

**From a new hydrogeological conceptual model for hard rock aquifers to enhanced practical applications (survey, management of the water resource, modeling, protection, etc.)**

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## **ABSTRACT**

Hard rocks (granites, metamorphic rocks) occupy large areas throughout the World. Groundwater resources located in hard rock aquifers are modest in terms of available discharge per well (from 2-3 up to #20 m<sup>3</sup>/h), compared to those from other types of aquifers. However, these resources are geographically widespread and therefore well suited to scattered settlement and small to medium size cities. They largely contribute to the economic development of hard rock subsoil regions, especially in arid and semiarid areas where the surface water resource is limited.

Significant advances have recently been made about the genesis, geometry and functioning of hard rock aquifers. The hydrodynamic properties of these aquifers appear to be mainly related to weathering processes, which are very similar in most hard rock areas of the world. The weathering profile, up to more than 100 m thick, is mainly composed of two stratiform and superimposed layers, the saprolite, playing a capacitive role, and the underlying fissured layer that assumes the transmissive function of the aquifer. All together and where saturated with groundwater, these two layers constitute a composite aquifer. The spatial distribution of such weathering profiles, or their remains after erosion, can be mapped at the catchment scale. Therefore, the 3-D aquifer geometry and the spatial distribution of the hydrodynamic properties of hard rock aquifers can also be mapped.

These new geological and hydrogeological concepts, that enable to regionalize hard rock aquifers properties, find numerous practical applications:

- the mapping of groundwater potential from the regional scale to the local one, through bore well sitting techniques and methods increasing the success rate in terms of exploitable discharge,
- sustainable water resources management at the watershed scale. This topic is crucial in areas where groundwater is the only water resource, as southern India for instance. A Decision Support Tool specially devoted to hard rock aquifers in the semi-arid context has been developed. These new concepts also allow the use of similar deterministic multilayer mathematical modeling tools as those already used for a long time to simulate the functioning of other types of aquifers (porous for instance),
- the management of groundwater quality issues, particularly when dealing with non point source pollutions and the evaluation of the time required to restaure the ecological good status of the concerned water bodies (for instance in the frame of the implementation of the European Water Framework Directive),

- and also various other applications such as town and country planning, the evaluation of the environmental impacts of various civil works, among which the adequate location of quarries, the impacts of tunnels at shallow depth (< 300 m below ground surface) on rivers, springs, piezometric levels as well as the prediction of tunnel water inflows (location, rate), etc..

## **INTRODUCTION**

Hard rocks (granites, metamorphic rocks) occupy large areas throughout the World (Africa, South and North America, India, Korea, several areas in Europe, etc.). Their groundwater resources are modest in terms of available discharge per well (from less than 2-3 m<sup>3</sup>/h up to 20 m<sup>3</sup>/h), compared to those in other types of aquifers (sedimentary, karstic or volcanic aquifers). They are, however, geographically widespread and therefore well suited to scattered settlement, and small to medium size cities. These resources contribute largely to the economic development of such regions, especially in arid and semiarid areas where the surface water resource is limited.

However, these aquifers are considered as highly heterogeneous. For example, two neighbouring wells may exhibit very contrasted behaviours: one of them yielding several cubic meter per hour, the other being of very low discharge. As a consequence, for most authors, their hydrodynamic properties feel quite unpredictable at the local scale and they are thus considered as “discontinuous aquifers”. Moreover, their properties also seem to be unpredictable at the catchment scale.

Significant advances have recently been made in our knowledge of the structure and functioning of hard rock aquifers. Their hydrodynamic properties (not only storativity, but also hydraulic conductivity) appear to be mainly related to the existence of ancient weathering profiles, even in areas not presently belonging to the tropical belt. The spatial distribution of such weathering profiles, or their remains after erosion, can now be mapped, even at the catchment scale. Thus, this newly developed approach enables to regionalize hard rock aquifers properties, and to find numerous practical applications.

These recent research results and their practical applications within a changing world (global change, climate change) will be presented at the Conference and are summarized within the present paper.

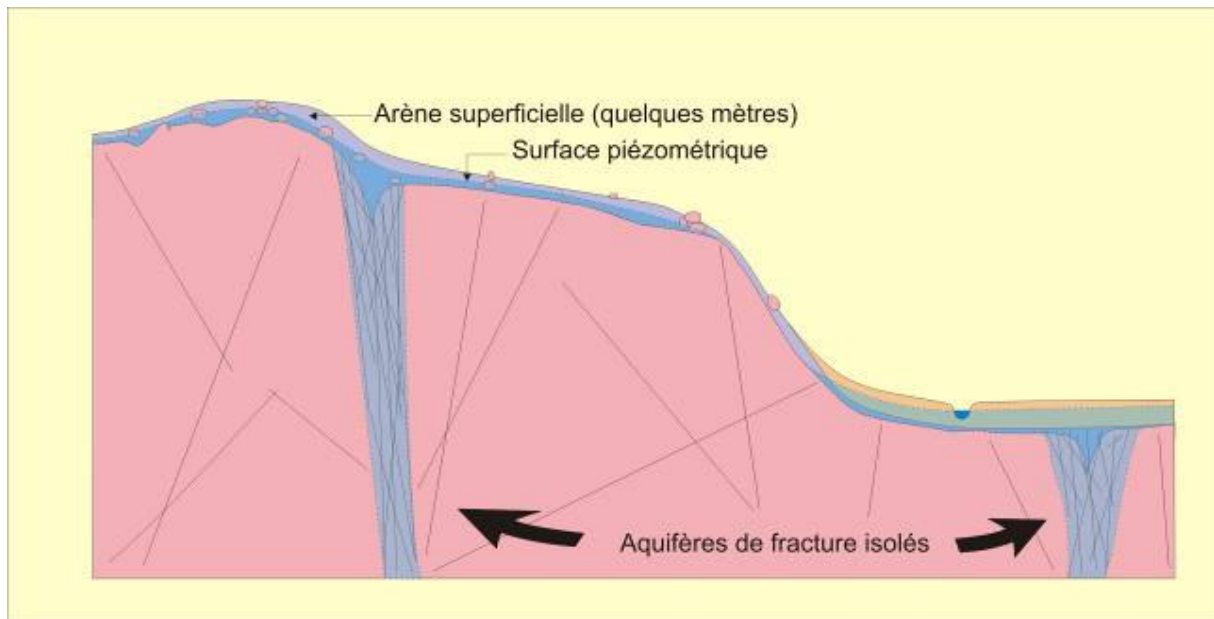
## **STRUCTURE AND HYDRODYNAMIC PROPERTIES OF HARD ROCK AQUIFERS**

### **The classical concept of discontinuous aquifer**

The “hard rock” aquifers, or “fissured aquifers”, that are present near the surface (within the first 100 m below ground surface) are considered as “discontinuous aquifers”, as a consequence of their discrete hydraulic conductivity. In fact, during a drilling, the first significant water bearing zones appear within the fresh (hard) rock. The well intersects an impermeable rock that is only very locally (along a few centimetres or decimetres) showing significantly permeable zones. Most of the wells exhibit a few of these water strikes (from 0 to 4 or 5 water bearing zones).

The classical concept of discontinuous aquifer has been developed during the seventies, mainly on the basis of the results of the large drilling campaigns performed in Africa (Detay et al., 1989). It considers that these water bearing zones are tectonic open fractures (Figure 1).

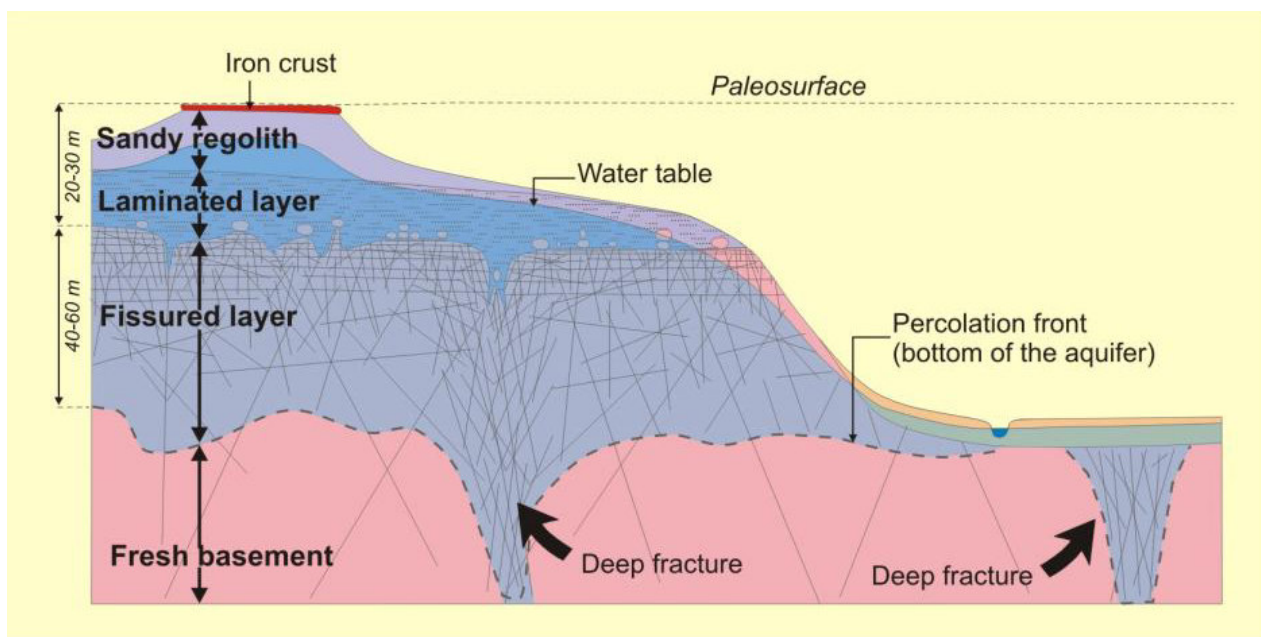
Several authors noticed a decrease of the occurrence of such water bearing zones with depth (within the first 100 m below the ground surface) and attributed it to the “closure” of these tectonic fractures, as a consequence of the increase of the lithostatic strain. These concepts influenced in the past, and still presently influence the methodologies used in such areas, for instance for water well siting.



**Figure 1 - The classical concept of discontinuous aquifer (translation – up to bottom: superficial unconsolidated weathering cover (a few meters), piezometric level, aquifers in isolated fractures)**

### **The new concept of continuous stratiform aquifer due to the weathering processes**

Most of the areas where metamorphic or plutonic rocks do outcrop are stable areas, emerged since a long time, that were thus exposed during very long periods (several tens of millions years) to the weathering processes, under rather humid climates. The outcropping rocks thus generally comprise a several tens of meters thick superficial weathered layer, where it has not been eroded. This superficial layers corresponds to a laterite type weathering profile (Dewandel, Lachassagne et al., 2006).

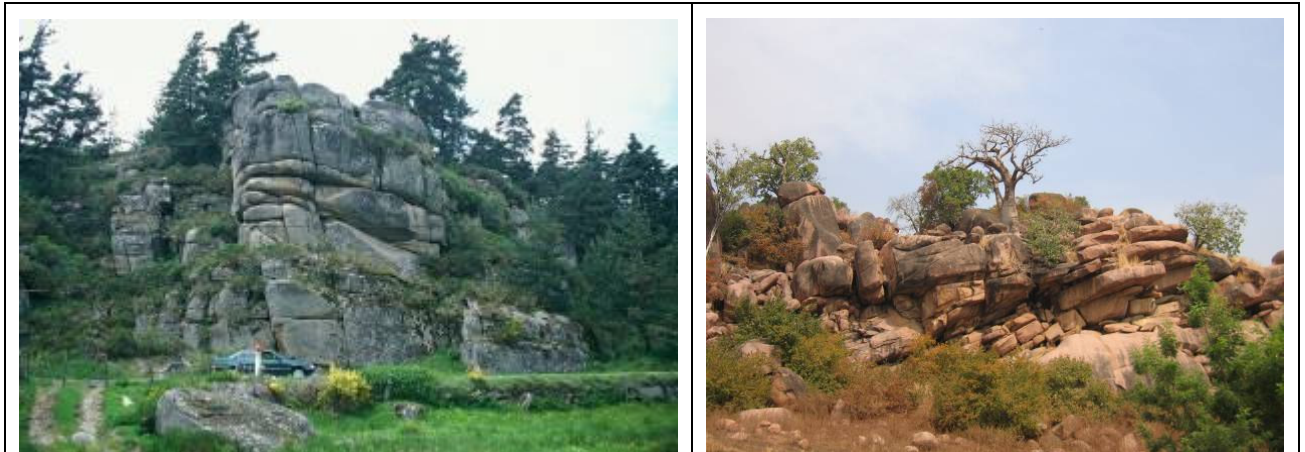


**Figure 2 - Stratiform conceptual model of the structure and the hydrogeological properties of hard rock aquifers (after Wyns et al. 2004)**

From recent results (see for instance Dewandel, Lachassagne et al., 2006; Wyns et al., 2004), a typical weathering profile (Figure 2) comprises the following layers that have specific hydrodynamic properties. All together (where and when saturated with groundwater), these various layers constitute a composite aquifer. From the top to bottom, the layers are the following (Figure 2):

- the laterite (or iron or bauxitic crust) that can be absent, due to erosion or rehydration of hematite in a latosol (for iron crusts), or resiliification of gibbsite/boehmite
- the saprolite or alterite, or regolith, a clay-rich material, derived from prolonged in situ decomposition of bedrock, a few tens of meters thick (where this layer has not been eroded). The saprolite layer can be divided into two sub-units: the alloterite and the isalterite into kaolinite (for bauxitic crusts):
  - o the alloterite is mostly a clayey horizon where, due to the volume reduction related to mineralogical weathering processes, the structure of the mother rock is lost,
  - o in the underlying isalterite, the weathering processes only induce slight or no change in volume and preserve the original rock structure; in most of the cases this layer takes up half to two thirds of the entire saprolite layer. In plutonic rocks, such as granites, the base of the isalterite is frequently laminated; this layer is thus named the 'laminated layer'. It is constituted by a relatively consolidated highly weathered parent rock with coarse sand-size clasts texture and a millimetre-scale dense horizontal lamination crosscutting the biggest minerals (e.g., porphyritic feldspars), but still greatly preserving the original structure of the rock. Because of its clayey-sandy composition, the saprolite layer can reach a quite high porosity, which depends on the lithology of the parent rock (bulk porosity is mainly between 5 and 30%; Compaore et al., 1997; Wyns et al., 2004), and displays generally a quite low permeability, about 10<sup>-6</sup> m/s. Where this layer is saturated, it mainly constitutes the capacitive function of the global composite aquifer;
- the fissured layer (Figure 3) is generally characterized by fresh (hard) rock cut by a dense horizontal fissuring in the first few meters and a depth-decreasing density of subhorizontal and subvertical fissures (Cho et al., 2003; Maréchal et al., 2004; Wyns et al., 2004). Several processes such as cooling stresses in the magma, subsequent tectonic activity or lithostatic decompression processes were invoked to explain the origin of these fissures. However, it has been demonstrated that fissuring results from the weathering process itself (Cho et al., 2003; Dewandel, Lachassagne et al., 2006; Wyns et al., 2004). Swelling of certain minerals results in a local increase of volume that favours cracks and fissuring. In granitic rocks, the most sensitive mineral to swelling is biotite. Where the rock texture is relatively isotropic (in granite for example), the generated fissures are orthogonal to the lower constraint vector ( $\sigma_3$ ), and thus subparallel to the topographic surface contemporaneous with the weathering process (Figure 3). In highly foliated rocks (i.e., gneisses or schists) the orientation of the fissures can be also controlled by the rock structure. The intensification of this horizontal fissuring at the top of the layer constitutes the overlying laminated layer. The fissured layer mainly assumes the transmissive function of the global composite aquifer and is drawn from most of the wells drilled in hard-rock areas. The hydrodynamic properties of the fissured layer are thus controlled by the distribution, the hydraulic conductivity, the anisotropy of hydraulic conductivity and the connectivity of the fissures (Maréchal et al., 2004). It thus constitutes an anisotropic medium. In these cases the covering saprolite layer has been partially or totally eroded, or may be unsaturated., the fissured layer assumes also the capacitive function of the composite aquifer; e.g., in French Brittany 80 to 90% of the groundwater resource is located in the fissured layer (Wyns et al., 2004);
- the fresh unfissured basement is permeable only locally, where tectonic fractures are present. The hydraulic properties of such fractures have been investigated in various

studies, particularly in details when the purpose of these studies is the storage of nuclear waste (Neuman, 2005). Even if these tectonic fractures can be as permeable as the fissures induced by the weathering processes described here above, in most of the geological contexts, their density with depth is much more lower than within the fissured layer (Cho et al., 2003). At the catchment scale, and for water resources applications, the fresh basement can then be considered as impermeable and of very low storativity (Maréchal et al., 2004).



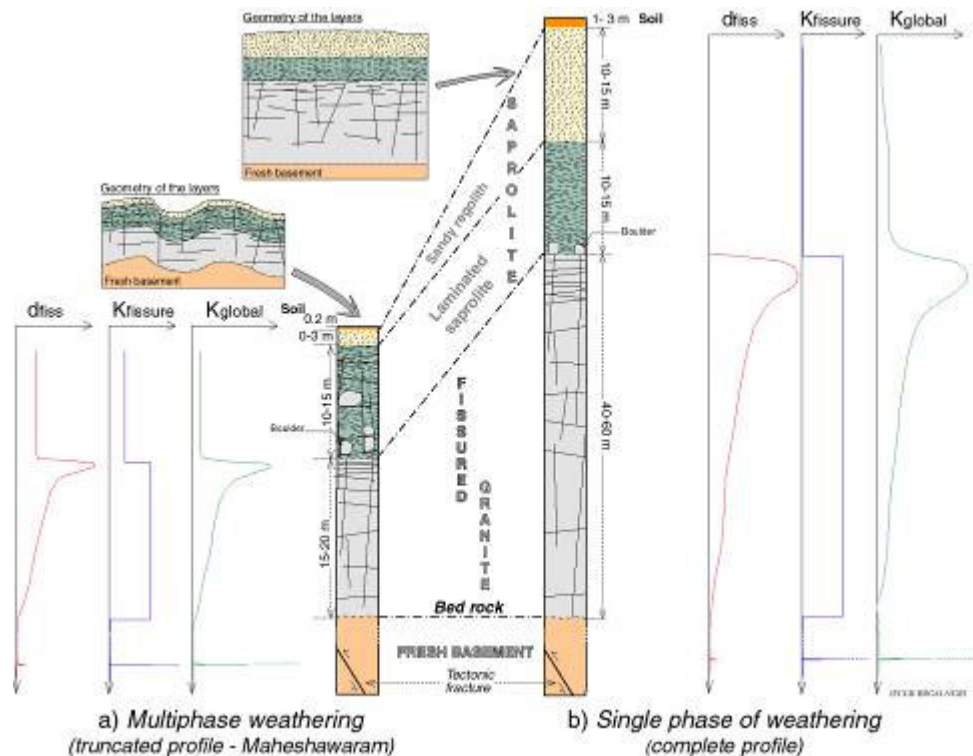
**Figure 3 - The fissured layer in granites (left; Margeride, Lozère, France; right: Burkina Faso)**

In addition to rock mineralogy, the development of such thick weathering profiles requires specific climatic conditions: mainly significant rainfall, in order to ensure mineral hydrolysis and, on the second order, quite high mean temperatures to favour the kinetics of the process. Overall, its development also requires long periods of time under stable tectonic conditions (a few millions to a few tens of millions years), the latest duration leading to profiles a few tens of metres thick. In addition, relatively flat topographic is required to avoid the erosion of weathering products (saprolite), but also to favour water infiltration. Thus, such profiles cannot develop in regions of sharp topography where the erosion rate is higher than the one of weathering.

An important consequence of this weathering process is that, from the hectometre scale to the regional one, these layers are parallel to the paleo-weathering surfaces (paleo-landscape) contemporaneous with the weathering phase and thus appear as stratified layers (Figure 2; Wyns et al. 2004; Lachassagne et al., 2001). Moreover, geological features (faults, dykes...) or contrasts in rock mineralogy or structure can locally modify the characteristics (mineralogy, thickness, etc.) of the weathering profile. These contrasts lead to differential weathering and in some cases to the development of positive topographic anomalies such as inselbergs.

More complex weathering profiles can result from multiphase weathering and erosion processes. In Southern India for instance at least two main phases of weathering have been identified (Dewandel et al., 2006).

A hydrogeological conceptual model has been derived from these observations and measurements, both for single phase or multiphase weathering profiles (Figure 4).



**Figure 4 - Generalized 3-D geological and hydrogeological conceptual model of granite aquifers controlled by single or multiphase weathering. (a) Maheshawaram (southern India) multiphase weathering and (b) Classical profile – single weathering – (idealized profile).  $D_{fiss}$ : density of conductive fissures,  $K_{fiss}$ : hydraulic conductivity of fissures and  $K_{global}$ : equivalent hydraulic conductivity of the layer (from Dewandel et al., 2006).**

## MAPPING THE LAYERS CONSTITUTING THE HARD ROCK AQUIFERS

The formation of the fissured layer is therefore closely related to the development of the alterites, and hence to the weathering front. An important consequence of this process is that, at the catchment scale, these weathered layers are parallel to the paleo weathering surfaces (paleo landscape) contemporaneous with weathering.

These ancient surfaces can have been affected by erosion processes posterior to the main weathering phase. Therefore, the saprolite and the fissured layer make up stratiform beds whose geometry at the regional scale can be linked to the more or less good preservation of paleoweathering surfaces. On the basis of the knowledge of these genetic principles, it is quite easy to map, at the watershed scale (Lachassagne et al., 2001; Dewandel et al, 2006):

- the altitude of:
  - o the limit between the saprolite (laminated layer) and the fissured layer,
  - o the base of the fissured layer,
- and thus to respectively compute the residual thickness of:
  - o the saprolite,
  - o the fissured horizon.

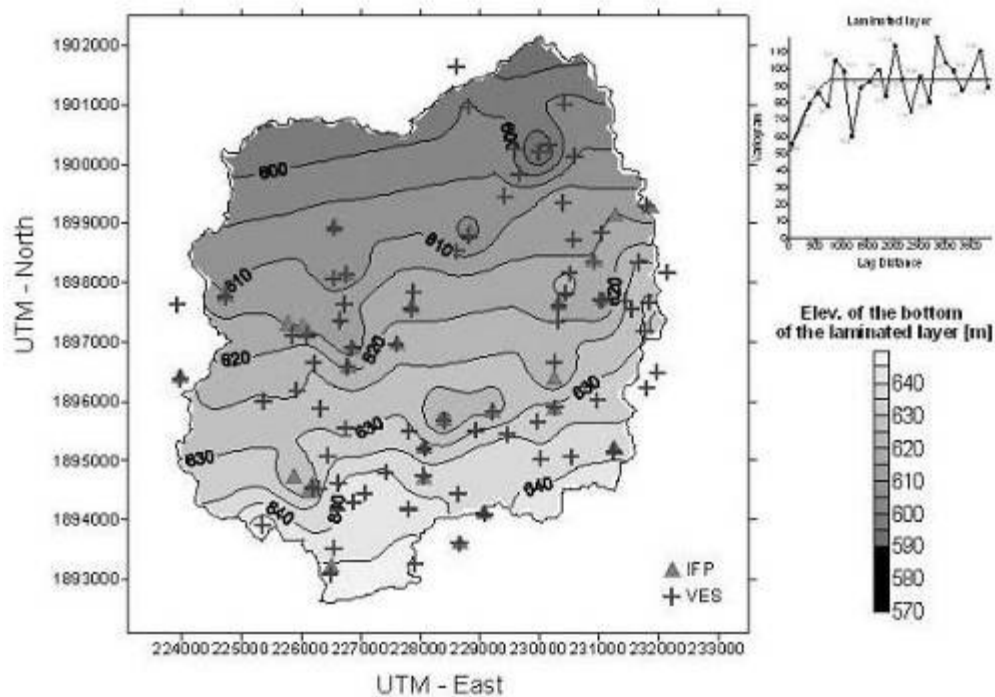
In most cases, the geometry of the base of the saprolite is determined at first, through the combined use of well data, geophysical data if any, and specific field surveys. Since the surface of the base of the saprolite is, in many places, cut by the present-day ground surface, notably near valleys, it is relatively simple, in the field, to determine the position of the saprolite/weathered-fissured layer interface.

On the basis of observations of the thickness of the fissured layer (observations on outcrops, statistical treatment of existing well data), the altitude of its base can also be directly



computed from the one of the alterite base. The altitudes of (i) the saprolite/fissured layer interface and (ii) fissured layer/fresh rock interface can therefore be subtracted from that of the present ground surface, as inferred from DEM data, in order to compute the residual thickness of respectively the saprolite and the fissured layer. In regions where the paleosurface(s) have partly been preserved from erosion, slope analysis from DEM data can also be used for the elaboration of such maps.

Figure 5 displays an example of such a map obtained on the southern India Maheswaram catchment (Dewandel et al, 2006), mainly from geophysical data (Vertical Electric Soundings), and well data (lithologs and geophysical measurements within defunct boreholes). It was completed by observations on outcrops (dugwells). These field studies were accomplished in a few field weeks.



**Figure 5 - Kriged map (45 borewell lithologs –IFP- and 80 VES interpretations) of the elevation (in m amsl) of the base of the saprolite (base of the laminated layer) on the 60 km<sup>2</sup> southern India Maheswaram catchment (from Dewandel et al., 2006). The plot in the right corner shows the variogram used for kriging**

## APPLICATIONS

Several applications have been inferred from these research results on hard rock aquifers. Most of these practical applications have been summarised here below.

Scientific results	Applications
<p><b>1. Knowledge of the structure of hard rock aquifers and particularly demonstration of the relationship existing between their permeability and the weathering processes.</b></p>	<p><b>1.1. Mapping of hard rock aquifers, potentialities evaluation at large areas scale</b> (several hundreds, thousands, or tens of thousands km<sup>2</sup>), on the basis (i) of the susceptibility of the various kinds of hard rocks to the weathering processes (development of an efficient fissured layer, mainly as a consequence of the rocks'</p>

	<p>mineralogical composition), (ii) of the state of the weathering profiles erosion, (iii) of the depth to the water table, etc. (Lachassagne et al., 2001; Courtois et al., 2008).</p> <p><b>1.2. Mapping and location of the areas</b> (a few km<sup>2</sup> to tens of km<sup>2</sup>) <b>favourable for field hydrogeological prospecting</b> ((Lachassagne et al., 2001)).</p> <p><b>1.3. Hard rock aquifers vulnerability maps</b></p>
<p><b>2. Characterisation of the hydrodynamic properties of the fissured horizon.</b> (Maréchal et al., 2004 ; Dewandel et al., 2006)</p>	<p><b>2.1. Long term forecast of high yield wells</b></p> <p><b>2.2. Parameters for the deterministic modelling</b> of hard rock aquifers</p>
<p><b>3. Development of geophysical methods</b> (especially PMR<sup>1</sup>) for the <b>characterisation of the thickness and the hydrodynamic properties</b> of hard rock aquifers. (Wyns et al., 2004)</p>	<p><b>3.1. Evaluation of the groundwater storage</b> within hard rock aquifers.</p> <p><b>3.2. Evaluation of the durability of diffuse source pollutions</b> within the aquifer. Implementation of the European Water Framework Directive.</p>
<p><b>4. Development of a methodology for the assessment of regional scale hard rock aquifers groundwater budget</b>, with specific applications to overexploited, semi-arid area, aquifers (Maréchal et al., 2006), that can take into account the spatial distribution of the weathering layers and the spatial variations of their hydrodynamic properties (namely their specific yield) in X-Y and with depth.</p>	<p><b>4.1. Evaluation of the sustainable water resource</b> of aquifers (annual recharge, irrigation return flow, water budget, relationships with surface waters, catchment scale efficiency of artificial recharge, etc.) (Maréchal et al., 2006)</p> <p><b>4.2. Decision Support Tools</b> for hard rock aquifers management (Dewandel, Gandolfi et al., 2006; Dewandel et al, 2008).</p> <p><b>4.3. Deterministic mathematical modeling</b> (Durand et al, sub., Lachassagne et al., 2001).</p>
<p><b>5. Hydrogeochemical tools</b> designed for hard rock aquifers (major elements, traces, isotopes) (Négre et al., 2000 ; Pauwels et al., 2001 ; Pauwels et al., 2006)</p>	<p><b>7.1. Comprehension of the functioning of the aquifers</b> (protection, management, etc.)</p> <p><b>7.2. Groundwater quality</b> (fluoride, arsenic and metallic elements, nitrates, etc.)</p>
<p><b>6. Other applications:</b></p>	<p>Such as town and country planning (sitting of landfill, quarry), shallow (less than 300 m deep) tunnels (water inflows estimation, impacts and surface waters, etc..)</p>

## CONCLUSION

Significant advances have recently been made in our knowledge of the genesis, geometry and functioning of hard rock aquifers. The hydrodynamic properties of these aquifers appear to be mainly related to weathering processes. The weathering profile, up to more than 100 m thick, is mainly composed of 2 superposed layers, the saprolite, playing a capacitive role, and the underlying fissured layer that assumes the transmissive function. All together and where saturated with groundwater, these two layers constitute a composite aquifer.

The spatial distribution of such weathering profiles (single or multiphase), or their remains, can be mapped at the catchment scale on the basis of various types of data: digital elevation

<sup>1</sup> PMR: Proton Magnetic Resonance (or Nuclear Magnetic Resonance)



model, observations on outcrops, drilling cuttings, geophysical measurements. Then, the spatial distribution of the hydrodynamic properties of granite type aquifers can also be mapped. A precise geological mapping not only of lithology but also of the weathering structure thus appears to be a prerequisite for groundwater management in hard-rock areas.

These newly developed geological and hydrogeological concepts, that enable to regionalize hard rock aquifers properties, can answer to several key issues: (i) evaluation of aquifer potentialities from large to small (a few hectares) areas; as a consequence, it helps in defining the characteristics of field surveys (geophysics, radon, etc.) and well siting, (ii) elaboration of water budget at the catchment scale, taking into account, among others, the piezometric level fluctuations in the various layers, (iii) input data for deterministic numerical modelling of the aquifer, (iv) elaboration of vulnerability maps, (v) guidelines for aquifer protection, for town and country planning (siting of landfill, quarry), tunnelling, etc..

Such a geological and hydrogeological model now requires being adapted to the geological contexts of weathered metamorphic rocks. The mapping methodology is also to be developed for applications at a larger scale, 1,000 to 10 000 km<sup>2</sup> for instance, through the integration of techniques such as remote sensing and spectrometric and radiometric aerial surveys.

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