



available at www.sciencedirect.com



journal homepage: www.elsevier.com/locate/jhydrol



A generalized 3-D geological and hydrogeological conceptual model of granite aquifers controlled by single or multiphase weathering

B. Dewandel ^{a,*}, P. Lachassagne ^{b,1}, R. Wyns ^c, J.C. Maréchal ^{b,1},
N.S. Krishnamurthy ^d

^a BRGM, Water Division, Resource Assessment, Discontinuous Aquifers Unit, Indo-French Centre for Groundwater Research, Uppal Road, 500 007 Hyderabad, India

^b BRGM, Water Division, Resource Assessment, Discontinuous Aquifers Unit, 1039, rue de Pinville, 34000 Montpellier, France

^c BRGM, Geology Department, Modelling and Applications Unit, BP 6009, 45060 Orléans cedex 2, France

^d National Geophysical Research Institute, Indo-French Centre for Groundwater Research, Uppal Road, 500 007 Hyderabad, India

Received 14 April 2005; received in revised form 21 March 2006; accepted 24 March 2006

KEYWORDS

Hard rock aquifer;
Crystalline rock aquifer;
Hydraulic conductivity;
Weathering;
Flowmeter test;
Granite

Summary The weathered layers of crystalline rocks form aquifers that are of prime interest for water supply in hard rock areas. These weathering profiles generally develop under both stable geodynamic conditions (weathering rate $\gg$ erosion rate) and a hydrolysing climate. They are composed of thick stratiform layers that follow the paleo-landscape (paleotopography) and thus present a gently dipping sequence at a regional scale.

The structure and the hydrodynamic properties of the weathering profile of a granitic area (53 km² Maheshwaram catchment, state of Andhra Pradesh, India) were characterized in detail and mapped from observations on outcrops, 80 vertical electric soundings and lithologs from 45 borewells in which flowmeter measurements and injection tests were also performed to characterize the hydraulic conductivities of the conductive fissure zones.

The structure of the weathering profile results from a multiphase process: an ancient weathering profile was partly eroded, down to its fissured layer. It was later re-weathered more or less parallel to the current topographic surface. This peculiar structure is linked to the geodynamic history of the Indian Peninsula that underwent alternate weathering and erosion-dominated phases. The profile is thus composed, from top to bottom, up to a total depth of 35 m, of sandy

* Corresponding author. Tel.: +91 40 23 43 46 57; fax: +91 40 23 43 46 51.

E-mail addresses: dewandel@ngri.res.in (B. Dewandel), p.lachassagne@brgm.fr (P. Lachassagne), r.wyns@brgm.fr (R. Wyns), jc.marechal@brgm.fr (J.C. Maréchal), nskrishnamurthy@ngri.res.in (N.S. Krishnamurthy).

¹ Tel.: +33 4 67 15 79 73; fax: +33 4 67 15 79 75.

regolith saprolite (1–3 m), 10–15 m of laminated saprolite containing unusual preserved fissures and a 15–20 m thick fissured layer.

By comparing various case studies in similar terrain, a generalized 3-D geological and hydrogeological conceptual model of granite-type aquifers (granites, gneisses, etc.) is proposed. In granite-type rocks, single weathering or multiphase weathering and erosion processes induce similar geological structures. A few main geological differences arise from the comparison of single phase and multiphase weathering profiles: (i) in the later, the respective thicknesses of the various layers can be deeply modified, (ii) the ancient fissured layer can be re-weathered, and the resulting new laminated layer may contain quite well preserved and conductive ancient fissures, and (iii) the upper part of the fissured layer is more densely fissured. As a result of the same weathering processes, the fissures from the fissured layer of single phase or multiphase profiles exhibit very similar hydraulic conductivities, and show both a higher density of conductive fissures at the top of the layer. The preserved ancient fissures within the laminated layer of a multiphase profile are partly obliterated by the recent weathering; their hydraulic conductivity is thus significantly reduced. Nevertheless, they do significantly contribute to borewell yield. These weathering-induced fissures provide most of the aquifer permeability.

The use of such a conceptual model for the precise geological mapping of the weathering structure appears to be a prerequisite for groundwater development and management in hard-rock areas as it answers to several key issues.

© 2006 Elsevier B.V. All rights reserved.

Introduction

Hard rock aquifers generally occupy the first tens of metres below ground surface (Detay et al., 1989). The hydrogeological characteristics (e.g., hydraulic conductivity and storage) of the covering weathered mantle (saprolite or alterite) and the underlying bedrock derive primarily from the geomorphic deep weathering processes (Wyns et al., 1999, 2004; Taylor and Howard, 2000, etc.). This process involves biogeochemical hydrolysis of the mineral constituents of the rocks and their mineral transformations at new surface conditions, mainly into clay-rich materials (Tardy, 1971, 1993, 1998; Nahon, 1991).

From recent results (Chilton and Smith-Carington, 1984; Chilton and Foster, 1995, Wyns et al., 2004, and other), a typical weathering profile (Fig. 1) 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:

- 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 resilicification of gibbsite/boehmite into kaolinite (for bauxitic crusts).
- The *saprolite* or *alterite*, or *regolith*, a clay-rich material, derived from prolonged in situ decomposition of bedrock, a few tens of metres thick (where this layer has not been eroded). The saprolite layer can be divided into two sub-units (Wyns et al., 1999): the *alloterite* and the *isalterite*. 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 (Jones, 1985; White et al., 2001). In the underlying *isalterite*, the weathering processes only induce slight or no change in volume and preserve the original rock structure (Gardner, 1980; Cleaves, 1993;

White et al., 2001); 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 named here 'laminated layer'. This layer is constituted by a relatively consolidated highly weathered parent rock with coarse sand-size clasts texture (Eswaran and Bin, 1978; Acworth, 1987; Sharma and Rajamani, 2000; Chigira, 2001) 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. Sometimes this particular layer is called 'micro-sheeting layer' (Chigira, 2001). 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%; Compagere et al., 1997; Wyns et al., 1999, 2004; White et al., 2001; Begonha and Braga, 2002), and displays generally a quite low permeability, about 10^{-6} m/s (Acworth, 1987; Rushton and Weller, 1985; Houston and Lewis, 1988; Barker et al., 1992). Where this layer is saturated, it mainly constitutes the capacitive function of the global composite aquifer.

- The *fissured layer* is generally characterized by a dense horizontal fissuring in the first few metres and a depth-decreasing density of subhorizontal and subvertical fissures (Houston and Lewis, 1988; Howard et al., 1992; Cho et al., 2003; Maréchal et al., 2003a; Maréchal et al., 2004; Wyns et al., 2004). Several processes such as cooling stresses in the magma, subsequent tectonic activity (Houston and Lewis, 1988) or lithostatic decompression processes (Davis and Turk, 1964; Acworth, 1987; Wright, 1992; Taylor and Howard, 2000) are invoked to explain the origin of these fissures. However, it has been demonstrated that fissuring results from the weathering process itself (Acworth, 1987; Wyns et al., 1999, 2004; Cho et al., 2003). Swelling of certain minerals

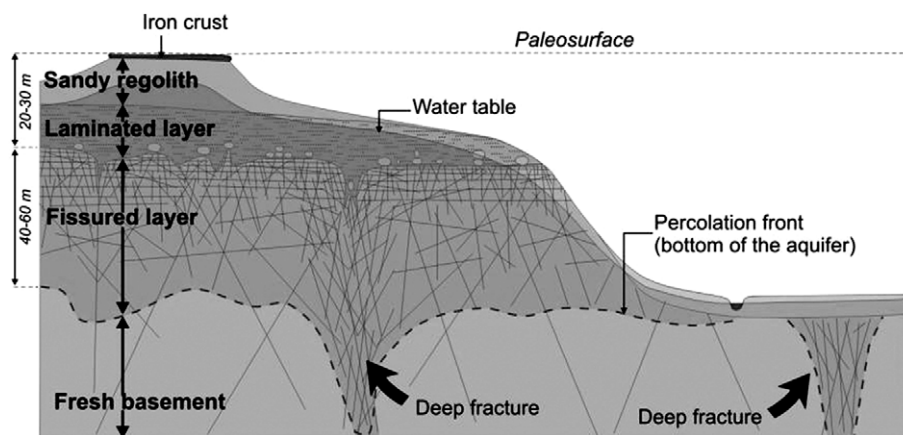


Figure 1 Idealized single phase weathering paleoprofile in a hard-rock, crosscut by the current topography (Wyns et al., 1999, 2004).

results in a local increase of volume that favours cracks and fissuring. In granitic rocks, the most sensitive mineral to swelling is biotite (Eggler et al., 1969; Ledger and Rowe, 1980). Where the rock texture is relatively isotropic (in granite for example), the generated fissures are orthogonal to the lower constraint vector (σ_3), and thus subparallel to the topographic surface contemporaneous with the weathering process. In highly foliated rocks (i.e., gneisses or schists) the orientation of the fissures can be also controlled by the rock structure (Pye, 1986; Sharma and Rajamani, 2000). The intensification of this horizontal fissuring at the top of the layer constitutes the overlying laminated layer. This layer mainly assumes the transmissive function of the global composite aquifer and is drawn from most of the wells drilled in hard-rock areas (Uhl and Sharma, 1978; White et al., 1988; Acworth, 1987; Houston and Lewis, 1988; Barker et al., 1992; Briz-Kishore, 1993; Drew et al., 2001; Gustafson and Krásný, 1994). However, the covering saprolite layer may have been partially or totally eroded, or unsaturated. In these cases, the fissured layer assumes also the capacitive function of the composite aquifer; e.g., in French Brittany 80–90% of the groundwater resource is in the fissured layer (Wyns et al., 2004).

- The *fresh basement* is permeable only locally, where tectonic fractures are present. The hydraulic properties of such fractures have been investigated in various studies (Pickens et al., 1987; Blomqvist, 1990; Walker et al., 2001; Kuusela-Lahtinen et al., 2003; Cho et al., 2003, etc.). 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. At 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).

In addition to rock mineralogy, the development of such a thick weathering profile requires specific climatic conditions (Peltier, 1950; Ollier, 1984; Tardy, 1971, 1993, 1998), mainly significant rainfall, in order to ensure mineral

hydrolysis and, on the second order, high mean temperatures to favour the kinetics of the process. Last but not least, its development requires long periods of time under stable tectonic conditions, a few millions to a few tens of million years; the latest duration leading to profiles a few tens of metres thick (Wyns, 1991). Thus, relatively flat topographic areas are 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, at a regional scale, these layers are parallel to the paleo-weathering surfaces (paleo-landscape) contemporaneous with the weathering phase and appear as stratified layers (Fig. 1; Wyns, 1991; Wyns et al., 1999, 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 (Pye, 1986; Taylor and Howard, 1998).

Given that saprolite can be considered as a porous media, its hydraulic properties can be quite easily measured in-situ and many hydrodynamic data are available (Acworth, 1987; Wright, 1992; Compaore et al., 1997).

However, due to its apparent heterogeneity, discontinuity and anisotropy, but also and mainly as a result of the absence of use of a conceptual geological model for this specific layer, the hydrodynamics of the fissured layer have not been described in details. Because yields or specific capacities were, for a long time, the only information available from large numbers of boreholes (from large operational drilling programmes), in the early years of work in these regions, the hydrogeological community related these parameters to various factors: borehole depth (Davis and Turk, 1964), their lithology (Houston and Lewis, 1988), their geomorphological situation (McFarlane, 1992) or the thickness of the saprolite (Detay et al., 1989; Foster, 1984), etc. The evolution with depth of transmissivity and storage in the upper part of the weathered crystalline basement was also studied (Chilton and Foster, 1995). More recently,

Taylor and Howard (2000) proposed a "tectono-geomorphic" model of the hydrodynamic properties of crystalline rocks from Uganda, which is an interesting attempt to understand the hydrogeology of such rocks in relationships with the local geomorphologic, and thus both weathering and tectonic evolution. Very recently, the hydrodynamic properties (permeability, storativity, anisotropy, fissures density, double porosity, scale effects) of the fissured layer of a granite aquifer have been characterized in India using hydraulic tests and a first comprehensive hydrodynamic model of the fissured layer has been proposed (Maréchal et al., 2004).

The objective of the present study is to link this first attempt of a comprehensive hydrodynamic model of hard-rock aquifer with the detailed structure of the weathering profile on the same study area. The structure has been characterized from the scale of the outcrop and to the one of the catchment. It results from the geological history of the area (chiefly weathering and erosion). Moreover, from these new observations and the ones published for other re-

gions of the world, this paper infers a generalized 3-D geological and hydrogeological conceptual model of granite-type aquifers (granites, gneisses, etc.). It allows, among other results, to infer hydrogeological information and practical operational applications from geological and hydrogeological knowledge.

Geological settings and description of the Maheshwaram weathering profile

The Maheshwaram pilot watershed (Figs. 2 and 7a), 53 km² in area, is located 35 km south of Hyderabad (State of Andhra Pradesh, India). The area is characterized by relatively flat topography with altitudes between 670 and 590 m above sea level and the absence of perennial streams. The region experiences a semi-arid climate controlled by the periodicity of the monsoon (rainy season: June–October). Mean annual precipitation is about 750 mm, of which more than

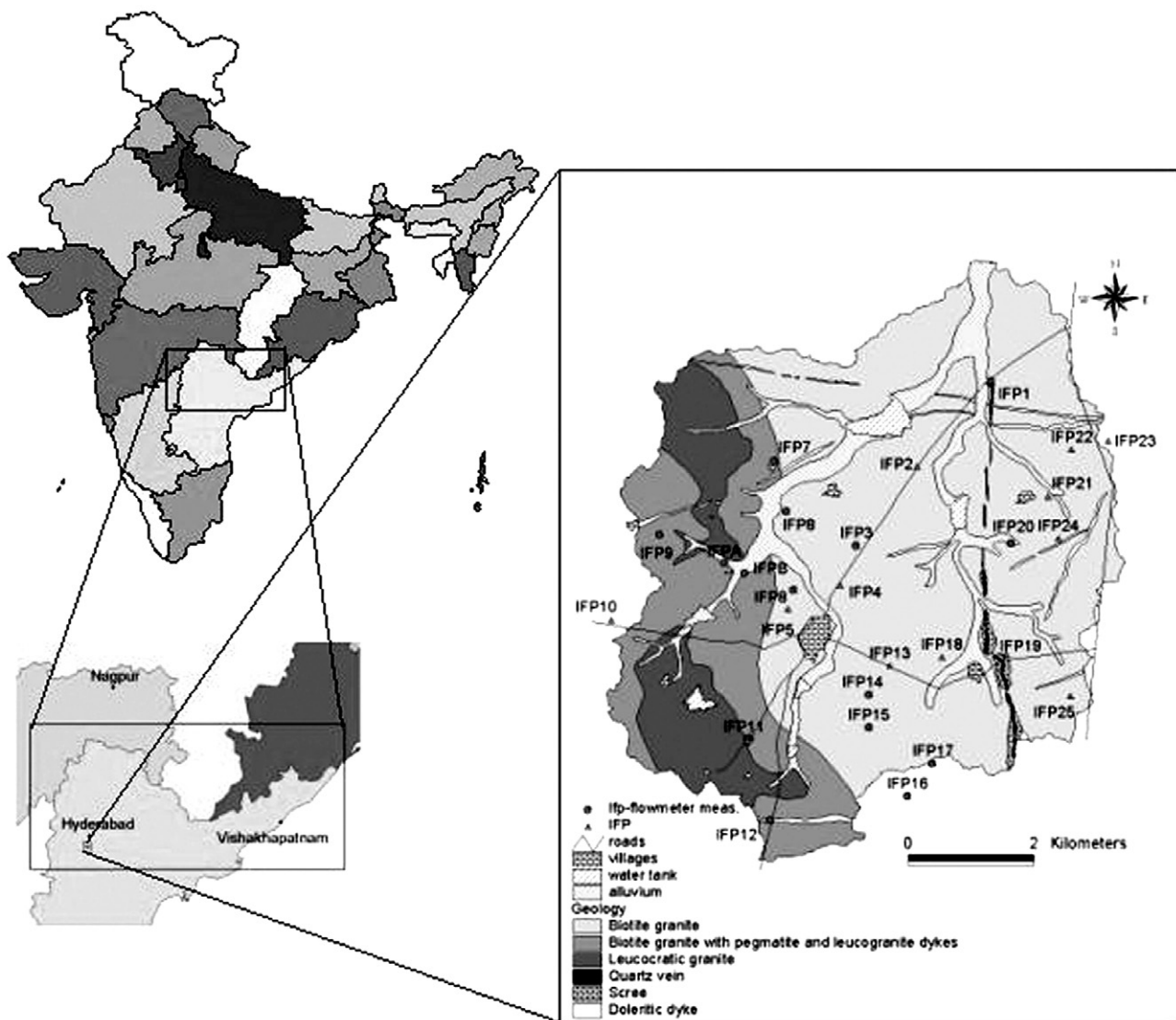


Figure 2 Simplified geological map of the study area with location of observation wells (IFP; circle: flowmeter test performed, triangle: flowmeter test not performed due to low borewell hydraulic conductivity).

90% falls during the Monsoon season. The mean annual temperature is 26 °C; however in summer (March–May) the daily maximum temperature approaches 45 °C.

The geology of the area (Fig. 2) is composed of Archean granites. The pilot watershed is mainly underlain by biotite granite (mm to cm grain size) with porphyritic K-feldspar (3–5 cm grain size). This granite is slightly metamorphosed and foliated (plastic deformation; Fig. 3a). Intrusive leucocratic granite (Fig. 3b), characterized by a lower content in biotite, infracentimetric grain size, occasionally with porphyritic K-feldspar, forms small hills in the landscape and mainly outcrops with boulders (Fig. 3c). The texture of the leucocratic granite is magmatic (controlled by the magmatic flow during intrusion), biotites are small in size (≤ 1 mm) and isolated. Decimetre-wide pegmatitic and leucocratic granite veins intrude the biotite granite in the vicinity of the leucocratic granite intrusion. Some younger kilometric scale features intrude all these granites: decametre-wide quartz veins (Archean age) and meter-wide doleritic dykes of several geological ages (2.5–1.6 Ga; G.S.I. 2002).

The weathering profile of these granites is observed in hundreds of dugwells (up to 20 m in depth) located throughout the watershed area. While dugwells provide mainly information on the upper part of the weathering

profile, i.e. down to the laminated layer and, in some dried dugwells, to the top of the fissured layer (Fig. 4), cuttings from 45 observation boreholes drilled during the research project (down-to-the-hole hammer drilling with 1 m sampling interval) up to 64 m in depth, provide deeper information. From the top to the bottom, the profile generally shows (Fig. 4):

- a thin layer of red soil (10–40 cm),
- a 1–3 m thick layer of sandy regolith, which is locally capped by a lateritic crust (<50 cm in thickness),
- a 10–15 m thick layer of laminated saprolite. This layer is characterized by a penetrative millimetre-spaced horizontal laminated structure and an unusual network of preserved mainly subhorizontal and some subvertical fissures partially filled up by clayey minerals (Fig. 4). Both sandy regolith and laminated saprolite layers contain a few granite corestones (preserved fresh rock). While such fresher blocks are only occasionally present in the biotite granite, they are very common in the leucocratic granite (Fig. 3c),
- the fissured fresh granite that occupies the next 15–20 m, where weathered granite and a few clayey minerals commonly partially fill up the fissures,
- the unfissured granite (bedrock).

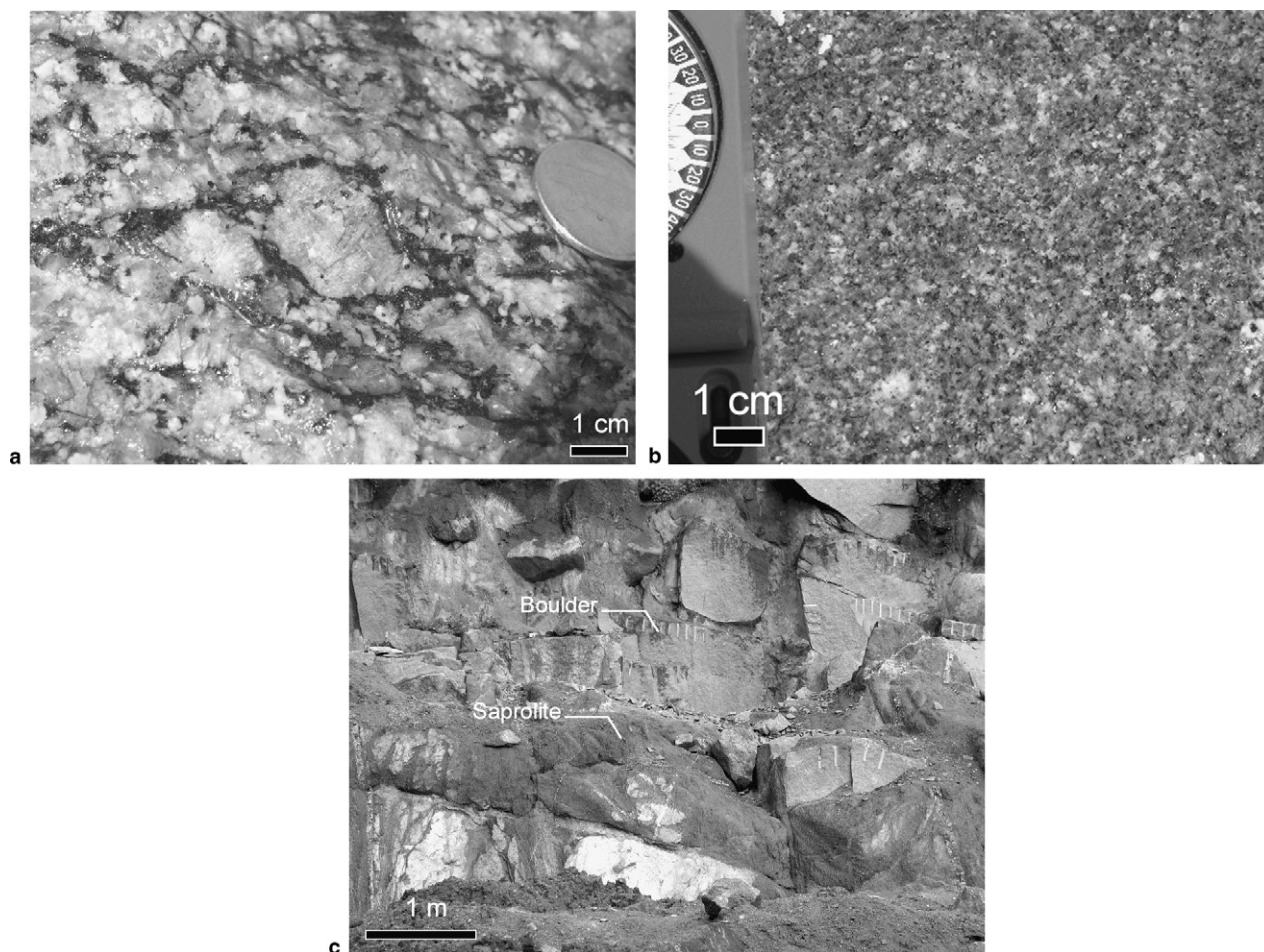


Figure 3 Field photographs: (a) biotite granite, slightly deformed granite with black 'strips' biotite, (b) leucocratic granite, and (c) example of weathering (saprolite) in leucocratic granite; note the large amount of fresh rock (boulders).

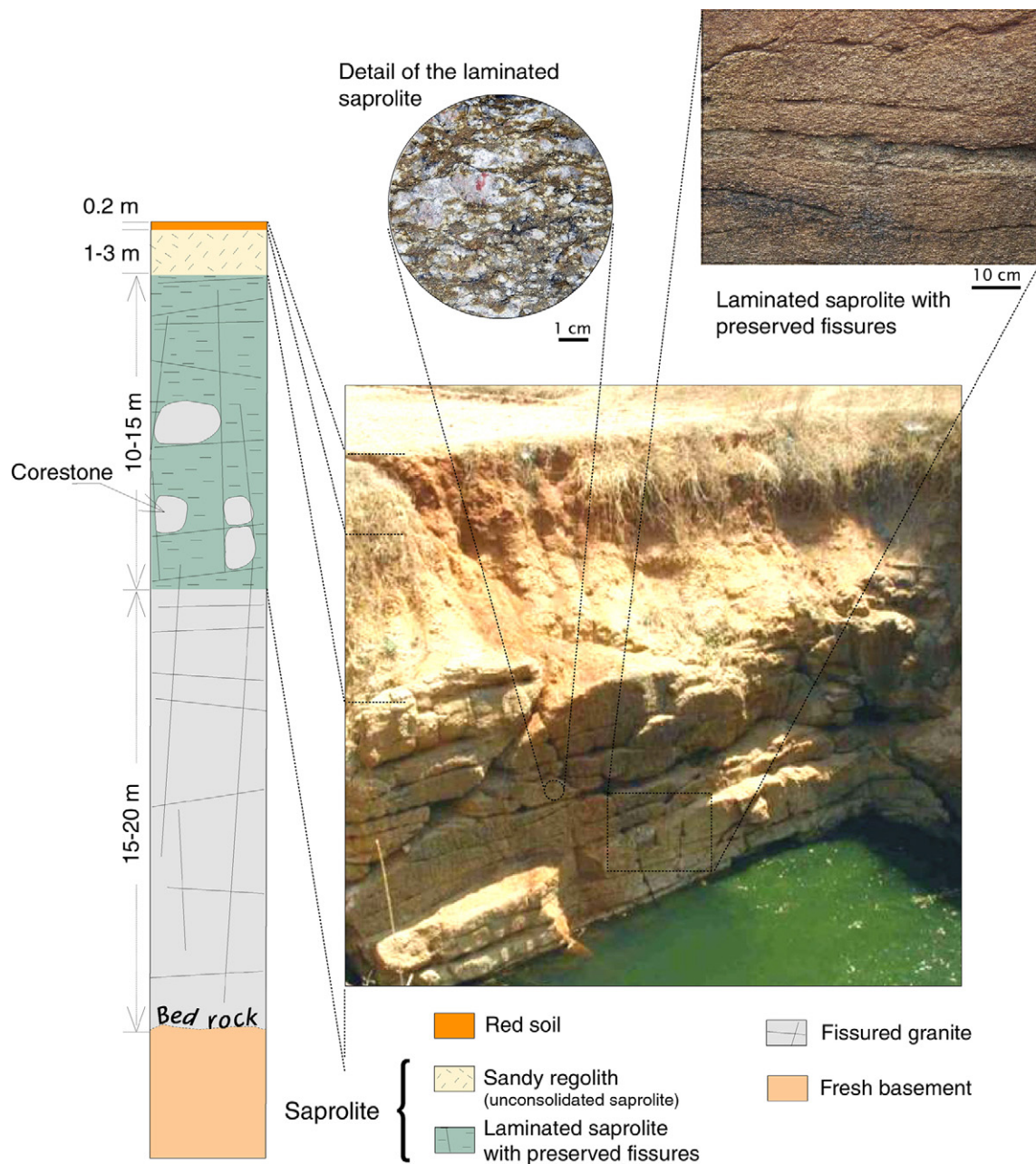


Figure 4 Weathering profile of Maheshwaram area. The dugwell, located in the biotite granite, shows the upper part of the weathering profile: sandy regolith (≈ 1 m), and more than 2 m of laminated saprolite with unusual subhorizontal and subvertical fissures.

This weathering profile is representative of the weathering profiles developed on granites in South India (e.g. [Sharma and Rajamani, 2000](#) and field observations performed by the authors in a radius of 70 km around Hyderabad and in the area of the city of Bangalore, Karnataka state).

(i) Because of the very low ratio sandy regolith thickness/saprolite thickness, 0.1–0.2 in Maheshwaram instead of 0.5–0.7 in the “classical” thick profiles, (ii) because of the small thickness of the fissured layer compared to that of the saprolite (ratio of 1 instead of 2) and (iii) because also of the presence of numerous preserved fissures within the laminated saprolite, the Maheshwaram weathering profile differs from

the “classical” deep weathering model ([Fig. 1](#)) and questions the weathering processes in South India.

Spatial structure of the weathering profile

Forty-five observation wells (Indo-French research Project wells named “IFPs”) drilled in the pilot watershed during the research project and more than eighty Vertical Electrical Soundings ([Krishnamurthy et al., 2002, 2003; Kumar et al., in press](#)) are compiled in order to characterize, in addition to dugwell and outcrop observations, the structure of the aquifer.

Observation wells lithologs (Fig. 5) were made up on the basis of the cuttings collected every meter during the drilling. The *sandy regolith* is identified from the cuttings by its clay-sandy to sandy-clay composition, sandy texture and by its reddish to yellowish colour, and often the presence many quartz grains. The *laminated layer* is identified from the cuttings by its coarse sand-size clast texture and its yellowish to brownish colour. When the drilling is performed in its vadose zone – which was the case on our catchment during the drilling period, some kinds of ‘ships’ (2–3 cm in length) are commonly excavated from the borewell during the drilling. They are friable but it is still possible to identify the structure of the *laminated layer* from them. Moreover, ‘sliced’ minerals (centimetric scale; e.g. porphyritic K-feldspar) are commonly found in the cuttings. They are not sliced by the drilling process, but by the weathering itself. This can be proved on one hand by the fact that such sliced minerals are also observed in dugwells and on the other hand because of the presence of oxidation – iron stain – on their sides. When this layer is saturated with water (drilling below the piezometric level) most of the ‘ships’ constituted of laminated saprolite are disaggregated by the presence of water, however the sliced minerals are still preserved and can be observed in the cuttings. *Fissures in the laminated layer* are identified as they are totally or partially filled up by clayey materials (yellowish to

green-white clay). When such fissures are drilled, the colour of the cuttings (and/or of the mud) radically changes from a yellowish-brownish colour (normal colour of the laminated layer) to a green-white colour. However, only the main fissures can be identified. Fig. 4 shows an example of such preserved fissures within the saprolite. The so determined thickness of the laminated layer has been found consistent to that measured in the neighbouring dugwells. In fact, most of them are dug down to the bottom of the laminated layer (as it is quite easy to dig in such quite smooth rocks) and thus most of them reach the top of the fissured layer (the first 1–2 m of the fissured layer, harder to dig, are then commonly observed at the bottom of the dugwells – due to groundwater overexploitation, most of the dugwells are dried in Maheshwaram). The *top of the underlying fissured layer* is identified by relatively fresh cuttings (relatively ‘hard’ granite not saprolitized, but with numerous iron coating) and the sudden decrease of the drilling speed. In the fissured layer, the fissures are surrounded by centimetre to metre-thick saprolitic material and light-green to whitish clays. These highly weathered zones into the fissured layer reflect that the weathering progresses from fissure borders towards the unaltered rock. Thus, the fissured layer is identifiable by alternate, usually thick ‘fresh’ rock layers, with often numerous microfissures underlined by iron coating, and thinner weathered zones. The *base of the fissured layer*

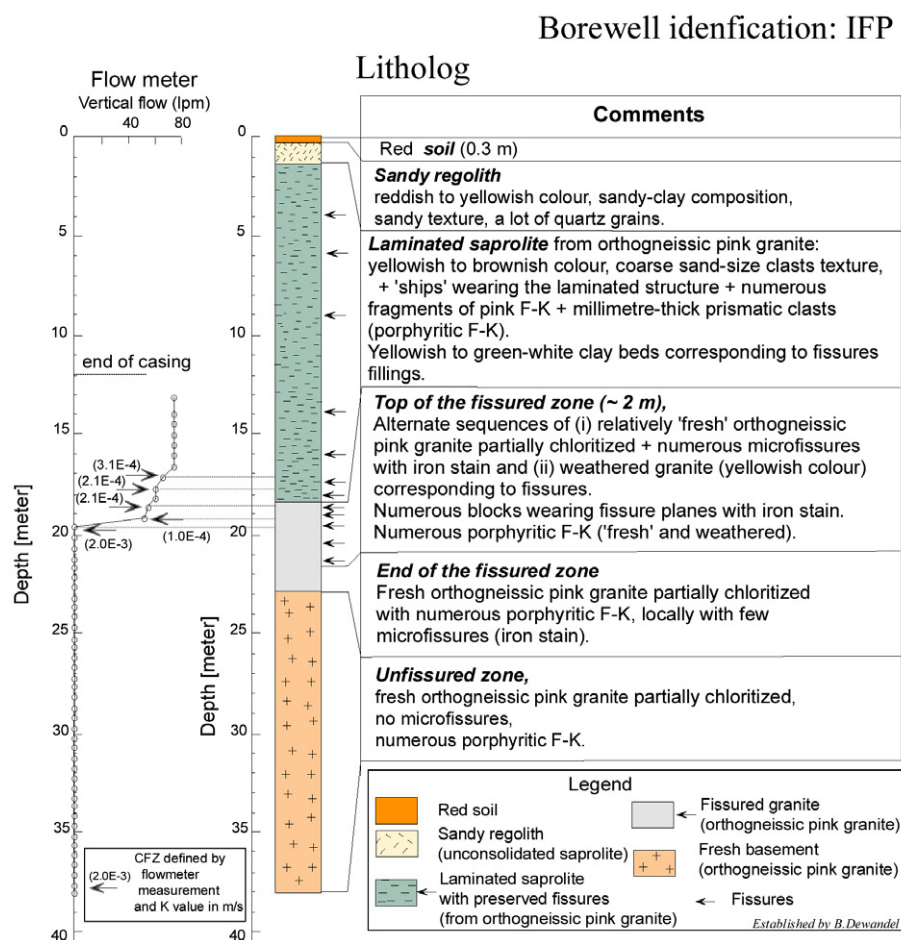


Figure 5 Example of produced litholog from drill cuttings and corresponding flowmeter measurements (IFP8).

is not so easy to identify since it is a statistical limit (very low to nil frequency of fissures) and, in depth, the fissures can be a few millimetres thick with only thin weathered borders. It was considered to be reached where no iron stain was observed on the cuttings. Drilling was then carried out for more than ten metres in order to confirm this first information. The depth to the bottom of the fissured layer was later cross-checked with flowmeter measurements (see Section 'Characterisation of fissures properties').

Eighty VES were carried out using Schlumberger configuration (maximum current electrode separation: 300 m, max. depth of investigation: 50 m) and the results have been interpreted with the help of an inversion program using the Jupp and Vozoff (1975) code (Krishnamurthy et al., 2002, 2003; Kumar et al., *in press*). Due to the large variation in resistivity of such formations and locally due to the progressive transition between some layers, mainly between the laminated layer and the fissured layer special attention has been paid to interpreting the whole set of VES in a coherent manner in order to reduce ambiguities in the interpretations. A methodology, combining a geostatistical approach based on the variographic analysis of the layers thickness determined on the forty-five borewell lithologs, and VES results has been implemented (Kumar et al., *in press*). The principle of the method is to interpret the VES soundings according to the reliable range of layers thickness estimates given by the geostatistical analysis; after a few iterations, VES interpretations were falling in the reliability range (Kumar et al., *in press*). Final results give resistivities of the soil + sandy regolith ranging between 4 (clayey saturated soil) and 1000 (dry sandy regolith) Ωm with thicknesses ranging from 0 to 3 m. The resistivity of the laminated saprolite ranges between 30 and 120 Ωm with thicknesses between 1 and 20 m, whereas the fissured zone resistivity is ranging between 120 and 500 Ωm with thicknesses from 1 to 35 m. The unfissured bedrock has resistivities higher than 500 Ωm but for most of the VES it reaches several thousands Ωm . It occurs at depths ranging from 5 to 42 m. An example of such an interpretation is given in Fig. 6.

The large amount of available data (observation well lithologs and VES inversions) allows the mapping (Fig. 7a and b) of both the base of the laminated layer and the base of the fissured layer (or the top of the bed rock).

Variogram analyses based on the data set of elevation of both horizons shows that the data are spatially structured and that krigging is able to give significant maps (Fig. 7a and b). Regardless of the lithology, the elevation of the bottom of the laminated layer ranges between 600 and 650 m amsl and that of the fissured layer between 590 and 650 m amsl. Both horizons show a general dip towards the North, with a gentle slope of about 0.5–1%, with some local variations (local deepening of some metres to a few tens of metres). Cross sections deduced from these two maps (Fig. 8a–d) also show that both horizons more or less follow the current topography and thus that their thicknesses are relatively constant at the watershed scale.

Lithological and local features locally interrupt the geometry of the weathering horizons. Leucocratic granite, due to its low biotite content, is less deeply weathered than the biotite granite. As a consequence, the base of the weathering profile is globally at a higher elevation in leucocratic granite than in the biotite granite (Fig. 8d). The quartz vein induces a local 10–20 m deepening of both layers (Fig. 8d). During the weathering phase(s), this discontinuity favoured local circulation of water within the unweathered rock. The lateral constraints resulting from the weathering of the surrounding granite induced a fissuring of the quartz vein that clearly appears on outcrops and can enhance the circulation of water and in return favoured a deepening of the weathering front.

A multiphase weathering model

The Maheswharam weathering profile (Fig. 4) shows some discrepancies when compared to the classical one presented in the introduction of the paper (Fig. 1). The sandy regolith (1–3 m) is very thin and is almost constant while it should

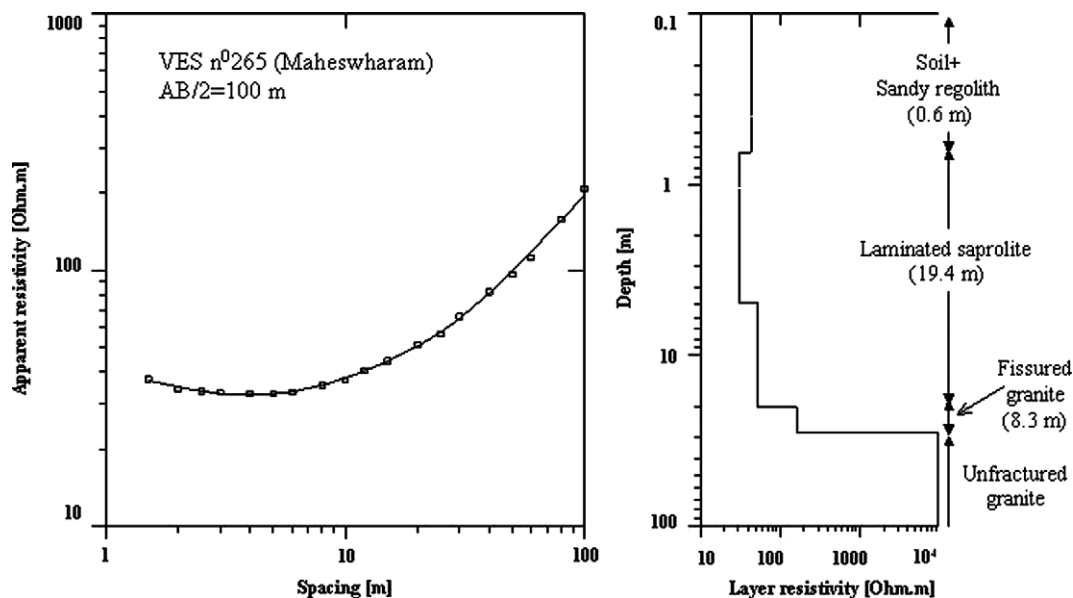


Figure 6 Example of vertical electrical sounding interpretation (VES no. 265).

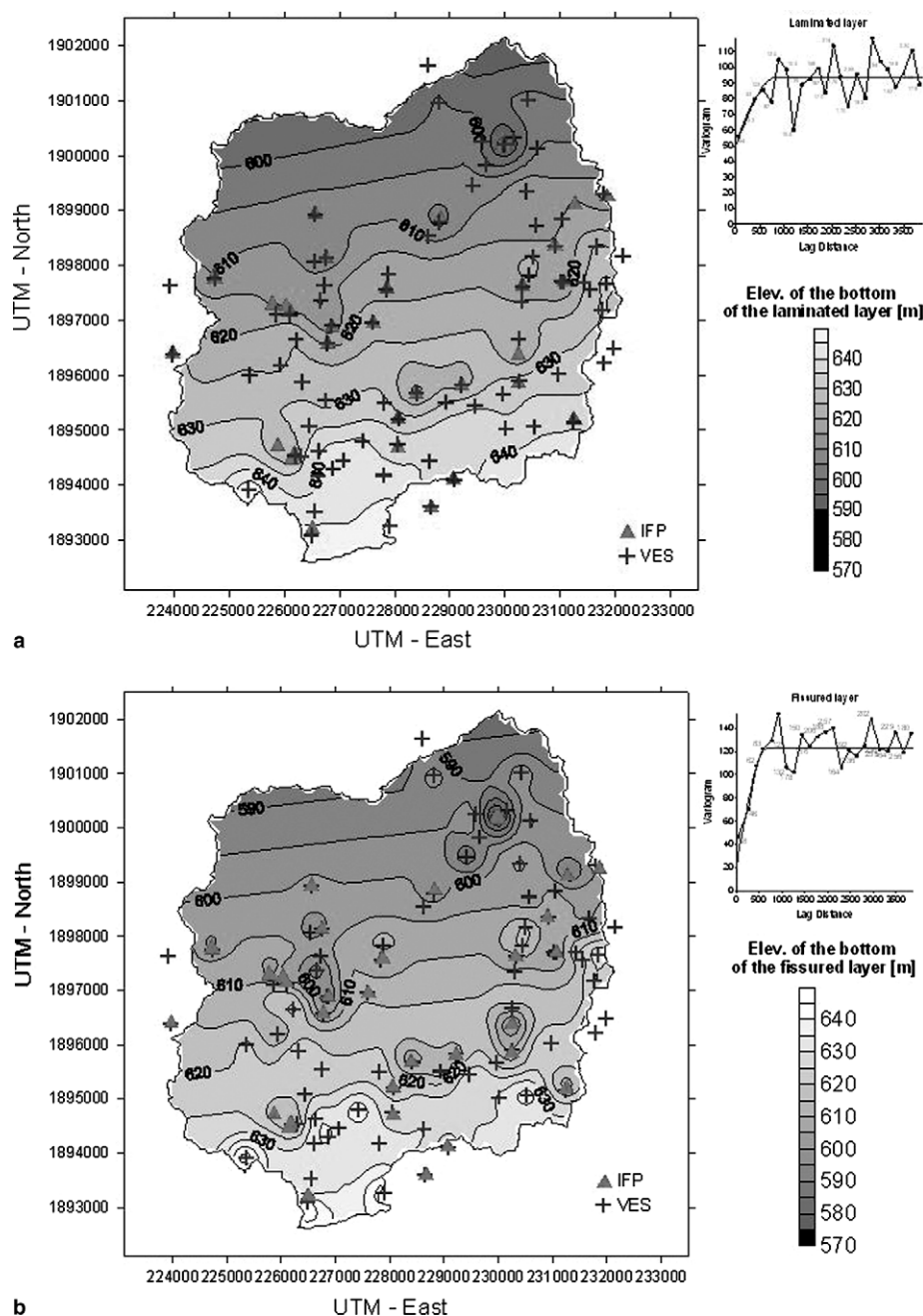
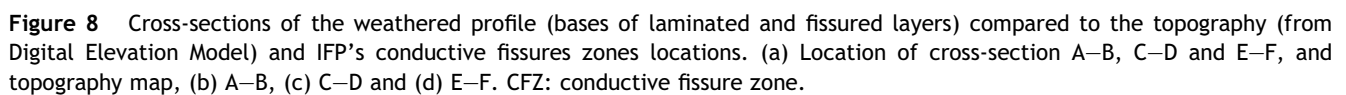


Figure 7 Kriggered maps (45 borewell lithologs and 80 VES interpretations) of elevation (in m above sea level) of the bases of: (a) the laminated layer and (b) the fissured layer (= top of fresh and unfissured basement). Plots in right corner show the respective variograms used for kriggering. UTM coordinates (system: WGS84).

be thicker in the plateau areas than in the valleys if the weathering had occurred earlier than the erosion that has shaped the present topography. As a consequence, the thickness of the laminated layer (10–15 m) is disproportionate compared to that of the sandy regolith (1–3 m), while in the classical weathering profile the laminated layer occupies only one third to half of the entire saprolite layer. The thickness of the fissured layer is small compared to that of the saprolite (ratio of ~ 1 instead of ~ 2). Moreover, the laminated layer presents preserved fissures (see Fig. 4), which are usually not observed in the classical model.

The Maheshwaram area thus appears to be composed of an old weathering profile (Fig. 9a), where only a part of the fissured layer has been preserved. An erosion phase, probably due to regional uplift, caused the erosion of the entire saprolite layer and a part of the fissured layer (Fig. 9b). Then, at least one more recent weathering phase, the latest being probably still active, is responsible for the saprolitisation of this truncated profile and explains the development of 1–3 m sandy regolith locally capped by an iron crust, and the lamination of a large part of the ancient fissured layer (Fig. 9c). The profile structure is thus controlled by a



Since the Indian Peninsula separated from 'Gondwana' and started migrating northward (Jurassic), the continent experienced numerous uplifts (Deccan Traps episode, when India passed over the Reunion island Hot Spot, different phases of collision with the Asian plate). It resulted in significant erosion, sedimentary deposits along the coasts and thus rejuvenated landscapes at the scale of the whole Peninsula (Babu, 1975; Vaidyanadhan, 1977; Radakrishna, 1993; Valdiya, 1998). This context was unable, excepted at a few

In order to characterize the hydraulic properties of the different weathering layers constituting such a hard rock aquifer, flowmeter measurements have been carried out on nineteen representative observation borewells of the Maheshwaram watershed (Fig. 2). These hydraulic tests complete the dataset from Maréchal et al. (2004). As the present geological model was not available, this previous study only assessed the vertical distribution of the fissures according to their depth below ground surface and not according to their location within the various layers of the

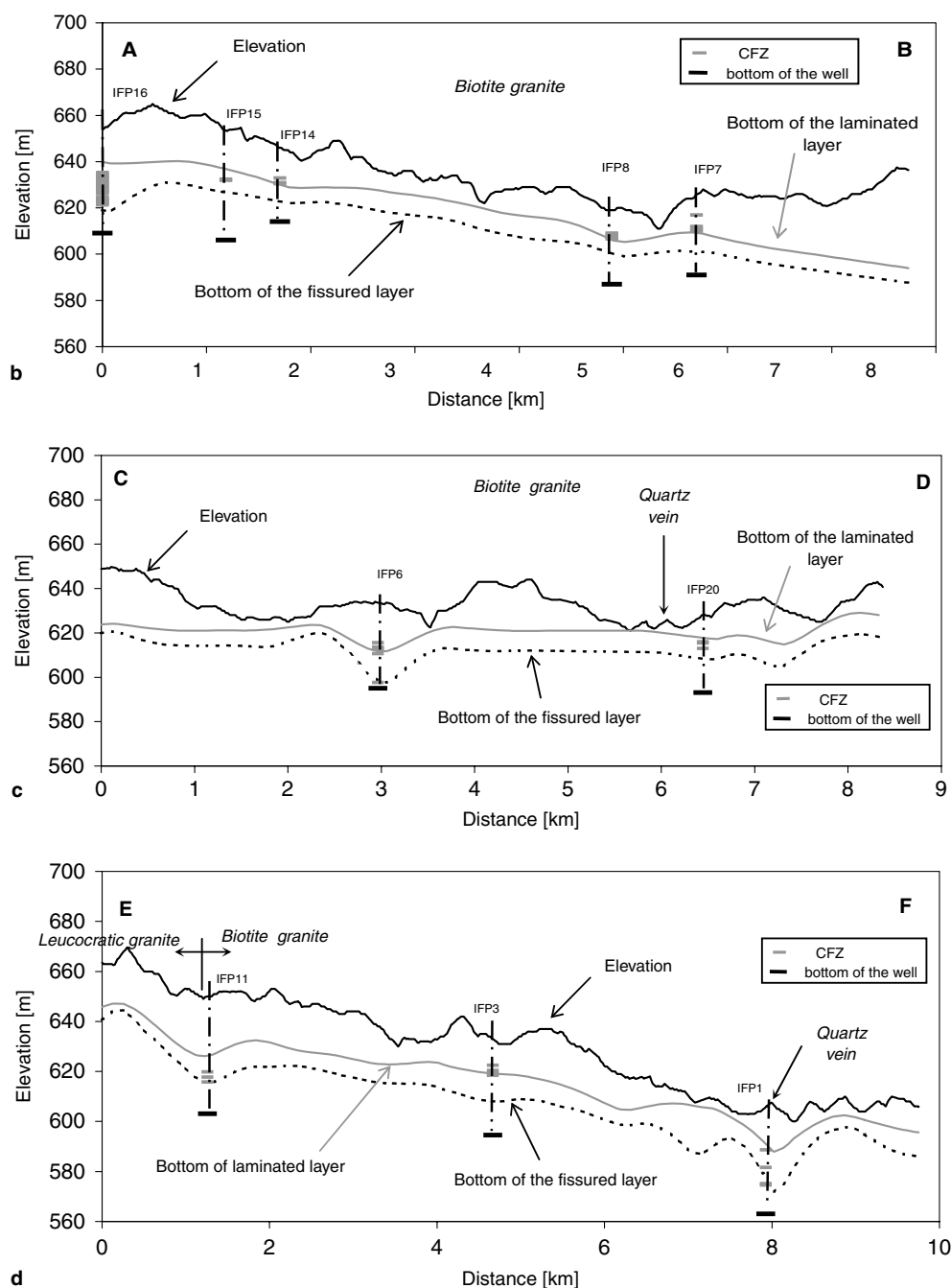


Figure 8 (continued)

weathering profile. Consequently, the flowmeter tests results were re-interpreted in order to precise these preliminary results and particularly to precisely characterise the hydrodynamic properties of the various layers of the weathering profile.

Characterisation of fissures properties

Methodology

The identification and location of hydraulically conductive fissures was performed through vertical profiles of flowme-

ter measurements within the non-equipped part of the borewell (mechanical flowmeter; propeller diam.: 50 mm, measures performed every 0.5 m). As the unsaturated zone is thick on the pilot watershed, the measurements are performed during injection tests rather than during pumping tests in order to increase the vertical extension of the investigated zone. A detailed description of the measurements and of the methodology used for data interpretation is provided in [Maréchal et al., 2004](#). The final result is a series of data providing vertical discharge $Q(z)$ as a function of depth z . Estimates of the permeability of the conductive zones were achieved by assuming a serie of horizontal

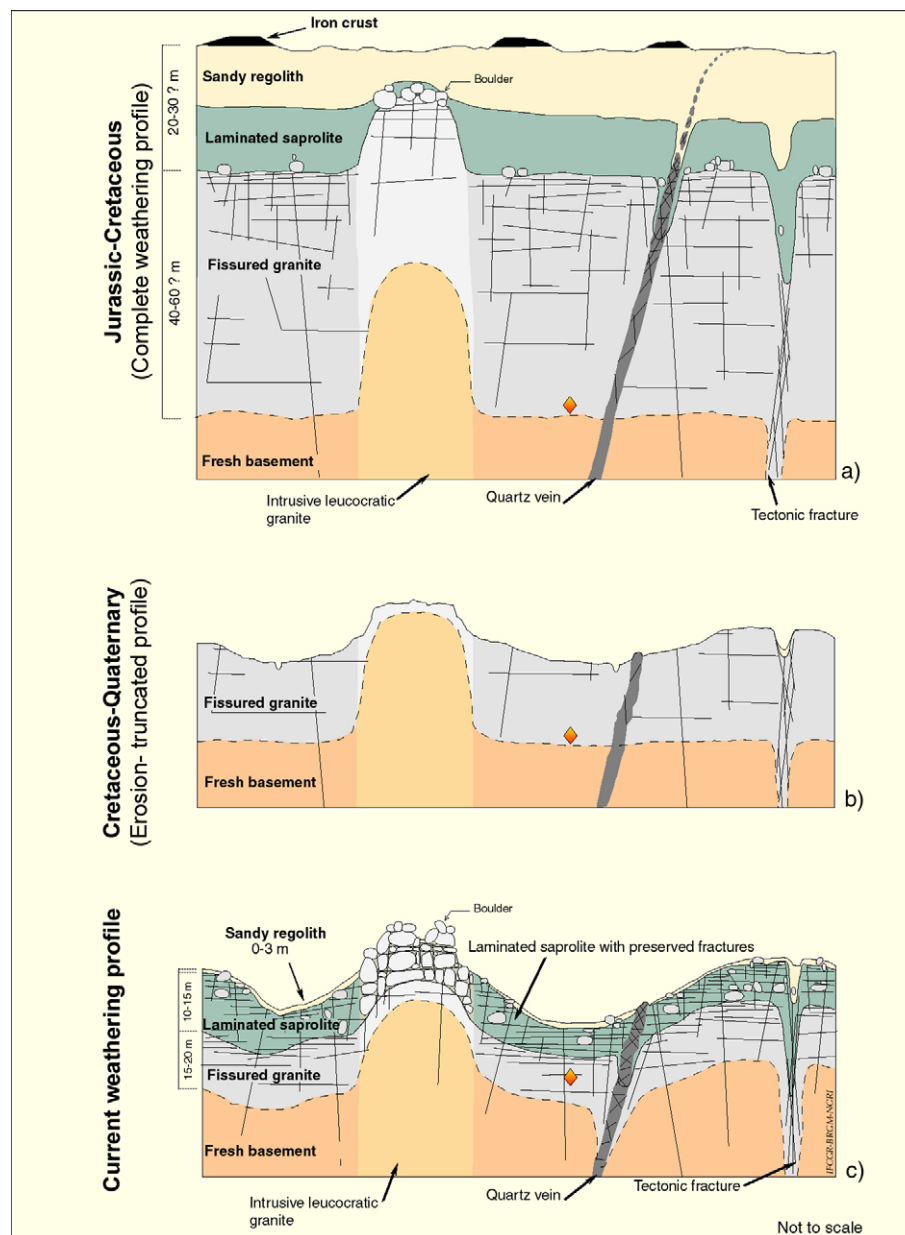


Figure 9 Idealized multiphase weathering conceptual model (vertical scale is deliberately exaggerated). (a) Probable weathering profile in Mesozoic Era (Jurassic-Cretaceous), complete profile, (b) truncated erosion profile due to Cretaceous to Quaternary uplifts, and (c) current weathering profile. Diamond = benchmark.

layers (Molz et al., 1989), then the Dupuit formula (1848,1863) for a confined aquifer and horizontal flow to a well is applied to each layer, which leads to the estimation of the layer's hydraulic conductivity. Previous study in the same area showed that the aquifer is under unconfined condition (Maréchal et al., 2003b, 2004). This is explained by the fact that the saprolite is poor in clayey materials and that the networks of horizontal and vertical fissures, within both laminated and fissured layers, connect the aquifer to the piezometric surface. Consequently, the hydraulic conductivities obtained, where corrected for unconfined condition (Dupuit, 1848,1863).

Results

Twenty-eight injection tests were conducted on the pilot watershed and were interpreted as pumping tests. Due to the sensitivity threshold of the flowmeter, the total injection flow (Q) during the flowmeter test required to be higher than 25 l/min (below 25 l/min the propeller does not rotate). Consequently, only nineteen flowmeter tests were conducted, in the most permeable IFP observation wells allowing a $Q > 25$ l/min (Fig. 2, Table 1). The identified conductive layers, the ones where the net radial flow is not nil (or, more precisely, is not below the flowmeter sensitivity)

Table 1 Details of the injection (28) and flowmeter (19) tests according to the weathering profile

Wells no.	Depth [m]	Casing depth [m]	Water table depth [m]	Thickness of the laminated layer [m]	Thickness of the fissured layer [m]	Fresh basement depth [m]	Flowmeter and injection test			Depth portion of laminated layer investigated by the injection test			Depth portion of transition zone (0–2 m fissured zone) investigated by the injection test			Depth portion of rest of the fissured layer (>2 m) investigated by the injection test		
							Flowmeter	K-injection test [m/s]	Total nb of CFZ	Percentage of the layer investigated	No. of CFZ	Density of CFZ [1/m]	Percentage of the layer investigated	No. of CFZ	Density of CFZ [1/m]	Percentage of the layer investigated	No. of CFZ	Density of CFZ [1/m]
IFP-1	42	8.8	16.7	18.3	19.2	37.5	Yes	1.3E-05	4	50	0	0.00	100	1	0.50	100	3	0.17
IFP-1/2	35	12.0	18.1	22.5	7.7	30.2	Yes	5.1E-07	2	46	1	0.10	100	0	0.00	100	1	0.18
IFP-1/3	35	5.7	18.5	17.0	12.0	29.0	No data ^a	1.9E-07	<i>u/k</i> ^b	69	<i>u/k</i>	<i>u/k</i>	100	<i>u/k</i>	<i>u/k</i>	100	<i>u/k</i>	<i>u/k</i>
IFP-2	35	0.6	14.8	18.0	2.0	20.0	No data	1.1E-05	<i>u/k</i>	92	<i>u/k</i>	<i>u/k</i>	100	<i>u/k</i>	<i>u/k</i>	100	<i>u/k</i>	<i>u/k</i>
IFP-3	37	6.3	11.9	17.1	6.4	23.5	Yes	2.7E-05	5	64	5	0.46	100	0	0.00	100	0	0.00
IFP-4	45	0.8	19.0	17.5	4.5	22.0	No data	5.6E-08	<i>u/k</i>	63	<i>u/k</i>	<i>u/k</i>	100	<i>u/k</i>	<i>u/k</i>	100	<i>u/k</i>	<i>u/k</i>
IFP-5	60	11.7	25.8	22.5	13.5	36.0	No data	1.7E-07	<i>u/k</i>	53	<i>u/k</i>	<i>u/k</i>	100	<i>u/k</i>	<i>u/k</i>	100	1	<i>u/k</i>
IFP-6	42	21.3	21.9	23.0	16.5	39.5	Yes	3.0E-05	6	8	1	0.54	100	3	1.50	100	2	0.14
IFP-7	38	14.8	20.5	18.0	0.5	18.5	Yes	2.6E-04	3	17	0	0.00	100	3	1.50	100	0	0.00
IFP-8	38	12.0	20.4	18.3	4.6	22.9	Yes	1.4E-04	5	33	2	0.33	100	3	1.50	100	0	0.00
IFP-9	42	12.0	28.4	19.7	13.8	33.5	Yes	2.2E-05	4	38	0	0.00	100	0	0.00	100	4	0.34
IFP-10	40	1.2	24.7	14.3	7.7	22.0	No data	9.7E-08	<i>u/k</i>	53	<i>u/k</i>	<i>u/k</i>	100	<i>u/k</i>	<i>u/k</i>	100	<i>u/k</i>	<i>u/k</i>
IFP-11	42	18.2	21.5	15.8	21.7	37.5	Yes	6.4E-05	3	0	<i>u/k</i>	<i>u/k</i>	0	<i>u/k</i>	<i>u/k</i>	91	3	0.52
IFP-11/3	42	19.0	21.9	33.0	2.2	35.2	Yes	1.7E-06	1	42	1	0.07	100	0	0.00	100	0	0.00
IFP-11/4	39	<12	23.5	25.3	9.7	35.0	Yes	2.1E-05	5	28	3	0.43	100	2	1.00	100	0	0.00
IFP-12	42	21.1	21.0	23.8	11.2	35.0	Yes	2.7E-06	4	12	2	0.69	100	2	1.00	100	0	0.00
IFP-14	38	15.0	20.0	14.6	9.2	23.8	Yes	2.1E-05	3	59	3	0.35	100	0	0.00	100	0	0.00
IFP-15	41	12.0	19.1	12.0	11.8	23.8	Yes	1.8E-04	2	0	0	0.00	50	0	0.00	92	2	0.20
IFP-16	42	14.8	15.2	10.0	26.6	36.6	Yes	2.0E-04	27	0	<i>u/k</i>	<i>u/k</i>	0	<i>u/k</i>	<i>u/k</i>	83	27	1.10
IFP-17	38	19.8	18.2	20.7	9.8	30.5	Yes	2.1E-06	3	4	0	0.00	100	3	1.50	100	0	0.00
IFP-19	41	5.8	13.2	2.3	20.2	22.5	No data	6.3E-07	<i>u/k</i>	0	<i>u/k</i>	<i>u/k</i>	0	<i>u/k</i>	<i>u/k</i>	68	1	<i>u/k</i>
IFP-20	41	18.1	19.2	13.8	7.3	21.1	Yes	8.2E-05	3	0	<i>u/k</i>	<i>u/k</i>	0	<i>u/k</i>	<i>u/k</i>	52	3	0.57
IFP-21	40	12.0	13.8	13.8	7.3	21.1	Yes	4.6E-05	5	16	0	0.00	100	3	1.50	100	2	0.38
IFP-22	41	9.7	15.1	9.2	31.8	41.0	No data	9.2E-08	<i>u/k</i>	3	<i>u/k</i>	<i>u/k</i>	100	<i>u/k</i>	<i>u/k</i>	100	<i>u/k</i>	<i>u/k</i>
IFP-23	42	13.8	21.1	19.2	19.8	39.0	No data	7.6E-07	<i>u/k</i>	81	<i>u/k</i>	<i>u/k</i>	100	<i>u/k</i>	<i>u/k</i>	100	<i>u/k</i>	<i>u/k</i>
IFP-25	46	5.5	22.5	16.0	26.0	42.0	No data	2.4E-07	<i>u/k</i>	0	<i>u/k</i>	<i>u/k</i>	0	<i>u/k</i>	<i>u/k</i>	90	1	<i>u/k</i>
IFP A	46	12.0	18.3	10.0	10.3	20.3	Yes	2.8E-04	2	0	No data	No data	0	No data	No data	42	2	0.24
IFP B	64	12.0	16.6	17.0	14.4	31.4	Yes	2.9E-03	1	7	0	0.00	100	1	0.50	100	0	0.00

CFZ: conductive fissures zone.

^a No data: for practical reasons.^b *u/k*: unknown data.

do coincide in depth with fissures identified from the borewell lithologs (Fig. 5). Even if some pegmatite veins and leucocratic dykes have been encountered in some borewells (IFPA and B), conductive fissures were found in the fissured granite only, far from these structures found in the upper saprolite layer. However, both the sampling rate of cuttings (every meter) and the interval between two flowmeter measurements (0.5 m) do not allow to determine if these conductive layers are constituted by a single fissure or by several fissures. Therefore, in order to avoid any confusion, the results are referred to "conductive fissure zones (CFZ)" without any hypothesis concerning their exact nature: single fissure or several fissures.

According to the geometry of the wells and the observed drawdowns, the sensitivity of the flowmeter limits the identification of CFZs to those exceeding 1×10^{-5} m/s in hydraulic conductivity, corresponding to a net radial flow of about 2.75 l/min in a 0.5-m-thick layer (transmissivity $\geq 5 \times 10^{-6}$ m²/s).

As a first result, CFZ locations have been plotted according to their elevation on the previous cross sections (Fig. 8a–d). It appears that the CFZs are located both in the laminated and in the fissured layers, which means that the fissures belonging to these two different layers and identified with the geological observations (dugwells and litholog, Figs. 4 and 5) comprise CFZ. This result differs from the classical weathering model (see Fig. 1) where the fissures are obliterated in the laminated layer and thus do not show a significant hydraulic conductivity. It also appears that the CFZ's location follows more or less the topography.

Thickness of the conductive layer

If the identified CFZs are plotted as a function of their depth below the ground surface (Fig. 10a, figure modified from Maréchal et al., 2004), this shows that the CFZ are located between 9 and 39.5 m depth, with a higher concentration between 15 and 30 m. However, observations are limited at shallow depths by the presence of casings in the borewells and deeper by the bottom of the wells. Thus, it is necessary to consider a statistical bias of the data introduced by unequal representation of the depth ranges for the investigated boreholes. A quality ratio is computed as the percentage of investigated borewells for each depth-interval (Fig. 10b). It shows that the most representative data are obtained between 15 and 42 m below the ground surface where the percentage of investigated wells is higher than 50%. The low rate of observations at shallow depths (down to 15 m; quality ratio < 50%) suggests that the apparent decrease in fissures number above 15 m is an artefact due to this bias in observations. Consequently, it can be reasonably supposed that the CFZ extend also into the upper part of the weathering profile, as observed on dugwells (Fig. 4).

The base of the fissured layer is better constrained. A first decrease of the CFZ number appears between 24 and 30 m and is followed by the almost total absence of CFZ below 35 m (i.e. absence of flow as measured with the flowmeter). This depth roughly corresponds to the top of the "fresh basement" identified by geological observations performed during the drilling of the wells; this depth is also correlated with a decrease of the drilling rate. This result is in accordance with previous works carried out in South-India, where the depth to the bottom of the permeable zone

was 25–30 m (Uhl and Sharma, 1978; Briz-Kishore, 1993). In African basement areas also, the base of the fissured zone is often in the range 25–40 m, although not necessarily following the topography as it does here (e.g. Chilton and Smith-Carington, 1984).

These observations confirm that the weathered-fissured layer has a limited vertical thickness in this part of India, and that it more or less follows the topography down to 35 m depth as an average. This is consistent with the location of CFZ plotted on cross-sections and with geological and geophysical investigations, which show that the top of the bedrock is more or less parallel to the topography (Fig. 8b–d).

Fissure hydraulic conductivity and weathering grade

In order to characterize the hydrodynamic properties of the laminated and the fissured layers, the CFZ hydraulic conductivities (Fig. 10c) have also been plotted according to another reference level: the interface between the laminated and the fissured granite, as identified on lithologs (Fig. 11). The number of observations is still limited at shallow depth; nevertheless good quality ratios are obtained for the whole fissured layer and for a significant thickness (more than 5 m) of the laminated layer (Fig. 11b).

The vertical distribution of CFZ (Fig. 11a) confirms their occurrence in both layers. Moreover, the density of CFZ is similar in both the laminated layer and the deeper part of the fissured layer. However, it appears that the first two metres of the fissured layer are significantly more fissured than the other parts of the two other layers, since about 25% of the total number of CFZ occurs within this zone. This result is consistent with previous studies, which show that the first metres of the fissured layer are generally characterized by a denser fissuring (Houston and Lewis, 1988; Howard et al., 1992; Cho et al., 2003; Wynn et al., 2004). Furthermore, the presence of such a dense fissuring in the first metres of the fissured layer confirms the location of the limit between the laminated and the fissured layers as identified on lithologs. We propose to name this zone the "transition zone".

Fig. 11c shows the location and the hydraulic conductivity of each identified CFZ. Separate histogram analyses of CFZ hydraulic conductivities from the various layers have been prepared. Distributions of CFZ hydraulic conductivities in the laminated layer (Fig. 12a) and in the deeper part of the fissured zone (>2 m, Fig. 12c) appear to be lognormal, even if information on CFZ of low hydraulic conductivity, particularly in the laminated layer, is limited due to the flowmeter sensitivity. Moreover, distributions of CFZ hydraulic conductivities have been studied in the deeper part of the fissured layer (>2 m) for two depth intervals of ten metres each (2–12 m, Fig. 12d, and 12–22 m, Fig. 12e). In both cases, the distributions of CFZ hydraulic conductivity are similar and comparable to the ones obtained for the whole deeper part of the fissured layer (Fig. 12c). Furthermore, the histograms do not show any significant decrease of CFZ hydraulic conductivity for the deepest part of the fissured layer, while the number of CFZ is decreasing (2–12 m: 30 CFZ, 12–22 m: 19 CFZ; Fig. 12e).

The distribution of CFZ hydraulic conductivity in the laminated layer (geometrical mean of available data:

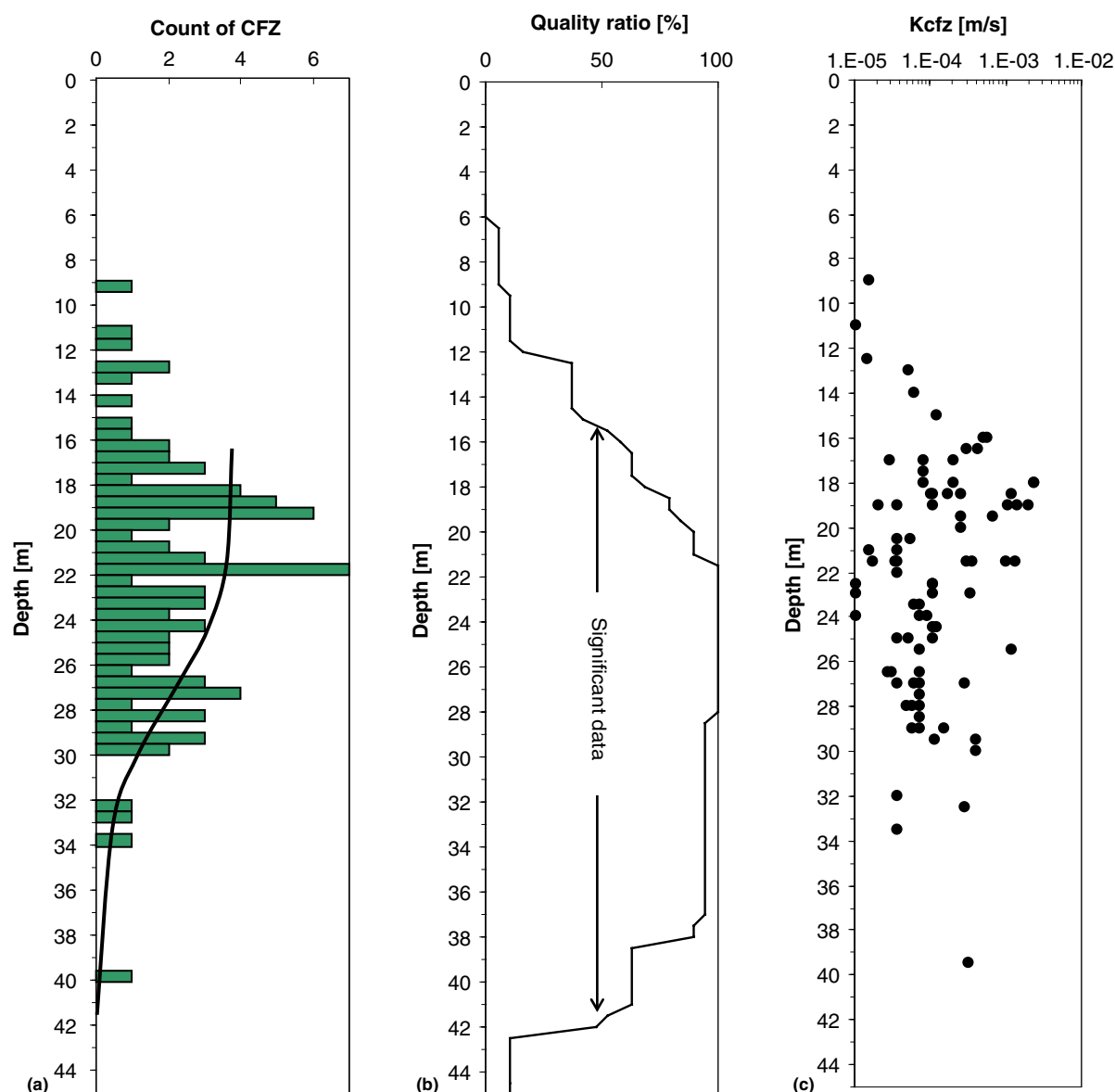


Figure 10 Interpretation of flowmeter measurements (19 wells) according to the ground level, by 0.5-m-thick aquifer portions (modified from Maréchal et al., 2004). (a) Number of identified hydraulically conductive fissure zones (CFZ). (b) Quality of observation expressed as the ratio between the number of available observations for each aquifer portion and the total 19 flowmeter tests. (c) Hydraulic conductivity of CFZ.

5.1×10^{-5} m/s) shows that CFZ are less permeable than in the deeper part of the fissured layer (>2 m; geometrical mean of available data: 1.2×10^{-4} m/s). This contrast in hydraulic conductivity can be explained by the relatively high grade of weathering in the laminated layer, which induces filling of the fissures with clay rich minerals, and thus their closure and/or clogging. Moreover, Fig. 11c suggests that the hydraulic conductivity of these inherited fissures decreases toward the top of the layer, as fissures are progressively filled up by clay-rich materials and obliterated by the weathering process.

The distribution of CFZ hydraulic conductivities in the 'transition zone' is not well structured (Fig. 12b; geometrical mean of available data: 1.8×10^{-4} m/s). It presents both high hydraulic conductivity values similar to those of the

deeper fissured layer and quite low hydraulic conductivity values as in the laminated layer. Moreover, this layer is marked by the highest CFZ hydraulic conductivities of the entire weathered-fissured layer (max. K_{CFZ} : 2.5×10^{-3} m/s). This 'mixed' hydraulic conductivities pattern is most probably a consequence of the dense fissuring, with probably more than one conductive fissure within each 0.5 m interval of flowmeter measurements. Thus, the transition zone only differs from the deeper part of the fissured layer by the density of the CFZ, but not by their hydrodynamic properties.

Estimation of the hydraulic parameters of the different weathered layers

CFZ density. For each well and each weathered layer, the vertical density of CFZ (ratio between the number of CFZ

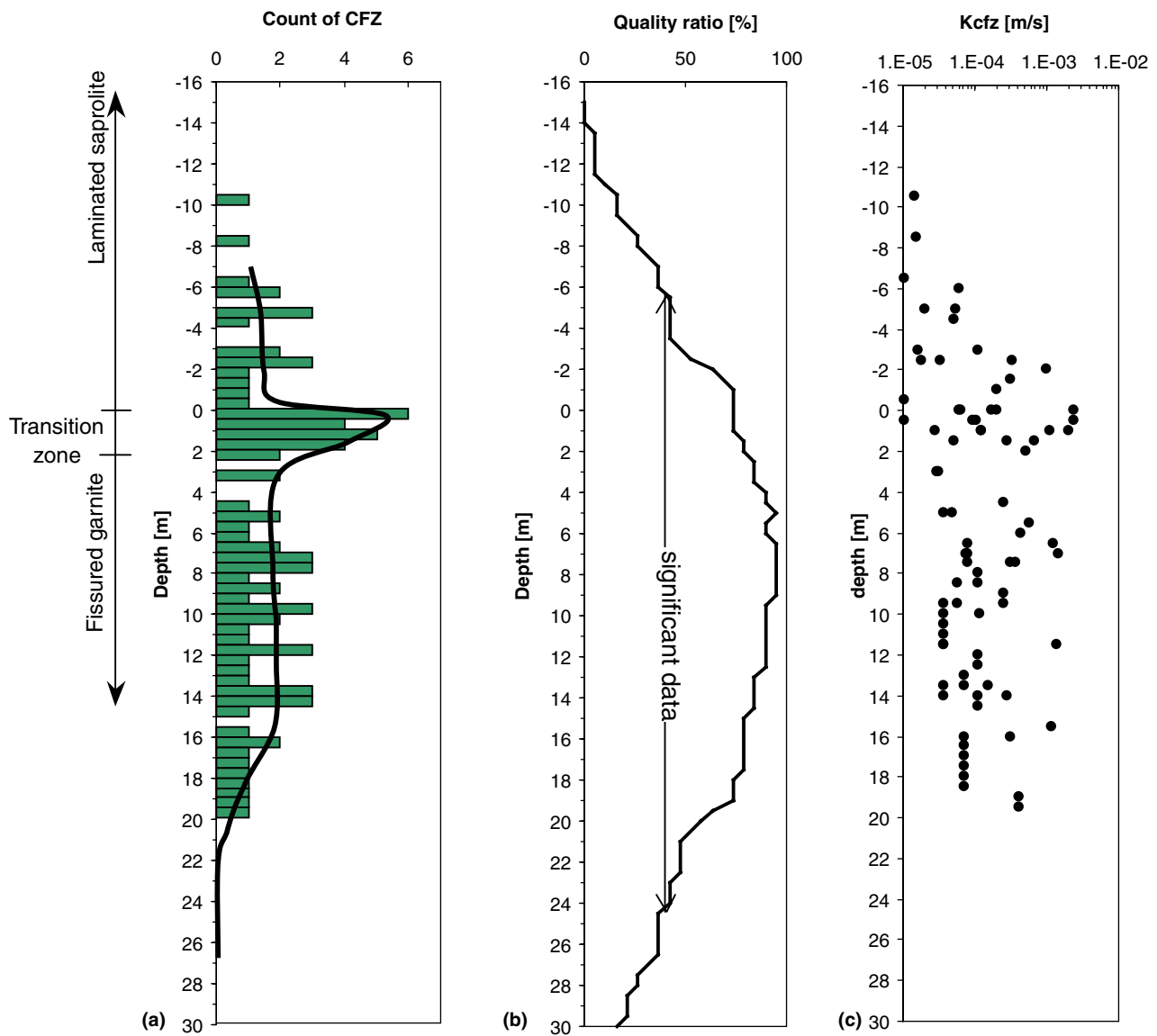


Figure 11 Interpretation of flowmeter measurements (19 wells) according to the laminated-fissured interface, by 0.5-m-thick aquifer portions. (a) Number of identified hydraulically conductive fissure zones (CFZ). (b) Quality of observation expressed as the ratio between the number of available observations for each aquifer portion and the total 19 flowmeter tests. (c) Hydraulic conductivity of CFZ. TZ: Transition zone.

and the thickness of the investigated weathered layer; Table 1) has been computed.

CFZ densities vary from 0.0 CFZ per meter, in the wells where no CFZ has been identified through the flowmeter measurements, up to 1.5 CFZ per meter in the transition zone, in the wells where 3 CFZ were detected (IFPs 6, 7, 8, 17, 21; Table 1).

While injection tests investigate the full range of global hydraulic conductivities (6×10^{-8} m/s up to 3×10^{-3} m/s), flowmeter tests could only be performed in the wells with a global hydraulic conductivity higher than 5.0×10^{-7} m/s. Thus, there is a lack of information for the nine low-conductivity wells. Consequently, the densities of CFZ computed from flowmeter measurements are estimated from a biased data set. It is thus proposed to range the CFZ densities for each of the three layers (Table 2). As the nine low-permeability wells -where no flowmeter test could be performed-

are not taken into account in the computation, the following estimates of CFZ density for the three layers lead to overestimates: 0.20 m^{-1} for the laminated layer, 0.70 m^{-1} for the 'transition zone' and 0.17 m^{-1} for the rest of the fissured layer (Table 2). On the other hand, considering that the nine low permeability wells do not intersect any conductive fissure (e.g., assuming a nil density in these wells) leads to underestimates of CFZ density for the three layers: 0.11 m^{-1} for the laminated layer, 0.49 m^{-1} for the transition zone and 0.20 m^{-1} for the rest of the fissured layer (Table 2). These two estimations allow to range the density of CFZ in each layers. Then, ranges of the vertical persistence (e.g., the distance between two consecutive fissures, equals to the inverse of the density) can also be computed: 5.0–9.1 m for the laminated layer, 1.4–2.0 m for the transition zone and 5.0–5.9 m for the rest of the fissured layer (Table 2). Thus, it clearly appears that both the laminated layer

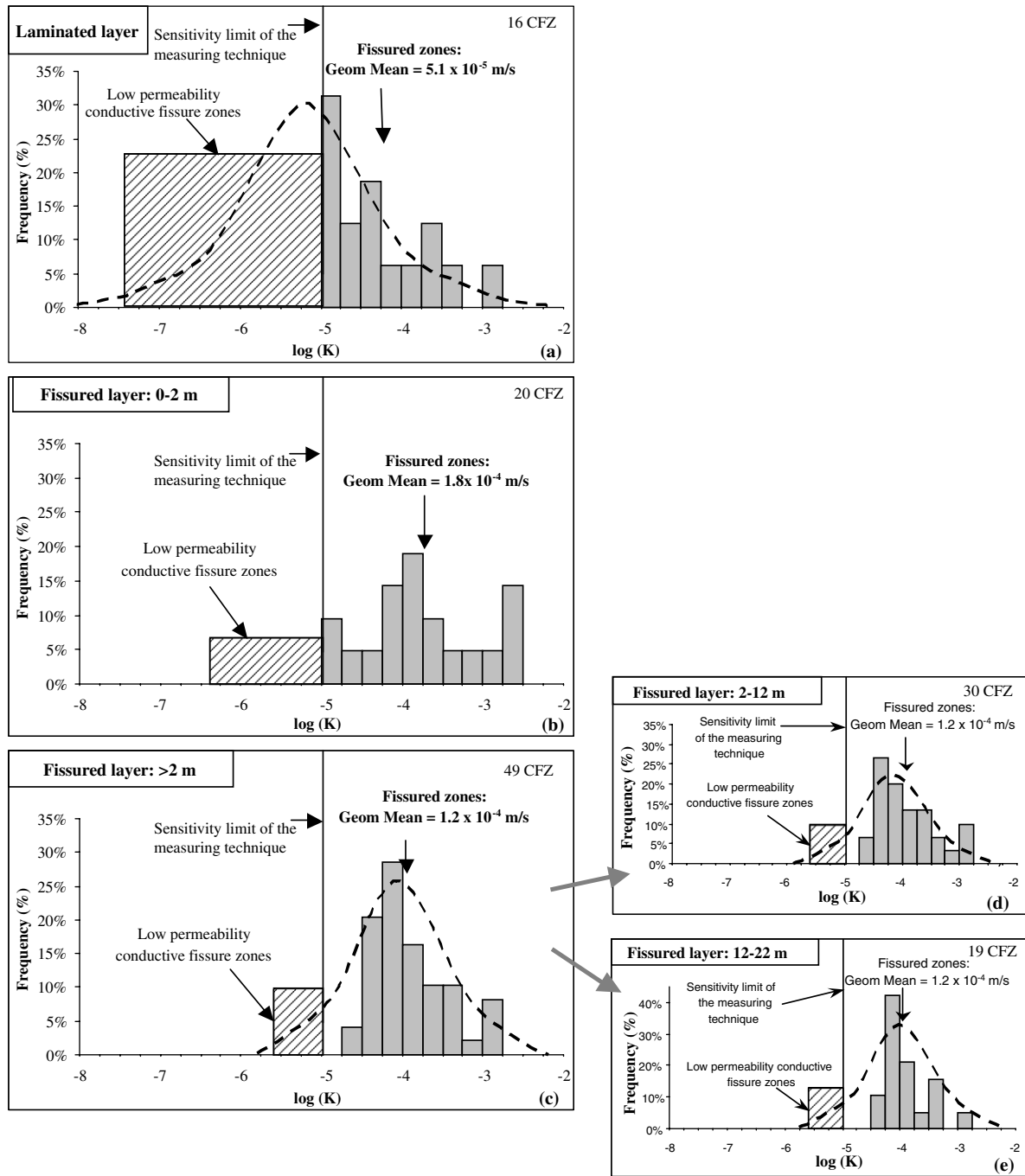


Figure 12 Logarithmic histogram of hydraulic conductivity in 0.5-m-thick fissure zones into the weathered-fissured layers. (a) The laminated layer, (b) the first 2 m of the fissured layer ('Transition Zone'), (c) the deeper fissured layer (>2 m, 2–22 m), (d) 2–12 m deeper fissured layer of the deeper fissured layer and (e) 12–22 m of the deeper fissured layer.

and the deeper part of the fissured layer (>2 m) are characterized by a quite similar density of conductive fissures, while the 'transition zone' is significantly more fissured.

Equivalent hydraulic conductivity of the different weathered layers. Given the statistical distributions of both CFZ densities and their hydraulic conductivities (Fig. 12), the equivalent hydraulic conductivity, K_{eq} , of each layer was computed as follows for each layer constituting the aquifer (Table 3):

$$K_{eq} = \frac{(d_f B_{layer}) K_{CFZ} e_j}{B_{layer}} = d_f K_{CFZ} e_j$$

where d_f is density of CFZs in the considered layer, B_{layer} is thickness of the layer and K_{CFZ} is CFZ hydraulic conductivity (geometrical mean) of the considered layer, e_j is thickness of the CFZ layer (0.5 m, see Section 'Methodology').

The CFZ densities (median of the intervals computed here above; Table 2) and the geometrical mean of the CFZ hydraulic conductivity of each layer, i.e. 0.16 m^{-1} and

Table 2 Estimation of the density of conductive fissures zone for the different weathering layer: laminated layer, transition zone (0–2 m of the fissured layer) and the rest of the fissured layer (>2 m)

Weathered layer	Density of CFZ [1/m]		Medium CFZ density ^a [1/m]
	Mean on wells where flowmeter tests were performed (19 wells)	Including the wells where no flowmeter tests could be performed (19 + 9 wells)	
Laminated layer	0.20	0.11	0.16
Transition zone (0–2 m of the fissured layer)	0.70	0.49	0.59
Rest of the fissured layer (>2 m)	0.17	0.20	0.19

^a The medium CFZ density corresponds to the mean of the interval.

Table 3 Estimation of the mean hydraulic conductivities (equivalent K) of the three different layers

Weathered layer	Layer thickness [m]	K_{CFZ} – geomean [m/s]	K_{CFZ} – geomean of the lowest conductive CFZ (30% of data) [m/s]	K_{CFZ} – geomean of the more conductive CFZ (30% of data) [m/s]	Interval of confidence (%) ^a	Equivalent K [m/s]
Laminated layer	10–15	5.1×10^{-5}	1.3×10^{-5}	3.0×10^{-4}	75	4.0×10^{-6} (7.3×10^{-7} to 3.0×10^{-5})
Transition zone (2 first metres of the fissured layer)	2	1.8×10^{-4}	2.9×10^{-5}	1.3×10^{-3}	74	5.3×10^{-5} (7.1×10^{-6} – 4.6×10^{-4})
Rest of the fissured layer (>2 m)	13–18	1.2×10^{-4}	4.1×10^{-5}	4.9×10^{-4}	86	1.1×10^{-5} (4.3×10^{-6} – 4.2×10^{-5})

Calculations use the density of CFZ of each layer, their corresponding hydraulic conductivity (K_{CFZ} -geomean) and the mean thickness of each layer. Values between brackets give the variability of the mean hydraulic conductivity; more than 75% of confidence. For each layer, these extreme values integrate the variability of the CFZ densities (see Table 2), and the geometrical means of the lowest conductive CFZ and the more conductive CFZ. geomean: geometrical mean.

^a Correspond to the percentage of CFZ used in the calculation.

5.1×10^{-5} m/s for the laminated layer, 0.59 m^{-1} and 1.8×10^{-4} m/s for the transition zone, and 0.19 m^{-1} and 1.2×10^{-4} m/s for the deeper part of the fissured layer, are used for this computation. The computed equivalent hydraulic conductivities are: 4.0×10^{-6} m/s for the laminated layer, 5.3×10^{-5} m/s for the transition zone and 1.1×10^{-5} m/s for the deeper part of the fissured layer.

In order to take into account the variability of CFZ hydraulic conductivity in each layer (Table 3, Fig. 12), the maximum and minimum equivalent hydraulic conductivities of the three weathered layers have been computed. The maximum hydraulic conductivities have been computed from the maximum CFZ densities and the geometrical means of the 30% more conductive CFZ of each layer. The minimum hydraulic conductivities have been computed from the lowest CFZ densities and the geometrical means of the 30% less conductive CFZ. Regardless of the layer, such a ranging process leads to a consideration of the interval within which more than 75% of the CFZ hydraulic conductivities are distributed; it also means that the interval of confidence for the range of equivalent hydraulic conductivities of the three layers is at least equal to 75%. Thus the intervals of equivalent hydraulic conductivities computed as described are: 7.3×10^{-7} to 3.0×10^{-5} m/s for the laminated

layer, 7.1×10^{-6} to 4.6×10^{-4} m/s for the transition zone and 4.3×10^{-6} to 4.2×10^{-5} m/s for the deeper part of the fissured layer (Fig. 13).

These computed equivalent hydraulic conductivities (mean value and intervals) show that the 'transition zone', due to its high density of CFZ and fairly good CFZ hydraulic conductivity, is the most conductive layer, whereas the laminated one is the less conductive.

In order to be able to compare these results with previous works performed in similar granitic terrain (Fig. 13, Tables 4 and 5), the global hydraulic conductivity of the entire fissured layer was also computed. The obtained value, 1.6×10^{-5} m/s, is very close to the one deduced from pumping tests in the same geological formation: 5×10^{-5} m/s (south India [Hyderabad]; Rushton and Weller, 1985) and 2×10^{-5} m/s as an average on the Maheshwaram catchment (Maréchal et al., 2004). This corroborates the approach used to estimate the global hydraulic conductivity of the different layers using data from flowmeter tests. The hydraulic conductivity of the fissured layer, as computed in the present study, is in the range of various fissured layers in India and Africa (Fig. 13, Table 5), even if, within most of these previous studies, the authors did not link the estimated hydrodynamic parameters to such weathering layers.

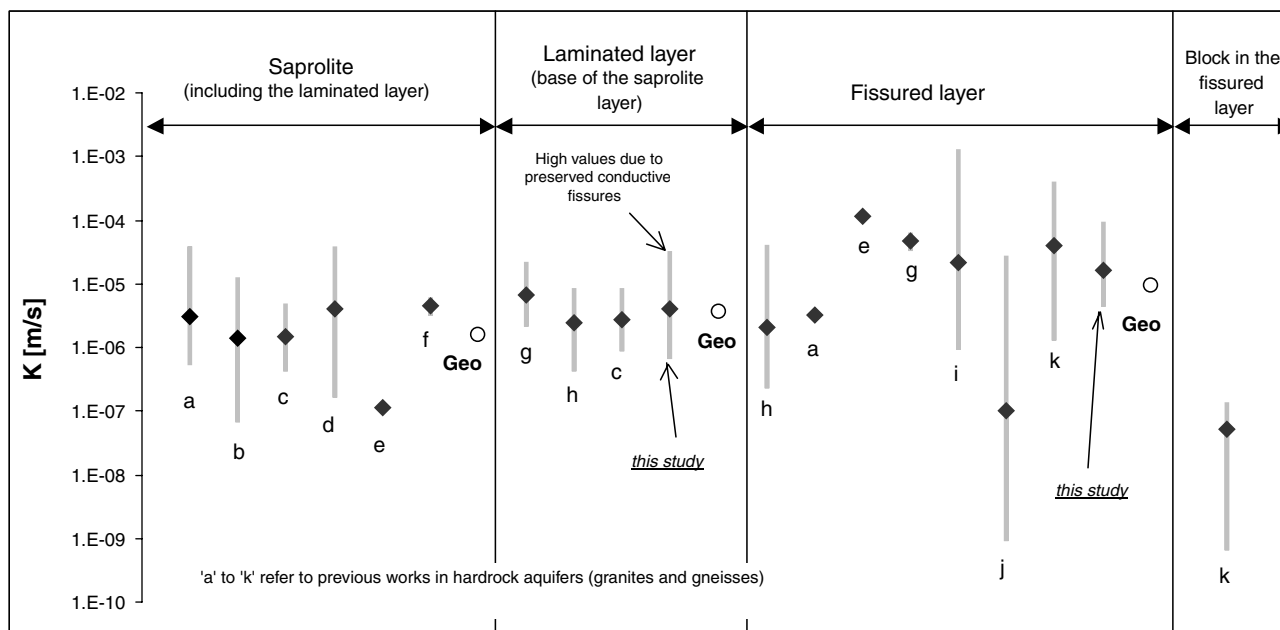


Figure 13 Hydraulic conductivity of the saprolite and the fissured layer in hard-rock (from Tables 5 and 6); the black circles denote the geometrical means and the vertical bars the variability of measurements for each study. a: Houston and Lewis (1988), b: Compaore et al. (1997), c: McFarlane (1992), d: Wright (1992), e: Jones (1985), f: Rushton and Weller (1985), g: Chilton and Smith-Carington (1984), h: Taylor and Howard (2000), i: Maréchal et al. (2004), j: Howard et al. (1992), k: Uhl and Sharma (1978). Geo (open circle): geometrical mean of each layer: entire saprolite layer: 2×10^{-6} m/s, laminated layer (base of the saprolite layer): 3×10^{-6} m/s, fissured layer: 9×10^{-6} m/s and block within the fissured layer: 5×10^{-8} m/s.

It suggests that the different weathering phases (multiphase process) at Maheshwaram do not induce a significant change in global permeability of the fissured layer.

Furthermore, the computed global hydraulic conductivity of the laminated layer, 4.0×10^{-6} m/s, is very similar to the one found by Rushton and Weller (1985) [pumping test in granitic aquifer, Hyderabad, south India]: 5.0×10^{-6} m/s. This value is similar to the one of other laminated layers (base of saprolite) studied in Africa (Fig. 13; Table 4), where no conductive fissures were described. However, where numerous preserved fissures are present, as in the Maheshwaram catchment, the hydraulic conductivity of this layer increases up to more than 10^{-5} m/s (Table 3), transforming this layer into a non-negligible transmissive zone. Such low hydraulic conductivities of the saprolite layer confirm the works carried out for other regions of the world (e.g. Chilton and Smith-Carington, 1984). The low permeability of the saprolite aquifer provides yields only enough sufficient for handpumps or large diameter wells (dugwells) benefiting from a capacitive effect (more than 400 dugwells within the Maheshwaram catchment).

Discussion

Generally, in hard-rock areas (granites, gneisses, etc.), the weathering profile (including its fissured layer), where not eroded, may constitute up to the first 100 metres below the ground surface (Detay et al., 1989) and is composed of thick stratiform layers (Wyns et al., 1999): mainly the saprolite and the fissured layer. In fact, the deepest profiles are around 100 m thick, thinner profiles are mainly due to

the young profile or to the erosion of a former profile. This study confirms the importance of such layers from a hydrogeological point of view. Thus, the structure of the weathering profiles governs the vertical and spatial structure of hard rock aquifers and their hydrodynamic properties.

The comparison of the characteristics of the Maheshwaram aquifer, resulting from a multiphase weathering process, with the ones of aquifers where the landscape mainly results only from a single main weathering phase (Chilton and Foster, 1995; Chilton and Smith-Carington, 1984; Jones, 1985; Acworth, 1987; McFarlane, 1992; Wright, 1992; Compaore et al., 1997; Wyns et al., 1999, 2004, etc.), leads to a generalized 3-D geological and hydrogeological conceptual model of granitic aquifers (Fig. 14). This can be different for other hard rock aquifer, e.g. see Dewandel et al., 2005 for the hydrogeological model of ophiolite hard rock aquifers.

Structure of the aquifer

The structure of the Maheshwaram weathering profile appears to result from a multiphase weathering process, controlled by the geodynamic history of the Indian Peninsula, producing alternate weathering and erosion phases (Fig. 9). As compared to classical single phase weathering profiles (Fig. 1, Wyns et al., 1999), this multiphase weathering profile indicates some differences:

- the total thickness of the weathering profile in Maheshwaram (25–40 m) is thinner than the one of a complete, mature (a few tens of millions years old), single phase

Table 4 Geometrical mean of hydraulic conductivity of the saprolite layer for hard-rock aquifers, the values between brackets correspond to the minimum and the maximum values

References	Geology and location	Hydraulic conductivity of the saprolite layer in [m/s]		No. of tests	Methods
		Unconsolidated saprolite	Laminated layer (base of the layer)		
Taylor and Howard (2000)	Granite Uganda		2×10^{-6} (5×10^{-7} to 8×10^{-6})	6	Slug tests
Chilton and Smith-Carington (1984)	H-R Malawi		7×10^{-6} (2×10^{-6} to 2×10^{-5})	7	Pumping tests
Houston and Lewis (1988)	Granite Victoria Province	3×10^{-6} (6×10^{-7} to 4×10^{-5})		64	Pumping tests
Compaore et al. (1997)	Granite Burkina Faso	1×10^{-6} (7×10^{-8} to 1×10^{-5})		8	Pumping tests
Wright (1992)	H-R Africa	4×10^{-6} (2×10^{-7} to 4×10^{-5})		6	Pumping tests
Jones, 1985	H-R Africa	up to 1×10^{-6}		<i>u/k</i>	Pumping tests
Rushton and Weller (1985)	Granite India		5×10^{-6} (4×10^{-6} to 6×10^{-6})	3	Pumping tests
McFarlane (1992)	H-R Malawi	5×10^{-7} to 5×10^{-6}	3×10^{-6} (9×10^{-7} to 8×10^{-6})	12	Pumping tests
This study	Granite India		4×10^{-6} (7×10^{-7} to 3×10^{-5})	28	Flowmeter tests

Note that most of the available data provides data on the entire saprolite layer only. H-R: various hard-rock; mainly granite and gneiss. *u/k*: unknown data.

Table 5 Geometrical mean of hydraulic conductivity of the fissured layer for hard-rock aquifers, the values between brackets correspond to the minimum and the maximum values

References	Geology and location	<i>K</i> of the fissured layer [m/s]	<i>K</i> of the block into the fissured layer [m/s]	No. of tests	Methods
Taylor and Howard (2000)	Granite Uganda	2×10^{-6} (3×10^{-7} to 4×10^{-5})	<i>u/k</i>	11	Packers tests
Houston and Lewis (1988)	Granite Victoria Province	3×10^{-6}	<i>u/k</i>	60	Pumping tests
Jones (1985)	H-R Africa	up to 1×10^{-4}	<i>u/k</i>	<i>u/k</i>	Pumping tests
Maréchal et al. (2004)	Granite India ^a	2×10^{-5} (1×10^{-6} to 1×10^{-3})	5×10^{-8} (7×10^{-10} to 1×10^{-7})	10	Pumping tests
Rushton and Weller (1985)	Granite India	5×10^{-5} (4×10^{-5} to 6×10^{-5})	<i>u/k</i>	3	Pumping tests
Howard et al. (1992)	H-R Uganda	1×10^{-7} (1×10^{-9} to 3×10^{-5})	<i>u/k</i>	22	Packers tests
Uhl and Sharma (1978)	H-R India	4×10^{-5} (1×10^{-6} to 4×10^{-4})	<i>u/k</i>	100	Pumping tests
This study	Granite India	2×10^{-5} (5×10^{-6} to 9×10^{-5})	<i>u/k</i>	28	Flowmeter tests

Note that most of the available data provides data on the entire saprolite layer only. H-R: various hard-rock; mainly granite and gneiss. *u/k*: unknown data.

^a Same location than this study.

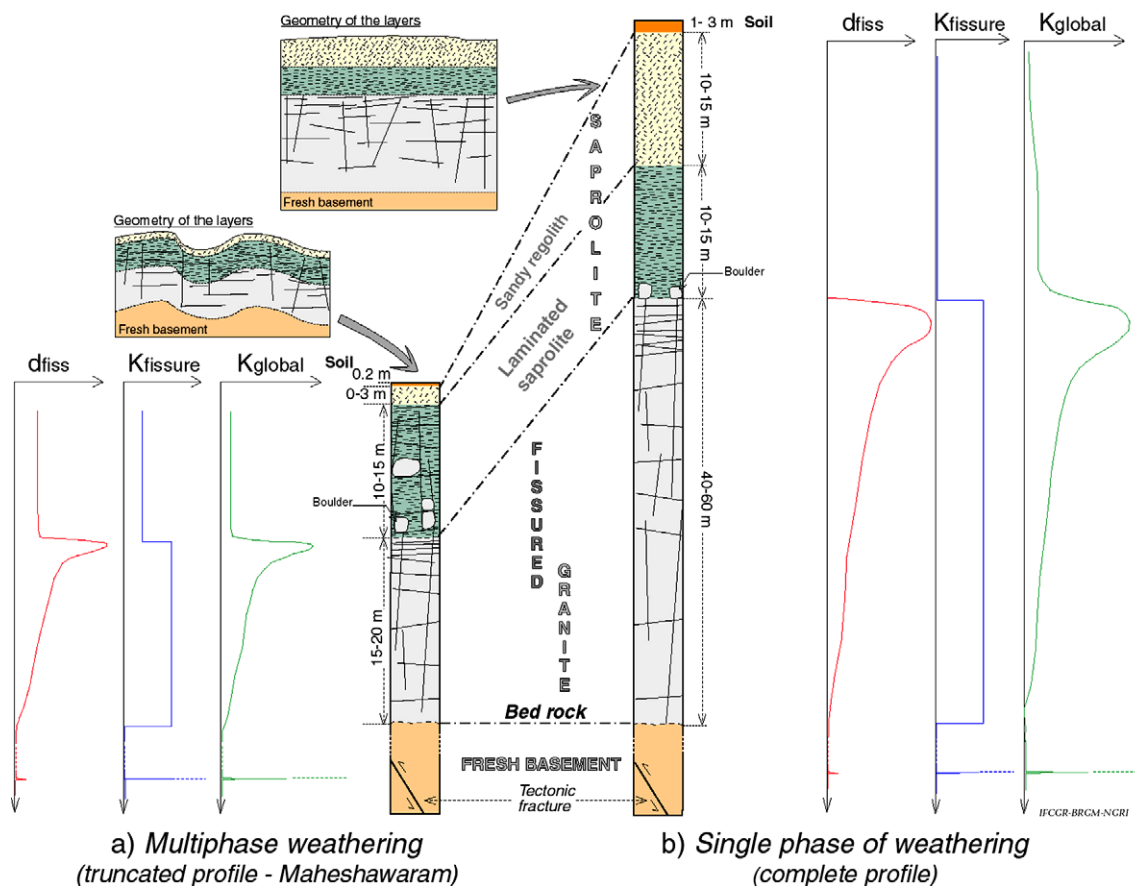


Figure 14 Generalized 3-D geological and hydrogeological conceptual model of granite aquifers controlled by single or multiphase weathering. (a) Maheshawaram profile – multiphase weathering (b) classical profile – single weathering (idealized profile). d_{fiss} : density of conductive fissures, K_{fiss} : hydraulic conductivity of fissures and K_{global} : equivalent hydraulic conductivity of the layer.

weathering profile (usually up to 100 m). However, the total thickness of a weathering profile depends on the duration of the weathering and of the lithology of the parent rock. At Maheshwaram, the erosion reduced the total profile thickness. The later phase(s) of weathering was(were) not long enough to completely rejuvenate the weathering profile,

- both saprolite and fissured layers more or less follow the current topography, which leads to a quite constant thickness at the watershed scale and not to stratiform subhorizontal layers,
- in Maheshwaram, the thickness of the fissured layer is similar to that of the saprolite whereas, in the case of single weathering, the thickness of the fissured layer is about twice that of the saprolite, which is itself subdivided in two equivalent layers in thickness, namely laminated layer and sandy regolith. The atypical Maheshwaram weathering profile is due to the fact that the current saprolite, mainly composed of laminated granite, developed under alternate erosion and weathering phases at the expense of an ancient fissured layer. These ‘unstable’ tectonic conditions also explain the unusual preservation of fissures within the saprolite, which appear to be relicts of the ancient fissured zone. The Maheshwaram fissured layer is thus mainly a relict of this older weathering profile.

Hydrodynamic properties of the different layers of the weathering profile

The different layers of the weathering profile of hard rocks make up a composite aquifer where hydrodynamic properties are an aggregation of the respective hydrodynamic properties of each layer. The properties of the laterite layer of the weathering profiles is not described here after as it has not been characterized in the frame of this research. Usually, it is a high permeability zone where it has not been transformed by the weathering process.

The saprolite

The saprolite layer of granite-type rocks (granites, gneisses, etc.) is generally characterized by a sandy-clay or clayey-sandy composition. It is usually assimilated to porous medium (Acworth, 1987; Wright, 1992; Compaore et al., 1997). The hydraulic conductivity of the entire saprolite layer is highly variable; the available data, from measurements performed in wells, range between 1×10^{-7} and 3×10^{-5} m/s (geometrical mean: 2×10^{-6} m/s; see Fig. 13 and Tables 5 and 6 for the source of data). The hydraulic conductivity closely depends on the content in clay-rich materials, which itself depends both on the mineralogical composition of the parent rock and on the degree of weathering, thus on the

considered location within the weathering profile (Jones, 1985; Acworth, 1987; Barker et al., 1992; Chilton and Foster, 1995). As a consequence, the hydraulic conductivity generally decreases towards the top of the saprolite layer (Fig. 14).

The total porosity is relatively high, up to about 10%, even more (Compaore et al., 1997; Wyns et al., 1999, 2004; White et al., 2001; Begonha and Braga, 2002). Nevertheless, as clayey materials are characterized by small pore sizes the effective porosity is only a few percent (0.5–10%; Bodelle and Margat, 1980; Compaore et al., 1997; Wyns et al., 2004).

The base of the saprolite layer is characterized by a sand-size clast texture, described by a horizontally laminated structure in granitic rocks. From available data on wells, this layer shows a hydraulic conductivity ranging between 5×10^{-7} and 3×10^{-5} m/s (geometrical mean: 3×10^{-6} m/s). It thus appears to be the more permeable level of the saprolite in the weathering profiles derived from single phase as well as multiphase weathering processes (Fig. 14). Given its laminated structure, this layer should not be strictly considered as an isotropic medium; nevertheless no quantitative data on its anisotropy of hydraulic conductivity is actually available.

Where a multiphase weathering process is responsible of the weathering profile, the laminated layer can comprise several preserved fissures (up to 0.20 m^{-1} in density) of significant hydraulic conductivity (5×10^{-5} m/s in average); Fig. 14. These fissures are inherited from the previous fissured layer. They contribute to increase both the global hydraulic conductivity of the layer, up to 3×10^{-5} m/s, and the anisotropy of the medium, making up in Maheshwaram a 10–15-m-thick anisotropic and transmissive layer where the flow is controlled by both pore and fissure hydraulic conductivity. Due to the closing and filling with clay-rich materials (swelling clays), the hydraulic conductivity of these fissures is less than that of the fissures in the fissured layer. Moreover, it is probable that the density and hydraulic conductivity of these inherited fissures, and thus the hydraulic conductivity of this layer, decrease towards the top of the layer, since fissures are progressively filled up by clayey minerals and thus obliterated by the weathering process (Fig. 14).

The fissured layer

The hydrodynamic properties of the underlying fissured layer are 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 and heterogeneous medium. It is the most permeable layer of the entire weathering profile and assumes most of the transmissive function of the aquifer.

Available data from wells show that the global hydraulic conductivity of the fissured layer is highly variable from one place to another. It ranges between 1×10^{-9} m/s, where the considered well does not intersect any conductive fissure, and 1×10^{-3} m/s, where the well intersects several conductive fissure zones (geometrical mean: 1×10^{-5} m/s, Fig. 13). Moreover, the global hydraulic conductivity of this layer appears to be a result of the number of conductive

fissures intersected by the considered well, and not the result of a higher hydraulic conductivity of a single (or more) conductive fissure (Maréchal et al., 2004). Indeed, the hydraulic conductivity of the conductive fissure zones belonging to this layer is relatively similar regardless of the case study location in the world (Fig. 13); it ranges between 10^{-6} and 10^{-4} m/s. Thus, it appears that granitic rocks exposed to weathering are affected by similar weathering processes that induce similar fissure hydraulic conductivities. Distribution of CFZ hydraulic conductivities presented in Fig. 11c and 12b and c can be considered as representative for granite aquifers (geometrical mean: 2×10^{-4} m/s).

As the hydraulic conductivity of this layer closely depends on the density of the conductive fissures, the variations in hydraulic conductivity from one well to another are explained by the variability in fissure density itself and not by the variability of fissure hydraulic conductivity. The present study confirms that the hydraulic conductivity of the fissures does not significantly decrease with the depth (Fig. 12b–e). The apparent decrease in hydraulic conductivity toward the base of this layer, largely observed worldwide, reflects only a downward decrease in density of the weathering-induced fissures (Fig. 14).

The presence of two main fissure sets, a horizontal and a subvertical one (Fig. 14), recognized both from geological observations and from pumping test interpretation (Maréchal et al., 2004), ensures good connectivity between the fissures and induces an anisotropy of hydraulic conductivity. In the same studied granite aquifer, Rushton and Weller (1985) and Maréchal et al. (2003a,b, 2004) founded a vertical anisotropy ratio close to 10 ($K_{\text{horiz}} \gg K_{\text{vert}}$), which is in agreement with the qualitative geological observations (Fig. 4).

The effective porosity of the fissured layer is relatively low, about 10^{-2} , and is mainly (90%) ensured by the low permeability fissure zones affecting the blocks (block permeability, including very low permeability fissure zones: 5×10^{-8} m/s, in this area), while the conductive fissure network contributes only 10% to the effective porosity (Maréchal et al., 2003b, 2004).

The top of the fissured layer is characterized by a few metres-thick high density fissured zone (Houston and Lewis, 1988; Howard et al., 1992; Cho et al., 2003; Wyns et al., 2004), named here the 'transition zone' (density: $0.7\text{--}0.5 \text{ m}^{-1}$); Fig. 14. This zone, 2-m-thick in the case of the young rejuvenated weathering profile studied in Maheshwaram, can reach more than 12 m in the case of old thick weathering profiles (French Brittany, Wyns et al., 2004). The hydraulic conductivity of the fissures belonging to this transition zone is comparable to that of the deeper part of the fissured layer. This 'transition zone' is the more permeable point of the fissured zone, thus of the entire weathering profile.

The underlying unfissured and fresh basement is permeable only locally, where tectonic fractures are present. Their hydraulic properties are highly variable (Pickens et al., 1987; Blomqvist, 1990; Walker et al., 2001; Kuusela-Lahtinen et al., 2003; Cho et al., 2003), and flows can be fractionalised, i.e. controlled by the fracture network orientation (Leveinen et al., 1998). They have been extensively studied, particularly in the frame of nuclear waste storage projects.

Conclusion

The classical geological and hydrogeological model of weathered granite-type rocks has been extended to the specific context of hard-rock having been exposed to multiphase weathering and erosion processes. The hydrodynamic properties of the various layers constituting such a weathering profile have been separately characterized and compared.

In granite-type rocks, single weathering or multiphase weathering and erosion processes induce similar geological structures: from top to bottom, the laterite, the saprolite that comprises a laminated layer within its lower part, and the fissured layer that directly covers the unweathered basement. A few main geological differences arise from the comparison of single phase and multiphase weathering profiles (Fig. 14): (i) in the later, the respective thicknesses of the various layers can be deeply modified, (ii) the ancient fissured layer can be re-weathered, and the resulting new laminated layer may contain quite well preserved and conductive ancient fissures, and (iii) the upper part of the fissured layer is more densely fissured.

As a result of the same weathering processes, the fissures from the fissured layer of single phase or multi-phase profiles exhibit very similar hydraulic conductivities, and show both a higher density of conductive fissures at the top of the layer. The preserved ancient fissures within the laminated layer of a multiphase profile are partly obliterated by the recent weathering; their hydraulic conductivity is thus significantly reduced. Nevertheless, they do significantly contribute to the borewell yield.

The spatial distribution of such weathering profiles (single or multiphase), or their remains, can be mapped at the catchment scale (it is now economically feasible for areas of 10–1000 km²) on the basis of various types of data: digital elevation model, observations on outcrops, drilling cuttings, geophysical measurements. Thus, 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 appears to be a prerequisite for groundwater management in hard-rock areas. It 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 the piezometric level fluctuations in the various layers (Maréchal et al., in press), (iii) input data for numerical modelling in the aquifer, (iv) elaboration of vulnerability maps, (v) guidelines for aquifer protection, for town and country planning (siting of land-fill, quarry), etc.

Such a geological and hydrogeological model now requires to be adapted to the geological contexts of weathered metamorphic rocks. The mapping methodology is also to be developed for applications at a larger scale, 1000–10,000 km², through the integration of modern techniques such as remote sensing and, spectrometric and radiometric aerial surveys.

Acknowledgements

This study has been carried out at the Indo-French Centre for Groundwater Research (BRGM-NGRI). The authors wish to thank the French Ministry of External Affairs and the Embassy in India Cooperation and Cultural Service for their support and the funding of missions of French scientists. The Indo-French Centre for Groundwater Research has also benefited from CNRS funding within the framework of the ACI Program "Water and Environment" and from funding from the IFCPAR (Indo-French Centre for the Promotion of Advanced Research). The authors are grateful to the two reviewers for their fruitful comments and remarks. This paper has benefited from the research assistance provided by Géraud Bournet, Jean-Baptiste Charlier, and Mohamed Wajiduddin.

References

- Acworth, R.I., 1987. The development of crystalline basement aquifers in a tropical environment. *Quarterly Journal of Engineering Geology* 20, 265–272.
- Babu, P.V.L.P., 1975. A study of cyclic erosion surfaces and sedimentary unconformities in the Cauvery basin – South India. *Journal of Geological Society of India* 16, 349–353.
- Barker, R.D., White, C.C., Houston, J.F.T., 1992. Borehole siting in an African accelerated drought relief project. In: Wright, E.P., Burgess, W.G. (Eds.), *Hydrogeology of Crystalline Basement Aquifers in Africa*, vol. 66. Geological Society Special Publication, London, pp. 183–201.
- Begonha, A., Braga, M.A.S., 2002. Weathering of the Oporto granite: geotechnical and physical properties. *Catena* 49, 57–76.
- Blomqvist, R.G., 1990. Deep groundwater in the crystalline basement in Finland, with implications for waste disposal studies. *Geologiska Föreningen i Stockholm Föreläsningar* 112 (4), 369–374.
- Bodelle, J., Margat, J., 1980. *L'eau souterraine en France* (Ground Water in France, in French), Masson, Paris, p. 208.
- Briz-Kishore, B.H., 1993. Assessment of yield characteristics of granitic aquifers in South India. *Ground Water* 31 (6), 921–928.
- Chigira, M., 2001. Micro-sheeting of granite and its relationship with landsliding specially after the heavy rainstorm in June 1999, Hiroshima Prefecture, Japan. *Engineering Geology* 59, 219–231.
- Chilton, P.J., Foster, S.S.D., 1995. Hydrogeological characterization and water-supply potential of basement aquifers in tropical Africa. *Hydrogeology Journal* 3 (1), 36–49.
- Chilton, P.J., Smith-Carington, A.K., 1984. Characteristics of the weathered basement aquifer in Malawi in relation to rural water supplies. *Challenges in African Hydrology and Water Resources*. In: *Proc. Harare Symposium*, July 1984, pp. 57–72.
- Cho, M., Ha, K-M., Choi, Y-S., Kee, W-S., Lachassagne, P., Wyns, R., 2003. Relationship between the permeability of hard-rock aquifers and their weathered cover based on geological and hydrogeological observation in South Korea. In: *IAH Conference on "Groundwater in fractured rocks*, Prague 15–19 September 2003, Prague.
- Cleaves, E.T., 1993. Climatic impact on isovolumetric weathering of a coarsed-grained schist in the northern Piedmont Province of the central Atlantic states. *Geomorphology* 8, 1991–1998.
- Compaore, G., Lachassagne, P., Pointet, T., Travi, Y., 1997. Evaluation du stock d'eau des altérites. *Expérimentation sur le site granitique de Sanon* (Burkina-Faso). In: *Rabat IASH Conference*, IASH, vol. 241, pp. 37–46.
- Davis, S.N., Turk, L.J., 1964. Optimum depth of wells in crystalline rocks. *Ground Water* 2 (2), 6–11.

- Detay, M., Poyet, P., Emsellem, Y., Bernardi, A., Aubrac, G., 1989. Development of the saprolite reservoir and its state of saturation: influence on the hydrodynamic characteristics of drillings in crystalline basement (in French). *Compptes Rendus de l'Académie des Sciences de Paris II* 309, 429–436.
- Dewandel, B., Lachassagne, P., Ladouche, B., Pinault, J.L., Al-Malki, A., 2005. A conceptual model of the structure and functioning of the Oman ophiolite hard-rock aquifer through a pluridisciplinary and multiscale approach. *Hydrogeology Journal* 13, 708–726.
- Drew, L.J., Schuenemeyer, J.H., Armstrong, T.R., Sutphin, D.M., 2001. Initial yield to depth relation for water wells drilled into crystalline bedrock – Pinardville Quadrangle, New Hampshire. *Ground Water* 39 (5), 676–684.
- Dupuit, J., 1848, 1863. *Etudes théoriques et pratiques sur le mouvement des eaux dans les canaux découverts et à travers les terrains perméables*, 1st and 2nd Ed. Dunod, Paris.
- Eggler, D.H., Larson, E.E., Bradley, W.C., 1969. Granites, gneisses and the Sherman erosion surface, Southern Laramie Range, Colorado, Wyoming. *American Journal of Sciences* 267, 510–522.
- Eswaran, H., Bin, W.C., 1978. A study of deep weathering profile on granite in peninsular Malaysia: I. Physico-chemical and micro-morphological properties. *Journal of Soil Science Society of America* 42, 144–149.
- Foster, S.S.D., 1984. African groundwater development – the challenges for hydrological science. *IAHS Publication* 144, 3–12.
- Gardner, L.R., 1980. Mobilization of Al and Ti during weathering-iso-volumetric geochemical evidence. *Chemical Geology* 30, 151–165.
- G.I.S., 2002. Geological Survey of India. Geological map: Hyderabad quadrangle, Andhra Pradesh.
- Gustafson, G., Krásný, J., 1994. Crystalline rock aquifers: their occurrence, use and importance. *Applied Hydrogeology* 2, 64–75.
- Houston, J.F.T., Lewis, R.T., 1988. The Victoria Province drought relief project, II. Borehole yield relationships. *Ground Water* 26 (4), 418–426.
- Howard, K.W.F., Hughes, M., Charlesworth, D.L., Ngobi, G., 1992. Hydrogeologic evaluation of fracture permeability in crystalline basement aquifers of Uganda. *Applied Hydrogeology* 1, 55–65.
- Jones, M.J., 1985. The weathered zone aquifers of the basement complex areas of Africa. *Quarterly Journal of Engineering* London 18, 35–46.
- Jupp, E., Vozoff, K., 1975. Stable iterative methods for the inversion of geophysical data, *Geophys. Journal of the Royal Astronomical Society*, 957–976.
- Krishnamurthy, N.S., Kumar, D., Negi, B.C., Jain, S.C., Ahmed, S., 2002. Resistivity investigations for identifying fractured aquifers in a granitic terrain. In: *Proceeding of Int. Conf. on Hydrology and Watershed Management*, 18–20/12/02, Hyderabad.
- Krishnamurthy, N.S., Kumar, D., Rao, V.A., Jain, S.C., Ahmed, S., 2003. Comparison of surface and subsurface geophysical investigations in delineating fracture zones. *Current Sciences* 84 (9), 1242–1246.
- Kumar, D., Ahmed, S., Krishnamurthy, N.S., Dewandel, B., in press. Application of geostatistics in reducing ambiguities in vertical electrical sounding interpretations. *Applied Geophysics*.
- Kuusela-Lahtinen, A., Niemi, A., Luukkonen, A., 2003. Flow dimension as an indicator of hydraulic behaviour in site characterization of fractured rock. *Ground Water* 41 (3), 33–341.
- Lachassagne, P., Wyns, R., Bérard, P., Bruel, T., Chéry, L., Coutand, T., Desprats, J.F., Le Strat, P., 2001. Exploitation of high-yield in hard-rock aquifers: Downscaling methodology combining GIS and multicriteria analysis to delineate field prospecting zones. *Ground Water* 39 (4), 568–581.
- Ledger, E.B., Rowe, M.W., 1980. Release of uranium from granitic rocks during in situ weathering and initial erosion (central Texas). *Chemical Geology* 29, 227–248.
- Leveinen, J., Rönkä, E., Tikkanen, J., Karro, E., 1998. Fractional flow dimensions and hydraulic properties of a fracture-zone aquifer, Leppävirta, Finland. *Hydrogeology Journal* 6, 327–340.
- McFarlane, M.J., 1992. Groundwater movement and water chemistry associated with weathering profiles of the African surface in Malawi. In: Wright, E.P., Burgess, W.G. (Eds.), *Hydrogeology of Crystalline Basement Aquifers in Africa*, vol. 66. Geological Society Special Publication, London, pp. 101–129.
- Maréchal, J.C., Wyns, R., Lachassagne, P., Subrahmanyam, K., Touchard, F., 2003a. Anisotropie verticale de la perméabilité de l'horizon fissuré des aquifères de socle : concordance avec la structure géologique des profils d'altération. *C.R. Geoscience* 335, 451–460.
- Maréchal, J.C., Dewandel, B., Subrahmanyam, K., Torri, R., 2003b. Review of Specific Methods for the Evaluation of Hydraulic Properties in Fractured Hard-rock Aquifers. *Current Science* 85 (4), 516.
- Maréchal, J.C., Dewandel, B., Subrahmanyam, K., 2004. Contribution of hydraulic tests at different scales to characterize fracture network properties in the weathered-fissured layer of a hard rock aquifers. *Water Resources Research* 40, W11508.
- Maréchal, J.C., Dewandel, B., Ahmed, S., Galeazzi, L., Zaidi, F.K., in press. Combined estimation of specific yield and natural recharge in a semi-arid groundwater basin with irrigated agriculture. *Journal of Hydrology*, in press, doi:10.1016/j.jhydrol.2006.02.022.
- Molz, F.J., Morin, R.H., Hess, A.E., Melville, J.G., Guven, O., 1989. The impeller meter for measuring aquifer permeability variations: evaluation and comparison with other tests. *Water Resources Research* 25 (7), 1677–1683.
- Nahon, D.B., 1991. *Introduction to the Petrology of Soils and Chemical Weather*. Wiley.
- Ollier, C., 1984. *Weathering*, second ed. Longman, London, 270 pp.
- Peltier, L.C., 1950. The geographic cycle in periglacial regions as it is related to climatic geomorphology. *Annals of the Associations of American Geographers* 40, 214–236.
- Pickens, J.F., Grisak, G.E., Avis, J.D., Belanger, D.W., Thury, M., 1987. Analysis and interpretation of borehole hydraulic tests in deep boreholes; principles model development, and applications. *Water Resources Research* 23 (7), 1341–1375.
- Pye, K., 1986. Mineralogical and textural controls on the weathering of granitoids rocks. *Catena* 13, 47–57.
- Radakrishna, B.P., 1993. Neogene uplift and geomorphic rejuvenation of the Indian Peninsula. *Current Science* 64, 787–793.
- Rushton, K.R., Weller, J., 1985. Response to pumping test of a weathered-fractured granite aquifer. *Journal of Hydrology* 80, 299–309.
- Schaeffer, C., Dalrymple, V., Dalrymple, J., 1995. Landscape evolution in Roraima, North Amazonia. *Zeitschrift Fur Geomorphology* 39, 1–28.
- Sharma, A., Rajamani, V., 2000. Weathering of gneissic rocks in the upper reaches of Cauvery river, south India: implications to neotectonics of the region. *Chemical Geology* 166, 203–233.
- Tardy, Y., 1971. Characterization of the principal weathering types by the geochemistry of waters from some European and African crystalline massifs. *Chemical Geology* 7, 253–271.
- Tardy, Y., 1993. *Pétrologie des latérites et des sols tropicaux*. Masson, Paris, 459 pp.
- Tardy, Y., 1998. *Dérive des continents, latérites et paléoclimats tropicaux*. BRGM, Orléans, 472 pp.
- Taylor, R., Howard, K., 1998. Post-Palaeozoic evolution of weathered lands in Uganda by tectonically controlled deep weathering and stripping. *Geomorphology* 25 (3–4), 173–192.
- Taylor, R., Howard, K., 2000. A tectono-geomorphic model of the hydrogeology of deeply weathered crystalline rock: evidence from Uganda. *Hydrogeology Journal* 8 (3), 279–294.
- Thomas, M.F., 1965. An approach of the problems of landform analysis in tropical environments. In: Whittow, J.B., Woods, P.D.

- (Eds.), 2004, *Essays in geography for Austin Miller*. Univ. of Reading, Reading, pp. 118–143.
- Uhl, V.W., Sharma, G.K., 1978. Results of pumping tests in crystalline-rock aquifers. *Ground Water* 16 (3), 192–203.
- Vaidyanadhan, R., 1977. Recent advances in geomorphic studies of Peninsular India: a review. *Indian Journal of Earth Sciences*, 13–35, S. Rav Volume.
- Valdiya, K.S., 1998. Late Quaternary movements and landscape rejuvenation in Southern Karnataka and adjoining Tamil Nadu in southern Indian Shield. *Journal of Geological Society of India* 51, 139–166.
- Walker, D.D., Gylling, B., Strom, A., Selroos, J.O., 2001. Hydrogeologic studies for nuclear-waste disposal in Sweden. *Hydrogeology Journal* 9 (5), 419–431.
- White, C.C., Houston, J.F.T., Barker, R.D., 1988. The Victoria Province Drought Relief Project. I. Geophysical siting of boreholes. *Ground Water* 26 (3), 309–316.
- White, A.F., Bullen, T.D., Schulz, M.S., Blum, A.E., Huntington, T.G., Peters, N.E., 2001. Differential rates of feldspar weathering in granitic regoliths. *Geochemica and Cosmochemica Acta* 65 (6), 847–869.
- Wright, E.P., 1992. The hydrogeology of crystalline basement aquifers in Africa. In: Wright, E.P., Burgess, W. (Eds.), *Hydrogeology of crystalline basement aquifers in Africa*, vol. 66. London Special Publication, pp. 1–27.
- Wyns, R., 1991. Use of continental paleosurfaces for thematic probability mapping (in French). *Géologie de la France* 1991 (3), 3–9.
- Wyns, R., Gourry, J.-C., Baltassat, J.-M., Lebert, F., 1999. Caractérisation multiparamètres des horizons de subsurface (0–100 m) en contexte de socle altéré. In: I. BRGM, IRD, UPMC (Eds.), *2ème Colloque GEOFCAN*, Orléans, France, pp. 105–110.
- Wyns, R., Baltassat, J.M., Lachassagne, P., Legchenko, A., Vairon, J., Mathieu, F., 2004. Application of SNMR soundings for groundwater reserves mapping in weathered basement rocks (Brittany, France). *Bulletin de la Société Géologique de France* 175 (1), 21–34.