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Geophysical demonstration of the absence of correlation between lineaments and hydrogeologically usefull fractures: Case study of the Sanon hard rock aquifer (central northern Burkina Faso)

Donissongou Dimitri Soro [a, b, *], Mahamadou Koïta [a], Chabi Angelbert Biaou [a], Eli Outoumbe [a], Jean-Michel Vouillamoz [c], Hamma Yacouba [a], Roger Guérin [b]

[a] *Laboratoire Hydrologie et Ressources en Eau, Institut International d'Ingénierie de l'Eau et de l'Environnement, 01 BP 594 Ouagadougou, Burkina Faso*
[b] *Sorbonne Universités, UPMC Univ Paris 06, UMR 7619, METIS, Case 105, 4 Place Jussieu, 75252 Paris Cedex 05, France*
[c] *Université Grenoble Alpes, IRD, CNRS, Grenoble INP, IGE, CS 40700, 38058 Grenoble Cedex 9, France*

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ABSTRACT

The conceptualization of hard rock aquifers in terms of their geometry and structure has undergone considerable progress over the last two decades. Despite these advances, hydrogeologists are still divided by the models used to describe two central concepts: (i) the influence of weathering processes on hydraulic conductivity; (ii) the influence of tectonics on the hydraulic conductivity of hard rock aquifers. In order to provide further insight into this debate, the present study proposes a conceptual model for hard rock aquifers, based on an integrated hydrogeological and geophysical approach, using information acquired at different scales. The data and observations used for this case study were derived from the Sanon experimental site, located in Burkina Faso, which is presently exposed to a Sudano-Sahelian climate.

The methodological approach consisted firstly in developing a description of the site's weathering profile at the scale of a borehole, based on lithologs and electrical resistivity logs. In a second step, the site's ridge to ridge (longitudinal) weathering profile was established from several 2D resistivity sections crossing a maximum number of lineament structures, which in some prior studies were considered to be the superficial manifestation of tectonic fractures.

The results show that at that scale the weathering profile is comprised of three main layers, which from top to bottom are referred to as: the saprolite, the fissured layer and the fresh rock. This weathering profile model is consistent with other models proposed in recent years, suggesting that the hydraulic conductivity of hard rock aquifers is a consequence of weathering processes, rather than tectonic fracturing. Tectonic fractures are not visible on the 2D sections of the ridge to ridge profiles, and the lineaments originally thought to be overground representations of tectonic fractures are likely to have different origins. The lack of a substantial correlation between tectonic lineaments and fractures appears to account for the high incidence of negative boreholes in hard rock aquifers, where the siting of drillings has systematically been based on lineament studies and on geophysical studies looking for vertical fractures such as profiling and vertical electrical sounding. There is thus a need to revise current hydrogeological concepts and methodologies to site wells based on tectonic fractures represented by lineaments.

1. Introduction

More than 80% of West Africa subsoil is composed of hard rocks (MacDonald and Davies, 2000) that are not intrinsically porous and pervious. However, they were or are still subjected to weathering processes which gave them hydrodynamic properties, in particular fracture permeability (Lachassagne et al., 2011). Thus, weathered

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* Corresponding author. Laboratoire Hydrologie et Ressources en Eau, Institut International d'Ingénierie de l'Eau et de l'Environnement, 01 BP 594 Ouagadougou, Burkina Faso.

E-mail addresses: dimitri.soro@gmail.com (D.D. Soro), mahamadou.koita@2ie-edu.org (M. Koïta), angelbert.biaou@2ie-edu.org (C.A. Biaou), outoumbe@gmail.com (E. Outoumbe), jean-michel.vouillamoz@ird.fr (J.-M. Vouillamoz), hamma.yacouba@2ie-edu.org (H. Yacouba), roger.guerin@upmc.fr (R. Guérin).

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zones of these hard rocks constitute aquifers which are increasingly exploited for the population water supply (e.g. Dewandel et al., 2010, 2008; Carter and Parker, 2009; Taylor et al., 2009; Chilton and Foster, 1995). These aquifers are sustainable water resources for West African rural populations (Courtois et al., 2009). Indeed, the groundwater stored in hard rock aquifers is geographically well distributed (Lachassagne and Wyns, 2005) and offers an alternative to pollution-prone surface water resources. Access to this groundwater is generally through boreholes. Thousands of boreholes have been drilled since the 1980s in the context of rural water supply projects. As many as 25%–60% (e.g. Vouillamoz et al., 2014; Courtois et al., 2009; Lutz et al., 2007) of the boreholes are "dry", indicating the complexity of hard rock aquifers and the need to develop suitable conceptual models and suitable methodologies to site boreholes.

Over the past twenty years, many advances have been made in the development of representative conceptual models for these aquifers. As an example, the role of fractures as hydraulic barriers was highlighted by Lachassagne et al. (2011). Some studies conclude that the fracture hydraulic conductivity of hard rock aquifers is due to weathering processes (e.g. Su et al., 2015; Koïta et al., 2013; Lachassagne et al., 2011; Courtois et al., 2009; Dewandel et al., 2006; Maréchal et al., 2004; Wyns et al., 2004), while others consider fracture hydraulic conductivity to be of tectonic origin (e.g. Kouamé et al., 2010; Kamagaté et al., 2008; Razack and Lasm, 2006; Wright and Burgess, 1992).

For the former group, the hydraulic conductivity of hard rocks is inherited from weathering profiles, within a fissured stratiform layer located immediately below the unconsolidated saprolite. In this model, the weathering profile includes, from top to bottom: (i) laterite, iron or bauxitic crust, which can be absent due to erosion or rehydratation of hematite in a latosol; and (ii) saprolite, a clay-rich material derived from prolonged *in situ* decomposition of the fresh rock, which has a thickness of a few tens of meters. The saprolite layer can be further divided into two sub-units (Wyns et al., 2004): the alloterite sub-unit (consisting of mostly clays), and the isalterite sub-unit (in which weathering processes preserve the original rock structure) whose effective porosity is normally between 3% and 10%. The weathering profile also includes: (iii) a fissured layer, which is generally characterized by dense fissuring in the first few meters below its top, with a relative high hydraulic conductivity and rather a low porosity; and finally (iv) fresh rock, which is unfractured hard rock and has a very low hydraulic conductivity and storativity (Maréchal et al., 2004). This model of a horizontally stratified reservoir has been successfully applied to various hard rock aquifers in India (Dewandel et al., 2010, 2006), Ivory Coast (Koïta et al., 2013), South Africa and East Africa (Taylor and Howard, 2000).

In the latter case, the hard rocks are considered to be highly heterogeneous, with their hydraulic properties deriving mainly from tectonic origins and lithostatic decompression. During drilling campaigns, the project supervisors in charge of selecting borehole sites have always searched for soil surface lineaments. These are supposedly the surface representation of subvertical fractures, and are detected by suitable processing of satellite images and aerial photographs.

This paradigm has oriented (1D) electrical resistivity sounding campaigns and borehole drilling (Savadogo et al., 1997; Wright and Burgess, 1992), but fails to explain the current 30%–40% of dry boreholes (Brunner et al., 2006; Sander, 2006). In view of this situation, the question arises as to whether some of these concepts, which the majority of applied hydrogeologists still consider to be relevant, should be reviewed. The aim of the present study is, thus, to provide answers to this question, by using an integrated approach to characterize and propose a conceptual model of a hard rock aquifer, based on information obtained at different scales.

Our methodology, firstly, involved a description of the weathering profile at borehole scale (1D) through the use of lithologs and electrical resistivity logs. Next, the weathering profile was characterized from ridge to ridge on a watershed by electrical resistivity sections (2D), crossing the maximum number of lineaments identified in previous studies.

The study was carried out at the Sanon experimental catchment site, which had already been the subject of groundwater research in the 90s (Compaoré, 1997; Compaoré et al., 1997; BRGM-Aquater, 1991).

In the following section we describe the methods used for the borehole scale investigations and to determine the ridge to ridge weathering profile. A conceptual model of the weathering profile is then proposed. Finally, our model is compared with the two aforementioned concepts (i.e. hydraulic properties due to weathering, and due to tectonic fracturing revealed by lineaments).

2. Description of the Sanon experimental site

2.1. Location and climate

The Sanon experimental site is located within a hydrological entity (surface sub-catchment of Red Volta river), approximately 40 km northwest of Ouagadougou (the capital city of Burkina Faso) between the longitudes of 1°45′35″ and 1°42′42″W, and the latitudes of 12°25′55″ and 12°29′10″N. It has a surface area of 14 km^2 and is characterized by a very weakly contrasted relief (Fig. 1). The ridges in this area are mainly covered by iron crust, between 350 and 370 m amsl. They form the boundaries of the surface hydrological entity. The central part of the site is characterized by a relatively broad, flat-bottomed valley, sloping from east to west.

The climate in this area is of the Sudano-Sahelian type, with a short rainy season (from June to September) and a long dry season (from October to May). The mean annual rainfall varies between 700 and 900 mm and the temperature ranges between 25 and 40 °C.

2.2. From regional to local geology

The geology of Burkina Faso is characterized by rocks belonging to the West African craton, which has one of the lowest seismicities in the world, characterized by earthquakes with a magnitude less than 4. This craton comprises two distinct entities: the Reguibat Shield in the North, and the Leo Shield, also referred to as the Man Shield, in the South (Fig. 2). These two groups are separated by sedimentary formations called the Taoudeni basin. In the Leo Shield, Paleoproterozoic formations crop out in nine West African countries: Burkina Faso, Ivory Coast, Ghana, Guinea, Liberia, Mali, Niger, Senegal and Togo (Lompo, 2010). The age of the formations is not exactly known, and diverse estimates have been proposed in different studies (e.g. Kouamelan et al., 2015; Lompo, 2010; Feybesse et al., 2006; Egal et al., 2002; Guiraud, 1988). However, this shield can be subdivided into two domains:

- The Archean or Kenema-Man domain (Fig. 2). This is characterized by two orogenic cycles: the Leonian, dated from 3500 to 2900 Ma, and the Liberian, dated from 2900 to 2600 Ma.
- The Baoule-Mossi domain (Fig. 2) is dominated by the Paleoproterozoic era. It was recorded in the second domain of the Eburnean orogenic cycle dated from 2400 to 1600 Ma. According to various studies (Sattran and Wenmenga, 2002; Savadogo et al., 1997), the Eburnean orogenic cycle is characterized by: (i) the fracturing of an ancient hard rock, in two directions (N15° to N20°E and N100° to N120°), (ii) the intrusion of granodioritic