Some mechanical properties for ice Ih

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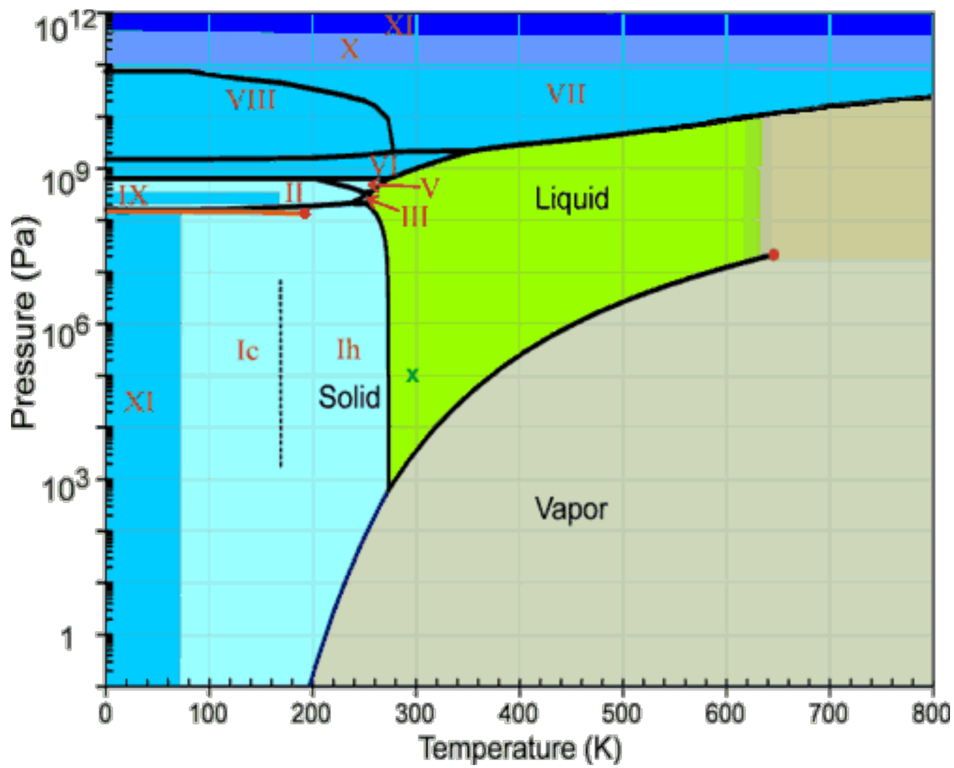
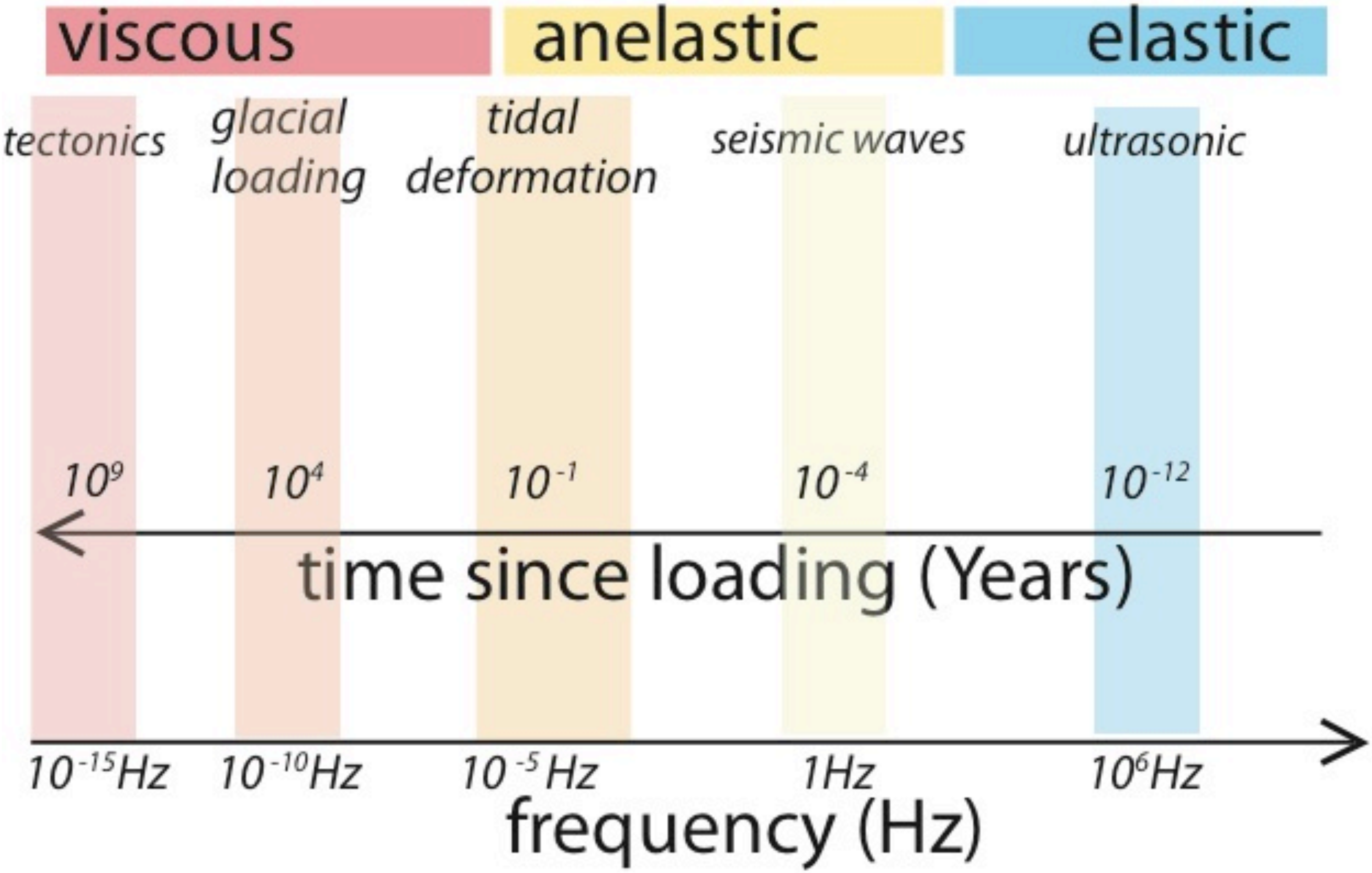


Mechanical response depends on timescale of loading



Elastic properties

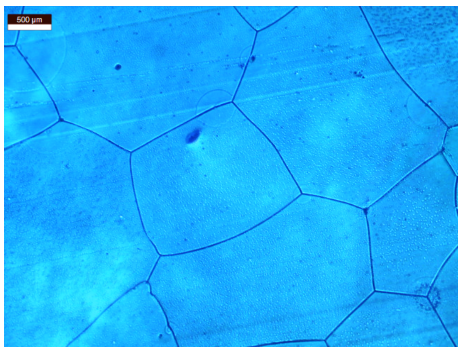
TABLE 4.1

Values for the Young's modulus Y, rigidity modulus G, Poisson's ratio γ, and bulk modulus K for polycrystalline ice at −5°C obtained by sonic techniques

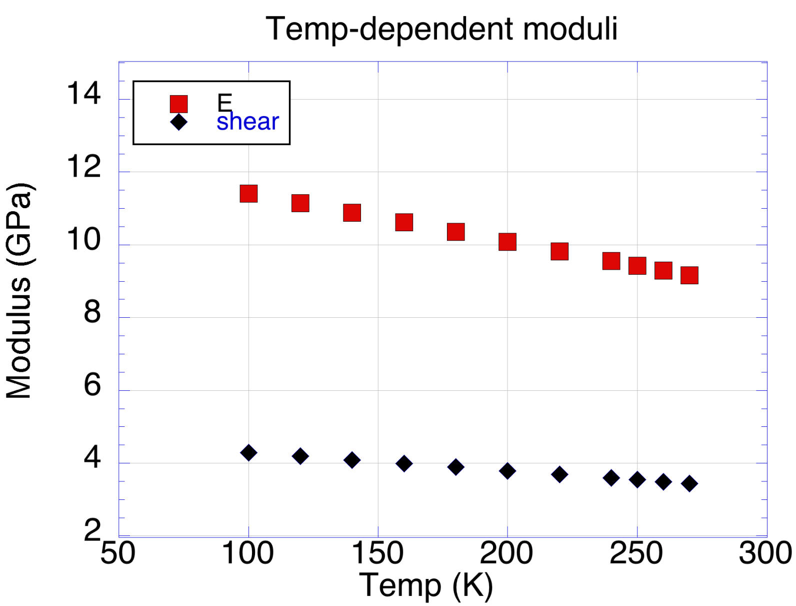
GPa=

Y (in units of 10^4 bar)	G (in units of 10^4 bar)	γ	K (in units of 10^4 bar)	Reference
8·95	—	—	—	Boyle and Sproule (1931)
9·17	3·36†	0·365	11·3†	Ewing *et al.* (1934)
9·80	3·68†	0·33	9·61†	Northwood (1947)
9·18–9·38	3·45–3·52†	0·33	8·81–8·92†	Jona and Scherrer (1952)
9·94	3·80	0·31	8·72†	Gold (1958)
8·69	—	—	—	Nakaya (1959a)

† Calculated from eqns (4.5 and 4.6).



Hobbs (1974)



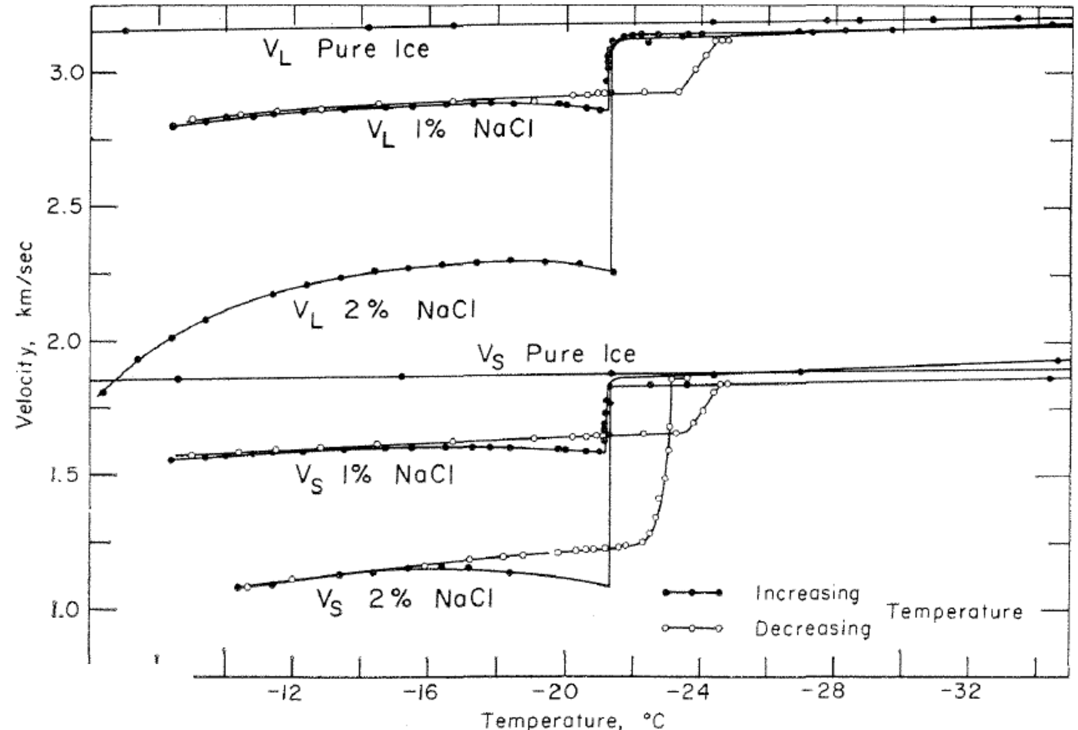
There is a modest temp-dependence for elastic response. What else affects unrelaxed modulus?

Porosity ↓ (poroelastic effects well-known)

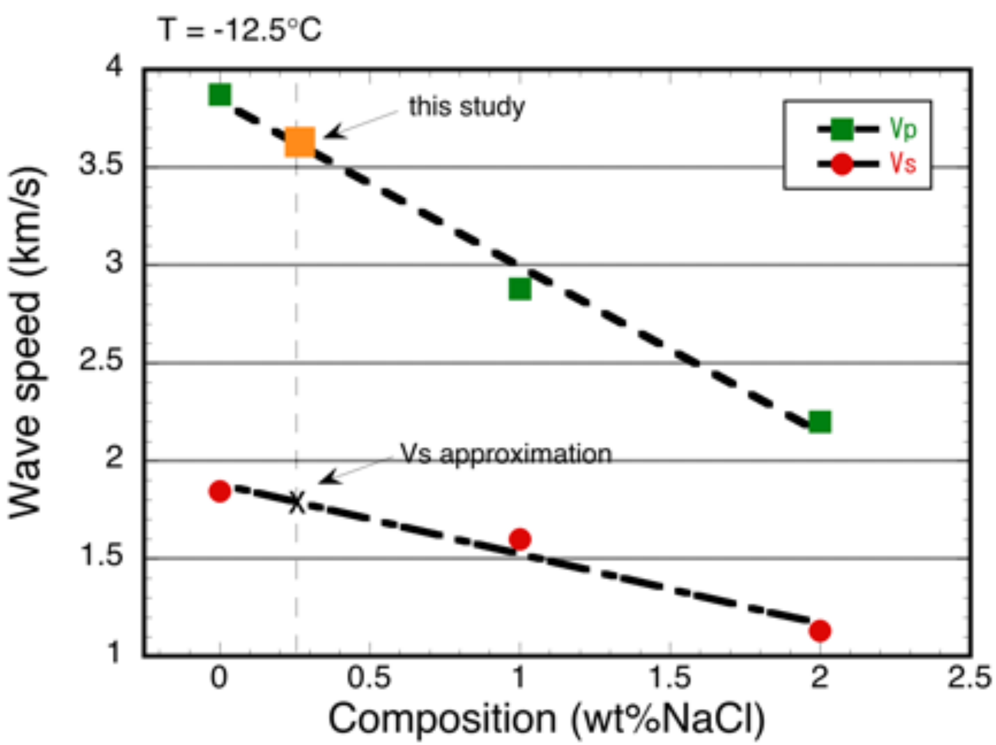
Grain size (No effect on elastic properties)

Modulus with impurities?

Greatly reduced if melt (above T_E)
Similar if subsolidus



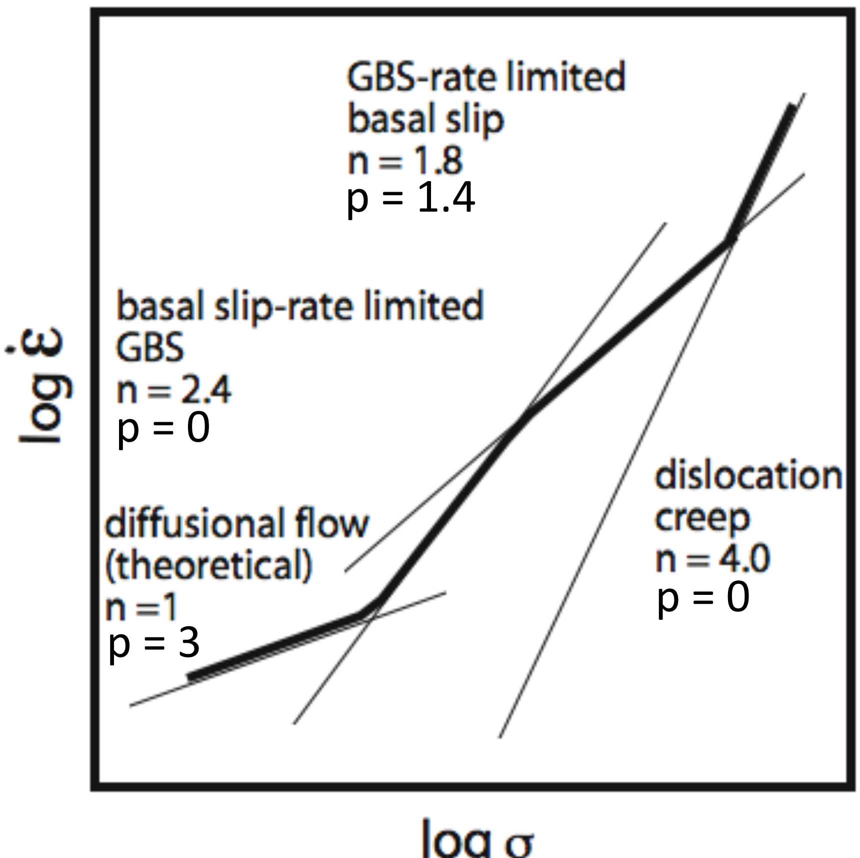
[Spetzler and Anderson, 1968]



Can calculate modulus from Vp and Vs (P and S wave speeds)

$$E = \frac{\rho V_S^2 (3V_P^2 - 4V_S^2)}{V_P^2 - V_S^2}$$

Flow law



[Goldsby and Kohlstedt, 2001]

Viscosity of ice is well known. An empirical flow law relates stress to strainrate:

$$\dot{\varepsilon}_{ss} = A\frac{\sigma^n}{d^p}\exp\left(-\frac{U}{RT}\right)$$

Where n is the stress exponent, p is the grain size, U is activation energy, R is the gas constant and T is temperature.

Static grain growth

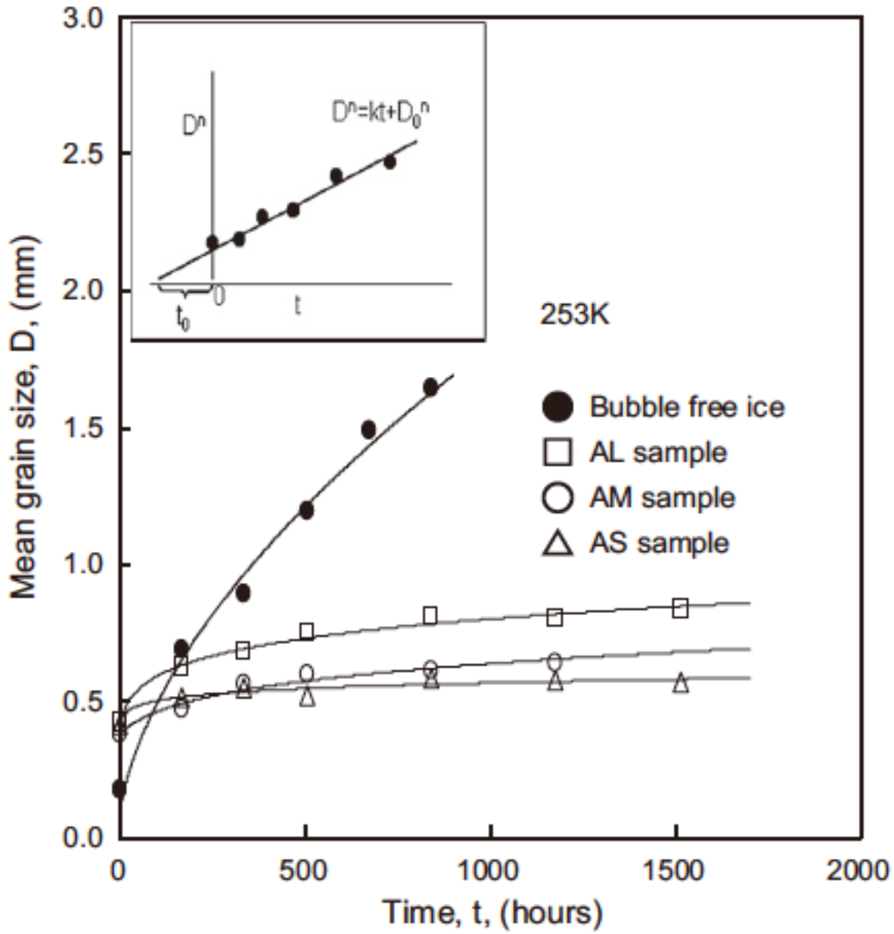


Fig. 3. Grain growth curves of ice samples at 253 K. In the inset figure, t_0 indicates the hypothetical incubation time, which is defined in Eqs. (2) and (3) in the text.

[Azuma et al., 2012]

Static grain growth depends on initial grain size, temperature and grain boundary mobility, which is influenced by bubbles and insoluble impurities (through "k")

$$D^n - D_0^n = kt,$$

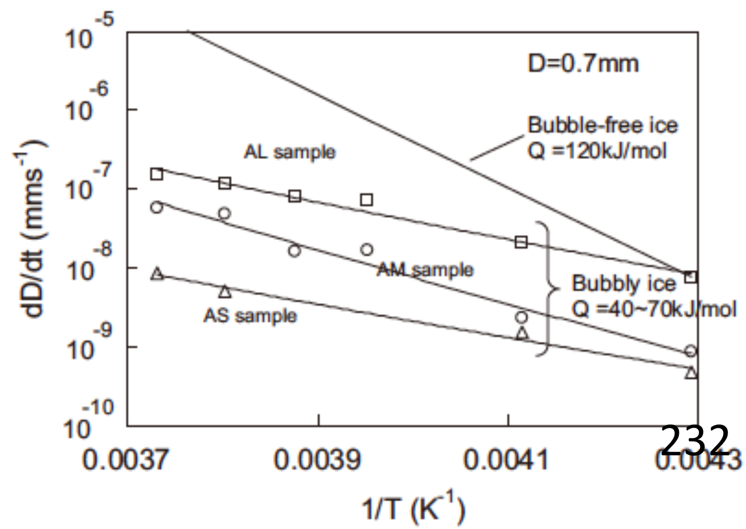


Fig. 9. Temperature dependence of grain growth rates of ice with bubbles and bubble-free ice at $D = 0.7$ mm. The activation energy for grain growth of samples with bubbles (40–70 kJ mol^{-1}) is similar to the apparent activation energy (50 kJ mol^{-1}) calculated from the temperature dependence of air bubble migration in ice. These results suggest that the slow grain boundary migration of ice with bubbles is controlled by the migration velocity of air bubbles in ice.

Grain/subgrain size piezometer for deforming materials [see Jacka and Li for ice-specific piezometer]

Twiss [1977] applied energy balance between grain/subgrain and free dislocations

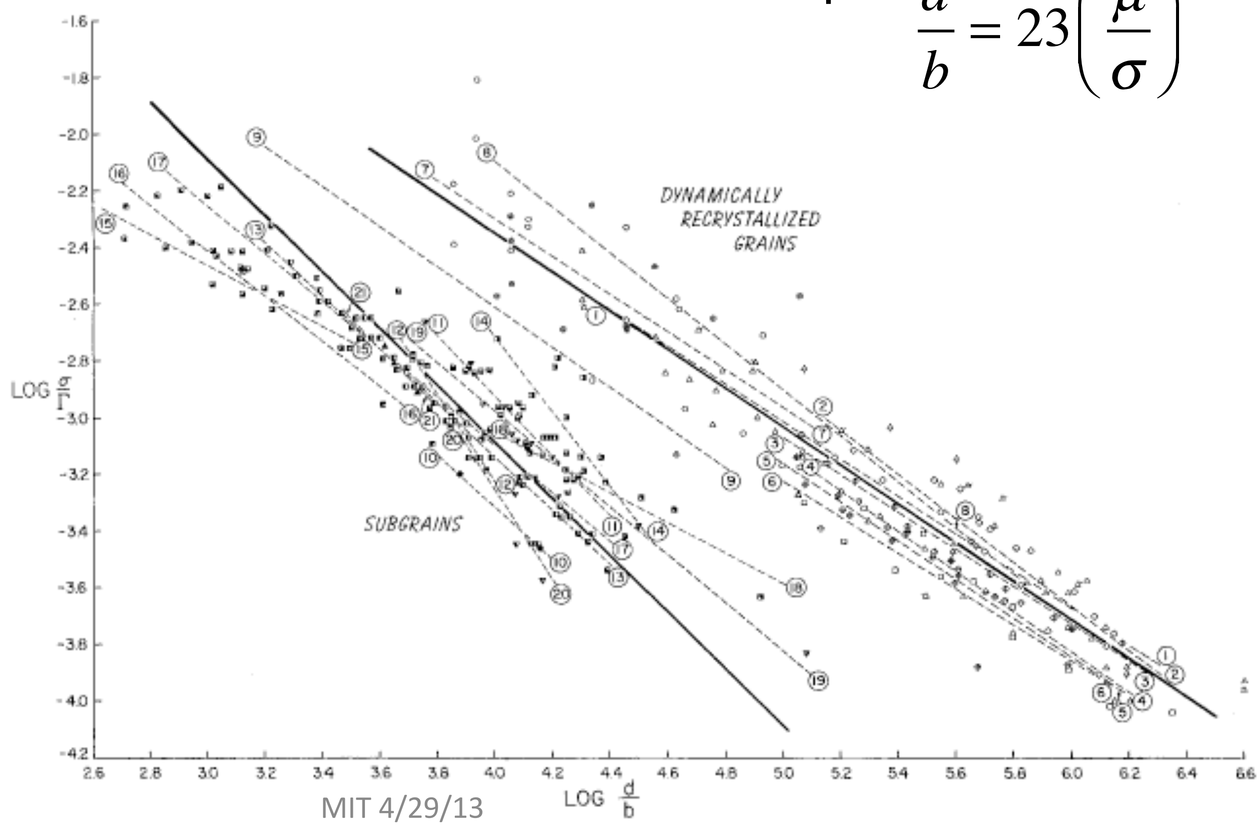
$$\frac{d}{b} = K\left(\frac{\Gamma}{\sigma}\right)^{p}$$

- σ is stress
- $\Gamma = \mu/(1-\nu)$
- μ is shear modulus
- ν is Poisson ration
- d is subgrain size
- b is burgers vector
- K and p are constants

(assumes all dislocations are edge, all boundaries are simple tilt, and crystals are elastically isotropic)

Raj&Pharr [1986] looked at many materials to determine K and p

$$\frac{d}{b} = 23\left(\frac{\mu}{\sigma}\right)^{1}$$

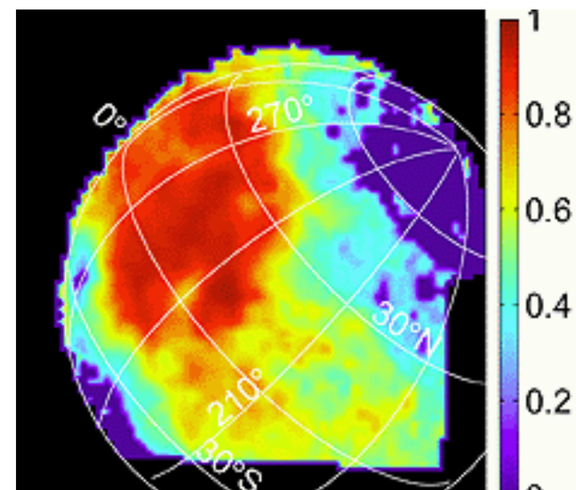


What's the non-ice stuff?

Some non-ice candidates:

- $Na_2SO_4 \cdot nH_20$
- $MgSO_4 \cdot nH_20$
- $Na_2CO_3 \cdot nH20$
- $H_2SO_4 \cdot nH20$
- $NaCl \cdot 2H_20$

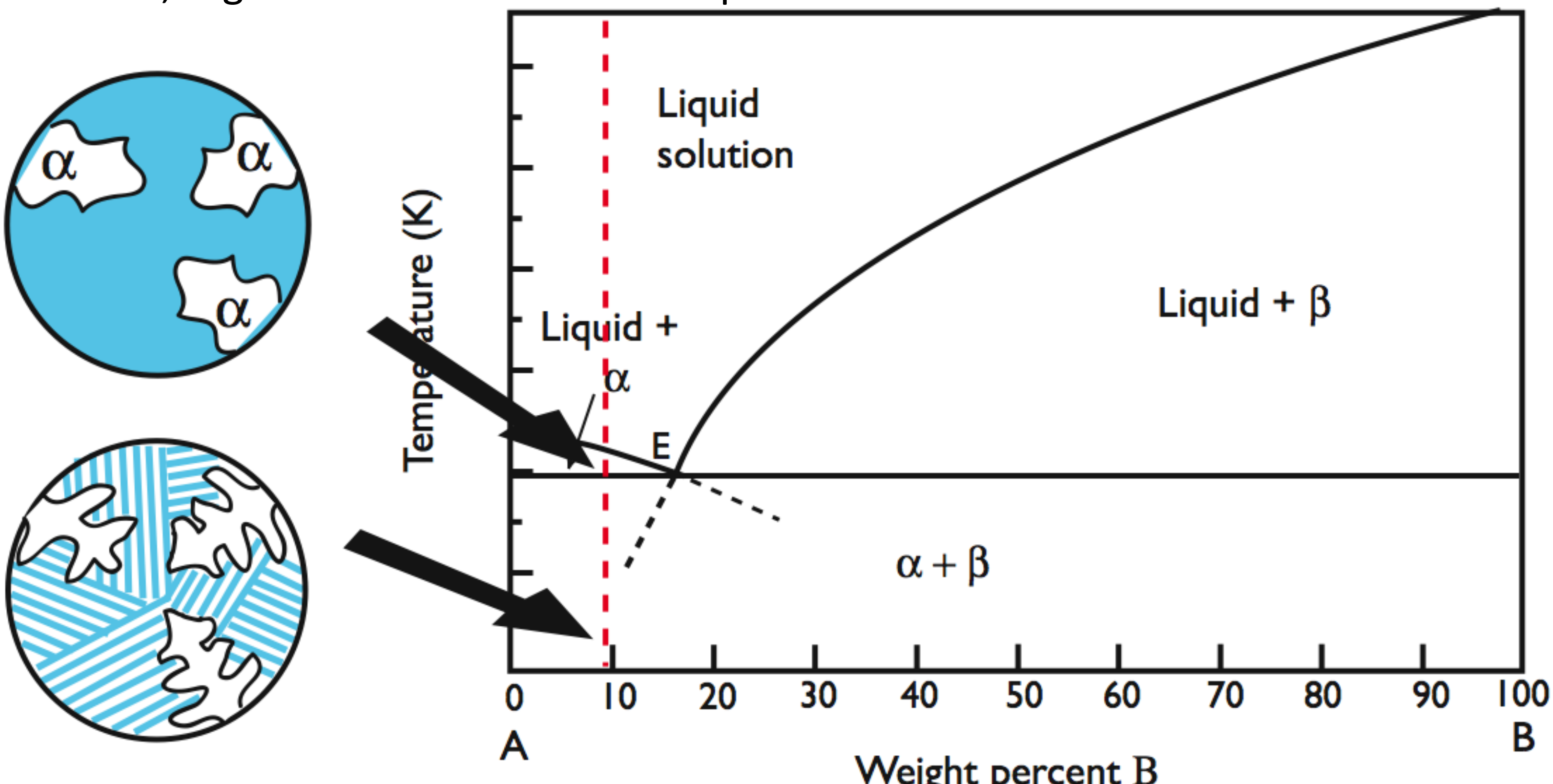
Near-Infrared Spectra indicates ice (blue) and non-ice, hydrated material (red) are on the surface



(from McCord and others, 1998, *Science*)

How does non-ice stuff affect the microstructure?

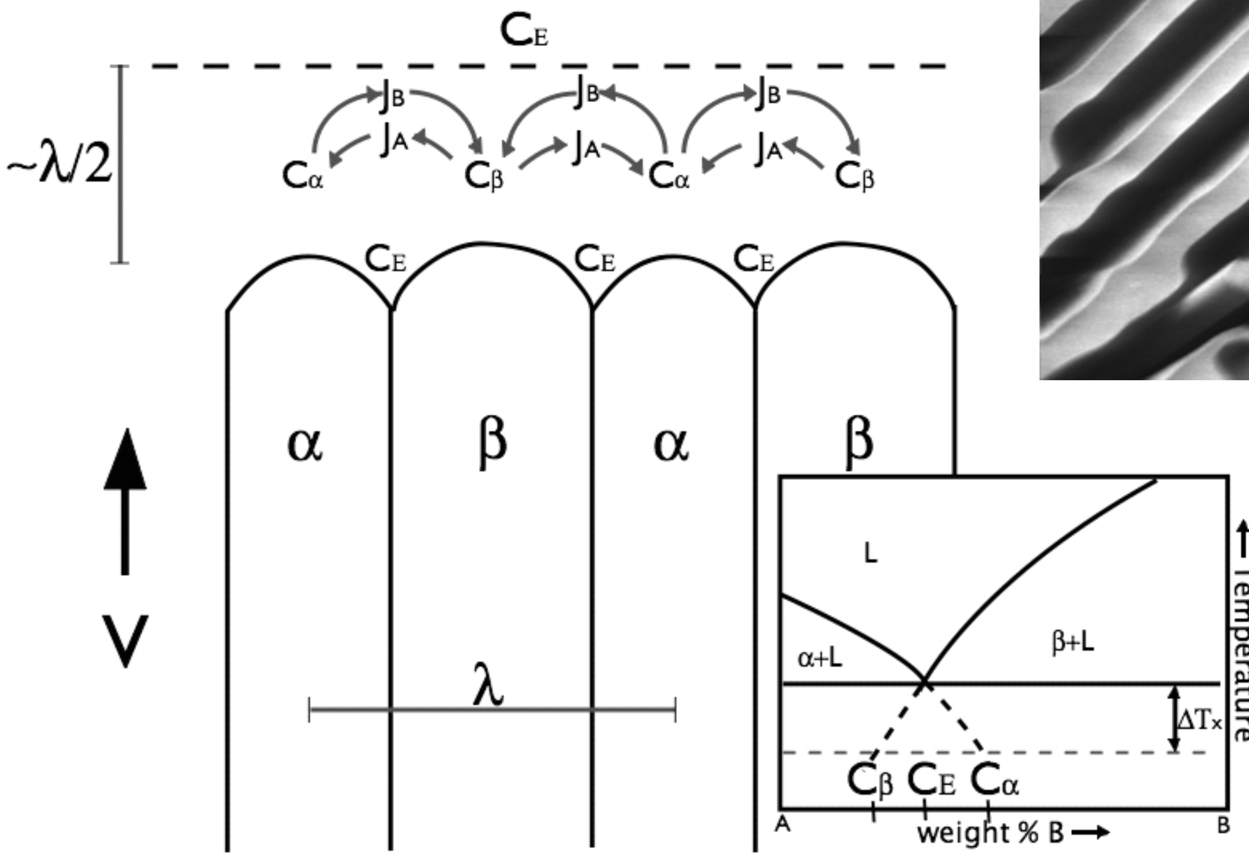
Do not picture a bunch of salt with specks of pepper. These are all soluble, so if it was ever liquid and froze, it will have eutectic microstructure. Composition of first melt will be eutectic, regardless of initial bulk comp.

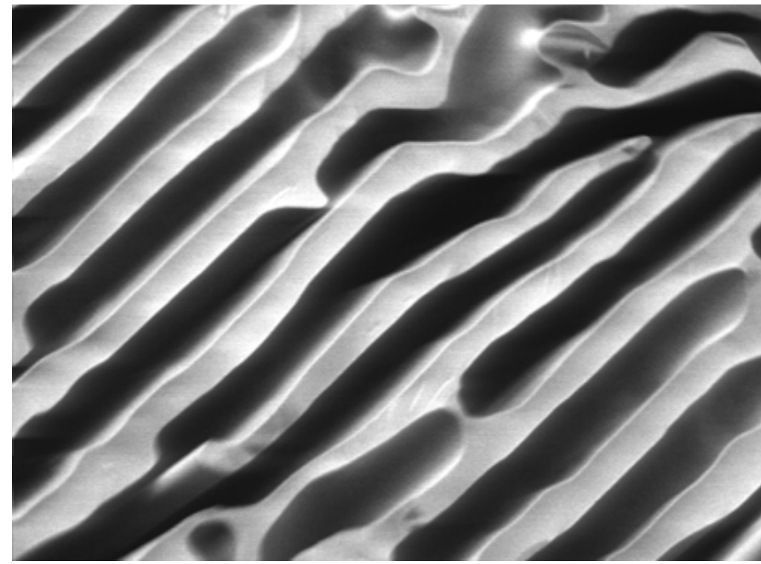


All candidate salts/acids form “simple binaries” with ice

Scale depends on ΔT during solidification

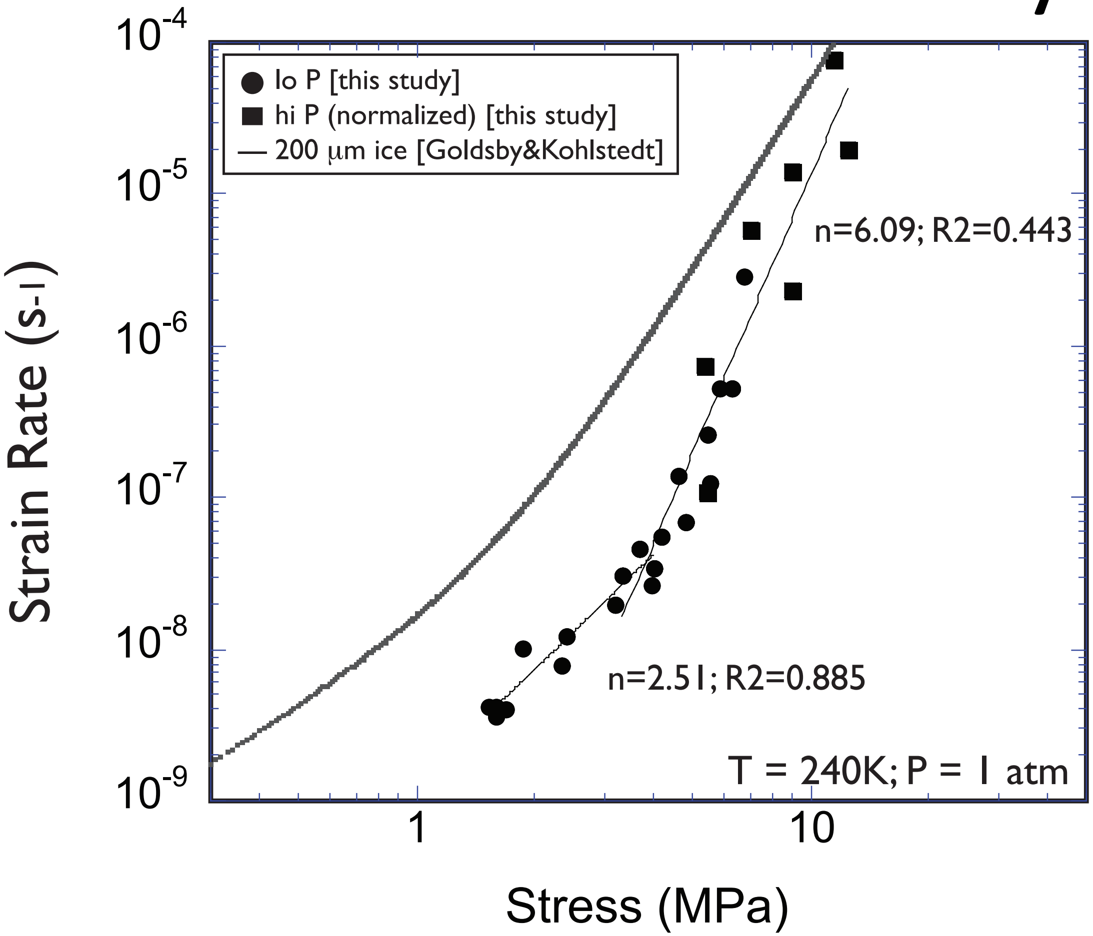
Two phases grow side-by-side into the liquid with velocity, V

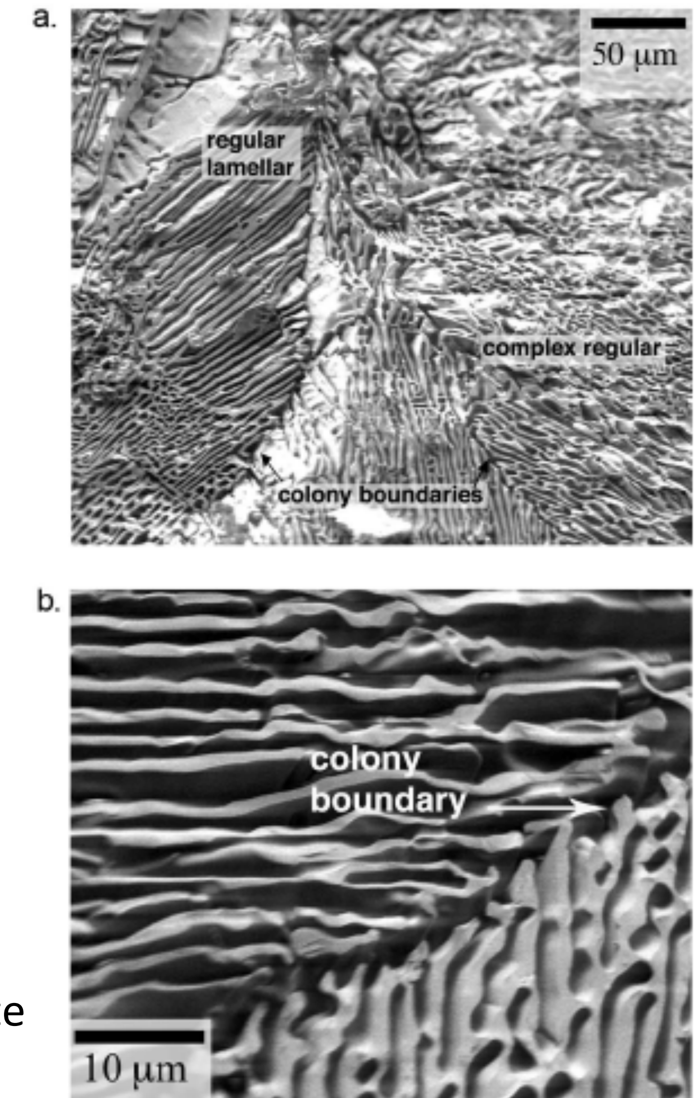




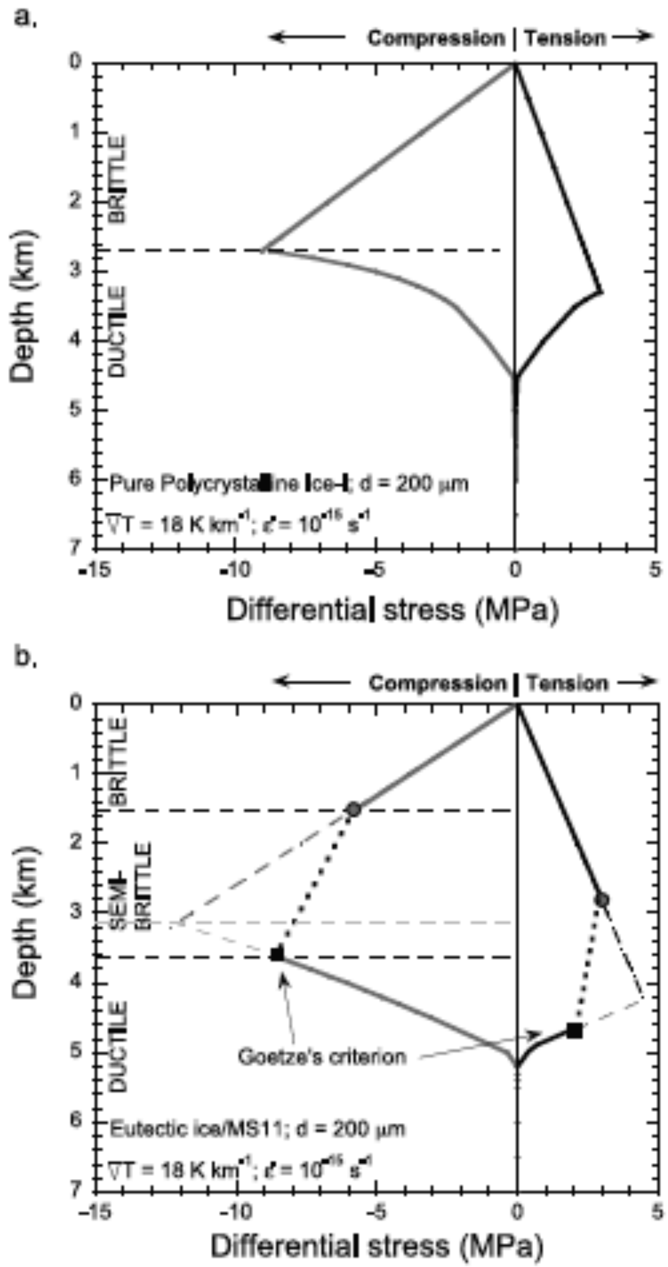
Classical lamellar eutectic

How does non-ice stuff affect the viscosity?





In McCarthy et al, 2011, I found that ice+magnesium sulfate had higher viscosity (at low stress) but weaker (lower fracture toughness?) at high stress.



The salts are more brittle at conditions where ice is still ductile, which means the eutectic displays semi-brittle behavior (as well as lower melting temperature and once even at partial melt a lower modulus)

Where might you find eutectic material? Anywhere you had melting and refreezing.