Magnetic Resonance Sounding (MRS) investigation of volcanic aquifers using Spin Echo measurements at Mayotte and Martinique (French overseas departments)

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SUMMARY

Volcanic aquifers well documented with hydraulic characteristics from boreholes, 3D resistivity model and high resolution magnetics were investigated using MRS Spin Echo measurements in Mayotte island (mainly basaltic) and Martinique island (mainly andesitic). Magnetic susceptibility of both basaltic and andesitic formation is varying but high, ranging from a few hundred to several thousand 10^{-5} SI. Amongst 18 investigated sites, SE signal was only observed at one where magnetic susceptibility ranges from 200 to 500 10^{-3} SI : inversion results are in reasonable agreement with borehole results but water content is low compared to what is expected for such a sandy aquifer. In several other sites where no signal is observed, magnetic susceptibility is significantly higher ranging from 1000 to 4000 10^{-5} SI. It is supposed that as magnetic susceptibility increases, relaxation increases : with the lower susceptibility (100-1000 10-5 SI), part of signal becomes too short to be detectable and then for higher susceptibility (>1000 10-5 SI) the whole signal is undetectable with current equipment such as Numis^{Plus}

Key words: MRS, SNMR, Spin echo, volcanics, magnetic susceptibility.

INTRODUCTION

MRS application in volcanic setting was, until recently, avoided because of the generally high content of magnetic mineral in volcanic rocks and the expected disturbing effect of magnetic gradient on MRS measurement (Legchenko et al. 2002, Roy et al. 2008). Hydrogeologists, working in volcanic setting nevertheless have a great demand for geophysical method able to precise the aquifers hydraulic characteristics as an alternative to the (popular) widely used resistivity methods. Because of the generally highly developed weathering and hydrothermal alteration, volcanic formation have varying clay content and mineralogy which resistivity response can't easily be distinguished from the water content one (Vittecoq et al. 2014). Legchenko et al 2010 and Legchenko 2014 have shown the feasibility of applying the double pulse (Hahn 1955) echo sequence in MRS investigation and various applications (Vouillamoz et al. 2011, Grunewald et al. 2014) have shown the possibility of determining MRS water content and transverse relaxation constant T_2 in aquifers submitted to high magnetic gradient using the so-called Spin-Echo (SE) procedure. Martinique (French caribbean island) and Mayotte (French island in the Indian Ocean) were quasi uniformly investigated by helicopter borne geophysical methods (magnetics and TEM) in respectively 2013 and 2010 (Deparis et al. 2014, Nehlig et al. 2013). Martinique and Mayotte then appear as convenient experimental sites for testing MRS in a volcanic setting with the benefit of 3D resistivity model for constraining aquifer geometry and of a high resolution magnetic field cover.

METHOD

In homogeneous geomagnetic field, MRS signal can be measured by transmitting a single pulse and observing the free induction decay signal (FID) after the pulse is terminated and an instrumental dead time. In inhomogeneous geomagnetic field, FID signal relaxation is increased and can be difficult or impossible to measure because of the dead time.

The set-up of MRS for spin-echo measurement is the same as that for the common FID measurement, but the measuring scheme consists of a two-pulse sequence. For measuring the spin-echo signal, the second pulse q_2 is generated in the loop with a delay $\boldsymbol{\tau}_e$ after the first pulse q_1. The second pulse such as q_2=2q_1 perform a 180° phase shift. It causes the hydrogen nuclei to refocus at time t=2 $\boldsymbol{\tau}_e$ thus creating a spin-echo signal that can be detected with the same loop, at time distance from the end of the second pulse, avoiding the dead time. The spin-echo signal $\boldsymbol{E_{SE}}$ reaches a maximum amplitude at time 2$\boldsymbol{\tau}_e$ and can be expressed as $\boldsymbol{E_{SE}}=\boldsymbol{E_0}\exp(-2\,\boldsymbol{\tau}_e/T_2)$ where T_2 is the transverse relaxation rate. T_2 and the initial amplitude of the signal $\boldsymbol{E_0}$ are calculated by performing SE measurements with different values of $\boldsymbol{\tau}_e$.

Field experiments were conducted in October 2013 in Mayotte and January 2014 in Martinique. Measurements were carried out with the Numis^{Plus} equipment from Iris Instrument. Three different loop were used depending on the field constraint and water level depth : 8-square-shaped 25, 38 and 50 m side, 2 turns. Spin-echo data were interpreted with Samovar Software v11.62 (Legchenko et al. 2010). Considering geomagnetic field intensity and the 4000 V maximum voltage of Numis^{Plus} equipment, investigation depth of the greater loops is limited to about 40 m. For all experimental sites, magnetic susceptibility was measured on rock blocks and outcrops as well as on soil surface often composed of alterite and sometimes of alluvial or beach sand using a Bartington MS2D susceptibility-meter.

Experimental sites were selected for their hydraulic conductivity measured in nearby boreholes and shallow aquifer in order to provide the most favorable MRS signal level as first criteria and for their varying MRS response corresponding to varying aquifer type and magnetic condition as second criteria. In Mayotte, selected experimental sites characteristics are the followings: boreholes transmissivities range from 1.5 10^{-4} to 2.0 10^{-2} m^2/s (Figure 1) for aquifers depths defined as the top of screen interval, between 9 and 30 m depth and water level generally shallower than 5 m. In Martinique, boreholes transmissivities range from range from 1.0 10^{-5} to 7.7 10^{-2} m^2/s for aquifers depths defined as the top of screen interval between 9 and 30 m and water level generally shallower than 10 m.

Mayotte is an intra-plate volcano with mainly basaltic geology while Martinique is an insular arc volcano with mainly andesitic products. Although they are located at more than 12000 km distance, in different hemisphere, both islands show similar magnetic field intensity (33350-35800 nT in Mayotte and 34000-34950 nT in Martinique) thus giving similar MRS background conditions. Basaltic as well as andesitic formations show varied but high magnetic susceptibility ranging from a few hundred to more than 5000 10^{-5} SI. Measurements in Martinique are illustrated in Figure 2: they are typically in the range of laboratory measurements made by Salomé & Meynadier (2004) in sand and rock sample from Martinique.

Because of the rugged topography of these small volcanic islands, the most productive boreholes are often located near the shore where electric power supply infrastructures are particularly dense. Then a significant part of sites revealed unsuitable for MRS experiment because of poor signal to noise ratio conditions. Finally 18 sites were investigated among the 40 initially selected one's.

RESULTS

No FID signal was observed in any site. SE signal was observed at only one site, Moya (Mayotte) in pyroclatic setting. The top of the main water layer define by MRS SE inversion (Figure 3) correspond to the mean sea level at Moya beach, located 150 m to the east and with the water level measured 1 m above sea level in Pama2 borehole, located 150 m to the north-west. 3D TEM resistivity model (not presented here) show that the area is composed by a continuous resistivity layer (75-150 Ohm.m) extending between Pama2 well toward east, through the area of Moya MRS sounding, up to Moya beach sand. This resistant layer overlay a conductive substratum (<30 Ohm.m) which traduces, partly at least, the salted invasion. It thus tends to demonstrate that a continuous aquifer with significant transmissivity develops below the Moya sounding area. The main MRS water layer develop between 16 and 33 m depth with a mean MRS water content of 5 % for a total volume of about 0.9 m3/m2. By reference to Pama2 well, it corresponds partly to pyroclastics in its upper part and to basaltic sands for its lower and main part (Figure 3). 5% is a low water content for a sand : it may indicate that part of the water signal is not observed. T_2* is about 30 ms. T_2 evaluated as about 390 ms (Figure 4) is typical for a sandy aquifer.

Magnetic susceptibility measured on the soil surface and pyroclastic outcrop along the track descending to the beach range from 100 to 300 10^{-5} SI. The beach sand which could be similar to the sand observed in the well and underlying the MRS sounding area has a susceptibility of 500 10^{-5} SI.

Moya MRS overall characteristics are close to those observed for a medium to coarse sand in Maniwaki in Canada (Legchenko et al. 2010) but the background geomagnetic field magnitude.

The other studied sites with neither FID or SE signal observed partly correspond i) to discontinuous aquifer whose average water volume at the loop scale may be too low to produce a detectable SE signal; ii) to continuous aquifer developed within high magnetic susceptibility formation: high magnetic gradient at the pore scale makes MRS signal undetectable with current equipment such as $\text{Numis}^{\text{Plus}}$.

Several sites of typical continuous alluvial aquifer, developed at shallow depth (0-5m) and characterised by water volume higher than 0.5 m^3/m^2 remains undetectable. Considering a magnetic relaxation characteristics similar to Moya (T_2*=30 ms, T_2=350 ms) they should have produced detectable SE amplitude between 10 and 45 nV considering the different loop and measurement configuration used. Magnetic susceptibility of 1000 to 2000 10^{-5} SI and 2000 to 4000 10^{-5} SI were observed on these sites, respectively in Martinique and Mayotte.

CONCLUSIONS

Eighteen different setting volcanic aquifers well characterized by borehole investigations, magnetic field mapping and a 3D resistivity models derived from heli-borne TEM were investigated by MRS using Spin Echo (SE) procedure in Martinique and Mayotte Island in 2013 and 2014.

Amongst the 18 investigated sites, MRS SE signal was observed only at Moya (Mayotte) in a continuous aquifer setting with a magnetic susceptibility of 200-500 10^{-5} SI. MRS inversion of SE signal defines a 5% water content aquifer layer in good agreement with borehole data. However, observed water content is quite low for this sandy aquifer, which may indicate that part of aquifer water is not observed. Under such high susceptibility condition, calibration taking in account rocks characteristics is recommended in order to correct underestimation.

Amongst the remaining 17 sites where no MRS signal was measured, some are typical continuous alluvial aquifer, with potentially detectable water volume higher than 0.5 m^3/m^2 at shallow depth. We suppose it is because of their high magnetic susceptibility ranging from 1000 to 4000 10^{-5} SI : relaxation is increased and very short SE signal can't be measured with current equipment such as $\text{Numis}^{\text{Plus}}$.

We conclude that the current MRS methodology using SE procedure may be applicable in volcanic aquifers where magnetic susceptibility is lower than 500 to 1000 10^{-5} SI, considering a geomagnetic field intensity of 35000 nT.

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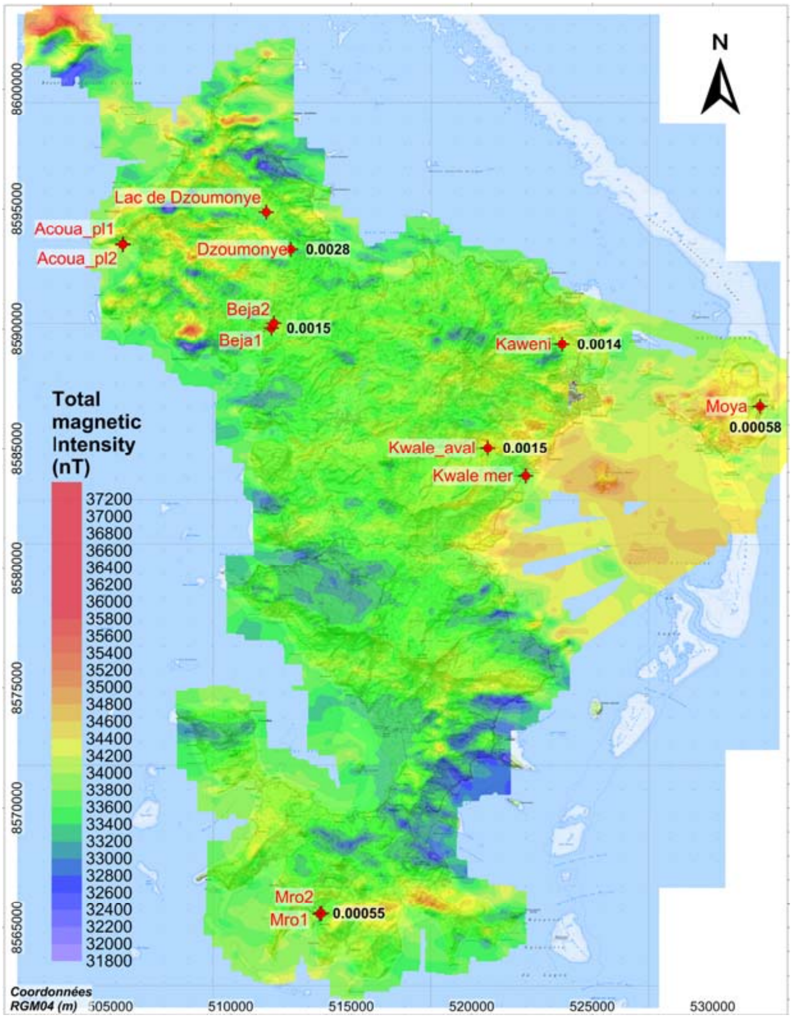

Figure 1 – Location of actually investigated MRS experimental sites with indication of hydraulic characteristics (to the right) superposed to the total magnetic intensity map of Mayotte (modified from Nehlig et al. 2013).

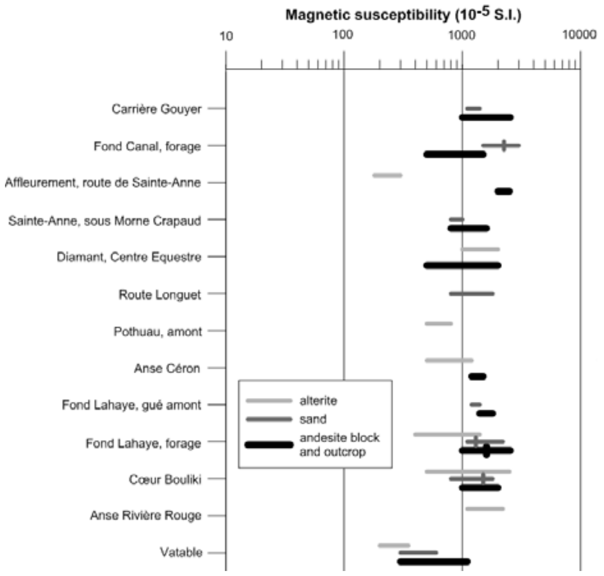

Figure 2 – Volume magnetic susceptibility measured on MRS experimental sites of Martinique.

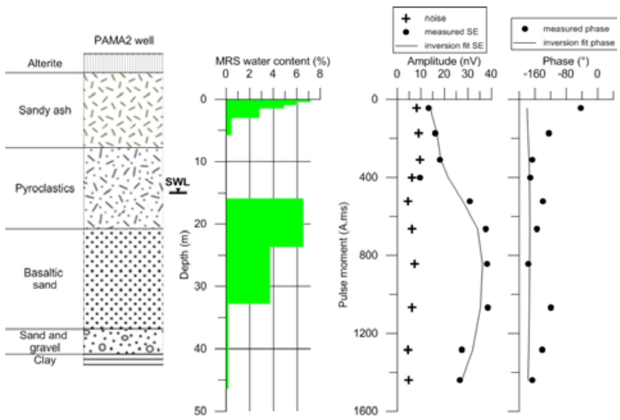

Figure 3- Measured amplitude and phase spin echo sounding at Moya site (right) and water content log resulting of MRS inversion compared to PAMA2 well located 150 m to the west at a 6 m higher elevation.

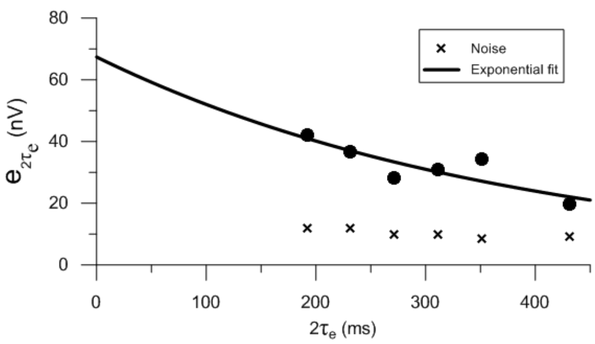

Figure 4- Measured spin echo amplitude versus varying delay between pulses and exponential fit with a relaxation time constant T2 of 390ms.