Monitoring the Excavation Damaged Zone by 3D reconstruction of Electrical Resistivity

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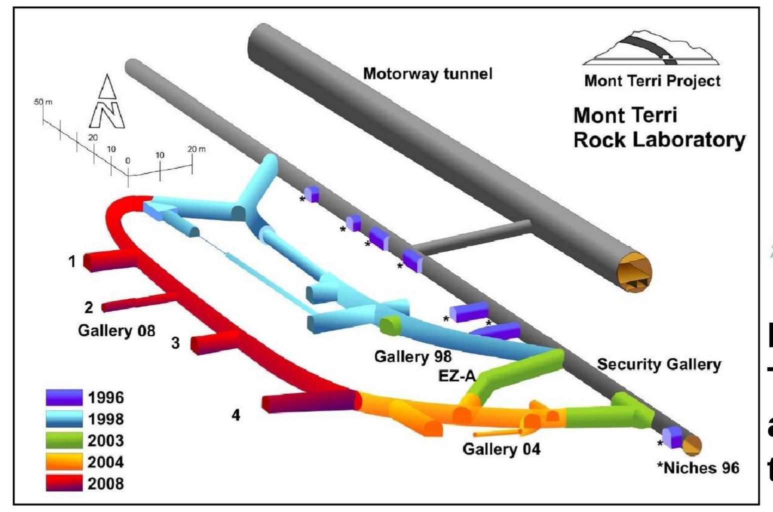
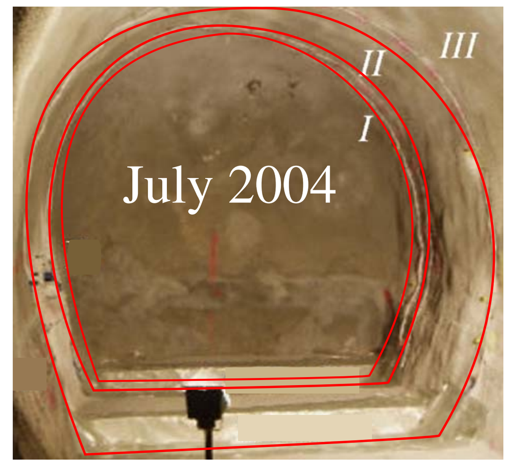
A) MONITORING THE EDZ

A damaged zone is formed during the excavation of underground galleries, altering the rock properties. A 3D electrical resistivity tomography of the Excavation Damaged Zone (EDZ) is developped in Opalinus Clay. This argillaceous formation possesses a very low permeability and a self-sealing behavior suitable for nuclear waste storage [4]. The Mont Terri Underground Rock Laboratory (URL), in Switzerland, is constructed in a such geological formation.



Plan and location of the Mont Terri URL, the experiments are located in the entrance of the gallery 04.

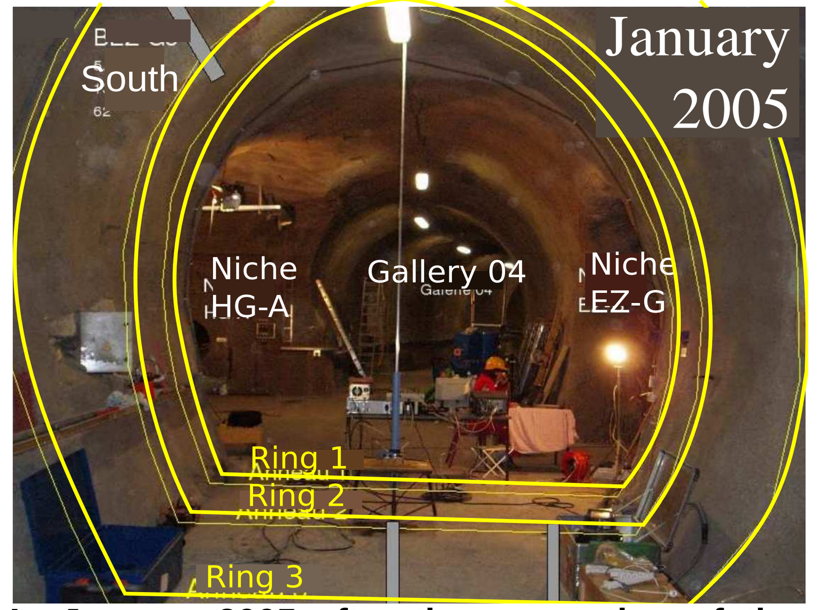
A non-invasive monitoring method is developped to follow the evolution of the EDZ with time. For this purpose a reconstruction of the media resistivity at different periods of the gallery 04 excavation is implemented.



Entrance of the gallery 04 in July 2004, from [3].

Electrical measurements have been carried out from three rings of 32 electrodes surrounding the gallery over four years. The electrodes have been setup in July 2004. At this period the gallery was partially excavated and the rings were located at a distance of 1, 1.5 and 4m from the gallery front-end [3].

In September 2004 the gallery was extended by 20m and by an additional 40m in December 2004. In the beginning of January 2005, two niches were excavated on both sidewalls of the gallery 04.

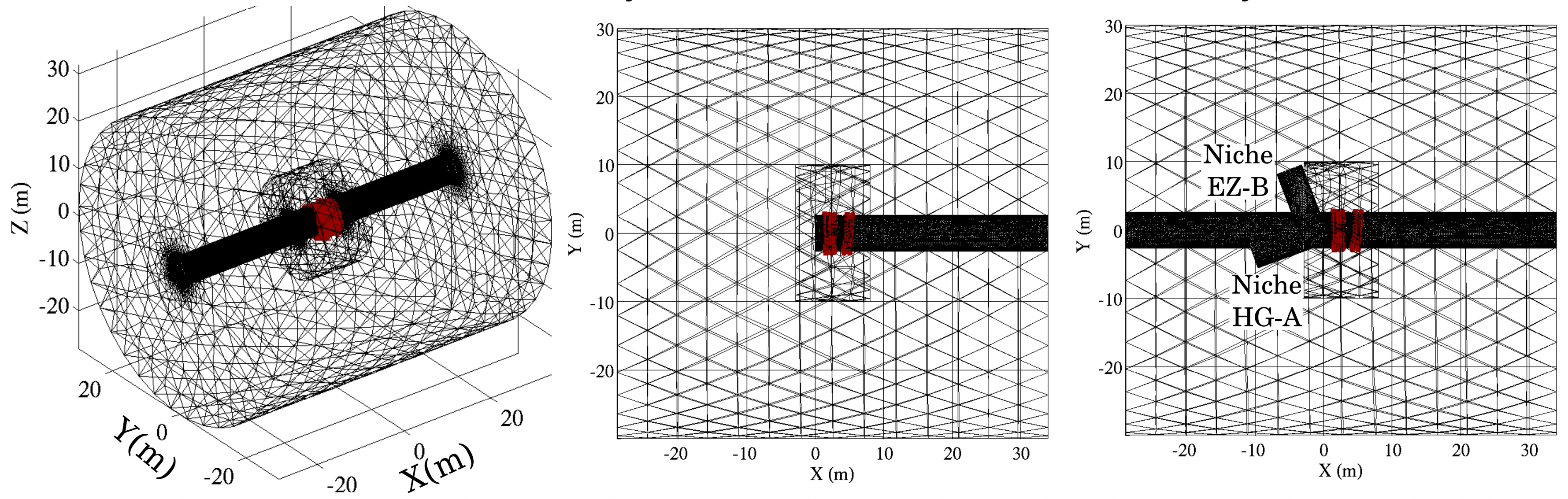


In January 2005 after the excavation of the gallery 04 as well as the niches EZ-G and HG-A.

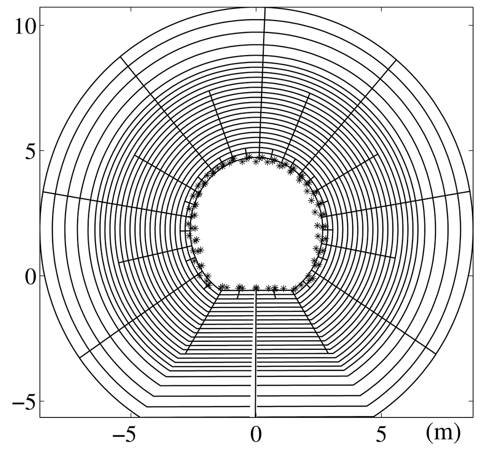
8 data sets have been acquired with the electrode rings between July 2004 and April 2008 with Wenner and Schlumberger protocols to monitor the evolution of the EDZ. Measurements have also been completed in boreholes located in between the electrodes' rings to determine the background resistivity of the media estimated of about 13Ω.m.

B) RECONSTRUCTION OF THE MEDIA RESISTIVITY

The reconstruction of the media resistivity is computed with the EIDORS software [1]. The media surrounding the gallery is represented with a Finite Element Model (FEM) using the NETGEN software. The tunnel shape is constructed from the position of the electrodes' rings. The shape is then extruded to form a cylinder with a diameter and a length of about 60m to avoid boundary effects. A finer mesh is designed near the electrodes and the presence of the niches may be taken into account depending on the period of acquisition of the analysed data set. Mixed boundary conditions are applied between the tunnel and the rock media. Neumann boundary conditions apply between the electrodes where a current is injected, elsewhere Dirichlet boundary conditions hold.

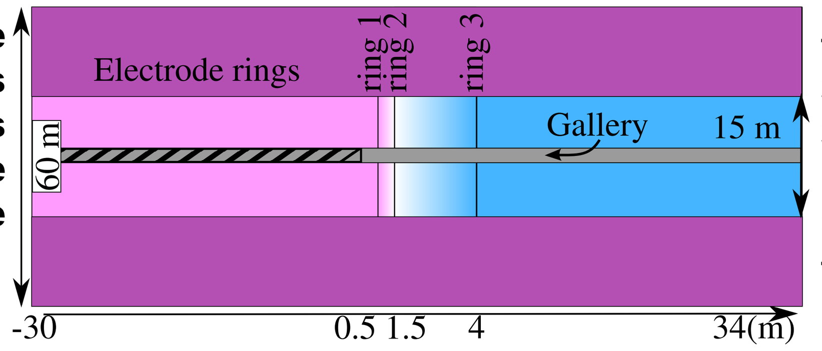


Models of the media surrounding the gallery 04 from left to right: basic, with front-end and with niches.



Mapping of the inverse problem. The 2D surface is divided into sectors coarser far away from the gallery. Stars represent the electrodes.

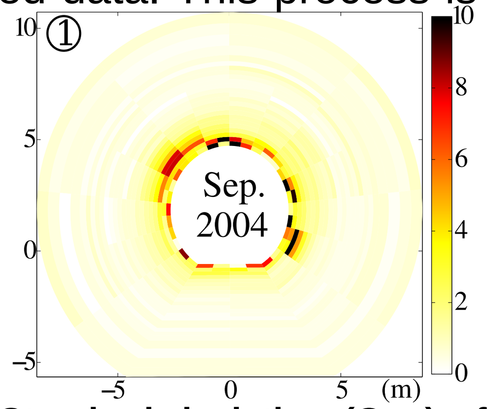
The inverse problem aims at reconstructing the resistivity distribution of the media in order to explain the measurements. In order to reduce the ill-posedness of the problem, the geometry of the reconstructed elements is defined differently from the FEM of the forward problem [2]. Data sets are acquired on 3 parallel rings, so the mapping of the inverse problem is defined in three 2D surfaces corresponding to the areas located around the electrode rings.



The estimated values by the inverse problem of the 3 patterns are extruded in 3D to reconstruct the media resistivity. The sought unknowns correspond to the logarithm of the resistivity.

The inverse problem is solved by the conjugate gradient method. The initial model values are thus slightly perturbed to fit the voltage estimation given by the forward model to the data acquired on field. The perturbation is evaluated by computing a truncated pseudo-inverse of Jacobian, setting the perturbation direction, after an analysis of its singular value. The amplitude of the perturbation is then procured by comparing three results of the forward problem with the observed data. This process is iterated 5 times to increase progressively the fit quality.

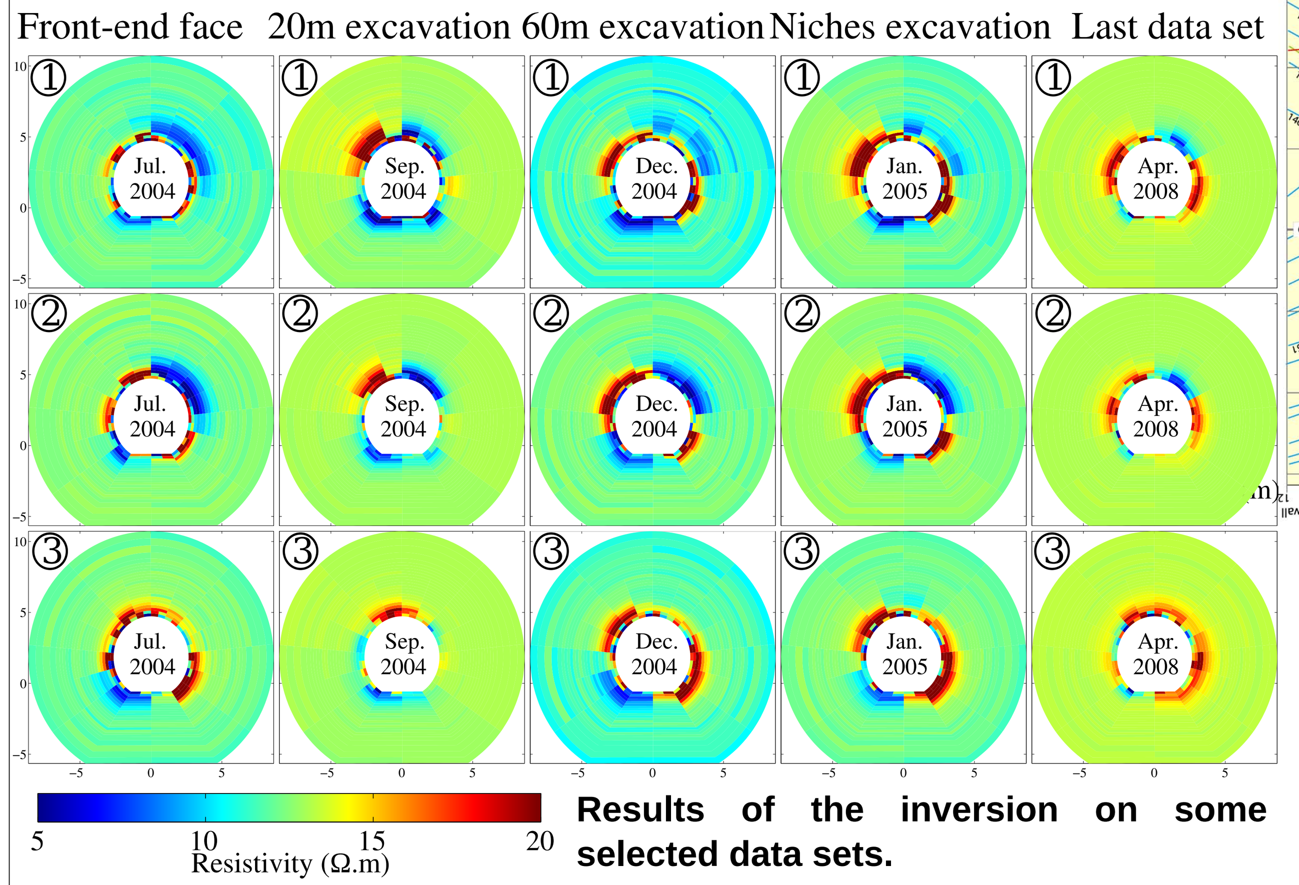
The reliability of the results is tested by adding a white noise to a data set. 100 of such perturbed data sets have been inverted to observe the distribution of the noise in the results. The standard deviation of the results shows that the most affected area is located in the 30 cm surrounding the gallery. At a distance larger than 1 m from the gallery walls the standard deviation remains under 2 Ω.m.



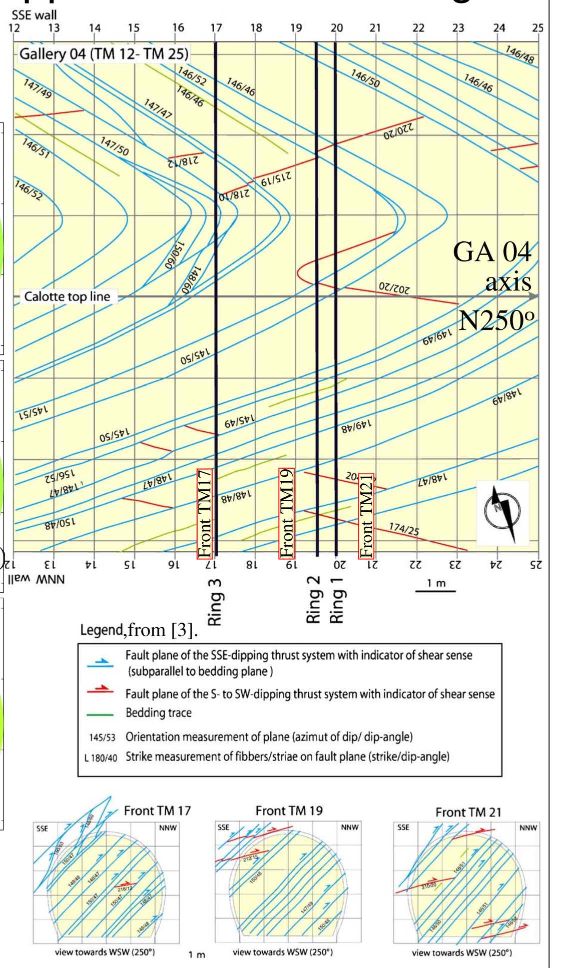
Standard deviation (Ω.m) of of noised data sets inversion.

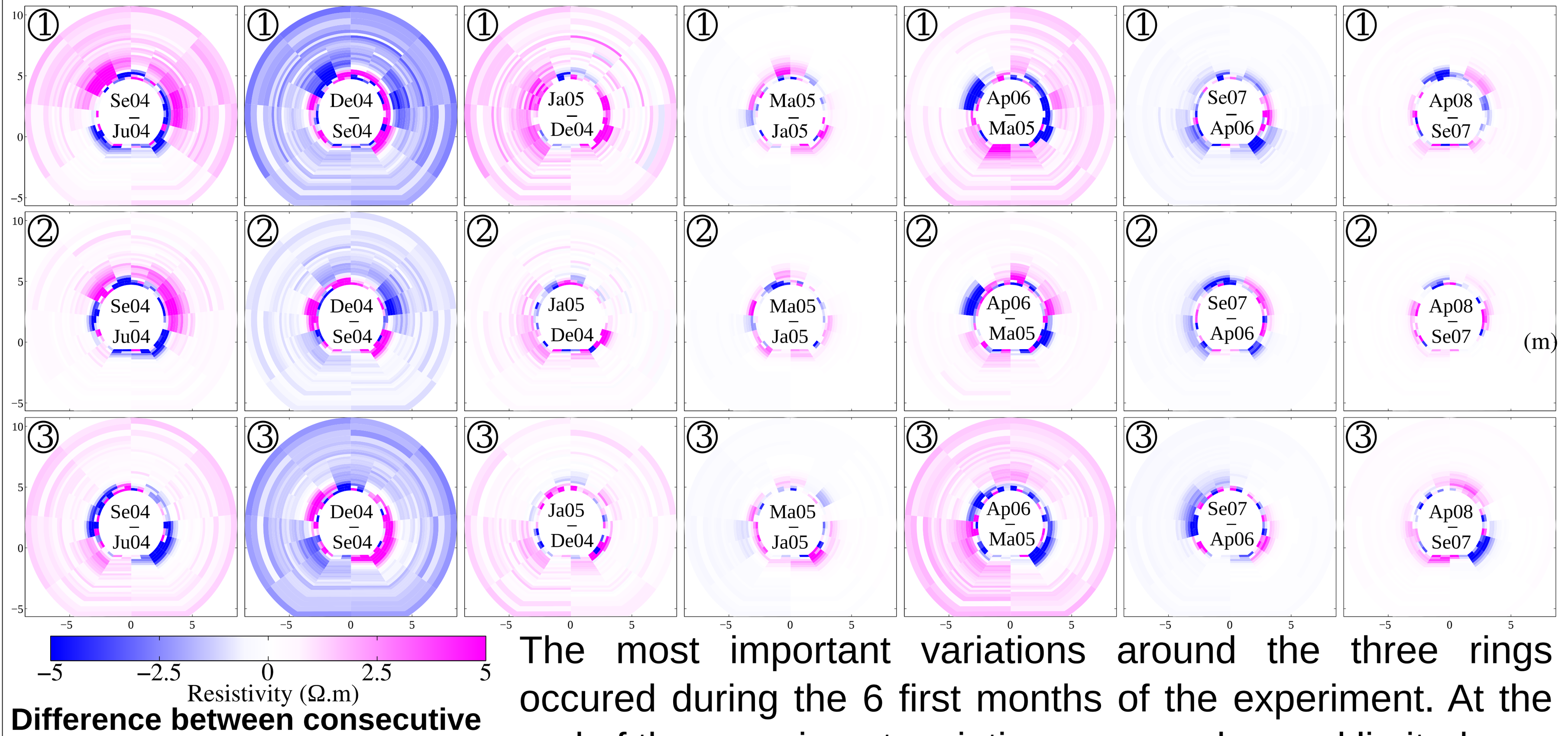
C) RESULTS AND INTERPRETATIONS

Results of the inversion show that the resistivity is inhomogeneous in the 2 first meters around the gallery. The shape of the contrasts vary with time, while the background resistivity remains stable. In July 2004 an important area with a high resistivity is present solely around ring 3. This pattern appear after the front-end disappearance around rings 1 and 2, that was closer to the front-end face.



Results of the inversion on some selected data sets.





Difference between consecutive reconstructed resistivities.

The most important variations around the three rings occured during the 6 first months of the experiment. At the end of the experiment variations are weaker and limited.

The resulting images underline the influence of the EDZ formation revealed by the high resistivity contrasts. The location of the contrasts around the gallery has to be compared with the stratification dip of 45° towards SE [3,5]. The difference between July and September 2004 shows an increase of resistivity in the first meters from the frond-end face. 3 months after the excavation the resistivity decreases consequently far away the first meter of the shell showing contrasts. The region is perturbed again in January with the niches excavation, creating a bigger area of EDZ on both sidewalls near ring 1. After, the extension of such regions is decreasing with time. This decline shows that electrical resistive measurements are sensitive to a slight evolution of the EDZ with time as a succion process is occuring. The pore pressure is indeed negative in the EDZ close to walls. This process is favoured by a high hydraulic gradient due to the excavation.

CONCLUSIONS

The choice of the inverse problem mapping allows finding some contrasts in the media without the use of any subjective constraint such as smoothing matrix. The quality of the resulting images is tested with the inversion of noisy data showing the stability of the inversion and the reduce area of the perturbed region. The resulting values of resistivity vary betwenn 3 and 35 Ω.m in agreement with previous estimation for the Opalinus Clay resistivity [3]. This study points out the fact that electrical resistivity measurement is sensitive to the EDZ and that they allow following its evolution. The 3D reconstruction developed here shows the presence of EDZ following the excavation of the Mont Terri gallery 04. The EDZ extension has a maximal depth of about 1.3m right after the excavation of the gallery. This EDZ is not present all around the gallery and some saturated conductive areas remain after this excavation. The reconstructions performed here underline the presence of a succion process in the region near the walls. To observe the self-sealing behaviour of the Opalinus Clay, a longer period of monitoring would be necessary.

REFERENCES

[1] Adler, A. & Lionheart, W.R.B., 2006. Uses and abuses of EIDORS: An extensible software base for EIT, *Physiol. Meas.*, **27**, S25-S42.

[2] Friedel, S., 2003. Resolution, stability and efficiency of resistivity tomography estimated from a generalized inverse approach, *Geophys. J. Int.*, **153**, 305-316.

[3] Gibert, D., Nicollin, F., Kergosien, B., Bossart, P., Nussbaum, C., Grislin-Mouëzy, A., Conil, F. & Hoteit, N., 2006. Electrical tomography monitoring of the excavation damaged zone of the Gallery 04 in the Mont Terri rock laboratory: Field experiments, modelling, and relationship with structural geology, *Appl. Clay Sci.*, **33**, 21-34.

[4] Nussbaum, C., Bossart, P., Amann, F. & Aubourg C. 2011. Analysis of tectonic structures and excavation induced fractures in the Opalinus Clay, Mont Terri underground rock laboratory (Switzerland), *Swiss J. Geosci.*, **104**, 187-210.

[5] Thovert, J.F., Mourzenko, V.V., Adler, P.M., Nussbaum, C. & Pinettes, P., 2011. Faults and fractures in the Gallery 04 of the Mont Terri rock laboratory: Characterization, simulation and application, *Eng. Geol.*, **117**, 39-51.

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