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Electrical resistivity imaging in transmission between surface and underground tunnel for fault characterization

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ABSTRACT

Electrical resistivity images supply information on sub-surface structures and are classically performed to characterize faults geometry. Here we use the presence of a tunnel intersecting a regional fault to inject electrical currents between surface and the tunnel to improve the image resolution at depth. We apply an original methodology for defining the inversion parametrization based on pilot points to better deal with the heterogeneous sounding of the medium. An increased region of high spatial resolution is shown by analysis of point spread functions as well as inversion of synthetics. Such evaluations highlight the advantages of using transmission measurements by transferring a few electrodes from the main profile to increase the sounding depth. Based on the resulting image we propose a revised structure for the medium surrounding the Cernon fault supported by geological observations and muon flux measurements.

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1. Introduction

Sub-surface fault zones can cause large discontinuities that affect rock properties in many ways, including lithological shifts, variations in permeability of several orders of magnitude, changes in porosity or fracturation, and variations in water saturation. Fluid circulation in the medium surrounding fault zones may be strongly affected due to the fault displacements: the fault structure might provide preferential paths or barriers for fluid flow. In fact, the fault structure, mechanism and fluid flow are related as they exert an influence on each other (Faulkner et al., 2010). Hence fluids might play an important role in the triggering of fault activity at depth as they act in stress transfer or friction reduction in fault zones (Sibson, 1996; Caine et al., 2010; Faulkner et al., 2010). The detection and monitoring of fluids in fault zones is thus important for understanding the role of fluids in fault functioning. Fault zones often have particularly heterogeneous structures from one side to the other, notably in terms of permeability. Such an asymmetry can affect the rupture propagation in the medium surrounding the fault zone when over-pressurized fluids help trigger a rupture (Cappa, 2011). Therefore, imaging of fault structures and location of fluid paths can supply key information for understanding of fluid migration around faults and thus for rupture forecasting.

Several geophysical tools can image fault structures, such as seismic imaging that detects reflectors corresponding to stratigraphical shifts along the fault sliding zone (Wang, 2002). Analysis of seismic waves produced by earthquakes allows imaging seismic velocity relatively deep in the crust (a few tens of kilometres) but at the cost of a reduced resolution (Chen et al., 2007). Ground penetrating radar (GPR) methods supply images with fine resolution for the shallow crust (Beauprêtre et al., 2012), but are strongly affected by clay and water circulation in the medium. Aeromagnetic mapping and magnetotelluric soundings show promise for detecting conductive reflectors at depth. However, the current methodology is not able to reliably create high resolution images (Blakely et al., 2002; Türkoğlu et al., 2015). Electrical resistivity imaging (ERI) provides a global view of the medium structures. ERI is particularly adapted for detecting water flow pathways or regions of water storage in porous media and thus water saturation variability (Slater and Binley, 1996; Hinnell et al., 2010; Loke et al., 2013). Electrical resistivity is then sensitive to the medium porosity, the rock matrix and the fluid resistivity together with the water saturation of the porous space. On the other hand, ERI has lower spatial resolution than seismic or GPR imaging, due to the diffuse propagation of electrical current.

ERI has been used in hydrology in order to detect water pathways (Slater and Binley, 1996), monitor plume propagation or water saturation variations (Slater et al., 2000; Brunet et al., 2010). ERI raw data can be acquired automatically making it suitable for time lapse studies that complete point hydrological data sets (Hinnell et al., 2010). Measurements performed along profiles allow soundings at a depth of

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about a fifth to a third of the profile length, with a resolution roughly equal to the electrode spacing in the shallow region. However, the resolution becomes coarser with depth at a rate depending on the medium resistivity and on the presence of heterogeneities (Miller and Routh, 2007; Oldenborger and Routh, 2009; Loke et al., 2014). Cross-hole ERI allows improved resolution in deeper regions (Danielsen and Dahlin, 2010), but the sounded area is restricted to the medium between boreholes. Cross-hole ERI also yields useful resolution for boreholes with separation smaller than about 0.75 times the boreholes' length and so gives relatively local information (Loke et al., 2013).

In this paper, we explore the use of placing ERI electrodes in a regional fault crossed by a tunnel, since this configuration allows performing transmission measurements in a vertical plane between the tunnel and the surface. Such measurements in transmission were previously performed across a volcanic dome and analysed to perform an image on an horizontal plane at the base of the dome (Lesparre et al., 2014). The ability to improve depth resolution in the resulting images by the use of transmission measurements is investigated by comparing image quality with our without data acquired in transmission from the analysis of point spread functions (Friedel, 2003; Miller and Routh, 2007; Oldenborger and Routh, 2009; Loke et al., 2014). The reconstructed image is furthermore interpreted in light of geological knowledge and density structure information obtained with the analysis of the muon flux detected across the fault zone since both electrical and muons methods proved to supply complementary information (Lesparre et al., 2012b).

2. Field experiment

2.1. Geological context

Measurements were performed at the experimental platform of Tournemire (Aveyron, France; Fig. 1). This site provides the opportunity for the French institute for radioprotection and nuclear safety (IRSN) to conduct research programmes in a clayey medium in order to improve expertise of the French storage project proposed by ANDRA (French national agency for radioactive waste management) in the Bure area (Meuse/Haute Marne). The confining properties of the clayey medium might indeed be affected by faults and fractured zones of tectonic origin. Therefore, geophysical investigations of such discontinuities are necessary to characterize potential fluid transfers.

The main tunnel of the platform intersects the regional Cernon fault that reaches the surface above the tunnel (Fig. 2). The Cernon fault is an old Palaeozoic E–W major crustal discontinuity of 80 km long (Fig. 1). During the Jurassic marine sedimentation, the tectonic movement was extensional and the Cernon fault was reactivated with normal kinematics and more than 200 m of vertical displacement is deduced from sedimentary analyses. The compressional Pyrenean tectonics (40–50 My) reactivated this major fault with reverse and strike-slip displacements of more than 500 m vertically as observed in the Tournemire sector. The different past tectonic events yield a complex structure of the Cernon fault with a large fault zone (Cabrera et al., 2001; Constantin et al., 2004).

The Cernon fault connects a northern block of fractured dolomitic rocks (Hettangian) with a southern monocline block of limestone-dolomites and clay rocks (Bajocian, Bathonian, Aalenian, Toarcian). The fault zone width is >10 m at the tunnel level but the deformation in the medium, presenting folds and minor fractures, on each side of the fault extends to about 100 m. The tunnel masonry, consisting of limestone blocks, does not allow a precise location of the fault in the tunnel and a detailed characterization of its structure. Recently two 6 m long boreholes were drilled at points 1525 and 1555 showing the presence of Toarcian clays. The extracted cores showed the presence of fractures and small faults indicating a complex and perturbed medium associated to the major Cernon fault. At surface, the fault is not clearly visible due to the dense vegetation and is then located from a regional mapping. Several resurgences of water are observed along the fault trace, supporting its localization.

On the southern side, the Toarcian layer is a clayey rock overlaid by an upper aquifer which flows from south to north, following the geological layers dipping to the Cernon fault. Above the Toarcian layer, the Aalenian, Bajocian and Bathonian layers are composed mainly of limestones. Fluid flows in these series might locally form some karstic structures along mainly N–S fractured zones. The Hettangian layer is also formed of dolomitic limestones able to host karsts. The aquifer circulating above the Toarcian layer has an outlet on the western wall of the tunnel (Fig. 2). Observations from barbicans and water resurgences on the tunnel walls show that the geology differs from one side to another of the aquifer outlet. On the northern side, water resurgences are loaded with carbonates and oxides, while on the southern side they are loaded with clay minerals. The intersection of the Cernon fault with the tunnel is thus located at the level of the outlet. At about 40 m from that water release, in the southern direction, tunnel walls present deformations (of about 20 cm inward, on each side of the tunnel) along a distance of about 50 m (Fig. 2). Such deformations might result from a destructured clay medium during the fault displacement and the propagation of fracturing and damage in the rock. Water circulation above the Toarcian clay layer favours such rock swelling. Previous ERI experiments have been performed from the surface along north–south and east–west profiles of 2.5 km with 64 electrodes separated by 40 m on the Tournemire

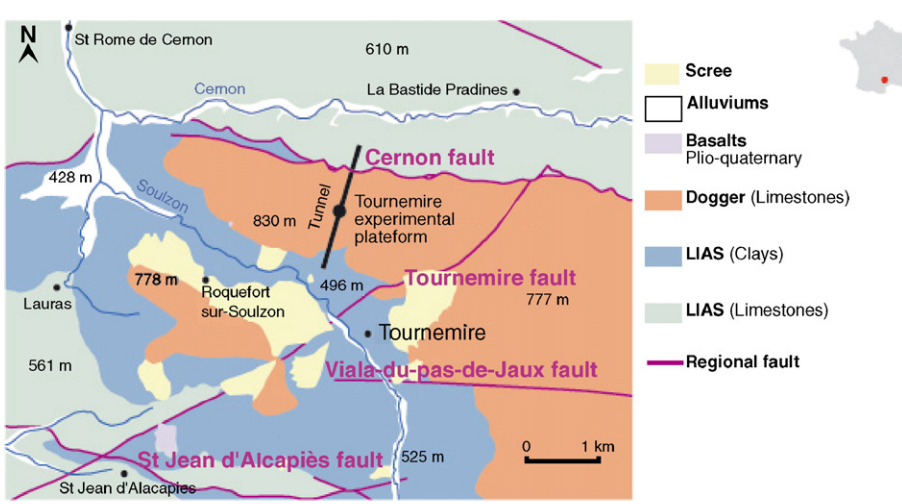

Fig. 1. Geological map of Tournemire region (from Cabrera et al., 2001).

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