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Interactive comment on "Post-glacial reactivation of the Bollnäs fault, central Sweden" *by* A. Malehmir et al.

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GENERAL COMMENTS

The paper shows an example of an integrated geophysical ground survey over a fault revealed by LiDAR data. Many different methods have been used and compared: magnetics, gravity, seismic refraction, ERT, RMT, GPR. I think that the paper could be a very interesting and original example of the geophysical signatures over a shallow fault and could be a good reference for future similar investigations. For these reasons it deserves publication. However, I think that the paper in the present form suffers from some imprecisions in the methodology and in the conclusion sections and should be improved. The weakness that in my opinion should be addressed are underlined in the following 'specific comments' section.

SPECIFIC COMMENTS

1 - Gravimetric method and interpretation

1.1 - Data processing and errors estimation

No information are given about gravimetric data processing and quality control. The final Bouguer anomaly data show a maximum pick to pick difference of only 6 gu, that is 0.6 mGal (see Fig. 5b). Therefore I think the following information could help the reader to evaluate the work performed and the resulting anomalies:

a) Particular equipment of the L&R G gravity meter, such as electronic levels, electronic beam indicator, electronic nulling system or other should be indicated, if present.

b) Mean and standard deviations of the closure errors

c) Error evaluation of a single measurement. If repeated measurements at some locations are not available, at least a heuristic estimation should be provided. An alternative could be to provide the standard deviation of the difference between the gravity values at the base station and the assumed drift curve (obtained as low order approximation of the measurements at the base station).

d) Error evaluation of the final Bouguer anomaly data, taking into account the error of a single measurement (see point b) and the elevation errors that affect free air, Bouguer plate and topographic corrections.

e) References to the formula or methods used for the latitude, free air, Bouguer and topographic corrections. The adopted topographic correction procedure should be explained in some detail.

f) Levelling errors check In the Bouguer anomaly map shown in fig. 5b and 5c, there is a clear level error along the second line starting from North. It is not visible in the free air map of fig. 5A and therefore it could be related to Bouguer and/or topographic corrections. At least a check should be performed on data processing to ensure this is not an artefact and a brief comment should be addressed in the text.

g) Residual maps The gravimetric data shown in figures 5a, 5b, 5c seem to be residual anomaly maps. I agree that the 'absolute' values are not important in this contest. However I couldn't find any explanation about the residual procedure in the text.

1.2 – Reference density for Bouguer and topographic corrections

The Authors show two different (residual) Bouguer anomaly maps in Fig. 5b and 5c with a reference density of 2200 and 2670 kg/m3 respectively. Both the maps are used for interpretation. However, the comparison along a profile between the (residual) Bouguer anomaly at 1800, 2200, 2670 kg/m3 (Fig. 10B) and the topographic profile (Fig. 10A) shows that the correct reference density is around 2200 kg/m3. In fact the 2670 kg/m3 (residual) Bouguer anomaly graph is anti-correlated with topography while the 1800 kg/m3 (residual) Bouguer anomaly graph is slightly positively correlated. The Authors themselves note that the correct value is 2200 kg/m3 at pag. 2845, rows 17-21. Therefore, the 2670 kg/m3 (residual) Bouguer anomaly map should not be shown and interpreted since biased by the topographic effect. I suggest a more careful analysis to find the correct reference density for the (residual) Bouguer anomaly map. At least two options are available:

a) Use the Nettleton approach along different profiles and compute the correlations between the Bouguer anomaly at different densities (for instance from 1700 to 2700 kg/m3, step 50 kg/m3) and the topographic profile. Then graph the absolute value of the correlation factor (y dependent variable) against the density (x independent variable): the correct density value is found at the minimum of the function.

b) Compute the gravimetric 3D forward effect of the topography at different densities. Then compute the RMS misfit between the calculated field and the measured free air anomaly and choose the density that gives the lower RMS misfit.

1.3 - Gravimetric interpretation

a) All the interpretations based on the 2670 kg/m3 (residual) Bouguer anomaly map must be avoided since this reference density correction is wrong. In particular: pag. 2839, rows 4-7; pag. 2845, rows 12-14 and 25-27. The gravimetric interpretation must be reassessed on the base of the correct reference density (residual) Bouguer anomaly map. Note also that using both the 2200 and 2670 kg/m3 density for the interpretation, the results appear somehow confused or contradictory. For instance, at pag. 2845, row 20-21: <... there is no detectable bedrock level difference from one side of the scarp to another>; then, immediately after: <... the fault location and depth to the body would be similar to that of the magnetic data (i.e., 25 m)>

b) In the case the final reference density will be close to 2200 kg/m3, the Bouguer anomaly will be similar to the map shown in Fig. 5b, where the Eastern side of the survey area shows values larger than the Western part of about 0.3-0.5 mGal. In the (very simple) case where the sedimentary cover and the bedrock are considered uniform, two different explanations of the observed (residual) Bouguer anomaly are possible. i) The bedrock is approximatively flat and the (residual) Bouguer anomaly is only due to the clearance between the measurement points and the bedrock (the distance from the supposed flat bedrock and the measurement points grows up moving from East to West due to the topography) or ii) there is also the effect of a step in the bedrock. I think that a simple 2D modelling could help to give an answer, even if many simplifying assumptions must be taken about the densities and the mean depth of the bedrock.

2 - Magnetic method and interpretation

2.1 – Definition of the magnetic lineament

The magnetic lineament cited firstly at pag. 2844, row 19, is not defined. That is, it is not clear which method and assumptions have been used to trace it.

2.2 – Short wave length signal

Data shown in Fig. 5d are affected by short wave length signal (apparently noise coming from the walk-gradient configuration) that disturbs the signature of the fault. Perhaps an upward continued or low pass filtered map could help the reader to concentrate on the signal coming from the bedrock and could be used to test the effectiveness of some digital enhancement techniques.

2.3 - Digital enhancement

To improve data processing some digital enhancement techniques could be tested and, if successful, included in the paper to better constrain the location and depth of the source originating the 'lineament'. For instance tilt derivative usually can map faults and discontinuities location, Euler deconvolution can map simple step/faulting in the bedrock and give an evaluation of the depth, the analytic signal and pseudogravity analysis can depict the magnetic sources.

2.4 – Magnetic interpretation

The situation is similar to the one discussed for gravity. To the East the magnetic values are about 200 nT higher than to the West. If we assume a magnetised bedrock against low magnetised sediments, again two different models must be tested by 2D modelling: i) the bedrock is approximatively flat and the anomaly derive from the variations of the source – measurement point distance that increases from East to West or ii) there is also the effect of a step in the bedrock.

3 - Seismic method and interpretation

3.1 – Refraction data analysis

First P arrival classical dromocrones are not presented, but they are usually very useful to give an idea of the whole data set to the reader. The cumulative first break picks shown in Fig. 7a are not enough to give a clear picture of the data set. Classical refraction modelling have been tested but results have been considered <... not convincing and hence ... not presented> (pag. 2841, row 10). However there is some contradic-

tion with what is stated at pag 2840, rows 24-28, where a refractor is described and identified with the bedrock that appears deeper on the western side of the scarp. Moreover in Fig. 6 different refractors are described and velocity assigned, without taking into consideration possible inclination of the refractors biasing the velocity estimations. Therefore I think that:

a) First arrival dromocrones should be shown to illustrate the data set with some detail

b) The failure of classical refraction data analysis should be investigated and discussed with more detail. Otherwise the reader will look with suspicious to the next refraction tomography analysis.

c) Refractors' identification and velocity assignments (pag. 2865, Fig. 6) should be discussed considering the possible geometry of the refractors. Ideally at least a simplified model obtained with the GRM method or similar should be presented. If not possible, they should be avoided.

3.2 – Refraction tomography

a) 3D modelling along a line

The adopted discretization model (pag. 2841, rows 19-23) with 15 m long cells along the transversal direction is necessary to force the software acting as a 2D software. Maybe the transversal length of the cells should be much longer than 15 m (7.5 m from one side and 7.5 m to the other) to ensure a 2D solution?

b) Travel time residuals

Travel time residuals as a function of offset for all the receiver locations are shown in Fig. 7b (pag. 2866). If possible, in order to have a deeper (and interesting) insight on the velocity model data fitting, also i) the measured vs the calculated dromocrones should be shown together with ii) the rays' path superimposed on the velocity model.

c) Far-offset data

It is not clear for me the explanation about the higher misfit of the far-offset data given at pag. 2841, rows 26-28, based on the <less ray coverage [at depth?] as opposed to the high-density ray coverage at the near surface>. If the ray coverage is reduced at depth, then it should be easier to find a velocity model that predicts the data, because there are less constraints to be accounted for. Therefore I think the explanation is another one. The shorter offset data number is much higher than the far-offset data, and they influence the shallow velocity distribution alone. On the contrary, the far-offset data depends on both the shallow and the deep velocity distribution. Therefore, in order to get a final low RMS misfit, it is preferable to fix the shallow velocity distribution in order to have a good fit for the many shorter offset data even if the far offset data would require some modification of the shallow velocity distribution to get a good fit.

4 - RMT method and interpretation

4.1 – Raw phase and resistivity data

Raw phase and resistivity RMT data are shown in Fig. 8 (pag. 2867) at three stations located in Fig. 11 (pag. 2870).

a) The computed phase and resistivity data should be superimposed on the measured ones, in order to give to the reader an idea of the model data fitting.

b) It is not clear to me what the red arrow in Fig. 8C would indicate: i) the one value drop of the apparent resistivity at about 25 KHz or ii) the whole frequency range 10-70 KHz that shows lower apparent resistivity values with respect to the other two stations. If it is the first case like the figure suggests, it is difficult for me imagine how the fault signature could influence just one frequency alone.

c) The phase values of Fig. 8f do not start close to 45° and appear very low. Are they reproduced by the model shown in Fig. 11a?

4.2 - Error floor

An error floor of 4% on apparent resistivity and phase has been used for the inversion

(pag. 2842, row 27). However, since the phase values are not intensity values, an absolute floor value (e.g. 2°) should be preferable for it. I cannot see any reason to explain why a phase value of 10° should have an error floor of 0.4° while a 80° phase value should have an error floor of 3.2°.

5 - ERT method and interpretation

Also in this case, I think that the acquired data set should be shown in some way to allow the reader to have a clear image of it. Is it possible to show the measured and calculated (from the final models shown) pseudo-sections for both the profile?

6 - GPR method and interpretation

6.1 – Time to depth transformation

In Fig. 13A (pag. 2872) an example of GPR profile is shown. The vertical scale is in metres. No reference in the text can be found about how the time has been transformed in depth. How was the electromagnetic velocity estimated? Moreover, two not coincident antennas were used (at what distance?) but nothing is said about the data processing, if any.

6.2 – GPR interpretation

The only interpretable signal in GPR data is a shallow (2 – 5 m) reflector dipping towards East, found in most of the profiles immediately east of the scarp and shown in Fig. 13a (pag. 2847, rows 1-2). At pag. 2847, rows 8-18, three different contrasting explanations of the reflectors are reported.

a) The reflection in the GPR data is likely generated by the interface between till and underlying silt and varved clays, revealed by a trench (indicated as 'Seminstation' in Fig. 3b and shown in Fig. 13b) along the same profile 1 (pag. 2847, rows 8-9). However, note that in the trench stratigraphy of Fig. 13b the reflector (red arrows?) is indicated at the interface between layers 'Till 1' and 'Till 2'; on the contrary, in the trench of Fig. 13c, the reflector is indicated at the interface between layers 'Till 2' and (varved) clay.

b) Moreover, <it is possible that the lack of continuity in the western-end of side of the GPR reflection at roughly where the scarp starts is an indication for faulted sediments> (pag. 2847, rows 13-14). However, from the text and the stratigraphy shown in figure 13b and 13c, it seems that no fault evidence has been revealed by the trenches that are coincident or close to the GPR profile (Fig. 13a). c) Moreover, <the reflection may also be from groundwater table and its interruption in the western side (Fig. 13c) due to water flowing suddenly into the faulted bedrock>. However, i) in Fig. 13 b the water table (dashed line) appears continuous along all the trench and extends over a much larger area than the reflector shown in the GPR section while ii) in Fig. 13c the water table (dashed line) has not been detected where the reflector is.

I think that the most realistic interpretation is the first (a) and the other two, on the base of the indications shown in the paper, should be omitted.

7 – Discussion and Conclusions

7.1 – Bedrock: flat or step?

The key question is: the bedrock shows a step below the scarp or is approximatively flat?. But, before, the Authors should answer to the following one: is the resolution of the methods and the collected data enough to see a step in the bedrock of the expected amount of 5 m? Therefore I think that the Authors should:

a) Perform some forward/inversion synthetic modelling (with noise) in order to gain an insight on the different methods resolution in the contest they are working.

b) Test 2D modelling on gravity and magnetic data (as suggest at paragraph 1.3 and 2.4), to understand if the data require a step on the bedrock or not.

c) Review the ERT, RMT and seismic interpretations, that at the moment indicate a flat bedrock (), and evaluate if the resolution is enough to exclude a step in the bedrock.

d) Give a final clear answer to the questions:

i) Has any of the methods detected a step in the bedrock?

ii) In the case of the methods that have not detected a step in the bedrock, is the resolution enough to exclude the step?

7.2 Discussion and conclusions

Discussion and conclusions should be readdressed with the new results of modelling suggested at the previous point and a definitive final more clear indications of the geophysical results.

TECHNICAL CORRECTIONS

Pag. 2836, row 1: typo mistake (o $\rightarrow$ to)

Pag. 2836, row 3-4: Authors state that the scarp <apparently cross cuts multiple units of glacial and post-glacial sediments (Fig. 2)>. However in Fig. 2 glacial and post-glacial sediments units are not shown. Maybe they would like to refer to Fig. 3?

Pag. 2837, rows 12-13: <we found additional segments, also in the LiDAR data, in the southern parts (Fig. 2a).>. It is not clear in Fig. 2A what are the found additional segments

Pag. 2838, row 25: were the tidal variations corrected by computations (based on the time of acquisition) or by the periodic measurements at the base station? Usually the first procedure is adopted.

Pag. 2845, row 13: <mgal> should be substituted by <mGal>

Pag. 2859, Tab. 1: in the acquisition system row, the model of the system should be indicated.

Pag 2860, Fig.1: The phrase in the caption: <Bollnäs prospective fault being much smaller in size and length was recently discovered from LiDAR-imagery (shaded re-

gions) as a 4–5m high scarp is the focus of this study.> is not clear (at least for my English level).

Pag. 2861, Fig. 2 i) The trace of the scarp superimposed on the tilt derivative map (b) does not look to precisely resamble the scarp trace in the LIDAR image (a). ii) The phrase: <(blue magnetic low, red magnetic high)> is not clear; are the shown values the tilt derivative or the total field magnetic values?

Pag. 2862, Fig. 3 i) In the caption the different location symbols used (blue crosses, triangles,...) should be described to help the reader to understand what method they refer to. ii) The number close to well symbols is not described in the caption: does it refer to the depth of the well, bedrock, water level? If available, depth of the bedrock should be reported as the most important information in this contest. iii) A contour of the elevation in one of the map could help the reader to have an idea of the topographic variations in the survey area

Pag. 2862, Fig. 5 i) In figures 5b and 5c titles <Bougue> must be corrected in <Bouguer>. ii) In figure 5d title <magentic> must be corrected in <magnetic>. iii) The blue points indicating the gravimetric stations are not well visible over the blue of the gravity lows. For instance they could be made in white. iv) The maps seem to be residual maps

Pag. 2867, Fig. 8 What does it mean <noisy data> in Fig. 8B? The frequencies below $\sim$15 KHz have been excluded from all the stations or just for station 10?

Pag. 2872, Fig. 13 In the trench stratigraphy of Fig. 13b the reflector (red arrows?) is indicated at the interface between layers 'Till 1' and 'Till 2'. On the contrary, in the trench of Fig. 13c, the reflector is indicated at the interface between layers 'Till 2' and (varved) clay.
