Emergence of tidewater and ice shelf calving dynamics using a granular model of ice

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Observations show

Floating termini (ice shelves and ice tongues):
1) Normal mode of calving is large tabular bergs that detach from rifts
2) Explosive disintegration is possible if the ice is sufficiently fractured

Grounded termini (ice shelves and ice tongues):
1) Normal mode of calving is ice-thickness sized bergs
2) Calving rate is (often) correlated with water depth
Can calving style be explained by a simple model?

1) Geometry:
   Ice thickness (H) & water depth (D) determines the stress field

2) Yield strength of ice:
   Normal and shear yield strength determines when the ice breaks

3) Density of pre-existing fractures
   Stress history of ice, surface melt pond assisted fracturing, englacial fracture networks determines how fractured the ice near the terminus is

![Disintegration](image1)
![Rifting](image2)
![Tidewater Calving](image3)
Conceptual Model of Ice: Molecular Dynamics

Atom: from Greek meaning uncuttable or indivisible
Molecule: Atoms held together by bonds

“Atoms” of ice are spherical boulders of ice 50 m in radius
“Molecules” are boulders of ice glued together by bonds with finite strength

continuous spectrum of behavior discrete
bonds have normal and shear strength
Conceptual Model of Ice: Molecular Dynamics

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**Spheres of ice interact through:** (1) elasticity, (2) friction, (3) bond forces

continuous (all bonds intact)  \[\rightarrow\]  spectrum of behavior \[\rightarrow\]  discrete (all bonds broken)

<table>
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<tr>
<th>bonds have normal and shear strength</th>
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music of the spheres?
Shear failure is important for thick, land terminating glaciers

H ~ 660 m

Bond strength: 150 kPa (normal), 1 GPa (shear)

(note the large crevasse ~ one ice thickness from the front)

H ~ 660 m

Bond strength: 150 kPa (normal), 10 GPa (shear)
Shear failure is important for thick, land terminating glaciers

Bond strength: 150 kPa (normal), 1 GPa (shear)

H ~ 660 m (note the large crevasse ~ one ice thickness from the front)

Bond strength: 150 kPa (normal), 10 GPa (shear)

(1) Increasing ice thickness decreases stability
(2) Increasing shear strength increases stability
(3) Insensitive to tensile yield strength
Just add water . . .

D ~ 100 m

D ~ 200 m

D ~ 300 m

QuickTime™ and a H.264 decompressor are needed to see this picture.
Just add water . . .

D ~ 100 m

D ~ 200 m

D ~ 300 m
Just add water . . .

But when the ice is already fractured . . .

30% of bonds broken

D ~ 500 m

Height-above-buoyancy calving is related to the transport of broken ice away from the terminus.

QuickTime™ and an H.264 decompressor are needed to see this picture.
Stable ice shelves are possible if the ice is intact

H ~ 350 m
Bond strength : 150 kPa (normal), 1 GPa (shear)
Percent of bonds broken: 0%
Transition from intact to rifting as fracture density increases

H ~ 350 m
Bond strength : 150 kPa (normal), 1 GPa (shear)

Percent of bonds broken: 0%

Percent of bonds broken: 40%
Eventually ice shelf becomes unstable and disintegrates

H ~ 350 m
Bond strength: 150 kPa (normal), 1 GPa (shear)

Percent of bonds broken: 0%  Time 0.0, mu 0.4, prob=0.3

Percent of bonds broken: 40%  Time 7196.8, mu 0.4, prob=0.4

Percent of bonds broken: 60%
Eventually ice shelf becomes unstable and disintegrates

H ~ 350 m
Bond strength: 150 kPa (normal), 1 GPa (shear)

Percent of bonds broken: 0%
Time 0.0, μ = 0.4, prob = 0.3

Percent of bonds broken: 40%
Time 7196.8, μ = 0.4, prob = 0.4

Percent of bonds broken: 80%
Transition to Disintegration

Increasing Ice Thickness

Intact → Rifting → Collapse

Increasing Fracture Density
Mode of calving determined by interplay between 3 variables

1) Geometry: specified for a given glacier
   Ice thickness & water depth determines the stress field

2) Yield strength of ice: determined from laboratory measurements
   Normal and shear yield strength determines when the ice breaks

3) Density of pre-existing fractures
   Stress history of ice, surface melt pond assisted fracturing, englacial fracture networks determines how fractured the ice near the terminus is

specified for a given glacier

provides upper and lower bounds on advance/retreat magnitude

tidewater water depth calving law