Paleo-ice sheet reconstructions constrained by glacial isostatic adjustment and geological data

Evan J. Gowan[1], Sara Khosravi[1], Xu Zhang1, Gerrit Lohmann[1] and Klaus Grosfeld[1]

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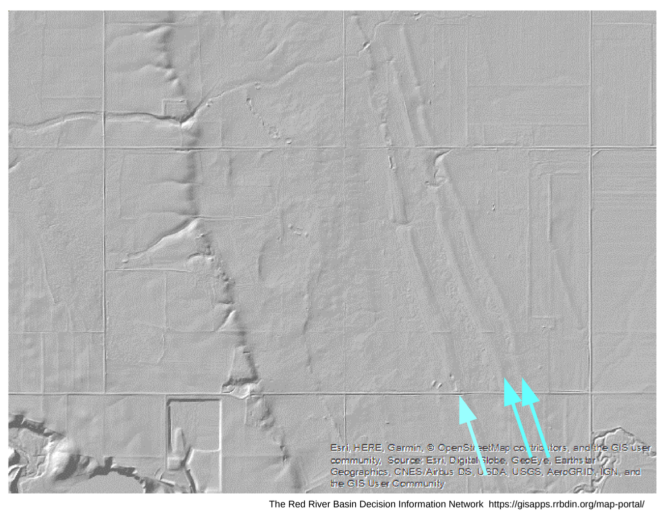
Ice sheet reconstructions based on geological and geophysical information

- Geophysical modelling of glacial-isostatic adjustment (GIA) processes has long been used to reconstruct paleo-ice sheets (e.g. Tarasov et al 2012, Peltier et al 2015, Gowan et al 2016a, Lambeck et al 2017). In order to do this efficiently, it is necessary to have strict control on the geometry of the ice sheet.
- These data have limitations due to the spatial distribution (i.e. sea level indicators are only located in coastal regions, glacial lake strandlines exist only in paleo-lake basins, end moraines are only located where a glacial margin remained stationary for some time).
- Ultimately, the reconstruction should have at least a minimal amount of glaciological realism. This can be achieved using our model, ICESHEET (Gowan et al 2016b), which uses perfectly plastic rheology.


Strandlines of Lake Agassiz


End moraines from the Erie Lobe of the Laurentide Ice Sheet

Methodlogy to make ice sheet reconstructions using ICESHEET

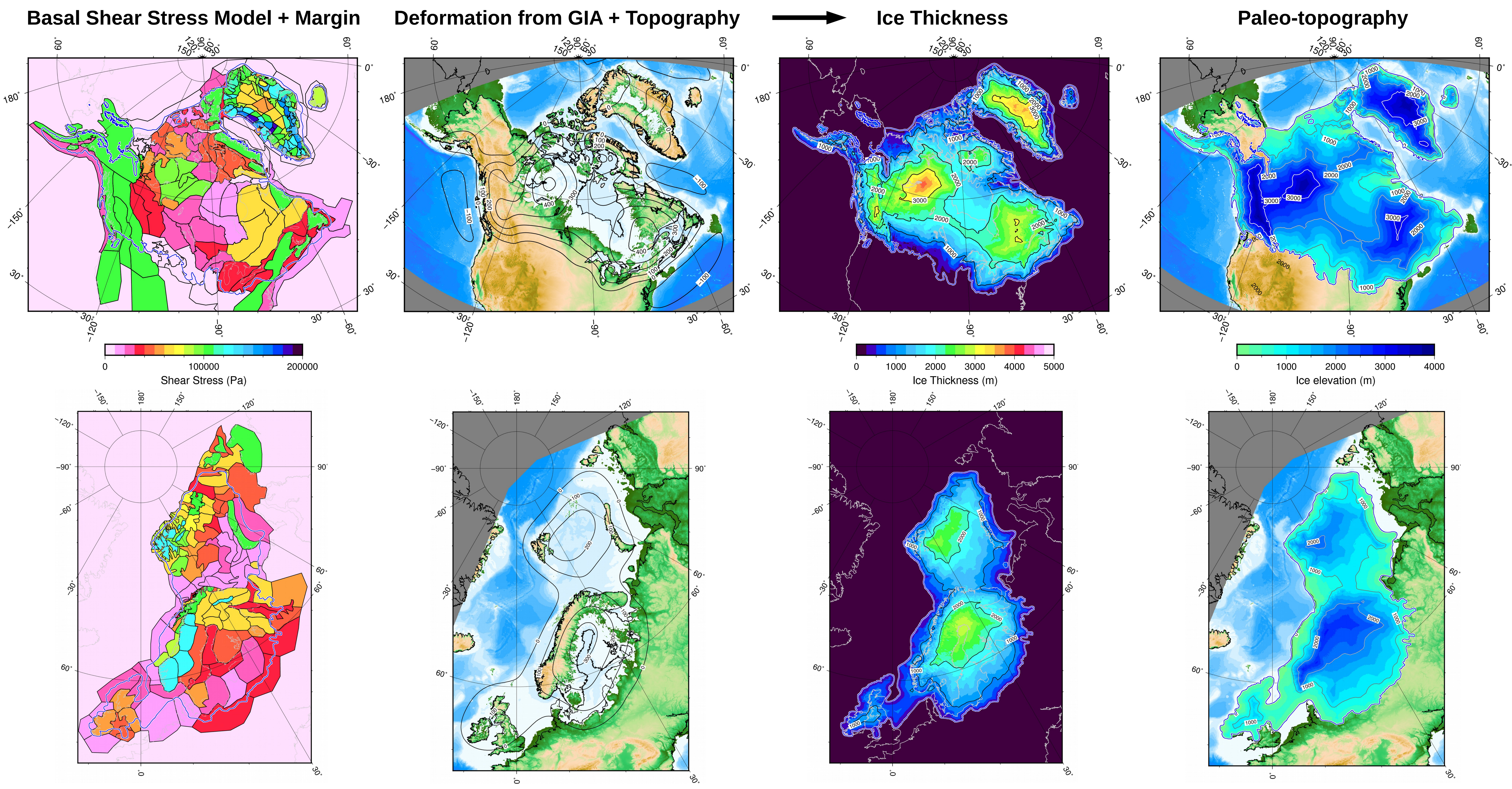
- Inputs for ICESHEET include the margin at discrete time periods, and a temporal variable basal shear stress model which controls the ice surface profile.
- Can include iterations of GIA to account for changes in basal topography from loading and sea level change. We use SELEN (Spada et al., 2012) to compute this.
- At present, we have setups for North American and Eurasian ice sheets.

North American Ice sheets at 20000 yr BP

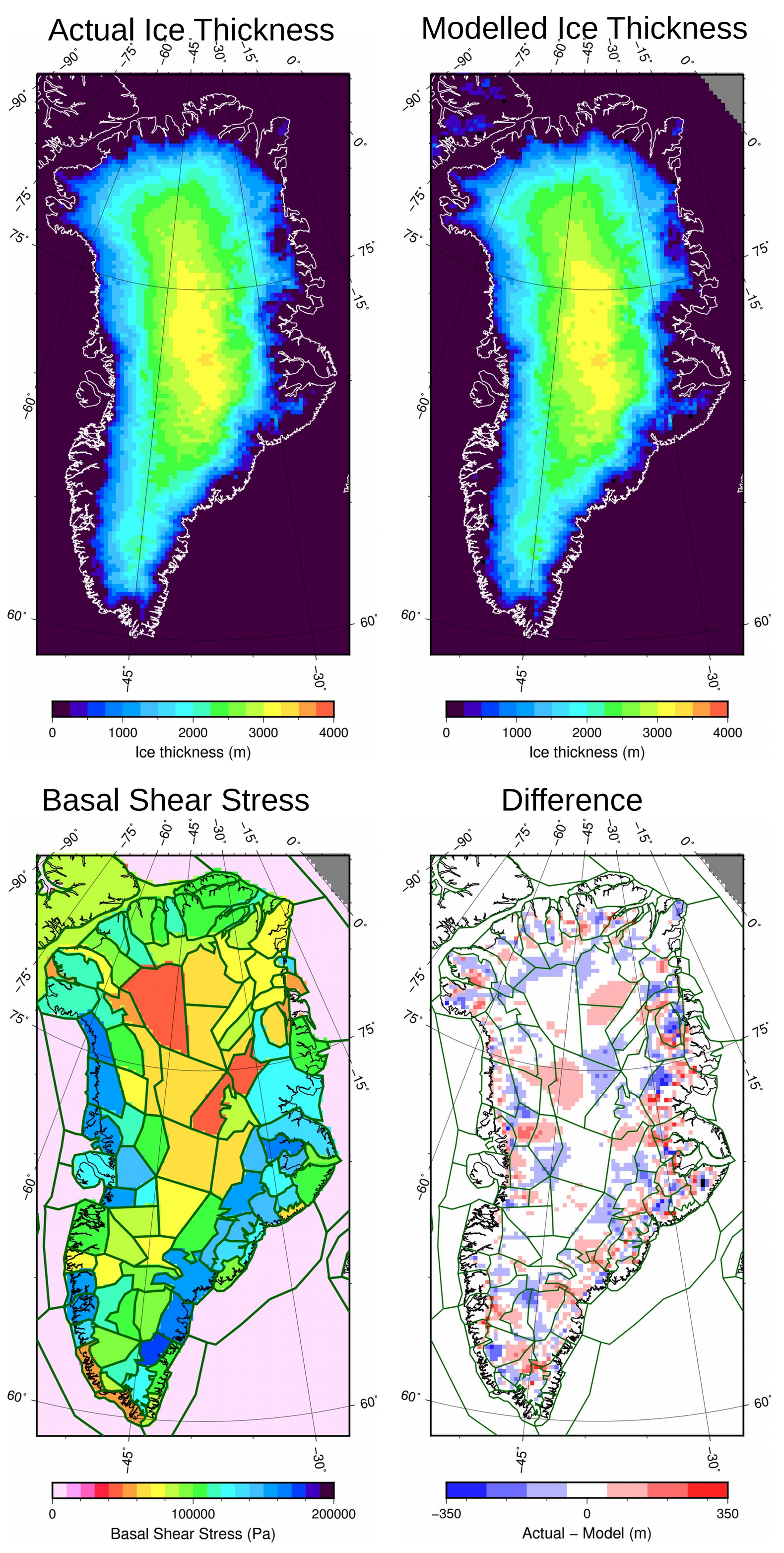
(blue line is the margin reconstruction from Dyke, 2004 and Gowan et al. 2016a)

Eurasian Ice sheets at 20000 yr BP

(blue line is the margin reconstruction from Hughes et al. 2016)



Greenland Ice Sheet



To test the utility of ICESHEET, it is instructive to show the results versus the contemporary Greenland Ice Sheet. The shear stress domains were adjusted to minimize the misfit of the modelled ice thickness and actual ice thickness. Even with the coarse resolution of the shear stress domains, the modelled ice thickness is generally within 250 m of the true thickness. The largest differences happen at the borders between the shear stress domains. Using coarser shear stress domains is advantages for paleo-reconstruction to reduce the amount of adjustable parameters.

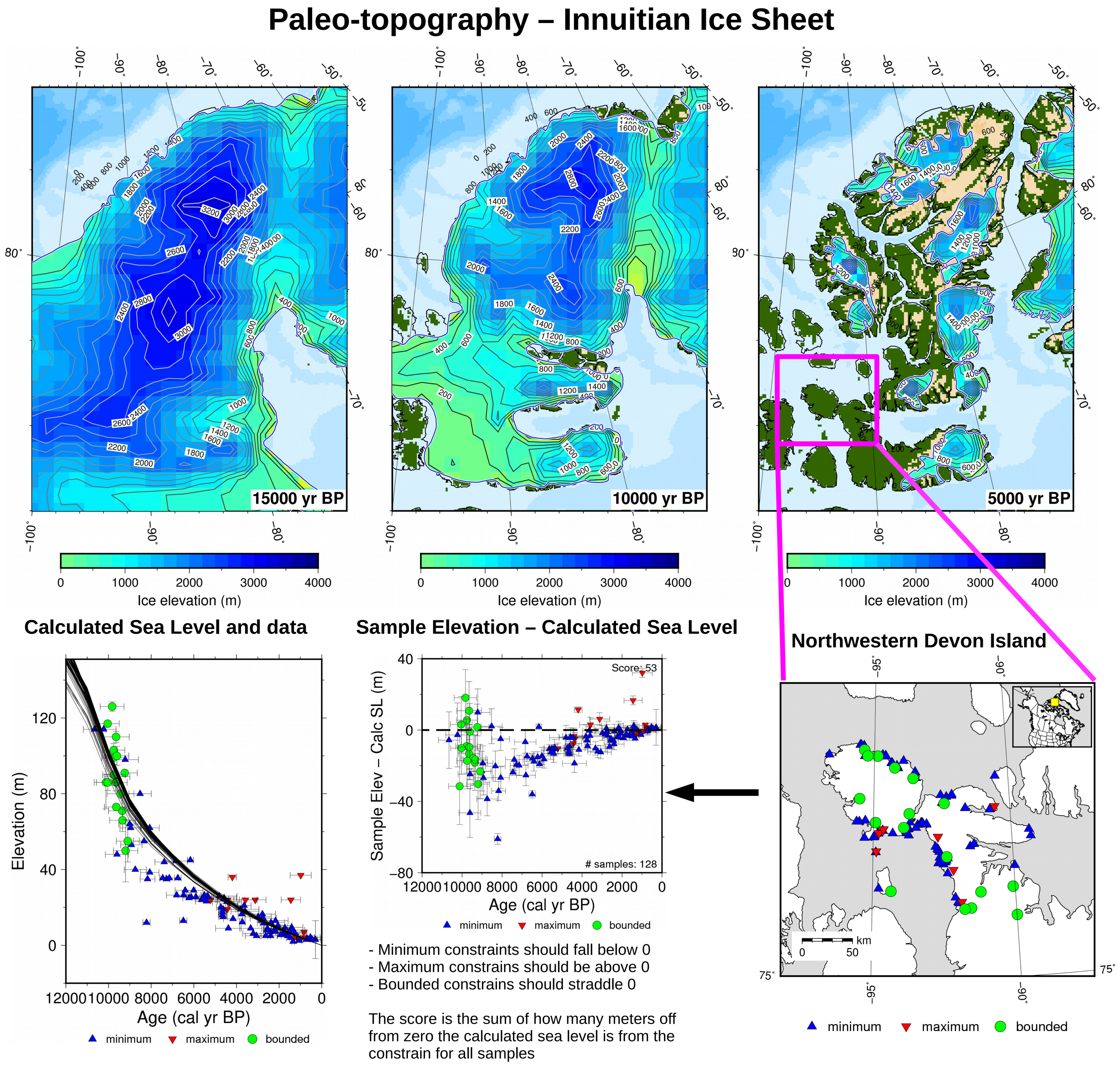
Refining the ice sheet reconstruction

Currently, we are refining the ice sheet reconstruction for the Innuitian Ice Sheet in Northern Canada. We are revising margins and sea level indicators using updated reservoir corrected radiocarbon dates (Butzin et al 2017).

The sea level data are classified based on whether they indicate that sea level was above (*minimum*) or below (*maximum*) the sample elevation, or intermediate of the sample and the local highstand position (*bounded*).

Sea level is calculated at the location of each sample, and a score is assigned based on the discrepancy between the observation and model (zero if there is no discrepancy). This score is used to assess the ice sheet reconstruction.

The basal shear stress or margin models are adjusted if there is a discrepancy in calculated sea level.



- Minimum constraints should fall below 0
- Maximum constrains should be above 0
- Bounded constrains should straddle 0

The score is the sum of how many meters off from zero the calculated sea level is from the constrain for all samples

References
- Butzin, M., Köhler, P. and Lohmann, G., 2017. Marine radiocarbon reservoir age simulations for the past 50,000 years. Geophysical Research Letters, 44(16), pp.8473-8480.
- Dyke, A.S., 2004. An outline of North American deglaciation with emphasis on central and northern Canada. Developments in Quaternary Sciences, 2, pp.373-424.
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- Hughes, A.L., Gyllencreutz, R., Lohne, Ø.S., Mangerud, J. and Svendsen, J.I., 2016. The last Eurasian ice sheets–a chronological database and time-slice reconstruction, DATED-1. Boreas, 45(1), pp.1-45.
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Acknowledgements
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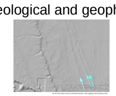

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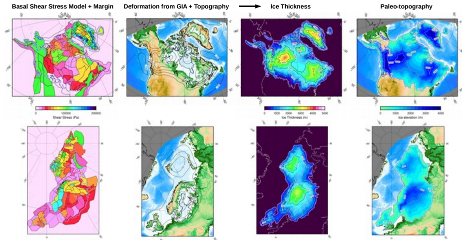

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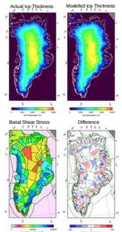

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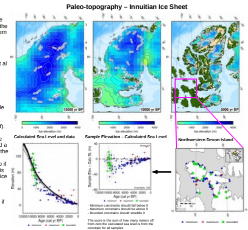
Paleo-topography – Innuitian Ice Sheet



References
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