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Discussion

Reply to comment on “Electrical Tomography of La Soufrière of Guadeloupe Volcano: Field experiments, 1D inversion and qualitative interpretation” by N. Linde and A. Revil

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1. Introduction

We thank Linde and Revil for their comment [1] (hereafter referred to as L&R) which gives us the opportunity to provide more details about our methodology and discuss our approach for interpreting electrical resistivity data acquired over complex geological structures. We observe that L&R mainly argue on a speculative basis and *“suggest that traditional smoothness-constrained 2D inversion … could represent a better option”*. In the present reply, we bring more precise arguments and address the main points of L&R’s comment concerning the coherence of pseudo-sections of apparent electrical resistivity, the parameterization of the models used in the inversion, the interest for stochastic inversion approaches, and the estimation of the noise present in the data. As discussed below, the choice of a particular class of models is a delicate enterprise which must be guided by both the geological information at hand and by a sufficient amount of geophysical data sustaining the definite choice. We disagree with L&R who believe that stochastic inversion is of no particular interest and *“belong to the future”*. Indeed, we are convinced that stochastic methods constitute the future of inversion methods because they allow detailed investigations of the space of models and assessment of uncertainties. We address the characterisation of the noise present in the data and we present field data from La Soufrière to show that randomly-repeated measurements are far more relevant than reciprocal measurements to derive the noise level.

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2. Pseudo-sections of apparent resistivity

A main claim of L&R is that *"apparent resistivity data can only be used for qualitative purpose"*. We of course fully agree with this statement and we remind L&R that the qualitative aspect of a part of our interpretation is explicitly mentioned in the title of our paper [2] and in other parts of the text. Acknowledging that *"pseudo-sections of apparent electrical resistivity are useful to get an indication of vertical and lateral variations of electrical resistivity"*, L&R raised concerns about the existence of some discrepancies between intersecting pseudo-sections. We confirm that most discrepancies of apparent resistivity values at intersections of the pseudo-sections are limited to a fraction of order of magnitude (i.e. a factor of 2 or 3), and may be considered small relative to the three orders of magnitude spanned by the apparent electrical resistivity observed in the pseudo-sections. It is normal that such discrepancies are observed, they agree with the approximate nature of the pseudo-sections but do not put in danger the global coherence of the whole data set.

3. Data inversion

L&R are also concerned with our inversion methodology and question several points we now examine in detail.

3.1. 1D, 2D and 3D models

The parameterization of an inverse problem is a difficult exercise, and the choice of a particular class of models to represent the Earth is always open to criticism. Regardless of the reasoning and the method adopted, they must conform to the state-of-the-art principles widely accepted by the scientific community. One of them, to which we chose to conform, is the so-called Ockham's razor principle which states that simpler models must be preferred to more complex models to explain a given amount of information (see e.g. [3]). It must be kept in mind that this amount of information contains both the observed data and prior information which may, for instance, indicate that only 3D models are acceptable. The availability of prior information depends on each particular case at hand. For complex geological structures like volcanoes it also critically depends on the spatial scales considered.

L&R claim that 2D models would be better to invert our data. We have some difficulties to reconcile this statement with their acknowledgement that volcanoes like La Soufrière have a complex 3D structure. Although, as we do in our study [2], 1D models are plausible when considering several local data subsets, we cannot reconcile the validity of a 2D geometry when long profiles across volcanoes are considered. Supposing that the 2D approximation might be acceptable, it should be validated at least with additional parallel and perpendicular profiles. Hence, unverified 2D inversions like the one cited by L&R [4] where a single resistivity profile acquired over the 3D Stromboli structure and topography (see Fig. 1 in [4]) is processed should be avoided in journal publications. Another example of an obviously abusive blind use of the 2D approximation may be found in [5].

It is our opinion that honest and simple approximate representations of the data like pseudo-sections of the apparent electrical resistivity are preferable instead of black-box and unverified applications of sophisticated methods.

3.2. Stochastic probabilistic inversion

We now address the staggering statements of L&R who claim that *"multi-dimensional inversions based on stochastic concepts, such as simulated annealing belong to the future"* and *"inversion of ERT (i.e. electrical resistance tomography) data is not a very non-linear problem"*. Concerning this latter vague statement, we invite the interested readers to refer to the abundant literature dealing with the notoriously non-linear nature of the ERT inverse problem, and recall that the non-linearity of the inverse problem is particularly important for high-contrast resistivity distributions [6] as encountered in La Soufrière.

We also recall, as explained in our paper, that the inverse problem we solve not only consists in inferring acceptable 1D geo-electrical models but also their corresponding data subset. This approach conforms with the most general definition of an inverse problem where the parameter manifold is obtained by joining the space of the physical parameters (i.e. those defining the geo-electrical model) and the space of the observable parameters (i.e. the data) [7]. Also, the statement that the simple shape of the marginal probability curves implies that the inverse problem at hand is not very non-linear is false. Simply recall that the inversion actually deals with the full posterior multi-dimensional probability density function whose topology may be complex with local maxima which are smoothed out by the multi-dimensional integration leading to the marginal probability.

The non-linear nature of the inverse problem requires the use of full non-linear inversion techniques among which simulated annealing has proved its efficiency. Contrarily to the assertion of L&R non-linear stochastic inversion of electrical resistivity data belongs to the present and is increasingly used both in the medical domain [8,9] and in geophysics [10–12]. Notwithstanding that L&R prefer to use 2D commercial software packages, in our experience we have observed that their numerical solutions have a tendency to converge towards unrealistic solutions even for favourable field conditions (i.e. for an assessed 2D geometry as discussed in [10]). This can be attributed essentially to the non-linear nature of the inverse problem in electrical resistance tomography. Another advantage of simulated annealing is the possibility to consider complicated likelihood functions as in [2].

The most modern visions, as recently recalled by Tarantola [13], consider that inverse problems must be formulated in terms of the refutation of a model among a set of a priori models. As researchers, it is in this direction that we focus our work in order to try to improve the toolbox available to invert electrical resistivity data.

3.3. Data and model uncertainties

A further argument justifying the use of stochastic inversion methods is that, as universally accepted by the scientific community, a measurement must be accompanied by its uncertainty. The most recent definitions of an uncertainty are based on probabilistic and Bayesian ideas. They advocate that the posterior probability density function is the recommended quantity to be used for quantifying uncertainty in measurements. This definition has been adopted by venerable metrological associations such as the International Organisation for Standardisation [14], the Deutsches Institut für Normung [15], and the USA National Institute of Standards and Technology [16]. The objective of our study was to determine the depth to the top of an electrically conductive layer supposed to correspond to a potential listric weakness plane characterised by reduced friction and fluid circulation that favour gravitational instability. Therefore this required that we also determine the uncertainty of our measured data.

We now turn to the point raised by L&R about the practical estimation of data errors. In order to illustrate the debate, we explain what we do in the field by taking the example of the Chemin des Dames profile visible in the foremost part of Fig. 5d in [2] and corresponding to segment H in Fig. 9 of [2].

We first confirm to L&R that we perform reciprocal measurements, but we contest their belief that this measurement procedure gives a reliable estimate of data errors. Some authors consider that the comparison of reciprocal and normal measurements is more significant in terms of assessing the quality of the data than the comparison of measurements repeated for a given normal (or reciprocal) electrode configuration. However, as stated in [17], reciprocal measurements are primarily useful to identify hardware problems leading to outliers in the data set. We insist that the statistics of the measurement variations are identical for both the normal and reciprocal configurations. Fig. 1 shows the histogram of relative variations of the normal and reciprocal measurements obtained along the Chemin des Dames profile.

Reciprocal and repeated measurements provide information about noise of mainly instrumental origin as correctly noted in [17] (e.g. cables, AD converters). However, in contrast to what L&R suggest, this type of data error is not appropriate for inverse problems. This is why we also perform additional field experiments where measurements are repeated after randomly moving the electrodes by less than a meter. We strongly believe that this is the correct methodology. The relative data variations observed for this kind of experiment are much more important than those obtained with repeated normal and reciprocal measurements without moving the electrodes (compare the histograms in Fig. 1). They thus reflect the random fluctuations of the electrical potential produced by the heterogeneities in the superficial volcano deposits. These small-scale heterogeneities are not accounted for by the class of models used in our inversion. Therefore the data variations

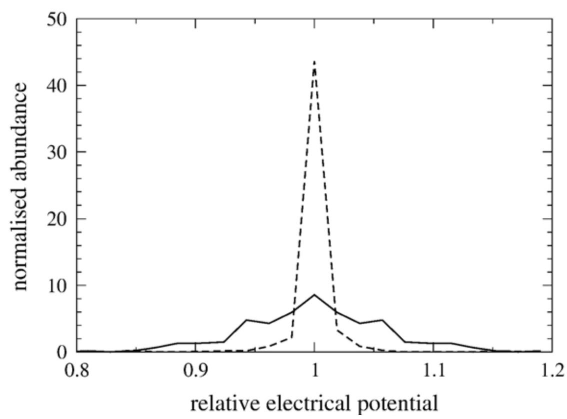

Fig. 1. Histograms of the relative variations of the electrical potential measured for: (1) multiple direct and reciprocal electrode arrangements (dashed line), and (2) random perturbations of the electrode positions (solid line). The relative variations account for the huge range spanned by the potential values (i.e. up to 5 orders of magnitude) and are obtained by dividing each measurement by the average potential corresponding to a given electrode quadrupole.

observed when the electrodes are moved give a minimum noise level that can be used to control the convergence during the inversion. In our inversions, the variance of the residuals remains greater than the variance of this minimum noise level. We recommend the use of this type of lower bound on the noise level to reduce the risk of model over-fitting. This risk is particularly important in inversions of models that consider too many parameters as illustrated in [4,5] and for which a good data fit is obtained despite the simplistic 2D approximation assumed in the models.

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