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Interactive comment on "Links between Baltic Sea submarine terraces and groundwater sapping" *by* Martin Jakobsson et al.

Martin Jakobsson et al.

martin.jakobsson@geo.su.se

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We thank Referee #2 Joonas Virtasalo for his constructive comments on the manuscript. Virtasalo states that the paper is well written and based on strong data, but he has two main concerns:

a) We do not discuss other mechanisms that can produce similar structures. b) The features in the form of terraces in the seafloor occur in areas of low hydraulic gradient.

We have addressed both these main concerns in a revised version of the manuscript. Concern a) is handled by including other potential mechanisms in the discussion, as requested, at the same time as making it clear that groundwater seeping cannot irrefutably be concluded to be the sole mechanism responsible for producing the sub-

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marine terraces we document.

In the paper we describe the morphological features with the new data, place them in a geological context, and address the previously proposed formation mechanism in order to further discuss the formation hypothesis. We do in fact agree with Virtasalo that there is no direct conclusive evidence for groundwater as the sole mechanism responsible for the formation of the seafloor terraces. However, we thought uncertainties were made clear in the paper and we have been careful to use words such as “potential”, “propose”, “likely” and included statements such as “more complex hydrogeological studies are required.” (Row 2, page 2). The final sentence in the opening introductions reads:

“This study provides a framework for continued investigations involving in situ observations of potential groundwater seeping at selected terraces and semi-circular depressions along Baltic Sea coasts.”

In any case, we believe it is important to clearly show uncertainties in science and are therefore happy to further emphasize them in our interpretations and also highlight in the discussion and abstract that we believe that the formation hypothesis should be tested with further observations.

In the revised version of the paper we have therefore done the following to meet the requirements of Referee #2 with respect to concern a):

1. Changed the title: “Potential links between Baltic Sea submarine terraces and groundwater seeping”

2. Changed the abstract to read “While submarine terraces can be produced by several processes, we interpret our results to be in support of the basic hypothesis of terrace formation initially proposed in the 1990s, i.e. groundwater flows through siltier permeable layers in glacial clay to discharge at the seafloor, leading to the formation of a sharp terrace when the clay layers above seepage zones are undermined enough to

collapse." This revision follows the suggestion of Virtasalo.

3. Changed the last sentence of the abstract to: "We propose that SGD through the sub-marine seafloor terraces is plausible and could be intermittent and linked to periods of higher groundwater levels, implying that to quantify the contribution of freshwater to the Baltic Sea through this potential mechanism, more complex hydrogeological studies are required."

4. Included more discussion on alternative formation mechanisms, specifically the topic raised by Referee #2 of liquefaction of course layers. We lead into this in the beginning of the discussion in the revised version by: "However, we cannot exclude that SGD not is the sole mechanism that can produce terraces in the seafloor similar to those we mapped in this study and, therefore, alternative formation mechanisms are discussed below."

We end the discussion with the following paragraph: "There are other mechanisms that potentially could have played a role in the formation of the seafloor terraces mapped in this study. For example, sliding and slumping of glacial varved clays has been suggested to occur due to liquefaction of layers during palaeoseismic events (Hutri and Kotilainen, 2007;Virtasalo et al., 2007). This could leave behind terraces at the seafloor formed in glacial clay. However, we do not observe any morphological evidence of sliding and most of the terraces we mapped occur in areas where the seafloor slopes at <1ïĆř and the terraces have nearly flat bases, as evident in the bathymetric profiles in Figures 2e, 3c and 4c. We also note that the terraces we mapped are widespread across the Baltic and systematically appear in glacial varved clay. It seems unlikely that slides would occur over such spatially large areas in several regions. Finally, the processes responsible for the formation of some of the terraces seems to be ongoing judging from the bottom photographs showing how small blocks of clay presently are falling down to form a sharp terrace (Fig. 6). While we cannot exclude that other processes formed the terraces mapped in this study, we interpret our results to be in support of the formation mechanism proposed by Söderberg and Flodén (1995). Our

study provides a geological and morphological framework for further research involving longer-term monitoring of potential SGD from the terraces."

With respect to concern b) we have thought of it. The fact is that we do not envision a process where ground water is vigorously escaping the glacial clay to form a seafloor terrace. Instead, it is more likely process where water is flowing slowly through permeable layers, much like is seen in gardens, where a very small hydraulic head is required. It should also be noted that the hydraulic head can be created from a far distance such as illustrated in Figure 9.

Virtasalo also brings up that the seeps that are illustrated in the paper are not connected to the terraces and questions why they are included. As we found an abundance of seeps in the multibeam water column data, the question whether they were related to the terraces or depressions in the seafloor immediately arouse since this could potentially be important for the interpretation. Furthermore, one of the main points with the paper is to document the geological context of the terraces, and here the occurrence of the seeps and their relation/no relation to the terraces is important. We have included the following sentence in the revised version on page 7 in order to better motivate why they are included:

"....Seeps from the seafloor were found to be a common feature (Fig. 2a), and the question immediately arose if the seeps were related to either terraces or depressions in the seafloor."

Detailed comments: Referee #2: "Page 2, line 25. Add "varved" between "glacial" and "clay". It would help the reader in case the varved clay structure was shortly explained already in this paragraph." Authors: Fixed

Referee #2: "Page 10, the first paragraph about glacial varved clays is very much dominated by Swedish publications. Please consider adding classical works by e.g. Sauramo in the discussion."

Authors: One of the classic works from Finnish geologist Sauramo on glacial clay is now also included with a reference. Page 10 in the revised version: “The use of glacial varved clay as a record documenting the ice retreat was adopted early also on the Finnish side of the Baltic basin (Sauramo, 1926). From the knowledge gained from these studies follows that. . .”

Referee #2: “Page 10, line 31. There is no compelling evidence for brackish Yoldia Sea northward and eastward from the south-central Sweden (Schoning 2001, Boreas). Yodia Sea is not necessarily relevant to the topic of the manuscript and it could be excluded from the discussion.”

Authors: We believe that the sentence on the Yoldia Sea provides a geological time context, which by Referee #1 brought up as important. Since we prefer to keep this, we have included that a brackish Yoldia may have been constrained to the eastern part of the Baltic with a reference to Schoning, 2001.

“A brackish water phase called the Yoldia Sea, perhaps constrained to the central Swedish side of the Baltic (Schoning, 2001), followed the Baltic Ice Lake (Björck, 1995), however it would take several hundred years for the Baltic to become brackish after the drainage and deposition of varved glacial clay continued close to the retreating ice margin (Andrén et al., 2011).”

Referee #2: “Page 11, line 4, “irrefutably”.”

Authors: Fixed

Page 11, lines 5-12. Perhaps the concretions formed already during glaciolacustrine or post-glacial lacustrine environments, and comparisons to present brackish-water Baltic Sea are not relevant?

Authors: Since there is no way to tell this, we have kept the comparison

Referee #2: “Page 12, lines 1-5. How about the O isotope composition of the post-glacial lacustrine phase? Perhaps it was similar to large lakes in Sweden and Finland

today?"

Authors: We can speculate that since d18O values have a relation to temp (and latitude) it is likely that they will be in similar range as the Baltic Sea today, however, the different Baltic Sea stages will matter as well. The larger lakes that we have in Sweden/Finland today are a little bit more negative in d18O values than the Baltic Sea. The Baltic Sea exhibits a gradient south to north but at the same time having a little bit higher values than the terrestrial freshwater lakes. This is caused by mixing in Atlantic Ocean/North Sea water and therefore the different stages of the Baltic sea probably exhibited the same type of changes when connected to the North Sea. When not connected, the Baltic Sea d18O values would have been more negative and during ice melt much more negative. We do not think it is helpful to the paper to include this in the paper, it is a bit beyond the scope and there are many uncertainties around it and no data records to reference.

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