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Interactive comment on “Tectonic and oceanographic controls on Abbot Ice Shelf thickness and stability” by J. R. Cochran et al.

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SUMMARY: This paper presents the results of the inversion of Operation IceBridge data over the Abbot Ice Shelf, inverting the free-air gravity anomaly for sub-ice shelf bathymetry. Radar and altimeter data are used to constrain ice shelf thickness. Densities are fixed according to existing geological knowledge, as well as known surface elevations beneath grounded ice and line-ties. These results are then used to address the oceanographic and tectonic setting of the Abbot Ice Shelf and their effects on ice shelf stability. The major control is attributed to ice-shelf thickness rather than sub-shelf bathymetry. The paper is well written and structured.

Although adjacent to Pine Island and Thwaites Glaciers, and in the topical Amundsen-Bellinghousen Sector, the Abbot Ice Shelf has been somewhat overlooked. The conse-

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quent sparseness of direct observations (geology and bathymetry) in the area limit the constraints which can be applied to the inversion of gravity data for bathymetry, and as such call into question the reliability of these results for assessing the oceanographic control on the ice shelf. These shortcomings have not been addressed in full or realistically quantified here, although the conclusions have been weighted such that the uncertain results are not overly relied upon.

See our response below to a similar comment.

The absence of a sediment layer in the inversion has significant implications for the derived bathymetry. However, the interpretation of the tectonic setting from the gravity inversion is more reliable as this influences the large-scale features of the gravity field and therefore can be better constrained by the known bedrock densities, depths and grounding line positions. The interpretation of the tectonic setting fits within the regional context as I understand it.

We have added a fuller discussion on possible sediments and their effects on our results and conclusions, as discussed below.

The discrepancy between the OIB draft and that of Bedmap2/Griggs and Bamber is probably the most significant result presented. Indeed, this puts the ice-shelf base close to the mixed layer/thermocline boundary, and results in melt-rate sensitivity to seasonal variation. However, how the sub-ice shelf bathymetry influences oceanographic flow is still very much an open question due to the uncertainties resulting from the lack of knowledge of sediment thickness (see major comments).

See our response to your comments on sediments below.

To me, the title of the paper implies that active tectonics control the Abbot Ice Shelf thickness. This is of course not the case. It is the remnant features of a tectonic episode 100 Ma which produce the rifted basin structure. This has then presumably been modified by sediment infill which is also not tectonically controlled. “Topographic and

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oceanographic ...” would be more fitting. However, as stated above, the topographic influence is still very much uncertain.

The title refers to the tectonic setting, not active tectonics. The Abbot overlies a rifted basin, which affects the nature and stability of its grounding line and its interaction with the ocean and is a major reason that it is in equilibrium. However, We are not tied to the title and will make it "Bathymetric and oceanic influences on ...)"

MAJOR COMMENTS: Full Screen / Esc

A number of highly relevant recent studies have been overlooked which have significant implications for the reliability of the gravity inversion as presented here.

(1) Missing reference: Rignot, E., J. Mouginot, and B. Scheuchl (2011), Antarctic grounding line mapping from differential satellite radar interferometry, *Geophys. Res. Lett.*, 38, L10504, doi:10.1029/2011GL047109. - In the absence of any direct measurements of sub-ice shelf bathymetry all available information must be used to constrain the gravity inversion. Use of the interferometric InSAR grounding line allows points of zero-depth sub-ice cavity to be constrained, especially where small-scale features below the resolution of the gravity data are present. Most notably, at the southern end of lines 6 and 7 of this study, grounded ice can be inferred and used to constrain the inversion where at present the gravity results indicate floating ice.

The Rignot et al. grounding line has significant gaps in the Abbot area. Specifically, it does not give the grounding line along most of Thurston Island or on the King Peninsula west of about 101°W. There are ice rises/rumples and changes in ice thickness on lines 6 and 7 caused by interaction with the uplifted footwall rims of half grabens, as discussed in the text. There is floating ice coastward of these features as in our models.

(2) Missing reference: Muto, A., Anandakrishnan, S., and Alley, R., Subglacial bathymetry and sediment layer distribution beneath the Pine Island Glacier ice shelf, West Antarctica, modeled using aerogravity and autonomous underwater vehicle data,

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Ann. Glaciol., 54, 27–32, 2013. - The study of Muto et al. utilises a more closely-spaced 3D dataset with AUV bathymetry data. However, PIG's proximity (which is referred to elsewhere in the manuscript) means this work cannot be overlooked. More specifically, the presence of faults is inferred, associated with high gradients in the gravity data. Of even more significance is the thickness of sediment (200-1000m) associated with a ridge, not dissimilar to the structural features presented here. The exclusion of sediment in the density profile in Abbot must therefore be justified when such significant thicknesses, and therefore bathymetric differences, have been reported in the regional setting.

-Thank you. We now use the Muto et al model results to illustrate the possible amounts of sediments present in the new discussion of the effects of sediments on our results and conclusions. However, it should be noted that Muto et al. do not infer the presence of faults associated with high gradients. They state that they assume a uniform bedrock density and no faults. Also, they made an arbitrary assumption of sediment density, as discussed below, which likely led them to overestimate the sediment thickness.

(3) Missing reference: Brisbourne, A. M., Smith, A. M., King, E. C., Nicholls, K. W., Holland, P. R., and Makinson, K., Seabed topography beneath Larsen C Ice Shelf from seismic soundings, *The Cryosphere*, 8, 1-13, doi:10.5194/tc-8-1-2014, 2014. - Although without ground truth data it is speculation to include a layer of sediments, this recent evaluation of the gravity inversion method using seismic soundings demonstrated that ignoring the presence of sediments can invalidate any derived bathymetry.

We have added roughly 1.5 pages at different places in the text specifically addressing various issues raised in your paper.

(4) Missing reference: Mueller, R. D., Padman, L., Dinniman, M. S., Erofeeva, S. Y., Fricker, H. A., and King, M. A., Impact of tide-topography interactions on basal melting of Larsen C Ice Shelf, Antarctica, *J. Geophys. Res.-Oceans*, 117, doi:10.1029/2011JC007263, 2012. - The study of Mueller et al. highlighted the sig-

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nificance of bathymetry on topographic effects on tidal melting of ice shelves. Errors introduced in the Larsen study mentioned above were demonstrated to significantly affect basal melt-rates. Although tides are likely less relevant in this region, the effects of tidally-forced melting should be outlined where sub-ice shelf cavity thickness is so variable.

Thank you. That is a very interesting paper. We now reference it.

(5) Missing reference: Dutrioux, P., De Rydt, J., Jenkins, A., Holland, P. R., Ha, H. K., Lee, S. H., Steig, E. J., Ding, Q., Abrahamsen, E. P., and Schröder, M.: Strong Sensitivity of Pine Island Ice-Shelf Melting to Climatic Variability, *Science*, 343, 174-178, 2014. - This study outlines in detail ice shelf sensitivity of PIG in the same regional setting as Abbot (published after the initial submission of this manuscript but essential for inclusion in any revised manuscript).

- We are aware of this paper and it is cited in the revised paper to illustrate the sensitivity of melt rates to variations in the depth of the thermocline.

SPECIFIC COMMENTS:

P5511/L18: Use of the term “facilitated” completely underplays the importance of bathymetry to potential basal melt rates. See Mueller (2012) reference above.

While we used the word “facilitated” because bathymetry is not the only parameter, the sentence has been reworded.

P5512/1: References to Bourne (2014)/Muto (2013) etc. The limitations of this technique need to be addressed in detail here.

You raise issues with both the technique and with the possible presence of undetectable sediments. The formal Parker-Oldenburg inversion technique [Oldenburg, 1974] used by Cochran and Bell [2012] assumes that the gravity anomalies arise from relief on a single interface (water/rock) with a uniform density contrast. It therefore requires the assumption of uniform geology, which is probably not realistic over an area

as large as the Larsen C ice shelf. It also means that the gravity effects of changes in sediment thickness are interpreted as bathymetric relief. An additional factor, particularly in areas of uneven and somewhat sparse gravity coverage such as the Larsen C, is that the Parker-Oldenburg technique requires a uniform grid of gravity anomalies and thus interpolation between measured gravity lines. However, here, we use a very different technique involving iterative two-dimensional forward modeling along flight lines, where the gravity anomaly, surface elevation and ice thickness are known. This technique also allows us to incorporate lateral variations in crustal density based on the local geology. We also do not invert interpolated values in areas with nor gravity data. We discuss the sediment issue below.

P5512/L5: References needed for the temperature profiles.

Actually, this is the first place that these temperature depth profiles have been published. However, the 1994 profile is included in an LDEO data rephort and Jacobs et al (2011) used the 2009 data, so I guess we can cite those references.

P5513/L8: Explain here why the base of the ice was not imaged.

Based on the appearance of the echograms, it was originally assumed it to be an instrumental problem. However, we have queried John Paden at CRESIS, who said he did not think that was the case and suggested the presence of accretion ice

P5513/L10: What mask was used to define floating ice? How far from the grounding line? The presence of the many islands must render the floating ice assumption invalid for a significant proportion of the ice shelf.

The area of floating ice on each profile was determined by visual examination of the elevation and ice thickness data, aided by INSAR-determined grounding lines, where available. The Rignot et al (2011) grounding line has significant gaps in the Abbot region.

P5514/L1: I fail to understand the significance of large positive and negative free-air

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anomalies, other than the fact that they occur over topographic highs or lows and are simply a result of the presence of absence of rock. Does the trade-off in density and elevation, especially when relative elevations are not specified, make this discussion redundant?

We are describing the data set that the paper is based on. The relevance of the anomalies comes with the modeling.

P5515/L4: Other useful reference: Leat, Storey and Pankhurst (1993) Geochemistry of Palaeozoic-Mesozoic Pacific rim orogenic magmatism, Thurston Island area, West Antarctica, Antarctic Science. 5(3) 281-296

Thank you.

P5515/L19: "Pink" granite. Does this mean felsic, which would perhaps be a more useful description?

The term "pink granite" was used because that is what the rocks were called by the geologists who mapped and described them (eg., Lopatin and Orlandko, 1972; White and Craddock, 1987; Storey et al, 1991; Pankhurst et al, 1993). I think granites are actually felsic by definition. We would rather use the term used by the people who studied these granites.

P5515/L16: Volcanics are exposed on southern and central parts of Thurston Island (Pankhurst).

Thank you. That observation supports the interpretation of the basin under the Abbot as a rift.

P5516/L11: Is it therefore reasonable to define a fault in the density model prior to inversion due to the high gradient? Otherwise, what is the nature of this boundary?

We do not define a fault prior to the inversion. We pin the model to a spot where the bed is observed and let the water depth adjust to match the gravity. We explain in the

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paper the logic for assuming that the high-density material under portions of Thurston Island does not extend offshore. This is also consistent with Storey's interpretation of aeromagnetic data.

P5517/L29: Peter I Island – readers cannot locate this with only the information within the manuscript.

The latitude and longitude are given in the next sentence.

P5518/L26: Significant sediment deposits are found beneath Pine Island (Muto, 2013). The evaluation here of 100m of sediment at 2.2 g cm⁻³ pales into insignificance when compared to 800m at 2.013 g cm⁻³ inferred at PIG. I would argue that the thicknesses assumed here in the assessment of uncertainties are very low, and the densities very high, resulting in reported uncertainties which are much lower than in reality.

-First, we were not suggesting that there is only 100 m of sediment, but that for each 100 m of sediment, we would overestimate the depth by 30 m. -Second, the density of 2.013 g/cm³ that you mention for PIG is not a measured density. Muto et al say "We have no knowledge of the appropriate density for the sediment; hence we chose porosity of 40% " and they then calculated a density based on that assumption. They point out that this gives them a density similar to the densities used by Roy et al (2005) and Filina et al (2008) at Vostok. Roy et al assume a sediment density of 2.0 g/cm³, but never give the basis of that density. Filina et al use 1.85 g/cm³, which they say is "typical value for water-filled unconsolidated sediments", but again with no specific reference. Third, thick sediment deposits are not going to have an average porosity of 40% or be unconsolidated. The density of 2.2 g/cm³ that we used was taken from JRC's experience in gravity modeling in marine environments over the past 40 years. It is also supported by physical properties measurements at the AND-2A core reported by Dunbar et al (2008), which is in a setting that is not dissimilar to Abbot. Measured densities from about 200 m to the bottom of the well at ~1140 m are consistently at or above 2.2 g/cm³. We continue to think that 2.2 g/cm³ is a reasonable average

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density for sediments, particularly if they have a substantial thickness. Fourth, we have rewritten the discussion of the possible effect of sediments to consider the effect of thick (1000 m) sediments in the deep basins of the rift on possible water flow under the ice.

P5519/6: The uncertainties of ~ 70 m in Cochran and Bell (2012) have been proven to be significantly underestimating the potential errors when sediment is ignored (Brisbourne, 2014).

We include a much fuller discussion of potential errors in the revised paper.

P5520/L2: The geology of the King Peninsula/Cosgrove is not discussed. What are the implications for the results?

There do not appear to be any outcrops along the King Peninsula. However, the technique that we used here of inverting individual profiles allowed us to determine that it must be underlain by a high-density body.

P5522/L9: Why was no firn correction applied?

We obtained the radar data from CRESIS, who did the processing. They have not applied a firn correction to any of their OIB data.

P5523/L24: Possible reference: Bradshaw, J. D., 1989, Cretaceous geotectonic patterns in the New Zealand Region

Thank you.

P5531/Fig1: The entire figure needs clearing up as stated by reviewer Padman. Consider including the Rignot InSAR grounding. Why not include bathymetry to the continental shelf edge and data points for bathymetry measurements which are very sparse in this region, as referred to in the text?

Figure 1 now uses a MODIS MOA image. The IBCSO bathymetry to the shelf edge is shown in a new version of Figure 4. and show and discuss the single available

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shipboard bathymetric line through the area.

P5536/Fig4: Leat, Storey and Pankhurst (1993) in Antarctic Science highlight dykes parallel to the coast on TI, related to extensional stresses associated with the mid-Cretaceous rifting. Their presence validates the interpretation of an extensional regime south of TI and so should be included in Fig. 4 and referred to within the body of the text.

Thank you. As those dikes predate 90 Ma and are intruded into 120 Ma - 155 Ma plutonic rocks, that helps to date the rifting.

P5537/Fig5: These two figures are an opportunity to present a realistic cross section, rather than such an idealised one, allowing the reader to associate anomaly gradients with density or bathymetry variation. Figure 4 presents a series of faults cross-cutting Lines 3 and 6. None of these faults are presented in Fig 5. On Line 6 the proposed faults are more or less coincident with the density boundaries although the vertical nature of the density boundaries do not fit with a half-graben model. On line 3 there are no density boundaries coincident with the proposed faults. Some of the faults produce a gravity anomaly gradient due to the density contrast across it resulting from surface-topography (basin). Not all the faults on Line 3 are however coincident with either basins or density contrasts though. The high-density boundary at the south of the King Peninsula is in fact dipping in the opposite direction to the inferred fault.

First regarding the definition of the boundaries of the dense body on the King Peninsula and its relationship to the faulting: In defining the extent of the body, we were guided by the location and width of the gravity high, but also tried to make its width and depth vary smoothly from line to line so that it forms a coherent, geologically reasonable structure without sudden along-strike variations in width and thickness. If we had magnetic data, we probably could have defined its extent in a more certain manner, as Storey et al were able to define a gabbro body under eastern Thurston Island. It also appears that the intrusion may predate the rifting, since some of the basins along the southern

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margin of the ice shelf are contained within it. So is not clear whether it would necessarily influence the location of faulting. Second, related to Figure 5 and whether we should draw in the faults: The filter applied to the gravity data causes the bathymetric slopes in the inversion to be shallower than the actual slopes at the faults. The actual faults will thus be somewhat oblique to the seafloor in the figure. The faults will be located at the mid point of the slope (the way they were located for mapping on Figure 4). We could draw an arrow to locate them on the figure. and will reevaluate Figure to see what is possible and useful.

P5539/Fig7: To be of use this figure needs to present the “corrected” Bedmap2 draft as discussed. Also, the scaling is such that the subtleties in the draft are not obvious. A scale weighted more to the 200-300m range is much more insightful and relevant to the oceanographic discussion.

We have redone the figure to show the corrected BM2 ice draft.

P5539/Fig7: To address the point raised by reviewer Padman, I would not like to see a map of seafloor depth as due to the uncertainties involved this would be highly misleading.

We also do not wish to present a bathymetric map because our lines are too far apart to grid. It would need to be hand drawn.

MINOR COMMENTS:

P5511/17: “difficult” is rather subjective. “Time-consuming (or challenging?) to achieve good spatial coverage” may be more accurate.

Sentence is reworded.

P5513/L15: mismatches in draft? – clarify what the mismatch is in.

OK - changed

P5514/L12: “This positive gravity anomaly ...” rather than “This band of positive gravity

...”

OK - changed

P5515/L24: change “as exposed on” to “from”

OK - changed

P5526/L7: "seismic" not "seiamic"

OK - fixed

P5529/L26: “in a” not “ina”

OK - fixed

P5532/Fig2: Lines 11 and 12 are not labelled but are referred to in the text.

There are no Lines 11 or 12, and I could not find a reference to any such lines in the text. Peter I Island could be labelled here if the map were extended but this may be prohibitive.

We agree that would be prohibitive and provide its latitude and longitude.

Interactive comment on The Cryosphere Discuss., 7, 5509, 2013.

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