Interactive comment on “Inner structure of the Puy de Dôme volcano: cross-comparison of geophysical models (ERT, Gravimetry, Muonic Imagery)” *by* A. Portal et al.

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Reply to Dominique Gibert:

We agree that the list of bibliographic references was rather sparse and we tried to improve it in the new version.

Section 2.1 - ERT processing:

p 706, line 24: you mention that Ohm law is used to derive apparent resistivity. Please indicate the geometrical correction used to perform the conversion.

The topography (altitude of electrodes) was incorporated in the 2D model. Apparent resistivity value is proportional to the Ohm law considering the following postulates: homogeneous, isotropic and semi-infinite ground. The proportionality factor, commonly known as the geometric factor *k*, depends on the quadripole geometry (*see Marescot, 2004 and references therein*). For each data acquisition along ERT profiles we used Wenner and Wenner-Schlumberger protocols. We have tried to somehow clarify these points in the text, taking into account, however, that these types of measurements are widely known in the geophysical community and routinely described in many papers.

Could you please give typical values of rock samples?

Typical values of the rocks of the Puy de Dôme are not available for the moment. We plan to measure soon the physical properties of different samples, in particular their electrical resistivity characteristics and their density. This will hopefully allow us to better constrain inversion models in the future. Here we have only set the range of density in the model to standard values for these types of rocks (trachytic dome and scoria cone): 2.00+/-0.64 $kg.m^{-3}$. We have inserted it in the text (*see paragraph 3.2*):

“The range of density variation in the model has been fixed at 2.00 +/- 0.64×10^{3} $kg.m^{-3}$ corresponding to standard values for trachytic domes and scoria cones.”

p 707, line 13: "the raw data were filtered out": could you please give more details about the filtering that was applied to the data and which consequences are expected on the inverted resistivity structure?

Before inversion data points are visualized in pseudo-section using Res2Dinv software. This data plotting method places each data point according to its horizontal location defined by the midpoint of the set of the electrodes and its vertical one that is proportional to inter electrode distance at the quadripole. Data points showing unrealistically large variation (one or several order of magnitude) compared to their trend are considered as aberrant points. They are removed from the set of data before inversion processing.

Figure 1 shows that the 3D topography of the dome has characteristic length scale of the order of the two ERT lines shown in Figure 2. We may then expect important 3D effects in the 2D inversion whose results are shown in Figure 3. Which part of the inverted resistivity structure can be attributed to unaccounted 3D effects? Which noise model was used to invert the data?

Here we are presenting results from two perpendicular ERT profiles. We agree that 3D effects cannot be excluded, although we cannot quantify these contributions in our 2D models. It is clear that a 3D model could better constrain structures inside the volcano, but attempting a 3D inversion would require to improve the existing data set thanks to new ERT profiles. We have tried to stress this issue in the new text. Concerning the noise aspects: (1) the resistivity surveying instruments record an estimate of the random noise for each measurement (made by repeating the same measurement several times, (2) the error was usually low in our case (<1%) although some important errors (up to 20%) were also observed, (3) models of inversion with and without incorporating the measurement errors were however not significantly different. However, since we are still working on this aspect, we have not developed this aspect in the present paper.

Section 2.2 - "High resolution gravity survey" and Section 3.2 "Bouguer map"
A discussion concerning the measurement noise due to both instrument drift and topography uncertainty is necessary. Is the "high-resolution" term used to qualify the 80m mesh of the survey or the precision of the data?
The processing of field data is rather usual and standardized practice. The instrument drift is corrected by measurements made on absolute or reoccupied gravity bases. The drift is considered as linear during a prospect so the correction applied is quite simple. Concerning topography, precise differential GPS positioning has been carried out during gravity survey, with altimetry and planimetry precision better than 5 cm and 7cm respectively. The resulting accuracy of the Bouguer anomaly has been added in the text (*see paragraph 2.2*):
"The resultant Bouguer anomaly obtained with an accuracy estimated to 0.05 mGal…"

The “High resolution” term is used to qualify both the average 80m mesh of the survey and the precision of the data acquisition and the resulting accuracy of the Bouguer anomaly models.

The various corrections listed at the end of the section should be justified. A figure showing the effects of these corrections would help the reader to get an idea of their influence on the residuals so obtained. It seems that these corrections may remove some information concerning the density structure of the dome. Is it right?
Please see the response above. References about gravity data reduction have been added in the text.

For instance, in section 3.3, it is explained that the density used to compute the Bouguer anomaly is chosen to minimize the correlation between the topography and the anomaly. Does that mean that the inverted density structure is then decorrelated from topography? This assumption seems false since we may expect a strong correlation between density structure and topography.
The density of correction value determined by the Nettleton method corresponds to an average density at the volcano scale. This value minimizes the anomaly-topography correlation. Camacho’s software calculates density contrasts which are independent from the correction density. We can set the range of contrast around the correction density value. The choice of the correction density does not change the density contrast distribution in the model. It only constrains the range of variability of the calculated Bouguer anomaly values during inversion process, for each correction density.

What is the uncertainty of the inverted density structure shown in Figure 4? Could you please give an idea of the model variability due to non-uniqueness ?
The rms inversion residual of the density model is less than 0.02 mGal. Quantifying the model variability due to non-uniqueness is beyond the goal of this paper that aimed at providing a preliminary first order models. For the future improvement of our modeling approach, we have chosen to investigate the density of rock samples representative of the rocks constituting of such a trachytic dome. This will allow to input more realistic constraints in the model.

Section 4.1 "Comparison of resistivity and density models"
The authors indicate that the resistivity and density images do not strongly correlate, and they seem give more confidence to the inverted density structure instead of the resistivity structure. No explanation is given to this choice. For instance, the statement "In our opinion, the density model is robust enough to interpret D1 as a massive trachytic structure" should be discussed on more quantitative arguments. Why is the density model qualified as "robust"? Is this because it better agrees with the muon radiography than the resistivity images do?

Whatever their precision, the density models always show a denser structure beneath the summit area. The same observations are made for the low density structures at the base of the dome. This is why we consider the gravity model as "robust", even if, in detail, the shape of the structures may slightly differ. Considering the geological nature of the Puy de Dôme, the dense central structure can be reasonably interpreted as a massive trachytic body. The fact that the same major structure is not individualized on the resistivity models indicates that density and resistivity are not strictly correlated. We thus propose that this massive formation could be fractured and therefore permeable to water and possibly altered. This would account for the observed strong resistivity heterogeneities. We agree however that at this stage of the analysis, both for electrical resistivity and gravimetry, as well as muon radiography, our interpretation is open to discussion. We tried to stress at different points in the paper that all our results are until now preliminary, but, we believe that they are meaningful enough to be shared.

Section 4.4 "Comparison of gravity and muonic models"

What is precisely "muon imagery" and what Figure 5 represents? For instance, does the "non-standardized attenuation" accounts for topography effects, acceptance of the muon telescope, more details should be given. According to the interpretation made by the authors, I understand that "red" is considered as "dense" in Figure 5. If correct, what is the origin of the "dense" margin along the topography profile?

We apologize for the language error. The “muon imagery” was replaced everywhere in the text by “muon imaging” and we tried to better explain Figure 5. We hope that the new label “opacity” is also clearer. The experimental and analysis details are developed in the companion paper by Cârloganu and al. (2012, this GI special issue). In short, to obtain the opacity, the absorption of the muons in the target is measured, corrected for the acceptance of the telescope, as well as corrected for the altitude and zenith effects on the flux. Then the topography (muon range in rock) is dis-entangled from the absorption to get what we called opacity. Theoretically, if the low energy component of the flux is well modeled, if the magnetic field and scattering in the target are well described and the detection energy threshold measured accurately, the opacity is 100% correlated with the density of the target.
Clearly, this is not yet the case for us, as the artefact present on the muon radiography shows, and that has been pointed out in this review. As such, we are sure that the under-summit structure visible in the opacity plot is real, but we cannot yet claim an “absolute” density measurement which would allow us to put a density value in each pixel.

We want to thank Dominique Gibert for the careful reading of the manuscript which allowed us to significantly improve it. We tried to implement in the text the answers to all the comments or stronger warnings about the preliminary status of the results when answers are not available yet.