

Interactive comment on “Unravelling the internal architecture of the Alnö alkaline and carbonatite complex (central Sweden) using 3D models of gravity and magnetic data” by Magnus Andersson and Alireza Malehmir

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We thank the reviewer for the numerous useful comments. We have revised all textual and unclear statements following the reviewer's suggestions. In this document we list both interactive and supplement comments and how we have addressed them in the revised manuscript.

Some short comment where we have been asked to remove a sentence is not added here, if we did agree to the suggestion:

From the Interactive comments:

I have reviewed the manuscript as a general, rather than specialist, reader and provide here my main comments and concerns. I am including an annotated supplementary pdf. Most comments and corrections are annotated there. Here I am focusing only on the most significant points. My most significant concerns are: a) the introduction should include a clear reason to investigate this carbonatite in detail; b) that the manuscript lacks a clear description of how the modelling was carried out and the model constrained. In the current version of the manuscript both points remain unclear, casting doubt on the validity of the preferred results. There must be an explanation added as to how each cell is assigned a value and how the value is constrained using surface geology and rock petrophysics. This same point has been raised by RC1. c) Section 4.2 describing the modelling results need a complete rewrite as it is not possible to follow it. Given these concerns, I suggest major revision followed by re-review. RESPONSE/ACTION: We thanks the reviewer for the comments. The comments mentioned here have been addressed below.

MAIN CONCERNS a) The first paragraph in the discussion provides a clear set of reasons as to why to carry out this work in Alnö. I suggest that most of this paragraph should be replaced in the introduction and worked into the text there. b) Methodology. It is unclear how each cell is assigned a value of density or magnetic susceptibility. The data misfit is taken to zero but just how are the iterations carried out to reach this misfit is not clearly explained. How are the values iterated so as to minimize the misfit and find an appropriate (non-unique solution)? I imagine that this is all in the reference to Li and Oldenburg (1996, 1998a) cited in p. 11, L. 19. This is not sufficient. A brief description of the process must be provided to make the manuscript reasonably self-contained. I was particularly puzzled by a density value modelled that is less than those values measured (density of 2419 kg/m³ in L. 4 p. 14 is below any measured sample). This does not sound reasonable to me and yet I had no information provided that helped me understand how the range of values in the model were derived. RESPONSE/ACTION:

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We think the manuscript now describe the inversion process in enough detail, especial since figure 8 also describe it on a conceptual level. However, if the reviewer request, we can go into more detail on this in the text.

The associated problem is: what constrains the distribution of these values? Geology? How is that done? We all agree that the results are non-unique, as is stated in the paper, but we need to know that this particular result presented is more likely to represent or approach reality than any other result. Finally, clarity in both the methodology and the use of geological constraints would make the results reproducible. RESPONSE/ACTION: This is addressed in the text below.

c) Section 4.2 needs a complete rewrite, organizing the interpretation in a clear and organized progression. Start from the beginning. Before interpreting the nature and geometric distribution of rocks, the manuscript must describe what parameters or combination of parameters were used to interpret rock type distribution. It is not sufficient to provide Table 1 with its average values and standard deviations. The text must say how it was used, particularly because each rock type has a wide range of values. I raise one example below (comment regarding P. 17 L. 29). RESPONSE/ACTION: We have rewritten parts of section 4.2, although it is not a complete rewriting of the section. We think it reads well now, and hope the new version meet the requests from the reviewer. However, we are willing to clarify this section further, if needed.

Throughout this part of the results section, I missed something like what is shown in Fig. 14b. This is a powerful image of the results: the isosurface marking the outer shell of a very high-density zone! Could you not bring this in to the results section. In fact, the entire Fig. 14 should be brought in to the results description. They state powerfully the nature of your model results. RESPONSE/ACTION: Figure 14 (iso-surfaces of density and mag susc) is now brought in to the result section.

The seismic lines are used to support the interpretation but the reader is not introduced properly to them. They are just thrown in. How is the reader to understand

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a sentence such as “This is less obvious in the west along Alnö1 and Alnö2 where the density model indicates vertical geology whereas the susceptibility model indicates outward dipping (D2/S2 in Figures 11c, d and 12e, g).” (p. 17)? Where are we to find this information? The actual figure being referred to is Fig. 12c, d and 13 e,g). In Fig. 12a the seismic section Alnö1 is presented, but nothing much is said about it. This needs proper introduction. Likewise Fig. 13a presents Alnö2 and 3. The reader needs a subsection/paragraph(s) introducing the sections and what they show. RESPONSE/ACTION: The seismic sections are better introduced now, since we also added one extra figure with them.

P. 17, L.29. The text here attempts to ascribe a specific anomaly to the presence of fenites. This needs to be expanded to provide some real basis to it. There is currently no acceptable reason for this link. Investigating the density values of rocks in Table 1, it seems nearly impossible to tell the fenite apart from other rocks with similar densities. So it must be a very particular combination of density signal and magnetic susceptibility, right? RESPONSE/ACTION: This is addressed below in this document.

P. 17 L. 27-30. Need rewriting for clarity. Too many ideas put together and it is hard to follow. Likewise the text in p. 18 is unclear, starting with the link between text and figure 12. RESPONSE/ACTION: We have revised the text.

Other points: P. 12, L. 3 if the horizontal width of 100m is justified on the distance between station, why make a vertical resolution that is so much shorter? RESPONSE/ACTION: Please find a discussion about this below in this document.

P. 14 L 26. Did you investigate sensitivity of results to cell size? RESPONSE/ACTION: Yes. For details, see below in this document.

Fig. 15. Explain the insets. Also the caption explains your preference for C but the ring is hardly visible in this case. RESPONSE/ACTION: The figure caption, and the text in the discussion, states that we prefer scenario B and C. The text says: “The rim would then comprise of a mixture of carbonatite and alkaline rocks, as the petrophysical data

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suggest high magnetic susceptibility for these rocks”. Where is this statement from?
RESPONSE/ACTION: Indeed “The rim would. . .” is a speculation from our side.

I probably don't understand what is been shown in Fig. 15. Do you mean that all diagrams shown (A-D) reproduce the ring structure at the surface? I am missing something here. P.24, L. 27 this seems to contradict previous figures and discussion where a $SI > 0.05$ has been shown in Fig. 14 and the model result showed even higher SI in the model. Can you explain what you mean hear to clarify? Conclusions: I don't think that the results implies the existence of a magma chamber. Only that the intrusive volumes are larger at depth: maybe multiple intrusions spread in time. Please reword it or remove this conclusion. RESPONSE: Different scenarios are shown here and it appears that regardless of what scenario is considered, a ring structure near the surface can be observed in most cases. This is not surprising in a way since we observed the ring-structure in the data too. This is not inconsistent. You are right that there may be a number of intrusions there but why is one so ring/rim-like looking and other not?
ACTION: No action.

From supplement:

p5 fig2? COMMENT: not clear in Fig., help the reader sees what you mean. RESPONSE: If this refers to fig 2, see above. ACTION: No action.

p6 fig 3a COMMENT: can you crop (a) a little to bring out the features more clearly? RESPONSE: Yes ACTION: We have cropped (a).

p6 fig 3b COMMENT: please label dark dyke and the coarser dyke and the boundary with country rock. Mention that country rock is deformed etc. RESPONSE: Agree ACTION: We have done this.

p7 COMMENT: consider adding an image from Anderson 2013? RESPONSE: Good idea. ACTION: We have added a figure showing the seismic section of the 3 seismic profiles. NB! It is placed as new figure 3 and the following figs are now incremented by

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1.

p8 COMMENT: why are they the most interesting? Surely the most interesting rock here is the most voluminous one or the most strongly magnetic??? RESPONSE: “Interesting” refer to the objectives of Andersson et al (2016). See also above. ACTION: The text has been re-written.

p8 COMMENT: refer to Table 1 in the text here. Also, the fenite has an average density of 2729 which is the same as the nepheline syenite 2727. So this statement is incorrect. Migmatite is not so different either.... RESPONSE: That is correct, the text is updated now. ACTION: Text updated and refers also to Table 1.

p10 COMMENT: references needed, estimated by whom? where? RESPONSE: This is what we have been told from the Geological Survey of Sweden, who provided the data. ACTION: No action.

p11 COMMENT: has this been used by any references? What is this based on? RESPONSE: Text already changed according to the suggestion from the anonymous reviewer. ACTION: No further action.

p11 COMMENT: there must be an explanation added here as to how each cell is assigned a value and how is the value constrained using surface geology and petrophysics. RESPONSE: Surface geology was not used as a constraint and petrophysics was used to justify ignoring the remnant magnetization and assigning bounds within a reasonable range (see also above about the bounds). ACTION: Not required.

p12 COMMENT: how do you justify this given that? The horizontal width of the cells of 100m is justified based on the distance between stations for gravity measurements, why make a vertical resolution that is so much shorter? RESPONSE: The code takes the topography into account by not assigning density values for cells above the terrain model. By choosing vertical cells that were 100 m in vertical direction we would not benefit much from this because the topography is about 110 m in Alnö Island and the

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highest point on the mainland is about 130 m. ACTION: No action required.

p14 COMMENT: add negative and positive signs to make it clear RESPONSE: Typo
ACTION: The text has been updated.

p14 COMMENT: did you investigate sensitivity of results to cell size? RESPONSE: Yes, prior to choosing the final cell size we did tests with both smaller and bigger cell sizes. With bigger cells the computing time was significantly shorter, but the resolution was of course not so high. And we had the ambition to identify object at the 100-meter-scale at least near the surface. With cell 50 x 50 m in horizontal directions the computation time got very slow for MAG3D and for GRAV3D it even crashed. The crash was probably due to problem for the memory to handle the number of cells. Because of this we chose to keep it to 100x100 m for gravity inversion (consistent with the gravity station spacing). And in order to make it easier to compare gravity and magnetic inversion we used the same “mesh” for both. ACTION: No action.

p17 COMMENT: this is difficult to accept without further explanations, given that fenite has, according to Table 1, a density range indistinguishable from other units RESPONSE: The suggestion that it is fenite here is based on the low density for this rock volume in the model and that it is mapped as fenite in the geological map. Considering the density it could as well be nepheline syenite or migmatite. ACTION: The text has been rewritten to also mention migmatite and neph. syenite as alternative options.

p18 COMMENT: mark these clearly on Fig. 12a, I cannot see what you mean, particularly the density seems to form a single high.... RESPONSE: This refers to the inverted models in Figure 12c-d. Comment: The discrepancy is probably because in Figure 12a it is ground gravity and ground magnetic measured along the profiles projected to the CDP-line of seismic line Alnö1, whereas in Figure 12c and Figure 12d it is a slice of the inverted model along the same CDP-line. ACTION: This is now clarified in the text.

p22 COMMENT: what is a world-class carbonatite? You mean type locality? or well-known? RESPONSE: Well-known. ACTION: Updated text so it says well-known.

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p22 COMMENT: help us see this in Fig. 13 RESPONSE: OK. ACTION: One sentence is added in this paragraph to direct the readers.

p24 COMMENT: reword: 0.01 refers to a difference in mag sus to a base value, right? Change caption as well RESPONSE: No, 0.01 SI is the cut-off value in figure 15a. Background value for the model is 0 SI. ACTION: No action required.

p24 COMMENT: do these correspond to the same S4 etc as seen in Fig.10b? RESPONSE: Yes. ACTION: Now also referring to fig 10b.

p24 COMMENT: this seems to contradict previous figures and discussion where a $SI > 0.05$ has been shown in Fig. 14 and the model result showed even higher SI in the model. Please explain RESPONSE: See above. ACTION: We have responded to this above.

p25 COMMENT: I can't see the ring structure in c! I marked it in a and b RESPONSE: Yes, it is hard to see the shape from only this figure, but we think it is possible in conjunction with Figure 10. ACTION: We have modified the figure.

p25, fig15 COMMENT: explain the insets RESPONSE: Agree. ACTION: Text has been added in the figure caption.

p26 COMMENT: I personally find this is gone too far in the discussion and recommend removing, but leave it up to you to decide. RESPONSE: Agree ACTION: Removed text: "The caldera collapse must have been preceded by intense sheet intrusion with low-magnetic, probably alkaline, magma whereas the caldera collapse has brought a new generation of magnetic magma. A similar magnetic ring-shape is expressed over the Richat Dome (Mauritania) and has been interpreted to relate to ring-dykes from a piston-like caldera collapse, however Richat Dome has two concentric ring-dykes and they are of gabbroic composition (Matton, 2014)."

p26 COMMENT: this sentence is disconnected from the previous sentences, it needs some words to link up RESPONSE: Agree. ACTION: The sentence is now linked to

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the beginning of the paragraph.

p26 COMMENT: I don't understand this scenario. Scenario 1 is logical in that it explains explicitly why the trend is trend 3, but scenario 2 seems to be discussing the origin of rocks but not relating to their petrophysical properties. RESPONSE: The text has been updated to address this. ACTION: The sentence above the scenario list is updated, it now says that a discussion will follow.

p27 COMMENT: this is somewhat misleading on two counts: a chamber is not a magma source, it is a source of dykes. More importantly, if the body at the surface is made of multiple intrusions over a period of time, their merging downwards only means that they have become a single larger body RESPONSE: We agree. ACTION: The sentence is removed.

p28 COMMENT: again, I don't think that it implies the existence of a magma chamber. Only that the intrusive volumes are larger at depth RESPONSE: The magma chamber has been speculated for a long-time given the geometry of the complex. This is why we refer to this in the shed of the existing data. ACTION: No action was required.

p28 COMMENT: shouldn't this have been said in section 5.2 and these names added to Fig. 15? This kind of information is out of place in the conclusions and the detracts from the main conclusions. RESPONSE: Agree. ACTION: The text is edited and moved to section 2.1 "Geological setting"

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