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Interactive comment on "Subglacial sediment transport upstream of a basal channel in the ice shelf of Support Force Glacier (West Antarctica), identified by reflection seismics" *by* Coen Hofstede et al.

Coen Hofstede et al.

coen.hofstede@awi.de

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My apologies for the delay, it took longer than I had expected. Please note these are comments on reviewer #2

General comments 1:

Thank you for making this point. We overlooked this and will back this up with literature and a more focused interpretation. We'd like to stress that we make an interpretation of the radar and seismic profiles so at best evidence is circumstantial. However, we do

believe the interpretation we provide is the best explanation of what we observe in the seismic and radar profiles. This is also supported by the evaluation of Adam Booth, reviewer #1, one of the seismic experts in glaciology.

In our answer we'll use the following terminology:

Grounded ice:

- Subglacial channel: a feature between the ice and the bed, probably water filled. Needs ice to be visible.

- Landform: a geomorphological feature of the bed – would be visible without the ice

Ice shelf:

- Surface channel: Meandering narrow long channel at the surface of an ice shelf

- Basal channel: The sub-ice shelf channel causing the surface channel through hydrostatic adjustment.

The seismic survey concentrates at a surface channel caused by a basal channel at the ice shelf of Support Force Glacier. The basal channel is formed upstream by a subglacial channel we see in radar profiles. At the grounded ice we can track the subglacial channel at radar profiles 3, 4 and 5. At profile 3, 7.1 km upstream from the grounding line, the subglacial channel is hardly distinguishable from the bed after which its height increases at profile 4, 4.4 km upstream from the grounding line, to approximately 100 m above the surrounding bed. At profile 5,1.8 km upstream from the grounding line, the top of the channel increased to approximately 250 m above the surrounding bed. Profile 6 lies at the grounding line: the western part has passed the grounding line, the eastern part has not. The basal channel, an extension at the ice shelf of the subglacial channel, now reached a height of approximately 300 m above the surrounding base of the ice shelf.

This is where we'd like to adjust our interpretation: Considering the comment of reviewer #1 that the refection coefficient of the off-nadir reflections is tricky (we don't think they are diffractions) and we might over interpret the data, we will only use its polarity which indicates the presence of water. The radar profiles show the subglacial channel increases its height from approximately 0 m to 300 m over a length of 7.1 km approaching the grounding line. This would place a landform within 7.1 km upstream of the grounding line which we think is unlikely. Summarizing, if we leave out the value of the reflection coefficient we see no evidence the off-nadir reflections in seismic profile I between radar profiles 5 and 6, are caused by a landform.

We interpret these reflections to come from the subglacial channel we see in the radar profiles 3, 4, 5 and 6. The increase in size, when approaching the grounding line, is likely caused by the ocean is interacting with the subglacial channel due to tidal motion thereby increasing its size due to melting of the channel walls as suggested by Drews et al. (2017), Horgan et al. (2013) and modelled by Walker et al. (2013). The radar profiles 3, 4, 5 and 6 show the subglacial channel interacting with the warm ocean. Once passed the grounding line this wide opening of the subglacial channel adjusts to hydrostatic equilibrium and forms the basal and surface channel in which the subglacial drainage water incises.

We plan to adjust our interpretation accordingly: At the grounded ice of Support Force Glacier radar profiles 3, 4, 5 and 6 show a subglacial channel connecting a basal at the grounding line. Approaching the grounding line the subglacial channel increases its size to 300 m height at the grounding line, which we attribute to ocean interaction. This setting is similar to the subglacial estuary described by Horgan et al. (2013). Because the subglacial channel connects to the only basal channel at the western side of the ice shelf, and because we have a large subglacial drainage influx modeled at the western side of the ice shelf, we interpret the subglacial channel to be a subglacial drainage channel.

The grounded part of profile I consists of a sediment layer judging by its reflectivity becoming more consolidated closer to the grounding line. So the drainage channel

probably travels over a layer of subglacial sediments with varying consolidation. The exact nature of the subglacial drainage system we do not know but the radar and seismic profiles do suggest channelized flow close to the grounding line. Possibly we are dealing with a channel that, upstream and outside the survey area, is coupled to a surrounding distributed system as described by Hewitt (2011). Close to the grounding line channelized flow is favorable which corresponds to our observations.

General comments 2:

To summarize our findings: We have a modelled large influx of freshwater on the western side of the shelf.

From the airborne radar data of the shelf we know the ice shelf has only one basal channel at the western side. That must be the place where the subglacial drainage channel enters the ocean.

There is a noble gas sample downstream of Support Force Glacier suggesting a freshwater influx of terrestrial origin coming from Support Force Glacier.

Along profile I (along-flow, 1.5 km east of the basal channel) shows an approximately 200 m thick sedimentary sequence close to the grounding line of different character then the seabed further downstream part of the ocean cavity. The sedimentary sequence is less consolidated and has chaotic reflections with high amplitudes. Across profile III, crossing this sedimentary sequence with chaotic reflections, shows this sequence is only present under the sub-shelf channel. Both on the far east and west side of profile III there is hardly any structure in the seabed except right under the channel. This sedimentation most likely has been transported by the subglacial channel.

Based on profile I and III we interpret the sedimentation to be point sourced and fan shaped, possibly a grounding line fan (Powell, 1990) or an ice-proximal fan (Batchelor and Dowdeswell, 2015). This explains the chaotic reflections (we referred to as disturbed), with high amplitudes in this sedimentary sequence and this material being softer as the further downstream part of the sea bed.

We realize there are concerns here as the fan has formed under an ice shelf of Support Force Glacier without surface melt, a characteristic of fans (Powell and Alley, 1997). But we do have evidence for channelized flow at the grounding line, a noble gas sample suggesting freshwater observation influx of terrestrial origin likely (Huhn et al. 2018) and a significant (190 x 106 m3 a-1) modelled channelized freshwater influx at one place on the west side confirmed by the presence of a single basal channel on the western side. We also have an unusual ocean cavity with a steeply descending seabed and, as argued in our paper, a stable grounding line. These are typical conditions for the formation of a fan at the grounding line (Powell 1990, Powell and Alley 1997, Batchelor and Dowdeswell 2015) . We will emphasize this in the text and update figure 4 with a schematic lay out as in figure 2 where we identify the sedimentary with chaotic reflections.

Can we proof all this and can we say how old this sedimentation process is? Not without sea bed samples of the sedimentary with chaotic reflections or an additional seismic across-flow profile passing the subglacial channel. Do we think this interpretation is likely and sound? Yes we do if we look at the glaciological setting; a grounding line environment where a subglacial drainage channel enters the ocean cavity with a descending seabed and seismic profiles show a sedimentary with chaotic reflections right under the basal channel.

General comments 3:

In our reaction to general comments 1 we explain our adjusted interpretation: the off-nadir reflections are probably caused by the enlarged opening of the subglacial channel, not the landform. In our reaction to general comments 2 we explain why, based on seismic profile I and III we interpret the sedimentary sequence with chaotic reflection to enter the ocean cavity through the subglacial channel.

We agree we should make a better case here. We've set out our reasons as to why

we think we can connect the sedimentary sequence with chaotic reflections we see in seismic profile I and III to the subglacial channelized flow and why we think this sequence probably resembles a fan.

Conceptual model: Is this like a picture explaining the model? It should be possible but it is quite some work, There are figures showing the formation of fans at grounding line like in Powell (1990). The difference in our case is that there will be a shelf at the grounding line instead of a cliff. But if you feel the paper needs it, we can provide it.

Specific comments:

Title: Updated.

Title evidence: Indeed sediment transport is an interpretation mainly based on the structure and reflectivity of the seismic sections presented as such we suggest: "Likely subglacial sediment. . ."

Addresses: Updated.

Abstract L1: Agreed, the surface channel at Support Force Glacier starts as a meandering surface channel at the grounding line, is not a flow stripe.

L5: Corrected. Floating part should be ice shelf.

L8: Agreed.

L10:It is an interpretation we give in our reply to the general comments. We will adjust the discussion text accordingly and will explain why we interpret this sequence as grounding line deposits.

L10: This will be removed as we interpret this feature no longer as a landform.

L15: Indeed the channel is 4 km east of the shear margin. We will remove this.

Page 2

L4: We'll remove the association with flow stripes: "They are often detected with satellite imagery like MODIS. . .”

L25-27: We disagree. Jeofry et al.2018 suggest a combination of a landform incising the base of the ice which when becoming afloat will cause a surface channel and basal channel. Quote: “we propose that the bedforms are dictating the position and form of the U channels.” Which is also why they checked the dimensions of landforms that are indeed at completely different locations which we also state in L26, 27. As the landform also organizes the drainage pathway, quote:”the water incises upward into the corrugation peak” also because fresh water will want to move upward will assemble in the by bedrock formed corrugation peak.

L29: The surface trough of the shear margin (that has a surface depression) induces a basal channel due to hydrostatic adjustment once it passes the grounding line. Once afloat, the surface trough is shallower while adjusting but then deepens again as a warm water plume thins the base of the ice in the channel.

L32-33: Indeed, we state that this observation is often missing, nothing more.

Page 3

L4: This is correct, the modeled drainage pathway is offset by 4 km from the basal channel. This model is coarse, it has a resolution of 1 km and does not take the physical nature of the bed into account that may steer the pathway somewhat differently. Although we did use the topography derived from the airborne radar data, the surrounding is of course still BEDMAP2. So the model is an indication of where one may expect a subglacial drainage system.

L8:Agreed.

L11: Thanks for making this point, we will rephrase “or does the substrate also consist of sediments.”

L16: Agreed.

L17: Agreed.

L18: Agreed.

L23-24: Thanks, corrected.

L24: Agreed.

L30: Just BEDMAP 2.

L30: Agreed.

Page 4

L2 : Correct, thanks.

L11: We will correct this.

L14 Jeofry et al: Good suggestion, thanks.

L14: Correct.

L16: Correct .

L27: Thanks for bringing it to our attention. The reference should be: Paden, J., Li, J., Leuschen, C., Rodriguez-Morales, F., and Hale., R.: 2010, updated 2018. IceBridge MCoRDS L2 Ice Thickness, Version 1. Antarctica., Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center.,https://doi.org/10.5067/GDQ0CUCVTE2Q, 2019.

L30: The model domain for the routing was the entire hydrological catchment of SFG. I attached a small figure, which we could put into the answer or appendix.

Page 5

Figure 1:We’d like to use an arrow head at each line.

L1: As explained (Page 3, L4) we use a model with its shortcomings. The main result is we can expect water drainage on the western side of the shelf. Keeping in mind that the resolution of the model is 1 km, and does not take the physical properties of the bed into account, we find 4 km acceptable.

Page 6

Table1: We will remove this.

Page 10

L16: Reviewer #1 pointed out that the phrase artefact is not accurate. We'd like to change the title to "seabed depth conversion" as he suggests.

L18: The morphology is a better phrase.

L20: Agreed.

L24: They are marked with double headed arrows on top of the figure: interval 1, 2, 3 and 4.

L28: Agreed.

L30: Yes we mean floating.

Page 11

Figure 2: labeling agreed. The shot numbering gives the shooting directions, but we can add this if you feel this is not clear.

Note: Is subsea bed acceptable? If we talk about sediments we are interpreting.

Weak reflections: The are probably side reflections of the ice-sea contact, the polarity is reversed just as the identified sea-bed contact which is why we think they resemble ice-seawater contacts. The shelf base here has a lot of topography.

Reflectivity zones: As mentioned we have defined the reflectivity zones. Please let me know if you find this ok. We can provide zooms of key features.

L1: Based on shot spacing and two-way travel time the dimensions are 1200 m long and the feature appears to be 50 m higher than the surrounding bed if it was nadir, hence we called it elongated although of course we do not know the across-flow dimension.

L3-4: We propose to call this "subglacial feature". We will provide a zoom of this subglacial feature in our response to reviewer#1 as we think we are dealing with reflections. As mentioned this part of our interpretation we want to change: We interpret this subglacial feature still as off-nadir reflections but no longer as a landform but as the top of the subglacial channel that in this area so close to the grounding line likely interacts with the ocean. This interaction with the ocean probably caused a rapid increase in height of the subglacial channel.

As reviewer #1 pointed out, a quantitative analysis its reflectivity is tricky as we have a complex subglacial structure off-nadir. To avoid over-interpretation we will not use the calculated reflection coefficient but its polarity.

L6: Agreed, concave cavity is a better term.

L8: Agreed.

L10 200m: It is as you observe, there is not a clear last sediment-bedrock reflection but the chaotic reflections fade out with increasing depth. Hence approximately 200 m.

L10 transparent: What we mean by transparent is that the seismic signal penetrates deep in the formation with little loss of amplitude.

We will use the phrase sedimentary sequence with chaotic reflections with high amplitudes as mentioned in our reaction to general comments 2.

Page 12

L15 Agreed.

L20: As this a complicated profile with two ice-sea contacts and two sea-seabed contacts, we'd like to take this figure out of the paper as reviewer 1 suggests. We hardly use it in our interpretation and the figure is complicated to explain.

L21: Yes the seabed is present here as we have the seafloor returns twice (two different ray paths: path 1 is along crest of the channel, path 2 is along base of the ice next to the channel and they likely have the same seabed depth. Converting the time migrated section to depth is not really possible as we must choose one of these two ray paths to convert to depth but then we automatically misplace the reflections of the other ray path.

L22: We will remove Figure 3 as profile II is difficult to interpret and probably causes misunderstandings. As reviewer #1 pointed out, profile II hardly contributes to the interpretation.

L23: Will be removed.

L24: Will be removed.

L31: Thanks.

L32: Thanks for pointing this out.

Page 13

Figure 3: There are two seabed reflections present due to different travel paths. See our reply at L21.

We will remove Figure 3

Figure 3 bed: Thanks, we will

L3-7 Agreed

L6-7: Yes that is what we claim, right under the basal channel, profile III shows thicker stratification (roughly from SP 3 to SP 24) under the basal channel then outside the basal channel. We plan to add schematic images (recommendation of reviewer 1) of

profiles 3,4 and 5 as in Figure 2 marking the stratification areas.

Page 14

Figure 4: Indeed I see the confusion. Profile V (as profile IV) has multiples causing apparent stratification. This is clearer to spot in the time migrated profiles. So no, there is not 400 m of stratification at profile V (Figure 4a), I come to no more than 100m. We will provide a schematic picture with our interpretation. The focus of the paper lies on the sedimentary sequence with chaotic reflections that profile III crosses.

Page 15

Figure 5: Thanks for the suggestion. What we like to provide is use both radar and seismic profile to show the development of the subglacial channel (grounded) and how this continues as a basal channel under the ice shelf. The present figure actually consists of 3 profiles, profile 4 is used twice. Reason why we displayed them like this is to get a good handle on where melt/widening of the basal channel takes place.

L5-12:We will clean this up.

L5: Agreed.

L6: We withdraw this interpretation.

L11-12: We will adjust our interpretation as we state in our reaction to general comments 1 and remove the concept landform. Looking at the radar profiles 3, 4, 5 and 6 we see that the subglacial channel we see at the grounded ice, increases in size as it approaches the grounding line. So there is no landform at the grounded ice, just a subglacial channel that increases its size due to interaction with the ocean.

L 15: Agreed.

Figure 6: Agreed that should be made clearer. Profile 6 lies at the grounding line.

Page 17

Figure 6 profile 5: We have no indication profile 5 is susceptible to grounding line migration. Profile 5 crosses seismic profile I at SP 5 where we have a positive basal reflection indicating consolidated material. To us that means the ice is grounded here. If ocean water would have reached this far it would have influenced the reflectivity. We do have an indication the MOA grounding line, crossing seismic profile I at SP 51, is not correct. Seismic profile I clearly shows ocean water being present upstream of the MOA grounding line down to SP 26. Are we absolutely sure profile 5 is fully grounded all the time? No but it is very likely.

Section 4.1: We will be clearer here. We wish to refer to figure 2, profile I here, and will add this in the text. The interferometric grounding line crosses profile I at SP 23 but this can't be chosen that precise, . The polarity switch at profile I lies at SP 26, so 150 m downstream of SP 23. This deviation may be caused by the unprecise choice of the grounding line here.

L14: Correct.

Page 18

Figure 7: We think the concept of Figure 7 is still not clear.

The figure should show that off-nadir reflections of the landform (represented by the radar profiles 5 and 6 and we now interpret as the subglacial channel) arrive at the same time as if there had been a 50 m high channel at nadir (represented by the red semi-circle). As reviewer #1 points out, the weakness of the reflections shown in figure 8 (a zoom of profile I, figure 2) already suggest these reflections (or diffractions as reviewer 1 points out) are off-nadir.

Section 4.3: Indeed, we adjusted our interpretation as described in our reaction to general comments 1 and will adjust the text accordingly.

Section 4.3: We will restructure this according to our interpretation: The reflections are off-nadir and represent the subglacial channel. The channel opening is enlarged here

due to interaction with the ocean. This interaction between ocean and a subglacial channel is described by Horgan et al. (2013).

L13: Indeed if the reflections are at nadir it would seem like an R-channel and that is represented by the red semi-circle. That this is most likely not the case is because there is only one basal channel visible at the western side of the ice shelf and we argue that this is where the subglacial channel enters the ocean cavity which is on the western side so off-nadir of profile I. Had the reflections been nadir, the R-channel would have entered the ice shelf elsewhere but we see no evidence of another basal channel in the radar data. That is our main argument as to why we think the reflections are off-nadir and are caused by the subglacial channel.

Page 19

L17-20: Correct, it is an interpretation.

Page 20

L14: Correct.

L16: We propose chaotic reflections with high amplitudes, as mentioned in our reaction to general comments 2.

L17-19: We are presenting an interpretation. Seismic profile I and seismic profile III most likely show the presence of a grounding line fan.

L31: Agreed

L32: If you follow the same flow line along profiles 3, 4, 5 and 6 (marked on the long profiles with an arrow and radar trace number it is quite obvious. We also have 38km long profiles that make a clearer case for this observation which we will provide as Figure 2.

L33: As we pointed out in the our reaction to general comments 1 we will withdraw the quantitative analysis of the reflectivity. We will just use the polarity of the off-nadir reflections.

Page 21

L1-23: There is clear evidence of subglacial drainage at the western side namely the basal channel itself which matches a modelled subglacial drainage pathway with a large water flux. The radar profiles 3, 4, 5 and 6 indicate the presence of a subglacial channel matching the location at the grounding line of the basal channel. The increase in height of the subglacial channel seen on profiles 4, 5 and 6, close to the grounding line can very well be explained by interaction with the ocean. This is what one would expect of channelized flow close the grounding line and has been suggested by Horgan et al. (2013) and Drews et al. (2017) and modelled by Walker et al. (2013) and Hewitt (2011). What we can't proof is that this channel is carrying sediments but it is likely that at the end of an ice stream the subglacial channelized drainage system carries sediments. We do have the observation in seismic profiles I and III, of a sedimentary sequence with chaotic reflections close to the grounding line (profile I) and the presence of this package only under the basal channel (profile III), exactly where one would expect sedimentation to take place if the subglacial channel would be carrying sediments.

L12-14: Profile III shows thick sedimentation only under the basal channel consisting of several levels and extending eastward. We agree we should emphasize this observation and it's interpretation more. This is what links the sedimentation to a grounding line fan where the subglacial channel enters the ocean cavity and forms the basal channel by adjusting to the hydrostatic equilibrium. Profile IV and V have also show sedimentation but are tricky as multiples occur between stronger reflections. See my reaction to your comments at Figure 4. These profiles also cross different formations that are beyond the focus of the paper. When calculating a reflection coefficient, the attenuation in ice and seawater over the entire travel path are taken into account as is pointed out in chapter 2.6, equation 2. As such reflectivity is compensated for the attenuation.

L29: The reflection coefficient characterizes the interface between two media but if there is a layered sequence the reflection coefficient can be influenced by interference. We will just stick to the polarity of the off-nadir reflections.

L31: Evidence for subglacial drainage I pointed out answering your comments at page 21, L1-23 The subglacial feature is most likely the subglacial channel interacting with the ocean as pointed out in the our reaction to general comments 1. Profiles I and III are evidence of a grounding line fan under the basal channel.

L32: As mentioned quite extensively in our reaction to general comments "we do have evidence for channelized flow at the grounding line, a noble gas sample suggesting freshwater observation influx of terrestrial origin likely (Huhn et al. 2018) and a significant (190 x 106 m3 a-1) modelled channelized freshwater influx at one place on the west side confirmed by the presence of a single basal channel on the western side. Seismic profile I and III suggest the sedimentary sequence with chaotic reflections is point sourced and fan shaped, possibly it is an ice-proximal fan (Batchelor and Dowdeswell, 2015). This explains the chaotic reflections and this material being softer as the further downstream part of the sea bed. We also have an unusual ocean cavity with a steeply descending seabed and, as argued in our paper, a stable grounding line. These are typical conditions for the formation of a fan at the grounding line (Powell 1990, Powell and Alley 1997, Batchelor and Dowdeswell 2015) ." Lastly we do not provide hard evidence but an interpretation.

Page 22

L18: Indeed it was a smooth operation.

Final comment: Your comments are highly appreciated. They force us to built up our case better which improves the manuscript. So thank you.

Coen Hofstede, August 15, 2020

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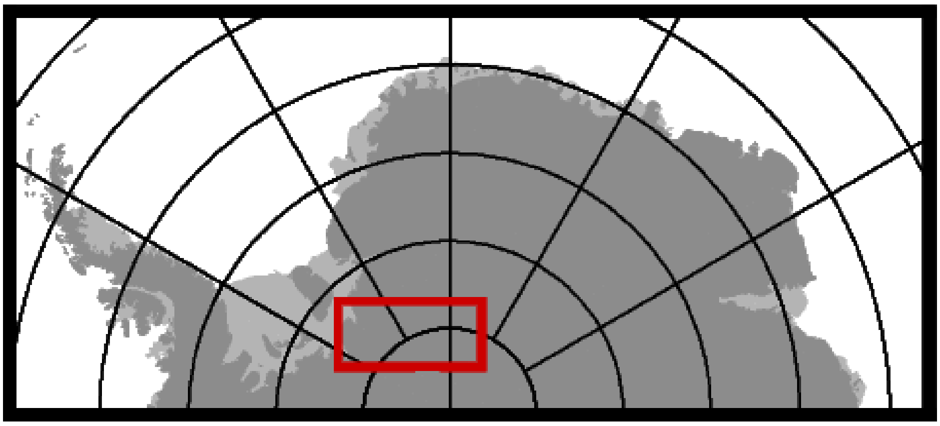

Fig. 1.

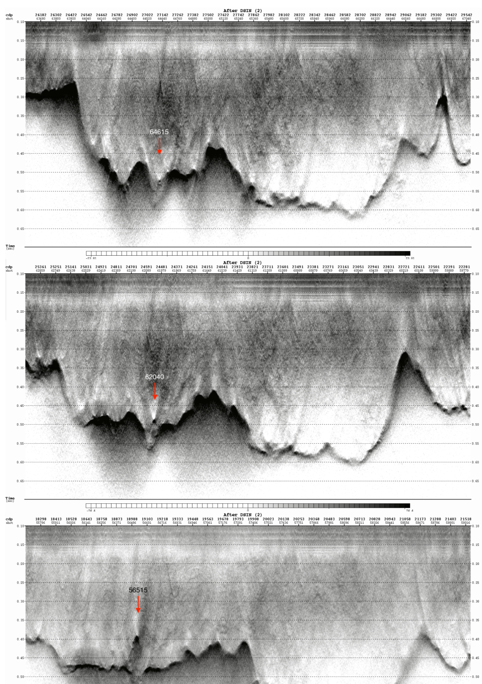

Fig. 2.