Mechanics of Hydrology & Calving Relevant for Glacier Seismology

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Glacier Seismology Training School

Understanding the Mechanics

- Tim showed many examples of hydro./calving obs.
- Can we understand them quantitatively?

- More importantly, can we quantitatively understand the implications for glacier dynamics?
- Observations cannot be made in a theoretical vacuum! (Too often in last 40 yrs in glaciology!)

How do obs. provide useful information?

If …

- We understand the physical processes
- Can predict the properties of (seismic) obs.
- And observables relate to model parameters of interest

Then

- Observations of seismic ground motion are useful to constrain properties of the physical processes

- **d**=f(**m**), f known, m affects d
- Empirical calibration can help, but only w/ extensive data: Don’t use ‘models’ with fitting params. unless well constrained

Understanding the Mechanics

- Modeling hydrology & basal mechanics, calving
  - Predicting seismic signals
  - Implications for mechanics

Predicting Seismic Signals

- Types of signals:
  - Mass acceleration, turbulent flow, cavitation, iceberg scraping & rotating

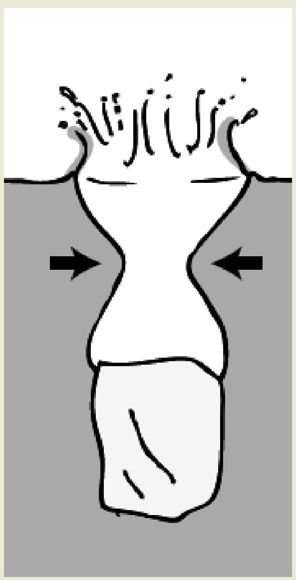
What do we need to know to model seismic signals?

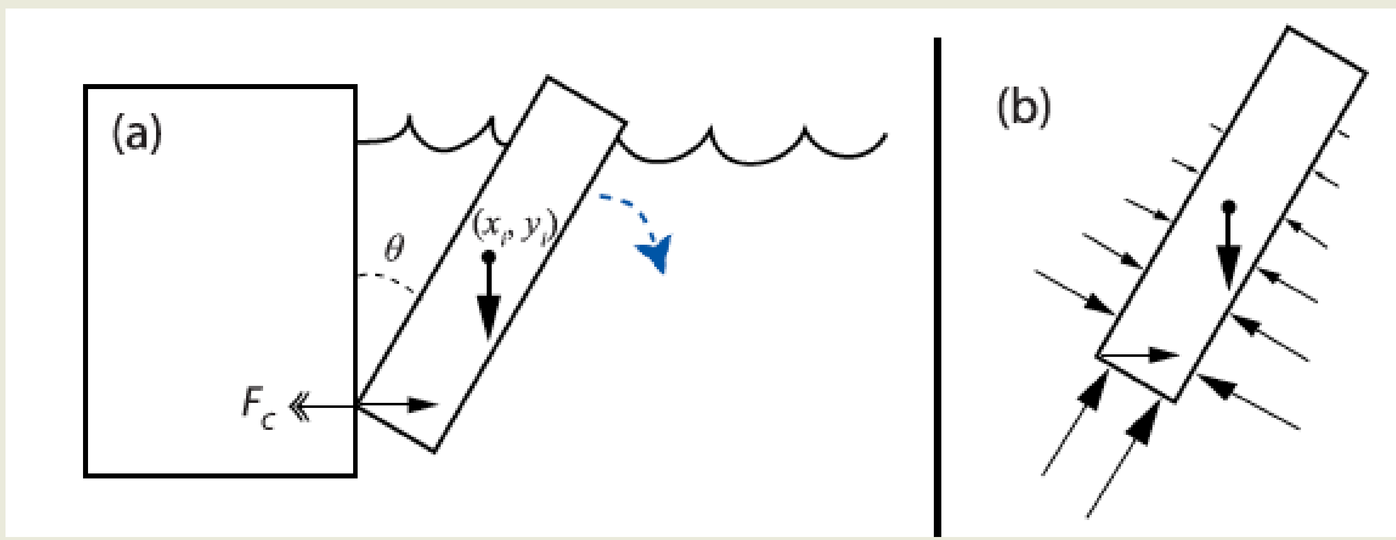
- What forces are relevant?
- How strong and how frequent are these forces?
- How do the forces add (coherently/stochastically)?
- How do the seismic waves propagate to stations?

Predicting Seismic Signals

What (types of) forces are relevant?

- Cavitation: Implosion (point) source
- Iceberg rotation: Contact (point) forces
- Turbulence: Oscillatory (stochastic) eddy motion
- Iceberg scraping: Friction





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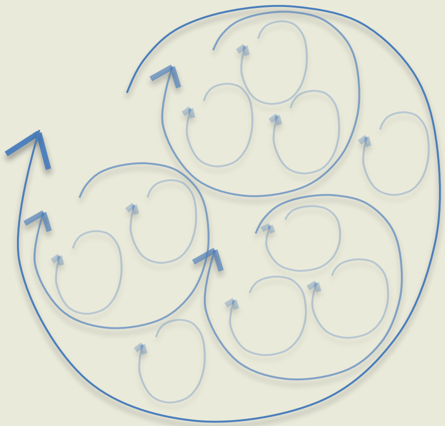
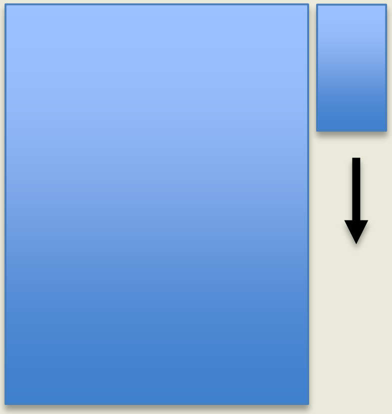
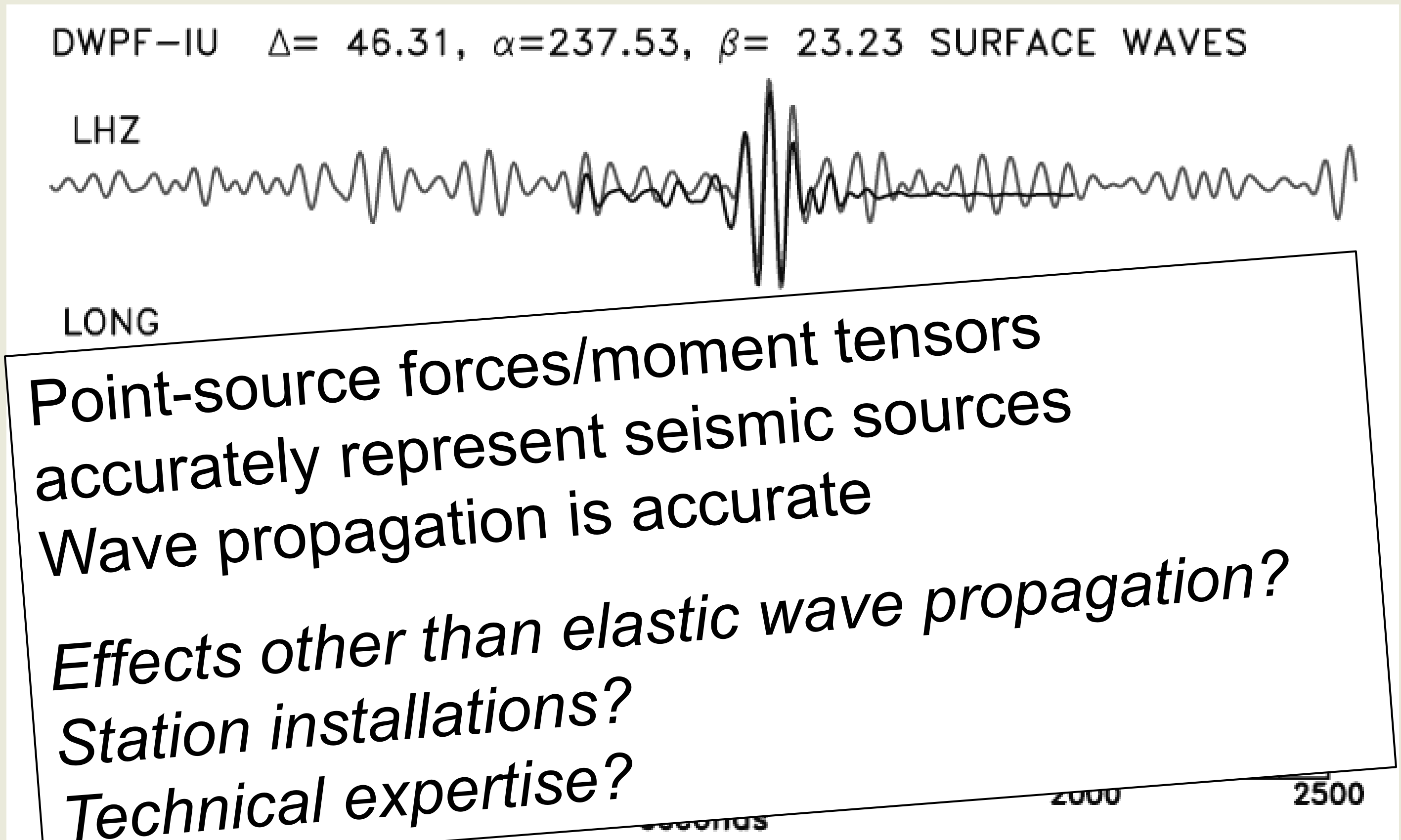




Predicting Seismic Signals

- Isolated forces are ‘easy’ to model
- Low-frequency wave propagation is understood



Point-source forces/moment tensors accurately represent seismic sources
Wave propagation is accurate

Effects other than elastic wave propagation?
Station installations?
Technical expertise?

→ 10^{12} Newtons in 40s

Consistent with rotating iceberg model

Tsai & Ekstrom 2007

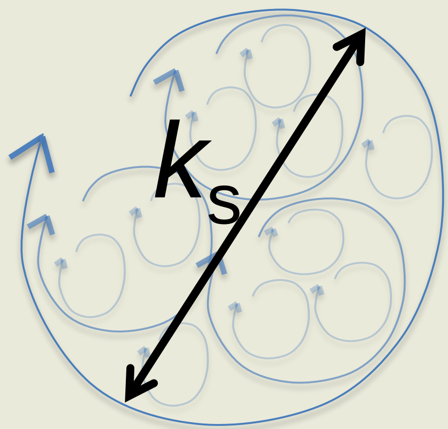
Predicting Seismic Signals

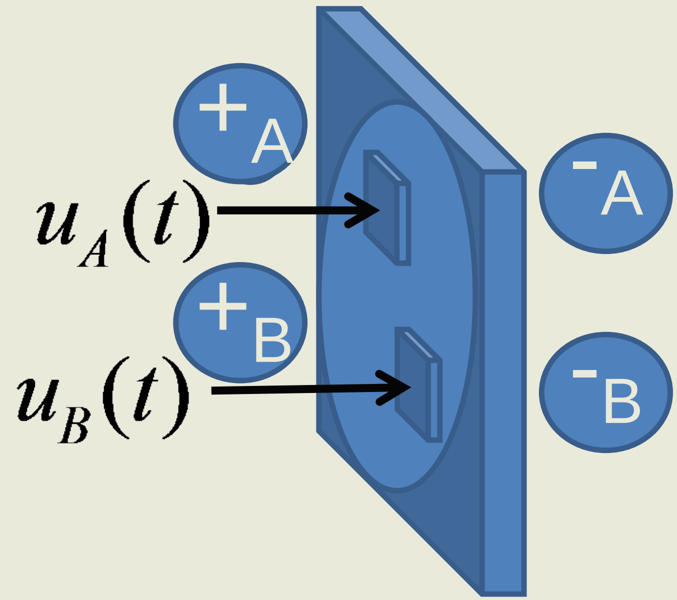
- What about high-frequency stochastic signals?

- Forces add together as $\sqrt{N}$ (Tsai et al. 2012)
- Seismic structure often not well measured
  - Require approximate structure (e.g. Tsai & Atiganyanun 2014)
- Need to understand physics relating features of interest and observable
  - e.g. for turbulence: flow rate → fluctuating eddy forces

Seismic Signal from Turbulent Flow

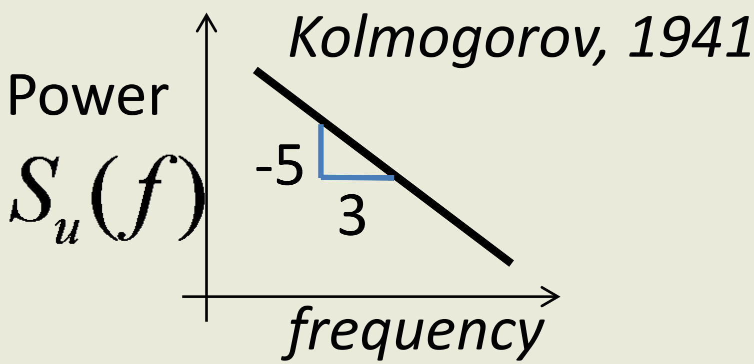
Turbulent Eddies Impinging on Channel Surfaces





$$\frac{d\tilde{F}_i(t)}{dA} = \tilde{C}_i \frac{\rho(\tilde{u}_2^{dA}(t))^2}{2}$$

Frequency scaling



PSD of Forces

$$S^g_{F_i}(f;D) = 4\left(\frac{\bar{F}_i}{\bar{u}_2(x_1^r)}\right)^2 S_u^{x_1^r}(f)\left|\chi_{fl}(f;D)\right|_g^2$$

Gimbert, Tsai & Lamb, *JGR*, 2014

Turbulent Model Prediction

$$P(f) \sim \xi(R/k) \cdot R \cdot u_*^{14/3} \cdot \phi(f)$$

- $P(f)$: Power at the seismic station
- $\xi(R/k)$: Apparent roughness
- R: Radius
- u_*: Shear Velocity
- $\phi(f)$: Frequency Scaling

where $u_* = \sqrt{gRS}$

- R: ~Channel radius
- S: Pressure gradient

Channel radius & pressure gradient control seismic noise amplitude

Gimbert, Tsai & Lamb, *JGR*, 2014

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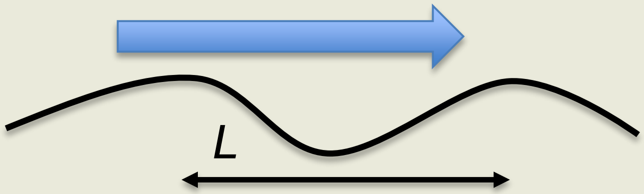
  - ✓ – Predicting seismic signals
  - ? – Implications for mechanics

Classic Glaciological Background

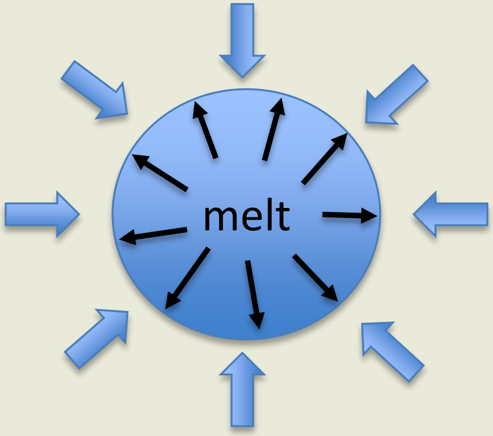
- Weertman sliding (1957)
  - Ice deformation & regelation around bed obstacles causes basal velocities
- Rothlisberger channels (1972)
  - Steady state channels exist balancing creep & turbulent frictional melt in subglacial channels
- Linked cavities (Kamb, 1987)
  - Cavities & channels can have very different pressures
- Crevasses and fracture (Weertman, 1973)
  - Fracture mechanics predicts crevasse lengths, water-filled crevasses grow unstably

Classic Glaciological Background

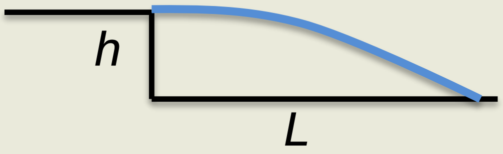
- Weertman sliding (1957)
  - $u_b = \frac{1}{c}\tau_b^m L^{1+n}, m \approx \frac{1+n}{2} \approx 2$



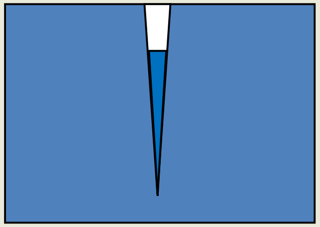
- Rothlisberger channels (1972)
  - $\frac{dp_w}{dx} = cQ^{-2/11}(p - p_w)^{8n/11}$



- Linked cavities (Kamb, 1987)
  - $L^2 = \frac{hu_b}{c(p-p_w)^n}$



- Crevasses and fracture (Weertman, 1973)
  - $\mathrm{H} = \frac{\pi\sigma_{xx}}{2\rho g}$



What Use is Seismology?

- If you can’t identify why it’s useful, it may not be worth spending a lot of time on…

- Subglacial hydrology can be observed?
  - Implications for sliding dynamics (not understood?)
- Subglacial deformation can be observed?
  - Implications for sliding dynamics (not understood?)
- Calving style can be observed?
  - Implications for calving mechanics (not understood?)
- Can measure incipient growing rifts?

How does *subglacial* hydrology affect sliding?

- What do you think?
- Vast majority of glaciologists misunderstand how hydrology affects sliding (for Antarctica/Greenland)
- Commonly assumed $u_b = \frac{\tau_b^m}{(p-p_w)^q}$ for no apparent mechanical reason!

- (Hard bed cavities have high stresses on contacts)
- See Tsai et al. 2015 reading

How is calving style affected by processes?

- There does not exist a satisfactory theory that explains ***any*** type of calving in a predictive way!
- Tensile stress, fracture, & water important… but how to relate quantitatively?

- Small-block subaerial calving
- Ice shelf rifting
- Iceberg size? Calving time?

- Challenge to use knowledge of style if this understanding is lacking

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