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Interactive Comment

Interactive comment on "Thermo-hydro-mechanical processes in fractured rock formations during glacial advance" *by* A. P. S. Selvadurai et al.

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Authors' replies to Reviewer's comments on GMD 2014-199

"Thermo-hydro-mechanical processes in fractured rock formations during glacial advance" A.P.S. Selvadurai, A.P. Suvorov and P.A. Selvadurai

Anonymous Referee # 1.

Referee's Comment 1.1 This excellent manuscript illustrates the thermo-hydro-mechanical as well as hydro-mechanical processes emerging through glacial advances. It thus investigates important scenarios in view if nuclear waste management, i.e. storage in the subsurface, which is a highly- debated problem in countries that were affected by glaciation at least once in 20,000 years. The paper though does not consider the overall glaciation process and consequently its large-scale effects known as glacial isostatic adjustment (GIA), but it presents assuming linear problem temporal and spatial changes of several parameters induced by further advance of an already existing ice sheet.

Authors' Reply 1.1 The reviewers' comments on the manuscript are appreciated. The issue of glacial effects on a repository is being investigated by almost all the countries that are developing deep geologic disposal concepts for long-lived radioactive waste. The influence of glacial loading is important as are the effects of glacial isostatic adjustment. Topics such as isostatic rebound over temporal scales associated with GIA also need to be considered in a comprehensive analysis of the problem for secular time-scales. A comment to this effect and additional references have been included in the revised version of the paper.

Referee's Comment 1.2 The manuscript is well written and the reader is guided through the sections. Figures are appropriate and visualize the results nicely. I liked reading this paper and I am willing to recommend its eventual publication subject to minor revision dealing with the few comments to follow. I hope these comments will further enhance the already excellent quality of the manuscript, provide a bit more information to the reader and perhaps broaden the readership as well.

Authors' Reply 1.2

The reviewer's suggestions are gratefully acknowledged and implemented in the revised manuscript...

Referee's Comment 1.3 Introduction: Although this is very thorough introduction citing a lot of previous work, I personally see it a bit too long. Especially page 7355 and lines 1-24 of page 7356 could be moved to later sections describing the model set-up and dedicated equations. Also, it was unclear to me until page 7360, lines 14-16, that you only model a small glacier advance (thus there is already a glacial load on the model). Please highlight that in the introduction.

Authors' Reply 1.3 To shorten the introduction, lines 1–30 from page 7355 and lines 1–4 from page 7356 were moved to Section 2.2. Lines 5–15 from page 7356 were moved to Section 5.2. The fact that only a small glacier advance is considered is now mentioned in the introduction: "In this work attention is restricted to a glacier of very large length, which is initially at rest and then starts to move along the bedrock surface. The glacier motion or advance is assumed to be very small compared to the glacier length. Since the glacier loading is highly non-uniform near the glacier front and very flat near its center, the major change in the response of the underlying bedrock caused by a small glacier advance is expected to occur near the initial location of the glacier front. Therefore, we place the rock mass model domain containing fractures near the glacier front initial position..."

Referee's Comment 1.4 Section 2: Please state if the final equations are solved by COMSOL, exactly that way or if you had to modify the software. The same on page 7368, lines 1-3.

Authors' Reply 1.4 It is now explained at the end of Section 2.1 that the final equations are solved with two (for HM problem) or three (for THM problem) Modules of the COMSOL program. As the governing equations are coupled, these Modules also need to be connected by the user and solved simultaneously: "The coupled THM problem described by the governing equations (5) to (7) is solved with the COMSOL finite element program. The equilibrium equations (5) are solved using the Structural Mechanics Module of the program; the fluid flow equation (6) is solved using the Earth Science Module (Darcy's Law); and the heat conduction equation (7) is solved using the Heat Transfer Module. By default, these Modules are uncoupled, but the user can connect them by adding additional terms to the appropriate equations of each Module as suggested by equations (5) – (6)."

Referee's Comment 1.5 Section 3: is the fracture network random? Does it represent a typical example? If so, for what? Please quantify the "most" on page 7361. Fractures as stated here have mostly "most" characteristics, so they appear to be all the same!?!

Authors' Reply 1.5 The dominant fracture network used in this work represents only large-scale faults and closely resembles the simplified version of the real fracture network found in a small (approx. 10x10 km) sub-region of the Canadian Shield described in the NWMO report by Chan and Stanchell (2008). In the given fracture network 14 fractures are subvertical with a high dip angle (close to 900), and 7 fractures are subhorizontal with a low dip angle (close to 00). Of the 14 subvertical fractures, 13 fractures span the entire thickness of the rock model. Fractures that do not span the entire thickness of the rock (e.g., subhorizontal) originate at the upper surface of the rock. The subhorizontal fractures are numbered from 1 to 7 on Figure 10.

Referee's Comment 1.6 Section 3.3: Please provide references for the chosen values! Are they realistic? The ice sheet appears to represent the last glaciation of North America, but I find a glacier advance in 5900 years very slow.

Authors' Reply 1.6 The specific form of the ice sheet thickness is adopted from the paper by Paterson (1972). The profile of the ice sheet, shown in Figure 3, is also similar to that shown in Figure 6 of the paper by Boulton and Caban (1995), in which, at a distance of 4000 m from the ice sheet front, the glacier thickness becomes equal to 300 m. The chosen glacier velocity (1.27 m/year) is indeed very small. This value of glacier velocity is about 100 times smaller than the one used by Chan et al. (2005) and about 10 times smaller than the velocity calculated by Aschwanden and Blatter (2009). Such a small glacier velocity is chosen to avoid problems with a loss of accuracy of the solution which arises when the glacier velocity becomes higher and the mesh is not sufficiently fine (see Section 4.1).

Referee's Comment 1.7 Section 3.4: What is "a reasonable time frame" in hours/days?

Authors' Reply 1.7 Clarification indicated. (Approximately 3 hours of runtime when solving HM problem and 8 hours for THM problem).

Referee's Comment 1.8 Section 3.5: Please provide references for these values!

Authors' Reply 1.8 These material properties for the rock mass and fracture zones are similar to those used by Chan and Stanchell (2008) for modeling the Canadian Shield sub-region.

Referee's Comment 1.9 Figures 4 and 5: I suggest another figure to each figure showing the behavior of the quantity along a profile in the model in a certain depth (or at the surface), so that the reader can see the overlap/difference better.

Authors' Reply 1.9 Additional figures showing the behavior of the quantity along a profile in the model at a certain depth were added (see new Figs. 7, 9, 11, 13, 15, 17, 19).

Referee's Comment 1.10 Section 5.1: Page 7369, lines 22-24; Please provide reference! Page 7370, last sentence: I suppose with "stress state resulting from glacial loading" you refer to the stress obtained for the advance. However, for a full analysis, it should be combined not only with geostatic stress, but also with the GIA stress (see Steffen at al. 2014) and possible tectonic background stresses.

Authors' Reply 1.10 The statement about fluid velocity values that are within the Darcy regime was removed from Section 5.1. It is mentioned that, for a failure analysis, the stress resulting from glacial loading should be combined with geostatic stress, GIA stress and possible tectonic background stresses: "It should be noted that for any failure analysis the HM stress state resulting from glacial loading should be combined with the in-situ geostatic stress, GIA stress (Steffen et al., 2014) and possible tectonic background stresses."

Referee's Comment 1.11 Section 5.2: 1 047 000 years is a very long time. Please put this in a realistic context. Or is your study basically a preliminary numerical study?

Authors' Reply 1.11 Yes, 1 047 000 years is a very long time. Since this study attention

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is restricted only to a small glacier advance, this time can never be reached during computational simulations, i.e., the glacier motion is supposed to terminate a long time before this time is reached.

Referee's Comment 1.12 Section 6: The two paragraphs on page 7373 should be discussed in view of former results and other works, or further highlights what is new from this study. Page 7374, line 10 ff: also the activation of faults is worth studying, e.g. in a combined analysis with large scale models of GIA.

Authors' Reply 1.12 What is new in the present study is now highlighted in Section 6 (in the Conclusion). Comparison with the former results is also given: "This study is closely related to the work performed earlier by Chan et al. (2005) and Chan and Stanchell (2005, 2008) in that it also examines the effect of the glacial loading on the behaviour of fractured bedrock. In their work the rock was modelled as a thermo-poroelastic medium and contained 3D (but narrow) fracture regions, which were also assumed to be thermo-poroelastic. The novelty of the present model is the use of a quite complicated fracture network consisting of 21 fractures whereas only 5 fractures were included into the models described in the papers by Chan et al. (2005) and Chan and Stanchell (2005). The NWMO report by Chan and Stanchell (2008) deals with a more complex fracture network consisting of 19 fractures but the fracture thickness was set to 20 m, whereas in the present work it is 10 m, which implies greater geometry and mesh complexity. In addition, in the present study the focus is on the transient response caused by highly non-uniform and moving glacial loading acting on the surface of the bedrock. This loading is directly linked to the specified glacier velocity and profile. Another novelty of this work is the investigation of the use of a commercially available finite element program, which can reduce the efforts of the users in solving the present problem with the finite element method." Possible extensions of the present work, including the activation of faults in a combined analysis with large-scale models of GIA, are now mentioned: "The modeling can be extended to include: activation of faults, e.g., in a combined analysis with large scale models of GIA..."

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Referee's Comment 1.13 Appendix: Parts are repetition of section 3.3. Please just mention what is really needed in each section.

Authors' Reply 1.13 Repetitions were removed from the Appendix and it is now shorter. . Referee's Comment 1.14 Technical comments None.

Authors' Reply 1.14 All items noted in the comments of the Reviewer 1 have been addressed.

Anonymous Referee # 2.

Referee's Comment 2.1 General comments:

This study delivers profound results on the thermos-mechanical response of a fracture network situated in a host rock undergoing a small glacial advance of an ice-sheet. It evaluates long-term changes in pressure and temperature, as well as induced stress changes and displacement. The manuscript puts great emphasis on technical aspects of the numerical models and discusses nicely the generated model results. The comparison of HM and THM processes on a fracture network is a very nice and new aspect of this manuscript. In my view, especially the generated mean effective stress distribution is a highlight of this study.

Authors' Reply 2.1 The authors appreciate the reviewer's observations and interest on the topic of the paper.

Referee's Comment 2.2 Major criticism is that for a reader it is not immediately clear on which specific geological setting the numerical study is based on or whether it is a purely conceptual. Along with that are some missing justifications/explanations for input parameters as in section 3.3 and 3.5 Overall the study is well structured, clear and results are illustrated in a satisfying way. The manuscript is recommended for eventual publication with minor revisions as followed:

Authors' Reply 2.2 The dominant fracture network used in this work closely resembles the simplified version of the real fracture network found in a small (approx. 10x10

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km) sub-region of the Canadian Shield described in the NWMO report by Chan and Stanchell (2008). The authors have also included a comment and a reference to the source used to obtain the material parameters used in the study. “The material properties for the intact rock and fracture zones are similar to those used by Chan and Stanchell (2008) for modeling the Canadian Shield sub-region.”

Referee’s Comment 2.3 P.7352 / Line 25: add a short comment on what specific geological setting the fracture network is based on (Ref. about the DECOVALEX Project?) or whether it is purely conceptual setting. This would help to understand the chosen material properties in section 3.5.

Authors’ Reply 2.3 The domain of interest, which contains the set of fractures, is derived from the international DECOVALEX III project (Chan et al., 2005). The highly idealized geosphere model is based on data from the Whiteshell Research Area (WRA) in Manitoba, Canada. The studies by Chan and Stanchell (2005) provide the database of material properties in the simulations conducted on stationary aspects of glacial loads with specific emphasis on the hydro-mechanical modelling that uses the continental scale model of the Laurentide ice sheet developed by Boulton et al. (2004). The dominant fracture network closely resembles the simplified version of the real fracture network found in a small (approx. 10km x 10km) sub-region of the Canadian Shield at WRA.

Referee’s Comment 2.4 P. 7356 / Line 10: maybe short justification for chosen subglacial temperature (warm/temperature glacier).

Authors’ Reply 2.4 It is a warm-based glacier with the temperature at the interface with the bedrock always above the freezing point.

Referee’s Comment 2.5 P. 7356 / Line 17: even if fractures include any type of separation in rock (joints & faults), maybe worth specifying here that fracture network represent a specific large-scale fault network, and any small-scale joints are neglected.

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Authors' Reply 2.5 The intact rock is assumed to contain small-scale joints, minor fractures, pores and voids; these are not explicitly included into the model. In contrast, the dominant fracture network used in this work represents large-scale faults and closely resembles the simplified version of the real fracture network found in a small (approx. 10x10 km) sub-region of the Canadian Shield described in the NWMO report by Chan and Stanchell (2008).

Referee's Comment 2.6 Section 3.1: Is a model depth of 1700m sufficient to neglect boundary effects at the bottom? Does the influence, especially of the mechanical load, not penetrate deeper than 1700m for e.g. along large-scale structures as presented here in this study? [Referring here to a study, which analyses the purely mechanical aspect of the problem (Ustaszewski et al., 2008 Composite faults in the Swiss Alps formed by the interplay of tectonics, gravitation and postglacial rebound ...) over a scale of 5 km depth.]

Authors' Reply 2.6 The basal rigid stratum will have an influence on the THM processes that are investigated. The depth of 1.7 km was chosen to conform to previous studies conducted by Chan et al. (2005) and Chan and Stanchell (2005) so that there is a basis for comparison. When appropriate computing resources are available, the extent of the domain can, of course, be increased to accommodate depths similar to those employed by Ustaszewski et al (2008) when examining composite fault in the Swiss Alps formed by the interplay of tectonics, gravitation and postglacial rebound occurring at depth regimes of up to 5 km. Our preliminary computational experiments on thicker model domains showed the fluid velocity field and even the mean stress values are not strongly affected by an increase in the thickness. But the vertical displacement increases considerably as the thickness increases. However, we believe that with the given thickness of 1700 m we are able to capture, at least qualitatively, the most important effects of the moving glacial loading on a fractured rock's response (such as distribution of fluid velocity near and within fractures). The depth of the model domain can, of course, be increased, provided that appropriate computing resources are

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available, and this will be the subject of the future research work.

Referee's Comment 2.7 P 7362 / Line 15-32: I suggest revising that paragraph for the relevance of the full presented problem.

Authors' Reply 2.7 A reference to the actual geometry of the model is now included into the text. The sentence in the first paragraph of Section 3.2 was changed to: "...for the given geometry of the rock mass, a parallelepiped with in-plane dimensions of 22 x 22 km and a thickness of 1700 m, "Normal" mesh parameters have the following values: maximum element size 2290 m, minimum element size 412 m, maximum element growth 1.5, resolution of curvature 0.6, resolution of narrow regions 0.5."

Referee's Comment 2.8 P 7363 / Line 5-11: I suggest revising that paragraph for the relevance of the full presented problem.

Authors' Reply 2.8 This paragraph was rephrased to the following: "If the error message appears during mesh generation, it is recommended that the mesh size parameters be modified; even a small change in a parameter value can sometimes allow COMSOL to successfully construct the mesh. For example, for the given geometry with 21 fractures, one could construct the "Custom" mesh if the minimum element size is set to 152–154, 157, 159, 161, 167, 168, 170, 172, 186, 189 m in the range of all values from 152 m to 192 m. Otherwise, a change in the geometry should be attempted, such as deletion of the fracture that caused the error or a small translation of this fracture in the x-y plane. For example, deletion of the sub-horizontal fracture 2, marked in Figure 10, extends the list of minimum element sizes for which the "Custom" mesh can be constructed to: 152–154, 157, 160, 161, 163, 164, 168, 170, 172, 173, 175, 177, 178, 180, 189, 190 in the same range from 152 m to 192 m. We note that even if a certain fracture was removed from the model due to the error messages, another fracture can still be inserted."

Referee's Comment 2.9 P 7363 / Line 15-18: Can glacier change be simplified on sliding and volume change? A glacier undergoes also ductile creep / flow. Although

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assuming a constant shape seems like a fair assumption for this specific problem.

Authors' Reply 2.9 The sentence in the first paragraph of Section 3.3 was rephrased to: "In the following, it is assumed that the advance of the glacier is caused by sliding and the glacier shape does not evolve." The authors agree that creep and thermal effects can influence the profile of the glacier. These modifications are considered to be of secondary importance to the THM modelling exercise.

Referee's Comment 2.10 P 7364 / Line 8: Since glacier velocity seems like an important parameter for the model, a short Ref. here might be useful to justify the chosen value. Are 5900y for 7500m glacier advance in realistic ranges as other studies might estimate for past glaciation cycles?

Authors' Reply 2.10 The chosen glacier velocity (1.27 m/year) is indeed very small. This value of glacier velocity is about 100 times smaller than the one used by Chan et al. (2005) and about 10 times smaller than the velocity calculated by Aschwanden and Blatter (2009). Such a small glacier velocity was chosen to avoid problems with a loss of accuracy of the solution which arise when the glacier velocity becomes higher and the mesh is not sufficiently fine (see Section 4.1).

Referee's Comment 2.11 P 7371 / Line 12 and equation (11 + 14): Temperature change is caused by glacier advance with the presented prescribed function. Does this equation take into account that the approximated/smoothed glacier thickness (as shown in Figure 3) covers the bedrock much earlier that it would without the smoothed approximation?

Authors' Reply 2.11 The equation (14) takes into account the approximated/smoothed glacier thickness; the glacier covers the bedrock earlier than it would without the smoothed approximation.

Referee's Comment 2.12 P 7374 / Line 2: Should it not be (thermo-mechanical) rather than (hydro-mechanical) there, or did I misread the content?

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Authors' Reply 2.12 Correction implemented.

Referee's Comment 2.13 Figure 1: Please distinguish better the two shown glacier stages (for e.g. dashed line

Authors' Reply 2.13 Two glacier contours are now distinguished in Figure 1.

Referee's Comment 2.14 Figure 5: Tough to see the difference between the bottom figure and top. Maybe plotting beside "Custom" mesh results, just the calculated difference in vertical fluid velocity between the two meshes?

Authors' Reply 2.14 Indeed, the difference between the bottom and top figures should be tough to see; otherwise the choice of the "Custom" mesh with much smaller number of nodes would be unjustified. It is not possible the plot the difference in fluid velocities between two the meshes as these two meshes have a different number of nodes.

Referee's Comment 2.15 Figure 9/10/12: Cross-profiles (as shown in Figure 6) through the fractured region could be very interesting for the reader especially for vertical displacement (Figure 9) and distribution of mean effective stress (Figure 10 and 12)

Authors' Reply 2.15 Many figures that show the behavior of the quantity (displacement, stress) along a profile at a certain depth have now been added to the manuscript (including Figs. 7, 9, 11, 13, 15, 17, and 19).

Interactive comment on Geosci. Model Dev. Discuss., 7, 7351, 2014.

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