Role of the Inherited Structure and the Paleo-Weathered Surfaces on the Reservoir Quality within the Basement

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ABSTRACT

Rifting zones and passive margins are two main extensive geodynamical domains where heat fluxes could be attended to be high and may be prospection targets for high enthalpy fluid production. Through the description of structures composing the network that control fluid flow at different scales, different models of reservoirs can be proposed with respect to rift or margin geometries. In these settings, large-scale porous networks consists faults, fracture networks and weathered horizons at the cover-basement interfaces. Their relationships and their shapes depend on the geodynamical context and the intensity of extension that could control the conservation of the weathered facies. The role of the inherited structures from the previous geological history on the reservoir development and on their transfer properties is also discussed. One example located in the eastern African rift system is presented here. In this case, a long geological history, with petrographic and structural heterogeneities, contributes to the reservoirs' structures, and controls its quality.

1. INTRODUCTION

Electricity produced from geothermal resources needs fluids with temperatures higher than 200°C (Bertani, 2012). These conditions could be obtained in the vicinity of volcanic structures (Larderello, Philippines, Iceland ...) at relatively low depth (Bertani, 2012, Lund et al 2011). This type of geothermal setting is currently the only operating one for this resource production around the world. However, only few countries have such high geothermal gradients, which usually occur on small area. In the case of normal geothermal gradients of about 30°C/km, depths greater than 6 km must be reached to get sufficient temperatures. This depth may be reduced in some rather favourable settings such as rifts or passives margins, but drilling depths greater than 4 km are still necessary. At these depths, one of the target reservoirs is the interface between the basement and the sedimentary cover. In the mining sector, this interface is identified as an area of important palaeo-circulations, with associated mineral deposits. This reservoir can be divided into two parts: (1) the sedimentary part mainly composed by the transgressive formations in the bottom of the infilling sequence, and (2) the basement part, itself divided in two parts, the fracture network and the weathered horizons (Younes et al 1998). Exploration of these deep reservoirs requires surface geophysical technics: seismic, magnetic, gravimetric, magnetotelluric and geophysical well data. However, these different datasets do not allow to define the pore network geometry at the whole reservoir scale (centimetre-scale resolution versus kilometre-scale reservoir). Thus, analogue outcrop studies are necessary to fill up this resolution gap between the geophysical and the well data and contribute significantly to the construction of geological model of basement reservoir (Caine and Tomusiak, 2003; Mc Caffrey et al 2003).

The aim of this paper is to present structural and petrophysical data acquired from a field study located in the "Albertine Rift" in Uganda. The selected study area can be considered as an analogue of basement reservoir and therefore provides information for the reservoir modelling. This surface analogue outcrop allows the analysis of the effect of the basement structural inheritance on the activation of faults and fractures networks, on the development of weathering processes and finally on the geometry of the porous network and on the reservoir quality.

2. THE STRUCTURAL CONTEXT.

Many studies on the porous network geometries of fault zones and on their petrophysical properties have been conducted (Caine et al 1996, Caine and Tomusiak, 2003, Faulkner et al 2010, Géraud et al 2010). Multiscale analyses of faults and cracks of a graben structure (*Le Garzic et al., 2011*) or along a passive margin (Bertrand et al., 2014) leaded to a model of multi-scale organization for basement blocks and bounding structures of various sizes (figure 1). According to one of these studies, three size orders are described. The first structural size order corresponds to basement blocks size of about 20 kilometres, bounded by fault systems of several kilometres thickness and of several tens of kilometres long. The fault systems of the second size order have thickness of about one kilometre and length of several kilometres long and limit blocks whose size is about ten kilometres. The last order consists of the smallest blocks of few kilometres in length, bounded by faults with a thickness of several hundred metres.

The "Albertine rift system" (ARS) is located at the northern end of the western branch of the eastern African rift system (EARS). This active rift propagates since Upper Miocene through Archaean and Proterozoic formations of different metamorphic and magmatic rocks accreted along a Proterozoic orogenic suture (Karp, 2012, Kohn et al 2008). The main rift structures are mainly oriented N40 in the northern part of the Rift rather N0 in the southern part (Ring 2008). The rift border faults developed strong conspicuous escarpments in the topography along which our study is conducted (Figure 2). The basin structure is controlled by a few number of faults observed on the seismic data. This study consists of the characterization of one of the main fault in the East part of the rift, the Toro-Bunyoro fault. A road oriented NW-SE allows the analyse of a cross section through the fault zone in the hanging wall. Measurements of the schistosity and the foliation of the metamorphic rocks and of the anisotropy of magnetic susceptibility (AMS) confirm the strong control of the inherited Proterozoic structures on the orientation of the rift (Figure 3), especially with a very similar orientation of the rock schistosity in the area of the border fault. Toward the SE, several others orientations are also observed and the AMS data acquired all along the road confirm the existence of these strain planes.
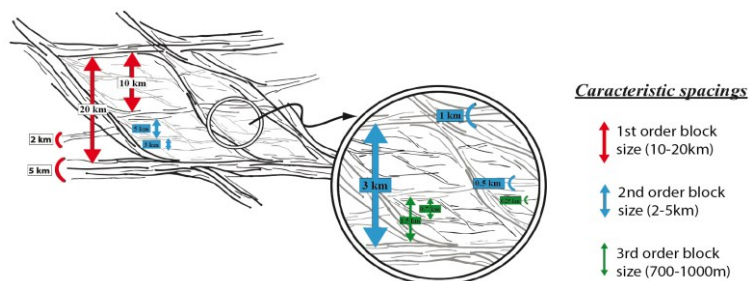
Figure 1: Distribution model of hierarchical basement block sizes. Colored arrows indicate the three identified characteristic block sizes. (*modified from Le Garzic, 2010 and Le Garzic et al., 2011*)
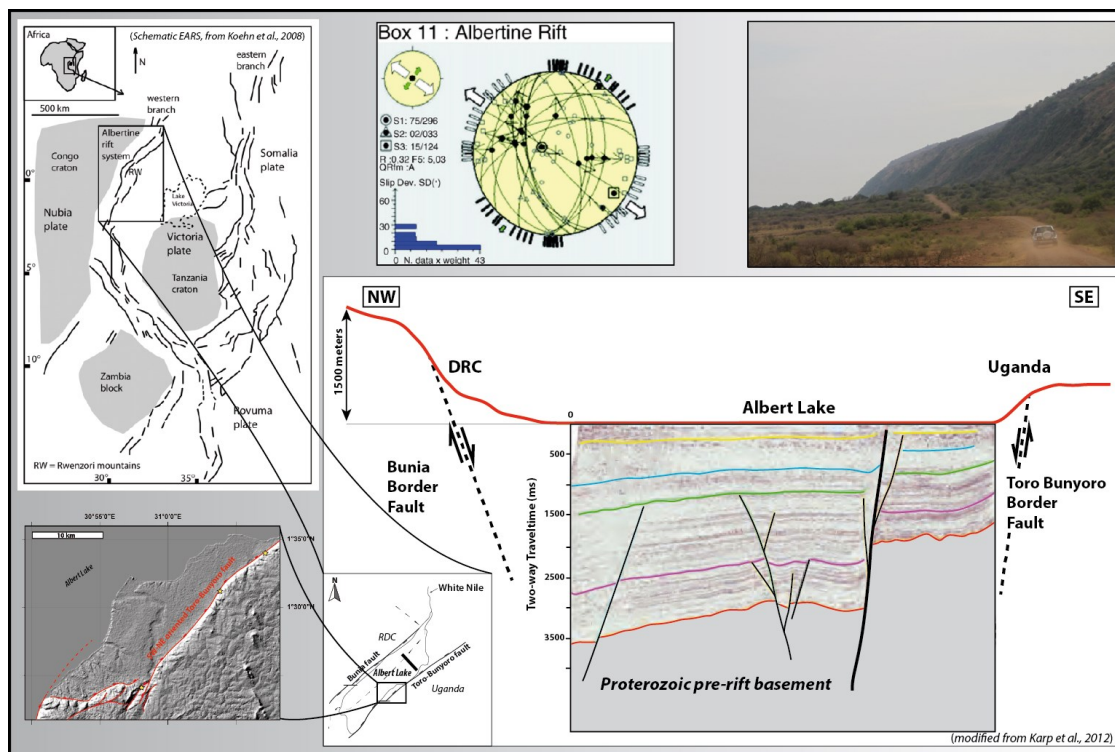

Figure 2: general map of the East African Rift, general map of the Albertine Rift, view of the fault scarp, Topographic map of the studied fault area. Seismic view of the Lake Albert.
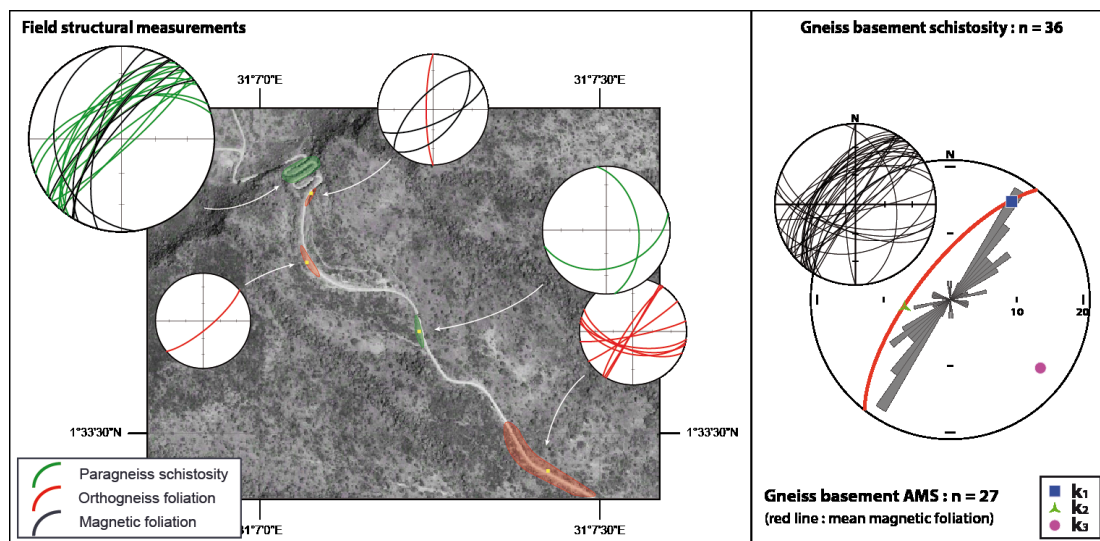

Figure 3: Left, Plots of schistosity and foliation measured in the basement formation. Right, fracture orientation of the rift, and AMS axis for several samples

3. IMPACT OF THE FAULT ON THE FRACTURE NETWORK AND THE MATRIX PROPERTIES (FIGURE 4).

The different compartments of the fault zone are determined from macroscopic and microstructural observations of the rock deformation. In the study area, the protolith is an orthogneiss/granulite facies, which evolves to an ultra-cataclasis material in the fault core. From rock samples, the P-wave velocities measurements show a strain hardening of the fault core with wave velocities greater than 5700 m/s, and secondly a low velocity zone in the hanging wall along the fault core, which is interpreted as a cracking damaged zone developed at the rheological interface between the cataclastic facies and the protolith. The matrix porosity of the fault core is very small and may represent a role of hydraulic barrier, while porous zones are well developed, one in the hanging wall of the fault core and second in some parts of the protolith. At the macroscopic scale, fracturing in the protolith is strongly controlled by structural inheritance with guidelines consistent with the measurements of cleavage and AMS. In the fault zone, a new fracture set appears to become predominant in the fault core. The fracture density in the fault core is large enough to assume a potential permeability, even in the cracked portion of the damage area. On the other hand, the damaged zone shows a lower fracture density. Thus, the different fracture and porous networks indicate that such compartments of a fault zone must be considered differently for a basement reservoir understanding.
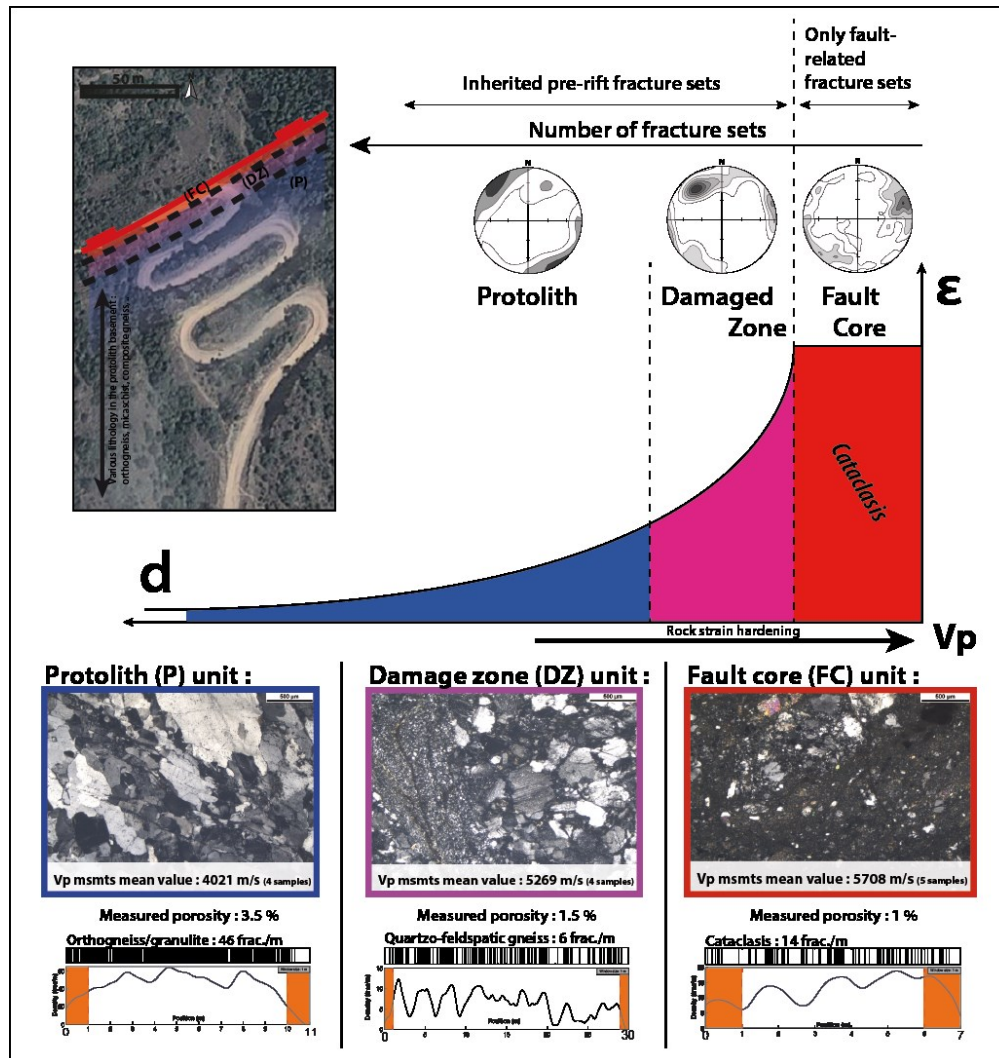

Figure4: Description of the fault zone, with the thin section views of each structural facies and their petrophysical properties. For each fault units, fracture density analysis is also presented.

## 4. PETROLOGIC CONTROL ON RESERVOIR GEOMETRY (FIGURE 5).

A petrographic control on the fracture density and on the matrix porosity can be highlighted in the protolith. Facies with important inherited features (schistosity, foliation) show lower values of porosity and fracture density. In the protolith, the orientation of fractures is clearly controlled by the structural inheritance, with important variations in fracture density of 5 fract/m in micaschist over 40 fract/m in orthogenesis. The matrix porosity follows the same behaviour with porosities ranging from 0.5 to 5% according to the facies. These variations are described at the reservoir scale and induce porosity and permeability heterogeneities that must be take into account to define the reservoir geometry and properties.

5. THE RESERVOIR PROPERTIES OF THE WEATHERING LEVEL, (FIGURE 6).

The second type of potential reservoir is developed at the interface between the top weathered basement and sedimentary cover. In order to characterize this weathered reservoir, 5 facies are defined according to the degree of alteration on a theoretical profile (1 to 5) from the protolith none or slightly weathered (fresh material) to the most altered facies. For each facies matrix porosity values,

concentrations and types of clays, and the P-wave propagation velocities are measured. The development of the weathering is marked by the appearance of smectite for the least altered facies, which is gradually replaced by illite and kaolinite with the increase of the weathering grade. The matrix porosity is characterized by mercury injection that provides access not only the connected pore volume but also to the void threshold size. Porosity increases from 0.7 to 38% with the development of alteration while the size of the access threshold increases from 10^{-2} to 10 micrometres. From these values, an increase of the matrix permeability can be expected, of 4 to 6 orders of magnitudes between protolith and the summit area of the weathered basement. These variations of microsctructural parameters are clearly associated to a decrease of Vp speed from 5400 m/s to 3400m/s for the top of the weathered part.
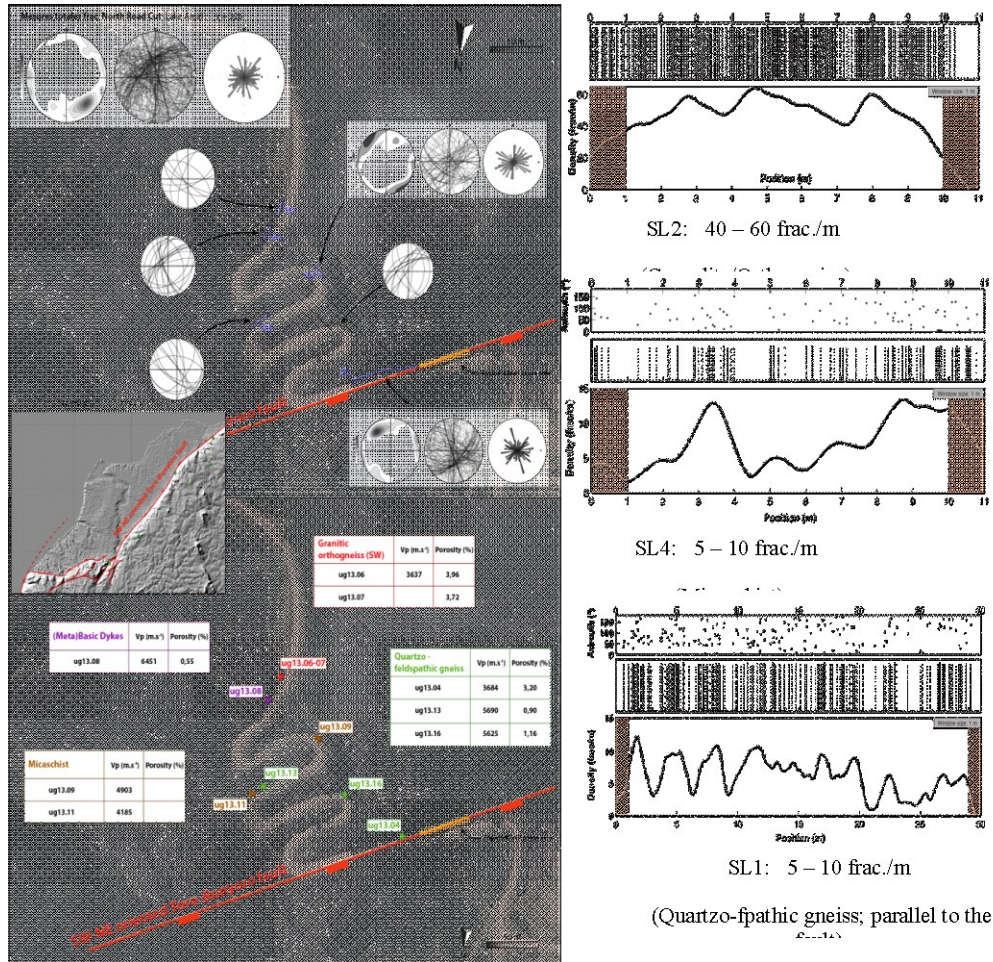
Figure 4: Control of the petrographic facies on the fractures network parameters and on the matrix petrophysical properties (porosity and VP).

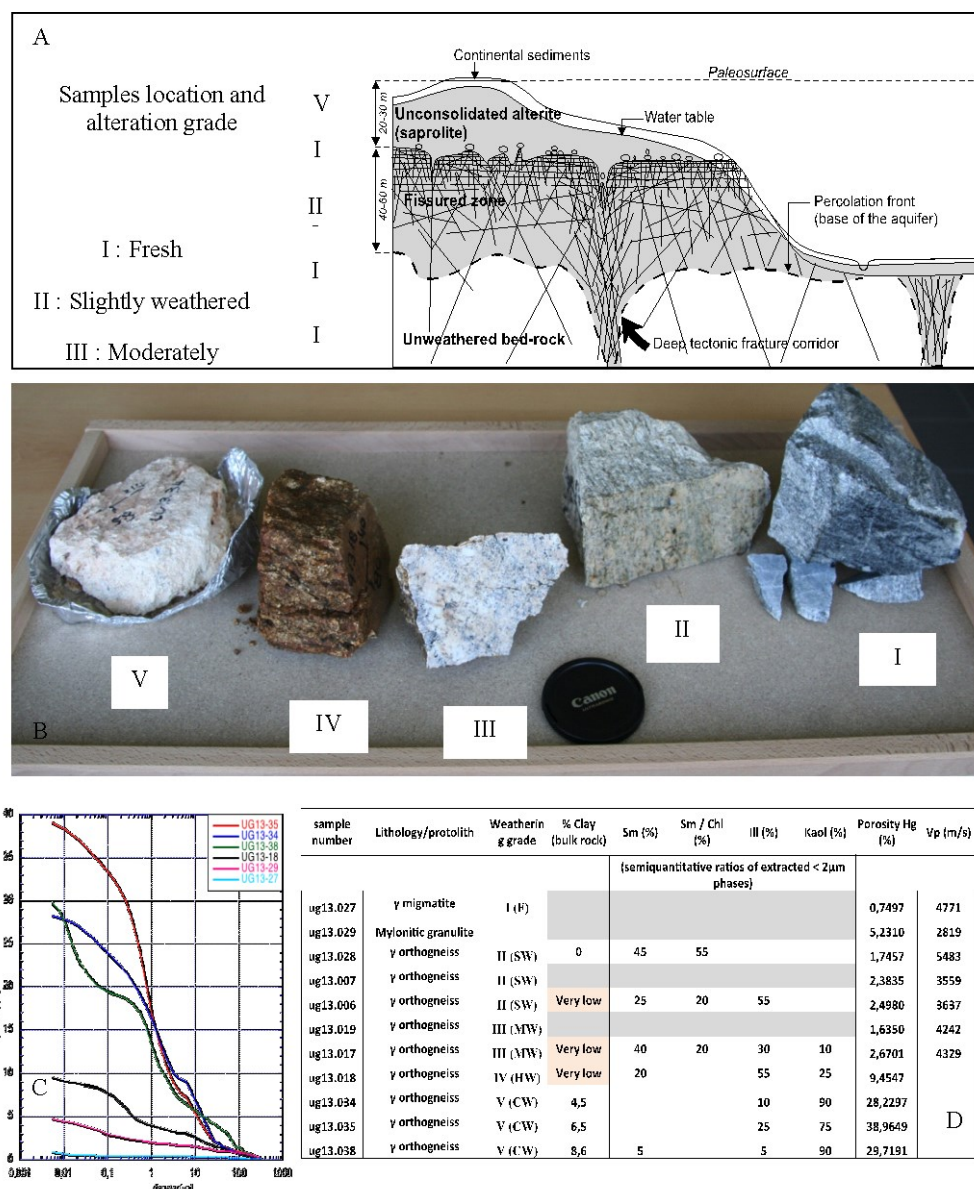## 5. TOWARD A GEOLOGICAL MODEL FOR BASEMENT RESERVOIR.

These datasets show that a geological model for the basement reservoir could be built from the fracture analysis and the matrix porosity data. Thus, a composite model of the reservoir may be constructed comprising three parts within reservoir block:

- A sub-horizontal or slightly sloped section that corresponds to the supergene alteration zone at the top of the block, where the fracture density and the matrix porosity increase toward the top of the block. The porosity values can be very high, up to 40% and more (Dewantel et al 2004). The thickness of this supergene weathered zone is very variable, up to 100 meters for example in Soultz-sous-Forêts batholith. Weathering process can also occur at greater depth with meteoric fluid circulations through fault structures. At Soultz-sous-forêts, basement rocks up to 500 meters laterally away from significant faults underwent matrix alteration with precipitation of hematite (Just and Kontny, 2012). The same process is observed at more than 2000 meters laterally away from the major fault of the Bach Ho field in Vietnam (Cuong and Warren, 2009). The sharp increase of the rock porosity in such weathered horizons can assume a significant increase of the matrix permeability.

- A more highly sloped section developed around fault zones that form the edges of the basement block. The fracture density and the matrix porosity depend on the initial petrography of the material and on the intensity of strain (Caine et al 1996). Indeed these fracture density and porosity can be significantly high in some parts of such fault zones. In the fault core, the ultracataclasite material has low porosity, and might play a barrier function for fluid in perpendicular direction. However, the fracture density allows to suspect some local passing through this cataclastic zone. The high fracture density of the fault core hanging wall, i.e. the damage zone, may act as a fluid-flow conduit, increasing the permeability in the direction parallel to the fault zone. In this damage zone, the orientation of some major fracture sets is related to the strain condition within the fault zone, while in the fault core the

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whole fracture network organization is fault-related. These common fault-related fracture sets of the fault core and of the damage zone increases the permeability anisotropy and the transfer properties of the fault zone at the edges of basement blocks.

- A more diffuse area in the central part of the block, where the organization of the fracture network and the matrix porosity depends on the rock lithology as described on other outcrops (Caine and Tomusiak, 2003) and also on the intensity of the fracturing. The fracture network depends on the petrographic nature of the material but also on the structural inheritance of the reservoir volume.

sample number	Lithology/protolith	Weathering grade	% Clay (bulk rock)	Sm (%)	Sm / Chl (%)	Ill (%)	Kaol (%)	Porosity Hg (%)	Vp (m/s)
				{semiquantitative ratios of extracted < 2µm phases}					
ug13.027	γ migmatite	I (F)						0,7497	4771
ug13.029	Mylonitic granulite							5,2310	2819
ug13.028	γ orthogneiss	II (SW)	0	45	55			1,7457	5483
ug13.007	γ orthogneiss	II (SW)						2,3835	3559
ug13.006	γ orthogneiss	II (SW)	Very low	25	20	55		2,4980	3637
ug13.019	γ orthogneiss	III (MW)						1,6350	4242
ug13.017	γ orthogneiss	III (MW)	Very low	40	20	30	10	2,6701	4329
ug13.018	γ orthogneiss	IV (HW)	Very low	20		55	25	9,4547	
ug13.034	γ orthogneiss	V (CW)	4,5			10	90	28,2297	
ug13.035	γ orthogneiss	V (CW)	6,5			25	75	38,9649	
ug13.038	γ orthogneiss	V (CW)	8,6	5		5	90	29,7191	

Figure 5 : Petrophysical characteristics of the weathering level developed at the basement-sedimentary cover interface, (profil from Dewantel et al 2006).

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