

Characterization and location of the laminated layer within hard rock weathering profiles from electrical resistivity tomography: implications for water well siting



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Abstract: This research aims to quantify the geophysical signature of the laminated layer, one of the main layers constituting the weathering profile of hard rocks. This laminated layer acts as a marker for locating the underlying groundwater productive stratiform fractured layer (SFL). The study is based at two sites on the interpretation of 50 km of electrical resistivity tomography (ERT) profiles, compared with outcrops and boreholes by geophysical modelling. For the first time, the geophysical signature of the laminated layer, located at the base of the saprolite, is characterized within granite formations. Where the stratiform weathered layer is detected by pole-dipole ERT profiles, the laminated layer is identified as a resistant layer on 90% of the SFL length using an appropriate inversion method. In addition, this layer is also revealed for the first time in certain types of metamorphic formations; here it is revealed in micaschists (62% of the SFL length). The location of the laminated layer in the weathering profile is important (1) for water well siting by determining if an underlying SFL exists in the weathering profile and (2) for assessing the residual thickness of the saprolite, and then evaluating water storage and the protection of the SFL aquifer.

Supplementary material: A table presenting the ERT profiles used in this study, with the type of array and inversion method, the inversion parameters (RMSE and number of iterations), and the length of the inverted profiles where the laminated layer (LL) and the stratiform fractured layer (SFL) are identified is available <https://doi.org/10.6084/m9.figshare.c.4088768>

It is now widely acknowledged that the permeability of hard rock aquifers (plutonic and metamorphic rocks) is related to weathering processes that, in particular, result in the development of a permeable stratiform fractured layer (SFL) (e.g. see [Lachassagne & Wyns 2001](#); [Lachassagne et al. 2011, 2014](#)). These weathering processes result in the development of stratiform superficial layers, several tens of metres thick; these layers are described ([Dewandel et al. 2006](#)) from top to bottom ([Fig. 1](#)) as follows.

The iron or bauxitic crust, which may be absent ([Lachassagne et al. 2014](#)). Where preserved from

erosion, small local aquifers may appear in it subsequent to intense rainfall events ('epikarstic'-type springs). This weathering profile unit in particular is hydrogeologically functional in high-rainfall areas such as those with wet tropical climates.

The unconsolidated alterite or saprolite ([Wyns et al. 1999](#)), generally rich in clay, comes from the advanced weathering of the parent rock. Two subunits are clearly visible, from top to bottom. (a) The alloterites represent the most clay-rich upper layer (long-duration mineralogical weathering of the parent rock). The structure of the parent rock is

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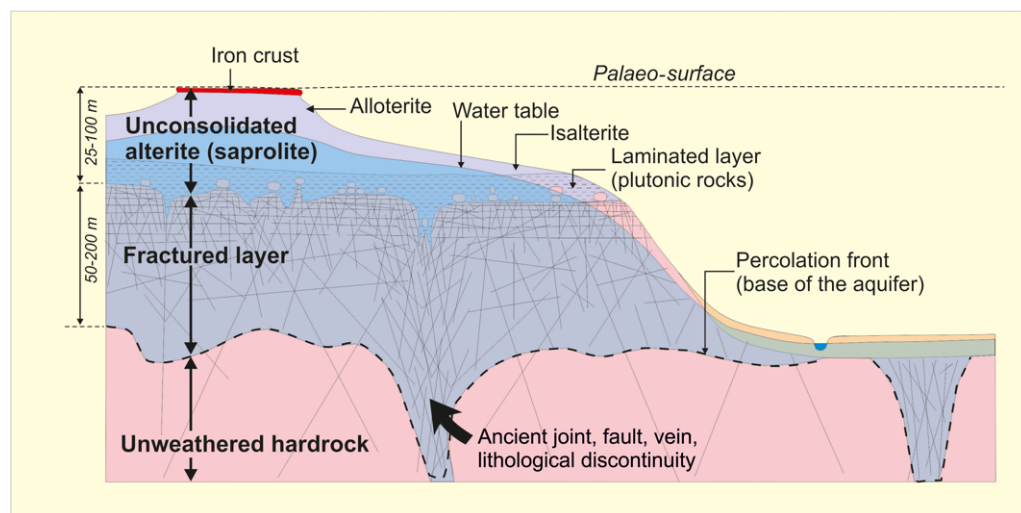


Fig. 1. Conceptual model of a partly eroded palaeo-weathering profile on hard rocks (from Lachassagne *et al.* 2014, modified).

not visible in this unit, which also shows a rock volume reduction due to powerful subtractive-type weathering (leaching of the chemical constituents of the rock). (b) The parent rock structure in the underlying isalterites is preserved with little or no volume change. In the granitic hard rock environment, the base of these isalterites very often shows a laminated layer of thickness 15 m to more than 30 m (Dewandel *et al.* 2006). This layer represents the highly weathered parent rock with a coarse sand-size clast texture and a millimetre-scale dense horizontal lamination cross-cutting the biggest minerals (e.g. porphyritic feldspars). Detailed pictures of the laminated layer (LL), at various scales, are available in Dewandel *et al.* (2006). This laminated structure is due to the multiplication of the number of subhorizontal fractures (tension cracks) at the top of the fractured layer, combined with an important increase in volume of the rock due to biotite swelling (Wyns *et al.* 2015).

Saprolite (alloterites and isalterites) is not very permeable, with an average hydraulic conductivity of $c. 10^{-6} \text{ m s}^{-1}$. The estimated hydraulic conductivity of the laminated layer is $<10^{-7} \text{ m s}^{-1}$ (Boisson *et al.* 2015), down to 10^{-9} to 10^{-8} m s^{-1} (Dewandel *et al.* 2017b). The whole saprolite, when saturated, plays a capacitive role on the overall scale of the weathering profile aquifer because of its high porosity (1–30%).

The SFL or fractured layer in Figure 1 (Wyns *et al.* 1999; Lachassagne *et al.* 2014) is characterized by a dense network of fractures in the first metres. The fracturing density, and therefore the permeability of the formation, then decreases with depth (Maréchal *et al.* 2004; Dewandel *et al.* 2006). The

SFL is also anisotropic (Maréchal *et al.* 2003); its drainage porosity is about 0.5% on average with a partition between blocks and clogged fractures (90%) and permeable fractures (10%) (Maréchal *et al.* 2002, 2004; Lachassagne *et al.* 2014). The SFL has a mainly transmissive function within the overall composite aquifer (SFL + saprolite).

On a catchment scale, and for water resource applications, the underlying *unweathered hard rock* can be regarded as impervious and as having very low storativity (Maréchal *et al.* 2004). Subvertical structures are permeable locally. They facilitate the downwards spread of supergene weathering along pre-existing structures (lithologic contacts, various veins, joints, former faults; Dewandel *et al.* 2011).

In a hard rock environment, water wells were formerly sited by looking for permeable tectonic fractures (e.g. see Lachassagne *et al.* 2011, 2014 for a review of the concepts and Lachassagne *et al.* 2001 and Reddy *et al.* 2006 for 'tectonic' fracture survey methods). The demonstration of the hydrodynamic role played by the whole SFL, no more a discrete fracture hard to identify but a thick horizon, has proven subsoil imaging in this type of environment is generally complex, particularly when surveying groundwater (Wyns *et al.* 2004; Dewandel *et al.* 2011; Lachassagne *et al.* 2011). Many biases may influence imaging results in these areas qualified as discontinuous in 2D, or even 3D. These biases further limit the validity of 1D methods (Alle *et al.* 2018) which, for technical reasons and cost-effectiveness, were nevertheless still used until recent years. Seismic methods are rarely used in this context mainly because of their cost, even if

they appear to give a relatively clear picture of the constitutive layers of the weathering profile such as the saprolite and SFL (St. Clair *et al.* 2015; Dewandel *et al.* 2017b). Electrical tomography methods are used much more and are particularly well suited because (1) they provide a 2D or 3D view of structures and (2) there is a correlation (significant vertical resistivity contrasts, with resistivities varying between a few and several hundred ohm-metres) between geophysical facies and weathering profile facies, or weathering index (e.g. Braun *et al.* 2009). In particular, electric tomography methods enable (i) certain saprolite constitutive layers (alloterites, isalterites) to be identified from their resistivity pattern, (ii) characterizing the reduction in the SFL fracturing with depth (increase of the resistivity) and (iii) showing vertical deepening of weathering along vein side walls, joints or various types of contacts. However, no objective criterion currently helps to identify areas where the SFL is potentially the most productive (permeability and/or thickness) or even where it is present (not eroded or unsaturated). The weathering profile is actually most often described as more conductive layers (a few to hundreds of ohm-metres) than the underlying unweathered parent rock (several thousands of ohm-metres). Nevertheless, its constitutive layers present distinctive geological and hydrogeological characteristics, and we demonstrate in this paper that the laminated layer can be identified and appear as more resistive than the overlying saprolite and the underlying SFL. For the first time, the concept of laminated layer is linked with an electrically resistant horizon.

A few studies have described such an increased-resistance horizon within the more conductive weathered zone of hard rock aquifers. For instance, Guihéneuf *et al.* (2014) provide an ERT profile of the weathering profile of Indian granites (Nalgonda district, Andhra Pradesh). The ERT only shows a regular gradient from the saprolite ($<500 \Omega \text{ m}$) to the SFL and the unweathered granite ($>3500 \Omega \text{ m}$). No resistive anomaly is identified in the saprolite. Wubda *et al.* (2017) performed resistivity logging along a weathering profile on granites in Burkina-Faso (Dangalé pond area). The resistivity in the fractured layer increases from about $100 \Omega \text{ m}$ to more than several hundred ohm-metres (bottom of the well). The resistivity of the saprolite decreases to c. $25 \Omega \text{ m}$ but does not exhibit any resistive layer or anomaly. Francés *et al.* (2014) provide similar results from weathered granites in Spain. The resistivity regularly increases from $<15 \Omega \text{ m}$ in the saprolite to more than several hundred ohm-metres in the SFL (again, the unsaturated zone is more resistant). Only one ERT profile (GB) among eight locally shows a SFL with a lower resistivity (c. $200 \Omega \text{ m}$) than the overlying saprolite (a few hundred ohm-metres). Braun *et al.* (2009) also image a resistivity

gradient in Indian gneisses from $<20 \Omega \text{ m}$ in the saprolite to several thousand ohm-metres in the unweathered rocks. They do not identify a resistive layer at the bottom of the saprolite.

However, Comte *et al.* (2012) clearly identified such a resistant horizon at the top of the more conductive fractured zone in Ireland using ERT. In some profiles on gneisses, they demonstrated that the superficial resistive layer is imaging the unsaturated saprolite or the unsaturated SFL. However, in schistoid formations, they identify a c. $1000 \Omega \text{ m}$ resistive layer up to 20 m thick at the top of the few hundred ohm-metres 20–60 m thick SFL. They interpreted this as a layer of ‘clay-leached broken schists’.

Alle *et al.* (2018) do not specifically identify the laminated layer in their geological cross-sections; however, from electrical logging performed in wells drilled in migmatitic gneisses in Benin, they show that the saprolite resistivity ranges over $100\text{--}400 \Omega \text{ m}$ and the SFL over $200\text{--}5000 \Omega \text{ m}$. There is clearly an overlap of resistivity values between the SFL and the overlying saprolite. Moreover, on some logs (boreholes 3 and 1), the bottom of the saprolite (the laminated layer?) has a higher resistivity ($200 \Omega \text{ m}$ on average) than the overlying saprolite (c. $150 \Omega \text{ m}$) and a similar resistivity than the underlying upper part of the SFL (c. $200 \Omega \text{ m}$). Statistically however, this configuration appears as relatively rare within this dataset of six experimental sites within various rock types from Benin.

From resistivity well logging performed in Indian granites, Dewandel *et al.* (2017b) identify slightly higher resistivity values within the bottom of the LL (c. $100 \Omega \text{ m}$), whereas the upper saprolite and the underlying top of the SFL show rather lower resistivities (c. $50 \Omega \text{ m}$). The resistive anomaly is only a few metres thick, however.

Soro *et al.* (2017) also performed resistivity logging along a weathering profile on migmatites in Burkina-Faso. The logging only begins in the fractured layer where the resistivity decreases to c. $70 \Omega \text{ m}$, a rather low value. The ERT profiles do not reveal a resistive laminated layer at the bottom of the saprolite, where resistivity decreases to $<50 \Omega \text{ m}$, but only a resistivity gradient within the stratiform fractured layer. The only identified resistive layer in the saprolite is the upper unsaturated iron crust.

Consequently, and to summarize, the existing studies show that the weathering profile is generally described as a saprolite conductive layer with a higher resistivity below, within the SFL, with a regular resistivity gradient (Guihéneuf *et al.* 2014; Soro *et al.* 2017; Wubda *et al.* 2017). The upper unsaturated part of the saprolite is more resistant (Comte *et al.* 2012; Francés *et al.* 2014; Alle *et al.* 2018). However, even if the authors do not describe this in detail, some studies show that the upper part of the saprolite can be less resistant than its lower part

(the laminated layer?) (Alle *et al.* 2018), and that the lower part of the saprolite (the laminated layer?) can be more resistant than the underlying SFL (Comte *et al.* 2012) or at least show a similar resistivity (Soro *et al.* 2017; Alle *et al.* 2018).

As a first conclusion, the specific electrical signature of the bottom of the saprolite (the laminated layer) sometimes appears as a resistive anomaly on some geophysical data, but it has never been characterized in detail. This research aims to quantify the geophysical signature of the laminated layer. In fact, it may be particularly useful to identify it as a marker for locating the underlying productive fractured layer, for instance to guide water well siting. This study is based on the interpretation of ERT profiles performed in both granitic and metamorphic hard rock environments, compared with several exploratory boreholes and observations on outcrops. About 50 km of profiles were studied in two different areas (metropolitan France and French Guiana). The profiles performed in metropolitan France (Supplementary Table S1) are performed on weathered hard rocks where a laminated layer was identified from previous field geological surveys.

Material and methods

General methodology

The surveys performed in this study are based on the combination of geological field observations, electrical resistivity tomography (about 50 km of profiles) and exploration drilling. These exploration boreholes are vertical with 203 mm diameter (rotary machine drilling and downhole hammer) or inclined with 114 mm diameter (core sample drilling with water as drilling fluid). They were sited for ground-water resource exploration from interpretations based on the geological context and the geoelectric cross-sections. These exploration boreholes were targeting either the stratiform subhorizontal fractured layer, the subvertical weathered-fracture structures or both. These boreholes have helped define the lithology of both the parent rock and the constitutive layers of the weathering profile (structure, mineralogy, thickness and fracturing). They have also helped to characterize their hydrodynamic properties: (1) with measurements as drilling progresses (flow rate measurements upon blowing in the holes drilled by downhole hammer, pumping tests during temporary drilling downtime periods); and (2) with pumping tests performed upon completion of the drillings.

Geophysical acquisition

ERT profiles were acquired using a Syscal-Pro Switch96 resistivitymeter (Iris Instruments, France)

with 96 metal electrodes regularly spaced 10 m apart over 950 m (Mathieu & Maurice 2016). The 10 m spacing between electrodes was chosen in Saint-Galmier to ensure both appropriate resolution of shallow subsurface resistivity (to characterize the stratiform weathering profile) and a maximum depth of investigation (ERT imaging) of about 250 m with a 950 m length pole-dipole array, the weathering profile in that area reaching a thickness of more than 100 m (Dewandel *et al.* 2017a).

On the Sparouine site, a 5 m spacing between electrodes was chosen to characterize the stratiform weathering profile with an appropriate resolution; it was implemented with a 475 m length dipole-dipole array as only a 80 m depth of investigation was targeted, the weathering profile being thinner in that area than at the previous site.

Electrode contact resistance is generally less than 3 k Ω for all profiles. The acquisition parameters for all the profiles and the different array configurations were: injection time periods, 0.5 s; number of measuring cycles, 3–6 (3 if $Q < 0.5\%$, 6 if $Q > 0.5\%$, where Q the standard deviation on the resistance measurements, a characteristic of repeatability); $Q < 0.5\%$; and injection voltage: 400 V. High Q factor is usually an indication of low signal-to-noise ratio.

The ERT profiles were acquired according to two geometrical arrays: the pole-dipole (PD) and the dipole-dipole (DD). The pole-dipole protocol, with a remote injection electrode, maximizes the signal-to-noise ratio of measurements and increases the exploration depth. The position of the remote electrode was determined in accordance with the recommendations proposed by Razafindratsima & Lataste (2014) to minimize its influence on the resistivity measurements, with a minimal distance of the remote electrode of 1700 m (perpendicular to the ERT profile). By respecting conditions proposed by Razafindratsima & Lataste (2014), the difference between the true geometric factor and approximate geometric factor is not relevant. The dipole-dipole array provides better resolution near the surface (down to a depth of *c.* 20 m) and also particularly of the vertical contacts, but a lower depth of investigation than the PD array because of a faster reduction in the signal-to-noise ratio with depth (Dahlin & Zhou 2004). We define n as the ratio of distance between transmitter dipole and receiver dipole divided by receiver dipole length for the DD array, and the ratio of distance between inline transmitter pole and receiver dipole divided by receiver dipole length for the PD array. Depth of investigation increases with n value. Signal-to-noise (S/N) ratio decreases with n^2 and n^3 with pole-dipole and dipole-dipole arrays, respectively.

The following measurement sequences were used.

- 1941 measurements were carried out with the PD array (96 electrodes, spacing 10 m): from $n = 1$ to 10 with single electrode spacing at receiver; from $n = 5$ to 10 with double electrode spacing at receiver; from $n = 5$ to 10 with quadruple electrode spacing at receiver; and from $n = 5$ to 7 with eight-times electrode spacing at receiver.
- 1636 measurements were carried out with the DD array (96 electrodes, spacing 10 m): from $n = 1$ to 8 with single electrode spacing at receiver; from $n = 4$ to 8 with double electrode spacing at receiver; from $n = 4$ to 8 with quadruple electrode spacing at receiver; and from $n = 4$ to 6 with eight-times electrode spacing at receiver.

After acquisition, the measurements were filtered to remove abnormal values. The raw data from electrical measurements were filtered (through Prosys software, Iris Instruments) on the following criteria: V (signal) > 0.3 mV and $Q < 5\%$. The resulting apparent resistivity data were then processed (correction of inconsistencies, smoothing) with X2IPI software (multi-electrode data processing, Bobachev Alexey, Moscow University; Robain & Bobachev 2004).

Inversion methods

Two-dimensional electrical resistivity inversions, an ill-posed problem (Caterina *et al.* 2014), were performed using Res2Dinv software (Loke & Barker 1996). The aim of the inversion process is the minimization of the objective function, which is the root mean square (RMS) error between modelled and measured resistivities (Loke & Barker 1996). Minimization is obtained with an iterative process where the objective function should decrease. The convergence of the minimization is a mandatory criterion. There is an infinite number of available models fitting the measurements with the same RMS error. It is therefore important to reduce the amount of mathematical solutions to more geologically plausible models by regularizing the inverse problem and incorporating all available prior information in the inversion process. Caterina *et al.* (2014) recommend adding prior information such as structural constraint, which seems to be indicated particularly when the limit is located in zones of low sensitivity for ERT. However, this prior information is usually absent and it is obvious that there is no specific set of parameters giving the 'real' 2D resistivity distribution. It is therefore proposed to carry out various inversions with specific parameters and constraints, such as each inversion imaging is particularly suitable for determining lithological and structural characteristics for the hydrogeological model.

Following this recommendation, after various tests three sets of parameters were selected and used to obtain an optimal convergence of three different solutions (Mathieu and Maurice 2016), a

minimal adjustment error of the model to measurements and a good characterization of the horizontal or vertical structures (Fig. 2).

- Robust or blocky (ROB) parameters are well suited for environments presenting high resistivity contrasts. They minimize the absolute value error and provide clearer boundaries between the various layers. ROB inversion shows more accurate results for determining the weathering profile to unfractured rock boundary.
- Standard parameters with horizontalizing (STDH) minimize the quadratic error and are a smoothed inversion. Combined with an anisotropy factor (filter ratio) of 0.3, this inversion enhances the horizontal structures, such as all the layers constituting the weathering profile (i.e. the subhorizontal stratiform fractured layer and the laminated layer) and also enhances the horizontal continuity of geoelectric layers (Caterina *et al.* 2014).
- Standard parameters with verticalizing (STDV) yields a smoothed inversion which minimizes the quadratic error. Combined with an anisotropy factor (filter ratio) of 2.0, it enhances vertical structures such as ancient faults, veins, etc. (see the introduction) which the weathering progressed subvertically along. Vertical contacts, veins and fracturing resistivity contrasts are enhanced in order to delineate these structural features.

Each selected inversion setting (ROB, STDH and STDV) is used alternatively and gives a specific solution, for example, a 2D electrical resistivity distribution. Advantages and disadvantages of blocky and smooth inversion methods are discussed by Loke *et al.* (2003). Each solution is interpreted independently, and all solutions are compared.

We make the hypothesis that the structures revealed with each solution (different flatness ratios) are considered realistic only if they are evident from the three inversion settings. This process allows the identification of both subhorizontal and subvertical realistic structures.

The resistivity values and geometries are then compared with geological facies to confirm the reality of the structures, particularly those constituting the subhorizontal weathering profile and subvertical structures, based on the exploration boreholes and/or outcrops observations. Inverted DD and PD profiles were interpreted following this comparison. The inverted profiles using the STDV method are mainly used to identify and characterize the vertical resistivity anomalies. The DD and PD inversion models using the STDH methods were mainly used to recognize the subhorizontal resistivity contrasts related to the stratiform weathering profile (Fig. 2).

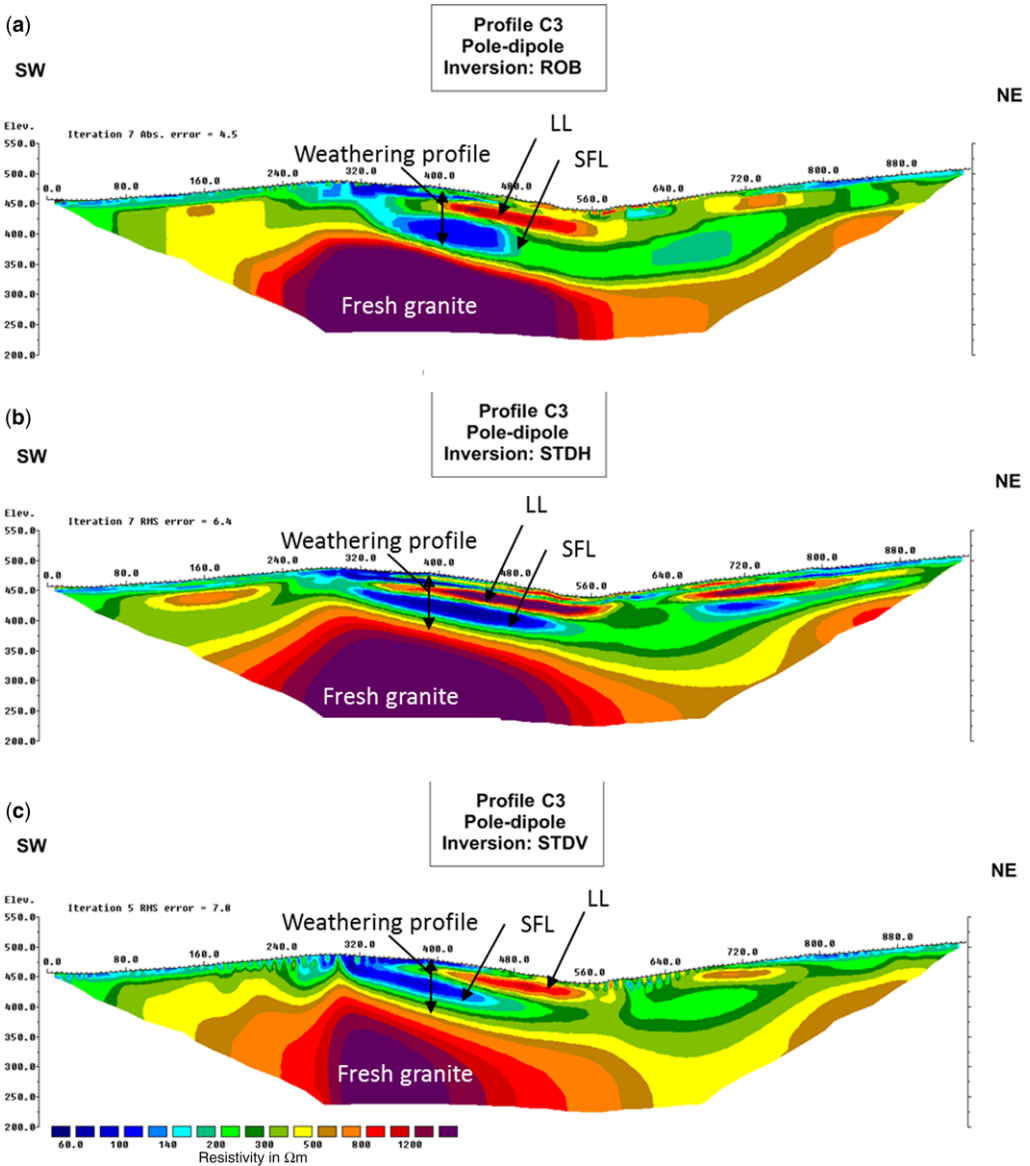


Fig. 2. Example of the C3 profile illustrating the different inversion modes used: pole-dipole acquisition with (a) ROB inversion parameters; (b) STDH inversion parameters; and (c) STDV inversion parameters. Note that the resistive laminated layer is evident by all inversion modes, even where of low thickness and extension (SW part of the profile).

Logically the STDH inversion setting provides the largest extension of the geoelectric horizons contained inside the stratiform weathering profile (Fig. 2). Consequently, the STDH inversion setting is preferentially presented in this study as it mainly deals with the characterization of the horizontal structures (LL, SFL) present in the underground, and not the subvertical structures. For each profile,

the results of the other inversion settings (ROB and STDV) are available in [Supplementary Table S1](#).

Geophysical modelling

Simple forward modelling was performed with Res2DMod software (Loke & Barker 1996) from a theoretical geoelectric cross-section to test how the

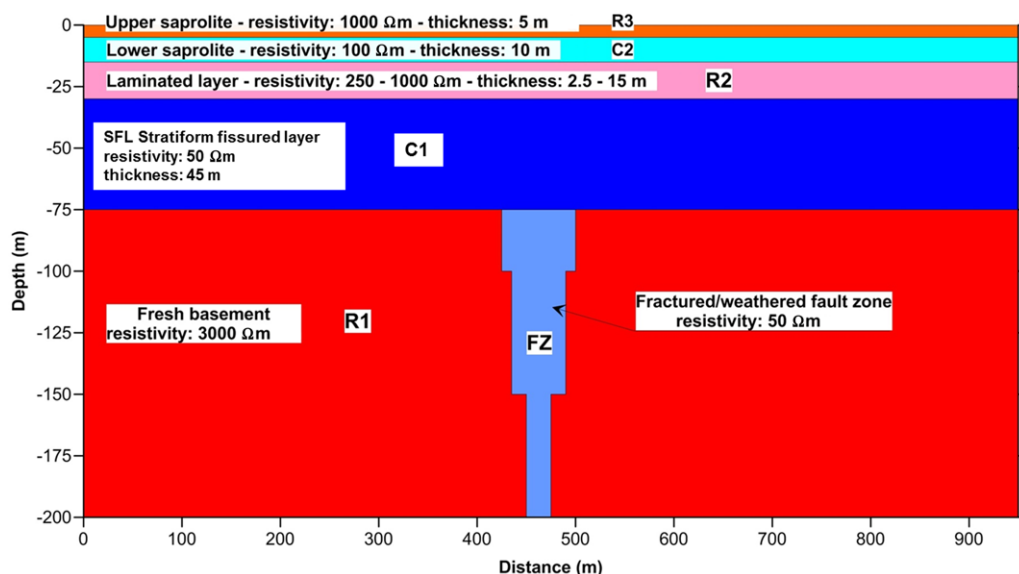


Fig. 3. Theoretical geoelectric cross-section used for geophysical modelling performed with Res2DMod. Sensitivity parameters for resistivity and thickness of the laminated layer were tested, varying the respective values from 250 to 1000 Ω m for the resistivity and from 2.5 to 15 m for the thickness of the laminated layer.

laminated layer parameters influence its ERT imaging, and also how they influence the imaging of the whole hard rock weathering profile. Forward modelling was carried out with a dipole-dipole array, using the measurement sequence described in the section on ‘Geophysical acquisition’. The inversion was performed using Res2DInv software with a dipole-dipole acquisition configuration, a device length of 950 m and an inter-electrode spacing of 5 m. No noise was added in the modelling process.

A resistivity model was developed from typical cross-sections obtained in Saint-Galmier and Sparouine fields (detailed results of this study) with, from the top down (Fig. 3):

- a 5 m thick resistant upper saprolite (e.g. unsaturated zone) with a resistivity of 1000 Ω m;
- a more conductive 10 m thick lower saprolite with a resistivity of 100 Ω m;
- a resistant laminated layer with resistivity of 250–1000 Ω m and a thickness of 2.5–15 m according to the simulations;
- a conductive stratiform fractured layer with a resistivity of 50 Ω m and a thickness of 45 m;
- an unweathered resistant granite with a resistivity of 3000 Ω m forming the base of the model; and
- a vertical zone of fractured/weathered granite with a resistivity of 50 Ω m in the centre part of the geophysical profile.

Theoretical forward models were re-inversed using Res2DInv inversion software with STDH

parameters to assess the influence of the resistivity and the thickness of the laminated layer.

Geological context

Saint-Galmier granite

Badoit’s Natural Mineral Water (NMW) exploitation site (in Saint-Galmier, Loire department, France) is characterized by a granitic hard rock environment (Fig. 4). The Saint-Galmier granite is porphyritic calc-alkaline with biotite. The granite, where weathered at outcrops and in boreholes, exhibits (Dewandel *et al.* 2017a): (1) a thin layer of sandy saprolite, a clay-rich material with coarse sand-size clasts, thinned by Plio-Quaternary erosion; (2) a thick laminated saprolite layer (15 m to >30 m thick), composed of a consolidated highly weathered parent rock with a coarse sand-size clasts texture and a millimetre-scale dense horizontal lamination cross-cutting the largest minerals; and (3) below these a SFL, rarely seen at ground surface but encountered in boreholes, which allows comparison with ERT. This layer is characterized by several sub-horizontal fractured zones with a depth-decreasing density. Some of these fracture zones include weathered materials similar to the sandy saprolite (isalterite).

The area where the Badoit spring historically emerges is located on the eastern edge of the Forez plain, along a normal regional fault in a 170° N

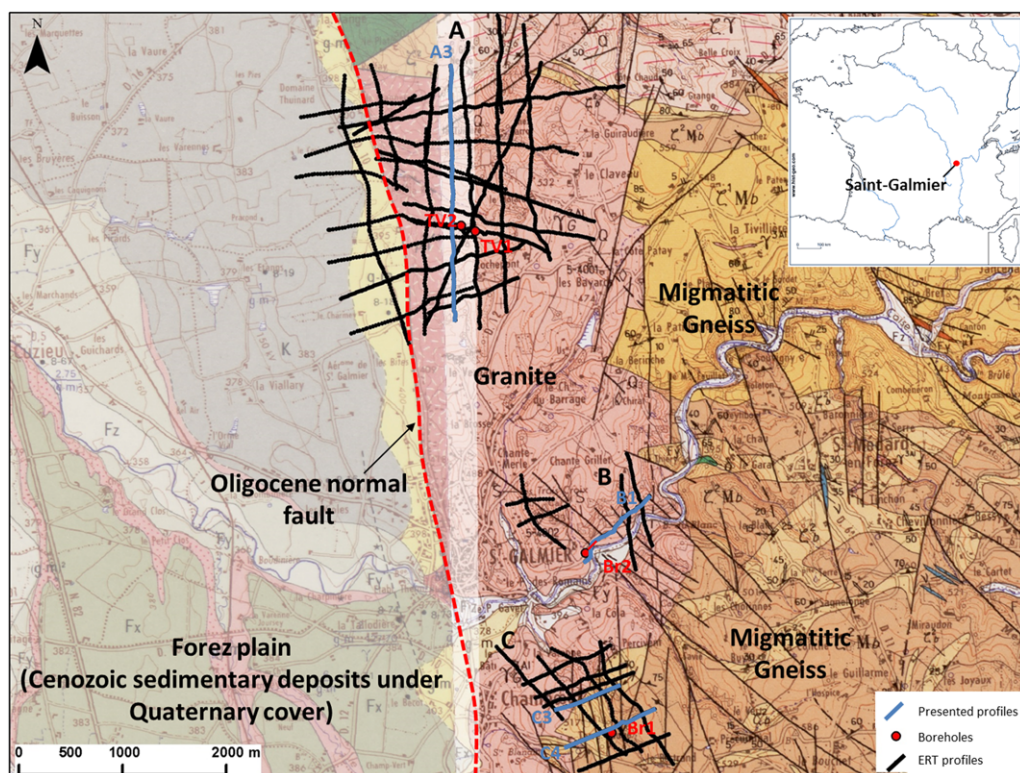


Fig. 4. Location of the ERT profiles on the Saint-Galmier area (bold black lines). This geological map also shows the sediments filling up the Oligocene graben west of the fault and granitic and metamorphic rock to the east. Note that three areas (A, B, C) were surveyed (blank map of France from <http://st.hist-geo.co.uk>; 1/50 000 BRGM geological map from Feybesse *et al.* 1996).

direction affecting this granite ('border' fault) (Fig. 4). This fault is the eastern boundary of a graben dating to the Oligocene period and is filled with fluvio-lacustrine-type continental sediments (Dewandel *et al.* 2017a). The survey areas (geophysical profiles and boreholes used for this project) are located to the east of this normal fault, where the granite and its weathering profile crop out (Fig. 4). As described above, all of this area exhibits a thick laminated layer at the base of the saprolite.

Sparouine micaschists

The second experimental site is located at Sparouine in the NW part of the French Guiana, on the South American continent (Fig. 5). The subsoil of this sector is composed of the Orapu series of shales (Choubert 1960) which, in northern French Guiana, forms a vast synclinorium that crosses the region from west to east. This synclinorium, 75 km wide to the west, is only a few hundred metres wide to the east. The Orapu is transgressive on the rest of

Guiana's rocks, except on the Caribbean Granites that intrude it on the northern half of the synclinorium. Under the local influence of the Caribbean Granites the shales of this formation, whose general metamorphism does not exceed the sericite stage, transform into micaschists with biotite, micaschists with garnet and staurolite, and micaschists with sillimanite or andalusite due to an increase in regional metamorphism and by contact metamorphism.

In the Sparouine area (Fig. 5), the geophysical surveys (Mathieu and Baisset 2015) and exploration boreholes (Brisset *et al.* 2017) were carried out on units of micaschists with garnet and staurolite.

Results

Stratiform weathered profile in a granitic environment (Saint-Galmier)

Most ERT profiles exhibit a similar vertical succession of layers within the weathering profile. The C4 profile is representative of all the profiles; it

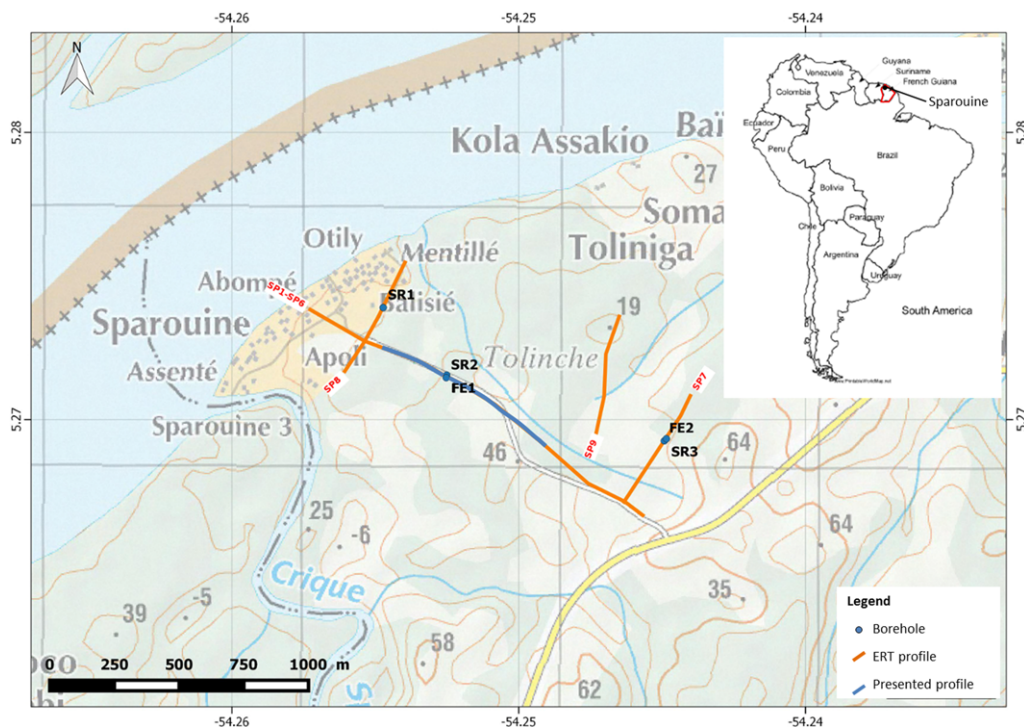


Fig. 5. Location of the ERT profiles and exploration drilling in the Sparouine area (topographic map of Guiana from the French National Institute of Geographic and Forest Information IGN).

reveals a succession of stratiform layers and subhorizontal bodies, with variable resistivity (Fig. 6):

- a conductive multi-metric layer (60–400 Ω m) on the surface 5–15 m thick;
- between less than 15 m (locally) and 30 m on average, a resistant layer (400–600 Ω m) about 10–20 m thick and relatively continuous and homogeneous is detected under the surface conductor;
- at thickness 40–70 m, a more conductive, continuous unit of resistivity of 80–400 Ω m; and
- depths >80 m appear significantly resistant, with (1) resistivity of 600–800 Ω m at the centre of the profile and (2) higher resistivity at both ends of the profile (>1000 Ω m).

The Br1 drilling can be compared with the C4 profile. It is a vertical borehole drilled 197.5 m deep using the downhole hammer (Fig. 6). From top to bottom it cuts through the following layers.

- Highly weathered granite at depths of 0–24 m, matching the upper part of the saprolite (isalterites); these formations are saturated but not very permeable.
- Granite grus containing little clay and locally rich in quartz at 24–36 m depth, more clayey at 36–44 m. It matches the laminated layer due to (1) its

intermediate position between the saprolite and the SFL and (2) knowledge of the weathering profile for this study area having demonstrated the existence of a thick laminated layer (Dewandel *et al.* 2017a). This level is saturated but not permeable in this borehole (no water inflow during drilling).

- ‘Clays’ were described at depths of 36–44 m, attributed to a highly weathered local vertical structure of thickness a few decimetres that has no perceptible influence on the ERT.
- Permeable fractured granitoid at depths 44–80 m. This interval is interpreted as the SFL.
- Unweathered granitoid at depths of 80–200 m with a subvertical fractured zone with permeable fractures at depths of 105–160 m.

The total flow rate upon blowing at the end of drilling is $10 \text{ m}^3 \text{ h}^{-1}$. The productive inflows of water are located (1) in the SFL, at depths of 44–80 m (20% of the total flow rate measured during drilling) and (2) in the unweathered granite fractured at depth along the subvertical discontinuity (80% of the flow rate), cut through between 105 and 160 m. This borehole therefore cuts through a productive SFL under the saturated but low permeability saprolite. The fractured zone cut through at depth is hydrodynamically separated from the SFL according to (1) piezometry:

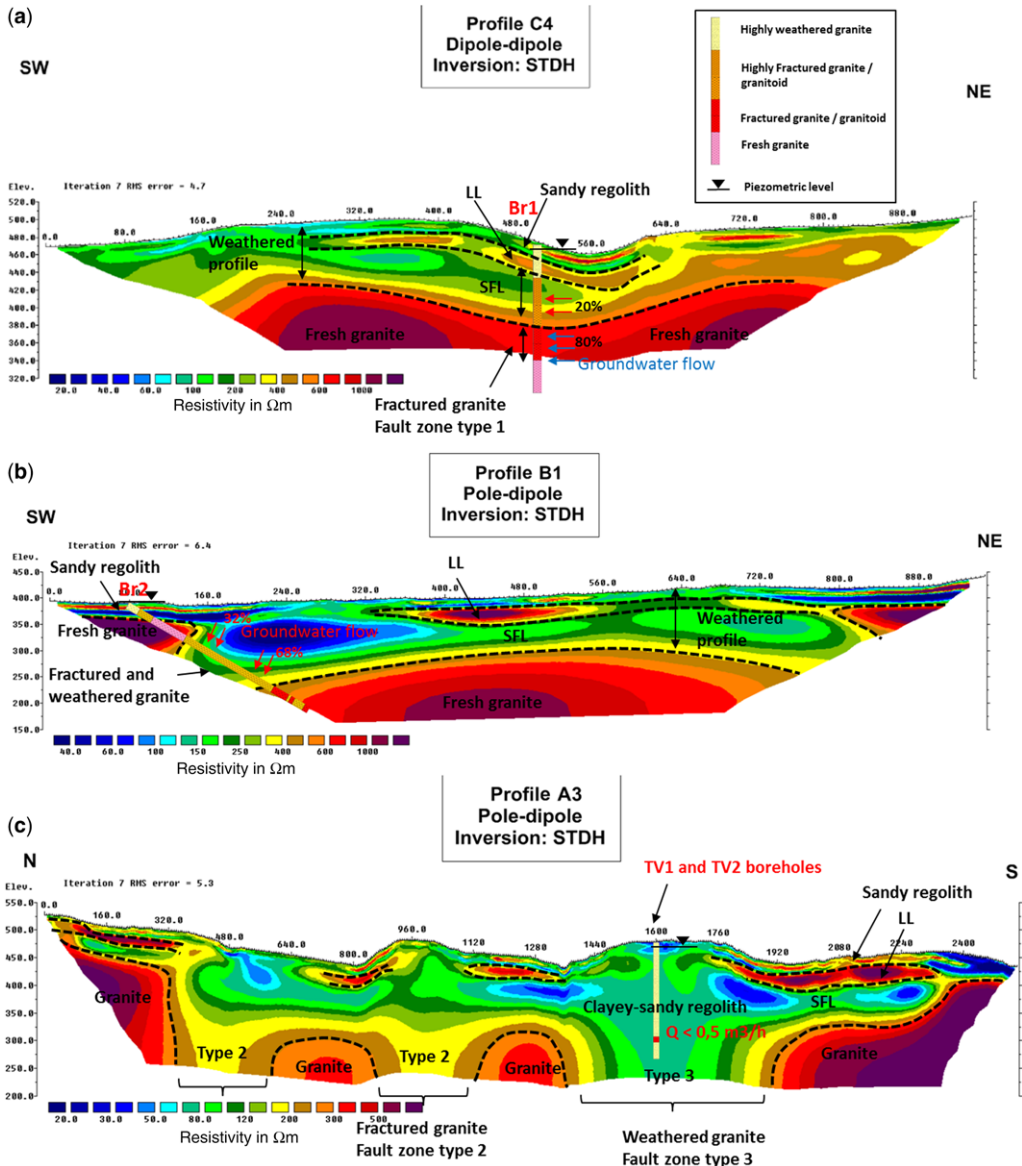


Fig. 6. (a) C4 STDH inversion model compared with the Br1 exploration borehole. (b) STDH inversion model of the A3 profile compared to the TV1 and TV2 exploration boreholes. (c) STDH inversion model of the B1 profile compared to Br2 exploration borehole. C4, A3 and B1 profiles acquired with a pole-dipole array.

hydraulic head difference of 8.7 m between the two aquifer levels (SFL piezometry > deep fracture piezometry); (2) pumping tests, which show very low hydrodynamic interference between the two levels; and (3) hydrochemical analyses, with major differences in hydrochemical signatures including Ca (48.4 mg L^{-1} in the SFL, 24.2 mg L^{-1} in the underlying fractures), Mg (22.7 mg L^{-1} in the SFL, 14 mg L^{-1} in the underlying fractures) and Cl

(12.4 mg L^{-1} in the SFL, 8 mg L^{-1} in the underlying fractures). This geological, hydrodynamic and hydrochemical information is consistent and helps to unambiguously identify a not-quite-eroded stratiform weathering profile locally overlying (at the borehole) a subvertical fractured zone. Information from the C4 profile and the Br1 borehole helps to identify and determine the geophysical

signatures of the various layers of the weathering profile.

- The surface saprolite appears rather conductive (250–400 Ω m) and continuous. Its top is roughly parallel to the morphology of the topographic surface.
- The underlying layer with higher resistivities (400–600 Ω m) and a thickness of 10–20 m is unequivocally attributed to the laminated layer by comparison between the ERT profile and the Br1 borehole. This geoelectric layer is relatively continuous, but shows local thinning or even interruptions. Its resistivity, depth of top and bottom, and thickness, as determined from the ERT data, doesn't significantly change depending on the survey type (PD, DD) or on the inversion method used (Fig. 2). As described in previous studies (see the introduction), this layer is rather narrow compared with the total thickness of the SFL.
- The SFL is quite conductive (250–400 Ω m on C4) with a resistivity gradient (gradient area of varying thickness depending on the type of inversion, e.g. in PD on C4: c. 30 m in ROB and 50 m in STDH). The resistivity within this layer is relatively homogeneous, with a very good lateral continuity. Heterogeneities are only due to subvertical structures (local deepening of the weathering profile), such as between abscises 400 and 700 m of the ERT profile (Fig. 6).
- Deeper down, the fractured unweathered granitoid, probably near a subvertical fracturing zone related to a discontinuity, appears resistant (600–800 Ω m) but not excessively.
- Laterally, the non-fractured unweathered granitoid represents the most resistant units identified along this profile ($R > 1200$ Ω m).

On the scale of all the data acquired in the study area, a stratiform weathering profile is highlighted on 27 km of the 50 km of PD arrays profiles with STDH inversion (Fig. 7a; [Supplementary Table S1](#)). The rest of the profiles are either sited in sedimentary rocks or in areas where at least the entire saprolite, and sometimes part of the underlying SFL, was eroded. Finally, the resistant laminated layer inserted in the weathering profile and

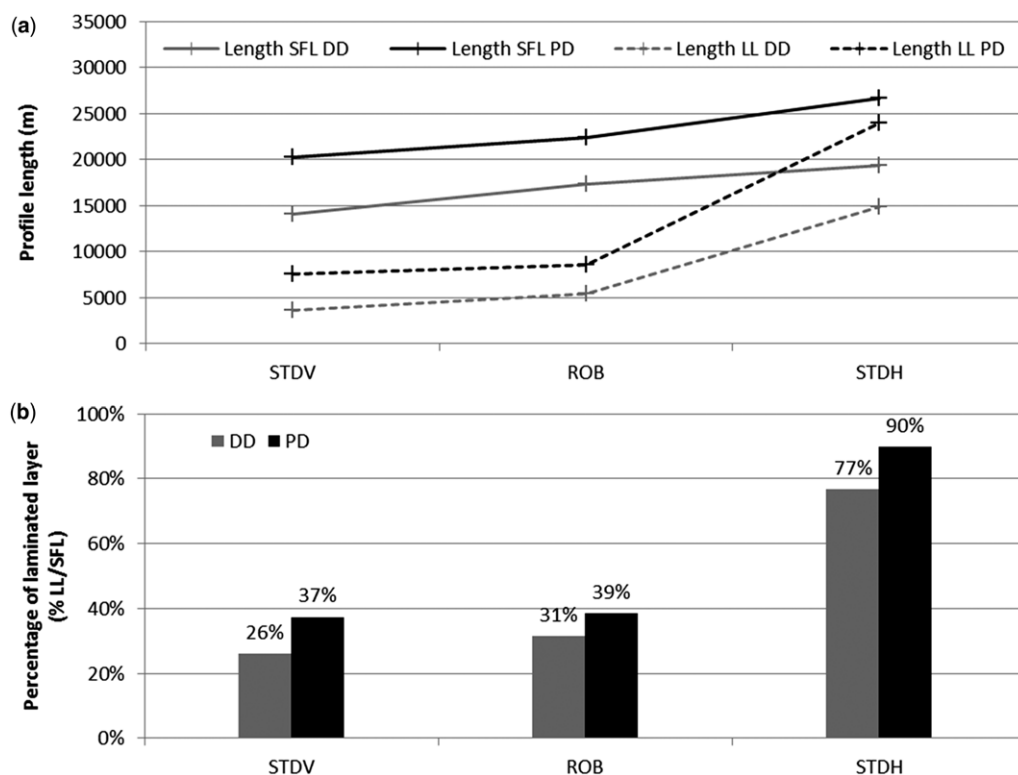


Fig. 7. (a) Profile length with SFL and LL as a function of the type of ERT array (DD or PD) and of the inversion method. (b) Percentage of detected laminated layer where a stratiform weathering profile is identified as a function of the type of ERT array (DD or PD) and of the inversion method.

the conductive fractured layer, as described above for the Br1 borehole and C4 profile, are highlighted on 90% of the 27 km of the PD ERT profiles with STDH inversion, and where a stratiform weathering profile is imaged. The STDH inversion (flatness ratio of 0.3) is well known for potentially adding horizontal artefacts within inversions results. Nevertheless, the laminated layer is not only detected with the STDH inversion (flatness ratio of 0.3), but also with the ROB inversion (flatness ratio of 1) on about 30–40% of the ERT profiles, and even with the STDV inversion (flatness ratio of 2) also on about 30–40% of the ERT profiles (Fig. 6). Consequently, the resistant laminated layer is not artificially produced by the choice of the STDH inversion, and is then not an artifact. The STDH inversion method only allows the length of detected LL to be maximized for both DD and PD arrays (Fig. 7a, b) as it increases the sensibility of the inversion regarding subhorizontal structures; in other words, a thinner or less-resistant laminated layer is better identified with the STDH than with the other inversion methods. A too-thin layer cannot be identified from the data, due to the suppression principle well known in electrical sounding. This limit of the method is tested by the ERT modelling in this research work.

Based on the observations of all profiles, the resistivity ranges of the different geoelectric horizons on the area of Saint-Galmier are, from top to bottom: $40 < R < 200 \Omega \text{ m}$ for the surface conductive saprolite; $150 < R < 1000 \Omega \text{ m}$ for the underlying layer with a thickness of 10–50 m, attributed to the laminated layer (LL); $400 < R < 400 \Omega \text{ m}$ for the conductive SFL; and $200 < R < 1500 \Omega \text{ m}$ for the unweathered granitoid.

The vast majority of geophysical profiles acquired from the study area confirm the existence of several distinctly individual geoelectric layers in the weathering profile, including the intercalation of the resistant laminated layer between the saprolite and underlying SFL.

The base of the SFL, on the inverted ERT imaging a weathering profile, represents an area of resistivity gradient without a localized sharp contact between two formations of very different resistivities (deep resistivity gradient). This is logical given the progressive decrease in the number of fractures with depth (as described for instance by Dewandel *et al.* 2006). This issue of a resistivity gradient will be discussed in the section ‘Geophysical modelling’ of the paper.

The layers that overly it show significant resistivity contrasts, with two resistant geoelectric layer intercalations. A relatively resistant continuous layer attributed to the laminated layer is systematically inserted between the conductive layer (attributed to the fractured layer by comparison with the

Br1 borehole) and the upper conductive saprolite. The fractured layer located in the lower part of the weathering profile appears relatively conductive compared to the underlying unweathered hard rock, with resistivity of 20–500 $\Omega \text{ m}$ (resistivity range sets from all the ERT profiles acquired on the Saint-Galmier site).

It should also be noted that, below the weathering profile, the ERT does not help to identify different types of lithologies of the unweathered parent rock, even if there are lithological contrasts in that area (Belle *et al.* 2016). ERT allows only the weathering layers to be identified, regardless of the lithology of the parent rock.

Vertical discontinuity in a granitic environment

There is a deepening of the conductive layers at depth, under the stratiform weathering profile in the resistant substratum (unweathered hard rock).

A first type of vertical discontinuity (VD type 1) is identified from observations made in particular on the Br1 borehole and along the C4 profile (Fig. 6). It is located at a depth of 105–154 m in this Br1 borehole and consists of five distinct water inflows. The fractured unweathered granite is saturated with low mineralization water ($350 \mu\text{S cm}^{-1}$ or about 30 $\Omega \text{ m}$). It shows high resistivity (200–500 $\Omega \text{ m}$ depending on the inversion method used), but less than those of the unweathered surrounding substratum ($>600 \Omega \text{ m}$). It should be noted that at the Br1 borehole this subvertical discontinuity produces a flow rate of about $3 \text{ m}^3 \text{ h}^{-1}$ (flow rate and drawdown stabilized over a period of several months).

A second type of VD (Type 2) was identified through observations of the inclined (at 40°) core sample drilling Br2 ($Q \sim 2.5 \text{ m}^3 \text{ h}^{-1}$, with a screened length of 80 m) (B1 profile, see Fig. 6c). This borehole cuts through a fractured zone over a linear depth of 80 m composed of alternate relatively unweathered fractured areas and partings significantly more weathered (alternating clay and sand). This second type of VD is characterized by more conductive anomalies than Type 1 VDs on the geophysical profiles (60–400 $\Omega \text{ m}$ depending on inversion methods; see Fig. 6b). The higher conductivity of Type 2 VDs compared with Type 1 is consistent with the lithology (higher weathering).

A third type of VD (Type 3) is only identified on the northern survey area. It represents very wide sub-vertical conductive corridors c. 400 m wide, with resistivity of 40–250 $\Omega \text{ m}$ depending on the inversion method. Both exploration boreholes (TV1 and TV2) which cut through these discontinuities encountered a highly weathered granite facies to a depth of 200 m without reaching the unweathered granite. The granite there has a saprolite-type and

clayey-saprolite facies, with the latter dominating in terms of volume. Logically, the productivity of these formations is low ($<0.5 \text{ m}^3 \text{ h}^{-1}$ in both bore wells despite a screened length of 200 m in each). The water is slightly mineralized with a similar mineralization as that present in the subvertical discontinuities described above.

The low resistivity of these weathered facies compared to their more resistant host rock ($>400 \Omega \text{ m}$) causes considerable lateral effects during ERT acquisitions. The profiles positioned parallel with these structures are greatly affected on a distance of up to c. 200 m in relation to the conductive vertical structure. This results in conductive artefacts in these parallel profiles, whose apparent depth increases with the distance separating the profile from the conductive structure.

Stratiform weathered profile in a metamorphic environment

The Sparouine ERT profiles as well as FE1 borehole in the Sparouine area's metamorphic environment help to accurately describe the resistivity change in the weathering profile. Despite the difference in lithology from the granitoids studied and described above, a stratiform series was also highlighted. It consists of an alternation between layered resistant and conductive units (Fig. 8) with, from the surface: a discontinuous resistant layer of thickness 2–5 m ($800\text{--}3000 \Omega \text{ m}$); a conductor of thickness 2–10 m ($200\text{--}600 \Omega \text{ m}$); a resistant layer of thickness

5–15 m ($400\text{--}3000 \Omega \text{ m}$); a conductive layer of thickness 20–30 m ($120\text{--}400 \Omega \text{ m}$); and a resistant substratum ($>3000 \Omega \text{ m}$).

The FE1 borehole (Fig. 5) was drilled by the coring method with water at the SP1–SP6 profile (Fig. 8). The geology encountered in Sparouine FE1 borehole is, from top to bottom (Fig. 9): highly weathered clays and shale at 0–4.8 m depth; weathered shale at depths 4.8–13 m with a saprolite type facies, not permeable (without any observed water inflow); less weathered shale at 13–24.4 m depth, not permeable (without any observed water inflow); fractured shale with weathering marks at depth 24.4–52.9 m, with five permeable fractures cut through at 25–51 m depth corresponding to the SFL; and a slightly weathered and locally fractured shale at depths 52.9–76.5 m, a last permeable fracture being cut through at a depth of 72 m. The latter is interpreted as the lower part of the SFL.

The density of the permeable fractures decreases with depth in the FE1 borehole, with fractures described at 25, 28, 36, 37, 45, 56, 63 and 87 m. The SFL therefore has a thickness of about 60 m.

The comparison between the geological section of the FE1 borehole and the SP1–SP6 geophysical profile (Fig. 8) enables the main geological layers identified during core drilling to be correlated with the positioning of the main geoelectric layers in the weathering profile. The base of the weathering profile (base of the SFL) is a resistivity gradient area without any key marker at its base (wide resistivity gradient). The layers that overly it show significant

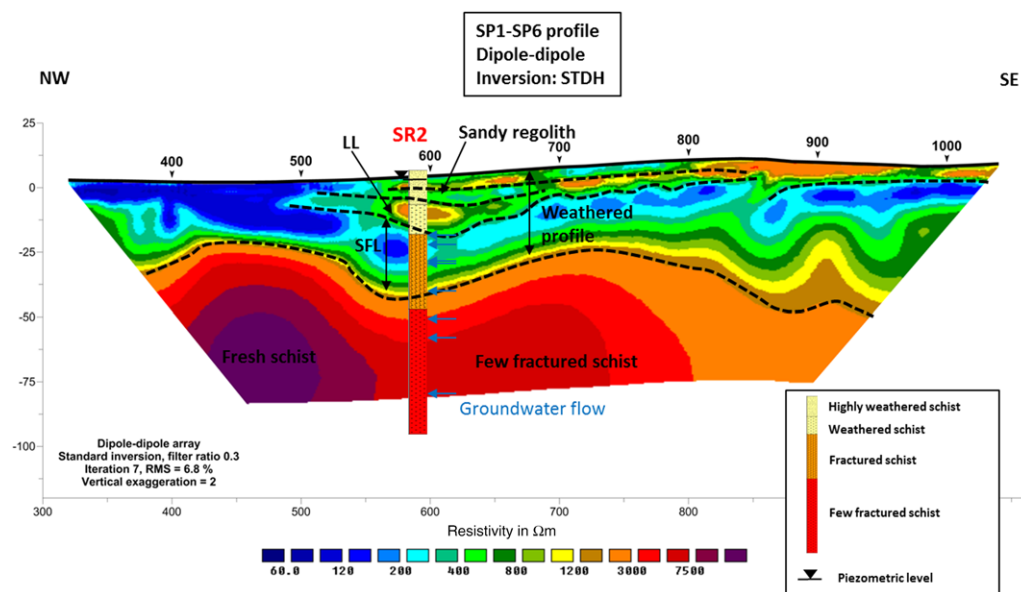


Fig. 8. STDH inversion model of the SP1-SP6 Sparouine ERT profile, acquired using a dipole-dipole array.

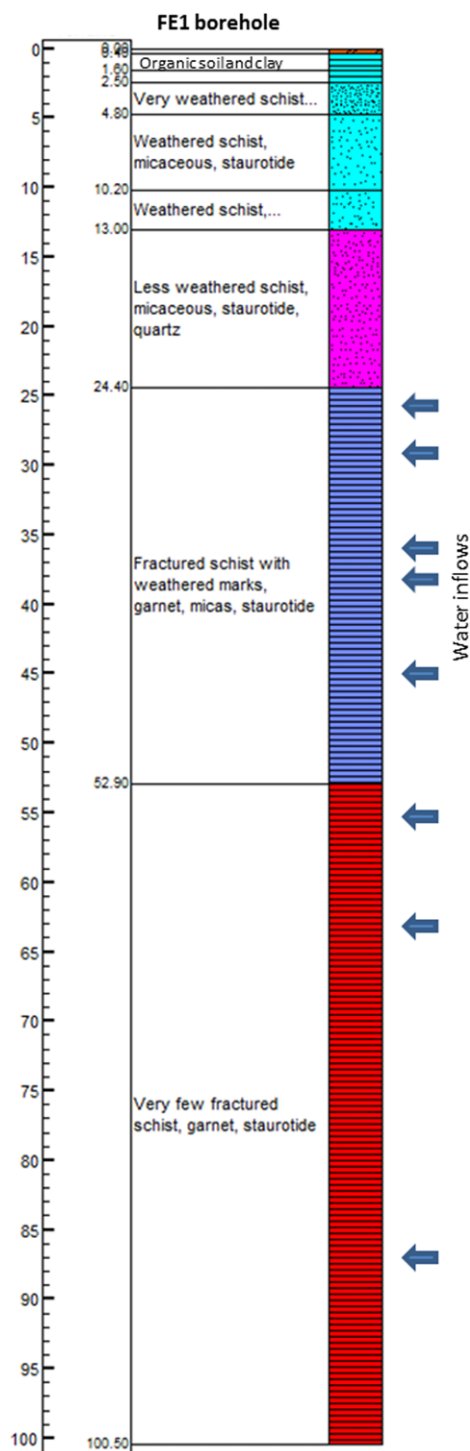


Fig. 9. Geological and hydrogeological logs of FE1 Sparouine borehole. Water inflows are identified with blue arrows in this figure.

resistivity contrasts, with two resistant geoelectric layer intercalations (Fig. 8). A relatively resistant continuous layer (resistivity 400–3000 Ω m) is systematically inserted between the conductive layer attributed to the fractured layer by comparison with FE1 borehole and the upper conductive saprolite. This resistant layer is attributed to less weathered and not very permeable shale that, for these metamorphic formations, seems to be equivalent to the laminated layer of granites. The fractured layer identified by drilling in the lower part of the weathering profile appears relatively conductive compared to the unweathered underlying hard rock, particularly in its upper part with resistivity of 120–400 Ω m. However, it extends downwards with a continuous gradient to reach high resistivity (up to several thousand ohm-metres).

Geophysical modelling

Simple forward modelling was conducted from a theoretical geoelectric cross-section to test how the laminated layer's parameters influence its ERT imaging, and also how they influence the imaging of the whole hard rock weathering profile.

Inversion modelling results provide several findings (Fig. 10). When the laminated layer is thin (2.5 m) and resistivity low (250 Ω m), it is not detected by the ERT methods used in this study. On the other hand, it is clearly imaged when much thicker (15 m in this instance) and even more so when its resistivity is set at a high value. When its resistivity is set at 1000 Ω m and its thickness at 15 m, the inversion model shows clear similarities to the results obtained on the Saint-Galmier and Sparouine sites in terms of (1) resistivity range for the different layers and (2) characteristics of the various interfaces, including the resistivity gradient characterizing the base of the fractured layer. Furthermore, it appears that the intercalation of the resistant laminated layer in the weathering profile (1) significantly increases the thickness of the gradient zone at the base of the fractured layer (from 50 to more than 100 m between model A and model D) and (2) reduces the resistivity of the unweathered hard rock under the weathering profile from 1000 to 400–500 Ω m between model A and model D (Fig. 10).

Discussion

This research provides a detailed characterization of the electrical signature of the various layers making up the hard rock weathering profiles in granitic and metamorphic environments. The laminated layer is highlighted by the ERT method for the first time to our knowledge, determining its (resistant) geoelectric signature. Previously, such a resistive layer at

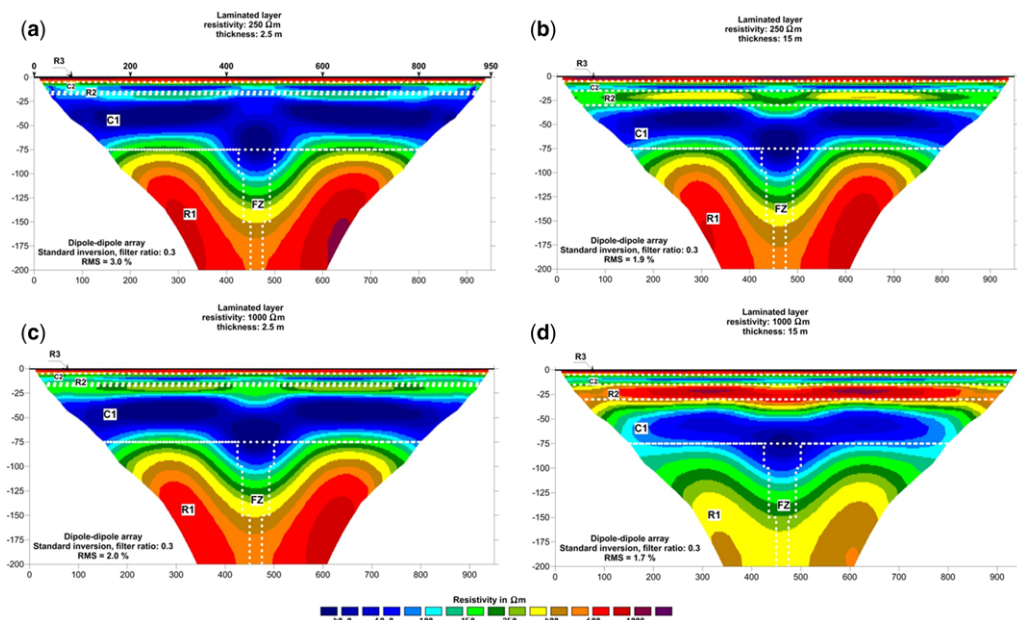


Fig. 10. Results from STDH-type inversions obtained from the theoretical geoelectric cross-section. The thickness of the laminated layer for a constant resistivity of 250 Ω m is (a) 2.5 m and (b) 15 m. For a constant resistivity of 1000 Ω m, the thickness of the laminated layer is (c) 2.5 m and (d) 15 m.

the bottom of the saprolite in Saint-Galmier was attributed, without comparison with borehole or outcrop data, to resistive unweathered boulders remaining at the base of the saprolite. However, both the calibration boreholes and observations on outcrops ruled out this initial hypothesis, and reinforced the proposed explanation (laminated layer).

The upper part of the fractured layer appears to be relatively conductive compared to the underlying unweathered parent rock. Its resistivity is 20–500 Ω m in the case of both granite and shale, while the resistivity of the unweathered parent rock is several thousand ohm metres. The base of the fractured layer shows a resistivity gradient without a characteristic marker at its base (the resistivity gradient extends over 30–50 m in granites of Saint-Galmier and 35–50 m for a SFL of 50 m or more in the Sparouine micaschists), which is consistent with the downwards decrease in connectivity of the fractures in this layer. This description of the geoelectric properties of the fractured layer has already been achieved on many measurement sites (Dewandel *et al.* 2006, 2011). Furthermore, the models produced in our paper reveal that the resistivity and thickness of the laminated layer influence the inversion models and, in particular, the thickness of the gradient zone at the base of the SFL. The gradient then appears more as an artefact due to the inversion process rather than a real geophysical property. This

issue should be addressed in further research: to develop inversion methods that are less sensitive to the effects of the resistant layers in the upper part of the weathering profile.

The overlying layers had not been described often prior to this research. They show significant resistivity contrasts, with two resistant geoelectric layer intercalations (Fig. 6). Geological and hydrogeological observations show that the main resistant layer is located between the roof of the SFL and the most superficial saprolite (e.g. Br1 borehole), and closely matches the laminated layer of weathering profiles; in a granite area, this layer is located at the transition between the saprolite and the SFL (Dewandel *et al.* 2011).

A conceptual diagram of the geoelectric layers making up the weathering profile is proposed based on the results obtained (Fig. 11).

The physical interpretation of the geoelectric signature of these various layers is complex, and the data available in this study and in the bibliography only permit us to propose simple and cautious statements. At Saint-Galmier the range of resistivity calculated in the SFL is 40–400 Ω m. These values are very close to the resistivity of the water which saturates this formation: 250 $\mu\text{S cm}^{-1}$ (i.e. 40 Ω m in Saint-Galmier and 140 $\mu\text{S cm}^{-1}$ in Sparouine, i.e. c. 70 Ω m). This is also close to the low resistivity of typical clay mineralogical facies (c. 10–25 Ω m).

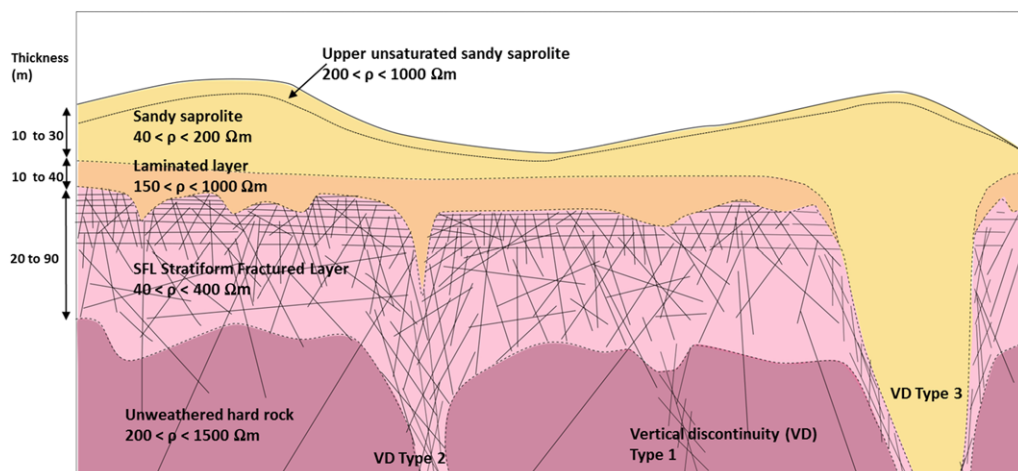


Fig. 11. Geoelectric conceptual diagram of the weathering profile in a hard rock area.

The laminated layer has a range of calculated resistivity of 150–1000 Ω m in Saint-Galmier. No water inflow was observed in this layer, whether in this case study in Saint-Galmier (see also Dewandel *et al.* 2017a) or in the bibliography (e.g. Dewandel *et al.* 2006).

From the ERT inversion, we calculated with a certain degree of uncertainty that the SFL underlying the LL has a lower resistivity than the LL. If we were considering this SFL as a porous media, and if we consider that its 40 Ω m lower value is true, then Archie's law provides unrealistic porosities (67% of total porosity with an imbibition water of 250 $\mu\text{S cm}^{-1}$). It confirms that Archie's law cannot be applied in such a non-porous media context. If we consider the SFL only as a fractured medium, then this medium must have the same resistivity as the water: 40 Ω m. Furthermore, no clay was found in the drill cuttings that could explain such a low resistivity.

If the ERT calculated resistivity is considered as a true representation of the resistivity at this depth, we have to consider that clays are present in the SFL. It is possible that either: (1) clayed fractures exist in the SFL and have not been intersected by drilling, or (2) clayed fractures cannot be identified in the cutting produced by such a destructive method.

To explain this low resistivity of the SFL more complicated physics can be considered, such as anisotropic effects due to a fracture system well oriented regarding the geophysical array. Investigating such hypotheses would require additional study, which is outwith the scope of this paper.

As a perspective, further research is needed to better understand the petrophysical controls on

bulk resistivity in this weathered/fractured media. Resistivity loggings could allow the physical origin of this possible decrease in resistivity to be explained. However, logging produces vertical current flows and could not be very well adapted to evaluate such anisotropic cases at the same large scale as the SFL.

In the metamorphic context of Sparouine (French Guiana), the so-called concept of laminated layer in a metamorphic environment has not yet been described in the scientific literature. Nevertheless, the results of geophysics for the micaschist formations characterized in Sparouine show the existence of a level with geoelectric resistivity properties similar to those of the laminated layer in a granitic environment. Observations made during drilling confirm the existence of a low-permeability and low-porosity level, characteristic of the laminated layer signature and therefore of a laminated layer in this case study. If we aim to generalize, it is very likely that a laminated layer exists in metamorphic formations (or its hydrogeological equivalent, i.e. with poor permeability and porosity), particularly those with a relative homogeneity: gneisses, orthogneisses in particular, mica-schists, etc. It now remains to formally demonstrate this on other study sites.

The identification and the location of this laminated layer in the weathering profile is important for determining whether an underlying fractured layer exists and locating its top, and then for siting productive water wells. In fact, where the laminated layer can be readily identified, it means that the underlying SFL is not eroded and that there is a good probability of reaching permeable fractures. Moreover, combining this geophysical information

with piezometric level data allows us to determine whether the SFL is saturated with water or not. It also allows an assessment of the residual thickness of the saprolite and an evaluation of how much water is stored in it, and the natural protection of the SFL aquifer. In fact, groundwater protection is more important when the saprolite and the laminated layer are both present above the SFL aquifer.

Conclusions

Previous studies have shown that the weathering profile is generally described as a saprolite conductive layer with a higher resistivity below, within the SFL, with a regular resistivity gradient.

For the first time, the geophysical signature (resistant) of the laminated layer, located at the base of the saprolite, is unambiguously characterized within granite formations. The laminated layer has also been revealed for the first time in certain types of metamorphic formations. Its resistant signature, as well as existing contrasts with the overlying saprolite and underlying stratiform fractured layer, both more conductive, is calibrated through observations on outcrops and by drilling.

In terms of applications, the identification and location of the laminated layer in the weathering profile is important for determining if an underlying SFL exists in the weathering profile and locating its top, and then for siting and dimensioning (provisional depth) productive water wells. Moreover, combining this geophysical information with piezometric level data allows us to determine whether the SFL and/or the saprolite are saturated with water or not, assess the residual thickness of the saprolite and then evaluate water storage. It also enables assessment of the natural protection of the underlying SFL aquifer.

A hard rock weathering profile geoelectric conceptual diagram is proposed, supported by field data and geophysical modelling. In addition, this research demonstrates the value of performing various types of geophysical data inversion, particularly where subvertical and subhorizontal structures coexist. We have shown that some types of inversion (such as STDH) better highlight the subhorizontal structures, such as the laminated layer, and that STDV inversion is better for subvertical structures. In such complex environments, hydrogeology and geophysics data must be iteratively combined during the inversion process in order to improve the soundness and reliability of the geophysical inversions. The most appropriate type of inversion should be deterministically selected according to the characteristics of the ERT profile, or even of a part of a profile, and the available data such as cuttings/cores and observations of outcrops.

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