Dear Editor,

Please find below responses to two reviewers comments and one short comment, for the paper entitled "Ice tectonics during the rapid tapping of a supraglacial lake on the Greenland Ice Sheet" submitted to The Cryosphere Discussions.

I would like to thank the reviewers for their detailed comments, which have led to many improvements to the manuscript. Both reviewers advised that the manuscript deserved publication in The Cyrosphere whilst making numerous suggestions for its improvement. These comments are repeated in blue italics with the associated response given directly below.

Kind regards,

Sam Doyle

On behalf of the co-authors

Response to comments from anonymous Reviewer 1.

RC1-1a: This paper is mainly a presentation of observations prior, during and after the drainage of a supraglacial lake on the Greenland Ice Sheet. According to their observations and conclusions the authors suggest hydraulic fracturing as main lake drainage mechanism to establish a temporal and efficient water pathway through the ice sheet. My main concern is how can the initiation of the main crack be explained? Once the crack is formed, its downward propagation can be explained according to Krawczynski et al. (2009) work. But the authors don't mention convincing arguments to explain why such a long (700 m) crack has formed after the lake started to drain.

AC: Discussion of the trigger mechanism that caused the crack to form is addressed further in the responses to comments RC1-1b,c and RC2-1a-e.

RC1-1b: According to the authors, the lake started to drain supraglacially into lake Z and Moulin M4. In the following, rapid tapping started through the crack. If this is correct, I propose to make this clearer in the manuscript.

AC: Sentence in Section 3.2 changed to:

> "Rapid discharge (here defined as $Q > 50\ \mathrm{m^3\ s^{-1}}$), associated with the tapping of the lake via in situ fracture propagation, occurred between 01:40 and 03:15 on the 30 June 2010 with the discharge peaking at $Q_{max} = 3300\ \mathrm{m^3\ s^{-1}}$ at 02:47."

RC1-1c: My question is whether the first stage of lake drainage through the Moulin could have initiated the crack formation at the surface which could further propagate into depth as proposed by Krawczynski. I think that this initial crack formation should be scrutinized as it seems crucial for explaining rapid tapping.

AC: First, it should be clarified that moulin M4 was relatively small (< 1 m in diameter) when we observed it on 28 Jun 2010.

> "This period of low discharge amounts to a volume of $3.6 \times 10^6\ \mathrm{m^3}$ and could be entirely accounted for by supraglacial discharge into Lake Z and moulin M4 (see Figs. 1 and 2). On 28 June 2010, water from Lake F traveled through a slow-flowing series of elongate ponds before a < 1 m wide supraglacial stream fed the water into moulin M4. During the slow-period of drainage the majority of water left Lake F via a (5 m wide) supraglacial river feeding into Lake Z."

However, the small size of - and low discharge into - M4 does not rule out the hypothesis that water accessing the bed via M4 initiated the fracturing and rapid tapping of the lake by causing localised acceleration and longitudinal (with-flow) extension across the lake. This hypothesis can be ruled out by the GPS observations, which show no longitudinal (with-flow) extension prior to rapid discharge. This is now discussed in the section entitled “Initiation Mechanism”:

> “Drainage of water into moulin M4, located to the west of Lake F, during the slow-discharge period prior to rapid tap- ping could theoretically cause localised uplift and acceleration leading to longitudinal (with-flow) extension. Alley et al. (2005) assert that the tensile stress caused by the acceleration of downstream ice may be important for initiating hydrofractures. However, discharge into 1 m wide, M4, was relatively low and prior to the tapping of Lake F there is no evidence for longitudinal (with-flow) extension (Fig. 7). On the contrary, the western GPS (1 and 2) are uplifted and accelerate several hours later than the eastern GPS (3 and 4), causing longitudinal (with-flow) compression across the lake in the hours preceeding rapid tapping (Fig. 7b and f). At this time there is also differential acceleration of the two slower northern GPS (1 and 4) in relation to the two faster southern GPS (2 and 3, Fig. 6) suggesting that pure shear (shear with compression) could be occurring along F1 prior to the transverse (cross-flow) north-south extension during fracture opening.”

RC1-2: Another point is the seismic analysis. Why do the authors use a butterworth filter 5-50Hz? I think the authors should justify this choice (by citing corresponding papers).

AC: A Butterworth filter with a 5 to 50 Hz passband was selected after visual inspection of the data revealed that the dominant frequency of the seismicity lay within this frequency range. The Butterworth filter preserves the seismic signal whilst removing any high frequency noise and noise associated with surface crevassing (> 50 Hz) whilst removing any spurious low frequencies (< 5 Hz) associated with the instrument response.

Paragraph changed to:

> “For each seismometer, the normalised root mean square (RMS) amplitude was calculated for 1 min time windows using an envelope function after applying a 2-pass 4-pole Butterworth filter. The 5 to 50 Hz passband of the Butterworth filter was selected, after visual inspection of the data, to reduce both high frequency noise (> 50 Hz) associated with surface crevassing (e.g. Neave and Savage, 1970) and any low frequencies (< 5 Hz) associated with the instrument response. To identify step changes in seismicity we calculated the normalised cumulative (seismic) energy from the RMS amplitudes.”

RC1-3: What is the order of the butterfly filter?

AC: A 2-pass, 4-pole Butterworth filter was applied and this has been added to the text.

RC1-4: Dimensions of the concrete slabs?

AC: 0.5 x 0.25 x 0.05 m - Added to the text.

RC1-5: "I am also wondering why the authors did not perform any location attempt of the seismic activity, at least at the glacier surface (e.g. Roux et al., JGR 115, 2010). If successful, this could reveal where fracturing occurred and, with some more elaborated techniques, provide some hints on the fracturing mechanisms (e.g. Walter et al., 2009, Bull Seism Society America, 99, 2A, 852-870)."

AC: The limited number of seismic stations, together with the large array aperture (1-2 km) and the high rate of seismicity during lake tapping resulted in spatial aliasing of the recorded data. In practical terms this means it is not possible to correlate individual onset times with a particular seismic event so we cannot get an accurate estimate of the event locations using the standard methods (e.g. Roux et al., 2010). These issues, together with a new method for locating seismic events based on amplitudes, are discussed in Jones et al. (2013).

The application of the location method described in Jones et al. (2013) and extended discussion of the seismic measurements was deemed beyond the scope of this paper. Instead, the TCD lake-tapping manuscript makes use of a subset of the passive seismic dataset in order to support its main story - measurements of ice motion and lake discharge during lake tapping.

RC1-6: It is not always clear how ''transversal'' and ''longitudinal'' are defined in the text, especially what concerns the orientation of the cracks. This should be defined.

AC: This has been clarified by adding with-flow and cross-flow for all occurrences of longitudinal and transverse respectively. I.e.. "...longitudinal (with-flow)..." and "... transverse (cross-flow)..."

RC1-7: Also the direction of glacier flow should be indicated in the figures. This would help to understand the ''simple shear'' discussion.

AC: Red arrows showing the direction of mean ice flow (265 deg to the west) have been added to Figures 2, 5, 6 and 9 and 10.

RC1-8: Section 3.2, line 16: discharge amounts to 3.6 10^6 m^3 – wrong unit

AC: [10^6 m^3] is the correct unit as it relates to the volume that the period of low discharge amounts to. To make this clearer this sentence has been changed to: "This period of low discharge amounts to a volume of 3.6 x10^6 m^3 and could be..."

RC1-9: Section 3.3, line 24: indicate on which day this happens (not only time)

AC: Added date "At 04:50 on 30 June 2010..."

RC1-10: Section 3.3, line 4 (> 1cm wide)

AC: Changed to (< 1 cm wide).

RC1-11: Section 3.3, line 25: A number of ice blocks had fallen – where from did the ice blocks fall?

AC: The ice blocks were part of the ice column and were detached during fracturing. Some subsided into the fracture and others were uplifted by floatation. You can see both of these on Fig 4a. To make this clearer a diagram of the subsided blocks has been added and the start of Section 3 has been changed to:

> "At 04:50 on 30 June 2010, ~ 0.3 m deep standing water was observed in the centre of the lake overflowing across the clean-cut edge of the main fracture F1. Fracture F2 was clean cut and open by ~ 0.2 m.
>
> On 1 July, the location, dip and strike of fractures were surveyed. The main fracture, F1, was mapped for 3 km but extended beyond this as a thin (< 1 cm wide) crack. F1 and F2 were sub-vertical, dipping towards the north and west, respectively (Fig. 2). Differential vertical displacement was only observed along F1 and the vertical displacement of the northern hanging-wall 01 to 0.3 m above the southern foot wall can be interpreted as a reverse dip-slip fault and evidence for transverse (cross-flow) compression (Fig 5a). The largest vertical displacement was measured in the deepest region of the lake, 10 m east of M2 (see Fig 4a).
>
> Along F1 a number of ice blocks, detached from the ice surface, had subsided into the fracture or been uplifted by floatation (see Fig. 4a). The structure of the subsided blocks is that of a high-angle normal fault with a dropped graben (see Fig 5b) and is evidence for transverse (cross-flow) extensional strain across F1 (Price and Cosgrove, 1994). Similar supraglacial fracture structures were associated with hydraulic fracturing, were observed following the Skeiðarjokull and Solheimajokull jokulhaups in 1996 and 1999 respectively (see Fig. 12 of Roberts et al., 2000)."

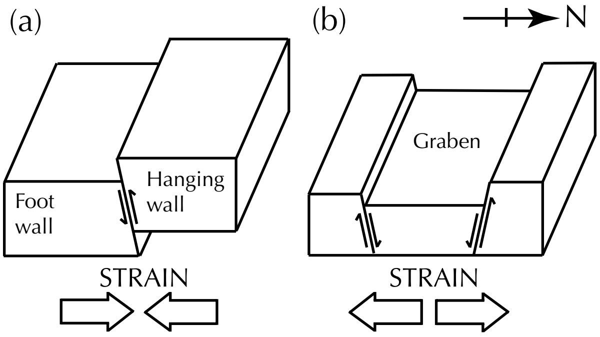

Fig 5. Supraglacial fracture structures observed along F1: (a) a reverse dip-slip fault, dipping 82 to 85◦ to the north, with the northern hanging wall vertically displaced above the southern foot wall, is evidence for a compressional strain regime; and (b) a high-angle normal fault with a dropped graben is evidence for extension across F1. Note the greater vertical offset of the northern wall compared to the southern.

RC1-12: Section 3.3: a photograph/cartoon showing the notch would be useful

Stenborg (1968) describe the formation of moulins in detail. A citation for Stenborg (1968) has been added and the text has been clarified:

> “The main ~ 5 m wide supraglacial river flowing into Lake F from the north was intercepted by a fracture, forming three moulins, collectively named M3 (Fig. 2). The evolution of the M3 moulins was observed over a number of days and is consistent with Stenborg (1968). Initially, water flowed into the clean-cut fracture at three discrete points and began to cut channels due to the frictional heat of melting. Over time the channels became wider and deeper. The channel of the largest moulin incised the fastest and ultimately captured all the flow.”

RC1:13: Section 3.4, line 23: discharge rate (dZ/dt) – wrong symbol

AC: Corrected to (dQ/dt).

RC1:14: Section 3.4, line 16: it would be helpful to mention the figure references where they should be for each figure separately and not all together

This has been corrected as suggested.

RC1-15: Figure 2: Where are the points P1 and P2?

AC: P1 and P2 have been annotated on Figure 2.

RC1-16: Section 4, line 10: at 3:15 the fractures are effectively closed. However, the seismic activity was still high then according to figure 8. Why?

AC: The sentence on line 10 of Section 4 has been changed from:

> “By the end of rapid discharge at 03:15 the fractures are effectively closed (Fig. 7)” is incorrect. Fig. 7 shows that at the end of rapid discharge the rate of closure is reducing but the fractures are still closing. This is also evident in the continued southerly motion of GPS1 and northerly motion of GPS after 03:15 (Fig. 6). The seismic activity after 03:15 was still high because the fractures were still closing and also due to continued subsidence of the ice surface. Subsidence continued for several hours post 03:15 as can be seen from the gradual lowering of GPS1 and GPS4 (Fig. 7c and f).

to:

> “In episode 3, fractures begin to close as the discharge and uplift reduces. Following, the end of rapid discharge the rate of closure reduces but it takes several hours before the inter-GPS separation rates stabilise (Fig. 7). We attribute the elevated seismicity post-03:15 (Fig. 8) to continuing ice deformation

> associated with fracture closure and the subsidence of GPS1 and 4 (Fig. 8c and f)."

To comply with this correction Line 4 of Section 4 has been changed to:

> "These episodes are bounded by the duration of rapid discharge and closure of fractures extended beyond 03:15."

RC1-17: It seems that figure 8 should also be referenced

AC: Reference to Fig. 8 added

RC1-18: Section 4, line 11: Both sentences are not linked to each other.

AC: As the line numbers on the reviewed manuscript (which differs from the accepted proof available online) are reset on a page-by-page basis, and section 4 spans 3 pages, there are 3 line 11's in section 4 and I can't work out exactly what this comment refers to. Please check whether this mistake occurs in the updated manuscript.

Response to comments from Reviewer 2, S. Sugiyama

RC2-1a: ***Triggering mechanism of the drainage.*** *I am wondering why the authors do not discuss the triggering mechanism of the rapid lake drainage. It is clear that the opening of the surface fracture initiated the drainage, but my question is why this fracture formed. The slow discharge before the rapid drainage (page 3869, line 13-18) might be a key to understand the mechanism of the fracture opening. Do you think water drained into moulin M4 reached the bed and changed the ice flow regime?*

AC: This question is now addressed in the discussion. Please see the response to RC1-1.

RC2-1b: Or alternatively, do you assume that drainage of other lakes in the region (page 3869, line 7-10) initiated the fracture opening?

AC: The drainage of an upstream lake could have initiated the rapid tapping of Lake F and Fig. 1 shows that several lakes within the same elevation band drained in the same 4 day interval as Lake F. Unfortunately, due to cloud cover we cannot determine which lake drained first.

RC2-1c: If GPS data are available before June 29, can you find any change in the ice motion, which might have triggered the drainage?

AC: GPS data before the 29 June are not available.

RC2-1d: Before the initiation of the drainage, was there a small crack or crevasse which grew up to the large fractures?

AC: We didn’t observe any new or recent cracks forming before rapid tapping however it would have been very difficult for us to observe small cracks forming within the lake.

When we walked the western perimeter of the lake on 29 June, a day before rapid tapping, we did observe healed crevasses similar to Fig. S5 of Krawczynski et al. (2009). We also observed large holes (potentially closed moulins) in the lake-bed prior to drainage in the positions of M1 and M5. It is possible the 2010 lake drainage was the re-initiation of a fracture formed in a previous year.

This is now described in section 3.3 Observations as:

> “Prior to rapid tapping on 29 June 2010, a healed crevasse, similar to Fig. S5 of Krawczynski et al. (2009), was ob- served running through the lake in an W-E direction from the western margin of the lake. Closed moulins were observed in the approximate positions of M1 and M5. It is likely that these features were formed by lake tapping events in previous years.”

And in the discussion as:

> “Prior to lake tapping a healed crevasse, consistent with Fig. S5 of Krawczynski et al. (2009), was observed running from the western margin of the lake easterly towards its centre. Closed moulins were observed in the approximate positions of M1 and M5. It is likely that the healed crevasse and closed moulins are relic features formed during tapping events in previous years. It is possible that the rapid tapping in 2010 was the re-opening of fractures and moulins formed in previous years however our observations do not reveal whether tapping involved the formation of a new fracture or the re- activation of a healed crevasse.”

RC2-1e: There should have been a certain time period when the fracture is deepened by the water pressure and approached to the bed (see Das and others, 2008, page 779, last paragraph). Did this fracture deepening process occur during the slow discharge period (June 25-29)?

AC: We didn’t observe premonitory drainage events preceding rapid tapping in the lake level or discharge record (Fig. 7a) like those described by Boon & Sharp (2003) so it is unlikely that the fracture deepening process occurred prior to rapid discharge at 01:40 on

30 June 2010.

The following paragraph has been added to the discussion:

> “Although it is possible that small events could be masked by changes in the supraglacial discharge it is unlikely that significant premonitory drainage events involving the downwards propagation of a hydraulic fracture occurred as observed by Boon and Sharp (2003).”

RC2-1f: In any case, interpretations and discussion on the triggering mechanism of the lake drainage will substantially improve the quality of the paper.

AC: The subsection entitled Initiation mechanism has been revised to:

4.1 Initiation mechanism

> Drainage of water into moulin M4, located to the west of Lake F, during the slow-discharge period prior to rapid tap- ping could theoretically cause localised uplift and acceleration leading to longitudinal (with-flow) extension. Alley et al. (2005) assert that the tensile stress caused by the acceleration of downstream ice may be important for initiating hydrofractures. However, discharge into 1 m wide, M4, was relatively low and prior to the tapping of Lake F there is no evidence for longitudinal (with-flow) extension (Fig. 7). On the contrary, the western GPS (1 and 2) are uplifted and accelerate several hours later than the eastern GPS (3 and 4), causing longitudinal (with-flow) compression across the lake in the hours preceding rapid tapping (Fig. 7b and f). At this time there is also differential acceleration of the two slower northern GPS (1 and 4) in relation to the two faster southern GPS (2 and 3, Fig. 6) suggesting that pure shear (shear with compression) could be occurring along F1 prior to the transverse (cross-flow) north-south extension during fracture opening.
>
> The observation of a compressive strain regime prior to lake drainage is consistent with Das et al. who measured compressive strain within the lake-bed and agree with Krawczynski et al. (2009). Krawczynski et al. found that water-filled crevasses can propagate without longitudinal (with-flow) tension and that a given volume of water has the propensity to propagate a water-filled crack further in regions with less tension (or even slight compression), as thinner cracks require less water to remain water filled.
>
> Although it is possible that small events could be masked by changes in the supraglacial discharge it is unlikely that significant premonitory drainage events involving the down- wards propagation of a hydraulic fracture occurred as observed by Boon and Sharp (2003).

RC2-2a ***Source of the seismic signals.*** *The origin of the seismic signals obtained by the geophones is not adequately interpreted. The author states that the "seismicity predominantly generated by the deformation of ice" (page 3872, line 28 - page3872, line 1), but not clear how and where ice deformation creates seismic activity. Do you assume that the signals were created at the bottom of the deepening fracture?*

AC: In this paper we analyse a time series of RMS amplitudes to support GPS and discharge measurements. We attribute the majority of seismicity to the deformation of ice during the opening and closure of fractures based on the observation of quiescence in seismicity coincident with the peak fracture width. We cannot say at this stage whether the seismicity is generated at the bottom of the deepening fracture. See the response to RC1-5 and Jones et al. (2013).

RC2-2b Are there signals due to ice sliding at the ice sheet bed?

AC: During initial inspection of the seismicity we did not positively identify any signals related to ice sliding at the bed.

RC2-2c Because seismic signals were monitored by an array of geophones, is it possible to identify the location of the signal source? More discussion on the seismic signals with citations of other works is advisable. Publications on the seismic measurements during the outburst events of Gornersee may help the discussion (Walter and others, Journal of Glaciology 2008; Roux and others, JGR 2010).

AC: Please see the response to RC1-5.

RC2-3a: ***Ice motion:*** *Apologies for referring to my own work, but the GPS data presented in this paper are very similar to those we measured during the outburst event of Gornersee in 2004 (Sugiyama and others, Journal of Glaciology 2007; Sugiyama and others, JGR 2008). Particularly, the horizontal ice motion deviating from the fracture, and the reversal in the ice motion (Figure 5) are common with the ice dynamics during the rapid drainage of Gornersee, an ice marginal lake in an alpine glacier. Comparison of the ice motion during these two lake drainage events will be interesting and useful for studies in the future. We also discussed elastic component of the ice motion in the above papers, which is also relevant to the GPS data during the fracture opening and closure.*

Discussion of the vertical motion of the GPS including its influence on horizontal motion has been expanded into a new section of the discussion, which is copied below:

4.3 Vertical ice surface motion

Ice surface uplift is typically attributed to bed-parallel motion, vertical strain and ice-bed separation due to high sub- glacial water pressures (Hooke et al., 1989). Fault deformation (Fig. 5) may also cause vertical ice motion (e.g. Walder et al., 2005). All four factors must be considered when interpreting vertical GPS motion.

The bed-slope beneath the GPS is highly variable (Fig. 11) and may be responsible for some of the observed complexity in the GPS motion (Fig. 6). In contrast to the smooth vertical motion of GPS1, GPS3 and GPS4 the vertical motion of GPS2 is characterised by sudden steps coincident with the start and end of the fracture opening episode. GPS2 is located on the strongest subglacial gradient of all the GPS, south of a conical subglacial peak (see Fig. 11). Horizontal motion along the inclined bed-slope can satisfactorily ex- plain the complex vertical motion of GPS2. At 00:00 on 30 June 2010 the trajectory of GPS2 is perturbed to the north- west coincident with ~5 cm of uplift. This vertical motion can be explained by north-westerly motion up the bed-slope (Fig. 11). Conversely, the subsequent southerly-motion of GPS2 down the bed-slope between 02:00 and 03:00, interpreted as fracture opening, is coincident with subsidence of GPS2. This subsidence is coincident with uplift at GPS1, GPS3 and GPS4 suggesting that the water delivered to the bed during rapid discharge did not access the area beneath GPS2. Finally, at 03:00 when GPS2 moves north up the bed- slope there is a second smaller magnitude (10 cm) period of uplift exclusive to GPS2.

Sugiyama et al. (2008) observed the greatest uplift near to the drainage centre during the subglacial drainage of ice marginal lake Gornersee in Switzerland and we therefore assert, like Das et al. (2008), that surface uplift was likely greater near the centre of the lake. The highest-magnitude uplift observed in this study of 0.9 m by GPS1 is the most consistent with the measurements of Das et al.. The bed-slope underneath GPS1 slopes down towards the north-west (Fig. 11) so north-west acceleration during the fracture opening episode is not responsible for the observed uplift at GPS1. Vertical strain cannot account for the uplift as extension (which would cause thinning and lowering) is observed for all the inter-GPS separations involving GPS1 during this episode (Fig. 7a, b, c). Fault deformation in the form of vertical offset of the fracture walls in a reverse dip-slip fault is attributed to compressional strain (Fig. 5b) which is unlikely to have occurred during the fracture opening episode when all inter-GPS separations were extensional ((Fig. 7). As neither motion along an inclined bed-slope, vertical strain or fault

> deformation can explain the vertical motion of GPS1 during the fracture opening episode the uplift at GPS1 can be attributed to ice-bed separation resulting from high subglacial water pressures caused by the delivery of a large quantity (6.7×10^6 m^3 or 90 % of the lakes pre-tapping volume) of water to the ice-bed interface.

Interpreting the reverse motion of GPS4 based on the similar observations of Sugiyama et al. (2008) is problematic as the behavior of the GPS around Lake F are related to the site-specific proximity to fractures and basal topography/bed-slope which also impacts subglacial water routing. In Sugiyama et al. (2008) the GPS motion reverses as the discharge decrease. In this study, reverse (opposite to the mean flow) GPS motion is only observed at GPS4 when the discharge is increasing presumably due to fracture opening.

A section on subglacial water routing based on the differential GPS motion, subglacial topography and fault structure has also been added to the discussion.

> ### 4.4 Subglacial water routing
>
> Subglacial water delivered to the ice-bed interface along F1 would be preferentially routed through a subglacial valley to the north-west (Figure 11) . Field measurements of the fracture structure and the differential motion of the GPS support this assertion. Based on the locations of F1 and F2, we can conceptualise the ice-mass structurally into three semi-independent blocks: the southern, north-eastern and north-western. The direction of dip of sub-vertical fractures F1 and F2, to the north and west respectively (see Fig. 2 and 5), together with the permanent offset of the northern hanging wall above the southern foot wall of F1, suggests that during the fracture opening episode the northern-western block was preferentially uplifted and ejected to the north- west. This is consistent with Figure 9 which demonstrates that during lake tapping the greatest seismicity was recorded by the most western seismometers (S1–3) corroborating with the GPS observation of the greatest horizontal and vertical motion of the north-western block on which GPS1 was located (Fig. 6a and e).

*RC2-4a: **Abstract.** The latter half of the abstract is not clearly written and only understandable after reading the main text. Please revise the text regarding the points listed below.*

AC: Taking into account comments RC2-4a-g addressed below the abstract has been revised to:

> **Abstract.** We present detailed records of lake discharge, ice motion and passive seismicity capturing the behaviour and processes preceding, during and following the rapid drainage of a ~ 4 km^2 supraglacial lake through 1.1 km thick ice on the western margin of the Greenland Ice Sheet. Peak discharge of 3300 m^3 s^{-1} coincident with maximal rates of vertical uplift indicate that surface water accessed the ice-bed interface causing widespread hydraulic separation and enhanced basal motion. The differential motion of four GPS located around the lake record the opening and closure of fractures through which the lake drained. We hypothesise that discharge occurred through a ~ 3 km long longitudinal (with- flow) fracture with a peak width averaged across its wetted length of ~0.4m. We argue that the fractures' kilometre-scale length allows rapid discharge to be achieved by combining reasonable water velocities with sub-metre fracture widths. These observations add to our currently limited knowledge of in situ supraglacial lake drainage events, which rapidly deliver large volumes of water to the ice-bed interface causing transient and localised uplift and acceleration.

RC2-4b: line 12: "brittle fracture" is not very clear.

AC: Removed sentence

RC2-4c: line 13: "longitudinal fracture" » longitudinal to what?

AC: All occurrences of longitudinal and transverse have been changed to “... longitudinal (with-flow) ...” “... transverse (cross-flow) ... ”.

RC2-4d: line 14: "perennial location of the supraglacial lake" is not discussed in the text.

AC: Removed.

RC2-4e: line 15: "control by subglacial topography. . ." » what controls what?

AC: Removed.

RC2-4f: line 17: "without longitudinal tension" » not clear and not evident in the data.

AC: Removed

RC2-4g: line 17-20: "The tapping of the lake . . ." » this is not a main subject of the paper.

AC; Removed

RC2-5: Conclusions are not very well organized. It looks to me somewhat a continuation of the Discussion section. The last paragraph is speculative and not related to the main subject of the paper. Please summarize what you measured and important findings in the data.

AC: The section on conclusions has been rewritten:

> ## 5 Conclusions
>
> Detailed measurements of GPS motion, discharge and seismicity during the rapid in situ drainage of a large annually tapping supraglacial lake through kilometre-thick ice on the western margin of the Greenland Ice Sheet contribute to our currently limited knowledge of rapid supraglacial lake tapping events.
>
> Horizontal ice motion during rapid tapping is dominated by the transient opening and closure of multiple fractures. We assert that during rapid discharge, drainage occurred along most of the fractures length. By reconstructing the fractures peak cross-sectional area from the differential GPS motion we find that the fractures’ kilometre-scale length allows rapid discharge to be achieved by combining reasonable water velocities with sub-metre fracture widths.
>
> The maximum uplift rate of 0.8 m h^{-1} occurred simultaneous with the maximum discharge of 3300m^3s^{-1} providing evidence that water rapidly attained the ice-bed interface raising subglacial water pressures above overburden over a large area of the bed. Basal topography and the gradient of hydraulic potential exert control on water routing, horizontal ice motion and uplift during lake tapping events. The greatest horizontal displacement and vertical uplift was observed above the preferential subglacial drainage route.
>
> Lake tapping events rapidly deliver large pulses of surface water to the bed of the Greenland Ice Sheet causing transient ice-bed separation and acceleration however it remains un- clear what impact this water delivery will have on the annual ice flux.

*RC2-6: **Title**. The terms "ice tectonics" and "tapping" are not often used in glaciological publications. If there is no specific reason to do so, I suggest the author to use terms more familiar to the readers, something like "ice surface motion" and "drainage".*

AC: The term “Ice tectonics” is used to specify that in this paper ice surface motion is attributed to structural deformation along a fault through which the lake drained.

The term ‘tapping’ has been replaced with “rapid in situ lake drainage” (or a similar phrase) up until “lake tapping” is defined in the second paragraph of the introduction. Tapping is used to distinguish between lakes that drain rapidly via an in situ hydraulic fracture propagated to the bed of the ice sheet and those that drain rapidly by supraglacial stream discharge into other lakes or moulins. Although not often used in glaciology the term ‘tapping’ has previously been used to describe the naturally occurring episodic drainage of ice-marginal lakes (e.g. Anderson et al., 2005; Clement, 1984, Fristrup, 1960, Knight & Tweed, 1991, Roberts et al., 2005, Tweed & Russell, 1991). The term is also used to describe the method of blasting a tunnel into a body of water in order to extract water for hydro-electricity (e.g. Cogan & Kintzer, 1984). Both these processes have similarities with the rapid in situ drainage of supraglacial lakes via the propagation of a hydraulic fracture through an ice mass, and the term tapping seems well suited and useful to distinguish between lakes that drain via in situ hydraulic fractures and those that drain over a short time-period via overland flow into other supraglacial lakes or moulins.

The title has been changed to:

> “Ice tectonics during the rapid in situ drainage of a supraglacial lake on the Greenland Ice Sheet”

RC2-7: page 3865, line 19: . . . a process termed dynamic thinning. This is not very accurate as "dynamic thinning" includes ice thinning by stretching ice flow regime.

AC: Dynamic thinning has been removed from this sentence, which has been changed in response to SC1-1.

RC2-8: page 3867, line 8-9: Uncertainties in the positions . . .. How were these numbers estimated?

AC: Changed to:

> “Assuming steady ice motion, uncertainties in the positions were estimated at < 0.02 m in the horizontal and < 0.05 m by examining the detrended position time series for GPS1 over a 2 day period in May 2011.”

RC2-9: page 3868, line 4: ... P1 and P2 ... Please define P1 and P2, and indicate the locations of the sensors in Figure 2.

AC: P1 and P2 have been defined on page 3867, line 2 by changing the sentence to

> “Two pressure transducers (P1 and P2, Solinst M15 Levelogger) were installed in Lake F…”.

The locations of P1 and P2 have been annotated on Fig. 2.

RC2-10: page 3868, line 19: . . . an automatic lake classification . . .Please describe more about this method and/or provide citations.

AC: This section has been extended to

> “To investigate the extent and timing of rapid draining lakes within the Russell Glacier catchment, an automatic lake classification was applied to daily-acquired cloud-free MODIS images. Lakes were classified using the Normalised Difference Water Index (NDWI) following the method described in (Huggel et al., 2002). An empirically determined NDWI threshold was used to distinguish between water and other objects with a low NDWI (e.g. ice with a low albedo). The lake classification was trained using lake perimeter measurements derived from Landsat 7 images and dGPS data. In combination with the NDWI threshold, thresholds for both the red and blue bands were used to further reduce misclassification of pixels with a similar spectral signal to water. Images with partial cloud cover were manually inspected.”

RC2-11: page 3868, line 24: . . . (potentially by rapid in situ tapping) . . . It is not clear what is meant here.

AC: The bracketed section has been removed. It was meant to remind the reader that not all the lakes that drained in < 4 days did so by in situ hydrofracture – some of these lakes could have drained through supraglacial rivers into moulins or other lakes.

RC2-12: page 3868, line 27-28: The drainage network shown . . .Please explain more the method (software) used here.

AC: Changed to: “The drainage network shown in Fig. 1 was created using hydrological modeling software (ArcGIS hydrological toolkit) from a 30 m resolution DEM derived from Systeme Pour l’Observation de la Terre (SPOT) data acquired on 2 July 2008.”

RC2-13: page 3869, line 25: A number of ice blocks . . . Where are these ice blocks from? How were they produced?

AC: Please, see the response to RC1-11.

RC2-14: page 3870, line 3: . . . fractures was . . .... fractures were ...

AC: Corrected from “was” to “were”.

RC2-15: page 3872, line 21-22: The transient reverse motion. . ..It is not clear what is meant here. Why is the opening a transverse fracture difficult? How is it related to the reverse motion?

This section has been changed to:

> “… short-term longitudinal (with-flow) extension between GPS1 and GPS4 of ~ 0.2 m (see Fig. 7b), involving the reverse motion of GPS4 commencing at 02:00, is interpreted as the opening of subsidiary fracture F2. The opening of F2 involves the displacement of GPS4 to the east up the bedslope (Fig. 11). As soon as discharge decreases after 02:47 (Fig. 8a) the force holding F2 open begins to reduce and, aided by the bedslope, GPS4 reverses in direction to the west (Fig. 6d), closing F2. The circular path of GPS4 during lake tapping (see Fig. 6d) can be interpreted as the combined effect of fractures F1 and F2 opening and closing.”

RC2-16: page 3873, line 20: ... 980 m of ... » ... 980 m thick ice of ...?

AC: Corrected to “through 980 m thick ice”.

RC2-17: page 3889, Figure 10: Please give a scale for the vectors showing the hydraulic potential gradients.

AC: A scale for the hydraulic potential gradients has been added to Figure 10 and its caption has been changed to:

> “Fig. 10. Map of the hydraulic potential gradients (assuming basal water pressures are at overburden) and subglacial topography for Lake F. The arrows indicate the direction of the hydraulic potential gradient and are scaled by the meters of hydraulic potential change per meter. The lake margin immediately prior to lake tapping is shown together with the locations of moulins, fractures and GPS. The contour interval for the basal topography is 10 m.”

On Figure 10 the units for the bed elevation have been changed from [m] to [m above WGS-84]. Additionally, the paragraph describing the method used to calculate hydraulic potential gradients has been improved by: (i) Moving it from the discussion to the methods section; (ii) Adding a citation for the radio-echo sounding method; and (iii) adding a sentence making it clear that the calculated hydraulic potential gradients can only be used to approximate the direction of water flow during the drainage of Lake F as they are based on the assumption that subglacial water pressures were everywhere equal to the ice overburden pressure.

The section describing the method used to calculate hydraulic potential gradients is now:

> **2.4 Mapping hydraulic potential gradients**
>
> Basal and surface elevation DEM’s collected by skidoo-based radio echo

sounding following the method of Pettersson et al. (2011) were used to calculate the gradients of hydraulic potential, assuming basal water pressures were everywhere equal to the ice overburden pressure (Shreve, 1972). The resulting hydraulic potential gradients (Fig. 11) can only be used to approximate the direction of subglacial water flow during the rapid tapping of Lake F, as subglacial water pressures likely exceeded overburden during rapid discharge.

Response to Short Comment from M. Pelto

SC1 – 1: 3865-19: This assumes the acceleration leads to an overall increase in velocity. You have cited some support for this. This maybe the case, but there is considerable literature suggesting it is not. Sundal et al, (2011) noted that ice velocity was enhanced by high melt rates early in summer; however, this was offset by velocity during the latter portion of warm summers being less. Van de Wal (2008) noted that the melt rate and ice velocity feedback mechanism was a short lived seasonal mechanism that may have a limited impact on ice sheet velocity. Das et al., (2008) noted that other than the 24 hours following drainage pre and post drainage velocities did not differ appreciably. Bartholomew et al, (2012) note that the ice velocity at elevations below 1000 m are dominated by speed up events of 1 day to 1 week. Colgan et al (2011b). Sundal et al (2011) and Batholowmew et al (2012) all noted the similarity of the subglacial drainage system response to that of smaller alpine glaciers. That basal sliding is enhanced when meltwater input exceeds the subglacial transmissivity and that basal sliding is reduced after during periods of reduced hydrologic head.

AC: Changed to:

> "The integrated effect of multiple lake tapping events, and the continued water flow into the hydraulic pathways they create, have the capacity to impact the annual ice flux in future years, especially as, in a warming climate, lakes are expected to form and drain earlier in the season (Liang et al., 2012) and at higher elevations (Howat et al., 2012). It is uncertain whether this increase in water delivery will increase the annual ice flux through a net increase in basal lubrication (e.g. Zwally et al., 2002), or decrease the flux due to an earlier seasonal transition to an efficient subglacial drainage system (e.g. Sundal et al., 2011)."

SC1-2: 3868-16: Any Landsat imagery from overlapping dates that could aid in assessing this error?

AC: Yes, Landsat imagery together with differential GPS measurements of lake perimeter were used to train and validate the classification of lakes on MODIS images using similar methods to Selmes et al., (2011) and Liang et al. (2012). To reduce the uncertainty and improve the lake volume estimates derived from MODIS we have recalculated the volumes given on Figure 3 by applying the method of Box & Ski (2007) to cloud-free MODIS images, instead of calculating lake volume from the bathymetry using MODIS-derived perimeters.

Page 3868 Line 16 has been changed to:

> "To extend the lake volume record, a time series of Lake F volume was estimated from daily-acquired atmospherically-corrected Moderate-resolution Imaging Spectrometer (MODIS) images by applying the method of Box and Ski (2007). Uncertainty in this method was estimated at ±15 % by comparing MODIS-derived lake volumes with independently collected lake bathymetry data."

Figure 3 has been updated with the new MODIS-derived volumes.

The maximum volume of the lake given in Section 3.2 of 1.5×10^7 m^3 has been updated to 1.8×10^7 m^3 by changing Line 14-15 on page 3869 to: "In 2010, Lake F began to form on 5 June attaining its maximum extent on 24 June with an area of 4.5 km^2 and a volume of 1.8×10^7 m^3 (Fig. 3)."

SC1-3: 3869-27: When exactly did F1 open? In general somewhere in the paper I would appreciate a description of the evolution of F1 beyond the actual drainage event. 3874-18: What is the structure of F1 a month after the event?

AC: The main opening of F1 is interpreted from the GPS data to have occurred at 02:00

when GPS2 reverses in its initial direction and moves to the south (see p.2872 L14 and L19). We did not observe any structural evolution of F1 beyond the drainage event as we only surveyed it once on 1 July 2010. We attempted to measure post-drainage differential motion across the fracture by drilling in bamboo but these melted out before we had the chance to re-measure them. 2010 was a record warm year (Cappelen, 2011; Van As et al., 2012) and the high ablation rate meant the ice surface in the drained lake-bed weathered quickly. The edges of fractures quickly became rounded and the fracture's structure became less distinct. It would have been interesting to measure the structural evolution of the fracture after the drainage event and future studies examining lake tapping events should consider doing this.

SC1-4: Is the main fracture, F1, observable in a similar orientation in imagery from previous years? Are there any other images of Lake F from before or after drainage that could illustrate this?

F1 is not observable in satellite imagery as far as I am aware. The resolution of Landsat imagery (15 m for band 8 panchromatic, 30 m for bands 1-7) is too coarse to pick out the fractures formed during the lake tapping, which in 2010 were at the most 5 m wide.

The actual resolution of the visible Landsat imagery used in Fig.1 is 30 m not 15 m and the caption for Fig. 1 has been corrected.

SC1-5: 3875-10: This indicates the fracture is a better means of drainage than a moulin. The fracture is different than the crevasses discussed by Colgan et al (2011a), which observed that moulins propagate meltwater pulses to the englacial system better than crevasse systems. Could you describe specifically how the fracture differs.

AC: The hydraulic fracture formed during the rapid tapping of a supraglacial lake through 1.1 km of ice differs in many ways to the crevasses of Colgan et al. (2011a). Colgan et al. (2011a) specifically discuss crevasse zone hydrology over seasonal time scales. We calculate the cross-sectional area of two large fractures at their peak width and we only state that the hydraulic fracture is efficient at transporting water for a short (< 2 hour or) period whilst the lake drains and the fracture is open. The difference in hydraulic efficiency between fractures F1 and F2 and moulins lies in the difference in cross-sectional area. At peak opening the fracture has a greater cross-sectional area than a typical moulin. For example the estimated cross-sectional area of fracture F1 at peak separation is 842 m^2, which is much greater than the cross-sectional area of the largest (~ 10 m diameter) moulin, M1 of 78.5 m^2.

SC1-6: 3876-21: Could the earlier lake formation and drainage lead to a longer period of each melt season being a period of reduced basal sliding since the mature subglacial hydrologic drainage system leads to reduced hydrologic head and lower velocity? This goes back to the first comment above and the similarity of the subglacial drainage system response to that of smaller alpine glaciers. Where high melwater input in the spring increases velocity as the subglacial hydrologic system is redeveloped, and is less with higher runoff later in the summer through the now efficient subglacial hydrologic system.

AC: This is a very good question that this short (5-day) dataset is not able to answer.

References

Alley, R., Dupont, T., Parizek, B. & Anandakrishnan, S. 2005. Access of surface meltwater to beds of sub-freezing glaciers: preliminary insights, *Annals of Glaciology,**40***, 8-13.

Anderson, R.S., Walder, J.S., Anderson, S.P., Trabant, D.C. and Fountain, A.G. 2005. The dynamic response of Kennicott Glacier, Alaska, USA, to the Hidden Creek Lake outburst flood, *Annals of Glaciology*, **40**, 237-242.

Bartholomew, I., Nienow, P., Sole, A., Mair, D., Cowton, T. and King, M.A. 2012. Short-term variability in Greenland Ice Sheet motion forced by time-varying meltwater drainage: Implications for the relationship between subglacial drainage system behavior and ice velocity, *J. Geophys. Res*.,**117**, F03002.

Boon, S. & Sharp, M. 2003. The role of hydrologically-driven ice fracture in drainage system evolution on an Arctic glacier, *Geophysical Research Letters*, **30**, 1-4.

Box, J. & Ski, K. 2007. Remote sounding of Greenland supraglacial melt lakes: implications for subglacial hydraulics, *Journal of Glaciology, **53***, 257-265.

Cappelen, J. (ed)., Laursen, E., Jørgensen, P. and Kern-Hansen, C. 2011. DMI Monthly Climate Data Collection 1768-2010, Denmark, The Faroe Islands and Greenland, *Danish Meteorlogical Institute, Technical Report 11-05.*

Clement, P. 1984. The drainage of a marginal ice-dammed lake at Nordbogletscher, Johan Dahl Land, South Greenland, *Arctic and Alpine Research*, **16**, 209-216.

Cloos, E. 1995. Experimental analysis of fracture patterns, *Bulletin of the Geological Society of America, **55***, 241-256.

Cogan, J. & Kintzer, F. 1984. Rock engineering for Tyee lake tap, *The 25th U.S. Symposium on Rock Mechanics,* American Rock Mechanics Association.

Colgan, W., Steffen, K., McLamb, W., Abdalati, W., Rajaram, H., Motyka, R., Phillips, T. and Anderson, R.: 2011a. An increase in crevasse extent, West Greenland: Hydrologic implications, *Geophys. Res. Lett*., **38**, L18502.

Colgan, W., Rajaram, H., Anderson, R., Steffen, K., Phillips, T., Joughin, I., Zwally, H. and Abdalati, W. 2011b. The annual glaciohydrology cycle in the ablation zone of the Greenland ice sheet: Part 1. Hydrology model, *Journal Glaciology*, **57** (204), 697-709.

Das, S., Joughin, I., Behn, M., Howat, I., King, M., Lizarralde, D., and Bhatia, M. 2008. Fracture propagation to the base of the Greenland Ice Sheet during supraglacial lake drainage, *Science*, **320**, 778–781.

Fristrup, B. 1960. Studies of four glaciers in Greenland, *Geografisk Tidsskrift*, **59**, p. 89-102.

Hooke, R., Calla, P., Holmlund, P., Nilsson, M. and Stroeven, A. 1989. A 3 year record of seasonal variations in surface velocity, Storglaciaren, Sweden, *Journal of Glaciology, **35***, 235-247.

Howat, I. M., de la Peña, S., van Angelen, J. H., Lenaerts, J. T. M. and van den Broeke, M. R. 2012. Brief Communication "Expansion of meltwater lakes on the Greenland ice sheet", *The Cryosphere Discussions, **6***, 4447-4454.

Huggell, C., Kääb, A., Haeberli, W., Teysseire, P. and Paul, F. 2002. Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps, *Canadian Geotechnical Journal, **39***, 316-330.

Jones, G. A. Kulessa, B. Doyle, S. Dow, C. F. & Hubbard, A. 2013. An automated approach to the location of icequakes using seismic waveform amplitudes, *Annals of Glaciology*, **54** (64), 1-9.

Knight, P. G. & Tweed, F. S. 1991. Periodic drainage of ice-dammed lakes as a result of variations in glacier velocity, *Hydrological Processes,* **5**, 175-184.

Krawczynski, M., Behn, M., Das, S. and Joughin, I. 2009. Constraints on the lake volume required for hydro-fracture through ice sheets, *Geophysical Research Letters, **36***, 1-5.

Liang, Y.-L., Colgan, W., Lv, Q., Steffen, K., Abdalati, W., Stroeve, J., Gallaher, D. & Bayou, N. 2012. A decadal investigation of supraglacial lakes in West Greenland using a fully automatic detection and tracking algorithm, *Remote Sensing of Environment, **123***, 127-138

Neave, K. & Savage, J. 1970. Icequakes on the Athabasca Glacier *Journal of Geophysical Research*, **75**, 1361-1362.

Pettersson, R. Christoffersen, P. Dowdeswell, J. Pohjola, V. Hubbard, A. and Strozzi, T. 2011. Ice thickness and basal conditions of Vestfonna Ice Cap, Eastern Svalbard *Geografiska Annaler: Series A, Physical Geography*, **93**, 311-322.

Price, N.J., and Cosgrove, J.W.: Analysis of geological structures, University Press, Cambridge, 1994.

Roberts, M. J., Russell, A. J., Tweed, F. S. and Knudsen, Ó. 2000. Ice fracturing during jökulhlaups: implications for englacial floodwater routing and outlet development, *Earth Surface Processes and Landforms, **25***, 1429-1446

Roberts, M.J. Palsson, F. Gudmundsson, M.T. Bjornsson, H. and Tweed, F.S. 2005. Icewater interactions during floods from Graenalon glacier-dammed lake, Iceland, *Annals of Glaciology, **40***, 133-138.

Roux, P.-F., Walter, F., Riesen, P., Sugiyama, S. and Funk, M. 2010. Observation of surface seismic activity changes of an Alpine glacier during a glacier-dammed lake outburst, *Journal of Geophysical Research*, **115**, F03014.

Selmes, N.; Murray, T. & James, T. 2011. Fast draining lakes on the Greenland Ice Sheet, *Geophysical Research Letters, **38***, L15501.

Shreve, R. 1972. Movement of water in glaciers, *Journal of Glaciology, **11***, 205-214

Stenborg, T. 1968. Glacier drainage connected with ice structures, *Geografiska Annaler*, **50A**, 25-53.

Sugiyama, S., Bauder, A., Huss, M., Riesen, P. and Funk, M. 2008. Triggering and drainage mechanisms of the 2004 glacier-dammed lake outburst in Gornergletscher, Switzerland, *Journal of Geophysical Research, **113***, F04019.

Sundal, A.V., Shepherd, A., Nienow, P., Hanna, E., Palmer, S. and Huybrechts, P. 2011. Melt-induced speed-up of Greenland ice sheet offset by efficient subglacial drainage. *Nature*, **469**, 521-524

Tweed, F. S. & Russell, A. J. 1999. Controls on the formation and sudden drainage of glacier-impounded lakes: implications for jokulhlaup characteristics, *Progress in Physical Geography*, **23**, 79-110.

van As, D., Hubbard, A., Hasholt, B., Mikkelsen, A., van den Broeke, M. and Fausto, R. 2012. Large surface meltwater discharge from the Kangerlussuaq sector of the Greenland ice sheet during the record-warm year 2010 explained by detailed energy balance observations, *The Cryosphere,* **6**, 199-209

van de Wal, R.S.W., Boot, W., van den Broeke, M., Smeets, C., Reijmer, C., Donker, J. and Oerlemans, J. 2008. Large and rapid melt-induced velocity changes in the ablation zone of the Greenland Ice Sheet. *Science*, **321**, 111–113.

Walter, F., Clinton, H., Deichmann, N., Dreger, N., Minson, S. and Funk, M. 2009. Moment Tensor Inversions of Icequakes on Gornergletscher, Switzerland *Bull. Seism. Soc. Am.,**99***, 852—870.

Walder, J.S., Trabant, D.C. Cunico, M. Anderson, S.P., Anderson, R.S. and Fountain, A.G. 2005. Fault-dominated deformation in an ice dam during annual filling and drainage of a marginal lake. *Annals of Glaciology, **40***, 174–178.

Zwally, J., Abdalati, W., Herring, T., Larson, K., Saba, J. & Steffen, K. 2002. Surface melt-induced acceleration of Greenland Ice-Sheet Flow, *Science, **297***, 218-222.