Satellite Observations of Ice Thickness and Deformational Properties in Antarctic Grounding Zones

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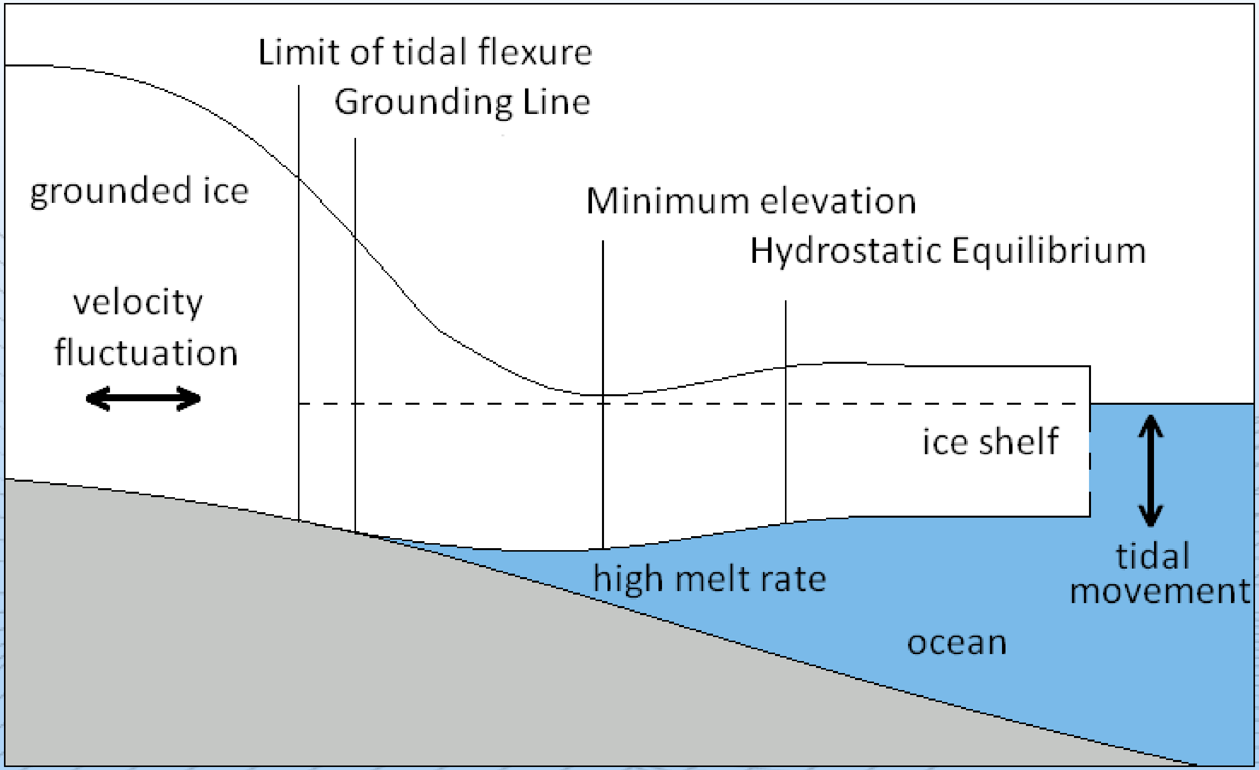
The Grounding Zone

"The GZ is the region of the ice sheet straddling the GL, encompassing the transition from fully grounded ice to ice in hydrostatic equilibrium with the underlying ocean"
- Fricker et al., 2009.

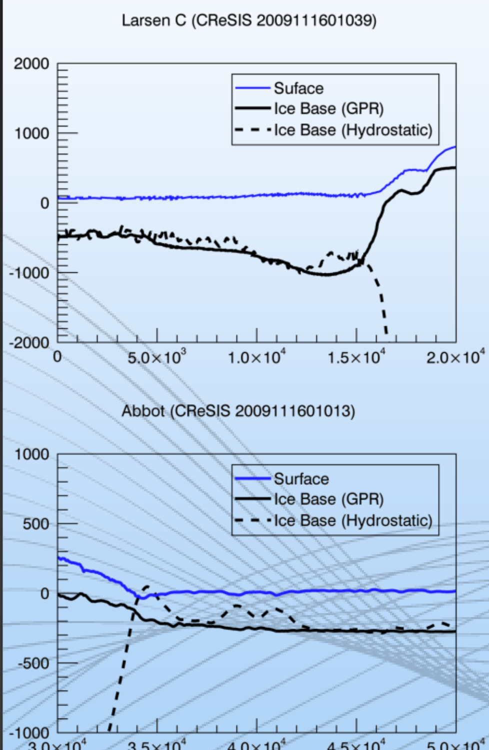


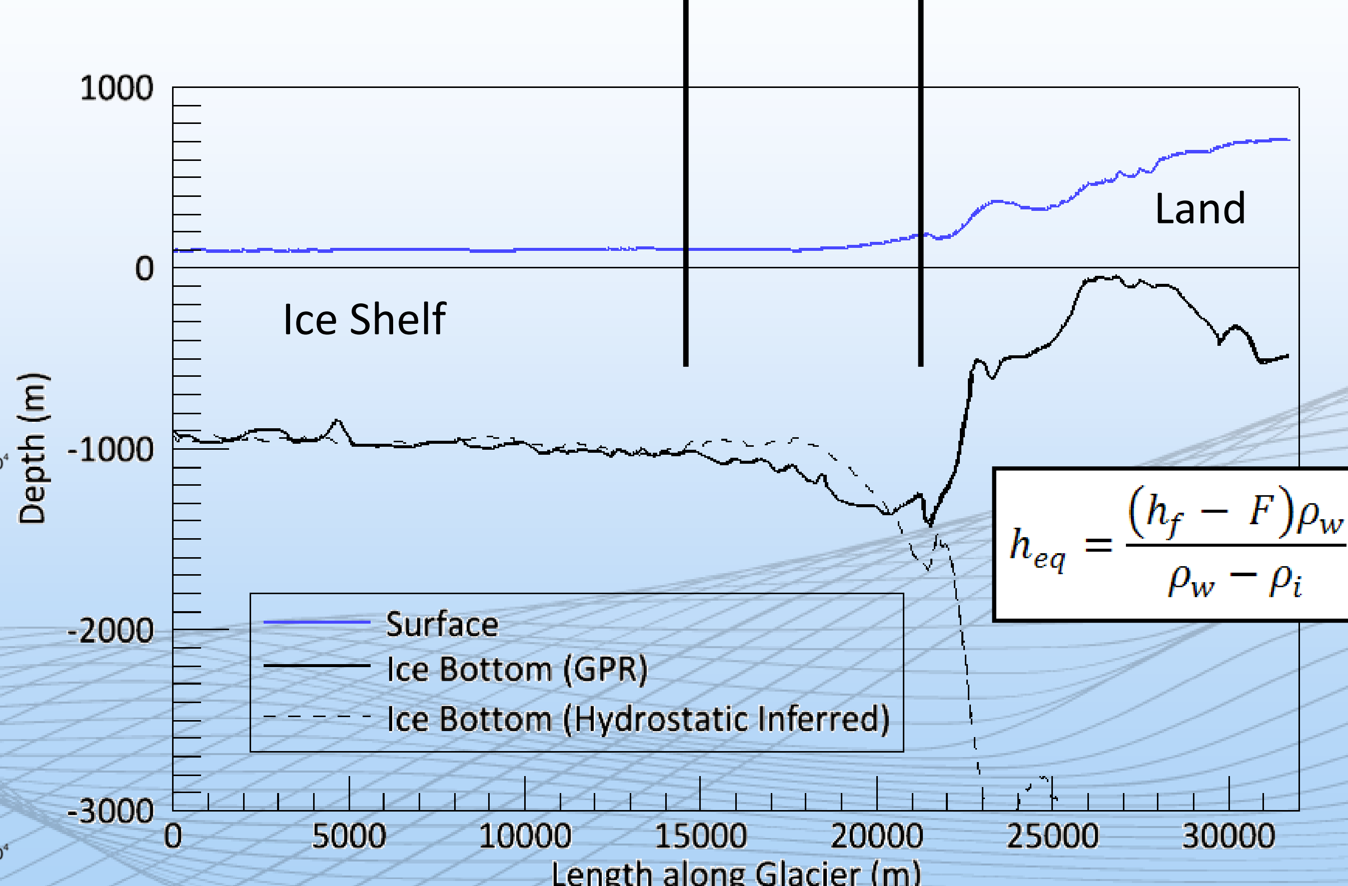
Important for:
Ice flux
Local mass-balance
Retreat / Stability
Melt rates

Adapted from Fricker et al., 2009

Profiles of the Grounding Zone

At steep grounding lines, hydrostatically-derived thickness is generally underestimated in the 1-5 km GZ



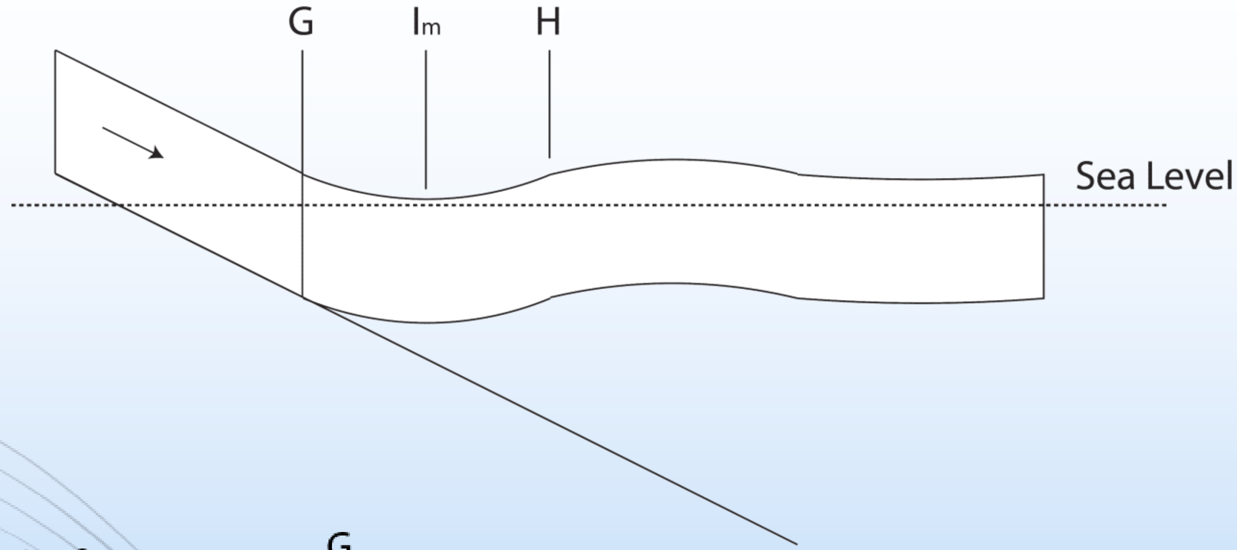


$$h_{eq} = \frac{(h_f - F)\rho_w}{\rho_w - \rho_i}$$

Data (CReSIS, 2012)

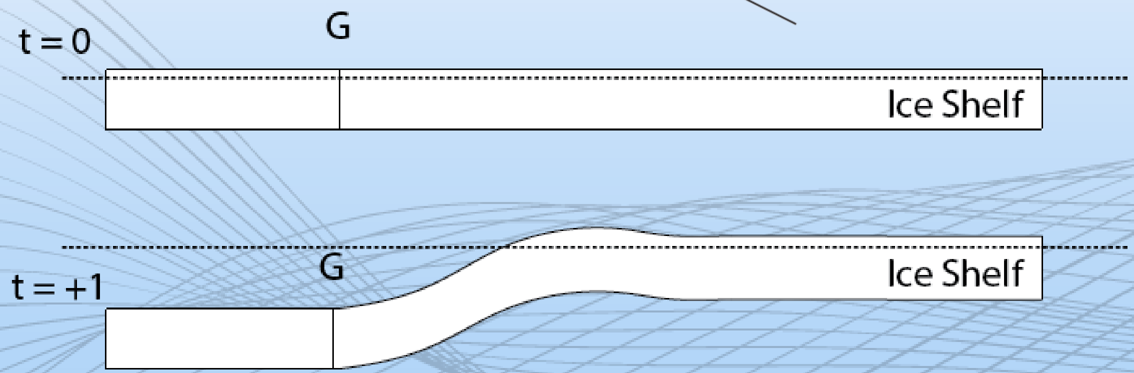
Profiles of the Grounding Zone

Static profile with ***dynamic*** (tidal) profile superimposed



Static

e.g. Bindschadler et al., 2011; Brunt et al., 2010



Dynamic

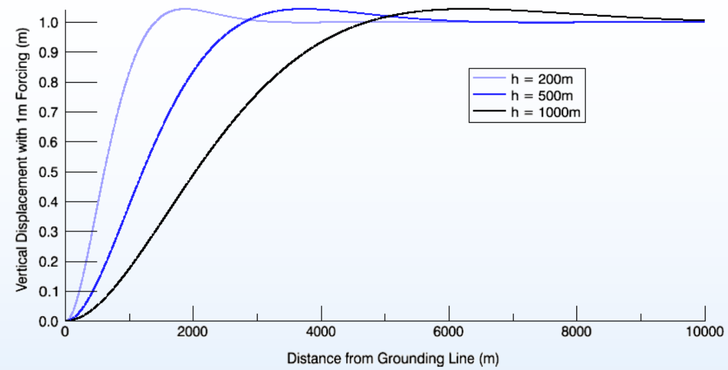
e.g. Rignot et al., 2011; Brunt et al., 2010

Characteristics of both profiles linked to ice stiffness
Flexural response to stress not constant over time…

Tides around Antarctica

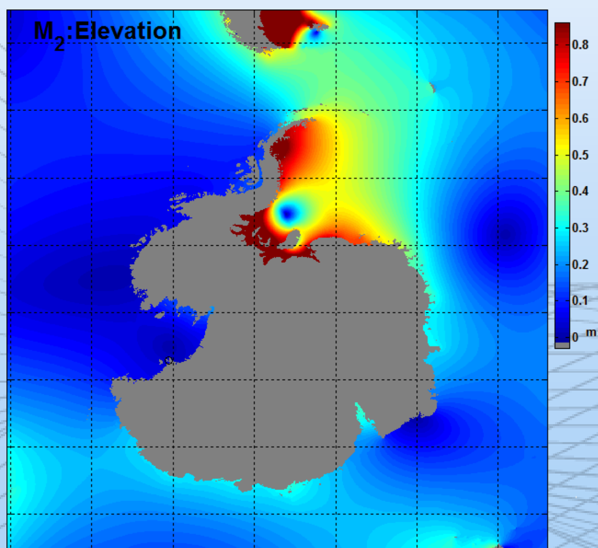
Mixed diurnal / semi-diurnal dominant regions
Generally 1-2m tides beneath ice shelves

$$\begin{cases} \nabla^2 M + \rho_w g w = \rho_w g T \\ M - D\nabla^2 w = 0 \end{cases}$$

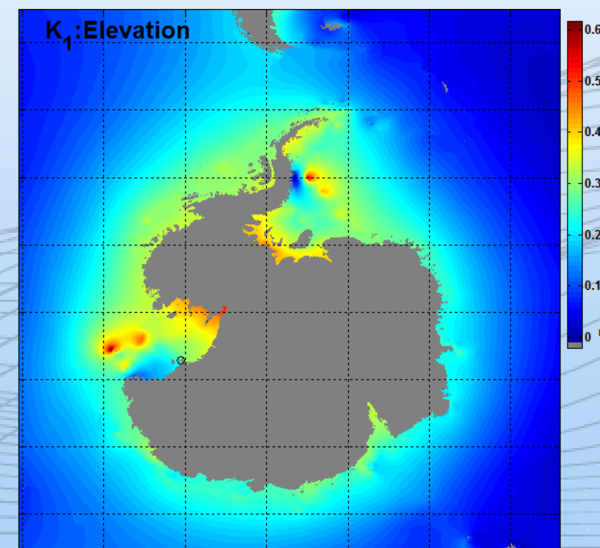


Elastic beam / plate model

$$D = \frac{E^* h^3}{12(1 - \upsilon^2)}$$



CATS 2008a Tide Model (Padman et al., 2008)



Inverse Model to Solve for Stiffness

Ill-conditioned for boundary conditions:
w(0) = w'(0) = w(L)'' = w(L)''' = 0

Tikhonov regularisation to constrain numerical solution

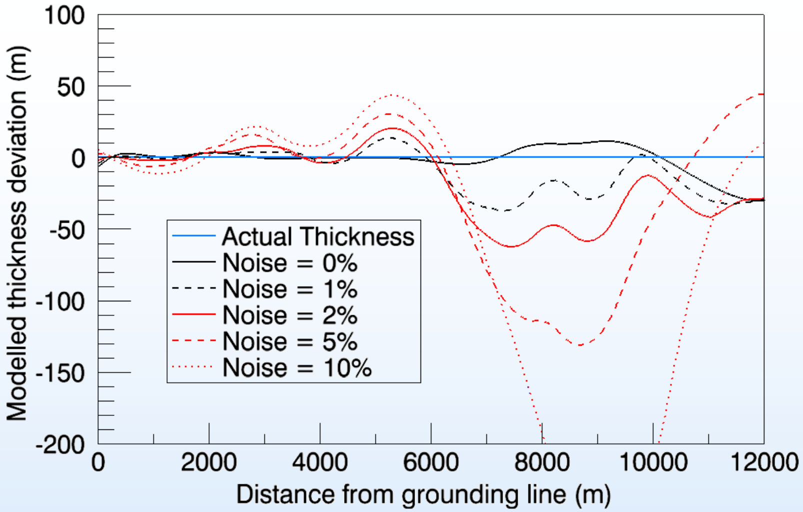
$$||w_{in} - w_{out}||^2 + \lambda||\nabla h||^2$$

Solving for stiffness, not thickness (assuming spatially constant E* and ν)

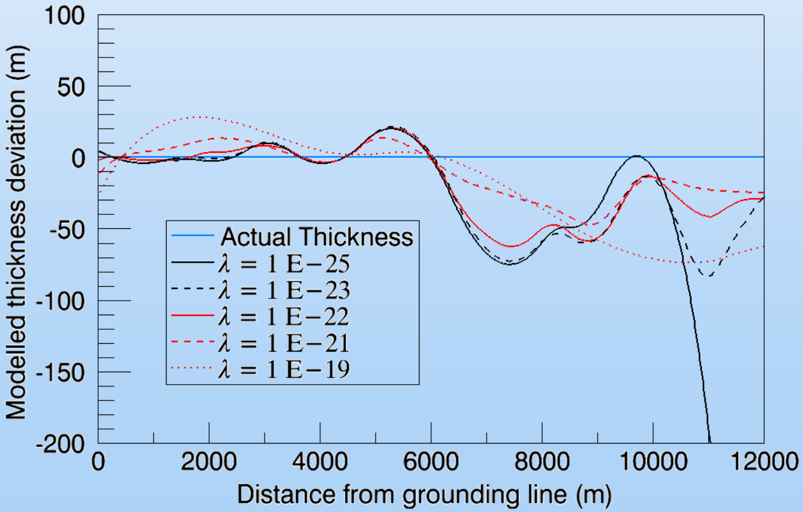
Noise dependent, regularization dependent

Good agreement in flexure zone

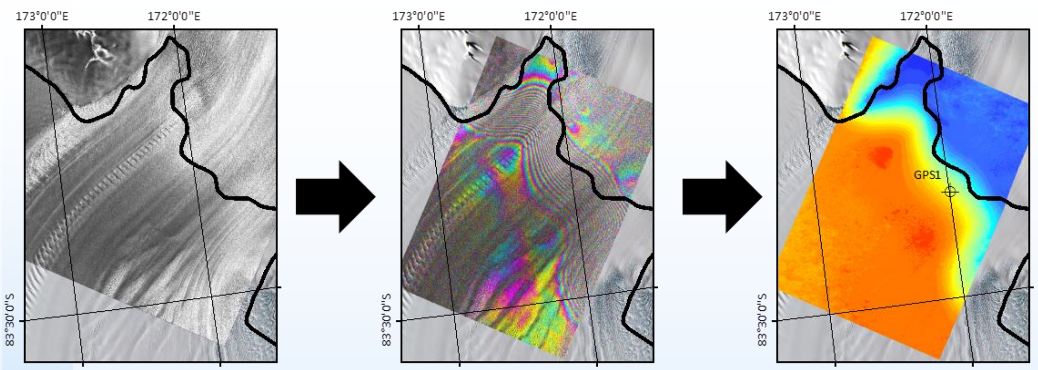
Increasing regularization leads to smoother profile

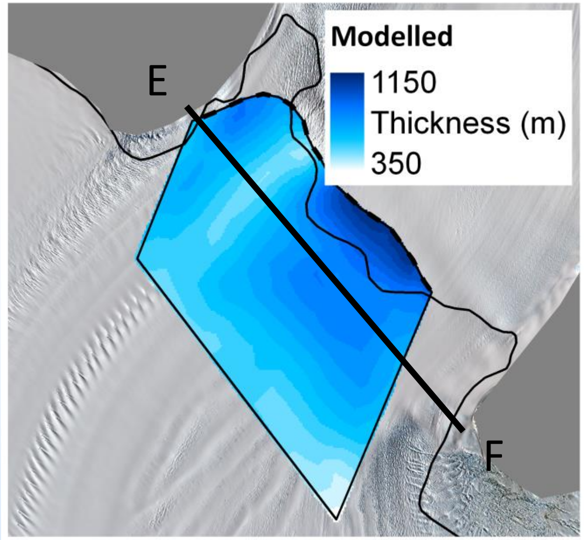


Model performance for synthetic GZ

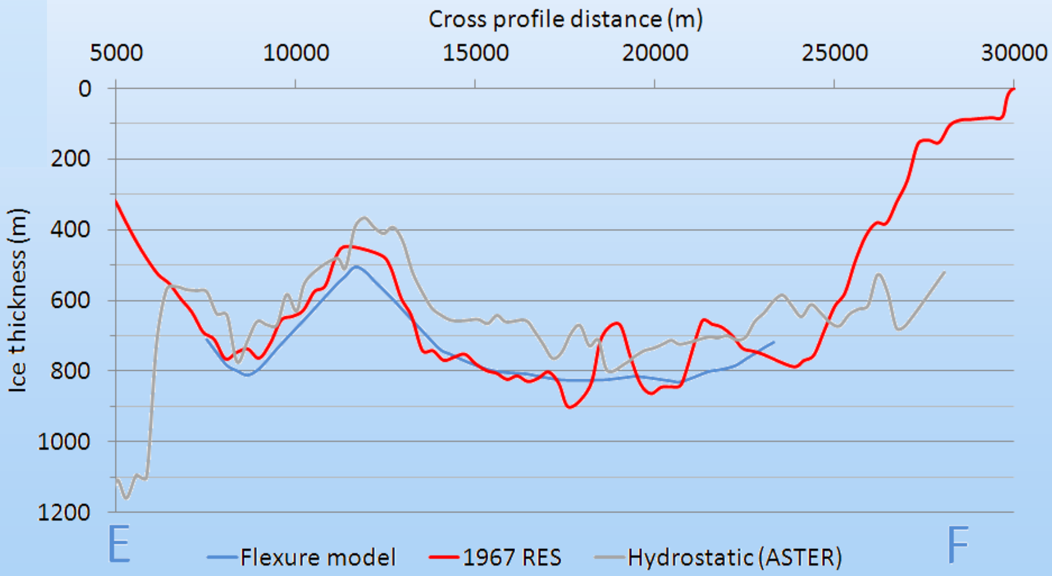


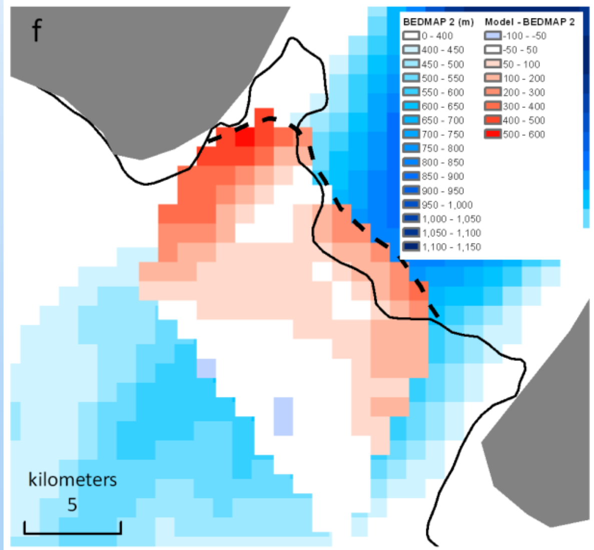
Field Validation





Beardmore Glacier

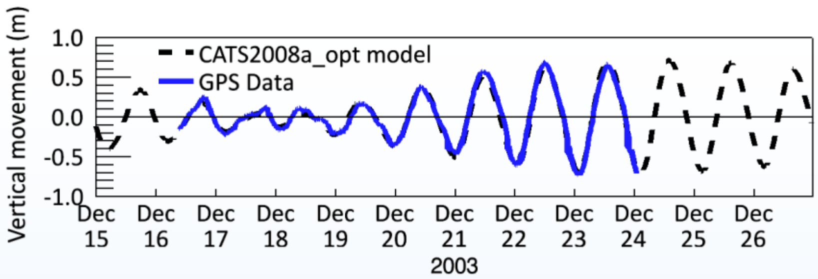




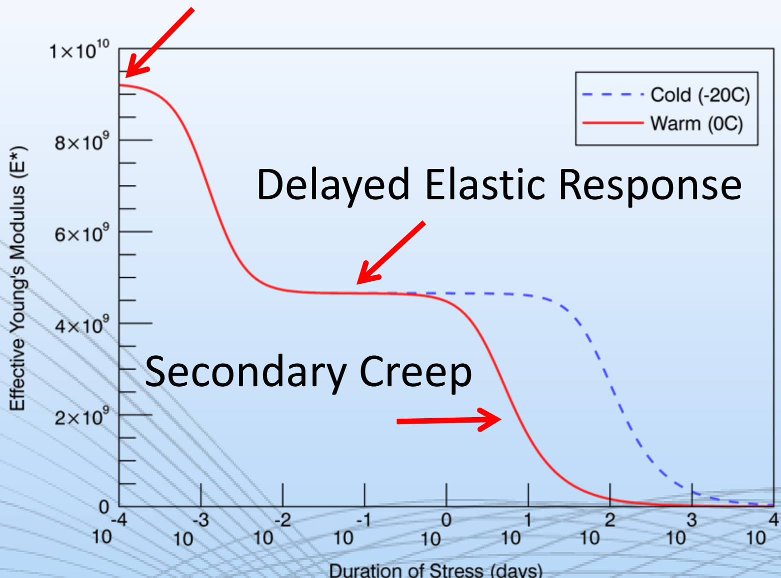
Effective Young's Modulus (E^*)

E* at Beardmore = 1.5 GPa

GPS lags Tide Model ~ 20 minutes

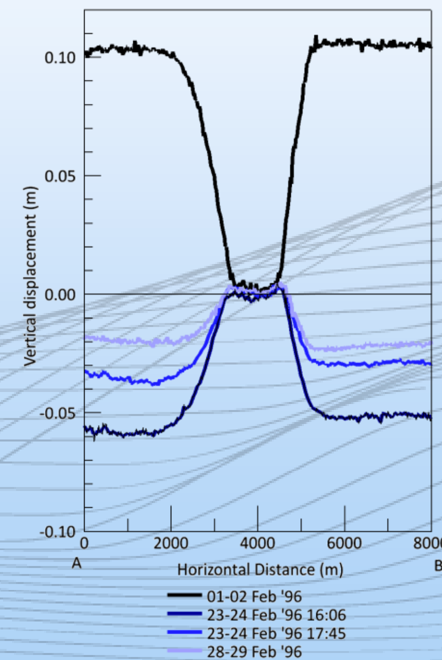


Instantaneous E (i.e. measured ultrasonically)



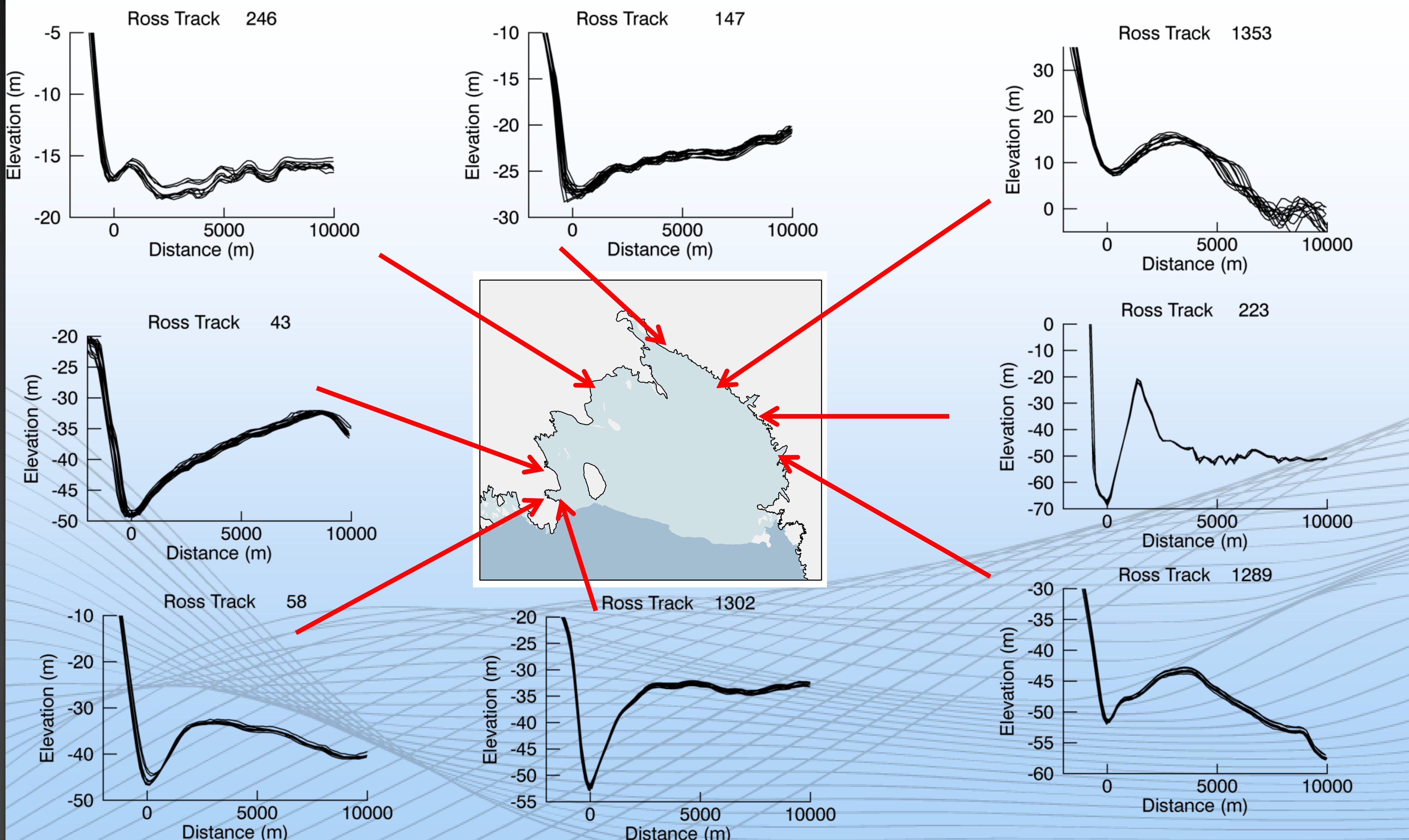
Diurnal oscillations close to expected limit of elastic behaviour

Multiple interferograms required to constrain viscous parameters



Magnitude of complex elastic modulus (Burgers model).
Adapted from Gudmundsson et al., 2007

Static Profiles of the Ross Ice Shelf



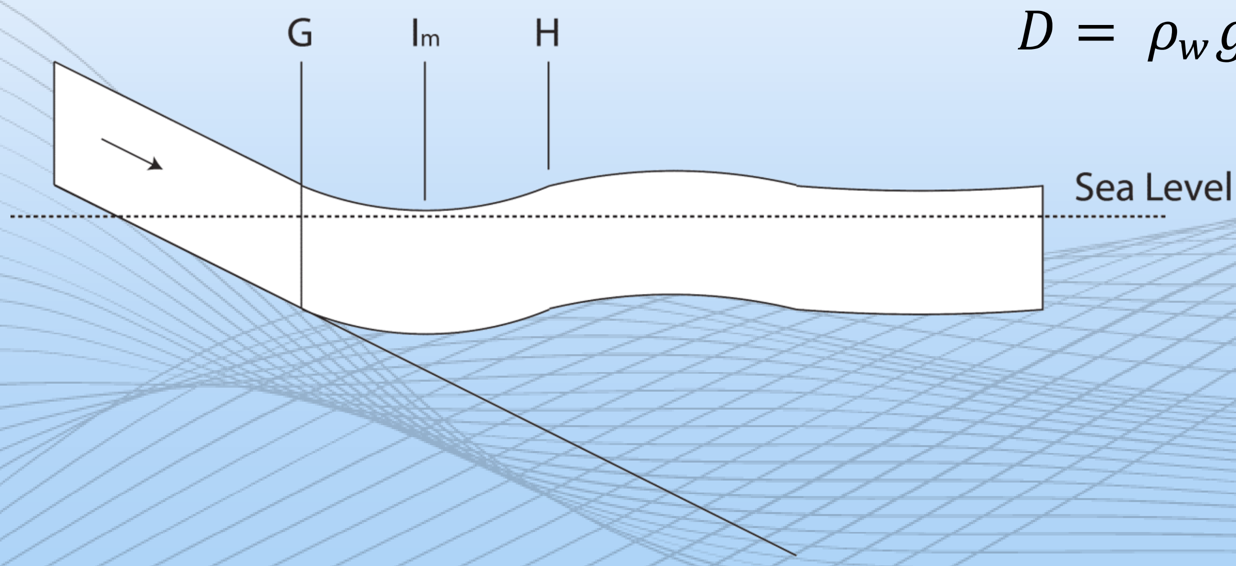
Static Profile

Continuous point force spread out over shelf (Schoof, 2011)

Buoyancy bending wavelength (distance between I_m and H) depends on ice stiffness in elastic case (Sayag and Worster, 2011) and horizontal velocity in addition in viscous case

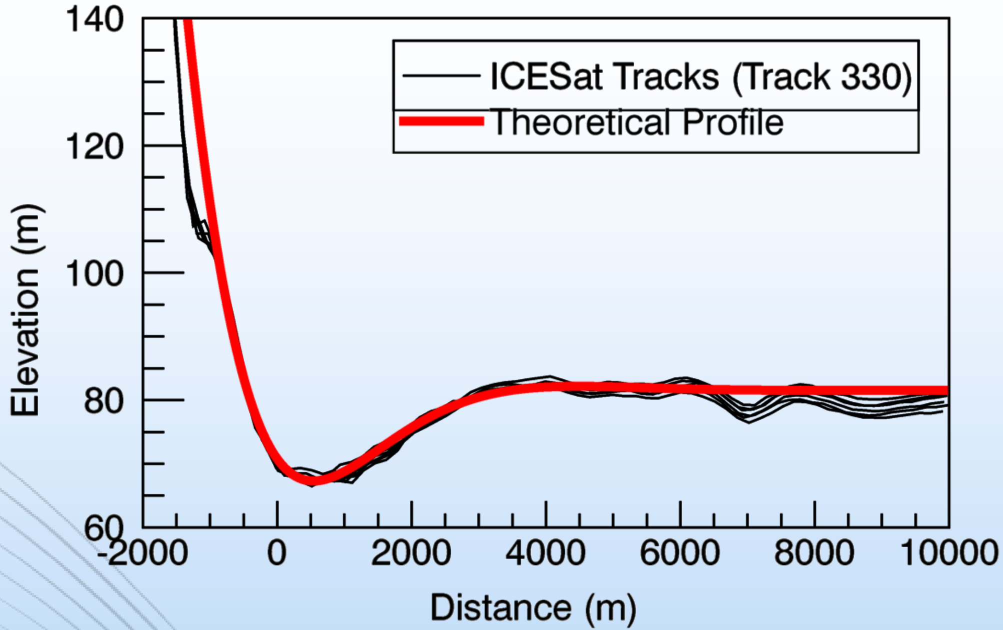
Amplitude of standing wave depends on grounding line slope and bed stiffness (not tidal amplitude)

$$D = \rho_w g \left(\left(\frac{2\sqrt{2}}{3\pi} \right) d \left[H - I_m \right] \right)^4$$



$$D = \frac{E^* h^3}{12(1 - \upsilon^2)}$$

Fitting to Elastic Theory



Slope = 8.5°
k0 = 1 x 10^6
E* = 2 x 10^8
H = 700

Essentially, bed stiffness controls the amplitude of the wave while ice stiffness controls wavelength

k0 varies between ~ 1 x 10^6 and 1 x 10^8 Pa m^{-1} (till / bedrock)
E* varies between ~ 1 x 10^5 and 1 x 10^9 Pa

Summary

Grounding zones act as a ‘natural laboratory’ to measure ice properties

An inverse elastic beam model satisfactorily reproduces GPR ice thickness at the Beardmore, improving on hydrostatic thickness estimates

The method requires high quality interferograms with errors in displacement < 2% of tidal amplitude

Static surface profile is indicative of a change in bed stiffness at the grounding line, although viscous effects become increasingly more important over long periods