Time-lapse resistivity imaging : CSEM-data 3D double-difference inversion and application to the Reykjanes geothermal field

Frédéric Dubois[1], François Bretaudeau[1]
[1]BRGM, 3 Av. Claude Guillemin, Orléans 45060, France

SUMMARY

Time-lapse resistivity tomography bring valuable information on the physical changes occurring inside a geological reservoir. In this study, resistivity monitoring from CSEM data is investigated through synthetic and real data. We present three different schemes currently used to perform time-lapse inversions and compare these three methods: parallel, sequential and double difference. We demonstrate on synthetic tests that double difference scheme is the best way to perform time-lapse inversion when the survey parameters are fixed between the different time-lapse acquisitions. We show that double difference inversion allows to remove the imprint of correlated noise distortions, static shifts, and most of the non-linearity of the inversion process including numerical noise and acquisition footprint. It also appears that this approach is robust against the baseline resistivity model quality, and even a rough starting resistivity model built from borehole logs or basic geological knowledge can be sufficient to map the time-lapse changes at their right positions. We perform these comparisons with real land time-lapse CSEM data acquired one year apart over the Reykjanes geothermal field.

Keywords: Controlled-Source Electromagnetics, time-lapse, inversion, geothermal monitoring, resistivity

INTRODUCTION

Geological reservoirs are exploited for various economic reasons: oil and gas production, power and heat generation from geothermal energy, C02 storage or water supply management. Monitoring of time-lapse resistivity changes in the reservoir properties using geophysical techniques can provide valuable information about the reservoir evolution, and is becoming more and more common, facilitated by permanent or semi-permanent acquisition systems. It consists in carrying out at different time a geophysical acquisition over a same region, and produce a structural image showing the temporal changes between the two acquisitions.

More specifically, electrical resistivity provides valuable information in many applications trough its sensitivity to permeability, fluids, clay content or temperature, and can be obtained using a large range of diffusive geophysical methods such as DC electrical resistivity tomography, time-domain electromagnetics, magnetotellurics or frequency domain controlled source electromagnetics (CSEM). Therfore monitoring electrical resisitivity may be very usefull.

For monitoring process, the first acquisition or reference dataset is generally called baseline and the following acquisitions are considered as monitors. In time lapse electric imaging studies, inversion of the baseline and monitor data sets are generally performed separately, or in cascade using baseline model as a starting guess for the monitor inversion. Then the difference between the two inverted models is presented as the time-lapse variation in resistivity of the reservoir. We call those schemes parallel and sequential time-lapse inversion. The high non-linearity and non-uniqueness of the resistivity imaging problems make the inversion results still strongly dependent of the path taken by the inversion. This effect may be exacerbated in presence of high level of noise, which can result in very different inverted models, even without significant model changes.

To overcome problems of parallel inversions, different time-lapse inversion schemes have been proposed, mostly based on the used of constrains between the time-lapse models to force the stability and keep consistency between the time lapse models. For common-acquisition setup between surveys (same geometry, same acquisition parameters), an alternative inversion technique is available to obtain more stable results by reducing the effect of noise and non-linearity of the inversion process. This scheme called double difference or differential inversion is based on the combination of baseline and monitor data. It is commonly applied in medical imaging, is used in seismic travel-time inversion and have been applied successfully to seismic Full Waveform Inversion by Asnaashari et al (2014). But its evaluation on time-lapse resistivity problems have not been reported yet.

METHODS

CSEM inversions are intrinsically non-linear, and iterative optimization methods have to be employed. For each iteration k, we try to minimized the data residual vector which is typically defined as the difference between observed data and data calculated in the current model m_k:

$$\delta d_k = d_{obs} - d_{cal}(m_k) \tag{1}$$

with the computed data d_{cal} related to the resistivity model m_k by the forward operator G.

We define two different data sets corresponding to a baseline acquisition (d_{obs1}) and a monitor acquisition (d_{obs2}). First, a baseline reconstruction needs to be done by minimizing the difference between d_{obs1} and d_{cal} generated in a m_0 starting model. However, at the end of this first inversion, discrepancies remain between observed and predicted data coming from our inability to properly build the true resistivity model.

We can split the different contribution of each data set as follows

$$d_{obs1} \quad = \quad d_{m_0} + \delta d_{m_0} + d_{static} + d_{noise_1} \tag{2}$$

$$d_{obs2} = d_{m_0} + \delta d_{m_0} + d_{static} + d_{noise_2} + d_{pert}. \tag{3}$$

with d_{m_0} the data predicted by the forward modelling, δd_{m_0} un-modelled effects in the forward modelling, d_{noise} and d_{static} the uncorrelated and correlated noise between the two acquisitions , and finally d_{pert} the time-lapse signal related to geological variations.

In case of *parallel* scheme, baseline and monitor inversions are completely decoupled. We compute the time-lapse image by taking the difference between the final inverted models. Baseline and monitor data set do not need to have the same geometry (number of data, number of receivers/sources). This seemingly advantage is a potential pitfall for inversion tuning. However, we may compare models with potentially different inverting mesh, regularization parameters and thus very different local resolution. This will induce signals in the time-lapse model mainly related to the resolution difference between baseline and monitor inversion. Besides, the inverse problem is highly non-linear which implies complex noise propagation between data and model estimates. In *double difference inversion*, extra care should be taken on the perfectly match between baseline and monitor data set geometry. First, the baseline is reconstructed exactly as in parallel inversion. However, in the second step instead of inverting the monitor data we invert the data difference (Asnaashari et al, 2014). We thus define data difference as $\Delta d = (d_{obs_2} - d_{obs_1})$. Then, we rewrite the data residual vector at an iteration k as:

$$\begin{aligned} \delta {d_2}^{dble} &= (d_{obs_2} - d_{obs_1} + d_{cal}(m_1)) \; - \; d_{cal}(m_1) \\ &= d_{pert} + (d_{noise_2} - d_{noise_1}). \end{aligned} \tag{4}$$

A very interesting feature of this approach is illustrated by Equation (4). The data residual is not anymore dependent on the error of baseline reconstruction δd_{m_1}, making the inversion much more robust against the starting model, numerical modeling inaccuracies and non-linearity of the inversion.

RESULTS

The three different inversion approaches are applied to a synthetic case with a resistive and conductive anomaly (Figure 1). This shows how different can be these three different inversion schemes and how weak are the artifacts in the double difference strategy. Then we applied the three different inversion strategies to the Reykjanes geothermal field located at the south-west of Iceland at the landward extension of the Reykjanes Ridge (Darnet et al, 2020). Two surveys are acquired one year apart, a first one in September 2016, while drilling of RN-15/IDDP-2 well. The other is performed in August 2017, after the thermal stimulation of the RN-15/IDDP-2 well. Darnet et al (2020) assess the influence of internal and external noise on survey repeatability between the two acquisitions. Over the whole frequency band, repeatability is within 2-3$\%$ and 2-3°for the amplitudes and phases respectively.

From the first data set, we build the baseline model noted m_1 by using a steepest-descent gradient optimization algorithm available in POLYEM3D. Once an acceptable baseline is found, we proceed to the inversion of the monitor data. Baseline reconstruction depicts the resistivity variations from the data set acquired in September 2016. Once an acceptable baseline is found, we proceed to the inversion of the monitor data by carrying out the three different time-lape inversion approaches. For parallel and sequential inversions: unfitted baseline structures, static shift structures and noise (correlated and not) are inverted in the same time as temporal resistivity changes. The parallel inversion is unable to discriminate between these different contributions, unlike the differential inversion which is focusing exclusively on time-lapse changes which limits drastically the number of artifacts.

CONCLUSIONS

In this study we investigate several time-lapse inversion strategies to infer the temporal changes of resistivity. We compare the commonly used parallel inversion framework with the sequential and double difference schemes. Unlike the parallel difference, the double difference inversion focuses on the time-lapse signal only. We show this approach is much more robust to noise since static noise and modelling errors are completely removed. Double difference is also less dependant on the starting model. Quantitative estimation of the time-lapse resistivity variations however is still dependant on the quality of the baseline model. It is also possible to image and localize resistivity variations even without a proper baseline reconstruction, or with a baseline model built with independent information. For instance, a large scale baseline model could be built with well logs, geological knowledge or a dense EM geophysical survey, and the monitoring performed with a reduced subset of the EM survey kept permanent between time steps.

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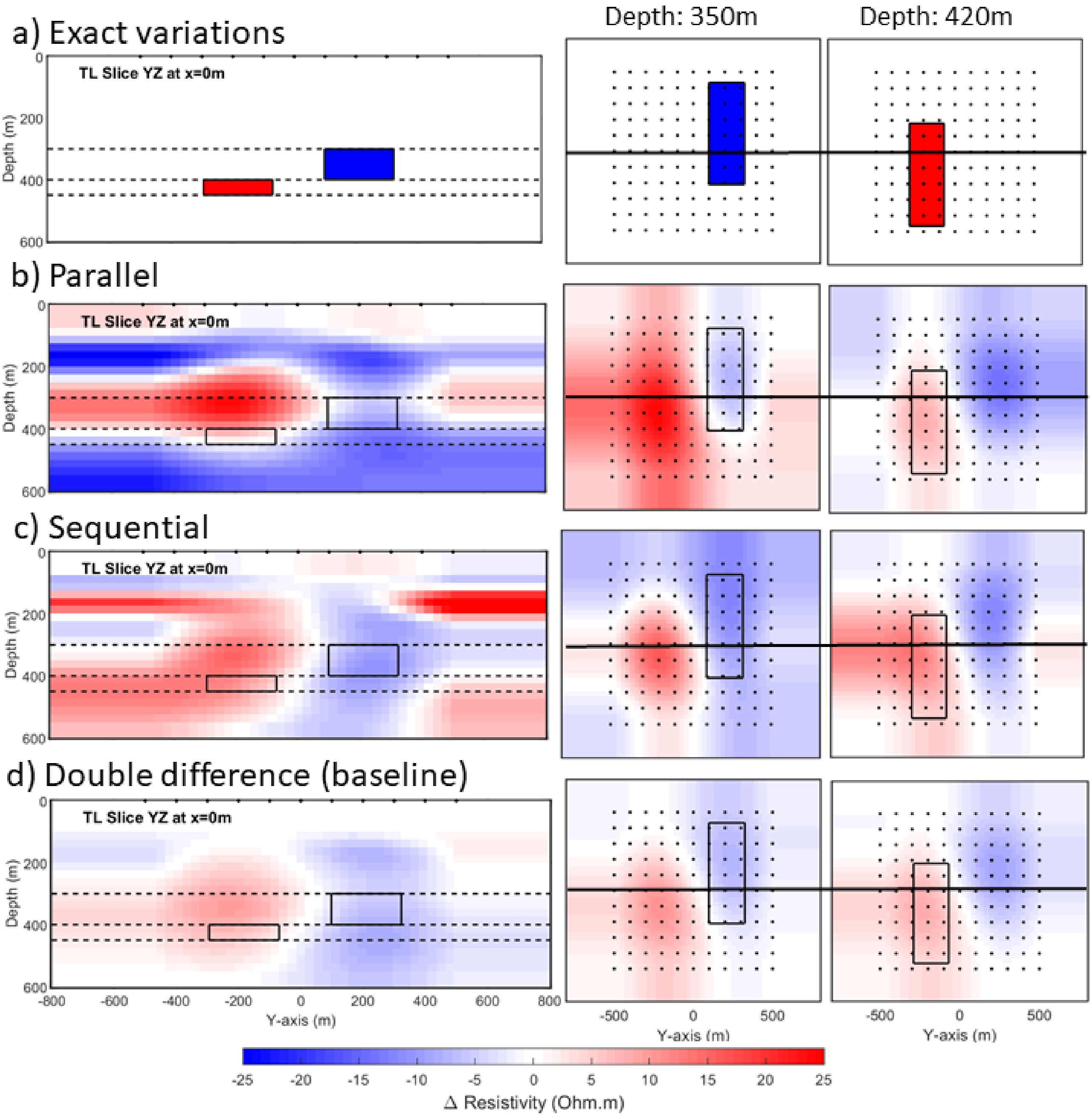

Figure 1: Slices of 3-D time-lapse resistivity models: (a) targets, (b) parallel, (c) sequential, (d) double difference, using a baseline reconstructed from the smooth 1D model, (e) double difference model using the exact baseline as a starting model and (f) double difference model using an homogeneous background as a starting model.