparison, we also note that the 25x25 m² loop configuration is large enough to give the information, even if the signal to noise ratio is smaller.

b) Analysis of the external electromagnetic noise

All the TDEM soundings performed on Maheswaram watershed during the survey in 1999 were affected by electromagnetic distortions. In order to illustrate this phenomenon, Figure 16 presents two typical curves obtained on the site of Mohabatnagar. Two types of distortions are noted.

- Distortion coming from an external source

These distortions are illustrated in Figure 16a). They come from external sources and are not produced by the equipment itself. The distortion appears at the 13th channel (sometimes 12th or 14th) and produces strong distortion on resistivity values. They were noticed in every part of the surveyed area.

The conclusions about this point can be summarized as follows:

- The origin of the distortion cannot be attributed to the presence of power lines (this is not 50 Hz distortion),
- It cannot be attributed to induced phenomenon from the Tx loop itself into the power lines,
The distortion is present all over the Maheshwaram watershed and its relative amplitude varies from time to time and following the ground resistivity.

The data distorted by EM noise were removed from the interpretation procedure. The origin of this distortion could be attributed to the presence of a radio-telecom antenna in Maheswaram village.

- **Power line distortions (induced by the equipment)**

An example of such distortion is given in Figure 16b). This occurs when the Tx loop is located at less than 25 m from a power line and does not depend on the presence of 50 Hz current. However, if 50 Hz current is flowing into the loop, the distortion is bigger. Data points resulting from such distortion are removed from interpretation.
• **Additional tests with a more powerful transmitter (2003 field survey)**

As previously mentioned, some tests were carried out in 2003 to try to overcome the distortion problem. By using a more powerful transmitter, the ground response was increased, while EM external noise remained the same; consequently, more information was obtained from the deeper part of the ground. In addition, a low noise receiver coil and a new receiver unit were used.

Tests were performed near the borewell IFP21 at GPS coordinates X= 230935 Y= 1898412 (UTM coordinates, WGS 84). The external EM signal was still present in the Maheswaram area. This result definitively eliminates an equipment problem.

c) **Determination of the spatial sampling interval**

In 1999, one sounding every 25 m was performed along profiles. Each sounding is interpreted with 1D assumption. 15 to 20 soundings can be carried out in a single day in "open field" places. This sampling interval is convenient to detect variations in the bedrock depth if there are no sharp variations of the bedrock shape (i.e. less than 25 m wide).

d) **Conclusion with regard to the field procedure**

We defined a field procedure that is the result of a compromise between many factors such as i) the signal to noise ratio, ii) the presence of many power lines, iii) the number of soundings that can be performed in one day, iv) the sampling interval necessary to define the bedrock topography in a convenient manner.

This compromise can be summarized as follows:

- 25x25 m² transmitter loop size,
- central loop configuration,
- one sounding every 25 m,
- 25-m distance from power lines.

3.2.5. **Evaluation of uncertainty for TDEM interpretation**

When comparing the TDEM01 interpretation (see Figure 15) with the borewell data, the depth to the substratum is not well defined. It ranges from 22 to 28 m, leading to a 20% error in the case of Figure 15, if the considered high resistivities actually correspond to the fresh rock. It is indeed possible that the high substratum resistivities correspond to the top of the FZ (the lithological description of this borehole is rough), which cannot be distinguished from the fresh rock with TDEM due to the lack of sensitivity of the method at high resistivity range (above 500 ohm.m). This illustrates the limitation of the TDEM sounding method for characterizing the thickness of the weathered zones, because resistive bodies are not the preferential targets for this method.

The 3-layers solution is moreover not unique. Temix software allows another resistivity model based on OCCAM inversion to be calculated. This type of inversion is able to
image the horizontally layered ground with smoothed out resistivity variations with depth. As an example, TDEM01 sounding data with a 25x25 m² transmitter loop is presented in Figure 17. A comparison with the 3 layers solution makes it possible to conclude that the TDEM sounding curves can be interpreted either with “simple solutions” (as the 3 layers case) showing abrupt resistivity changes between layers or with a smooth variation of resistivity with depth.

Figure 15 also shows that aquifer thickness can only be defined with a 6 m uncertainty and with varying formation resistivity values. Due to equivalence phenomena, aquifer resistivity and thickness cannot be defined precisely and separately without additional information (fixing thickness or resistivity). Since formation resistivity, which varies significantly according to water conductivity or clay content, cannot be fixed, the geometry determination can only be obtained with a 20% uncertainty (in this example). Furthermore, since the weathered layer thickness is generally unknown, the formation resistivity cannot be precisely defined.

![Smoothed inversion using the OCCAM algorithm (25x25 m² central loop acquisition)](image)

**Figure 17: Smoothed inversion using the OCCAM algorithm (25x25 m² central loop acquisition)**

### 3.2.6. Comparison of TDEM sounding profiles with ERT

Some TDEM sounding profiles (1999 survey) were located along ERT profiles on the KB Tanda site and on the Mohabatnagar site (see Appendix 1 and Appendix 4). For each sounding, the interpretation was carried out using a multi-layered smooth model with Occam inversion assuming a 1D case. When reading the results, one should keep in mind that i) the smooth resistivity variations could sometimes lead to unrealistic values of resistivity (especially for bedrock resistivity) and ii) the 1D assumption is likely to be erroneous because of sharp variations of bedrock depth or dike structures. The parameters of the inversion are the same for all the soundings: 8 layers have been taken into account and the depth of interpretation has been limited to 80 m. This value
of 80 m can be considered as a maximum depth of penetration of the method with this configuration. Very conductive superficial layers can significantly lower this investigation depth.

The result of the inversion is interpolated with the nearest sounding using SURFER Software (Golden Soft. Inc.). The resulting image is a 1D resistivity cross section along the profile. Once again, it reflects a 1D case and should not be considered as a 2D interpretation. The resistivity colour scale has been chosen in order to point out the limit between resistivity lower than 150 ohm.m (blue-green dominant) and higher then 150 ohm.m (orange-red dominant). Considering well-logging resistivity ranges, this arbitrary limit reflects the possible transition between saprolite and the underlying FZ.

As an illustration of these limitations, Figure 18 and Figure 19 present a comparison between ERT and TDEM on the Mohabatnagar and KB Tanda sites, where the TDEM and ERT acquisition were taken exactly at the same place.

![Image](image_url)

*Figure 18: Comparison between ERT and TDEM at Mohabatnagar (NW of IFP21). The 110 ohm.m isocontour of the ERT cross-section is superimposed on the TDEM cross-section.*

To facilitate the comparison, the 110 Ohm.m isocontour has been underlined using a bold line. The TDEM gives a larger thickness of weathering, particularly in the central part of the profile. At the SW end, the TDEM isocontours do not display the same pattern as ERT. The TDEM response is highly distorted in this part due to the 2D electrical structure evidenced by ERT, and highly suspicious distorted TDEM sounding curves were not interpreted for the greater depth.
For the KB Tanda site, the comparison between ERT and TDEM also displays severe discrepancies in the south east. The TDEM interpretation displays a very thin conductive layer (< 3m), while the ERT displays a thicker conductive layer (5-7 m). Even if the conductive facies is a good target for EM sounding, TDEM is not so accurate in the first few metres due to the turn off delay.

As a conclusion from this comparison, it is obvious that TDEM gives only a rough estimate of the weathering thickness and characteristics.

3.2.7. Conclusion on TDEM application in the weathered granite setting of Hyderabad

From the 1999 survey and the tests in 2003, the following conclusions can be drawn for the TDEM prospecting technique in the Maheswaram area:

- Is it possible (or not) to detect accurately the alterite resistivity and thickness with TDEM?

The sensitivity of TDEM to conductive bodies allows us to say that the method could be used to delineate the saprolite with a reasonable degree of confidence: the depth to its base can be determined within 20% accuracy but the underlying FZ and
unweathered rock cannot be distinguished. In case of sharp 2D (or 3D) distribution, the TDEM interpretation can be strongly distorted. Consequently, we do not recommend the TDEM method for an accurate determination of the weathering thickness, especially when 2D structures are under investigation.

- **Is it possible to use TDEM as an alternative to 1D-DC electrical soundings?**

TDEM can be used as an alternative to 1D electrical soundings with the same limitations of the 1D assumption. However, we do not recommend the TDEM method if an accurate determination of the resistivity of the resistive substratum under investigation is required. The main advantages of TDEM versus 1D DC electrical sounding are the absence of contact with the soil, lower sensitivity to lateral heterogeneities and the rapidity of the sounding measurement.

- **ERT or profiles of TDEM soundings?**

Regarding the field procedures, we have experienced that a 2D electrical imaging with 64 electrodes and 4 metre’s electrode spacing makes it possible to cover a profile 400 to 600 metres long in a day when good survey conditions prevail. This performance is increased while using a high speed acquisition system. With TDEM, 25 soundings can be performed on the same line using a 25x25 m transmitter loop, which corresponds to nearly the same length. Consequently due to the dense sampling with ERT, and the corresponding 2D inversion of the data, ERT is much more suitable than TDEM for the survey of the weathered mantle.

To summarize, if the objectives are as follows:

- to map the 2D weathered mantle,
- to give a correct estimate of the resistivity of the fresh substratum,
- to accurately locate 2D structures,

we do not recommend the use of TDEM because of:

- the 1D assumption when interpreting the data,
- the poor sensitivity of the method to high resistivity formation,
- severe distortions due to external EM noise in the Maheswaram area,
- possible distortions close to power lines and fences (this not only applies to Maheswaram but also to other sites in India or elsewhere).

In future, if the objective is to obtain an estimate of the weathering thickness, one could take advantage of the MRS loop to perform a quick TDEM sounding at the same time. If no distortion is present and if a 1D assumption is possible, the TDEM is able to estimate the depth and the resistivity of the weathered mantle with relative confidence.
3.3. ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT)

3.3.1. The ERT method

The purpose of electrical surveys is to determine the subsurface resistivity distribution from measurements on the ground surface. Underground resistivity is related to various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock. Electrical resistivity methods have been used for many decades in studies focusing on the determination of overburden geometry or groundwater resources (Keller and Frischknecht, 1966, Kunetz 1966).

The resistivity measurements are generally taken by injecting current into the ground through two current electrodes (C1 and C2) and measuring the resulting voltage difference at two potential electrodes (P1 and P2). From the current, I and the voltage, V an apparent resistivity, \( \rho_a \) is calculated as: \( \rho_a = \frac{K \cdot V}{I} \) where K is the geometric factor which depends on the arrangement of the four electrodes (Figure 20).

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Turnbull 1985, Griffiths et al. 1990, Barker 1992, Griffiths and Barker 1993). Tens of electrodes may be connected to such a resistivity meter. Apparent resistivity measurements are recorded sequentially sweeping any quadripole - A B (current electrodes) M N (potential electrodes) - within the multi-electrode array. As a result, high-definition pseudosections with dense sampling of apparent resistivity variation at shallow depth (0-100 m) are obtained in a short time. This allows a detailed interpretation of 2D resistivity distribution in the ground (Loke and Barker 1996).

To obtain a good 2D picture of the subsurface, the coverage of the measurements must be 2D as well. As an example, Figure 21 shows a sequence of measurement for a dipole-dipole electrode array for a system of 18 electrodes. In this example, the distance between successive electrodes is ‘a’. The first step is to make all the possible measurements with a distance between the current and potential electrodes D equal to ‘a’ and produce a first level of measurement n=D/a=1. For the first measurement, electrodes with numbers 1, 2, 3 and 4 are used as respectively current electrodes C1, C2 and potential electrodes P1, P2. For the second measurement, C1, C2, P1, P2 are shifted to respectively electrodes with numbers 2, 3, 4 and 5 and so on until the last positions of electrodes 15, 16, 17 and 18 are reached. Secondly, in order to increase the depth of investigation, all possible measurements with D=2a are performed in the same way and produce the line n=2 and so on until n=6 or 7 is reached after which accurate measurements of potential are generally difficult due to the low signal to noise ratio. In a third step, in order to increase the signal to noise ratio and continue the depth investigation, the distance between electrodes (C1 and C2, P1 and P2) is increased to 2a and another series with different values of n is measured (not shown on the figure).

![Figure 21: Sequence of measurements for a dipole-dipole array.](image)

After carrying out the whole sequence, the acquired data are downloaded from the resistivity-meter memory to a laptop computer and presented as a pseudosection, where measured apparent resistivities are located horizontally at the mid-point of the set of electrodes used and vertically at a distance that is proportional to the level number n. For a dipole-dipole array this point is conventionally placed at the intersection of two lines starting with a 45° angle to the horizontal from the midpoint of the C1-C2 and P1-P2 segment.
Pseudosections are inverted using the RES2DINV software based on a finite difference model and a non-linear least square technique of inversion (Loke and Barker, 1996; Loke and Dahlin, 2002). In the case of rough relief, surface topography encountered along the profiles is incorporated into the model.

3.3.2. ERT equipment

A 10-channels resistivity meter, namely SYSCAL Pro, recently developed by Iris Instruments in the framework of a project funded by the French Ministry of Research and coordinated by IRD (Figure 22) was used during the December 2003 fieldwork. This new equipment performs measurements approximately 10 times quicker (automatic sequence mode) and even 100 times quicker (high speed mode) than any former resistivity meter of the SYSCAL type (namely SYSCAL, SYSCAL R1, SYSCAL R2 or SYSCAL switch). A SYSCAL switch 48 was also operated by the Indian team for all other fieldwork.

![SYSCAL Pro equipment from Iris Instrument.](image)

3.3.3. Objectives assigned to ERT

ERT is proposed for delineating the structure and geometry of subsurface potential water-bearing structures. In the particular context of our small-scale experimental site,
it was preferred to a more rapid mapping method such as EM-VLF or EM Slingram because it provides, at the same time, the structure location and depth.

Thus, ERT surveys were performed in order to locate interesting water-bearing structures for testing MRS methodology and, as research objectives, in order to answer the following questions:

- Is it possible to characterize accurately (or not) the weathering granite formation resistivity and thickness with ERT?
- What confidence may be placed in the ERT results?

3.3.4. Resistivity range of the weathering profile

In an attempt to evaluate how the different formations of the weathered profile could be characterized by the resistivity parameter, the range of resistivities measured in the well or obtained after ERT inversion at the well location are compiled in Figure 23: The corresponding formation is defined on the basis of the borehole lithology (see Figure 6, Figure 8 and Figure 9).

SN resistivities, which are often significantly lower than LN resistivities, should not be considered as an accurate evaluation of the actual formation resistivity because of the too short SN spacings and possible effect of increased porosity due to the drilling work within the first decimetres at the hole wall combined with low fluid resistivity. The actual formation resistivity should be close to the LN and OA=1m resistivities - when they are corrected for the “mud effect” (see 3.1.1) – which have larger spacings.

ERT results neither can be taken as perfectly determined formation resistivity since the inversion of ERT measurements from the ground surface is an ill-posed problem and several equivalent solutions can satisfy the same data set. The presented ERT results are one particular solution within a range of equivalent solutions but they nevertheless give a figure within the possible formation resistivities.

Despite these limitations, it appears (Figure 23) that the different formations defined from borewell lithologs are characterized by well-contrasted resistivity ranges such as:

- Saprolite : mainly lower than 200 ohm.m,
- FZ : mainly between 200 and 1000 ohm.m,
- Fresh rock : mainly greater than 700 ohm.m.

3.3.5. ERT synthetic model of the weathering profile

On the basis of the above defined resistivity ranges and taking into account the different thicknesses of the saprolite and of the FZ observed in the KB Tanda, Recharge and Yalamakana sites, two resistivity models of the weathered zone were constructed. The differences between model 1 and model 2 mainly reside in the fact
that the larger resistivity contrast is at the limit between the FZ and the fresh rock for model 1 and at the limit between saprolite and the FZ for model 2 (Table 4 and Figure 24). The layer thicknesses are based on the average values observed on the three sites (Table 1) and the resistivities are inspired by Figure 23. Although water is the target of our investigations, the effect of aquifer water on resistivity is not treated by these models because it would further complicate the problem and because obvious effects of water content on the low resistivity, clayey formation (for the saprolite) or low porosity formation (for FZ) were not observed. Furthermore, it would have constituted a study subject on its own and it was decided to concentrate our efforts on MRS, concerning water particularly.

These models are used to test the capability of the ERT method to characterize the geometry of the weathered formations. Apparent resistivity pseudosections were calculated by the finite difference method using RES2DMOD forward modelling software (loke 1999) for each model. They were then inverted using RES2DINV software (Loke and Barker 1996, Loke and Dahlin 2002) with the robust inversion option which tends to produce models with sharp interfaces between different regions with different resistivity values. Considering the relatively marked contrasts shown by resistivity well-logging at the formation boundaries (see Figure 6 and Figure 9), it is assumed that this option is the most suitable for inverting this set of data and correctly defining the limits between the different formations.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Model 1</th>
<th>Model 2</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Resistivity</td>
<td>Resistivity</td>
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<tr>
<td></td>
<td>Resistivity ratio</td>
<td>Resistivity ratio</td>
</tr>
<tr>
<td>Saprolite</td>
<td>$\rho_1 = 50$ ohm.m</td>
<td>$\rho_1 = 80$ ohm.m</td>
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<tr>
<td>Fissured zone</td>
<td>$\rho_2 = 200$ ohm.m</td>
<td>$\rho_2 = 500$ ohm.m</td>
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<tr>
<td>Fresh rock</td>
<td>$\rho_3 = 2000$ ohm.m</td>
<td>$\rho_3 = 1500$ ohm.m</td>
</tr>
</tbody>
</table>

Table 4: Characteristics of synthetic resistivity models of the weathered zone

As expected (Figure 24), the intermediate resistivity formation (the FZ) is suppressed and a gradient of resistivity appears between the surface and deep resistivities, which correspond quite well to the initial model values.

An attempt was made to localize the formation boundaries at the maximum resistivity gradient calculated as $(\rho_j - \rho_i) / (z_j - z_i)$ with $\rho_j$ ,$z_j$ and $\rho_i$ ,$z_i$ being the resistivity and mean depth of the respectively jth and ith layers of the inverted model.
Figure 23: Resistivity ranges for the different formations of the weathered profile from well-logging and ERT crossing borewell location.
Figure 24: Resolution of synthetic resistivity model of the weathered profile using RES2DINV software (finite difference method and robust inversion option). Initial model geometry is shown by horizontal black lines and corresponds to the average depth observed on the three sites. Initial model resistivities are shown by figure labels. The coloured resistivity cross-sections represent the inverted models also designated by the vertical step lines. White arrows indicate maximum resistivity gradient.
As a result, in model 1 where the FZ-Fresh rock boundary is more clearly marked, the maximum gradient defines the fresh rock depth quite well (the uncertainty in determination is lower than 5%) while in model 2, where both boundaries have more similar resistivity ratios, the maximum gradient is defined between them (uncertainty on locating the boundary higher than 10%).

As a conclusion, within the resistivity condition of the weathered granite of the Hyderabad region, ERT can only define the FZ-Fresh rock boundary when it presents a very clearly marked resistivity contrast, otherwise the maximum resistivity gradient appears within the FZ with a precision not better than 10%.

ERT cannot accurately define the resistivity and the thickness of the different weathered formations since the intermediate medium resistivity layer (FZ) is suppressed: a continuous gradient of resistivity is observed between the upper and the lower layer resistivity values, which are however quite correctly defined. On the other hand, it can be observed that, qualitatively, for a given resistivity log, the shape of the weathered layer interfaces is faithfully reproduced by inverted images even for depth variations as low as 3 m at 20 m depth.

3.3.6. ERT as a pseudo-3D tool for imaging substratum geometry

For investigating an area for a detailed study, a set of ERT parallel profiles are usually performed. The IFP21 site is an example of how ERT profiles can be combined in order to image 2D and 3D variations in resistivity. 10 cross sections were measured using a Schlumberger array along 188 m long profiles composed of 48 electrodes with a 4-m spacing. The interpreted resistivity sections were inverted using RES2DINV software (Figure 25).

The 2D interpretations of the 10 profiles have been merged layer by layer (at the same interpreted depth) in order to build a 3D view (Figure 26). With comparison to a real 3D calculation, which will have been an under-parameterized problem in this case, this approach appears to be satisfactory. In particular, the independent interpretation of close profiles, e.g. L03-L07, L03-L08, L04-L08, L05-L09 provides the same resistivity levels for nearby parts of the profiles.

The various results are clearly highlighted in Figure 26:

- A more resistive basement in the north western corner of the surveyed area.
- A low resistivity zone of north-south direction cross the site; deeply rooted in the eastern part of the site, it may correspond to a fractured zone.
- Superficial conductive anomalies correspond either to water pond or to irrigated paddy fields.

3.3.7. Conclusions on ERT application in the weathered granite setting around Hyderabad

ERT can accurately define the depth to the unweathered substratum only when it is marked by a highly contrasted resistivity interface. The FZ with intermediate resistivity
Figure 25: IFP21 site: Calculated vertical resistivity cross-sections (SW to the left, NE to the right, Schlumberger array, 4-m spacing between electrodes).
Figure 26: IFP21 site: Calculated resistivities presented as interpolated horizontal layers at various depths (SW to the left, NE to the right).
is masked and cannot be defined. In other respects, undulations of weathered layers are qualitatively and faithfully reproduced by inverted resistivity images even for depth variations as low as 3 m at 20 m depth.

In the general case, ERT can be used as a tool for qualitatively imaging the weathering profile and mapping the substratum topography. A quantitative characterization should however also be obtained when inversion can be constrained using geometry and resistivity measurements from boreholes. Since reliable formation resistivity cannot be obtained easily, the way to evaluating water content through Archie’s law or similar empirical relationship is not obvious. These conclusions support our choice of preferring MRS for this purpose.

A minimum depth of investigation of 60 m is necessary to correctly investigate the whole weathered profile when it is the thickest. In order to improve depth penetration while maintaining a reasonable signal to noise ratio, 10 and 20 m electrode spacings should be used in complement to the short spacings (5 m usually) on at least 300 m long profiles.

3.4. MAGNETIC RESONANCE SOUNDING (MRS)

3.4.1. Background

To an outside observer, the MRS field set-up appears very similar to that of Transient EM with a coincident transmitting/receiving loop. A wire loop is laid out on the ground, normally in a circle of 10 m to 150 m diameter depending on the depth of the target aquifer. The loop may also be laid out in a square or, to improve signal to noise ratio (S/N), in a “figure of eight” shape (Trushkin et al. 1994).

The method is based on the fact that protons possess a non-zero magnetic moment. The resonance behaviour of proton magnetic moments in the geomagnetic field ensures that the method is selective and sensitive only to groundwater. The resonance frequency $\omega_0 = 2\pi f_0$ is given by the spin Larmor resonance condition $\omega_0 = \gamma_p B_0$, with $B_0$ being the magnitude of the geomagnetic field and $\gamma_p / 2\pi = 4.257707 \times 10^{-7}$ Hz/T the gyromagnetic ratio for protons. The Larmor frequency is obtained from measurements of the geomagnetic field ($B_0$) on the surface using a proton magnetometer. Depending on the global geographical location of the investigated area, the geomagnetic field varies between approximately 20,000 and 60,000 nT, and the Larmor frequency correspondingly varies between 800 and 2800 Hz.

Using the classical model (Slichter 1990), in which the coordinate system rotates with an angular frequency $\omega = -\gamma B_0$, the local macroscopic spin magnetization of protons in a water sample $dV$ can be presented as a vector $\mathbf{M}$ with the amplitude
\[ M = |\mathbf{M}| = M_0 \, dV, \] where \( M_0 = 3.287 \times 10^{-3} \, B_0 \) at 293°K (20°C) and is the spin magnetization of hydrogen protons per unit volume. In the equilibrium position, \( \mathbf{M} \) is oriented along the geomagnetic field and the angle \( \theta \) between the spin magnetization and the geomagnetic field is equal to zero \((\theta = 0)\), as is shown in Figure 27a.

Figure 27: Precession of spin magnetization in rotating with the Larmor frequency coordinate system.

The magnetic resonance signal is generated only by a perpendicular to the earth’s magnetic field component of the spin magnetization \( M_\perp = M \sin(\theta) \), so no signal exists at this time. A pulse of alternating current then energizes the MRS loop:

\[ i(t) = I_0 \cos(\omega_0 t), \quad 0 < t \leq \tau, \quad (1) \]

where \( I_0 \) and \( \tau \) are respectively the pulse amplitude and duration. The pulse causes precession of the spin magnetization around the geomagnetic field, which produces a non-zero flip angle (Figure 27b):

\[ \theta = \frac{\gamma \, B_\perp(r)}{2I_0} \, q, \quad (2) \]
where $q = I_0 \tau$ is the pulse parameter, $B_{1\perp}(r)$ is a perpendicular to the geomagnetic field component of the loop magnetic field, and $r = r(x, y, z)$ is the coordinate vector. For a sample $dV(r)$, the flip angle $\theta$ is larger for larger values of the pulse moment $q$ (Figure 27b and c). Transmissions from the loop magnetic field can be calculated numerically, and in general they decrease with increased distance $r$ between the loop and the sample $dV(r)$ as a cubic function ($B_{1\perp}/I_0 \sim 1/r^3$).

Consequently, for fixed $q$, the flip angle $\theta$ depends on the water location. The magnetic resonance signal is proportional to $\theta (M_{\perp} = M \sin(\theta))$ and thus, by measuring the signal on the surface for various values of the pulse moment $q$, the location of a water sample $dV(r)$ can be derived from Equation 2. This is the principle of Magnetic Resonance Sounding.

**Water content**

Precession of the spin magnetization $M$ around the geomagnetic field caused by the current pulse in the loop creates an alternating magnetic field that can be measured, using the same loop, after the pulse cut-off. Oscillating with the Larmor frequency, the magnetic resonance signal $e(t)$ has an exponential envelope and is a function of the pulse moment $q$:

$$e(t, q) = e_0(q) \exp\left(-t/T_{2}^*(q)\right)\sin\left(\omega_0 t + \varphi_0(q)\right),$$

where $T_{2}^*(q)$ is the spin-spin relaxation time, and $\varphi_0(q)$ is the phase.

The signal induced in the receiver loop is proportional to the sum of the flux of all precessing magnetic moments $M_{\perp}$. Using the reciprocity theorem, and neglecting the higher harmonics of the pulse and a possible frequency offset between the Larmor frequency and the current frequency, the induction in the loop voltage thus becomes (Legchenko et al. 2002a)
where \( \psi_0 \) is the phase shift caused by electrically conductive rocks, and \( \omega_0 \leq w(r) \leq 1 \) is the water content. As both \( M_0 = \gamma_p B_0 \) and \( \omega_0 = \gamma_p B_0 \) are proportional to the geomagnetic field, it follows from Equation 4 that the amplitude of the magnetic resonance signal depends on the geographical location of the investigated area \( e_0 \sim B_0^2 \) (Legchenko et al. 1997).

Assuming that the stratification is horizontal, and the vertical distribution of resistivity is known, Equation 4 of the signal amplitude \( e_0 \) can be simplified to a Fredholm linear integral equation of the first kind (Legchenko and Shushakov 1998):

\[
e_0(q) = \int_0^L K(q,z)w(z)dz,
\]

where \( K(q,z) = \frac{M_0}{I_0} \int_{x,y} B_{1\perp}(r) \sin(\theta(r,q)) dx dy \).

Numerical results show that distant protons produce a negligibly small signal and, hence, integration can be limited by approximately \( x^2 + y^2 < (1.5D)^2 \), where \( D \) is the loop diameter (or side for a square loop). Consequently, \( L = 1.5D \) can be considered as the maximum possible depth of water detection by MRS, and a cube with side \( 1.5D \) as the approximate maximum possible volume. It should be noted that in heterogeneous geological environments, MRS data about aquifers are the averages of readings for a volume proportional to the size of the loop.

Considering the one-dimensional water distribution, the vertical distribution of water content \( w(z) \) is resolved by Equation 5. This linear equation may be solved by projecting it onto finite dimensional subspace, as approximated by the projected equation.
\[
\sum_j \left( h_j(q) w_j \right) = e_{0i}, \quad (6)
\]

where \( i = 1, 2, \ldots, I \), \( j = 1, 2, \ldots, J \) and \( h_j(q) \) is a set of kernel vectors obtained by projecting the kernel \( K(q, z) \) on a set of basis functions \( b_j(z) \), so that \( w(z) = \sum_j \left( w_j b_j(z) \right) \), \( (7) \)

and \( h_j(q) = \int_0^L K(q, z) b_j(z) dz \).

From a physical point of view, the problem allows the basis functions to be assumed as box-car functions. Hence, the kernel vectors are the elementary responses from the layers of water \( (w_i = 1) \), characterized by their depth \( z \) and thickness \( \Delta z \). If the depth intervals are \( 0 \leq z \leq L, \Delta z = z_{j+1} - z_j \) and \( L = \sum_j \Delta z \), then the basis functions are \( b_j(z) = 1 \), \( b_j(z < z_j), \quad z \geq z_{j+1} = 0 \) and the kernel vectors are

\[
h_j(q) = \int_{z_j}^{z_{j+1}} K(q, z) dz. \quad (8)
\]

In a matrix notation, projected Equation 6 can be written as

\[
A w = e_0, \quad (9)
\]

where \( A = \left[ a_{i,j} \right] \) is a rectangular matrix of \( I \times J \) with the elements \( a_{i,j} = h_j(q_i) \), \( e_0 = (e_{01}, e_{02}, \ldots, e_{0i}, \ldots, e_{0I})^T \), \( e_{0i} = e_0(q_i) \) being the set of experimental data,
The MRS inverse problem is ill-posed. It means that it is impossible, for a particular layer, to know both the layer thickness and the water content, which is giving rise to layer equivalence. Two layers at the depth $z_e$ with the thicknesses $\Delta z_1 < \Delta z_2$ are equivalent if $w_1 \Delta z_1 = w_2 \Delta z_2$. The equivalent layers cannot be resolved. The thickness $\Delta z_e$ is defined by the vertical resolution of the method, which depends on the electromagnetic field created by the loop; the larger the gradient of the field, the better the resolution. The electromagnetic field created with a loop on the surface by passing a current through it is well known; the gradient of the field is large close to the surface and decreases with increasing depth. Consequently, the resolution of the MRS is also better close to the surface. Figure 28 shows the relative errors of resolution for a synthetic model consisting of a 10 m thick layer ($w = 20\%$) versus the layer depth. A square 100 m side loop is assumed.

![Figure 28: Numerical modelling: resolution of a 10 m-thick layer when using a 100-m-side square loop.](image)
The errors were calculated as 

$$\varepsilon = 100\% \times \left( \frac{P_{\text{inv}} - P_{\text{mod}}}{P_{\text{mod}}} \right) / P_{\text{mod}},$$

where $P_{\text{inv}}$ and $P_{\text{mod}}$ are, respectively, a parameter from the inversion and its true value given by the model. It can be seen that both the water content and the thickness are better resolved when the layer is close to the loop, and that errors increase with distance from the loop. At a depth greater than about one half of the loop side, the 10 m thick layer cannot be resolved. However, note that the resolution accuracy of the product $w \times \Delta z$ is much better.

In practice, measurement of the signal is not possible without an instrumental delay ("dead time") of $\tau_d$. Consequently, for each value of $q$, the initial amplitude $e_0$ cannot be measured but is obtained by the extrapolation

$$e_0 = e(\tau_d) \exp(\tau_d / T_2^*).$$

(10)

The non-linear fitting scheme of Legchenko and Valla (1998) is used for estimating $e(\tau_d)$ and $T_2^*$ from records after the pulse time series. The pulse duration for currently available MRS instruments is about 40 ms and the "dead time" is $\tau_d = 30 \div 40$ ms; this is a limitation that does not allow the measurement of short signals with $T_2^* < 30$ ms.

The water content derived from MRS data is calculated as follows:

Let $V$ be the total volume of the subsurface; $V_w$ and $V_a$, the parts of subsurface filled with water and air respectively, and $V_R$, the part of subsurface occupied by rocks. Thus, $V = V_w + V_a + V_R$. The water $(V_w)$ can be separated into two parts: water $V_{\text{short}}$, characterized by a very short MRS signal, which cannot be measured by MRS instruments, and water $V_{\text{long}}$ that produces a measurable signal with sufficiently long relaxation time ($V_w = V_{\text{short}} + V_{\text{long}}$). Thus, the MRS water content can be defined as
the part of the total volume of the subsurface occupied by measurable MRS water:

\[ w = \frac{V_{\text{long}}}{V} \times 100\% . \]

Water in porous media can be divided into two parts (after Castany 1982): capillary-bound water and free water \( (V_w = V_{\text{bound}} + V_{\text{free}}) \). The capillary-bound water \( (V_{\text{bound}}) \) is attached to grain walls and cannot be extracted by gravity. The free water \( (V_{\text{free}}) \) is located at some distance from the grain walls and, therefore, can be extracted by gravity. Capillary-bound water generally dominates in the unsaturated zone, but both capillary-bound and free water are normally present in the aquifer. In highly permeable water-saturated rocks such as sand or gravel, most of the water is free. On the contrary, in water-saturated rocks with low permeability, such as clay, most of the water is capillary-bound. Experiments involving magnetic resonance measurements in porous media show that capillary-bound water is characterized by shorter relaxation times, and free water by longer relaxation times (Chang et al. 1997). In some rocks, capillary-bound water may have \( T_{2}^{*} < 30 \text{ ms} \), and free water \( T_{2}^{*} > 30 \text{ ms} \). As MRS instruments are able to measure only relatively long signals \( (T_{2}^{*} > 30 \text{ ms}) \), it is clear that in these rocks MRS is sensitive mostly to free water (Schirov et al. 1991).

In nuclear magnetic resonance logging, the magnetic resonance response is correlated with the effective porosity. Obviously, MRS water content \( w \) is also related to the effective porosity, but there is currently insufficient experimental data to establish a quantitative relationship.

The relationship between the measured signal \( e_{0}(z) \) and water content \( w(z) \) shown in Equation 5 was verified experimentally in the early 1980s, when field measurements were carried out on an ice (0.8 m thick) covered lake in Russia using HYDROSCOPE equipment (Schirov et al. 1991). The magnetic resonance signal from bulk water in the lake has a long relaxation time \( (T_{2}^{*} > 800 \text{ ms}) \) and, hence, all the water contributes to the MRS water content. The theoretical signal calculated for the model of a 10 m thick water body \( (w = 100\%) \), derived from mapping the lake bottom, fits particularly well with the initial part of the experimental data where the contribution of lake water into the total signal is maximal (Figure 29). No information was available about possible aquifers below the lake, so MRS data for greater depths could not be evaluated.
MRS estimation of water volume

MRS provides an estimate of the total amount of water in the subsurface $V_{\text{MRS}} \ (m^3)$. In a general case, $V_{\text{MRS}} = \int_V w(r) dV(r)$. Assuming a horizontal stratification, an estimate of the volume of water per surface unit in a layer of thickness $\Delta z$ (a column of a height $\Delta z$) can be obtained from

$$V_{\text{MRS-H}} = \int_{\Delta z} w(z) dz . \quad (11)$$

This volume $V_{\text{MRS-H}} \,(m^3/m^2)$ provides an estimate of the amount of water in horizontally stratified earth and corresponds to a hydrostatic water column used in hydrogeology.

When quantitative interpretation of MRS measurements is not possible, an estimation of the maximum possible volume of water per surface unit can be made using Equation 11.
Relaxation Times

Other important characteristics of the magnetic resonance signal are; longitudinal relaxation time $T_1$, transverse relaxation time $T_2$, and the observed relaxation time $T_2^*$ (Slichter 1990). In porous media, the relaxation times $T_1$ and $T_2$ ($T_1 \approx 1.5 \times T_2$) are proportional to the mean pore size (Kleinberg et al. 1994; Kenyon 1997):

$$T_{1(2)} \approx \frac{V_p}{\rho_{1(2)} S_p},$$

(12)

where $S_p$ and $V_p$ are the surface and volume of pores respectively; and $\rho_{1(2)}$ is the surface relaxivity (when using $T_1$ or $T_2$), which depends on rock mineralogy. In magnetic resonance logging, both $T_1$ and $T_2$ are used for estimating aquifer permeability.

Because of technical difficulties for measuring $T_1$ and $T_2$ in large volumes from the surface, only the MRS $T_2^*$ relaxation time, which can be derived from the envelope of the magnetic resonance signal (Equation 3), was used initially (Schirov et al. 1991). Whilst it is known that $T_2^*$ is proportional to $T_2$, $T_2^*$ is also sensitive to local inhomogeneities in the geomagnetic field $\Delta B_0$ caused by rocks (Farrar and Becker 1971);

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \gamma_p (\Delta B_0 / 2),$$

(13)

which makes $T_2^*$ less reliable than $T_1$ or $T_2$ for pore size estimation.

Examples of $T_2^*$ and $T_1$ measurements in rocks with different magnetic properties are presented in Table 1 (Legchenko et al. 2002b).
<table>
<thead>
<tr>
<th>Rock type</th>
<th>Magnetization (A/m)</th>
<th>Susceptibility (SIU)</th>
<th>$T_2^*$ (ms)</th>
<th>$T_1$ (ms)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reef limestone (Cyprus)</td>
<td>$1 \times 10^{-4}$</td>
<td>$-9.1 \times 10^{-6}$</td>
<td>80</td>
<td>220</td>
<td>Unsaturated zone</td>
</tr>
<tr>
<td>Fractured limestone (Cyprus)</td>
<td>$2.8 \times 10^{-4}$</td>
<td>$-8.5 \times 10^{-6}$</td>
<td>130</td>
<td>430</td>
<td>Aquifer</td>
</tr>
<tr>
<td>Highly fractured limestone (France)</td>
<td>$8.1 \times 10^{-3}$</td>
<td>$1.5 \times 10^{-3}$</td>
<td>280</td>
<td>800</td>
<td>Aquifer</td>
</tr>
<tr>
<td>Karst limestone (Cyprus)</td>
<td>$4.5 \times 10^{-5}$</td>
<td>$-7.2 \times 10^{-6}$</td>
<td>460</td>
<td>1000</td>
<td>Aquifer</td>
</tr>
<tr>
<td>Clay and fine sand (France)</td>
<td>$1.4 \times 10^{-3}$</td>
<td>$1.4 \times 10^{-4}$</td>
<td>70</td>
<td>310</td>
<td>Aquifer</td>
</tr>
<tr>
<td>Medium sand (France)</td>
<td>$3.9 \times 10^{-4}$</td>
<td>$2.9 \times 10^{-5}$</td>
<td>120</td>
<td>420</td>
<td>Aquifer</td>
</tr>
<tr>
<td>Gravel and coarse sand (France)</td>
<td>$7.5 \times 10^{-4}$</td>
<td>$4.4 \times 10^{-4}$</td>
<td>330</td>
<td>600</td>
<td>Aquifer</td>
</tr>
<tr>
<td>Sandstone (USA)</td>
<td>$3.2 \times 10^{-4}$</td>
<td>$2 \times 10^{-4}$</td>
<td>80</td>
<td>-</td>
<td>Aquifer</td>
</tr>
<tr>
<td>Basaltic gravel (Cyprus)</td>
<td>$1.3 \times 10^{-1}$</td>
<td>$4.8 \times 10^{-3}$</td>
<td>10</td>
<td>-</td>
<td>Aquifer</td>
</tr>
</tbody>
</table>

Table 5: Magnetic properties of rocks and MRS relaxation times.

Thus, in non-magnetic rocks like limestone, both free and capillary-bound water contribute to MRS water content. In magnetic rocks however, even free water cannot be detected.
The saturation recovery method (Dunn et al., 2002) can be used for measuring $T_1$. This consists of applying two pulses, separated by a delay $\tau_p$, to the investigated sample and measuring the magnetic resonance response after the second pulse. Each pulse flips the spin magnetization to the exact angle of $\pi/2$. Under laboratory conditions, only small samples are investigated and special care is taken to have both the static and alternating magnetic fields as homogeneous as possible inside the sample. In the laboratory, therefore, the pulses can be set up so that the flip angle is equal to exactly $\pi/2$. In field conditions however, the flip angle in a volume $dV$ depends on its distance from the surface loop and, within the studied volume, the flip angle caused by the same pulse may vary widely for different samples $dV(r)$, which is why $T_1$ cannot be measured directly.

The saturation recovery method, however, can be adapted to MRS. Two pulses are applied to the investigated volume and, after the first pulse, the spin magnetization $M$ of the sample $dV$ is turned off at the angle $\theta$ (Equation 2), as shown in Figure 27. During the delay $\tau_p$, it builds up towards equilibrium along the geomagnetic field with the time constant $T_1$. Assuming the spin system to be linear, and neglecting relaxation during the pulse, $(\tau << T_2^*, T_2, T_1)$, the perpendicular to the earth’s magnetic field component of the spin magnetization after the second pulse can be described by the equation:

$$M_{\perp}(\tau_p) = M_0 \exp(-\tau_p / T_1) \sin(\theta + \theta_2) + M_0 \left(1 - \exp(-\tau_p / T_1)\right) \sin(\theta_2),$$

where $\theta_2$ is the flip angle caused by the second pulse. If both pulses are set to be equal ($q_1 = q_2 = q$) and the phase shift between the current of the second pulse is equal to $180^\circ$ relative to the current of the first pulse, then $\theta_2 = -\theta$ and Equation 14 can be simplified to:

$$M_{\perp}(\tau_p) = -M_0 \left(1 - \exp(-\tau_p / T_1)\right) \sin(\theta).$$

For calculating the amplitude of a MRS signal measured after the second pulse, Equation 4, which describes the amplitude after the first pulse will be replaced by:
Geophysical characterization of a weathered granite aquifer near Hyderabad

\[ e_{02}(q, \tau_p) = \frac{M_0 M_0}{I_0} \times \]

\[ \times \int_B \left( 1 - \exp \left( -\frac{\tau}{\tau_p} / T_1(r) \right) \right) B_{1x} (r)e^{j(2p_0(r)+\pi)} \sin(\theta(r, q))w(r)dV(r) \]

If horizontal stratification is assumed and:

\[ x(z) = 1 - \exp \left( -\tau / \tau_p / T_1(z) \right), \quad (17) \]

then Equation 16 can be resolved by applying the same approach as for the resolution of Equation 4. Thus, using the notations introduced for Equation 9, and just one value for the delay between the pulses fixed at \( \tau_p = (2 \div 3) \times T_2^* \), it follows that:

\[ (Aw)x = e_{02} \], \quad (18) \]

where the water content \( w \) is obtained by the resolution of Equation 9, \( e_{02} \) is the set of experimental data measured after the second pulse, and \( x = (x_1, x_2, \ldots, x_j)^T \) is the solution vector. Equation 16 allows easy calculation of

\[ T_{1j} = -\tau / \tau_p / \log(1 - x_j) = T_1(\Delta x_j), \]

which is a vertical distribution of the relaxation time \( T_1 \). If it is possible to carry out measurements with different values of \( \tau_p \), then this will improve the accuracy of results, but will also increase the time required for the data acquisition.

It is instructive to now compare \( T_1 \) measurements at two different sites. The Site 1 aquifer is composed of coarse sand, and the borehole yield is about 120 m\(^3\)/h. The Site 2 aquifer is composed of chalk, and the borehole yield is about 3 m\(^3\)/h. For demonstration purposes, \( T_1 \) was measured for just one value of the pulse parameter \( q \), with varied delays between the pulses \( \tau_p \), which gives the apparent relaxation time...
$T_{1a}(q)$ rather than the real one $T_{1}(z)$. However, as only one aquifer exists at each of these sites, the apparent $T_{1a}$ may be considered as the real $T_{1}$. Normalized amplitudes measured at each site versus the delay $\tau_p$ are shown in Figure 30. As expected, a longer $T_{1}$ was observed at the site where the aquifer has a larger yield.

![Figure 30: Comparison of two different aquifers: normalized amplitude of the MRS signal measured after the second pulse versus the delay between the pulses.](image)

**MRS estimation of hydraulic conductivity**

In nuclear magnetic resonance logging, the hydraulic conductivity of water-saturated porous media can be estimated as (Chang et al. 1997; Kenyon 1997):

$$k_{NML} = a \phi_{NML}^b T_{1}^c,$$

(19)

with $k_{NML}$ being the hydraulic conductivity estimated using magnetic resonance data, $\phi_{NML}$ and $T_{1}$ the porosity and the relaxation time derived from NML measurements,
and $a, b, c$ are empirical constants. Other suggested formula, such as $k_{NML} = aT^b / F^c$, where $a, b, c$ are empirical constants and $F$ is the electrical formation factor. Both formula work equally well within experimental errors. Different estimation methods, based on Equation 19, have also been developed; first, $b = 1$ and $c = 2$ were proposed by Seevers (1966), and later it was shown that, for sandstones, better accuracy can be achieved using $b = 4$ and $c = 2$ (Timur 1968, 1969a, 1969b; Kenyon et al. 1988). In MRS, a formula based on Equation 19 is actually used for estimating the hydraulic conductivity

$$K_{MRS} = C_p w^a T^b_1.$$  \hfill (20)

Hydraulic conductivity is a scale-dependent parameter. Taking into account that MRS results are averaged over a large area defined by the loop size, pumping tests, which also provide results averaged over a large volume, are used for calibration.

Pumping test transmissivity values reflect the hydraulic conductivity and thickness of the aquifer $T_{bh} = K_{bh} \Delta z_{bh}$. Estimates of both hydraulic conductivity and aquifer thickness can be derived also from MRS measurements, and the MRS transmissivity estimate is:

$$T_{MRS} = \int_{\Delta z} K_{MRS}(z)dz,$$  \hfill (21)

where $K_{MRS}(z) = C_p w(z) T^b_1(z)$, and $\Delta z$ is the thickness of the aquifer estimated by MRS.

Two estimators, based on Equation 19 ($\sim wT^2_1$ and $\sim w^4T^2_1$), were tested using MRS measurements in France (an area between Chartres and Orleans). For each estimator, the constant $C_p$ was selected so that the MRS estimated transmissivities matched the best pumping test transmissivities. It was found that, when applied to MRS measurements, the ($\sim wT^2_1$) estimator gave better results than the reportedly more accurate ($\sim w^4T^2_1$) estimator. A comparison between the MRS and borehole pumping test results is shown in Figure 31; the error bars were calculated taking into account the accuracy of MRS data and possible equivalent solutions.
In conclusion, we need to discuss the principal limitations of the applicability of MRS to a non-invasive estimation of the hydraulic conductivity.

Samples investigated in laboratories, using borehole NMR tools or performing MRS measurements all have very different scales. Thus, the results obtained with these methods may be different. An example of two aquifers of different type is presented in Figure 32.

In aquifers with a single porosity (type A), the water is located in similar pores and the hydraulic conductivity of such aquifers is closely related to the pore size. In this case, information about the aquifer derived from magnetic resonance measurements is also related to hydraulic conductivity, even if investigated samples are of a different volume.

In aquifers with a double porosity (type B), as shown in Figure 32, most of the water is located in large pores, but hydraulic conductivity mostly depends on small pores. In this case, if the volume of the investigated sample is small (laboratory measurements), the results of the hydraulic conductivity estimation depend on whether the selected sample represents small or large pores. A large-scale method like MRS will provide us with information mostly related to large pores, since they contain larger quantities of water than small pores. Obviously, the hydraulic conductivity estimation is much less accurate in this case.

In practice, different types of porosity are usually mixed and the measured magnetic resonance signal is often composed of a sum of signals decaying with different relaxation times and thus contains information about different pores.
3.4.2. The depth of investigation

The magnetic resonance signal is sensitive to different natural factors, which makes the performance of the method site-dependent. The most common and practically important variations in the magnetic resonance signal are related to the natural geomagnetic field and the electrical conductivity of rocks (Semenov et al., 1989; Shushakov, 1996; Legchenko et al., 1997; Valla and Legchenko, 2002). The electrically conductive subsurface attenuates alternative electromagnetic fields by a factor characterized by the “skin depth” that is proportional to $\sqrt{\rho/f}$, where $\rho$ is the resistivity of the subsurface and $f$ is the frequency of the electromagnetic field. The Larmor frequency used in MRS is proportional to the geomagnetic field magnitude $f_0 \sim H_0$. Consequently, in areas with a low geomagnetic field (towards the equator), the frequency is smaller and the attenuation caused by the subsurface is less important than in areas with a high geomagnetic field (towards the poles). However, the magnetic resonance response is proportional to the square of the geomagnetic field ($E \sim H_0^2$), which improves the signal to noise ratio in areas with a high geomagnetic field, while
even taking into account the attenuation caused by the subsurface. The inclination of the geomagnetic field also modifies the magnetic resonance signal (Legchenko et al., 1997). A numerical demonstration of the influence of these natural factors on the maximum depth of investigation of the MRS method is presented in Figure 33. The maximum depth of detection of a one metre thick infinite horizontal layer of water (100% of the water content and $T_2^*=1000\text{ms}$) in a noiseless environment is depicted versus the half-space resistivity. Calculations were performed for different geomagnetic fields using the NUMISPLUS standard configuration: a square loop with a side of 100 m, a signal detection threshold of 10 nV and a maximum pulse of 12000 A-ms.

We can see that the magnitude and inclination of the geomagnetic field is a major factor that defines MRS performance when the subsurface is non-conductive. The influence of electrically conductive layers becomes important when the resistivity of these layers is less than 50 ohm-m approximately.

Inversion of MRS data ($E_{0d}(q)$ and $T_2^*(q)$), provides the depth ($z$), the thickness ($\Delta z$), the water content ($w$), and the relaxation times $T_2^*$ and $T_1$ for each water-saturated layer.

![Figure 33: The maximum depth of detection calculated for a 1-m-thick layer of free water (w=100%) versus the half-space resistivity.](image-url)
Figure 34: One-layer model.

Figure 35: Resolution of the one-layer model.
However, like many other geophysical problems, the MRS inverse problem is ill-posed and therefore the solution is non-unique (Legchenko and Shushakov, 1998). We present “smooth inversion” results performed following the Tikhonov regularization method, but other methods such as the linear programming and Monte Carlo inversion could also be used (Guillen and Legchenko, 2002; 2002a).

The resolution of the MRS method decreases with increasing depth. In order to demonstrate the MRS vertical resolution against the depth, we computed MRS signals from an inclined 10 m thick water-saturated layer, as is shown in Figure 34. We assumed that soundings are performed along a profile from the deepest part of the layer toward the shallow part. Results of 1D inversion for the water content ($w$), and for the relaxation time ($T_{2*}$) are plotted versus the distance (Figure 35). The dashed lines in the plot show the model. We can see that the resolution degrades progressively with increasing depth. While the top of the layer ($z$) is relatively well resolved down to 100 m, the thickness of the layer is still resolved down to about 60-70 m. Below 70 metres the thickness ($\Delta z$) and the water content ($w$) cannot be derived from MRS data. The relaxation time ($T_{2*}$) is well resolved down to 100 m for this model.

### 3.4.3. Example of MRS results

An example of MRS results obtained in France is presented in Figure 36. the investigated aquifer is composed essentially of medium to coarse sand. Field measurements were carried out near a borehole where the pumping tests were carried out.

The increase in the water content observed in the MRS log corresponds to the water table indicated by the borehole. However, the relaxation time corresponding to this zone is short ($T_1 \approx 50 ms$). It means that the permeability of the rock between 15 and 30 metres is low and that most of the water is capillary-bound water. The increase in the relaxation time corresponds well to the top of the aquifer indicated by the lithological log. The MRS permeability estimation also shows that the top of the aquifer is about 15 m below the water static level. A good agreement between the transmissivity estimated by MRS ($T_{MRS} = 4.7e - 3 (m^2/sec)$) and that derived from pumping tests ($T_{bh} = 4.6e - 3 (m^2/sec)$) is observed. Unfortunately, lack of data about the effective porosity does not allow us to calibrate the MRS water content.
3.4.4. Status of MRS applied to a hard rock environment

Legtchenko et al. (1997, 2002a) have revealed a clear correlation between air lift yield and MRS amplitude measured in a metasediment of the Saudi Arabian shield while the absence of a signal in a neighbouring area intersected by diorite dikes was attributed to geomagnetic field inhomogeneities.

Legtchenko et al. (2004) have imaged the contrasted hydraulic properties of a weathered granite aquifer across a small catchment in French Brittany using MRS combined with ERT. MRS estimated hydraulic transmissivities and water table satisfactorily correlate with pumping tests and borehole data but no hydraulic data were available for MRS water content comparison.

Wyns et al. (2004) used MRS coupled with geometrical aquifer modelling for mapping groundwater reserves in varying weathered basement rocks over a 270 km² study area in French Brittany. The MRS water content range defined over more than five different granites varied from 5 to 10% for alterite and was less than 5% for the FZ.

Vouillamoz et al. (2005) attempted to characterize a crystalline basement aquifer in Burkina-Faso by comparing MRS results with lithology and pumping tests data from 13 boreholes. MRS water content for alterite varied from 1 to 6% (3% mean value) and from 0.2 to 2.5% for the FZ (1% mean value) while MRS transmissivities were respectively lower and higher in the different formations in agreement with the proposed conventional conceptual model for a crystalline basement aquifer. However, the storativity estimation from MRS data is found to be not reliable, whereas the
transmissivity calibration with pumping test data is satisfactory and aquifer geometry appears to be accurately described by MRS results.

Legtchenko et al. (2005) discussed the ability of the method to detect weathered crystalline basement aquifers using the MRS estimation of the aquifer water volume (product of the aquifer water content and thickness) and concluded that the unweathered fractured bedrock characterized by mean water content lower than 0.5% cannot be detected. The screening effect of shallow aquifer, which may corrupt the deeper aquifer characteristics if it contains significantly less water than the shallow one, and the limited resolution of inversion of the coincident loop sounding using 1D assumption over structures of limited extension are also discussed.

3.4.5. MRS equipment

The MRS equipment used is NUMISPLUS from Iris Instrument with the following accessories:
- 900 metres of measurement cables.
- 1 Elsec proton magnetometer.
- 1 Kappameter KT5 from Exploranium.
- 1 Laptop computer.

The NUMISPLUS instrument consists of an oscillating-current generator, a receiver, a MRS signal detector, an antenna and a microprocessor (Figure 37 and Figure 38). The antenna is used for both transmission of the oscillating magnetic field and reception of the MRS signal. The microprocessor switches the antenna from generator to receiver mode by an electronic switch. It also controls the generation of the reference frequency equal to the Larmor frequency. An envelope of the signal from the phase-sensitive detector is recorded by the microprocessor in digital form. A portable PC is used for data processing. The PC is connected to the microprocessor by a standard RS-232 serial link.

![Figure 37: Scheme of the NUMISplus instrument.](image-url)
3.4.6. Objectives of MRS investigations

Within the combined methodology associating electrical/electromagnetic methods, Magnetic Resonance Sounding is dedicated to aquifer hydrodynamic characterization. However, the investigation capability of a geophysical method should be analysed through the following progressive steps: detection, localization and characterization, which could be traduced by the following questions:

- What are the conditions and limits of detection of the weathered granite aquifer using MRS?

- Is it possible to characterize accurately the geometry of a weathered granite aquifer?

- Is it possible to characterize accurately the hydrodynamic properties of a weathered granite aquifer?

Treating these questions will then lead to answer to the more general question : How can MRS results be used by hydrogeologists to contribute to better management of a weathered granite aquifer in the Hyderabad region?
3.4.7. Field methodology

Because of the dense network of power lines supplying agricultural pumped borewells and the low water content in such hard rock aquifer, the signal to noise conditions were difficult on most of the investigated sites. For this reason, a 8-shape square loop, which is a noise reducing device (Trushkin et al. 1994), was mostly used (see Table 6). At first, a small size 37.5 m loop was chosen for its relatively good lateral resolution, but since the S/N ratio remained too low larger loop sizes were tested in order to increase the signal level. Various other filtering devices were also tested such as a subtraction filter, rejection (notch) filter (Legchenko A., Valla P. 2003) and weighted stack (Legtchenko and Valla, 2002).

For MRS data quality estimation, the following parameters can be used:

1) External noise level after stacking and filtering is compared with the NUMIS instrumental noise as,

\[ \frac{EN}{IN} = \frac{\text{ext.noise}}{\text{instr.noise}} = \frac{\text{noise}}{5} \]  \quad (22)

considering that NUMIS\textsuperscript{plus} instrument has an instrumental noise that can be decreased by a stacking process down to about 5 nV. In the ideal case, when the external noise is very small, the EN/IN ratio is about equal to 1. When the magnetic resonance signal is very small, the stacking should be carried out until \( \frac{EN}{IN} \simeq 1 \). When \( \frac{EN}{IN} \simeq 1 \), the sounding can be considered as of a good quality, even if the signal has not been detected.

2) The signal to noise (observed noise includes both external and instrumental noises) ratio

\[ S / N = \frac{\text{signal}}{\text{noise}}. \]  \quad (23)

Usually data are considered of good quality when S/N>2. In this case, a quantitative interpretation of MRS data is possible and reliable information about aquifers can be derived from MRS data. If \( \frac{EN}{IN} \simeq 1 \) and S/N=1 (signal is not detected), a quantitative interpretation of MRS data is not possible. However, it can be concluded that there is no water (detectable by current MRS equipment) in the subsurface.

For example, on the Recharge site, where various filters were tested, no signal was observed despite the fact that the external noise level was lowered as to be close to the instrumental noise level (EN/IN=1.26). Whilst the signal to noise ratio is low (0.86), the sounding quality can be considered as fairly good (see Table 6). In this site conditions, where noise level is not excessive, the subtraction filter moreover did not prove to be efficient. The subtraction process generates artefacts in the centre of the spectrum, i.e. around the expected signal frequency. This artefact thus cannot be filtered and renders the records unsuitable (Girard et al., 2005). After this test, the subtraction filter was abandoned and the following procedure was then recommended:
- waiting for good EM noise conditions: electrical power is supplied only half of the time in most rural villages and this fact was exploited to plan MRS measurements when the electric power was switched off,

- using an “eight-shape” antenna and seeking the optimal orientation that best lowers the noise level.

- applying 300 to 500-stack programs with the weighting technique and a notch filter for removing power supply harmonics.

Generally, data can be considered as fairly good with EN/IN lower than 2 but only a few soundings with S/N greater than 1.5 are suitable for quantitative interpretation (Table 6).

<table>
<thead>
<tr>
<th>PMR sounding</th>
<th>Loop, side length (m)</th>
<th>Date</th>
<th>Water level depth when measuring (m)</th>
<th>Ambient noise (before filtering) (nV)</th>
<th>Stack number</th>
<th>EN/IN</th>
<th>S/N</th>
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</thead>
<tbody>
<tr>
<td>IPMR21</td>
<td>8-Square, 37.5 m</td>
<td>Nov-99</td>
<td>5</td>
<td>115 - 380</td>
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<td>1.27</td>
<td>1.84</td>
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<td>Dec-03</td>
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<td>1.01</td>
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<td>5.97</td>
<td>1.23</td>
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<tr>
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<td>13000-21000</td>
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<td>210-520</td>
<td>500</td>
<td>1.26</td>
<td>0.85</td>
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<td>1.09</td>
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<td>400</td>
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<td>2.00</td>
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<tr>
<td>KALTANK2</td>
<td>Square, 50 m</td>
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<td>19</td>
<td>300-775</td>
<td>400</td>
<td>1.67</td>
<td>1.55</td>
</tr>
</tbody>
</table>

Table 6: MR Soundings characteristics.

3.4.8. MRS detection of a weathered granite aquifer

a) 1D MRS modelling

The MRS signal magnitude is directly linked to the underground volume of water. Moreover, the MRS estimation of underground water volume, $V_{MRS}$, is easily obtained in the case of a horizontally stratified subsurface using equation (11) and is equivalent
for several layer configurations, of different thicknesses and water contents, located at a given depth. It is also better defined, as a result of MRS inversion, than thickness or water content, which cannot be defined separately without external information.

The 1D problem of MRS detection, which could be expressed as “what is the maximal depth at which a water-bearing layer of given thickness and water content can be detected considering a given noise level threshold?” can thus be simplified by replacing the thickness, \( \Delta z_i \) and water content, \( w_i \), parameters by their only product \( V_{\text{MRS}} = \sum \Delta z_i \cdot w_i \).

**Figure 39:** Maximum MRS amplitude responses of synthetic aquifer characterized by their depth and water volume computed for 37.5–m, 50-m-side 8-shape square loop and 75-m-side square loop.
Based on the 1999 MRS experiment at Maheshwaram, the lithology observed in boreholes and the conceptual model of the weathered hard rock aquifer (see 2.1), weathered granite aquifer can be simplified, as a first approach, as a one horizontal layer model with the following characteristics:

- thickness varying from 10 to 50 m,
- water content varying from 1 to 10%,
- water level varying from surface to 50 m.

The electrical method has shown that underground resistivities range from 10 to 200 ohm.m but generally are greater than 50 ohm.m, which insures that in most cases the conductivity effect on the MRS investigation can be negligible (see 0). Taking into account a geomagnetic field of 42230 nT with an inclination of 21°, which corresponds to the Hyderabad condition, and a homogenous earth with a 50 ohm.m resistivity, the MRS amplitude response was computed for different aquifers in order to study the detection capability of the method. This modelling was performed for the different loop configurations used during the field surveys and are presented in the graphs of Figure 39.

Assuming that an aquifer is considered as detected if its maximum MRS amplitude is twice the noise level and that the instrumental noise level of NUMIS\textsuperscript{PLUS} is about 5 nV, a threshold of detection could be taken at 10 nV. With such a threshold, the Figure 39 graphs show that a 10-m-thick aquifer of less than 1% water content ($V_{\text{MRS}} < 0.1$) can not be detected if it is deeper than 20 m, whatever the loop used, and if it is deeper than 10 m in the case of the 37.5-m-side eight-shape loop. However a 20-m-thick aquifer of 1.5% water content ($V_{\text{MRS}} = 0.3$) could be detected up to 25 m depth with a 37.5-m-side eight-shape loop and up to more than 50 m using the 75-m-side loop.

![Figure 40: Maximum depth of layered aquifer detection as a function of their water volume for different loops considering a noise threshold of 10 nV and 20 nV.](image_url)
Fixing the noise threshold, these master curves can be simplified in another set of curves where the different loop performances can be compared (Figure 40). This type of curve is useful when conceiving a survey for choosing the appropriate loop with respect to the depth, thickness and water content characteristics of the target and taking into account the level to which the noise will be lowered. The loop investigation depth could also be approached from these graphs at the depth for which the curves tend towards a vertical asymptote, taking into account the noise level and within the limit of equivalence. It is thus possible from Figure 40 to estimate that the maximum investigation depth of the 37.5-m-side eight-shape loop is less than 40 m for a 10 nV noise threshold and less than 30 m for a 20 nV noise threshold. If this loop thus appears a little bit too shallow for studying the complete weathered profile when it is the thickest (as on the Recharge site and Wailpally), the other used provide the necessary investigation depth.

b) 2D/3D MRS modelling

Background

According to the Bloch’s equations, MRS signal reaches a maximum when the tilt angle between the magnetization vector and the geomagnetic field is 90° (Slichter 1990). The MRS signal (eq. 1) of a unit volume of water dV(p) at a location p is recorded in the loop after the power is turn off and is characterized by its initial amplitude E0 (nV), decay time T2* (ms), phase ϕ0 (degree) and pulsation ω0 (rad/s).

\[ E(q,t) = \int \text{dV(p)} \left[ E_0(q,p) \cos(\omega_0(p)t + \phi_0(p)) e^{-\frac{t}{T_2^*(p)}} \right] + \text{Noise(t)} \] (eq. 24)

The integrative behaviour of the MRS method is well known. Responses from all the water molecules below the loop (from 25 to 150 m diameter) add together.

MRS data are usually inverted using the standard 1D scheme with the software Samovar (Iris Instrument 2001). It provides vertical logs of water content and permeability estimations. When several soundings are performed (or modelled) along a profile, amplitude of soundings, water content and permeability can be interpolated along the profile as it was done in 1999 on KBTanda and Mohabatnagar sites (Baltassat & Legchenko, 1999) . This method is referred as 1D profiling and provides good estimation of lateral variations if these variations are of the same size as the loop diameter. The main drawback of 1D inversion of 2D/3D structures is a false estimation of water content (Warsa, 2002; Legchenko 2006). When applying this approach to imaging of 2D-3D targets that have the size much smaller than the loop (as it could be the case for vertical fractured zones of tectonic origin) the resolution may be not sufficient for satisfactorily imaging the geometry of the target.

In the framework of the present project, a 3D modelling software has been developed. It makes it possible to compute the response of water inside a precisely delimited
volume for a given loop. Up to four different volumes of arbitrary shape defined by up to 18 points (X,Y) in the horizontal plane and limited in depth by Zmin, Zmax can be computed (Figure 41). These responses can be added together and/or added to a surrounding 1D layered response.

Practically, first a linear filter is calculated, taking in account the loop geometry, the 3D volume geometry and the underground conductivity with the software MRS04_5. It is stored in a file called “matrix” (extension .mrm). This matrix file is then used by the Samogon7x03 software to compute the sounding curves above 3D arbitrary shaped volumes of water (cf. Appendix 17) characterized by definite relaxation time constant. Future work should aim to develop a true 2D inversion scheme.

Figure 41: Definition of a parallelepiped for modelling according to the loop location and the magnetic north direction. More complex shape including up to 18 points X,Y (in the horizontal plane) at a given depth (Zmin, Zmax) can be also defined.
Case study of recharge

This experience aims to investigate underground above the static level, which may be wet below the paddyfield, and dry aside. The recharge due to the irrigation of the paddy field can be then estimated. A second point of interest would be to check if the infiltration is just limited below the paddy field or not.

The 3D modelling software developed in the framework of the present project has been used here to compute a PMR profile crossing the paddyfield. In this simulation, the “deep aquifer” is considered as 1D (classical processing). But the limited volume below the paddyfield is 3D.

The 1D model we considered is coherent with the PMR field measurement (signal lower than 15nV) and with the observed static level (21.5m) within the Maheshwaram basin in 2005. We therefore choose a 2% water content between 21.5m to 40m deep. This is more optimistic in term of water content than what is actually observed (in the FZ).

![Figure 42 - Location of five PMR soundings with a 50m “eight shape” loop, in a paddyfield area (red rectangle) for a simulation.](image-url)
The infiltration zone below the paddyfield is characterised by 1% of water content and limited to the irrigated area. Outside, no water is considered between the surface and the 21.5m depth of the water table. The location of the simulated PMR soundings are shown by their eight-shape loops on Figure 42.

Figure 43 shows that a mean amplitude increase of 7 nV and a quasi linear descending curve should be expected as a signature of such infiltration zone if we compare a central sounding (purple curves, location (0,0)) and any other sounding. One can notice that if the loop if half-part outside the paddy field (green curves), response is similar to a sounding completely aside (blue curve).

Practically, to answer the question of the quantitative estimation of the water content below the paddyfield, we only need one sounding completely inside the irrigated area, and one outside. The difference would allow to estimate the infiltration. To confirm the assumption of a drastic vertical limit of the horizontal extension of the infiltration zone, a third sounding across the limit of the paddyfield should be similar to a PMR sounding completely outside.

An attempt to validate this simulation on the well documented KBTanda site, during the 2005 fieldwork, was not successful because of a too weak S/N ratio. The methodology could however be used somewhere else.
3.4.9. Field characterization of the weathered granite aquifer

a) KB Tanda

On the KB Tanda site, MRS were repeated at about the same location, in a heavily irrigated area of paddy field, during different field surveys in 1999, 2003 and 2005 (Figure 44) while the water level respectively deepened from 5 m to 12 m and 21.5 m below ground level. IPMR11, measured in November 1999, showed a well expressed MRS signal with a maximum amplitude of about 30 nV. KB1, which was measured in December 2003 in the same post monsoon period when water levels are shallow, showed a mean amplitude of about 7.5 nV which did not emerge from the noise (Figure 45). A measurement repeated in March 2005 on KB1 (not shown in Figure 45) also did not show any signal emerging from the noise although it was still lowered (4 nV).

Different equivalent models were tested for interpreting IPMR11. A smooth model with a maximum water content of 2.8% at 9 m depth and a regular decrease with depth up to 20 m is equivalent to two layers models with an upper layer of 2.5 to 3.2% water content corresponding to the saprolite and a lower one of 0.8 to 1.5% water content corresponding to the FZ. The two layers model 2 has, amongst other things, the advantage of fitting both the 1999 and the 2003 measurements.

The difference observed between the MRS water table estimation and the borehole measurements, which are always deeper, is attributed to local inhomogeneities since the borehole measurements were not taken exactly at the MRS location.

b) Recharge site

No MRS signal was observed on the Zera 5 site (Figure 46) in 2005 while the water level was at 17 m BGL even though the amplitude measurement was lowered to the very low level of 6 nV. From the borehole lithology, a 24-m-thick aquifer composed of 8 m of saprolite and 16 m of FZ is assumed. Considering the amplitude level of 6 nV and this geometry, which gives an aquifer mid depth at 29 m, a maximum possible value of water volume can be estimated using the previously calculated master curves for the 8-shape 50-m-side antenna used (Figure 47). Assuming that the Recharge site aquifer may be simplified as a one layer aquifer, a maximum possible water volume of 0.12 m is obtained. For the borehole aquifer thickness of 24 m, a mean water content can be estimated at 0.5%, which appears quite low since the aquifer includes 8 m of water-bearing saprolite (Table 7 and Figure 8).

An abnormal low water content could however be explained on this site by the shallow high resistivity, high magnetic susceptibility zones, which are attributed to boulders or weakly weathered rock intercalated within the saprolite as observed on IFP27/5 (see 3.1.2 and Figure 48). The conceptual model of weathered granite as presented in 2.1, which can only be considered as more or less uniform at a regional scale, may locally be affected by anomalies such as boulders of hard rock where water contents is low.
Figure 44: Location map of investigations on the KB Tanda site, in the region of borewells.
Figure 45: KB Tanda site: amplitude sounding curves measured in 1999 and 2003, calculated sounding curve and corresponding water content models. Note that the water level which was at 5 m in 1999, deepened to 12 metres in 2003.
Whatever the loop used (see Appendix 3, Appendix 9 and Table 7) on the IFP16 site, no signal emerges from the noise level, which was lowered to about 10 nV for two soundings. Considering an aquifer mid-depth at 25 m and the measured amplitude levels, it is possible to define, using the curves of Figure 47, that the aquifer water volume is less than 0.22 (0.22 to 0.27 according to the various loops used). For the borehole defined aquifer thickness of 21 m, a maximum possible average water content of 1.0 to 1.3% can then be defined. Maximum possible water contents defined through modelling using a slightly different geometrical hypothesis (Appendix 9 and Table 7) range from 0.6 to 1.1%.

During the MRS investigation, the FZ only was saturated. It can then be assumed that these low water content correspond to the FZ.

d) IFP21

In the IFP21 area, the measured amplitude was lowered to 11 nV. Assuming that the MRS signal is lower than 11 nV, considering an aquifer mid-depth at 15 m, the 37.5-m-side loop graph in Figure 47 indicates that the aquifer water volume in IFP21 area is lower than 0.18 m. With a 7 m aquifer thickness, it gives a maximum water content of

Figure 46: Location map of investigations on the Recharge site, in the region of borewells
2.6%. For comparison, a 2% one layer was modelled (Appendix 9), considering a water level at 11 m depth.

Since IFP21 lithology indicate a 14 m thick saprolite overlying 4 m of FZ, this less than 2.0-2.6% aquifer is assumed to correspond partly to the saprolite and partly to the FZ.

Figure 47: Maximum values of water volume, $V_{MRS}$ estimation for each studied site from the maximum amplitude of measurement and aquifer mid-depth.
<table>
<thead>
<tr>
<th>Site</th>
<th>MR Sounding</th>
<th>Loop</th>
<th>Date</th>
<th>Max. amplitude of measurement (nV)</th>
<th>Noise level (nV)</th>
<th>Water level depth (m)</th>
<th>Aquifer base depth (m)</th>
<th>Aquifer thickness (m)</th>
<th>$V_{MRS}$ (m) from master curves</th>
<th>$W^{\text{Average}}$ (%)</th>
<th>$W$ from modelling (%)</th>
<th>Thickness from modelling (m)</th>
<th>$V_{MRS}$ from modelling (m)</th>
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<tr>
<td>KB Tanda</td>
<td>IPMR11</td>
<td>eight square 37.5 m side</td>
<td>Nov-99</td>
<td>28</td>
<td>6.5</td>
<td>5.0</td>
<td>24.0</td>
<td>19.0</td>
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<td>0.47</td>
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<td>eight square 37.5 m side</td>
<td>Dec-03</td>
<td>10</td>
<td>7.5</td>
<td>12.0</td>
<td>24.0</td>
<td>12.0</td>
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<td>7.5</td>
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<td>12.0</td>
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<td>18.0</td>
<td>7.0</td>
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<td>0.18</td>
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<td>41.0</td>
<td>24.0</td>
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<td>square 50 m side</td>
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<td>1.4</td>
<td>3.7</td>
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</table>

Table 7: Characteristics and results of MRS studied sites (“modelling” refer to results of constrained forward modelling as presented on Figure 45, Figure 51, Appendix 9, Appendix 10).
Figure 48: ERT investigation on the Recharge site showing a deep weathered profile and shallow high resistivity zones attributed to boulders.
e) Yalamakana & Kalvakuntala (Wailpally watershed)

In the Wailpally watershed, contrasted MRS responses were observed on sites 2 km apart with similar weathering conditions, as assessed by ERT, but different groundwater exploitation conditions.

ERT assessment of weathering conditions

An ERT investigation depth ranging between 50 and 60 m (Figure 49) is not sufficient to make it possible to define the depth to the unweathered bedrock, which is located, from borewell lithology (see 2.3), between 40 and 55 m depth. Due to the lack of data below these depths, the gradient processing tested above (see 3.3.4) does not apply. However, a comparison of the resistivity log with the litholog shows that resistivity values greater than 1000 ohm.m correspond to the unweathered rock (Figure 9).

In comparison with Yalamakana ERT, since the Kalvakuntala ERT profiles doesn’t show resistivities greater than 1000 ohm.m, it is assumed that unweathered rock is not reached at 40 m depth (the maximum investigation depth of these profiles) on this latter site (Figure 50). Furthermore, considering that the upper part (above 30 m) of the resistivity logs from both sites are quite consistent within a five metres depth shift difference (Figure 51), the weathering conditions are considered similar on both sites, given a 5 m uncertainty. The average weathered profile depth model of Yalamakana (Table 1) is then used for the purpose of interpreting Kalvakuntala MRS data.

MRS results

On the Yalamakanna site, where the water table is at 19 m BGL because of intense pumping, a signal does not emerge from a 12 nV noise level while a 65 nV signal is observed at the non-irrigated site of Kavakuntala, where the water table is at 9 m BGL.

Different equivalent models were tested for interpreting KALVA1. Water content ranging from 2 to 6% and 0.5 to 1% are respectively obtained for the saprolite and the FZ. A three layer model constrained by using the litholog geometry is found to also fit the YALA sounding. In this model, the saprolite is characterized by a 4% water content in its upper part and a 2% water content in its lower part; the FZ having a 1% water content. For the YALA sounding, the upper 4% water content layer has disappeared since it is above the water level (Figure 51).

As on the KB Tanda site, the difference between the MRS water table estimation and the borehole measurements (2 to 3 m) is attributed to local inhomogeneities, since the borehole measurements were not taken exactly at the MRS location.
Figure 49: ERT profile across the Yalamakana site.

Figure 50: ERT profiles across the Kalvakuntala site.
3.4.10. Screening effect of the saprolite aquifer

Legchenko (2005) has shown that at large pulse moments, water in shallow aquifers may generate a signal comparable in amplitude to a signal generated by water in deeper aquifers. He developed an improved mathematical model that takes into account the higher harmonics of the transmitted pulse and a non-zero offset between the transmitted and the actual Larmor frequency for a better modelling of the shallow water effect. This model is used here for modelling the screening effect.

As the studied aquifer is composed of two layers, the potential screening effect of the upper water-bearing saprolite on the lower FZ must be discussed. For this purpose the response of the two layers aquifer is modelled on the basis of the average depth profile presented for KB Tanda and Wailpally in Table 1. The obtained synthetic soundings are then inverses using Samovar software (Figure 52). Results are presented as errors, $\epsilon$, on the MRS water volume estimation produced after inversion, $V_{\text{inv}}$, compared to the initial model volume, $V$ such as $\epsilon = \frac{(V_{\text{inv}} - V)}{V}$ (Figure 53). These graphs show that the screening effect starts to be really considerable (more than 40% of the FZ is taken up) when the saprolite depth is 1.8 times less than the FZ depth (saprolite depth /FZ depth <0.55) or when the saprolite water volume is twice the FZ water volume (VFZ/Vsaprolite <0.5). It should also be noted that the saprolite layer determination is also affected, particularly when the water table is shallow. Relative errors on volume ratios however always remains lower than 40%.
Figure 52: Synthetic example of the screening effect of the upper water-bearing saprolite on the lower FZ. The layer geometry corresponds to the mean values in Table 1 (Improved mathematical model with 3 harmonics of the transmitted pulse and no frequency shift).

Figure 53: Screening effect of the upper water-bearing saprolite on the lower FZ as a function of the layers’ water volume ratio (left) and the layers’ mid-depth ratio (right).
3.4.11. Comparison with hydrogeological parameters

1D MRS is an integrating method and its estimations of hydrogeological parameters, which should be considered as average values, concern a large volume of rock that can be compared to that involved in pumping tests (Vouillamoz 2003). Pumping test results are thus considered as choice parameters for MRS results calibration.

Pumping test data are available on KB Tanda (Dewandel, pers. comm.) as well as on Yalamakana (Dewandel 2005, see Appendix 15). This set of data is too limited to allow a calibration of the present MRS data using some statistical approach. The transfer function established by Vouillamoz et al. (2005) for the Burkina Faso granite, such as $S_{y\text{MRS}} = C \cdot W_{\text{MRS}}$ where $C=0.28$, is used for comparison (Figure 54). Using this relation, the MRS determination of specific yield on both sites appears consistent with the pumping test data and within the uncertainty range of Burkina Faso data.

![Figure 54: Comparison of MRS water content determination on Yalamakana and KB Tanda with specific yield from pumping test using the transfer function established by Vouillamoz et al. (2005) for Burkina Faso granites (circles correspond to Burkina observations).](image)

The above analysed data concern the saprolite and the FZ together considered as one single layer (see Table 8). In order to bring some comparison element to the MRS water content evaluated for the saprolite, we made an attempt to measure water content in the laboratory on saprolite samples collected in a well dug on the Kalvakuntala site. Samples were collected above the water table, in other words in the non-saturated zone, and had to be re-saturated before oven drying and weighing measurements. During this preparation, some samples splintered and additional...
porosity was thus created. Mercury porosimetry was performed on less than 7 gram samples (about 2 cm³ samples) and thus applied to evaluate the matrix porosity.

The results are presented in Table 9. The porosity measured using the weighing technique on re-saturated samples present much higher values (9 to 29%) than the MRS water content. This porosity corresponds to the total water content including small pores (including clay), which are not observed by MRS. Moreover, rock shattering during preparation and swelling after sampling also caused additional porosity and meant that these measurements were not significant in comparison with MRS water contents. The samples used for mercury injection were too small to comprise fissures and were thus also not completely representative of the formation rock even though the measured values are closer to the observed MRS water content range for saprolite, particularly when the pore throats greater than 10 µm are considered (Table 9).

These measurements are definitely not useful for comparison and calibration of MRS water contents.

<table>
<thead>
<tr>
<th>Site</th>
<th>W_MRS (%)</th>
<th>Corresponding depth range (m)</th>
<th>Specific Yield from pumping tests, Sy</th>
<th>Prompted aquifer depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KB Tanda</td>
<td>1.4 – 1.7</td>
<td>4 - 21</td>
<td>0.014 – 0.017</td>
<td>n.a.</td>
</tr>
<tr>
<td>Yalamakana</td>
<td>2.2 – 2.5</td>
<td>15 - 46</td>
<td>0.002 – 0.004</td>
<td>16 - 46</td>
</tr>
</tbody>
</table>

*Table 8: MRS and pumping test characteristics of the weathered aquifer.*

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Depth (m)</th>
<th>Water content estimation using drying oven and weighing</th>
<th>Mercury porosimetry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>W_sat (%)</td>
<td>ρ_d</td>
</tr>
<tr>
<td>1</td>
<td>5.2</td>
<td>3.8</td>
<td>2.43</td>
</tr>
<tr>
<td>2</td>
<td>4.0</td>
<td>7.8</td>
<td>2.22</td>
</tr>
<tr>
<td>3</td>
<td>3.0</td>
<td>9.2</td>
<td>2.28</td>
</tr>
<tr>
<td>4</td>
<td>4.0</td>
<td>18.8</td>
<td>1.89</td>
</tr>
<tr>
<td>4a</td>
<td>4.0</td>
<td>14.9</td>
<td>1.88</td>
</tr>
<tr>
<td>5</td>
<td>5.2</td>
<td>8.3</td>
<td>2.17</td>
</tr>
<tr>
<td>6</td>
<td>5.7</td>
<td>14.1</td>
<td>1.90</td>
</tr>
</tbody>
</table>

*Table 9: Laboratory measurements on saprolite samples. W_sat = gravity water content; n = porosity = W_sat • ρ_d; ρ_d = dry density; ρ_s = saturated density; N = total mercury porosity*
3.4.12. Summary of MRS results

MRS results are summarized in Figure 55 and Figure 56. In Figure 55, the average water contents resulting from master curve evaluation or from modelling are reported. On most sites, these estimations involve both the saprolite and the FZ except on KB Tanda in 2003 and IFP16 in 2003 where the FZ only is concerned. From these latter, only a maximum possible value of water content can be defined for the FZ. Depending on the evaluation procedure used, the water content ranges are lower by 0.8 to 1.7% on KB Tanda sites and lower by 0.6 to 1.3% on IFP16. For both cases, as well as for most of the studied sites, estimations indeed correspond to an upper limit of a possible range of water contents, which is deduced from an amplitude measurement buried in noise. In such conditions, the only result is that the MRS signal of a potential FZ aquifer would be lower than the measured amplitude level from which a maximum potential volume of water can be derived. Since these conditions of water content are at the sensitivity limit of the method, the FZ cannot be completely resolved using the current equipment.

![Figure 55: Summary of water content observations averaged over the whole aquifer thickness.](image-url)
The whole set of water contents estimated in the Hyderabad region is presented in Figure 56 and compared to other determinations performed over granite settings in French Brittany (Wyns et al. 2004) and in Burkina-Faso (Vouillamoz et al. 2005). The saprolite water contents ranging from 1 to 6% correspond exactly to the Burkina Faso observation but are significantly lower than the Brittany range. However, significantly higher values would be expected if the upper saprolite layer was characterized thanks to a shallower water table. Another explanation would be that the weathered profile of the Hyderabad region is supposed to be truncated with its upper part (i.e. the saprolite) removed by erosion (Dewandel et al. 2006). Higher water contents indeed are generally expected in the upper, most weathered part of the weathering profile. Conversely, in Brittany, MRS sites were selected on hill tops where the weathering profile was the most complete (Wyns et al. 2004), which can explain the higher values for the French Brittany saprolite but this does not explain the difference for the FZ.

The FZ water content determined on KB Tanda and on Kalva1 as a result of geometrically constrained modelling using detailed lithology gives a limited range of values between 0.5 and 1.5%. These determinations however are at the sensitivity limit of the method. They thus should not be taken as a definite determination even though they are typically in the range measured on Burkina-Faso granites. These latter determinations, which are the results of inversion, should moreover be affected by the screening effect and thus may be underestimated.

Finally, the limit between both weathered formations can be placed between 1 and 2% (FZ water content lower by 2% and saprolite water content are higher by 1%).

Figure 56: Range of water contents observed in the Hyderabad region, compared with previous observations in French Brittany (Wyns et al. 2004) and in Burkina-Faso (Vouillamoz et al. 2005). Dashed lines indicate the range of potential values bounded by an upper limit.

The contrasted observations made on the KB Tanda site and in the Wailpally watershed show that MRS is able to assess the groundwater table depletion over time or spatially in agreement with piezometric measurements and with local groundwater exploitation condition. The efficiency of the method for such applications is however
limited to cases where the saprolite is saturated. In other words, the groundwater assessment capability of the MRS method is limited to the water-saturated saprolite; when the water table reaches the FZ, the MRS determinations are not reliable because the sensitivity limit of the current equipment is attained.

**Effect of magnetic field gradient**

A bibliography study of the “paramagnetic ion effect on NMR” was achieved within the framework of this project (Girard 2005, Appendix 16). A linear dependence between the concentration of paramagnetic ions (Fe III and/or Mn II) is generally observed but the corresponding effect on actual surface relaxivity is thought to be limited particularly when natural rock sample is considered. The dominant role of adsorbed ions on the pore surface in comparison with dissolved ions is demonstrated. The authors concluded that any change in paramagnetic content should be suspected, as well as pore size variation, to explain a change in NMR relaxation.

However, these conclusions are mainly based on laboratory measurements on synthetic material and cannot be easily transposed to MRS field measurements because of the difference in the magnetic field strength applied and because of the absence of magnetic particles within the grain or at the grain surface, as is the case with rocks and particularly with granite, which often contains magnetite.

Following Roy and Lubczynski (2005), magnetic field gradient effects on MRS must not be underestimated. They are observed at various scales such as:

- the field scale of measurement, which is defined by the loop size: the magnetic field map or preliminary measurement for Lamor frequency evaluation will generally help to detect magnetic anomalies caused by structures of contrasted susceptibility with respect to their environment or remanent magnetization. When such anomalies are observed, the loop is displaced to an area where the geomagnetic field gradient is lower (less than 40 nT/100 m). In the case where remanent magnetization is suspected, its effect on inclination should be taken into account. On the investigated sites of the Hyderabad region, no magnetic field anomalies that could reveal remanent magnetization were observed.

- the sample scale, where mainly magnetite grains may create large field gradients at the pore scale because of the large susceptibility contrast between magnetite (0.1< μ<10 s.i.) and other minerals: This occurrence is controlled using susceptibility measurements in the field and in the laboratory. Magnetic susceptibility observations in the Hyderabad region revealed that contrasted magnetic properties characterize weathered granites. As a consequence a) the corresponding vertical geomagnetic field gradient should be taken into account in MRS model computing (at the loop scale) b) potential additional MRS relaxation caused by magnetic field inhomogeneities at the pore scale should be suspected when susceptibility increases.

- at the film scale, magnetic oxide coatings or paramagnetic ions (Fe and Mn) adsorbed on the pore wall: Only laboratory experiments could tackle this phenomenon, but they require a lot of care in sample preparation, specific know-how and equipment.
Field scale and grain scale effect are presently controlled using proton magnetometer and susceptibility-meter measurements. Further developments on the potential effect of magnetic field inhomogeneities at the pores scale related to the observed magnetic susceptibility gradient could be envisaged at the MRS scale on well constrained sites such as KB Tanda or Wailpally, but they will need to gain at least one order of magnitude in S/N ratio.
4. Geophysical model of the Hyderabad region granite

From the above analysis of observations on four sites of the Maheswaram watershed and two sites of the Wailpally watershed, despite the scarcity of MRS with high S/N, a geophysical model of the Hyderabad region weathered granite aquifer is proposed, where the different water-bearing zones can be distinguished by their MRS, electrical and magnetic characteristics (Figure 57).

These characteristics can be completed by the MRS relaxation time constant, T2* which is defined, mainly on the basis of the 1999 data, between 50 and 200 ms (Table 10). Relaxation times, which are linked to the aquifer mean pore size, are determinant for hydrogeological application as they give access to hydraulic parameters (permeability, transmissivity). But their estimations are very few and not accurate because of the too low signal to noise ratio encountered on the studied sites.

Thanks to the water content determination, MRS can thus help to study the capacitive role of the aquifer but the hydraulic conductivity cannot be tackled because reliable evaluations of relaxation time constants are not possible with the current equipment under such low signal conditions.

Amongst the different characteristic parameters of the model, the magnetic susceptibility observations particularly need to be confirmed because the procedure of measurement on cuttings has important shortcomings. The variations observed along the weathered profile are however considered as significant and are an indicator of potential magnetic field inhomogeneities that could significantly affect the MRS response. It should however be noted that it was not necessary to invoke them for
interpreting the contrasted MRS responses observed from one site to another one as they are fully explained by water table variation.

<table>
<thead>
<tr>
<th></th>
<th>Resistivity (ohm.m)</th>
<th>Magnetic susceptibility (s.i.)</th>
<th>MRS Water content (%)</th>
<th>MRS Relaxation time constant (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saprolite</td>
<td>10 – 200</td>
<td>0.02 – 0.4</td>
<td>1 – 6</td>
<td>50 – 200 ms</td>
</tr>
<tr>
<td>Fissured zone (FZ)</td>
<td>100 – 1500</td>
<td>0.1 – 1.0</td>
<td>&lt; 1.5</td>
<td></td>
</tr>
<tr>
<td>Unweathered rock</td>
<td>700 - 4000</td>
<td>1 – 30</td>
<td>&lt; 0.5</td>
<td></td>
</tr>
</tbody>
</table>

*Table 10: Geophysical characteristics of the weathered granite aquifer of the Hyderabad region.*
5. Data storage

5.1. DATABASE ORGANIZATION

All geophysical data obtained in the framework of this project, completed by data from the 1999 survey, are stored in digital format in a database. The following organization has been adopted

- One directory for each site; in each site directory:
  - One subdirectory for each method; in each method subdirectory:
    - One Raw data subdirectory (raw data shall be read-only files)
    - Processed data subdirectory (as many directories as processing steps)
    - Presentation subdirectory (figures and maps to present the data)

- One subdirectory for summarizing the different method results.

5.2. FILE FORMAT

The data files format used in the database is described in the Table 11.

<table>
<thead>
<tr>
<th>Type of data</th>
<th>Raw data</th>
<th>Processed data</th>
<th>Interpreted data</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity and Magnetic susceptibility logging</td>
<td>Excel file</td>
<td></td>
<td>Excel file</td>
<td></td>
</tr>
<tr>
<td>TDEM</td>
<td>Geonics format, *.RED file</td>
<td>Interpex format, *.TEM file</td>
<td>Interpex format, *.IMG and *.MDL files</td>
<td>See Appendix 11</td>
</tr>
<tr>
<td>ERT</td>
<td>Iris Instrument binary format *.BIN file</td>
<td>RES2DINV data format, *.DAT file</td>
<td>RES2DINV inversion format, *.INV file</td>
<td></td>
</tr>
<tr>
<td>MRS</td>
<td>ASCII Numis/Samovar files</td>
<td>ASCII Numis/Samovar files</td>
<td>ASCII Numis/Samovar files</td>
<td>See Iris Instrument 2001</td>
</tr>
</tbody>
</table>

Table 11: Format of data files constituting the database.
6. Conclusions

On the basis of geophysical observations from the surface using Magnetic Resonance Sounding (MRS), Electrical Resistivity Tomography (ERT) and Time Domain ElectroMagnetism (TDEM) backed up by borehole geology, borehole geophysics (resistivity well logging and magnetic susceptibility on cutting samples) and hydrodynamic characteristics obtained with the help of IFCGR, the following geophysical model of the weathered granite aquifer was constructed in the framework of the present project.

The different compartment of the weathering profiles appears well characterized by contrasted resistivity and magnetic susceptibility that increase with depth. MRS water content conversely shows a continuous decrease with depth. Below the saprolite which water-content ranges from 1 to 6%, the fissured zone range is lower than 1.5 % and the fresh rock one which cannot be detected with the currently used instrumentation should be still lower.

This model is in agreement with the one developed for Burkina Faso granite and is thus confirmed. The lack of good quality relaxation time determination did not make it possible to complete the hydraulic conductivity aspect of the model. These results nevertheless could then be transposable to other regions around the world with similar granitic environments.

The different MRS observations made in the region of Hyderabad between 1999 and 2005 can be fully explained by the varying water level from place to place and during the considered period of time, taking into account this geophysical model of the weathered granite aquifer. Modelling carefully constrained by geometry provided by lithologs show that the MRS signal disappears when the water table depth comes close
to the Fissured Zone (FZ) top because the low water content of this unit corresponds to the sensitivity limit of the current equipment (NUMISPLUS). The MRS screening effect of the saprolite water layer on the underlying FZ is also discussed and the limit of application of the inversion schema of interpretation in this context is also underlined.

Within this low water content environment, MRS measurements were carried out under various field condition and led to contrasted MRS responses:

a) on KB Tanda rice fields in 1999 and 2003 (Maheshwaram watershed), while the water table had respectively deepened from 5 to 12 m below groundwater level (BGL)

b) on two sites of the Wailpally watershed, where water levels are respectively at 9 m BGL in a non-irrigated area and 19 m BGL because of intense pumping,

This demonstrates that MRS is able to assess groundwater table depletion over time or spatially in agreement with piezometric measurements and with the local agricultural activity. The efficiency of this method for such applications is nonetheless limited to those cases where the saprolite is saturated. In other words, the groundwater assessment capability of the MRS method is limited to the water-saturated saprolite because when the water table reaches the FZ, MRS determinations could only provide maximum possible water content estimations.

The observed significant variations in magnetic susceptibility along the weathered profile are an indicator of potential magnetic field inhomogeneities, which could significantly affect the MRS response, but it is not necessary to invoke them for interpreting the observed contrasted MRS responses as they are fully explained by water table variation. From the observations made, there is no proof of an effect of magnetic inhomogeneities on the MRS response.

Further determination of the FZ water content or hydraulic conductivity in this context as well as further developments on the potential effect of magnetic field inhomogeneities will require a gain, at least, of one order of magnitude in the S/N ratio. The well documented sites investigated in the Hyderabad region during this project could be the laboratory for such future experiments. They would be facilitated by the database, which gathers all geophysical raw data acquired in the framework of the present project completed with the former 1999 data.

Electrical and electromagnetic methods are recommended in a combined methodology with MRS, since they can qualitatively image the weathering profile and map the substratum elevation at reasonable cost. Electrical Resistivity Tomography is preferred to Time Domain Electromagnetism as the FZ is too resistive to be distinguished from the underlying unweathered rock by the latter. A quantitative characterization should however be possible when inversion can be constrained using geometry and resistivity measurements from boreholes or surface borehole tomography. But as a reliable formation resistivity cannot be easily obtained, the way to evaluating water content through Archie’s law or a similar empirical relationship is not obvious. These latter conclusions support our choice of preferring MRS for this purpose.
On the basis of this better knowledge of MRS capabilities within the weathered granite aquifer setting, the geophysical contribution to hydrogeological modelling or exploration and furthermore to groundwater management could be redefined as follows:

- MRS water content estimation for the saprolite compartment can be used for evaluating and modelling the weathered granite water resources.

- Electrical-Electromagnetic methods can be used for delineating deepening of the substratum topography, which could be an indicator of fractured zones of tectonic origin and hence high porosity, conductivity zones favourable for borehole sitting. In an operational methodology, electrical-electromagnetic methods are used for locating such target zones and then MRS is applied for operating a second level of selection on the basis of the most favourable hydrodynamic parameters.

Recommendations

Since further MRS development should make it possible to significantly lower the instrumental noise level,

- the MRS signal from the FZ could be measured and characteristics of the FZ could be made clearer and completed. The model of the weathered granite aquifer could thus be completed.

- 2D structures of groundwater interest (deepening of weathered and highly fractured zones) could be investigated and characterized.

A set of boreholes with hydrodynamic tests is proposed on the Kalvakuntla site in order to:

- attempt to characterize the saprolite hydrodynamic characteristics, which are poorly characterized because in the Maheshwaram region the water level is generally at the base or lower than the saprolite depth.

- characterize the highly hydraulically conductive FZ, independently of the overlying saprolite.

- complete the set of data on the Wailpally watershed.

These boreholes should be drilled while benefiting from the remaining high groundwater level after the monsoon. Despite several attempts being made, these drillings were not possible in September 2005 because the area was flooded and could not be reached by the drilling machine. It should be noted that the time-schedule of fieldwork in such terrain has to be conceived and adapted in accordance with the monsoon season and actual field conditions, which control the accessibility to the experimental site as well as the groundwater levels. The project management should take into account these constraints, forming one of the main reasons why the project had to be extended by one year after the autumn 2004 fieldwork had been cancelled.
and the consequent winter 2005 drilling works postponed during the less convenient autumn 2005 period.
7. References


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Geophysical characterization of a weathered granite aquifer near Hyderabad

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Geophysical characterization of a weathered granite aquifer near Hyderabad
Appendix 1

Location map of boreholes and geophysical investigation: KB Tanda site
Geophysical characterization of a weathered granite aquifer near Hyderabad

LEGEND
- Magnetic point
- ERT profiles 1999
- TDEM sounding
- Borehole
- Dugwell

UTM projection
WGS 84 ellipsoid

Easting (m)

No.

KB1
KB2
OB1-1
OB1-2
OB1-3
MW1
IFW11

UTM projection
WGS 84 ellipsoid

North

Line A
Line E
Line B
Line C

Easting (m)

225350
225400
225450
225500
225550
225600
225650
225700
225750
225800
225850
225900
225950
226000
226050
226100
226150
226200
226250
226300
226350
226400

225350
225400
225450
225500
225550
225600
225650
225700
225750
225800
225850
225900
225950
226000
226050
226100
226150
226200
226250
226300
226350
226400

Appendix 2

Location map of boreholes and geophysical investigation: Recharge site
Geophysical characterization of a weathered granite aquifer near Hyderabad

Legend:
- Magnetic point
- ERT profiles
- MRSounding
- Borehole
Appendix 3

Location map of boreholes and geophysical investigation: IFP16
Geophysical characterization of a weathered granite aquifer near Hyderabad

UTM projection
WGS 84 ellipsoid

North ing (m)

Easting (m)

- Magnetic point
- ERT electrodes
- PMR sounding
- Borehole
- Dugwell

Thalweg
Quartz vein outcrop

IFP16_1
IFP16_2
IFP16_3
Appendix 4

Location map of boreholes and geophysical investigation: IFP21
Geophysical characterization of a weathered granite aquifer near Hyderabad
Appendix 5

Location map of boreholes and geophysical investigation: Yalamakana site
Geophysical characterization of a weathered granite aquifer near Hyderabad

LEGEND
- Magnetic point
- ERT profiles
- MRSounding
- Scientific borehole
- Agricultural borehole
Appendix 6

Location map of boreholes and geophysical investigation: Kalvakuntala site
Appendix 7

Correction of “mud effect” for Normal array resistivity logs
Correction principle using the 1947’s Schlumberger chart (from Beck M. & Girardet D., 2002); Rt= formation resistivity, Rw= fluid resistivity, Rm= mud resistivity, Ra= measured apparent resistivity.

<table>
<thead>
<tr>
<th>AM Spacing</th>
<th>Hole diameter</th>
<th>R\text{a}/R\text{m} Range</th>
<th>Polynomial equation</th>
</tr>
</thead>
</table>
| 1 m        | 165 mm        | <12.5                     | \begin{align*}
Rt/Rm &= 0.076954 + 0.96957 \cdot (Ra/Rm) - 0.016792 \cdot (Ra/Rm)^2 + 0.00022190 \cdot (Ra/Rm)^3 \\
\end{align*} |
|            |               | >12.5                      | \begin{align*}
Rt/Rm &= 3.3206 + 0.52730 \cdot (Ra/Rm) + 0.00056582 \cdot (Ra/Rm)^2 - 7.0970 \cdot 10^{-8} \cdot (Ra/Rm)^3 \\
\end{align*} |
| 1 m        | 228 mm        | <12.5                      | \begin{align*}
Rt/Rm &= 0.027675 + 1.0268 \cdot (Ra/Rm) - 0.038768 \cdot (Ra/Rm)^2 + 0.0016385 \cdot (Ra/Rm)^3 \\
\end{align*} |
|            |               | >12.5                      | \begin{align*}
Rt/Rm &= 2.5394 + 0.56912 \cdot (Ra/Rm) + 0.00089909 \cdot (Ra/Rm)^2 + 1.5177 \cdot 10^{-3} \cdot (Ra/Rm)^3 \\
\end{align*} |
| 64°        | 165 mm        | <400                       | * Log (Rt/Rm) = 4.6735 \cdot 10^{-2} \cdot \log (Ra/Rm)^3 + 1.9214 \cdot 10^{-1} \cdot \log (Ra/Rm)^2 + 1.1027 \cdot \log (Ra/Rm) |
|            |               | >400                       | * Rt/Rm = -7.5962 \cdot 10^{-9} \cdot (Ra/Rm)^3 + 1.9968 \cdot 10^{-7} \cdot (Ra/Rm)^2 + 5.0429 \cdot 10^{-3} \cdot (Ra/Rm) |
| 16°        | 165 mm        | <34.5                      | * Log (Rt/Rm) = 1.7533 \cdot 10^{-2} \cdot \log (Ra/Rm)^3 + 7.4843 \cdot 10^{-2} \cdot \log (Ra/Rm)^2 + 8.0911 \cdot 10^{-1} \cdot \log (Ra/Rm) |
|            |               | >34.5                      | * Rt/Rm = -6.0016 \cdot 10^{-4} \cdot (Ra/Rm)^3 + 3.7491 \cdot 10^{-3} \cdot (Ra/Rm)^2 + 7.5793 \cdot 10^{-1} \cdot (Ra/Rm) |

Polynomial equations applied for correction (*modified from Beck M. & Girardet D., 2002).
Appendix 8

MRS Data and results presentation
The data interpretation software developed for NUMISplus system is very flexible and provides users with a wide range of possibilities to configure the output page. In this report, the configuration presented in the following figure is used. MRS results are presented by the following graphs:

1) **NUMIS signals** - free induction decay signals after the first pulse (FID1) and inversion fits versus the time are arranged by increasing pulse parameter from the bottom to top.

2) **NUMIS inversion** – vertical distribution of the water content with the relaxation time $T_2^*$ presented by the colour scale.

3) $T_2^*(z)$ - vertical distribution of the relaxation time $T_2^*$.

4) **FID1: $E(q)$** – amplitude of the FID1 signal and calculated fit versus the pulse parameter.

5) **FID1: phase($q$)** – phase of the FID1 signal and calculated fit versus the pulse parameter.

6) **FID1: $T_2^*(q)$** - relaxation time $T_2^*$ versus the pulse parameter.

7) **FID1: phase($q$)** – phase of the FID1 signal versus the pulse parameter.

8) **FID1: freq($q$)** – the Larmor frequency versus the pulse parameter.

9) **Ambiant noise** – noise measured before each pulse stack sequence.

In the header, information about parameters used for the interpretation is presented.
Geophysical characterization of a weathered granite aquifer near Hyderabad

Site: KB Tanda; Sounding: IPMR11; Smooth model
Date: 08.03.2004;   Time: 13:18

NUMIS data set: D:\Etudes2\cefipra\INDIA03\visit12-03\KB1\RMPnewmod\IPMR11.inp
matrix: D:\Etudes2\cefipra\INDIA03\visit12-03\KB1\RMPnewmod\IPMR11_0_0.mrm
loop: eight square, side = 37.5 m
geomagnetic field:
inclination= 21 degr, magnitude= 42042.25 nT
filtering window =  198.8 ms
time constant = 15.00 ms
average S/N =  1.84; EN/IN =  1.27
fitting error: FID1 = 19.92%; FID2 = 122202.89 %
param. of regular.: modelling
permeability constant  Cp = 7.00e-09

Example of NUMISplus output page.
Appendix 9

Data and results of MRS soundings - Maheshwaram watershed
Site: KB Tanda; Sounding: IPMR11; Smooth model
Date: 08.03.2004; Time: 13:18

NUMIS data set: D:\Etudes2\cefipra\INDIA03\visit12-03\KB1\RMnewmod\IPMR11.inp
matrix: D:\Etudes2\cefipra\INDIA03\visit12-03\KB1\RMnewmod\IPMR11_0_0.mrm
loop: eight square, side = 37.5 m
geomagnetic field:
inclination = 21 degr, magnitude = 42042.25 nT
filtering window = 198.8 ms
time constant = 15.00 ms
average S/N = 1.84; EN/IN = 1.27
fitting error: FID1 = 19.92%; FID2 = 122202.89 %
param. of regular.: modelling
permeability constant \( C_p = 7.00 \times 10^{-9} \)
Site: KB Tanda ; Sounding IPMR11 ; 2 layers model 1

NUMIS data set: D:\Etudes2\cefipra\INDIA03\visit12-03\KB1\RMPnewmod\IPMR11.inp
matrix: D:\Etudes2\cefipra\INDIA03\visit12-03\KB1\RMP_simpmod\IPMR11_0_0.mrm
loop: eight square, side = 37.5 m
gemagnetic field:
inclination= 21 degr, magnitude= 42042.25 nT

filtering window = 198.8 ms
time constant = 15.00 ms
average S/N = 1.84; EN/IN = 1.27
fitting error: FID1 = 22.21%; FID2 = 112751.72 %
param. of regular.: modelling
permeability constant  \( \mathcal{C}_p = 7.00 \times 10^{-9} \)
Site: KB Tanda ; Sounding IPMR11 ; 2 layers model 2
Date: 08.03.2004;   Time: 13:18
NUMIS data set: D:\Etudes2\cefipra\INDIA03\visit12-03\KB
Tanda\IPMR11_constrfit\IPMR11.inp
matrix: D:\Etudes2\cefipra\INDIA03\visit12-03\KB
Tanda\IPMR11_constrfit\IPMR11_0_0.mrm
loop: eight square, side = 37.5 m
geomagnetic field:
inclination= 21 degr, magnitude= 42042.25 nT
filtering window = 198.8 ms
time constant = 15.00 ms
average S/N = 1.84;  EN/IN = 1.27
fitting error: FID1 = 18.05%;  FID2 = 110424.23 %
param. of regular.: modelling
permeability constant  $C_p = 7.00 \times 10^{-9}$
Site: KB TANDA ; Sounding: KB1 ; 2 layers model 2

NUMIS data set: D:\Etudes2\cefipra\INDIA03\visit1203\KB
Tanda\KB1_constr_model\KB1.inp
matrix: D:\Etudes2\cefipra\INDIA03\visit1203\KB
Tanda\KB1_constr_model\IPMR11_0_0.mrm
loop: eight square, side = 37.5 m
gemagnetic field:
inclination= 21 degr, magnitude= 42164.32 nT
filtering window = 198.2 ms
time constant = 15.00 ms
average S/N = 1.01; EN/IN = 1.52
fitting error: FID1 = 14.05%; FID2 = 26.10%
param. of regular.: modelling
permeability constant  Cp = 7.00e-09

![Graph of Amplitude vs q](image1)

![Graph of Phase vs q](image2)
Site: MAHESHWARAM IFP16 ; Sounding: IFP16_1
Loop: 4 - 37.5 Date: 08.12.2003 Time: 02:18

NUMIS data set: D:\Etudes2\cefipra\INDIA03\visit12-03\modelling\IFP16_1B.inp
matrix: D:\RMP\Matrice\matric_8\matric_carr\matric_38m\IN8_37.MRM
loop: eight square, side = 37.5 m
geomagnetic field:
inclination= 21 degr, magnitude= 42190.14 nT
filtering window = 198.1 ms
time constant = 15.00 ms
average S/N = 1.09; EN/IN = 1.64
fitting error: FID1 = 47.49%; FID2 = 32.03 %
param. of regular.: modelling
permeability constant $C_p = 7.00e-09$
Geophysical characterization of a weathered granite aquifer near Hyderabad

Site: MAHESWARAM IFP16; Sounding: IFP16_2
Loop: 2 - 75.0 Date: 15.12.2003 Time: 07:47

NUMIS data set: D:\Etudes2\cefipra\INDIA03\visit12-03\modelling\IFP16_2.inp
matrix: D:\RMP\Matrice\matric_norm\matric_carr\matric_75m\IN_75.MRM
loop: square, side = 75.0 m
geomagnetic field:
inclination= 21 degr, magnitude= 42190.14 nT
filtering window = 198.1 ms
time constant = 15.00 ms
average S/N = 1.01; EN/IN = 4.79
fitting error: FID1 = 28.96%; FID2 = 7.22 %
param. of regular.: modelling
permeability constant \( C_p = 7.00e-09 \)
Geophysical characterization of a weathered granite aquifer near Hyderabad

Site: MAHESHWARAM IFP16 ; Sounding: IFP16_3
Loop: 4 - 56.0    Date: 15.12.2003    Time: 12:24

NUMIS data set: D:\Etudes2\cefipra\INDIA03\visit12-03\modelling\IFP16_3.inp
matrix: D:\Etudes2\cefipra\INDIA03\visit12-03\modelling\IN8_56.MRM
loop: eight square, side = 56.0 m
geomagnetic field:
inclination = 21 degr, magnitude = 42190.14 nT
filtering window = 198.1 ms
time constant = 15.00 ms
average S/N = 0.91; EN/IN = 2.47
fitting error: FID1 = 47.13%; FID2 = 107101.60 %
param. of regular.: modelling
permeability constant $C_p = 7.00e-09$
Geophysical characterization of a weathered granite aquifer near Hyderabad

Site: MAHESHWARAM IFP21; Sounding: IFP21
Loop: 4 - 37.5 Date: 10.12.2003 Time: 02:46

NUMIS dataset: D:\Etudes2\cefipra\INDIA03\visit12-03\modelling\IFP21_1.inp
matrix: D:\Etudes2\cefipra\INDIA03\visit12-03\modelling\IN8_37.MRM
loop: eight square, side = 37.5 m
geomagnetic field:
inclination = 21 deg, magnitude = 42190.14 nT
filtering window = 198.1 ms
time constant = 15.00 ms
average S/N = 1.23; EN/IN = 5.97
fitting error: FID1 = 46.63%; FID2 = 81.97 %
param. of regular.: modelling
permeability constant Cp = 7.00e-09
Geophysical characterization of a weathered granite aquifer near Hyderabad

Site: Recharge site; Sounding: zera5
Loop: 4 - 50.0 Date: 10.03.2005 Time: 09:53

NUMIS data set:
D:\Etudes2\cefipra\INDIA05_jfg\Maheshwaram\recharge_site\PFR\zera5\inv
ersion_jmb\ZERA5.inp
matrix: D:\Etudes2\cefipra\model1D\loop8sq50\HYD8_50_0_0.mrm
loop: eight square, side = 50.0 m
geomagnetic field:
inclination = 21 degr, magnitude = 42312.21 nT
filtering window = 199.7 ms
time constant = 15.00 ms
average S/N = 0.83; EN/IN = 1.26
fitting error: FID1 = 56.86%; FID2 = 53143.52%
param. of regular.: modelling
permeability constant \( \mathbb{C}_p = 7.00 \times 10^{-9} \)
Appendix 10

Data and results of MRS soundings – Wailpally watershed
Geophysical characterization of a weathered granite aquifer near Hyderabad

Site: Yalamakana; Sounding: Yalamakana
Loop: 4 - 50.0 Date: 16.03.2005 Time: 11:34

NUMIS data set:
D:\Etudes2\cefipra\INDIA05_jfg\wailpalle\Yalamakanna\PMR\Yala\yala_T2\YALA.in
matrix: D:\Etudes2\cefipra\model1D\loop8sq50\yala_0_0.mrm
loop: eight square, side = 50.0 m
geomagnetic field:
inclination = 21 degr, magnitude = 42281.69 nT
filtering window = 199.9 ms
time constant = 15.00 ms
average S/N = 1.09; EN/IN = 2.11
fitting error: FID1 = 47.08%; FID2 = 71.64 %
param. of regular.: modelling
permeability constant \( C_p = 7.00e-09 \)
Geophysical characterization of a weathered granite aquifer near Hyderabad

Site: Kalvakuntala ; Sounding: Kalval
Loop: 4 - 50.0 Date: 14.03.2005 Time: 11:16

NUMIS data set:
D:\Etudes2\cefipra\INDIA05_jfg\wailpallele\kalvakuntla\PMR\kalval\inverion_JMB\KALVAL.inp
matrix: D:\Etudes2\cefipra\model1D\loop8sq50\kalval_0_0.mrm
loop: eight square, side = 50.0 m
geomagnetic field:
inclination= 21 degr, magnitude= 42251.17 nT
filtering window = 197.8 ms
time constant = 15.00 ms
average S/N = 2.06; EN/IN = 1.53
fitting error: FID1 = 29.82%; FID2 = 1281882.16 %
param. of regular.: modelling
permeability constant Cp = 7.00e-09

![Amplitude and Phase graphs](image1)
![Depth and resistivity graphs](image2)
Geophysical characterization of a weathered granite aquifer near Hyderabad

Site: Kalvakuntala; Sounding: Kaltank2
Loop: 2 - 50.0 Date: 15.03.2005 Time: 12:11

NUMIS data set:
D:\Travail\RMP_encours\CEFIPRA\INDE2005\data\wailpalle\kalvakuntla\PMR\kaltank2\inversion_3\KALTANK2.inp
matrix:
D:\Travail\RMP_encours\CEFIPRA\INDE2005\data\matrix\process\kalvatk2_0_0.mrm
loop: square, side = 50.0 m
gemagnetic field:
inclination= 21 degr, magnitude= 42281.69 nT
filtering window = 199.9 ms
time constant = 15.00 ms
average S/N = 1.55; EN/IN = 1.67
fitting error: FID1 = 29.47%; FID2 = 25050.69 %
param. of regular.: modelling
permeability constant Cp = 7.00e-09
Appendix 11

File format of TDEM data
• The files *.IMG are the results of the smooth inversion. Format example:

```
DATASET: TDEM01  NORTH:  711260.00  EAST:  2581016.00  ELEVATION:  655.00

LAYER   RESISTIVITY  THICKNESS
1  2.31345E+02  3.00000E+00
2  2.82166E+02  1.70486E+00
3  1.92790E+02  2.67370E+00
4  7.22385E+01  4.19313E+00
5  3.11013E+01  6.57603E+00
6  3.85824E+02  1.03131E+01
7  1.91121E+03  1.61739E+01
8  2.89011E+02
```

Note: the GPS coordinates are given in Indian III A grid system. Please refer to the location maps if no coordinates are given.

• The files *.MDL are the results of the 2 layers inversion. Format example:

```
DATASET: TDEM114  NORTH:  0.00  EAST:  0.00  ELEVATION:  0.00

LAYER   RESISTIVITY  THICKNESS
1  8.36982E+00  7.61270E+00
2  8.77895E+02
```

• The files *.RED are the raw data downloaded from GEONICS equipment. Please refer to the Geonics notice to obtain the necessary information on the raw files.

Data from Geonics TEM58 RX.
```
0       0       0       0       0       0       0       0       0       0       0       0       0       0       0       0       0       0       0
0       0       0       0       0       0       0       0       0       0       0       0       0       0       0       0       0       0       0
2611 0888 00000H HDR REF a 8+ RXA=31.4m*m
261199 0       0       0       0       0       0       0       0       0       38       0
2611 0888 00000Z OPR REF u 1a 4+
149000 2900 1361 661.1 316.7 152 81.77 35.1 16.26 6.833 2.23 .3824 .02506 .1756
.04396, .1173 .02758 .02817 .01401 .05891 -.01461 .018 .006813 2 625
2611 0888 00000Z OPR REF u 1a 4+
149000 2897 1363 661.9 316.8 152.2 81.88 35.19 16.28 6.847 2.23 .3886 .00006
.2062 .054 .1206 .03177 .02596 .0934 .05658 -.01078 .018 .006813 2 625
2611 0888 00000Z OPR REF u 1a 4+
149000 2893 1364 661.8 316.7 152.2 81.94 35.19 16.26 6.861 2.219 .3956 .01344
.1858 .05224 .116 .02297 .02377 .01367 .06056 -.00923 .0018 .006813 2 625
2611 0888 00000Z OPR REF u 2a 4+
149000 6018 2793 1351 642.5 312.1 160.3 71.84 32.59 13.54 4.5 .7818 .08656 .2539
.07941 .1768 .05317 .02482 .01563 .06051 -.00835 .0018 .006813 2 625
2611 0888 00000Z OPR REF u 2a 4+
149000 6011 2792 1349 642 312 160.1 71.8 32.57 13.53 4.456 .8299 .07037 .2526
.07425 .1684 .03484 .02647 .01614 .05908 -.01359 .0018 .006813 2 625
2611 0888 00000Z OPR REF u 2a 4+
```
- The files *.TEM are the data corrected from distortion, ready for inversion. Format example:

```
TDEM05  CLHZ     0.000  GEON         0.0000       0.0000
CEFIPRA                                 11-nov-99
MAHESWARAM WATERSHED                    05
Hyderabad                          CEFIPRA
2.000     1.800   237.500    31.400     0.000    7   58 F F
25.000     0.000     0.000    25.000
No.      TIME (msec)     nV/m**2
1   1.1130E-02   2.3032E+04
2   1.4190E-02   1.1422E+04
3   1.8070E-02   5.8834E+03
4   2.3060E-02   3.4093E+03
5   2.9440E-02   1.5607E+03
6   3.7560E-02   6.8607E+02
7   4.7940E-02   3.7828E+02
8   6.1330E-02   1.9968E+02
0.000    75.000    62.500    31.400     0.000    3   58
```

- The files XYTDEMS1(2).dat are the results of the smooth inversion formatted for SURFER drawings, for site 1 (Mohabatnagar) and site 2 (KB Tanda) respectively
Appendix 12

Test site selection within the Maheshwaram watershed (near Hyderabad, India) - Intermediary report, March 2003

Baltassat J.M., Robain H., Dewandel B., Krishnamurthy N.S., Kumar D., Marechal J.C.

(cf. the compact disk enclosed)
Appendix 13

Preliminary geophysical survey of test sites near Hyderabad (India) - Intermediary report, December 2003


(cf. the compact disk enclosed)
Appendix 14

Complementary geophysical survey of test sites near Hyderabad (India) – Intermediary report, March 2005

GIRARD J.F., GOUEZ J.M., KRISHNAMURTHY N.S., DUTTA S., CHANDRA S., KUMAR D., DEWANDEL B., GANDOLFI J.M, VOUILLAMOZ J.M.

(cf. the compact disk enclosed)
Appendix 15

Wailapaly boreholes - Drilling and Pumping test report, September 2005

Dewandel B.

(cf. the compact disk enclosed)
Appendix 16

Paramagnetic ions effect on NMR

Girard, J.F.
This is a synthesis of two articles: Foley et al., 1996, from the Schlumberger-Doll Research Center (Connecticut) and Bryar et al. from the department of Earth and Ocean Sciences of the British Columbia University (Canada).

These experiments use packed samples of non-natural material, which tends to simulate sedimentary rocks (mainly sand). The range of measured intrinsic parameters leads one to assume the results obtained are representative of these kinds of natural rocks. We must bear in mind that extrapolation to intrusive rocks (granite) may be not as obvious, since paramagnetic contents and type porosity are really different.

When water is confined in a pore, the relaxation time is often found to be much less than $T_{lb}$ (the bulk liquid relaxation time). This increased relaxation (the shorter the relaxation time, the higher the relaxation effect) has been attributed to the presence of relaxation sites on the surface of the solid. Proton nuclear spins in water molecules present in the bulk pore fluid and adsorbed on the surface of the pore relax at different rates, $1/T_{lb}$ and $1/T_{1s}$, respectively. The two relaxation mechanisms contribute in parallel to the decay:

$$\frac{1}{T_1} = \frac{1}{T_{lb}} + \frac{1}{T_{1s}}$$

Adsorbed water molecules exchange with those in the bulk pore fluid. If the exchange is fast enough to maintain uniform magnetization across the pore during decay, that is, *if all water molecules interact with the surface during the lifetime of the decay*, then the surface relaxation time is proportional to pore size:

$$\frac{1}{T_1} = \frac{1}{T_{lb}} + \rho \left( \frac{S}{V} \right)_{pore} \text{ when } \rho \ll D \left( \frac{S}{V} \right)_{pore}$$

where $D$ is the self-diffusion coefficient of the bulk liquid, $(S/V)$ is the surface area to volume ratio of the pore and $\rho$ is called the surface relaxivity.

The fact that dissolved paramagnetic ions affect the NMR signal has been known for a long time. Fe(III) and Mn(II), which are generally the most abundant paramagnetic substances in rocks (Clark, 1982), can vary dramatically in concentration and speciation in subsurface materials. However, most researchers have assessed the role of dissolved paramagnetic ions in NMR of natural geological materials to be minimal. For example, Vogele and Moses (1992) have concluded that concentrations of aqueous Fe(III) and Mn(II) will be too small to influence NMR measurements due to the low solubility of most iron- and manganese-bearing materials.

Foley et al. (1996) have carefully studied PMR longitudinal ($T_1$) and transversal ($T_2$) relaxation times of water-saturated powder packs. The powders were a series of synthetic calcium silicates with known concentration of iron or manganese paramagnetic ions. They have pointed out two very interesting conclusions. Firstly, one should note that the main difference between the synthetic materials used and the
natural rocks is that they are free of clays and other high-surface-area minerals. Although the sandstones have a high clay content, the ranges of the synthetic materials relaxation rates overlap rocks measurements. It is thus assumed that clay, which occupies a distinct range in T distribution, has not to be taken in account.

They have found the rates of water proton relaxation to be linearly proportional to the concentration of paramagnetic ions. However the rate only varied by a factor of 5 over the entire range of iron and manganese concentrations tested whereas pore size distributions in natural materials vary over 4 orders of magnitude. They suggested the relative constancy of the surface relaxivity to be an answer to the surprising success of the correlation of NMR relaxation time with hydraulic permeability.

Surface relaxivities of calcium silicates doped with various iron concentrations: longitudinal (open squares) and transverse (solid circles), taken from Foley, 1996.

Dependence of the relaxation rate of bulk solutions on Fe(III) ions concentration at pH approximately 2.5 (from Bryar et al., 2000).

More recently, Bryar et al. (2000) have measured surface relaxivity on pure quartz sand close to zero in the absence of paramagnetic impurities. They have also
measured a linear dependence of relaxation rate of bulk solutions on Fe(III) ions concentration. They have found the correlation coefficient to vary if the species vary.

In a very interesting experiment they have compared the relaxation time $T_1$ for a constant iron concentration but with varying pH. One should note that at the lowest pH, Fe(III) ions will stay in solution but they will adsorb on the solid if pH is increased.

Concentration of Fe(III) ions sorbed as a function of pH for silica gel equilibrated with 5.0 mg/L Fe(III) solution, from Bryar et al., 2000.

If dissolved paramagnetic and adsorbed ions were equally efficient relaxing agents, we would expect to see $T_{1b}$ increase as iron was lost from solution and $T_1$ of the saturated sand remain constant (total concentration of iron in the sample remains constant). As shown hereafter, $T_{1b}$ appeared to increase a little with pH but the observed $T_1$ for the pore water appeared to decrease with increasing pH: adsorbed paramagnetic ions on the surface significantly affects surface relaxation $T_1$ while the role of dissolved ions is secondary: adsorbed Fe(III) is a better relaxing agent than dissolved Fe(III).

Dependence of $T_1$ relaxation time on pH for pure quartz sand equilibrated with 0.5 mg/L Fe(III) solution, from Bryar et al., 2000.
In their experiments, observed NMR relaxations were very sensitive to the presence of paramagnetic solid phase. They have found the surface relaxivity to increase linearly from $10^{-3}$ to $10^{2}$ μm/s for solids with increasing surface concentrations of Fe(III). However, because of the natural concentration of iron and manganese in rocks, they conclude that surface relaxivity in natural samples will probably be higher than 1μm/s. They propose that it is because iron concentrations are high enough in many rocks that surface relaxivity could be considered to be relatively constant. Nevertheless any change of paramagnetic content should be suspected as well as pore size variation to explain a change in NMR relaxation.

**References**


Appendix 17

Presentation of the 2D/3D modelling package
COMPUTING THE LINEAR FILTER : MRS04_5.EXE

The first step in Magnetic Resonance Sounding processing is to compute the linear filter (also called "matrix") used to model and process the data.

The matrix consists in a 100 x 100 array where the MRS elementary response is computed for:

- 1m thick layers at 100 depths quasi-logarithmically spaced: the maximum depth depends on the maximum depth of investigation required,

- 100 pulse moments: the maximum pulse value depends on the maximum depth of investigation required.

In the example described below is used the MRS04_5.exe program.

```
layer number:68/100; field calc.:33/33; signal calc.:91/100
HELLO. This is a matrix calculation program for NUMIS system.
File name to store the matrix ? (#.mrm) test2d.mrm
Today the following antennas are available:
1 - circular, 2 - square, 3 – eight, 4 - eight square,
Select one, please (int): 2
antenna size: diameter of the loop for 1,3 or side of the square for 2,4 (m,float) ? 50
number of turns (int) ? 1
Larmor reference frequency (Hz,float) = 2000
pulse duration (ms,float) 40
```

Information about the computation progress could be found in the upper line of the screen.
Geophysical characterization of a weathered granite aquifer near Hyderabad

<table>
<thead>
<tr>
<th>Number of 3-D objects 0..4 ?</th>
<th>Number of 3D volumes with a non zero water content (up to 4 volumes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>choose nb=0 for all volume integration</td>
<td></td>
</tr>
<tr>
<td>nb = 1</td>
<td></td>
</tr>
<tr>
<td>X&gt;0 = North and Y&gt;0 = East</td>
<td></td>
</tr>
<tr>
<td>3-D Object nb(1) :</td>
<td></td>
</tr>
<tr>
<td>nb points of the polygone 2&lt;..&lt;19= 4</td>
<td></td>
</tr>
<tr>
<td>X(1) = 2.5</td>
<td></td>
</tr>
<tr>
<td>Y(1) = -300</td>
<td></td>
</tr>
<tr>
<td>X(2) = 2.5</td>
<td></td>
</tr>
<tr>
<td>Y(2) = 300</td>
<td></td>
</tr>
<tr>
<td>X(3) = -2.5</td>
<td></td>
</tr>
<tr>
<td>Y(3) = 300</td>
<td></td>
</tr>
<tr>
<td>X(4) = -2.5</td>
<td></td>
</tr>
<tr>
<td>Y(4) = -300</td>
<td></td>
</tr>
<tr>
<td>Zmin(1) = 5</td>
<td></td>
</tr>
<tr>
<td>Zmax(1) = 50</td>
<td></td>
</tr>
</tbody>
</table>

* the horizontal extension of the 3D object is the area inside the convex limit described by up to 19 points (X>0 in the north direction, Y>0 toward the eastern direction).

** the vertical limits of this object should be inside the limits of calculation of the whole matrix. If the depth of the studied object is limited, the calculation will be faster because only the layers inside the object are computed.

<table>
<thead>
<tr>
<th>max depth of the matrix (m,float) ? 80</th>
<th>Maximum depth &amp; pulse value of the calculated response, and local inclination of earth magnetic field</th>
</tr>
</thead>
<tbody>
<tr>
<td>geomagnetic field inclination (degr,float) ? 60</td>
<td>Number of sounding positions</td>
</tr>
<tr>
<td>max value of q (A-ms,float) ? 8000</td>
<td></td>
</tr>
<tr>
<td>X&gt;0 = North and Y&gt;0 = East</td>
<td></td>
</tr>
<tr>
<td>nb of antenna positions (default =1) : 5</td>
<td></td>
</tr>
<tr>
<td>X(1) = 20</td>
<td></td>
</tr>
<tr>
<td>Y(1) = 0</td>
<td></td>
</tr>
<tr>
<td>X(2) = 10</td>
<td></td>
</tr>
<tr>
<td>Y(2) = 0</td>
<td></td>
</tr>
<tr>
<td>X(3) = 0</td>
<td></td>
</tr>
<tr>
<td>Y(3) = 0</td>
<td></td>
</tr>
<tr>
<td>X(4) = -10</td>
<td></td>
</tr>
<tr>
<td>Y(4) = 0</td>
<td></td>
</tr>
<tr>
<td>X(5) = -20</td>
<td></td>
</tr>
<tr>
<td>Y(5) = 0</td>
<td></td>
</tr>
<tr>
<td>number of conductive layers (n=1..6,int) ? 1</td>
<td></td>
</tr>
<tr>
<td>layer 1</td>
<td></td>
</tr>
<tr>
<td>resistivity of the layer (ohm-m,float) ? 100</td>
<td></td>
</tr>
</tbody>
</table>

Coordinates of the loop centers along a profile (North to South in this example )

Geoelectrical layered model***
***The subsurface from 0 to 100 m is 100 Ohm.m, and from 100 m to infinity is considered as non-conductive in this case. The program stops when a calculation of signal for the total number of layers is completed.

The files created are all in ASCII format:
###_X_Y.mrm : the matrix file
###.txt : copy of the parameters
anten.dat : geometry of the loop
loops.dat : positions of the loop

The successive matrix files for the different loops locations are named: name_X_Y.mrm (ex: test2d_20_0.mrm, test2d_10_0.mrm …etc).

The shape of the 3D volume may be cubic (as in this example) but may also be described by up to 18 points (in the horizontal plane) and limited between (Zmin and Zmax)
MODELLING THE MAGNETIC RESONANCE SOUNDING (MRS) : SAMOGON_7X03.EXE

Once the program is started, the following window will appear:

1. **Name of a file with NUMIS matrix** that will be used for the modelling.

2. **Name of a file with field data** for a comparison with the model.

3. **View of the matrix and data.** This function allows the user to check the matrix and data that have been loaded. For that, the radio button for the matrix or data should be selected and then "info" button pressed. An example of matrix and data information is presented:
• Matrix informations : antenna type and size, geomagnetic field (inclination and corresponding Larmor frequency), geoelectric model (layered earth), maximum depth of modeling, maximum pulse for modeling.
• Data informations : data files, loop used for acquisition, Larmor frequency, matrix used for processing, filtering parameters, S/N ratio estimation, inversion parameters (regularization, etc..)

4. **Model layers table.** It allows the creation of your model. The model consists of a number of water-saturated layers in the subsurface defined by the matrix. For each layer, the following parameters should be defined:

- Depth of the top and of the bottom (m) of the layer.
- The water content (0-100%) inside the layer.
- The decay time of the signal from this layer.
- The difference between the Larmor frequency for the PMR signal from this layer and the Larmor frequency defined by the matrix. For example, if the matrix has been calculated for 2000 Hz, and the Larmor frequency inside of the layer is supposed to be 2003 Hz, a value of +3 Hz should be entered (unused).

5. **Layers editor.** It allows to add or to subtract layers from your model.

6. **Configuration of the synthetic sounding.** It allows to define:

- A number of pulses and the maximum value of the pulse moment for signal computation. If the option "data" is activated, these parameters of your model will be taken equal to the parameters of the field data. In this case the discrepancy between the synthetic signal and the field data will be calculated.
- The magnitude of a random noise that will be added to the computed signal.

7. **Load/Make model.** This function allows the user to load / save a model. When a model is saved, all the files that are necessary for a simulation of NUMIS sounding will be automatically created.

8. **Graphical windows** for visualisation of synthetic and real signals.

9. **Graphics control.** It allows to:

- Change scaling.
- Print the graphic
- Save the graphic into a file. The format of saved data depends on the file extension:
  
  • ".bmp" - bitmap.
10. **Adjustment of the model.** If a field data file has been loaded, it is possible to adjust the synthetic signal to the data by varying one of the model parameters. For that, one of parameter in the model layers table should be selected by a mouse, and then, it could be increased or decreased by using the "+" and "-" buttons. The signal will be calculated in real time. If the option "data" has been activated, the RMS will be calculated. Once the adjustment is finished the model should be saved by using the "make" function.