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Solid Earth Discussions

Interactive comment on "Numerical models for ground deformation and gravity changes during volcanic unrest: simulating the hydrothermal system dynamics of an active caldera" *by* A. Coco et al.

A. Coco et al.

acoco@brookes.ac.uk

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First of all, we would like to thank the referees for their valuable comments, which allowed us to enhance the quality of the manuscript, highlighting the strengths of the numerical model and improving the discussion of the results. The paper has been modified according to the observations of the referees. Some additional changes have been carried out as well. First, we report the additional changes, and then the replies to the referees' comments. Every change is highlighted in blue in the re-submitted manuscript. Please observe that the page numbers specified in the replies refer to the

original submission of the manuscript.

Major changes

- Although the models are set up on the Campi Flegrei caldera, the scope if this paper is not to fit a particular data set or to provide a quantitative assessment of the unrest periods. A stronger emphasis of this aspect has been achieved by shortening or modifying the relevant sections. In particular: - In the abstract, "Based on data for the Campi Flegrei caldera (Italy)" has been replaced with "Informed by constraints available for the Campi Flegrei caldera (Italy)" - The description of the Campi Flegrei of Sec. 2 has now been shortened removing details that are irrelevant for the scope of this paper. The following sentence has been added at the end of the section: "It is important to note that, while models are informed by data on the solid and fluid mechanics of the CF, we do not attempt to replicate or fit observations made during the ongoing unrest at CF." - In Sec. 3, the sentence: "The model is designed such that the La Solfatara fumarolic field is on its rotational axis."has been replaced with: "Both models are based on information available for the CF and designed such that a central fumarolic field is situated on its rotational axis."

Minor changes

- The nomenclature "active caldera" has been replaced throughout the paper (including the title) with "restless caldera" or just "caldera" since we thought it is more appropriate. - The acronym CFc for Campi Flegrei caldera has now been replaced with only CF (now CFc is "CF caldera"). - In Sec. 3, the sentence: "The geometry of the faults is modelled according to fault planes derived from local earthquake data (De Natale and Pingue, 1993; Troise et al., 2008), as well as the inverse modelling by Beauducel and De Natale (2004)." has been removed and a shorten and more appropriate description is now given at the beginning of the paragraph. - In Sec. 4.1.1, the brief literature review on the selection of the different molar ratios has been shortened. - We removed most of the Sec. 6 Conclusion, since it is a repetition of what has already been discussed

in the Sec. 5 Discussion. - page 2079, lines 22-23. In the sentence “between 2.7 and 5 km (Gottsmann et al., 2006c, a; Amoruso et al., 2014)” one more citation has been added.

Anonymous referee #1

Comment

General comments

This is a very interesting work concerning modelling of hydrothermal circulation in Campi Flegrei region. I see the core novelty of the paper in that the hydrothermal circulation is simulated with the presence of ring faults. One can learn from this paper how the faults influence the fluid flow in the hydrothermal system and associated surface uplift and gravity changes. The TOUGH2 code is used for modelling the fluid flow, whereas for deformations and gravity changes the authors apply their own programs. The simulations are done correctly, and their results are in line with literature.

I have few critical comments (see below). One of them, concerning the influence of the faults on the conduit beneath La Solfatara, is the most critical one. This, general for the whole paper, comment concerns the core novelty of the work. Thus, I recommend the authors revise many formulations in the text thoroughly according to the points raised below.

I recommend publishing this work in Solid Earth journal.

Specific comments

1) According to the simulations done, it seems to me that the processes (hydrodynamics, deformations and gravity changes) in the primary permeable conduit beneath La Solfatara are not affected by the processes in the faults A and B. This can be concluded from (the list is incomplete): a. figure 5 – the pore pressure, temperature and saturation changes are similar in all considered scenarios both in spatial distribution and in maximum values; b. figure 7 – I believe if you calculate ground deformations

for a model without faults, there will be only a minor changes in the distribution of the ground deformation; c. The authors make several remarks about that there is a minor influence of the conduit on faults and vise versa – page 2072, lines 18-20; page 2077, lines 9-14; page 2079, lines 8-10; page 2069, lines 11-13; d. The authors do not provide any concrete results showing how the faults influence processes at La Solfatara, and they do not provide any discussion on how this influence comes out, although the authors state many times that there is a strong influence on page 2076, lines 7-9; page 2078, lines 21-22; page 2079, line 3; page 2081, line 22,23,29.

It seems that since the processes in the conduit and in faults are running independently, the authors solve at once three separate problems, namely one for the conduit and two others for each fault. If the authors simulate separately the conduit and each fault and then sum the uplift and gravity from every simulation, will the result be different from the simulations done? The equations (5) for the deformations and equations (7) for the gravity variations are linear, thus a sum of two solutions is also a solution.

Since the introduction of faults is a core novelty of the work, the effect attributed to faults should be discussed sharper. When reading the paper, an impression appears that the faults drastically change parameters beneath La Solfatara. If there is a strong influence of the conduit on the faults or vice versa (as you state on page 2076, lines 7-9; page 2078, lines 21-22; page 2079, line 3; page 2081, lines 22, 23 and 29) then please discuss it deeper making references to figures. If there is only a minor influence (as you state on page 2072, lines 18-20; page 2077, lines 9-14; page 2079, lines 8-10; page 2069, lines 11-13) then please make weaker the statements in other places.

Please state explicitly, whether there is a strong influence or there is only a minor influence for this particular model of CF, and align the text with this statement in all mentioned places and other places of the paper as well.

Reply

When we state that there is a strong influence of faults on the hydro-dynamical and

mechanical behavior of the system (page 2076, lines 7-9; page 2078, lines 21-22; page 2079, line 3; page 2081, lines 22, 23 and 29) we refer to the influence on the area adjacent to the faults and not on the central conduit La Solfatara. Usually the faults affect the mechanical behavior also at the centre of the model, as can be seen, for instance, in Folch, A. and Gottsmann, J (2006). In detail, although the source of deformation beneath the fumarole causes a certain uplift in an homogeneous medium, the presence of ring faults with a lower rigidity value will amplify the uplift at the centre (regardless of injection of fluids at the basis). This is not observed in our simulation, since the source of deformation is too shallow with respect to the radial distance of the faults (page 2077, lines 9-11). A small amplification of the signal at the centre is however observed in Scenario III, due to the higher injection rate at the base of the faults, as specified on page 2077, lines 11-13, and page 2079, lines 8-10.

Finally, although the eqs. (5) for the deformation and (7) for the gravity are linear, eq. (1) for the hydrothermal system is nonlinear, and then the three hydrothermal processes (in the central conduit and in the two faults) are not necessarily independent, even though the mutual influence is not too evident in this model, since the ratio between the model depth and the radial distances of the faults is small.

Thanks to your comment we realised that this was not clearly communicated and have modified the text accordingly. In particular, we specify that the influence of faults is mainly referred to the surrounding of the fault zones (page 2078, lines 21-22; page 2079, line 3; page 2081, lines 22, 23 and 29). We didn't modify 2076, lines 7-9, since we thought that the general meaning is now clear, provided the changes in the text mentioned above.

Comment

2) Page 2061, line 21 – For completeness I suggest to mention which TOUGH2 module you used in the simulations (EOS2 or another module).

Reply

We now mention the EOS2 module where specified by the referee and added a comment in Sec. 3.1: "This mixture is simulated by the EOS2 module of TOUGH2."

Comment

3) Page 2062, lines 20-25 and page 2063, lines 1-3 – I doubt TOUGH2 is capable of flows in anisotropic permeability field when the primary directions of permeability tensor are not aligned with grid blocks. In this case special finite-difference numerical scheme (namely "nine-point" scheme) is required (e.g. see Yanosik et al. 1979 A Nine-point, finite-difference reservoir simulator for realistic prediction of adverse mobility ratio dis- placements// SPEJ. http://dx.doi.org/10.2118/5734-PA). I think you are neglecting k_rz term of the tensor when running TOUGH2. If you do not neglect this term, please provide an explanation of how you account for it. If you neglect it, then please discard most of this paragraph because you are just changing the vertical and horizontal permeability in the grid blocks which the fault penetrates. It is better to discuss here (or earlier) how you fit the rectilinear grid to inclined faults. Can a grid block comprise both the core and the damage zone? When reading this paragraph, you create an impression that you take into account fluid flow in the vertical direction affected by the pressure change in the horizontal direction and vice versa (page 2062, lines 22-24). But if you neglect k_rz when applying in simulation the unnumbered formulas in the last line on page 2062, then you neglect the effect. I also want to make a remark that with the maximum dip angle of 15 degrees for the fault B cos(15)ËĘ2=0.933 is approximately equal to 1.0 and sin(15)ËĘ2=0.067 is approxi- mately equal to 0.0. Therefore, what you are discussing in this paragraph has a minor influence on the flow because k_r is approximately equal to k_xi and k_z is approxi- mately equal to k_eta. I think this permeability alteration (related to multiplication of permeability by cos(15)ËĘ2 and sin(15)ËĘ2) is irrelevant for qualitative analysis, at least because you do not know the geological data with such a precision.

Reply

The off-diagonal term k_rz is actually neglected in the TOUGH2 simulations of this paper and so some of the comments are not relevant. We added a description of how the grid fits the faults. In particular, given a cell of the TOUGH2 finite-volume mesh, the vertical permeability is the same for the whole cell, according to the position of its center (whether it falls into the core or damage zone of the fault). Then, a cell cannot comprise both damage and core zones.

Comment

4) Page 2067, lines 5-9: When reading the article for the first time, it is not easy to understand the difference between Scenarios 2 and 3. Only analysis of units in Table 3 helps. One can measure the flux per square meter of cross section area or think of it as assigned to the total horizontal cross-section area associated with faults. Consider corrections like – “mass equal to” -> “total mass flow rate equal to” in line 6 and “flux rate equal to” -> “specific (per square meter) mass flow rate equal to” in line 8.

Reply

Thank you for this suggestion. We realized that “mass” without specifying “flow rate” can be interpreted as a fixed amount of mass for the whole simulation, which is not the case of our simulations. We changed the text according to your suggestions.

Comment

5) Page 2067, lines 25 and 26 – Not really, at the least the magnitude of the injection rate was discussed recently by Afanasyev et al. (2015).

Reply

We now cite the paper and modified the text accordingly.

Comment

6) Page 2076, line 17 – I suggest replacing “The radius of the plume reaches 500 m at the surface” by “The radius of the plume reaches 500 m in a shallow region close to

the surface”. I believe if you use a good grid resolution for the shallowest part of the system you will not get the gas zone at the surface at 500 m from the centre (although some temperature alterations will be there).

Reply

We agree and modified the text as suggested.

Comment

7) Page 2077, line 14 – What do you mean by “Rock expansion due to heat conduction”? What about convective heat transfer, is it irrelevant? Possibly, you mean “Thermal expansion of rocks” or “Expansion of rocks due to temperature changes”.

Reply

Rock expansion due to heat convection is certainly significant, then we reworded as “Rock expansion due to temperature changes”. Thank you for detecting this inaccuracy.

Comment

Technical corrections 1) Page 2061, lines 16 to 18 – Reformulate or discard “The 2D axisymmetric model extends 10 km in the radial direction in order to cover the entire CF volcanic area, the radius of which is estimated to be some 12 km”. The 10 km is still shorter than 12 km, thus you are not covering the entire CF. 2) Page 2068, lines 1 and 3 – “Although” is met twice what is not good for fluent reading. Consider replacing one of them. 3) Page 2069, lines 6 and 8 – Consider making the following corrections: “values de- crease” -> “value decreases”; “hot fluids rise up” -> “hot fluid rises up”; “values continue” -> “value continues”; 4) Page 2069, line 11 – replace “close the surface” -> “close to the surface”; 5) Page 2071, line 21 – replace “importance increase” by “importance increases”; 6) Page 2076, line 10 – replace “La Solfara” by “La Solfatara”. 7) Figure 11 – make the symbols larger. It is hard to distinguish them. The difference can be seen only if zoom in.

Reply

1) We decided to discard the sentence to avoid confusion.

2) We replaced the first “although” with “albeit”.

3) We followed the suggestions of the referee and changed the text in Sec. 4.2 accordingly. In particular (page 2069): lines 5-6: “After 3 years ΔP values decrease” -> “After 3 years ΔP decreases” line 6: “hot fluids rise up” -> “hot fluid rises up” line 8: “ΔP values continue” -> “ΔP continues” line 9: “while ΔT values keep increasing” -> “while ΔT keeps increasing” lines 22-23: “ΔT values continue to increase” -> “ΔT continues to increase” lines 23-24: “ΔP values peak at 3 years” -> “ΔP peaks at 3 years”

4-7) Done. Thank you for detecting them.

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Please also note the supplement to this comment:
http://www.solid-earth-discuss.net/7/C1695/2015/sed-7-C1695-2015-supplement.pdf

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