We first would like to thank our reviewers for an insightful consideration of both geophysical and glaciological aspects of this work. Their comments echo many concerns and ideas we encountered during our analysis while also providing suggestions that have improved and clarified the work.

After integrating the reviewers' suggestions with respect to the analysis and interpretation, our fundamental result is the definition of approximately 1 km of sediment beneath the Jakobshavn Isbrae (JI) trough that contributes to the outlet glacier's overall velocity. Our analysis highlights the geophysical evidence that geology in the vicinity of JI is variable and the bedrock on the north side, on average, is less dense than that on the south side. Considering some feasible geologic configurations, we have developed a range of possible sediment thicknesses. Using either 2D or 3D methods, our estimate of 1 km of sediments beneath JI is robust. Given the role wet basal sediments play in ice dynamics, the definition of sediments beneath the JI must be integrated into studies of the systems' flux and stability. In this response, we first address the major concern of each reviewer. Then we address other issues and clarifications point by point. We will comply with editorial comments in the updated manuscript.

Review #1: Anonymous

The primary concern expressed in Review #1 is the range of potential solutions incorporated in the manuscript. In particular, concern is raised that the north side gravity anomaly is the same amplitude as the trough-centered anomaly on lines T34 and T44. To address this concern we have presented a series of possible density distributions that match the observed gravity (Figure 1, below). The critical result is, that while each model includes additional low density material north of the central trough, all four models require sediment beneath the known JI trough.

A simple starting assumption is that the origin of the north side anomaly and the trough-centered anomaly is the same low density body (Figure 1, Profile A). With a single body, single density configuration, the sediment under the JI trough is in excess of 7 km deep. Given that 7 km of sediment is an extreme result and the north side anomaly separates from the trough anomaly inland of 54 km, we explore alternative configurations to explain the anomalies.

One alternative configuration considers sediments under the trough and a second low density body north of the trough. Figure 1, Profile B shows the case of a surface low-density body that is laterally continuous with the trough. This model configuration provided the previous minimum sediment estimate in the original manuscript.

A second alternative is to assume that a low density body is situated on both sides of the central trough as shown in Fig. 1, Profile C. The trough is, as before, underlain by lower density sediments. Lowering the background density on both sides of the trough produces sediment predictions typically within 50m of the estimate based on a north-side-only body, though the difference was 200m on one line.

A third alternative is that a low density body occurs in the subsurface and continues under the JI trough as shown in Fig. 1 Profile D. This geometry has the largest impact on predicted sediment depths. The body begins at 3km depth (arbitrarily chosen) and is increased in thickness until the north side residual is resolved (full depth not shown). Any remaining gravity residual at the JI trough is modeled as sediment as described in the manuscript. These models provide a new shallower, minimum sediment depth estimate.

Of the four geologic configurations shown in Fig 1., only Profile A seems geologically unreasonable leaving one to discriminate between the remaining solutions. As profiles B and C produce very similar results, we focus on the differences between model types in Profile B and D. Profile B could be explained by slight compositional differences within a granite while Profile D is more suggestive of a low density intrusion within a granite body. Though we cannot be certain which is a better representation, we lean toward models represented by Profile B. We will incorporate Profiles B-D showing potential geologic configurations as well as the shallower minimum depth estimates from Profile D-type models in the final version of the manuscript.

Review #2, Martin Lüthi

The primary concerns of this reviewer are the selection of the flow law parameter, A, and treatment of highly deformable Ice Age ice at the base of JI.

Clarke and Echelmeyer (1996, see page 228) address this concern in their definition of T_o and calculation of the flow law parameter A. They begin with the assumption that ice velocity is entirely due to internal deformation. Using the temperature profile of Iken et al., (1993), A is calculated as 2.85x10-24 Pa^{-3} s^{-1}, which corresponds to a deformationally-weighted mean temperature of -3°C. This is warmer than the actual mean ice temperature because of highly deformable Ice Age ice at the base of JI. Upstream regions are likely to be colder so values of A for -3°C and -8°C are used in their work. We consider values between -3°C and 0°C to test the sensitivity of our results to the value of A and to avoid over-estimating the importance of basal sliding. The along-trough distribution of basal sliding does not change significantly when more deformable (0°C) ice is considered.

Review #3 Theresa Diehl

The primary concerns of this reviewer are our treatment of gravity error, the nomenclature of gravity residuals and the validity of the 2D assumption for the gravity modeling.

Figure 2 shows the full complement of data used in this analysis. Both the Twin Otter and OIB surveys are designed with sufficient cross-overs to constrain the gravity errors. Many OIB lines are coincident with Twin Otter Lines from 2008. Our analysis of error within the gravity data is based both on the repeat tracks and the cross over points. Cross over errors are <= 0.5 mGal.

The reviewer caught a confusing typo in our introduction of the gravity residual convention. Our sign convention was mis-stated in the text on pg 346 Line 21-22. This confusing (inaccurate) statement has been corrected. The sign convention we use is now clearly defined and consistent throughout the work. We specifically chose this sign convention so that the residual map shows positive values where the forward modeled gravity is too high and negative values where the modeled gravity is too low. Since we begin with the forward model and lower it by adding low density bodies, we feel this sign convention works best with the 2D models shown and the procedure we used and describe in the work.

Early in our work we evaluated the amplitude of residuals based on 2D calculations vs. those from 3D forward models. We calculated a 3D residual gravity anomaly using the Parker (1972) forward model to remove ice surface and ice-bed interface gravity anomalies. Along the survey lines, the difference between the residuals from 2D and 3D forward calculations are typically 2-4mGal. The maximum difference between the 2D and 3D approaches were found on trough sidewalls between T9-T24, where the trough bends. This discrepancy is most pronounced on T14 shown in Figure 3 below.

Because there is insufficient gravity data from the fjord to the grounding line, we considered 3D modeling techniques only inboard of the grounding line. Using the 3D extension of Oasis Montaj, we estimated a minimum sediment distribution along JI (red profile, Figure 4 below). The inversion of the 3D residual for sediment depth and a 2D model predicts similar amounts of sediment in the curve of JI, ~1km below the radar detected bed. Both models vary in depth along the trough.

Point by Point response to Review #1

Introduction

Now reads: “In response to the disintegration of a 15 km long floating ice tongue beginning in 1998.”

We have removed reference to a southern branch from this work but still mention the slower velocity observations south of the main trunk at locations shown on the map.

Ice Bay is referred to as Kangia as suggested by Reviewer 2.

4. Constraining Gravity Signals

We have indicated that crevasses are generally shallower and a depth of 100m is more reasonable. We've added “At Jakobshavn Isbrae, the crevasses are likely only 100m deep but often create broad surface openings.”

5.1 Inland Profiles

We include the possibility that the bed is fluidized here and in the discussion.

5.1.1 Minimum ...
This is addressed above and a figure has been added to the manuscript to explain the considered models. A new minimum model is included in our summary Figure.

5.3 Sediment Description
We have indicated that higher errors in the radar lead to sediment depth inaccuracies with an **ice thickness : sediment thickness** ratio of **1:3**.

Discussion
Now reads "center line is fluidized or underlain by lodgement till and/or sediments within the density range of 2000-2500 kg/m^{3}"

Now reads "Although set in a Proterozoic basement, the trough is sediment filled, potentially as the result of deposition"

We've included "A more recent model of the glacier's response to the loss of its buttressing ice tongue characterizes the bed as weak, failing above 50kPa (Thomas, 2004)."

Now reads: "The velocity of the glacier has been attributed to the trough geometry which produces excess shear heating in the highly deformable Ice Age ice, contributing to warm englacial temperatures (Iken et al., 1993; Funk et al., 1994)."

Shape factors and lateral drag
We assume that the ice outside of JI is rigid. The shape factors we estimate from CReSIS "Glacier Elevation Data" are between .39 and .65 along the main trunk of JI and larger at the fjord mouth and at the trough onset in the interior. These values are somewhat smaller than the minimum values predicted by Clarke and Echelmeyer (1996).

Previous models of soft bed
We've included references to Thomas (2004) and Clarke and Echelmeyer (1996) here.

Point by Point response to Review #2

All now read "Jakobshavn Isbrae".

The ice bay is now referred to Kangia.

p.342 Radar accuracy- The reported cross over error is 30m, however we considered the interpretive uncertainty to be higher, possibly 100m which would result in sediment estimates that are too thick or thin by up to 300m. This is the uncertainty stated for our fjord profiles (pg 14, 9-12) but the same ratio is applicable to all the data. We've included: "In the trough, where radar error may be larger (perhaps 100m), ice thickness trades off with sediment thickness in a 1:3 ratio (up to 300m)."

p. 346 Ice density- On T54, where sediments are predicted to pinch out, the trough geometry is best fit by the density contrast when the ice is 918 kg/m3 and the bed is 2700 kg/m^{3}. The chosen ice density is commonly used in gravity modeling of ice sheets.

p. 346 Uniform/Background density- A new figure (figure 1 below) shows the various low density bodies that may be causing the north side anomaly that are considered in this work. As suggested by Reviewer #1, we have added the scenario where this low density body is a slab that underlies part of the JI trough.

P347 Now reads "North of"

p347 Now reads: Dense crevasse fields characterize glaciated regions with <u>high transverse and longitudinal stresses.</u>

p. 349 Sediment density- Clarke and Echelmeyer (1996) suggested a range of 2000-2500 kg/m^3. We chose 2130 kg/m^3 because it is at the lower end of the range, while allowing for some sediment compaction with depth. The non-uniformity of density here would have only a minor effect on our result and depends on the predicted sediment depths. Incorporating this correction would require some circular reasoning.

p.350 Underestimation: There is a trade off in gravity modeling between the overall size of the body and its density contrast with surrounding rock. In the 2D models, we constrain the width and change a body's size by changing its depth extent. The lower the density of the assumed sediment, the smaller (less deep) it will have to be to explain the trough gravity low.

p.351 Ice bergs in the fjord- The whole fjord was modeled as 1000kg/m3. Mean surface elevation within the trough is 30m above sea level. Adding a sikkussak layer (~300m thick) of 900kg/m^3 over sea water of 1030 kg/m^3 changes the gravity residual by 0.5-0.7 mGal. We will include this in the discussion of sources of error.

p.352 Radar Accuracy: See above.

p. 352 Is JI along a Fault?

We will include the following paragraph in our discussion:

The presence of a fault boundary could contribute to the depth of the fjord, explaining in part why the JI trough is deeper with respect to sea level than other fjords in Greenland and Norway. Nearby faults in rock of similar age are thrust faults, that have East-West trends nearly parallel to JI (GEUS, geologic map). Though receiver function solutions are sparse in Greenland, they reveal a distinct trend of thinner crust to the north and thicker crust to the South, leading previous authors to conclude there is a geologic boundary in the vicinity of JI (Dahl-Jensen et al., 2003). Though these observations create intrigue, we only suggest a possible geologic boundary under the ice but cannot definitively show it is present.

p. 352 Have similarly thick sediment fills been seen in other fjords?

Sediments of a few hundred meters thickness have been observed in other Greenland fjords. Kangerdlussuaq fjord, East Greenland has 500m of sediment (Andrews et al., 1994). We created topographic profiles across other fjords. The peak to trough relief of JI is not unique. Fjords in North Eastern Greenland have similar relief when the height of adjacent, exposed mountains is considered and also show sediment filled outlet fjords of uniform bathymetric depth. What is unique about JI is its position with respect to sea level.

p.353 Now reads: " Saturated basal till layers are known to lubricate ice flow" p.353 Now reads “3-8kPa shear stress”

p.353 Iken et al., 1993 is cited.

p.354 Now reads “englacially transported water”

p.354 Now reads: “The velocity of the glacier has been attributed to the trough geometry which produces excess shear heating in the highly deformable Ice Age ice, contributing to warm englacial temperatures (Iken et al., 1993; Funk et al., 1994).”

p.354 Special circumstances: Lüthi et al., 2003 talks about this location but refers back to Lüthi et al 2002 as a reference for the basal velocity. Likewise, Truffer and Echelmeyer (2003) does not provide the original observations of 60% basal sliding but generalizes this number to contrast JI with (West Antarctic) ice streams. We feel the 2002 reference suffices here but now site Lüthi et al., (2003) elsewhere in the manuscript.

p.354 We now refer to Tb as the driving stress and have made other efforts to clarify this paragraph.

p.355 We have included the value of A: Now reads “ A is a temperature dependent flow-law parameter that has been deformationally-weighted ($A=2.85 \times 10^{-24}$ Pa^{-3} s^{-1}). H is the ice thickness and the flow law exponent is assumed to be 3. As Clarke and Echelmeyer (1996) state, the presence of temperate ice at the base enhances deformation, causing the ice to behave as a body of -3ºC despite the fact that actual mean temperature is much colder (Iken et al., 1993).”

p.355 Shape Factors: Our shape factors are calculated using the radar to constrain the width and depth of the trough and assume that the ice on the sides of the JI trough are rigid. Along the main trunk, the values are between 0.38 and 0.65. The largest values occur where the trough is shallower, near the grounding line (0.84) and inland of 54km from the grounding line (0.91). Previous work also assumed a parabolic shape and used a value of 0.5 (Truffer and Echelmeyer, 2003) which is similar to our average value in the main trunk. Clarke and Echelmeyer found minimum values between .48 and .55.

p.355 We now include that the surface slope has increased and is could drive some of the increase in velocity.

p.356 Stress transfer to the sides is described somewhat by the shape factor, which reduces the center-line driving stress by up to 62%.

p.356 Temperatures: see above.

p.356 Where predicted basal traction exceeds driving stress, basal slip is not required to explain the velocity of the glacier. We now include that it is possible that our value of A could be too high since we have purposely tested the upper limit.

p.356 Although the shallow ice approximation is not valid near the grounding line, other determinations of driving stress are beyond the scope of this work. The importance of basal slip near the grounding line is not as interesting or important a result as our finding that a weak bed may underlie the trough to 54km inland.

We have corrected Bibliography spelling errors. Thanks for catching these!!

Figures
We will work with the publisher to assure that figures are appropriately sized for print when the final version of the manuscript is prepared in portrait page layout. We will keep the magnetics map because it provides justification for including geologic bodies of variable density and is referenced in the Discussion section.

Profile Figures: We will label North, South and observed gravity on each profile.

Review #3 Point by Point response

1) p341, line 11: We have used the 2008 grounding line because that is when the bulk of our survey data was collected and is concurrent with our surface elevation data (ATM). We don't feel an additional sentence is necessary as this is a commonly used benchmark.
2) p341, line 15: We have added some of the references from our discussion section to support this statement.
3) p361: See "Figures" in Review 2. Caption now reads "A) CReSIS's Jakobshavn Glacier Data-bed elevations derived from ice penetrating radar.".
We have used the 2008 data everywhere it is available and the 2010 OIB data where it covers a larger spatial extent. This is stated in the text.
We are not going to include a colorscale for Landsat as it clutters the figure and that information has no bearing on this work.
3) p341, line 25-26: Both surveys are drape flown at 1500ft above the surface and use the AirGRAV gravimeter mounted at the center of mass of the respective aircraft. Most other aspects of survey design are the same; resolution differences arise from the flight velocity which we determined using aircraft GPS and time stamps.
The first paragraph of section 2.1 now includes references to the 5 km grid and 1500 ft flight elevation.
5) p342, line 7: The AirGRAV gravimeter is owned and operated by Sanders Geophysics Limited (SGL). We have credited their part of this work in the way that they mandate. Many of their technics, specifically GPS processing, are proprietary. SGL installs their own dual frequency GPS onboard the aircraft and a base station for differential GPS processing and employs independently developed methods to remove the plane motion from the gravity observations (as summarized in Sanders et al., 2004). Empirical tests have shown this system to be precise when ground truthed and accurate, producing good repeat measurements even when the flight conditions are not ideal (Studinger et al., 2008). The sub mGal accuracy we report is empirical from test flights and cross over analysis, not theoretical instrument accuracy.
The gravity is filtered with a cosine filter as described in Studinger et al., 2008.
Every data set shown in this work is defined wrt the WGS84 ellipsoid.
As we mentioned above crossover lines as well as repeat tracks were flown, yielding an empirical error estimate of 0.5mGal after GPS correction for motion of the aircraft. We have added the empirical cross over error to the data description.
6) p341-342: GPS processing applied by Sanders Geophysics was developed within their organization and is purposely withheld from publication. We provide empirical error estimates of the gravity from cross over (0.5mGal). The cross over error of our laser system is 30 cm, meaning the GPS is sufficient to provide at least 30cm of vertical accuracy. For the OIB lines, the 10 cm accuracy of ATM laser elevations provide a measure of the minimum accuracy of their aircraft GPS.
7) p342, line 23: OIB lines are longer than the Twin Otter lines providing more data and thereby

more constraint on geology in the region. They do not constrain methods used later in the paper.

8) No reply needed.

9) No reply needed.

10) p345-346: Residual anomalies calculated using 2D forward models are within 2-4mGal of residuals calculated from 3D grids. The sediment thicknesses predicted from 3D calculations are ~1km in the bend of Jakobshavn Isbrae, in good agreement with the sediments predicted from 2D calculations. 2-4mGal represents about 10-20% of the trough centered anomaly.

11) to 13) Thanks for catching this error. We misrepresented our sign convention in the text and have changed it to read "The residual gravity anomalies are defined by subtracting the observed free-air anomalies from the 2-layer modeled gravity anomalies." As stated above, this sign convention was intentionally used here.

14) p348, line 21: After including a crustal step in the forward model, we plotted the predicted gravity at the same scale and on the same axes as the original gravity anomaly. There is a long wavelength trend in the crustal model that is not present in observed gravity over JI. This effect is clear in filtered and un-filtered versions of these data.

15) p348, line 28: See above. No additional reply needed.

16) p349, line 22: We have created models that fit the data to 1mGal since the empirical accuracy of the AirGRAV is sub mGal.

References for this Response (informal)

Andrews et al., 1994. Sediment Thicknesses and Holocene Glacial Marine Sedimentation Rates in Three East Greenland Fjords (ca. 68ºN). The Journal of geology. V 102, p.669-683.

Dahl Jensen et al., 2003. Depth to Moho in Greenland: receiver-function analysis suggests two Proterozoic blocks in Greenland. Earth and Planetary Science Letters 205, pp 379-393

Argyle, M., S. Ferguson, L. Sander, and S. Sander, 2000, AIRGrav results:A comparison of airborne gravity data with GSC test site data: The Leading Edge, **19**, 1134–1138.

Sander, S.,M.Argyle, S. Elieff, S. Ferguson,V. Lavoie, and L. Sander, 2004, The AIRGrav airborne gravity system: Australian Society of Exploration Geophysicists Airborne GravityWorkshop
(This is a meeting publication and is no longer available on the SEG website).

M. Studinger, R. Bell, N. Frearson, Comparison of AIRGrav and GT-1A airborne gravimeters for research applications, Geophysics 73(2008) I51-I61.

List of References added to the manuscript (informal)

Dahl Jensen et al., 2003. Depth to Moho in Greenland: receiver-function analysis suggests two Proterozoic blocks in Greenland. Earth and Planetary Science Letters 205, pp 379-393

Thomas, 2004. Force-perturbation analysis of recent thinning and acceleration of Jakobshavn Isbrae, Greenland. Journal of Glaciology, Vol 50, No 168. pp57-68.

M. Studinger, R. Bell, N. Frearson, Comparison of AIRGrav and GT-1A airborne gravimeters for research applications, Geophysics 73(2008) I51-I61.

M.P. Lüthi et al., Indication of active overthrust faulting along the Holocene-Wisconsin transition in the marginal zone of Jakobshavn Isbræ, Journal of Geophysical Research 108(2003).

List of other changes we have incorporated.

- Clarify that the sediment only model (formerly Figure 4) yields an unrealistic result because it does not account for regional geologic contrasts. Remove the corresponding (deepest) curve from the final figure.

- We will incorporate the estimates of sediment depth from the 3D forward model of the residuals and 3D inverse solution of sediment depth.

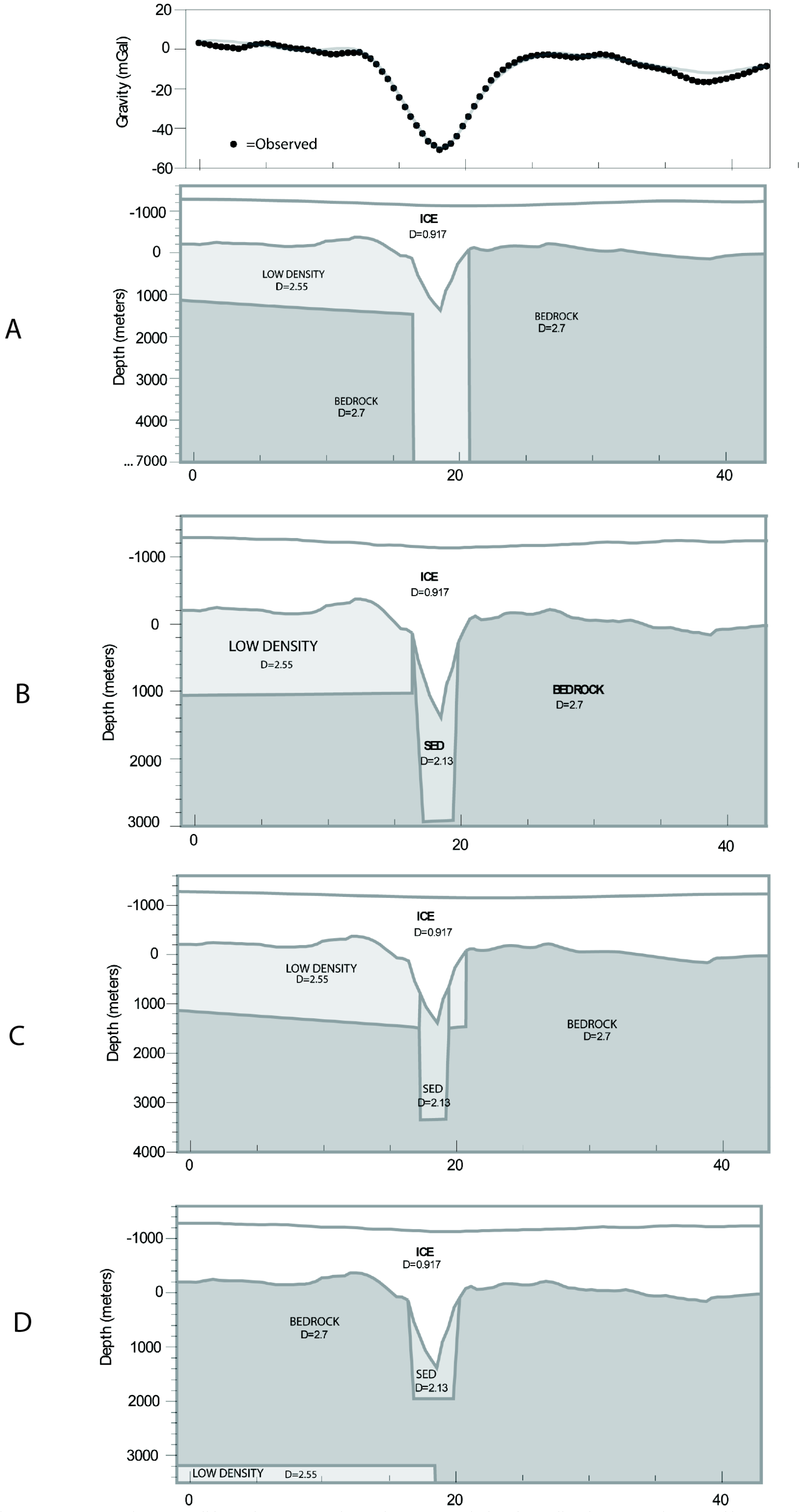

Figure 1: Gravity profile of T44 and various models that fit the gravity well. A) Single body, single density configuration. Not likely. B) a surface low density body is on the north side (this provided the previous minimum as reported in the original manuscript. C) Northern low density body exists on both sides of the trough. D) North side anomaly is caused by a subsurface body that extends below the trough.

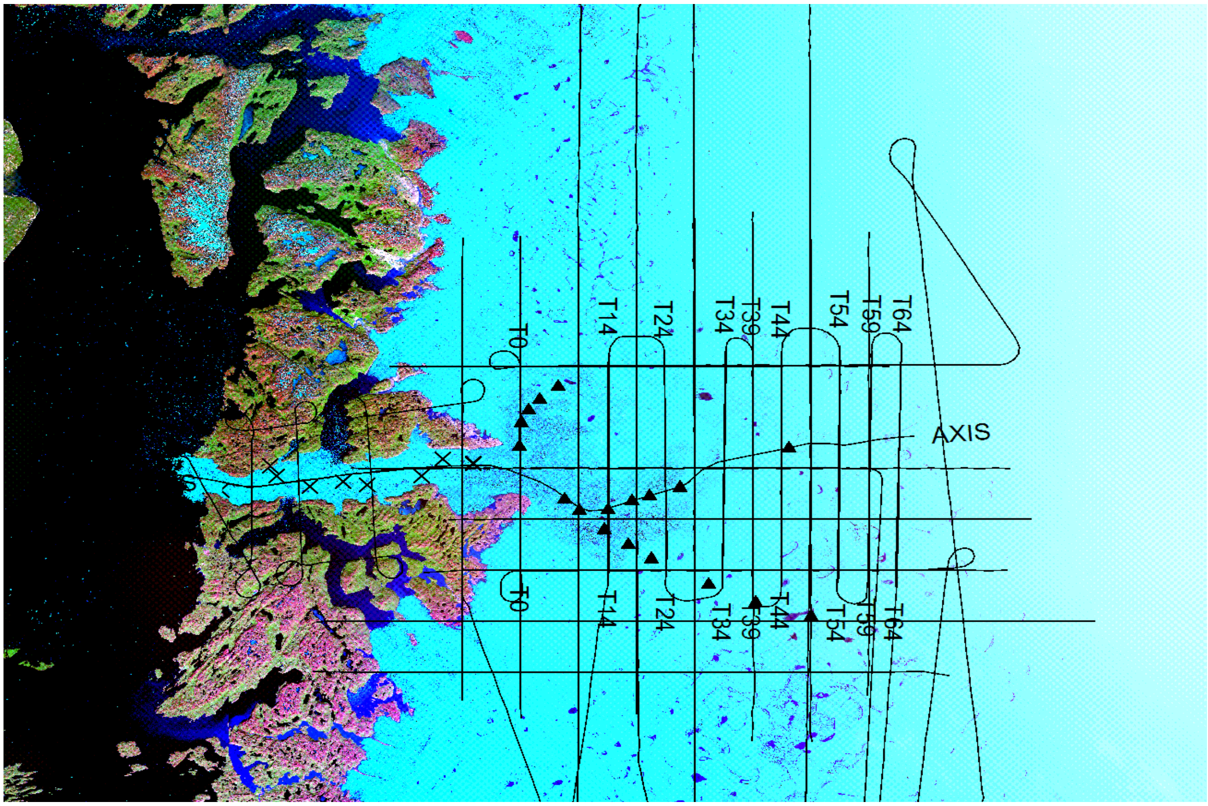

Figure 2: Survey lines from 2008 and 2010 in the Jakobshavn region. The 2008 survey included three tie lines while OIB flew 6 tie lines, many of which overlap. Both datasets are used in our gravity calculations. The calculation of residuals is spatially limited by the CReSIS radar coverage and the gravity spacing near the grounding line.

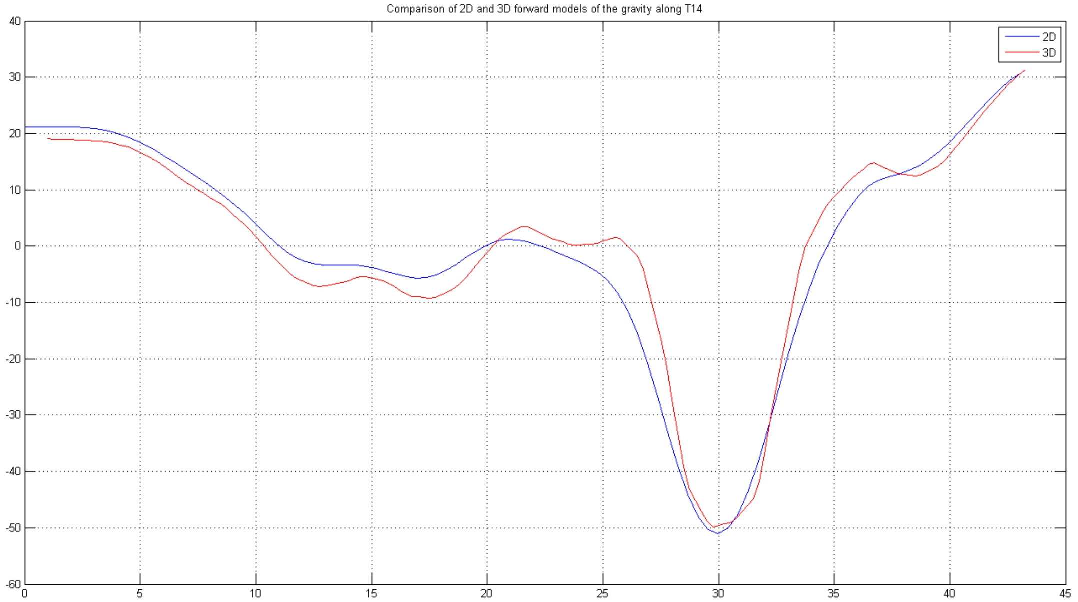

Figure 3: Profile comparison of 2D and 3D gravity residual calculation 14 km inland of the grounding line (T14). The 3D model is shown at full resolution based on forward models from CreSIS's Glacier Elevation Data at 125m. The 2D model has a 4.5km along track resolution. Before modeling the data in 2D, we preformed calculations to access the difference

between a 2D and 3D forward model and residual anomaly values. Over the fjord, the differences are negligible. Discrepancies are largest at the bend in the fjord between T9 and T24.

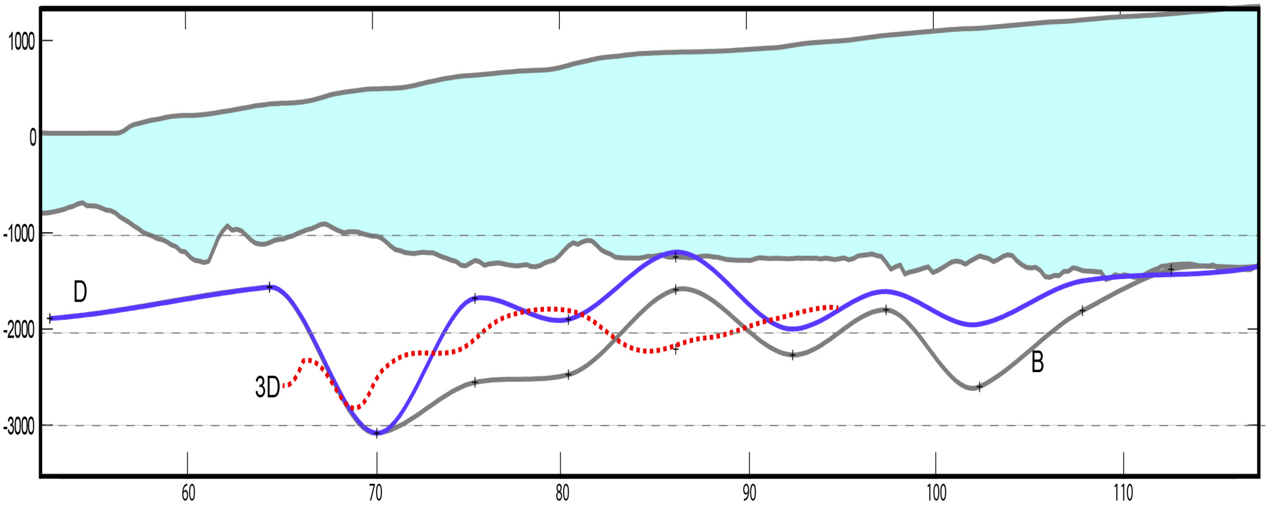

Figure 4: Range of potential sediment depths. Depth model from a north-side low density body (like Profile B) is shown in grey. This is the original reported minimum model. Depth results from a low density body on the north side that extends under the trough (Profile D) is shown in purple. A 3D minimum sediment model is shown between T9 and T24 in red stipple.