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REPLY

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Reply to comment by Christopher Talbot on "Approach to estimating the maximum depth for glacially induced hydraulic jacking in fractured crystalline rock at Forsmark, Sweden"

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1. Introduction

The Swedish Nuclear Fuel and Waste Management Company (SKB) has applied to the Swedish government for a license to construct a nuclear waste repository at Forsmark in southeastern Sweden. The hydromechanical response of the repository rock mass to future glacial loading and unloading is an issue of relevance to the assessment of the long term performance of the repository and may include permeability disturbances caused by glacially induced hydraulic jacking, which is the topic addressed in our paper [*Lönnqvist and Hökmark*, 2013]. In a comment to the paper, *Talbot* [2014] argues that we play down the maximum jacking depth by making questionable assumptions regarding the thickness of a future ice sheet, the impact of seasonal water pressure variations at the ice-bed interface and the influence of jacking along preexisting shallow fractures on the supply of overpressured meltwater. Although we generally disagree with *Talbot*'s [2014] arguments, we appreciate this opportunity to further clarify some of our statements.

In our paper, we first observe that, at Forsmark, the vertical stress will be smaller than both horizontal stresses at all depths and during all periods of a glacial cycle. This means that horizontal fractures will be the first ones to jack open, i.e., to dilate in response to water pressures higher than the sum of the fracture normal stress and tensile strength and to lose the mechanical interaction between the fracture surfaces. Consequently, estimating the maximal jacking depth is essentially a question of estimating the pore pressure evolution at different depths and positions beneath the ice, around the ice margin and outside the ice, and then comparing the pore pressure with the local, easily calculated, vertical stress. We identify two situations in which hydraulic jacking potentially could occur at large depths in the Forsmark region. These are first, in front of an ice sheet advancing over frozen ground and second, behind the margin of a warm-based ice sheet retreating rapidly after a long continuous period of high water pressures at the ice-bed interface. We conclude that, at Forsmark, hydraulic jacking will be confined to the uppermost 200 m of rock.

2. Ice Thickness

Talbot [2014] correctly observes that the maximum ice thickness is set at SKB's reference maximum (3000 m) in our study, whereas 3700 m is also mentioned in SKB's climate report [*Swedish Nuclear Fuel and Waste Management Company (SKB)*, 2010]. One should, however, observe that the 3700 m thickness is a result of an extreme case of a sensitivity test and that SKB concludes that it is unlikely that, in reality, a Fennoscandian ice sheet would ever reach its maximum equilibrium size, i.e., the size simulated in SKB's numerical experiments. More importantly, at the time at which hydraulic jacking would be a potential concern for the Forsmark repository, i.e., when the ice margin is advancing or retreating over the Forsmark region, the ice sheet will be far from its maximum size. Figure 1a shows the topography of SKB's reference reconstruction of the Weichselian ice sheet at time 12 ka B.P., i.e., when the Forsmark region was still well covered by the retreating ice. The areal extension of the ice cover when the front of the growing ice advanced over the site, thousands of years earlier, is unlikely to have been very different. Figures 1b and 1c show corresponding ice sheet profiles during advance and retreat, respectively, along the transect capturing the steepest surface gradient during advance [*SKB*, 2010,

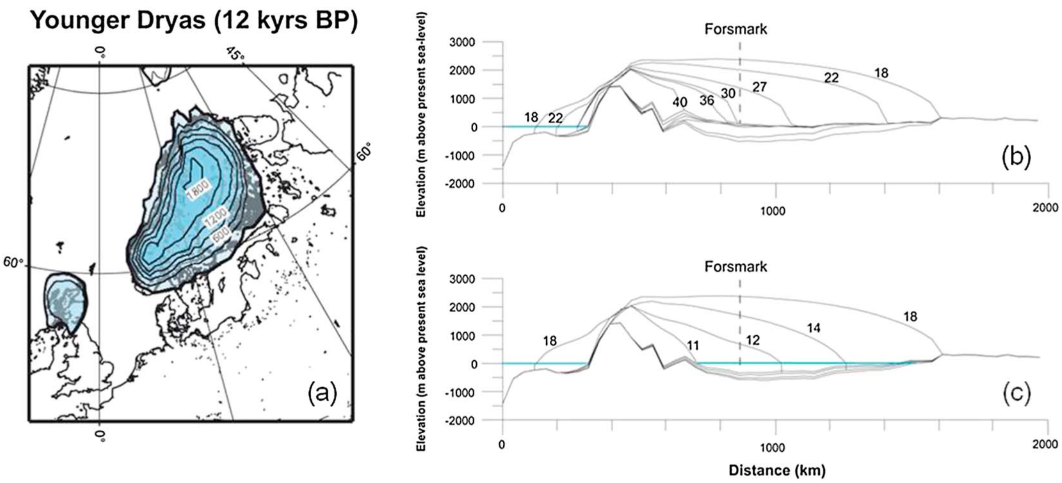

Figure 1. (a) Extent of Fennoscadian ice cover at the time of ice retreat over the Forsmark region [*SKB*, 2010]. (b and c) Ice sheet profiles during advance (b) and retreat (b), [*SKB*, 2010, Appendix 2].

Appendix 2]. The maximum ice thickness at these instances of time (time of advance and time of retreat over Forsmark) does not depend on the maximum ice sheet extension or thickness during other, following or preceding, periods of the glaciation. The upper bound jacking depth estimates obtained in our study are based on an ice sheet model that overestimates the maximum ice elevation over the Forsmark site by at least 500 m (even with account of an, approximately, 400 m depression of the Forsmark region at the time of ice retreat) compared to the ice sheet profiles established in SKB's climate report [*SKB*, 2010, Appendix 2]. Additionally, the theoretical ice sheet profile assumed in our study overestimates the slope steepness considerably compared to the reference reconstruction at all times and it underestimates the distance between the ice margin and the position of the ice crest at all times. In summary, we are not "playing down the maximum [jacking] depth … by making questionable assumptions" regarding the ice sheet thickness.

3. Seasonal Variations

We naturally agree with *Talbot*'s [2014] statement that "structures tend to fail at maximum not average applied stresses" and do not suggest anything else in our paper. At a distance of a few kilometers from the pressure boundary, the maximum water overpressure is not equal to the maximum boundary pressure, but to the time average of that pressure. This is clearly described in our paper and lucidly illustrated in Figure 4: at about 3 km distance from the pressurized ice-bed interface, the overpressures during summer, spring, and winter are the same and correspond to a constant ice-bed pressure of around 60% of the maximum pressure (we are hence not, as suggested by *Talbot* [2014], assuming 40% of the maximum pressure). We take account of this when we estimate the maximum jacking depth around the margin of an ice sheet advancing over frozen ground and where the distance to the water pressure boundary, i.e., the permafrost melt zone behind the advancing ice front, is many kilometers. In actual fact, it would be relevant to account for temporal water pressure variations at the ice-bed interface also in other cases. Outside the margin of a retreating ice, for instance, the residual overpressure will depend not only on the permeability conditions and on the current shape of the ice, but also on the boundary pressure history, i.e., on the history of the water pressure at the ice-bed interface. In our calculations we have assumed that the boundary water pressure has been 98% of the mechanical ice load for the entire duration of the preceding ice-covered period. This will maximize the overpressures accumulated in the low-permeable rock at large depths and contribute to overestimate residual overpressures in the more permeable rock at the repository horizon and above. We do not, however, have any defensible model for estimating or describing the historical, long-time variations in water pressure at the ice-bed interface. Seasonal variations are, for instance, likely to have been very different during different glaciation stages, possibly with averages close to the maximum (98% of the mechanical load) during late stages, i.e., the deglaciation period. That the maximum overpressure equals the year average of the

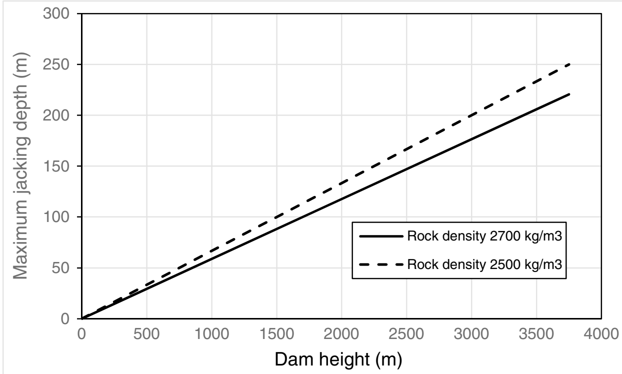

Figure 2. Jacking depth under crest of dam as function of water level elevation, assuming crest height to coincide with the glacial lake elevation.

boundary pressure at a few kilometers distance from the pressure boundary is not a "questionable assumption", it follows directly from the equation of diffusion.

4. Impact of Jacking at Shallow Depths

Talbot [2014] suggests that we assume "that the supply of overpressured meltwater ceases soon after the first preexisting fracture is jacked open". This is not correct. We are not anywhere in our text attempting to assess the way the drainage associated with jacked-open fractures would impact on the water pressure anywhere at the ice-bed interface. In all our analyses the water pressure at the ice-bed interface is assumed to be independent of the water flow in the bedrock below, irrespective of the nature of that flow.

We are noting, however, that, at least for stress conditions such as those reported for the Forsmark site, with both horizontal stresses at all times being significantly larger than the vertical stress, the requirements for hydraulic jacking will be first fulfilled for subhorizontal fractures at shallow depths. When an escape route for glacial meltwater has been established along a jacked-open, preexisting shallow fracture, the water pressure within that fracture will drop by different amounts at different positions along the flow path. The pressure drop will depend on the distance to the connection with the overpressured ice-bed interface, the distance to low pressure regions outside the margin and on variations in flow resistance. This means that shallow jacking, if it results in increased fracture flow, will contribute to decrease the pore pressure in the fracture network below the jacked-open fracture. Since we do not, in our study, account for any such pressure reductions we are likely to overestimate the maximum jacking depth. This, and nothing else, is what we are suggesting in the discussion section of our paper. *Talbot*'s [2014] statement that "they interpret their Figure 7 as implying a maximum jacking depth nearer to 200 m than 350 m by assuming that the supply of clean melt water will cease immediately after initiating one or more hydraulic fractures" is incorrect. Figure 7 deals with the influence of the distance between two positions (the front of an ice advancing over frozen ground and the permafrost melt zone behind that front) on the jacking depth for different assumption regarding the large-scale hydraulic diffusivity of the rock mass and the seasonal water pressure variations.

One reason for not accounting for the pressure reduction effects of shallow jacking is that some shallow jacked-open fractures could be poorly connected to low-pressure regions outside the ice cover, for instance by terminating against low-transmissivity vertical fractures that are clamped by high horizontal stresses. This would tend to suppress the flow and preserve high water pressures within the fracture also at large distances from high pressure fracture segments close to the pressurized ice-bed interface. Another reason is that there is, at least theoretically, a possibility that the shallow, jacked-open fracture is poorly connected to the fracture network below.

5. Megafloods

Talbot [2014] comments that we are claiming that "Huge water bodies can accumulate behind dams of cold-based distal ice until their hydraulic heads are sufficient to … hydraulically jack an escape path beneath a roof of ice and hundreds of m of bedrock". This is not correct. We do not write anything to that effect anywhere in our paper.

In *Talbot*'s [2014] Figure 1B, a horizontal fracture is jacked open below the crest of an ice dam. If the dam height is 250 m, as for the Ojibway glacial lake example given by *Talbot* [2014], the maximum jacking depth for horizontal fractures would be around 15 m, not hundreds of meters. This is a trivial result of matching water pressure and vertical stress at different depths. Figure 2 shows the maximum jacking depth for horizontal fractures located below a dam, as in *Talbot*'s [2014] Figure 1B, as a function of the dam height. For jacking to occur at 200 m depth below the dam, the dam height needs to be between 3000 and 3500 m, depending on the density of the bedrock.

6. Summary

As illustrated in Figure 2 of our paper and as noted in numerous previous studies by *Talbot* [1990, 1999] and others [e.g., *Chan et al*., 2005; *Vidstrand et al*., 2008], the water pressure at the ice-bed interface many kilometers behind the margin of an advancing, stationary, or retreating ice sheet would be sufficient to jack open fractures at depths of several hundred meters in the region around the ice margin. This has raised the question of whether or not hydraulic jacking should count as a potential concern for the nuclear waste repository projected at about 450 m depth in Forsmark. However, as explained in our paper, for these high pressures to actually be effective in the region around the ice margin, unrealistic assumptions regarding the fracture network and the background permeability have to be made. The objective of our study and our calculations is to establish more realistic upper bound estimates of the water pressure around the margin, and consequently of the maximum jacking depth, by taking due account of the actual large-scale hydrological conditions in the Forsmark region. The theoretical ice sheet profile assumed in our models has a significantly steeper slope than corresponding profiles of SKB's reference reconstruction of the latest Fennoscandian ice sheet. Its maximum height overestimates the reconstruction maximum height by about 1000 m during advance and by about 500 m during retreat. This, in combination with worst case assumptions regarding ice retreat speed, distance between permafrost melt-zone and ice margin, and last but not least, regarding the extension, homogeneity, and permeability of the proglacial permafrost, is therefore highly likely to have given overestimated water pressures below the margin. We are therefore not "playing down the maximum depth to which this process [hydraulic jacking] can reach by making questionable assumptions" as *Talbot* [2014] claims. The comment made by *Talbot* [2014] regarding seasonal variations appears to be based on a misunderstanding. That we are "assuming that the supply of overpressured meltwater ceases soon after the first pre-existing fracture is jacked open" is incorrect, although we note that shallow jacking is likely to reduce water pressures at larger depths and conclude that not accounting for this in our study probably has resulted in jacking depth overestimates.

We do not question that there has been very spectacular megafloods, resulting in dramatic erosion of sedimentary material, in the past and that some even may have "inspired Great Flood stories". The floods that potentially could result from failure of ice damming a glacial lake within the ice sheet remaining when the margin retreats over the Forsmark site (cf. Figure 1a) would, however, be significantly more modest than the Great Flood. To get a relevant perspective: Glacial Lake Ojibway had 75 times the water volume of Lake Ontario according to *Talbot* [2014], whereas the entire area covered by the ice sheet at the time of retreat over the Forsmark site corresponds to about 50 times the area of that lake. A glacial lake dammed somewhere within the limits of that ice sheet could be drained by breach of the ice dam, by a flood under the ice or, as *Talbot* [2014] suggests, by hydraulic jacking in the rock below the dam crest. However, as explained above and illustrated by Figure 2, the jacking depth would then be a few tens of meters at maximum, i.e., in agreement with observations made at the Forsmark site and with the overall conclusions of our paper. There is nothing in *Talbot*'s [2014] discussion on megafloods that relates quantitatively to the maximum jacking depth, and nothing that supports the claim that a megaflood originating upstream of Forsmark would have the potential to incise down to the repository at 450 m depth. Any serious recommendation to reconsider the repository depth or the repository concept must be based on more rational, quantitative, and physically defensible analyses.

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