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Improved recovery of sub ice shelf bathymetry from gravity data using an isostatic correction: A case study from the Dotson and Crosson ice shelves, West Antarctica

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Abstract. Bathymetry beneath ice shelves is challenging to observe yet is vitally important for modelling how ice sheets will evolve into the future. An alternative to direct observation of bathymetry is to invert airborne gravity data for the bathymetric signal. Appropriate gravity data can be collected via remote sensing above the ice shelf and be used to provide an initial estimate of sub-ice-shelf bathymetry, typically at wavelengths of ~5 km and above. However, lateral variations in density associated with the underlying geology can distort the gravity field biassing the results. We show that techniques which tie inversion results to known bathymetry and topography, although solving some of these issues, may be insufficient in the case of large and deep basins lacking centrally located tie points. Using new direct observations of the Dotson and Crosson ice shelves as a case study, we show that gravity inversion for bathymetry can be improved by considering and removing a model of the gravity field due to crustal isostatic compensation prior to inversion. We finally present our updated and improved bathymetric model for the Dotson-Crosson and Thwaites Glacier Ice Shelf system and discuss where our method can be best applied in future.

1 Introduction

Bathymetry beneath ice shelves around Antarctica is one of the most important boundary conditions for models of these systems. It provides a first-order control on where, and how, relatively warm and salty ocean water can access and melt the

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grounded ice sheet, through bathymetric steering of ocean currents and through provision of deep troughs through which the dense warm water can penetrate. The bathymetric roughness also determines the turbulence in the water influencing heat transfer within the cavity (Richter et al., 2025). However, due to the challenges of accessing the ice shelf cavities, direct observations of bathymetry are rare. Inversion of gravity data measured from aircraft flying above the ice shelf has therefore become an important tool for interpreting sub-shelf bathymetry away from the sparse direct observational data points (Millan et al., 2017; Cochran et al., 2014; Muto et al., 2016; An et al., 2019; Tankersley et al., 2025).

Inverting bathymetry from gravity data works since variations in gravity are typically dominated by the signal of local bathymetric variations, reflecting the large density contrast between water and underlying rock. Geological features including lateral gradients in crustal thickness and the presence of rocks with different densities at shallower crustal levels can confound such inversions. One simple scheme for removing the impact of such geological features is to tie the output of the gravity inversion to known observations of the bedrock elevation (Jordan et al., 2020; An et al., 2019; Tankersley et al., 2025). By interpolating the difference between real and modelled bedrock elevation, a regional adjustment grid can be created and applied to an initial topographic model derived from gravity inversion. This technique was previously applied to the Thwaites and Dotson/Crosson ice shelves in the southeastern Amundsen Sea (Jordan et al., 2020). New bathymetric data collected in the Dotson/Crosson ice shelf area by autonomous underwater vehicles, oceanographic profiling floats which were released to drift beneath the ice shelf, and seismic observations from the ice shelf surface, allow for re-evaluation of the original gravity-derived bathymetric data product. Here we consider the likely causes of errors revealed in the previous gravity-derived bathymetry, and create a new bathymetric model for the Thwaites, Dotson and Crosson region using an updated variant of the original method (Jordan et al., 2020).

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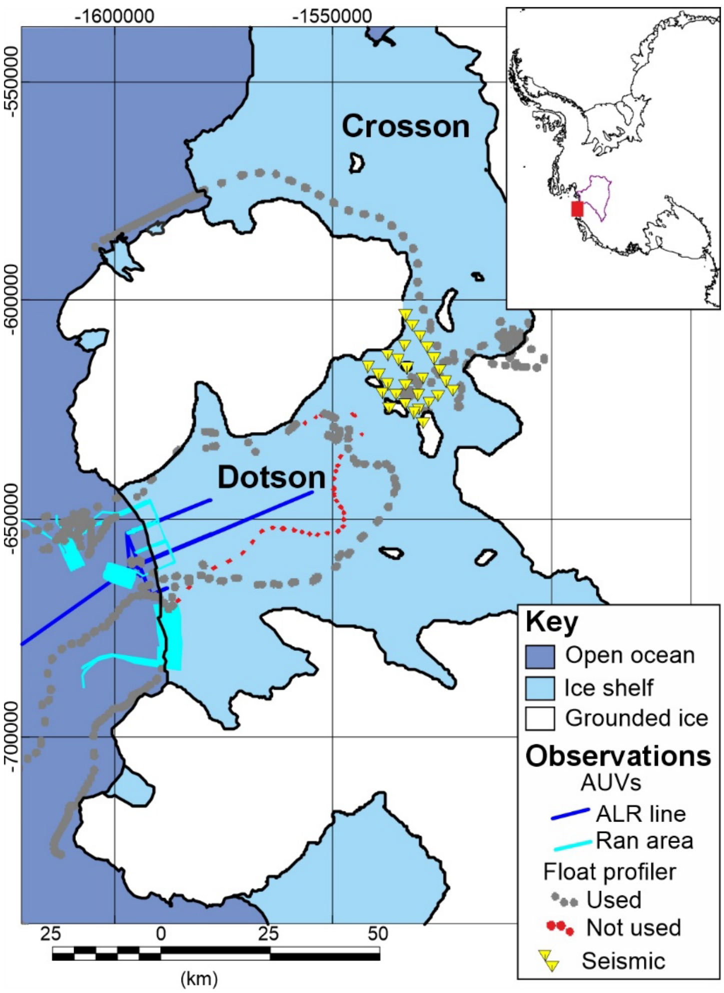

Figure 1. Location of new bathymetric data beneath the Dotson and Cosson ice shelves. Data from Autonomous Underwater Vehicles (AUVs) Ran (Wåhlin et al., 2024) and Autosub Long Range (ALR) (Richter et al., 2025) coloured lines. Profiling float (Girton et al., 2019) and seismic data (Muto et al., 2024) shown as points. Note profiling floats in areas of grounded ice reflect areas of known ice shelf grounding line retreat (Rignot et al., 2014). Inset show's location (red box) relative to wider Thwaites Glacier region (purple) in Antarctica. Projected map coordinates Polar Stereographic (m), true scale -71°.

Comparing the previous gravity-derived estimate of bathymetry with new observational data shows that the bathymetry beneath the Dotson Ice shelf was underestimated in places by at least 400 m (Fig. 2a). Although the observational data are subject to errors associated with navigation and processing assumptions discussed below, there are clear long wavelength (>30 km) discrepancies between the observed bathymetry and the gravity-derived estimates which consistently underestimate the depth. Despite the long wavelength errors, the pattern of bathymetric variation indicated by the initial gravity inversion at intermediate wavelengths (10-30 km) is confirmed along individual profiles (Fig. 2b). At the shortest wavelengths (<10 km),

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errors are present and expected as such features are below the resolution of the existing airborne gravity data, which are filtered at 5 km wavelength and collected on a survey grid with 10 km line spacing.

The presence of long wavelength differences between the initial estimate from gravity data and new direct bathymetric observations suggests that there is a systematic bias in the gravity method as originally applied (Jordan et al., 2020). Such a bias is likely due to an unconsidered geological/tectonic feature beneath the ice shelf, which is changing the observed gravity signal, but is not corrected for or constrained by the topographic and bathymetric observations in the adjacent regions. The underestimate of the bathymetry suggests that the observed gravity anomaly is not as low as would be expected from the thickness of the low-density water body. This can be explained by a broad excess of dense material beneath the ice shelf region, which would generate a relative positive anomaly, masking the amplitude of the negative bathymetric gravity anomaly. Alternatively, if rocks surrounding the basin had a significantly lower density of ~2.20 g cm^{-3}, typically expected for unconsolidated sediments, the same reduction in amplitude of the observed anomaly would be seen. Such a major discrepancy in the density of the rocks surrounding the cavity is unlikely given that the main outcropping rock types include granodiorite and gneiss metamorphic basement (Cox et al., 2023), both consistent with typical crustal rock densities of ~2.67 g cm^{-3}.

One mechanism by which additional dense material can be present directly beneath a deep and relatively large basin is isostatic compensation of the topography. This process is akin to that where a floating iceberg has a keel proportional to its height, but in this case the low-density continental crust is floating on the denser underlying mantle. As the basin was formed, mostly likely by glacial erosion, the reduction in mass would have led to an upwarp of the Moho, the boundary separating the dense mantle and less dense crust, isostatically compensating (balancing) the mass removed at the surface. This up-warping of the Moho brings dense material towards the surface directly beneath the deepest part of the basin, cancelling out part of the negative gravity anomaly due to the lower density water replacing rock within the eroded basin.

In this study we present a revised bathymetric model for the Dotson/Crosson ice shelf area and show that use of an isostatic assumption improves the recovery of bathymetry in regions where there are fewer constraining data. We first describe the existing and newly available observational datasets. Subsequently we describe our new method and test it against the new data, before finally presenting the new bathymetric model.

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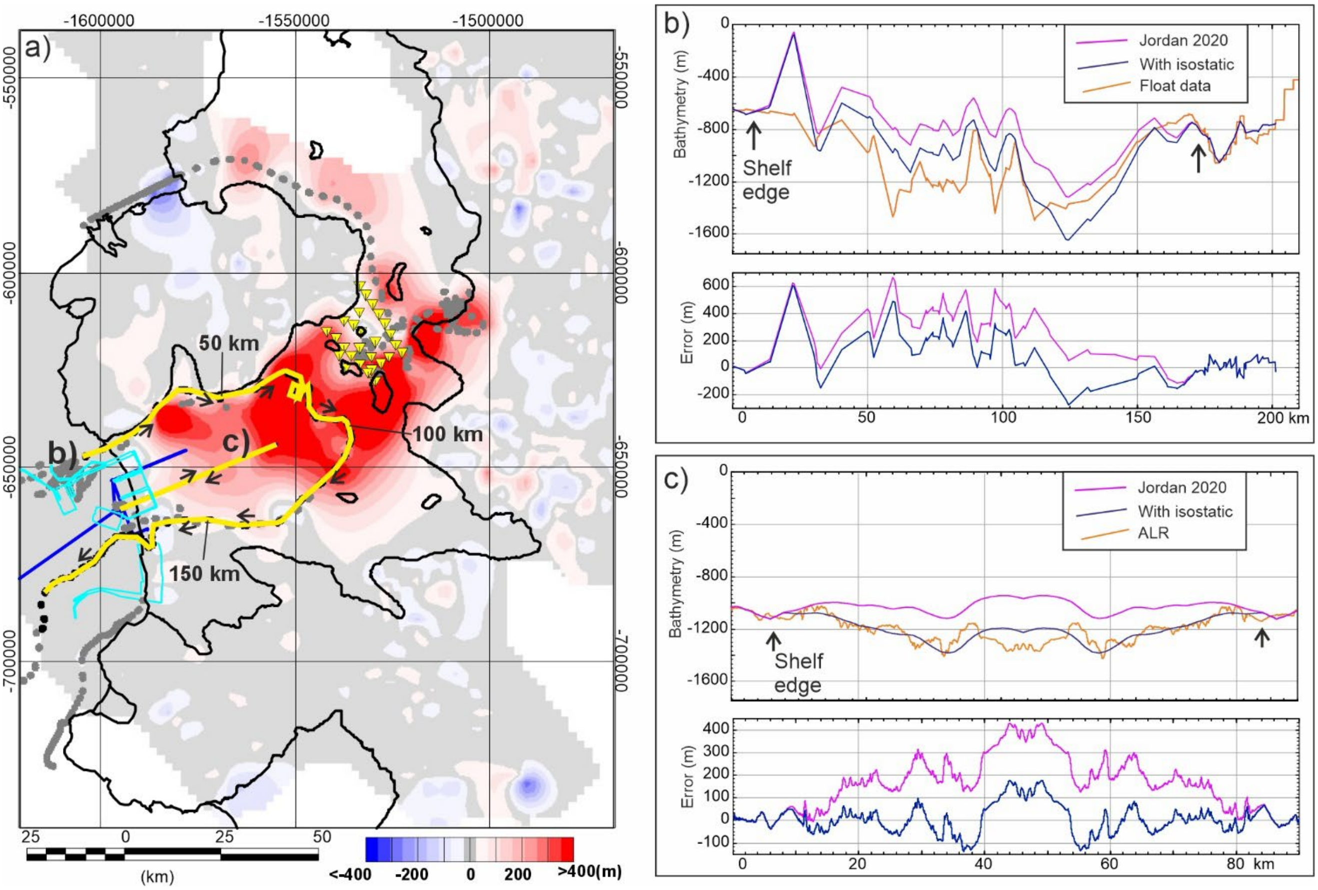

Fig. 2 Comparison of new sub-shelf observations and gravity-derived bathymetry. a) Map of error between original gravity-derived bathymetry (Jordan et al., 2020) and new interpolated model constructed from all direct elevation observations. Positive values show where gravity-derived model is too shallow. Yellow lines locate profiles in b and c. Arrows show direction along cross section profile, other features as in Fig. 1. b) Profile comparing float observations, gravity derived bathymetry from Jordan et al. (2020) and a new gravity inversion incorporating isostatic correction. Note in both inversions no sub-shelf data were used to constrain the results. c) Same as (b) but comparing Autosub Long Range (ALR) data with results of gravity inversions. Note symmetry of in-bound and out-bound leg reflecting consistent and relatively high-quality ALR navigation.

2 Methods and data

2.1 Input data

Gravity data used to constrain the sub-ice-shelf bathymetry come from Operation Ice Bridge and a dedicated aerogeophysical survey conducted as part of the International Thwaites Glacier Collaboration (ITGC), together with marine gravity data from cruise NBP19-02, integrated into a single database and gridded as for the previous assessment of sub-shelf bathymetry in this region (Fig. 3a) (Jordan et al., 2020). Regional sub-ice-sheet topography from airborne radar data as well as offshore bathymetry data used in the previous study provided the initial constraint. Additional new data on the water depth beneath the Dotson and Crosson ice shelves comes from autonomous underwater vehicles Autosub Long Range (ALR) (Richter et al.,

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2025) and Ran (Wåhlin et al., 2024), as well as sub-shelf profiling oceanographic floats (Girton et al., 2019) and seismic observations from the ice shelf surface (Muto et al., 2024) (Fig. 1).

The autonomous underwater vehicles ALR and Ran collected numerous bathymetric profiles from the ocean-facing front of the Dotson Ice shelf during the ITGC field campaign on the RV Nathaniel B. Palmer in January-March 2022 (NBP22-02). The Ran system targeted the ice shelf marginal zone with detailed survey grids extending 3 to 4 km beneath the ice shelf margin (Wåhlin et al., 2024). Ran measured bathymetry using a Kongsberg EM2040 multibeam system, and sub-shelf positioning was based on a Doppler velocity log (DVL) aided inertial navigation system. Analysis of the resulting swath data indicates that positional accuracy of this system is high (<40 m absolute error and relative error <10 m). The ALR platform collected data along three sub-shelf profiles, extending 2, 16, and 39 km inboard from the ice shelf margin (Richter et al., 2025). Sub-shelf bathymetry was measured using a single beam depth sounder giving an accurate local profile of depth. The sub-shelf location of the ALR was calculated using acoustic 300 kHz Doppler current profiler (ADCP) aided dead-reckoning, coupled with tracking the seabed. The accuracy of the navigation is not well defined; however, the close agreement between the observed bathymetry along the inbound and outbound sub-shelf profiles suggests the horizontal accuracy is relatively high (<1 km) compared with the resolution of the gravity data (>5 km).

Assessment of bathymetry beneath more remote parts of the Dotson-Crosson cavity were made using three ORBIS EM-APEX profiling floats (Girton et al., 2019). This type of buoyancy-driven float moves up and down within the water column, carried laterally by the prevailing currents. The float turned from descending to ascending ~2 m above the sea floor, and from ascending to descending just beneath the overlying ice shelf based on an acoustic trigger. These inflection points in the depth profiles were taken as a proxy of sea floor and base ice shelf depth. The primary method of locating the floats beneath the cavity was based on an acoustic navigation array deployed at the ice shelf margin, with an estimated uncertainty of ~1 km. Where contact with the navigational array was lost, dead-reckoning and comparison between ice shelf draft measured by the floats and estimated from surface elevation was used to estimate the float position. In this latter case there is significantly less confidence in the true location of any bathymetric observation. We therefore cross-checked the float bathymetry against the original gravity derived model and observational data from ALR. Where the broad pattern of variation was generally consistent, as in Fig. 2b, we considered the float data as valid. Where the float observations showed discrepancies of hundreds of meters and no consistency in pattern compared to the gravity model, or ALR data, we suggest that the float dead-reckoning navigation algorithm had most likely gotten lost and therefore exclude these data from further calculation (Fig. 1).

Data from an array of 27 active seismic shot points (Muto et al., 2024) provided the final new constraint for the revised estimate of sub-shelf bathymetry. These data provided information close to the critical boundary between the Dotson and Crosson sectors of the ice shelf where numerous pinning points may be helping to stabilise the ice shelf. An explosive seismic source was used, and data recorded on a 24-channel geophone array extending 480 m from the shot point. Depth of the sub-shelf cavity was determined from the inversion of the recorded two-way travel time of the seismic waves, with correction for compressional-wave velocity changes in the ice shelf based on a seismic refraction survey conducted during the same season. The compressional-wave velocity of the seawater was assumed to be the same as the average value under nearby Thwaites

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Eastern Ice Shelf that was determined from temperature, pressure and conductivity measurements of a CTD cast through a borehole (Wild et al., 2025), then converted to the compressional-wave velocity. The uncertainty in the depth estimate is assessed to be 37.2 m, based on comparison with direct observations with sea floor depth made through boreholes. Horizontal position was precisely determined using differentially corrected GNSS data.

A new reference elevation model was created by combining the 1 km resolution raster of radar- and swath-derived elevation data used in the previous study (Jordan et al., 2020) with the new sub-shelf point data described above. This was done by converting the original reference model into an array of points and adding the new point observations. This augmented observed elevation dataset was converted back to a 1 km raster, with the new reference elevation being the weighted mean of all points within the area of each 1 km grid cell. The existing swath and radar data were given a weight of 0.9, while new data were given a weight of 0.1, to prevent potentially less accurate data from sub-shelf floats biassing the results outside the ice shelf. Where no data were available, the reference elevation raster was filled with dummy values (Fig. 3b).

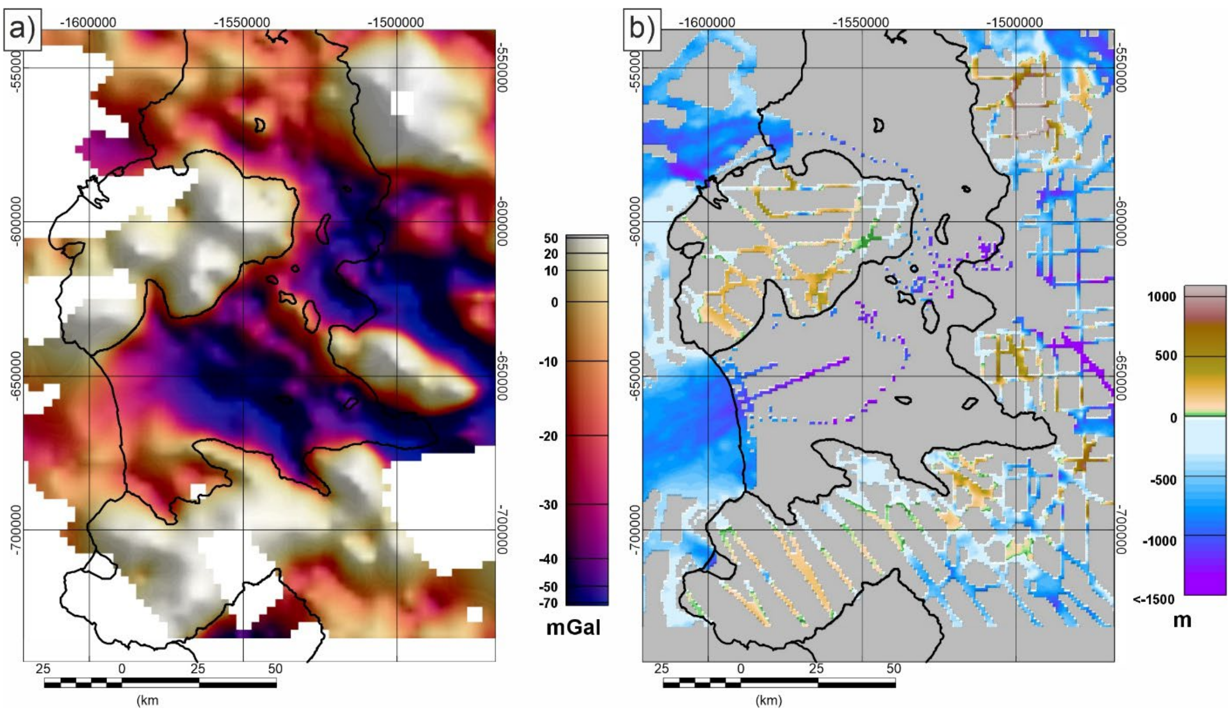

Fig. 3 Input data local to the Dotson/Crosson Ice shelves. a) Free air gravity compilation. b) Topographic compilation including new sub-shelf information.

2.2 Recovery of a new bathymetry including isostatic considerations.

The new method for recovering bathymetry from gravity data constrained by sparse observations is laid out in Figure 4. As noted previously, the inversion without subglacial constraint (Jordan et al., 2020) showed systematic errors (Fig. 2), which we

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attribute to the Moho gravity effect of isostatic compensation of the eroded sub-ice-shelf cavity. The gravity effect of isostatic compensation of any hidden basin must therefore be removed prior to inversion for the final bathymetry (Fig. 4a).

The impact of isostatic compensation on the gravity field is a function of the strength of the crust, the size of the eroded topographic depression, the density of the crust and mantle, and the depth of the Moho. We assumed that the crust had no lateral strength (Airy isostatic assumption), which is likely valid in this region as it lies on a rifted margin, in the region of the Marie Byrd Land hotspot, both factors which reduce the rigidity of the crust and underlying mantle. Previous studies have also suggested low crustal rigidity in this region (Jordan et al., 2010). Use of an Airy isostatic model does not imply that we believe that it is a robust model for the Moho in this region, rather we think it is a reasonable model of the gravity effect generated by all forces acting to isostatically compensate the surface topography. A Moho depth of 30 km for reference crust with topography at sea level, and crustal and Mantle densities of 2670 and 3300 kgm^{-3} respectively, were assumed. This Moho depth is deeper than generally estimated from local seismic models (O'donnell et al., 2019), but is a reasonable global average which may be more appropriate given the uncertainty in the crust and upper mantle density structure in this region. The initial estimate of topography and hence eroded material came from a simple Bouguer slab transformation of the observed free air gravity anomaly to elevation. However, as we know that this is an underestimate of the true amplitude of the bathymetry (Fig. 2), the isostatic compensation was calculated assuming that the topography was displacing air rather than water. This amplifies the calculated Moho topography by 1.6 times, increasing the amplitude of the isostatic correction and compensating for the initial underestimate of the bathymetry. The gravity field associated with the compensating Moho surface was calculated using a fast Fourier transform method implemented in the open-source software package GMT with the gravfft command. The calculated isostatic Moho gravity effect was subtracted from the free air anomaly and the corrected gravity field was used as input for recovery of the bathymetry following the method used previously (Jordan et al., 2020) (Fig. 4b and c).

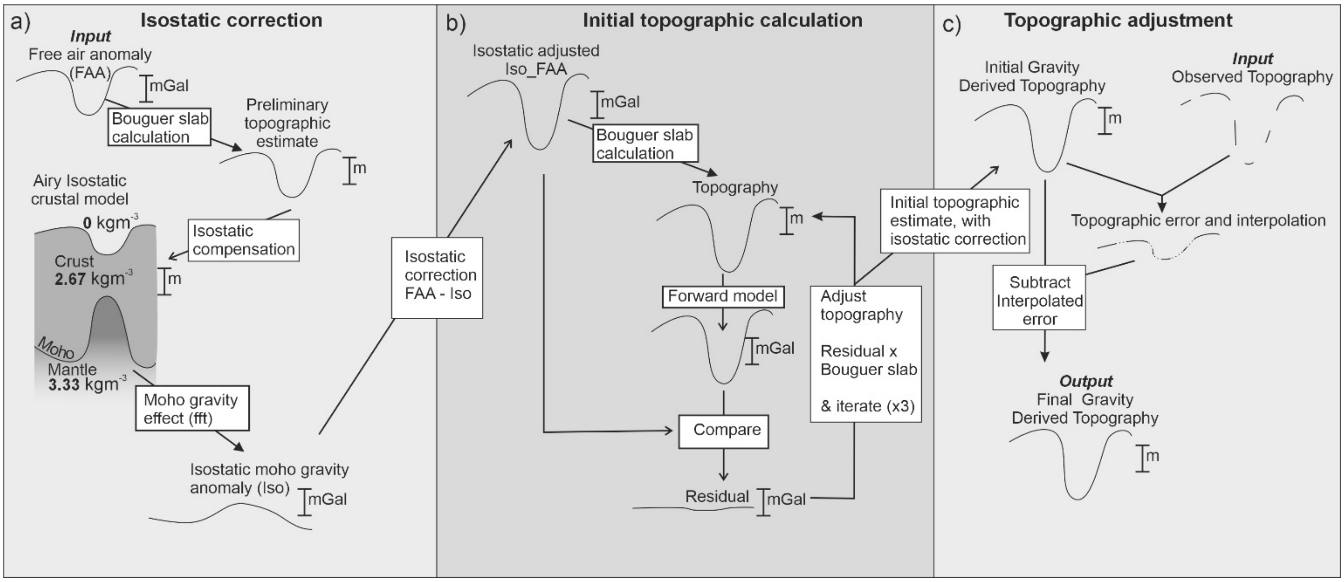

Fig. 4 Flow diagram showing revised method for recovering topography from gravity data. a) Isostatic correction based on preliminary topographic estimate. b) Gravity anomaly after removal of isostatic gravity effect inverted for effective topography. c) Topography adjusted to match observational constraints.

3 Results

To test if including isostatic compensation in the inversion improved the recovered bathymetry, we used the new constraining sub-shelf data as a reference dataset. The bathymetric model including isostatic compensation, but excluding sub-shelf control points, predicts the basin beneath the Dotson Ice Shelf to be ~300 m deeper than the original gravity derived model (Jordan et al., 2020) (Fig. 5a and b). Comparison with the float data (Fig. 2b) shows a reduction in the mean error beneath the shelf from 313 m to 135 m, although the standard deviation of the error remains 187 m in both cases. Comparison with the longest Autosub section (Fig. 2c) shows a reduction in the mean sub-shelf error from 195 m to 3.2 m, and a reduction in the standard deviation from 105 m to 70 m. The smaller reduction in the mean error and consistently high standard deviation when compared with the float data may be due to two complicating factors. First the floats appear to have followed the coast of Bear Island which has elevated onshore coastal topography (~300 m), while the depths recorded by the floats immediately adjacent are ~-700 m. Such a significant topographic step of ~1 km is not recoverable using gravity data, which is limited to >5 km wavelength due to processing. Secondly the navigation of the floats has relatively large uncertainty (estimated to be 1 km or more) so the depth measured by the floats may be somewhat mislocated, adding apparent noise to the calculated error. In contrast the ALR profile lies close to the centre of the basin, likely away from steep fjord walls, and the consistency of the topography on the in-bound and out-bound leg points to higher navigational accuracy. The error against the ALR profile therefore provides a better estimate of the quality of the method under ideal conditions.

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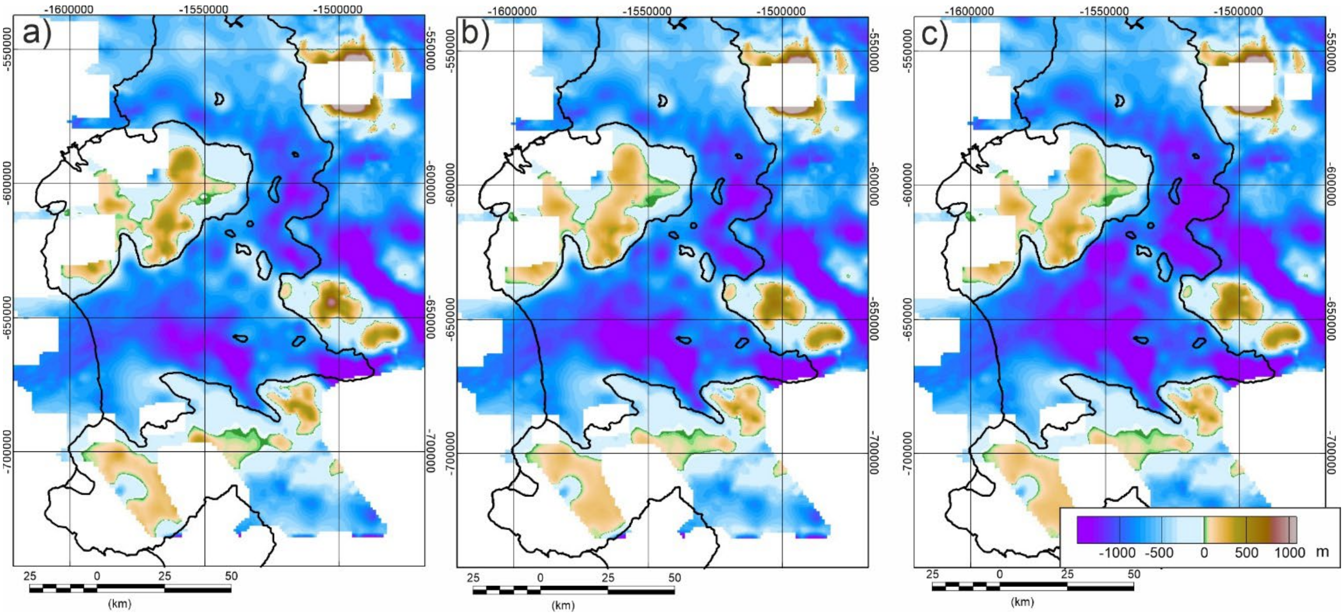

Figure. 5 Gravity-derived models of sub-shelf bathymetry. a) Model from Jordan et al., 2020. b) Revised model incorporating isostatic correction. c) Final bathymetric model incorporating isostatic correction and new sub-shelf observational tie points.

A grid of the errors between the gravity-derived topography with an isostatic correction and observational points shows a reduction in error across all regions (Fig. 6a), compared with the errors associated with the model without isostatic compensation (Fig. 2a). We attribute these residual errors to a combination of unmodelled geological factors, short wavelength topography which could not be resolved from the gravity dataset, and navigational errors in the observational dataset. The reduction in errors and the improved visual fit to the new bathymetric data profiles (Fig. 2b and c), indicates that inclusion of the isostatic correction improves the recovery of bathymetry from gravity data. This is likely to be especially relevant where broad (10s of km) topographic lows are present, as such regions will likely be isostatically compensated at the Moho leading to an underestimate of the bathymetry without isostatic correction, or use of intermediate tie points.

A final revised model of the sub-shelf bathymetry was created by including the new bathymetric observations in the inversion. This used the full improved reference topography which was input into the inversion scheme shown in Fig. 4c in place of the previous observational topography. The output revised topography (Fig. 5c) is like that derived just using the isostatically corrected gravity data (Fig. 5b) but is slightly deeper in places. As expected, comparing the final grid with the input control data (Fig. 6b) shows lower error than the unconstrained isostatic model (Fig. 6a).

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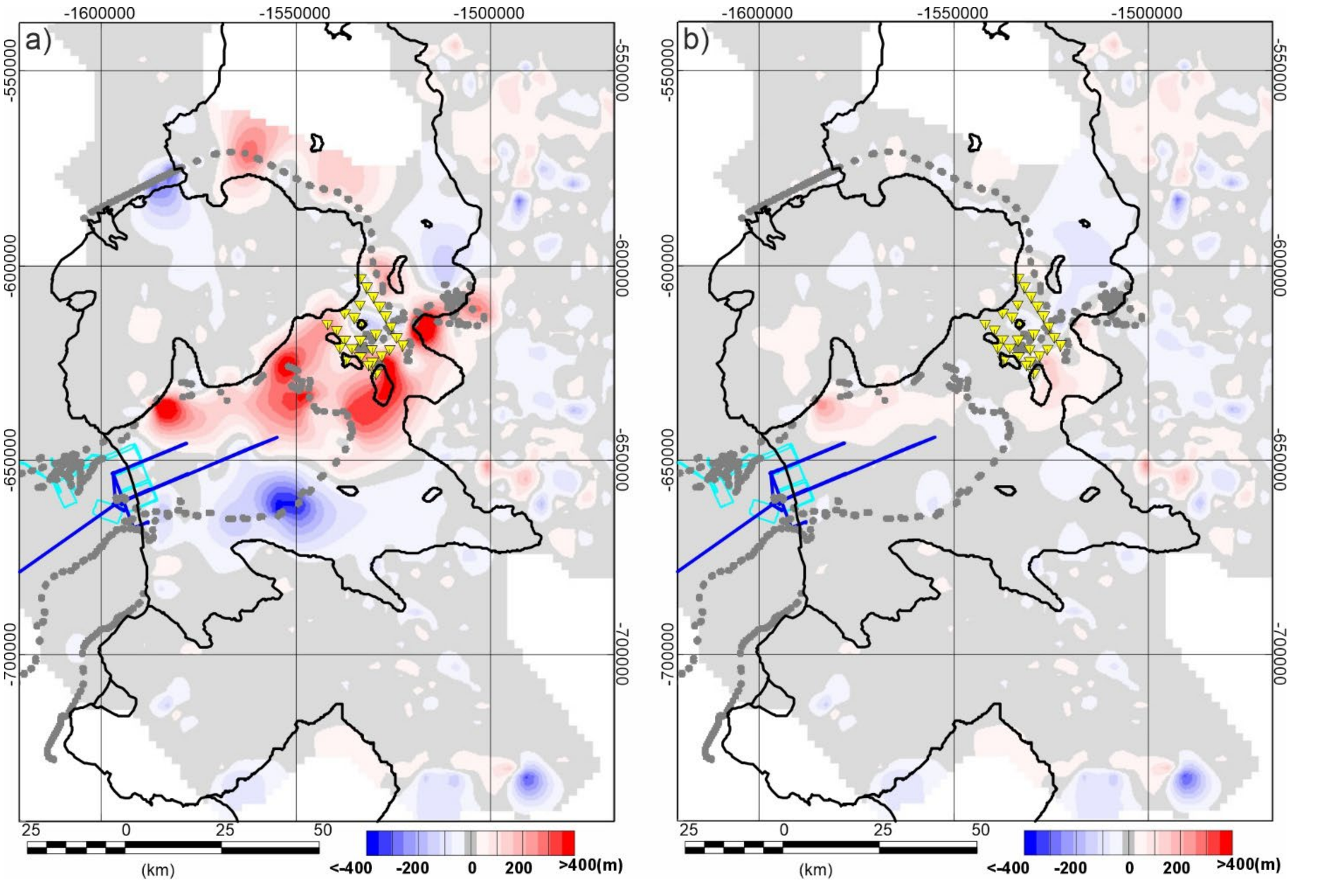

Fig. 6 Error between direct observations and gravity-derived bathymetric estimates. a) Isostatically corrected gravity-derived topography without sub-shelf observations. b) Isostatically corrected gravity-derived topography with sub-shelf control. Note minimal sub-shelf error due to use of observational data as a control.

4 Discussion

New observational data have shown that the bathymetric model produced by Jordan et al. (2020) is too shallow in the Dotson ice-shelf and also to a lesser extent in the and Crosson ice-shelf area. This means that models of sub-shelf circulation (e.g. Goldberg and Holland 2022) may have underestimated the volume of warm water flowing beneath the shelf, as such flow is restricted by shallow sills. This issue highlights the need for caution when using gravity derived bathymetry. Such bathymetry provides the best estimate in regions lacking other data, but geological processes can give rise to relatively large and difficult to quantify errors. Models using such data may therefore need re-evaluation in light of new observations. The impact of some geological factors, such as lateral density variations in the upper crust, can only be resolved by tying bathymetric models to direct observations. However, here we have shown that by considering the process of isostatic balance, which creates a long wavelength distortion of the gravity field and hence bathymetry, bathymetric predictions can be improved, removing consistent regional scale errors on the order of 200 to 400 m.

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We show that our model error has a standard deviation of 90 m when compared with observations away from extremely high amplitude and short wavelength bathymetric features. This error incorporates the impact of un-resolved short wavelength topography, intrinsic errors in the gravity observations, and local variability in subsurface geology. As such this error estimate is location specific and may-not be a valid estimate for the error associated with this method in other regions. Our work confirms the theoretical analysis of Tankersley et al., 2025, who showed that adding selected data points can significantly improve the accuracy of the recovered bathymetry compared to where none are present. However, our real-world errors are an order of magnitude higher than predicted in the theoretical study which used a conceptually similar method. Use of improved inversion techniques may reduce the error (Tankersley et al., 2025), but un-known geological complexity will remain a hard to quantify factor impacting the quality of bathymetry recovered from gravity data.

To assess if the wider bathymetric model of the Thwaites/Dotson and Crosson sub-shelf area produced by Jordan et al. (2020) requires revision and the applicability of this method in other regions, we consider the new inversion, including all topographic constraints, applied across the wider region (Fig. 7a). It is apparent that the largest changes from the model of Jordan et al. (2020) are restricted to the region beneath the Dotson and Crosson ice shelves (Fig. 7b). The gap in direct bathymetric observations around the Dotson and Crosson ice shelves in the Jordan et al. (2020) study is only slightly larger than the data gap beneath the Thwaites Glacier ice shelves (Fig. 7c). This could suggest that similar significant and systematic errors in recovered bathymetry associated with isostatic compensation are present adjacent to Thwaites Glacier. However, comparison of the inversion results with and without isostatic correction show little change in the Thwaites Glacier area. We attribute this difference to the pattern of isostatic compensation in the two areas. The gravity field derived from the isostatic compensation at the Moho shows the isostatic correction across the data gap adjacent to Thwaites Glacier has a low amplitude and approximately linear gradient (Fig. 7c). In contrast the Dotson and Crosson area shows a correction with higher amplitude and more variable gradient within the original gap in data coverage (Fig. 7c). In the case where the gradient of the isostatic correction is low and approximately constant, tying the recovered bathymetry to observed data either side of the data gap, with no consideration of isostatic compensation, will produce a reasonable result. In contrast, where the isostatic correction predicts a highly variable field, as in the Crosson and Dotson case, errors created by not considering the isostatic correction are likely to be more significant, as they will not be removed by interpolating the error between the observed topographic controls.

Our study shows that isostatic compensation is an important process that can result in long wavelength errors of several hundred meters in bathymetry derived from gravity data. Such errors have the potential to significantly change the outputs of simulations testing the vulnerability of the Antarctic ice sheet to warming oceans as they raise the seabed above important thresholds, artificially blocking the influx of warm water. As isostatic compensation has most impact on recovery of bathymetry where deep basins are entirely unconstrained by direct observations, it is likely that this consideration has most impact for smaller and less explored ice shelves, rather than over the major Ross, or Ronne-Filchner ice shelves. Such ice shelves have been identified for example by Tankersley et al., 2025. Although small relative to the Ross, or Ronne-Filchner many of these ice shelf systems are many 10's of km wide, and are likely to have been erosionally over deepened by flowing ice, meaning isostatic compensation is likely to distort the gravity signal due to the local bathymetry. Consideration of isostatic

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compensation, in addition to direct observations, is therefore required to provide the best bathymetric estimate for many ice shelves around antarctica.

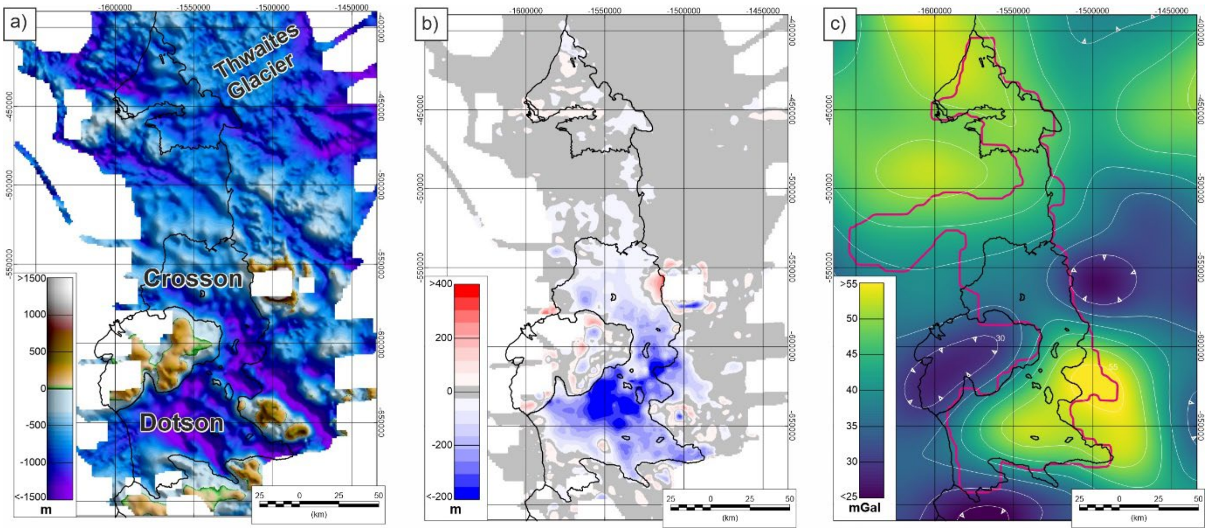

Fig. 7 Bathymetry of the wider Dotson, Crosson and Thwaites area. a) New regional bathymetry from gravity data, including an isostatic correction. b) Change in bathymetry/topography from Jordan et al. (2020), to a model including isostatic correction to gravity data. Blue colours show regions where the new model is deeper. Note that the impact of the isostatic correction is minimal away from the deep basin beneath the Dotson and Crosson ice shelves. c) Moho gravity anomaly based on an isostatic model with 5 mGal contour. Note more complex form in the Dotson/Crosson ice shelf area relative to the ice shelf adjacent to Thwaites Glacier. Pink line outlines area with no direct bathymetric constraints prior to this study.

5 Conclusion

Including an isostatic correction, based on an initial topographic estimate from the free air gravity anomaly, provides a better estimate of the sub-shelf bathymetry than simply inverting the Free air gravity anomaly with no isostatic correction. However, in some situations, such as adjacent to Thwaites Glacier, where the predicted isostatic correction has a low and generally uniform gradient, inclusion of the isostatic correction will be less important. Our study highlights the need to consider both the shallow geology, and the deeper, more regional impacts of isostatic compensation when recovering bathymetry from gravity data, especially where constraint by direct observations are lacking.

6 Data availability:

Data and results presented in this manuscript can be accessed at the NERC UK Polar Data Centre. Jordan, T., Heywood, K., Wahlin, A., Hall, R., Muto, A., Dutrieux, P., Hogan, K., Girton, J., Alley, K., & Pettit, E. (2025). Updated gravity-derived bathymetry for the Thwaites, Crosson and Dotson ice shelves (2009-2022) (Version 1.0) [Data set]. NERC EDS UK Polar

Data Centre. https://doi.org/10.5285/baef2e88-300f-42bc-8ccb-bfdff147a492. *Note full access will be available after publication.*

7 Author contribution:

TJ devised and caried out the revised gravity inversion and prepared initial manuscript. KH, EP and RH devised the ship-borne study, collected and provided Autosub data, AW collected and provided Ran data, AM and KA collected and provided seismic data, PD and JG collected and provided profiling float data, KH assisted with manuscript initiation. All authors contributed to the manuscript through the drafting process.

8 Competing interests:

The authors declare that they have no conflict of interest

9 Acknowledgements:

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