Peering into deep blue ice: achievements and challenges

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Acknowledgements

- Japanese Antarctic Research Expedition (1998-)
- US Antarctic Programs (2002-)
- Belgian Antarctic Research Expedition (2008-)
- Norwegian Antarctic Research Expedition (2011-)

- Charlie Raymond, University of Washington
- Shuji Fujita, National Institute of Polar Research
- Frank Pattyn, Univ. Libre de Bruxelles
- Joe MacGregor, Univ. Texas

Contents

- Introduction
- Effects of ice properties on radio-wave propagation
  - Alighments of ice crystals (crystal-orientation fabrics)
  - Ice temperature and chemistry
- Deep ice
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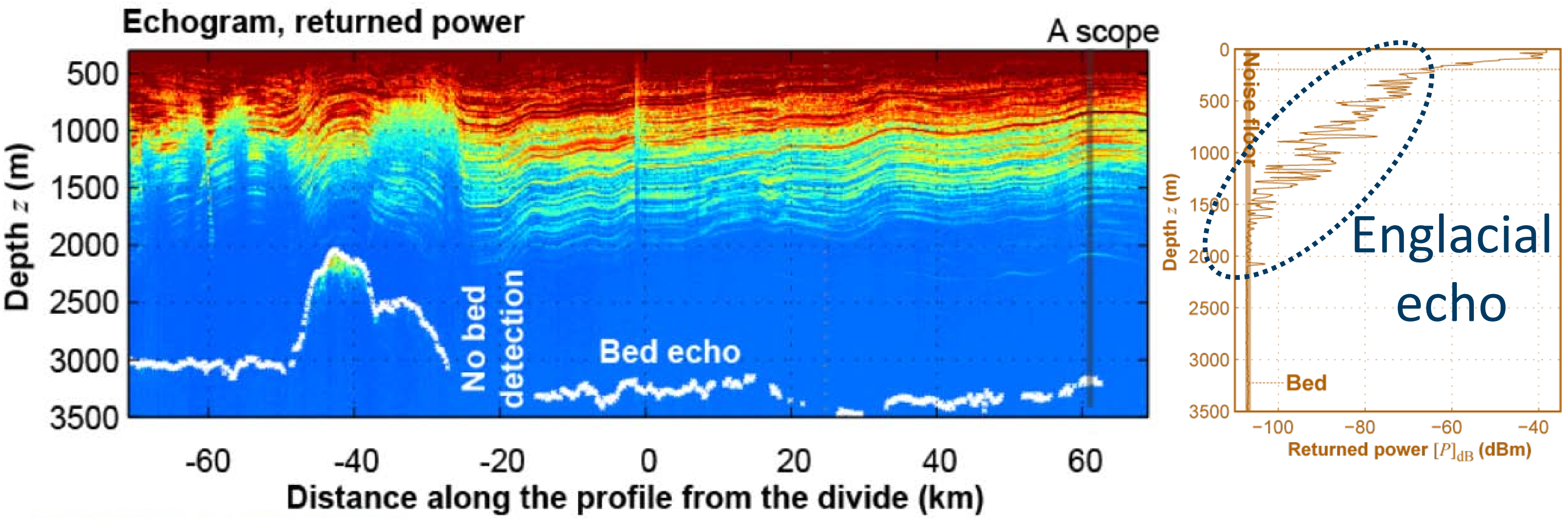
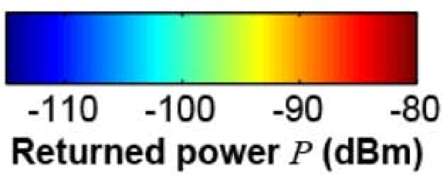
Radar data



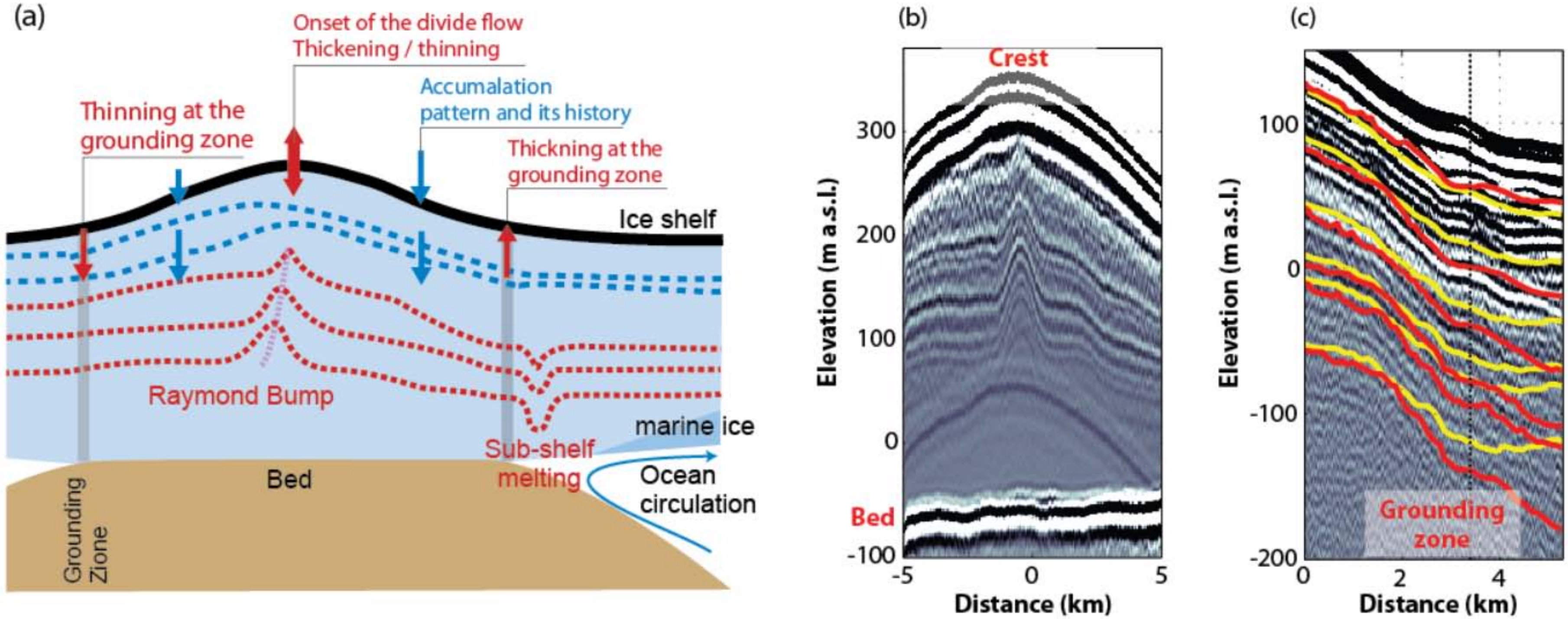


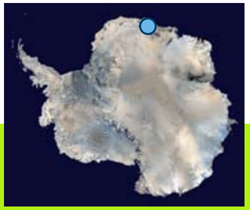
Phase of the radar signals has been used only for the beam focusing (SAR), but not yet for glaciological purposes.

Matsuoka, Morse and Raymond (2010) *JGR Earth Surface*

Radar reflectors ~= isochrones

Histries of surface accumulation, subglacial melting and ice flow





Pattyn, Matsuoka et al. (in review)

Wave propagation within ice

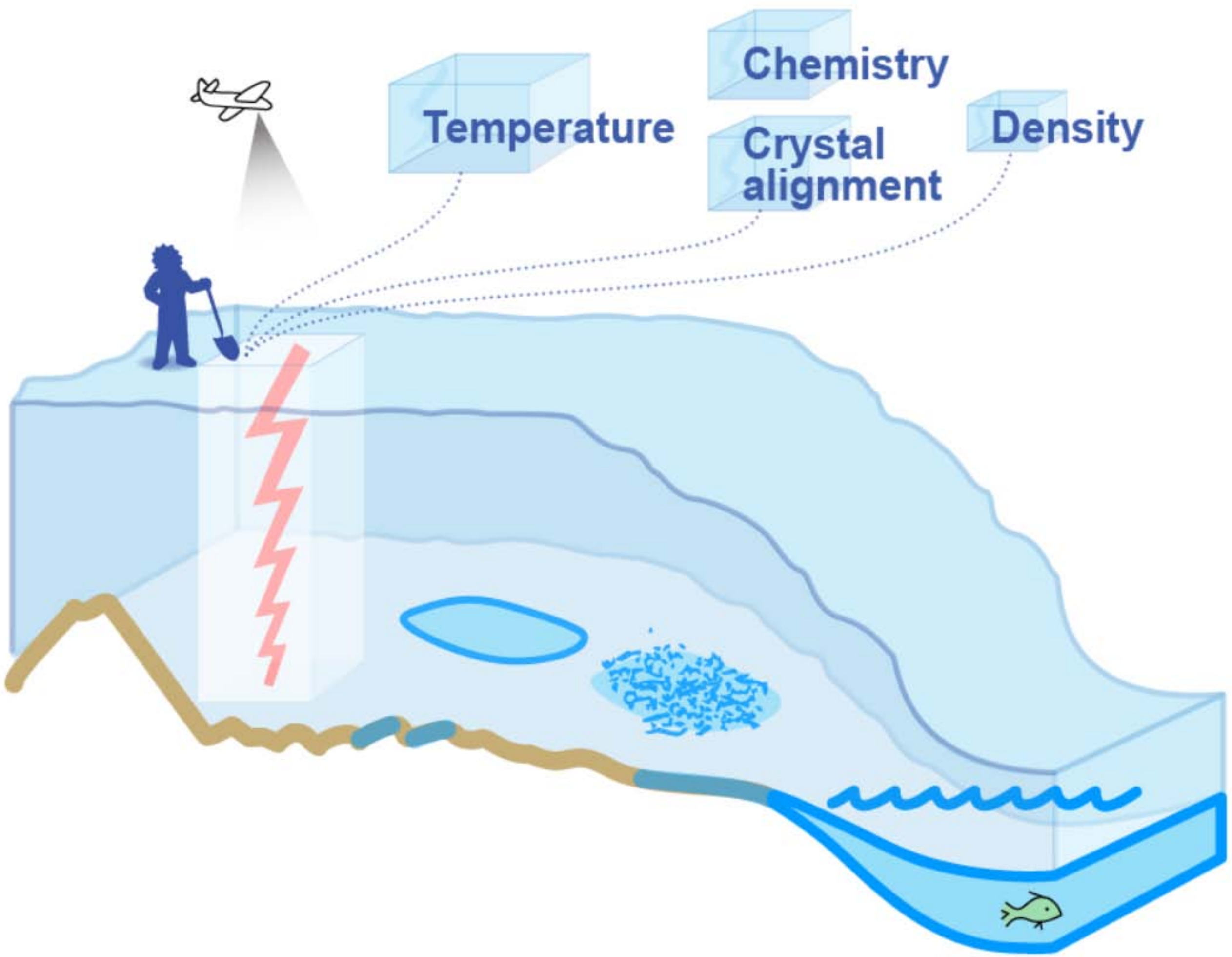


Illustration: Beth Tully (UW Edit-design Center)

Radar returned power (theory)

$$[P]_{\mathrm{dB}} = [S]_{\mathrm{dB}} - [G]_{\mathrm{dB}} + [I]_{\mathrm{dB}}$$

When S is stable, geometrically corrected returned power P^{c} is

$$\left[P^{\mathrm{c}}\right]_{\mathrm{dB}} \approx [P]_{\mathrm{dB}} + [G]_{\mathrm{dB}} \approx [I]_{\mathrm{dB}}$$

$$[I]_{\mathrm{dB}} = [B]_{\mathrm{dB}} + [R]_{\mathrm{dB}} - [L]_{\mathrm{dB}}$$

S: Instrumental factors

G: Geometric factor

I: Ice properties

B: Signal reduction due to ice-fabric-induced birefringence

R: Reflectivity

L: Attenuation

B and R: frequency/polarization dependent
L: frequency/polarization independent

e.g. Matsuoka (2011) *GRL*

Dielectric anisotropy of single crystal

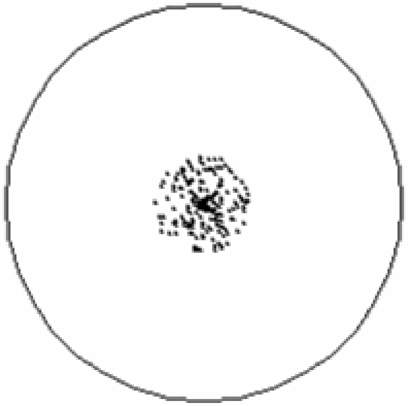
- Permittivity ε
  - 1.07% anisotropy $\varepsilon_{\parallel c} = 1.0107\varepsilon_{\perp c}$
  - Anisotropy is uniform over radio/microwave frequencies and terrestrial temperature range
- Conductivity σ
  - Insignificant anisotropy

Fujita et al. (2000) in Physics of Ice Core Records

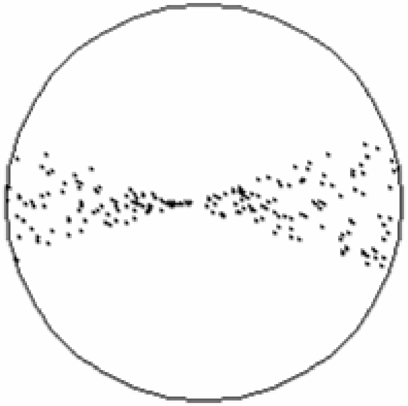
Alignments of ice crystals

Schmidt-net projection of ice fabric patterns

Vertical single-pole fabric



Vertical girdle fabric



Ice core vs. ice sheet

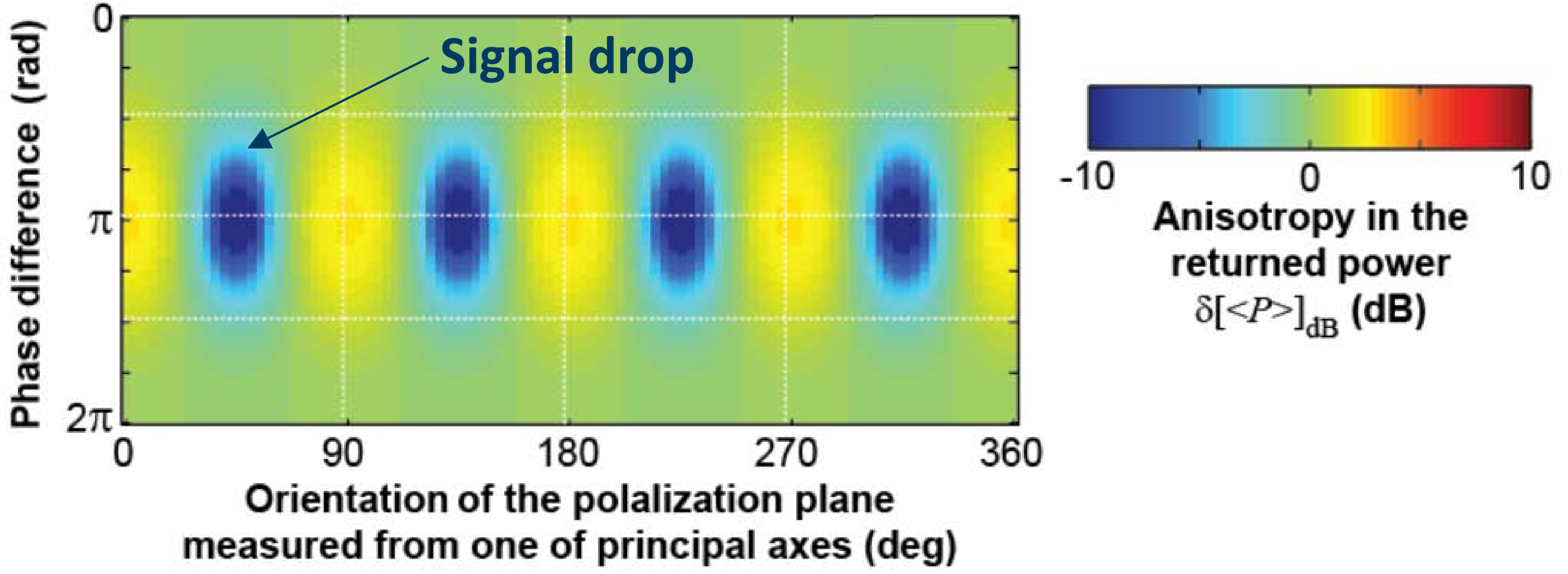
- Optical research of thin sections ($z = 10^{-3}$ m) / ($\lambda = 10^{-7}$ m)
- Radar research of the ice sheet ($z = 10^{3}$ m) / ($\lambda = 10^{0}$ m)

Signal drops due to birefringence

Phase difference $\phi = 2\pi z \sqrt{\Delta\varepsilon}/\lambda$

Anisotropy $\sqrt{\Delta\varepsilon} = \left(\varepsilon_{\parallel c} - \varepsilon_{\perp c}\right)\Delta C$

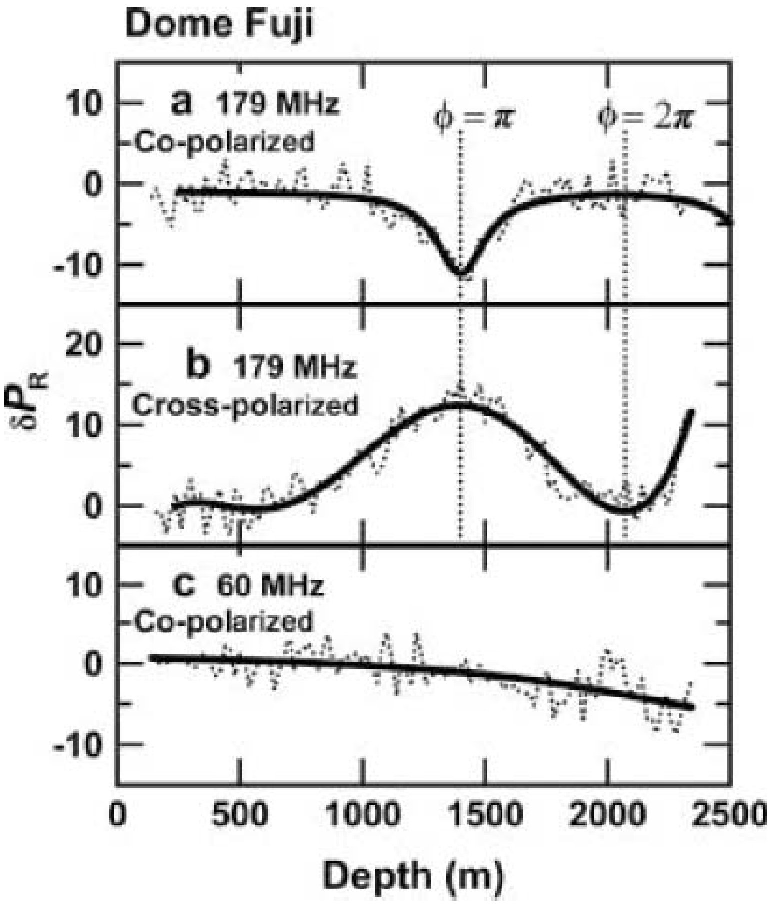
ΔC: fabric anisotropy in the plane right to the propagation axis



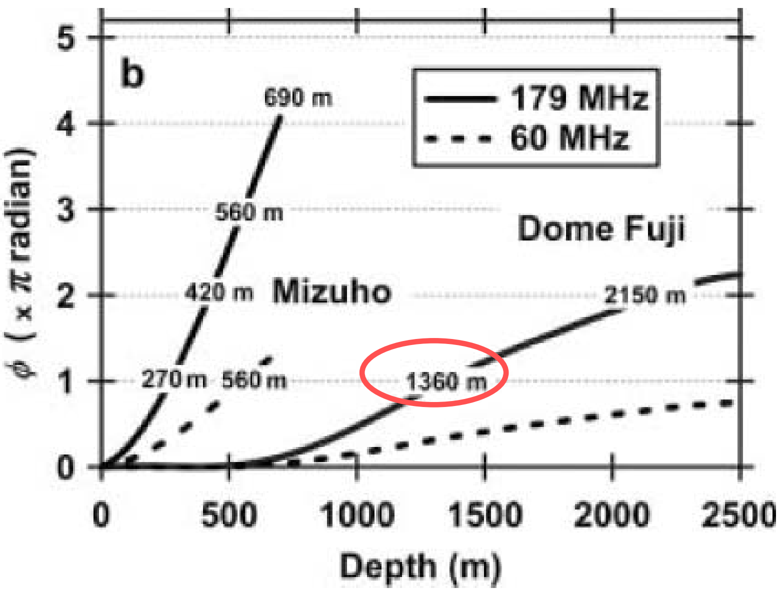
e.g. Hargreaves (1977) *J. Phys. D*

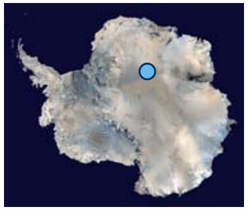
Signal-drop depths (radar vs. Ice core)

Radar data



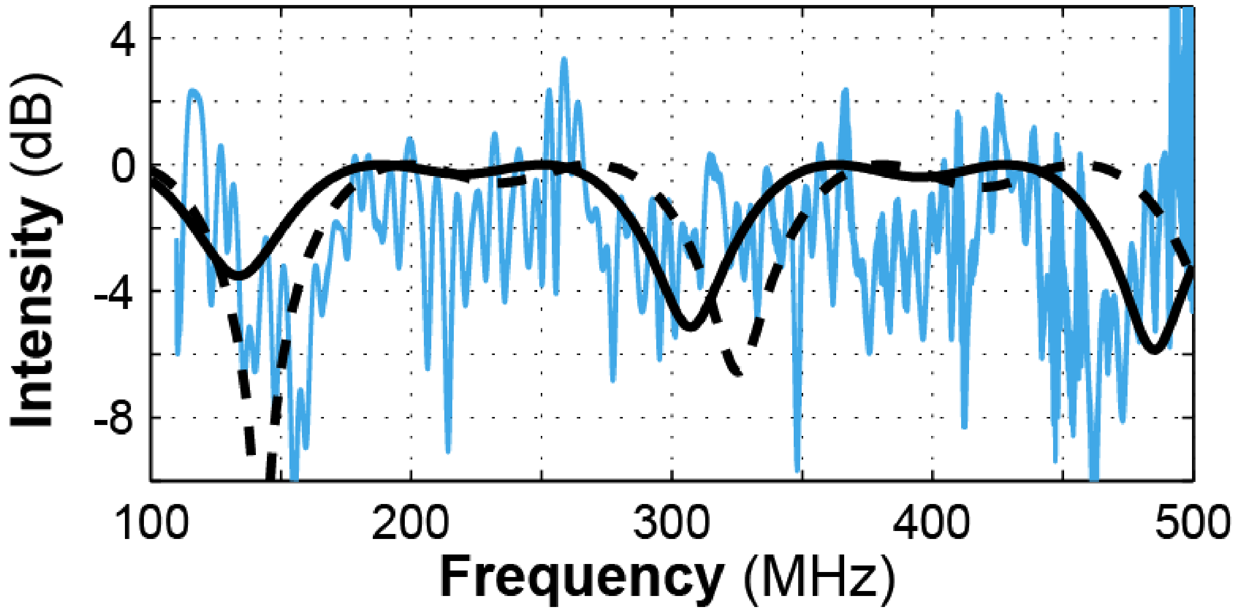
Estimates with ice cores





Fujita, Maeno and Matsuoka (2006) *J. Glaciol.*

Frequency dependence of bed-returned power (Greenland)



Blue curve: CReSIS, Univ. Kansas

Bed returned power measured with a bistatic configuration

Black curves: Estimates using the ice-core data

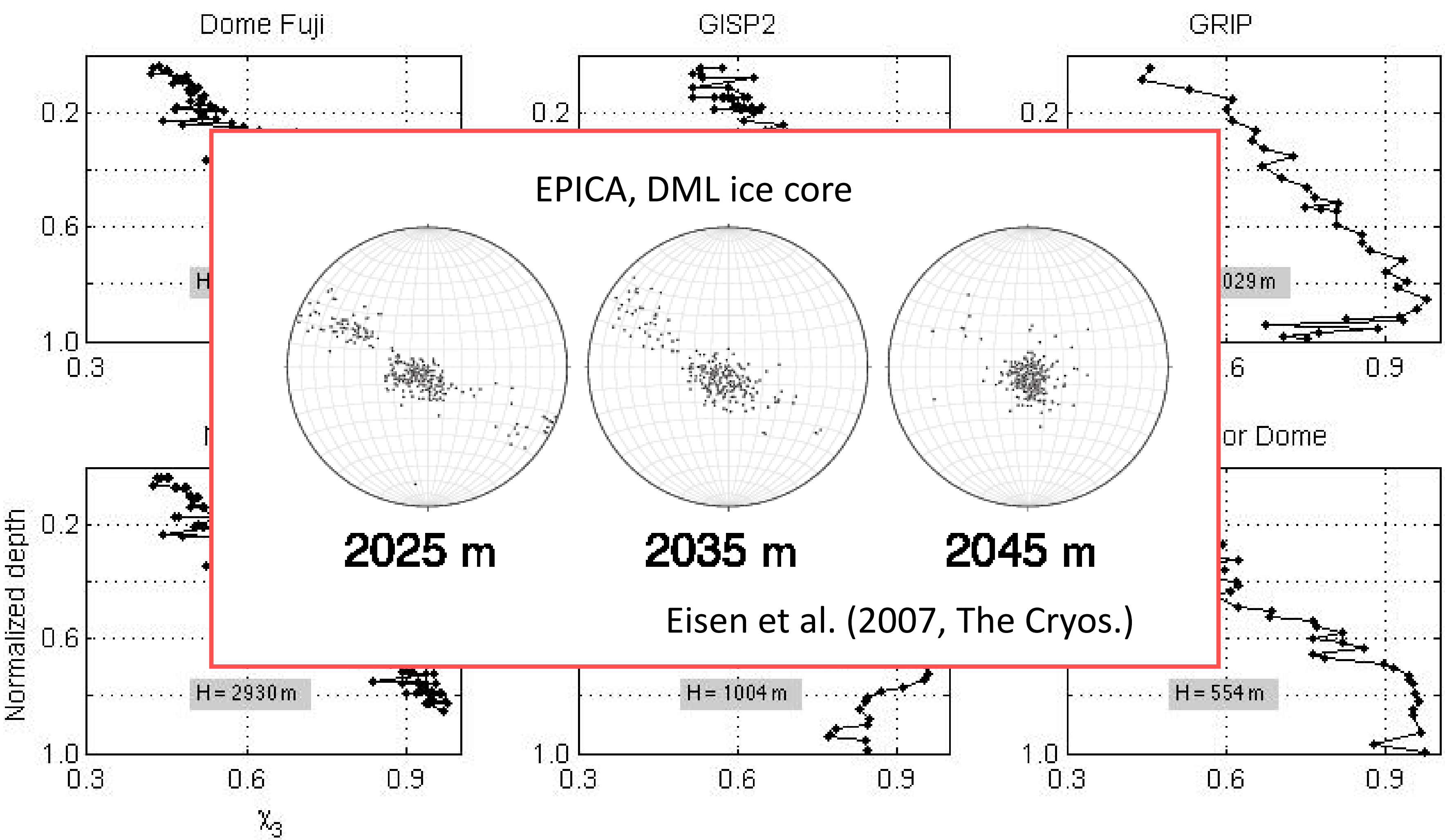
Matsuoka et al. (2009) *IEEE-TGRS*

Reflection causes

- Density contrasts
  - Significant only at depths roughly < 500 m
  - No reflections from gas hydrates
- Acidity contrasts
  - Correspond to large volcanic events
- Ice-fabric contrasts
  - Dominant at high frequencies (> 50-100 MHz)

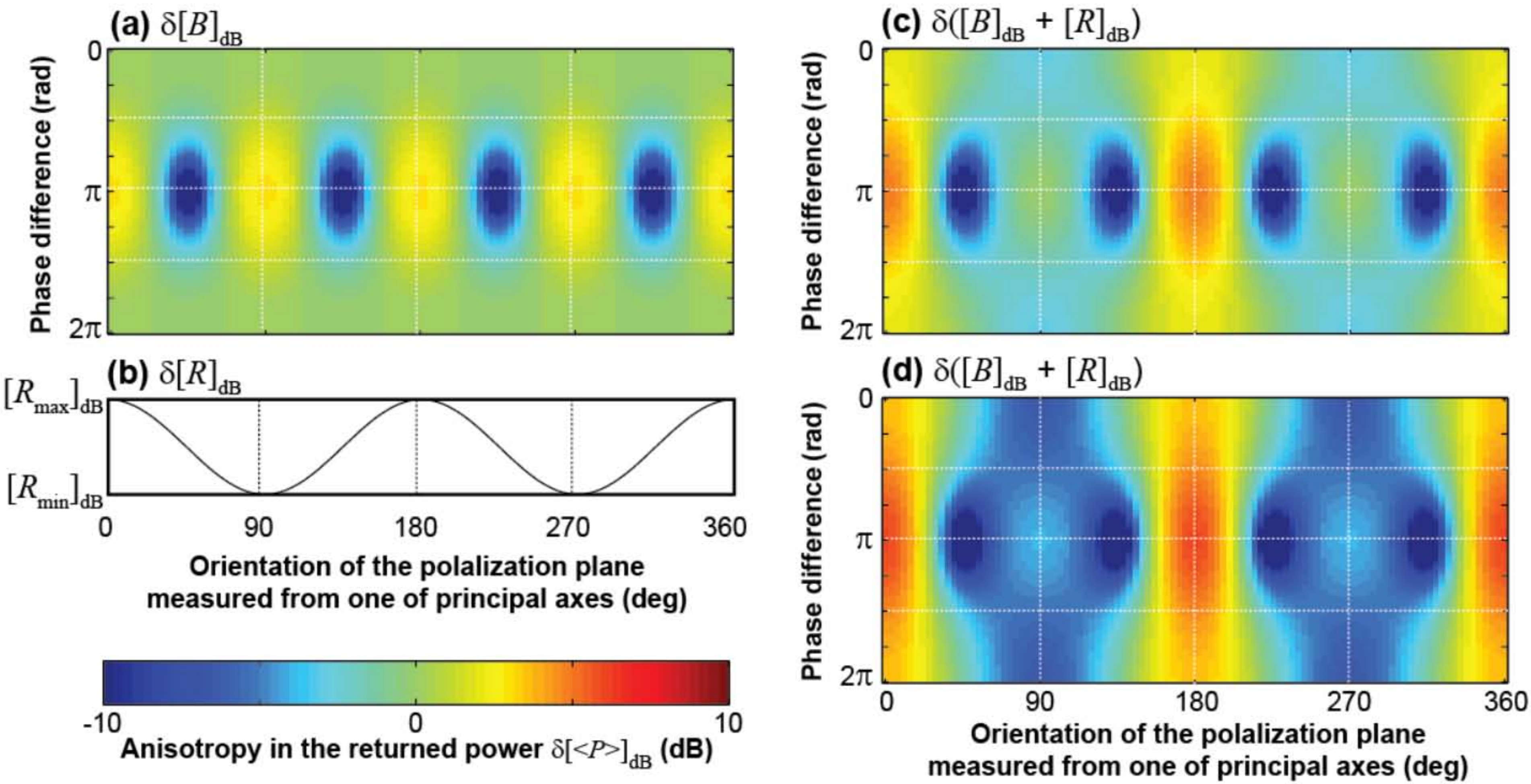
e.g. Fujita et al. (2000) in *Physics of Ice Core Records*

Fabric-origin reflections



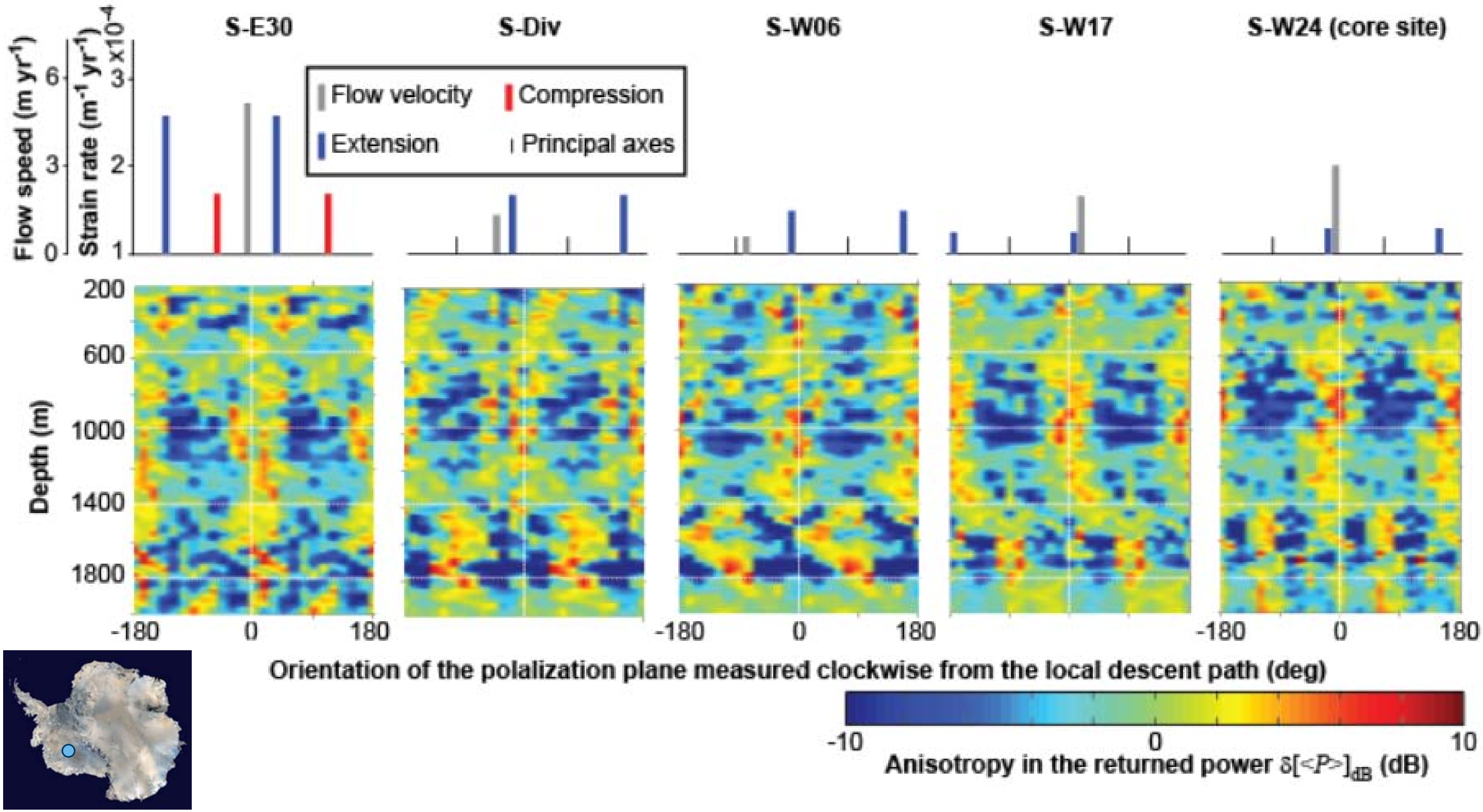
Matsuoka et al. (2009) *IEEE-TGRS*

Birefrigence + anisotropic reflection



Matsuoka et al. (in prep)

Polarimetric radar signatures and GPS-measured ice-motion data

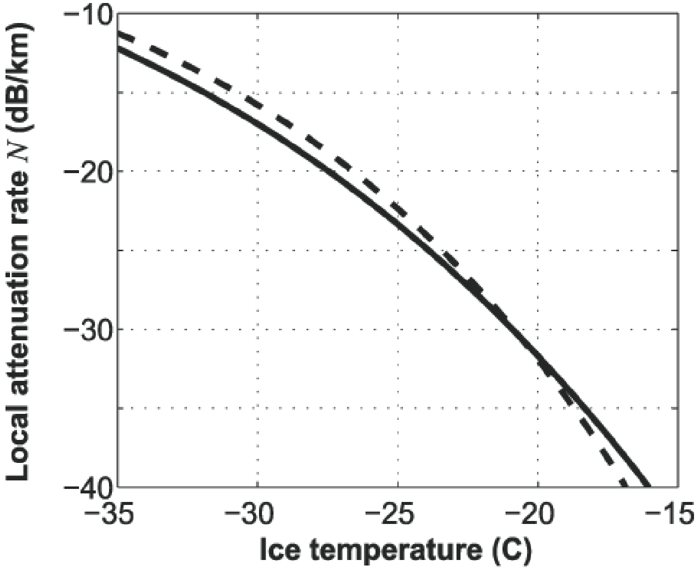


Matsuoka et al. (in prep)

Modeling radar attenuation

$$\left[L(z_2)\right]_{\mathrm{dB}} - \left[L(z_1)\right]_{\mathrm{dB}} = 2\left[\int_{z_1}^{z_2} N(z)dz\right]_{\mathrm{dB}}$$

Local attenuation rate N = function(ice temperature, chemistry)



$$N = \frac{1000(10\log_{10} e)}{c\varepsilon_0\sqrt{\varepsilon}}\sigma$$

$$= 0.914\sigma = 0.914\sum_{i=0}^{2}\sigma_i^0 C_i \exp\left[-\frac{E_i}{k}\left(\frac{1}{T}-\frac{1}{T_r}\right)\right]$$

i = 0: pure ice contribution

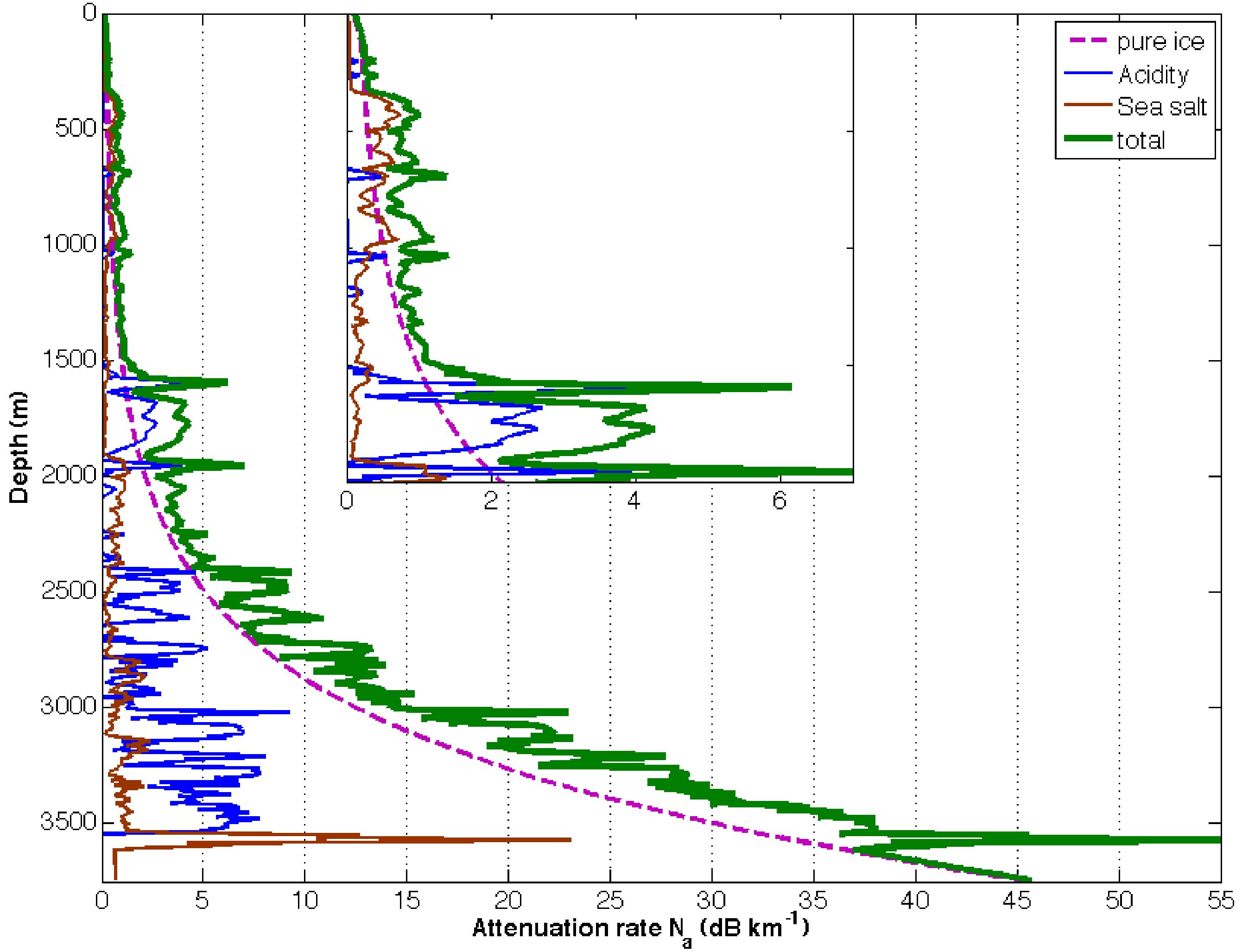
i = 1: acidity contribution

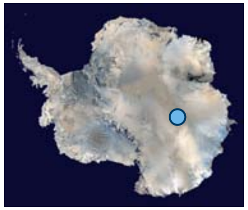
i = 2: sea-salt contribution

T: ice temperature

MacGregor et al. (2007) *JGR*; Matsuoka et al. (2010) *JGR*

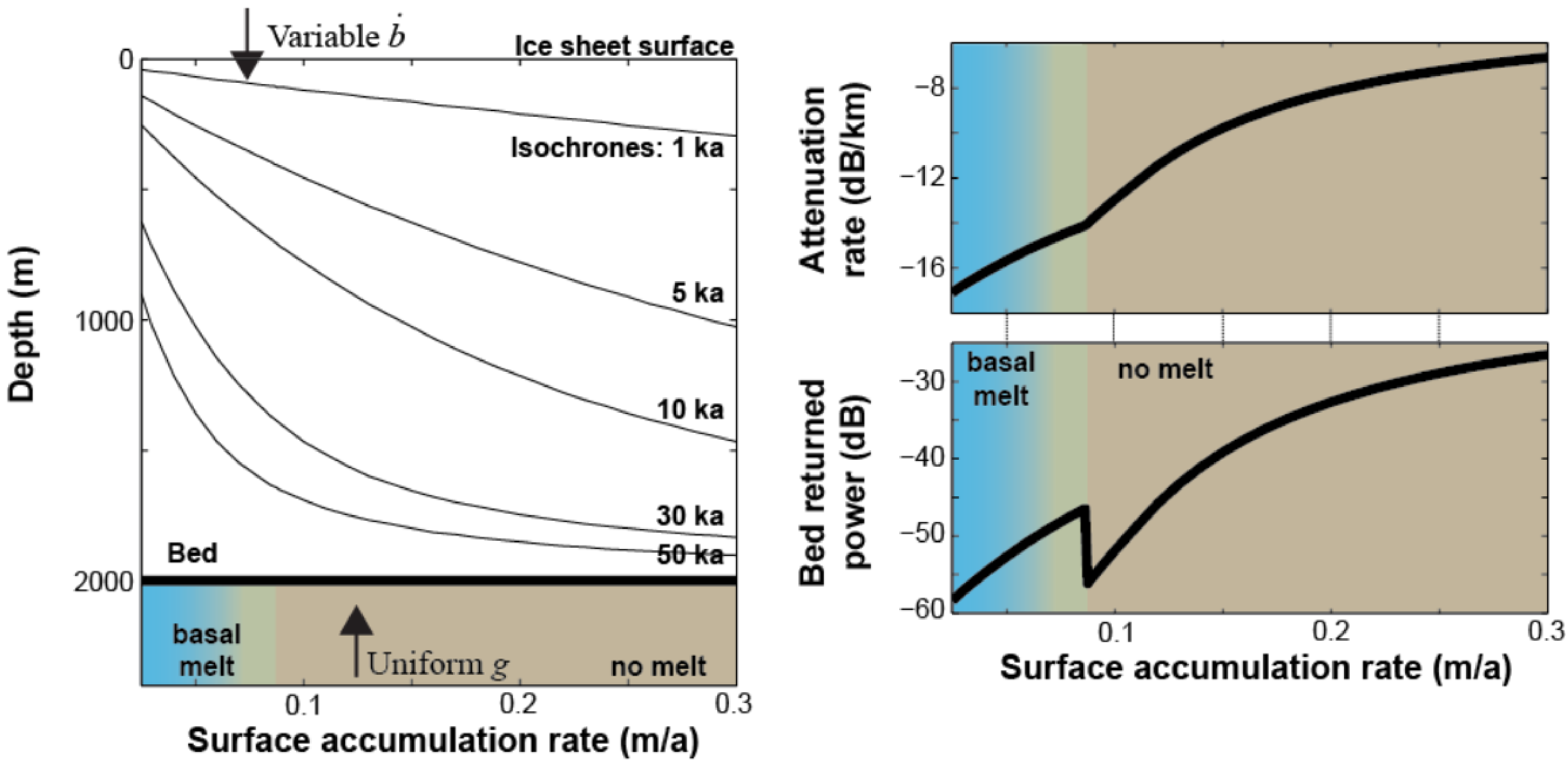
Attenuation estimates from ice core





MacGregor, Matsuoka, and Studinger (2009) *EPSL*

Attenuation estimates using thermo/mechanical model

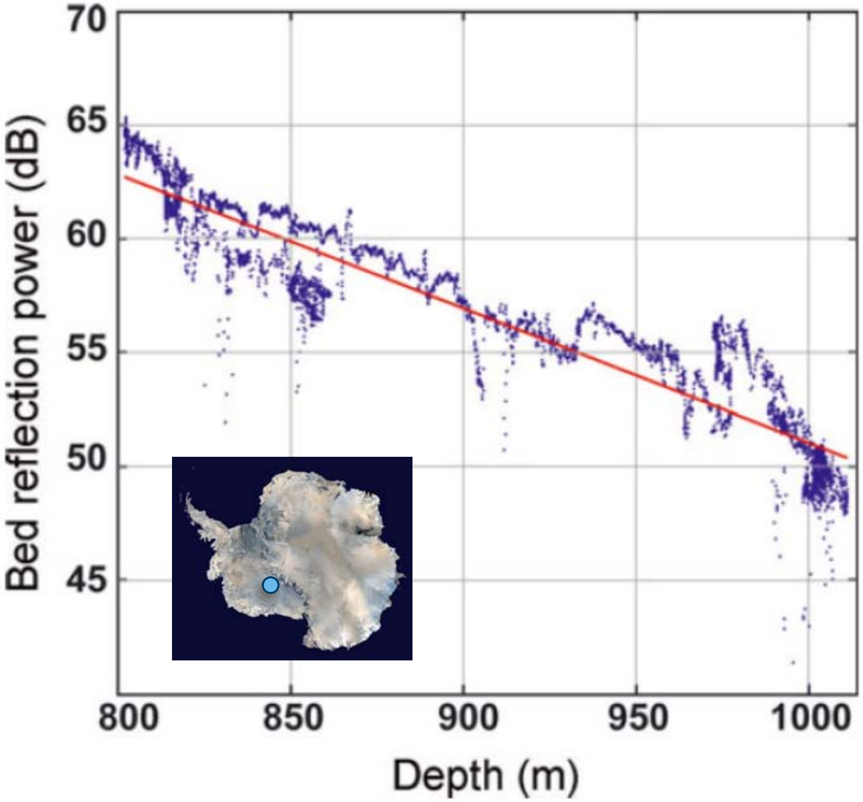


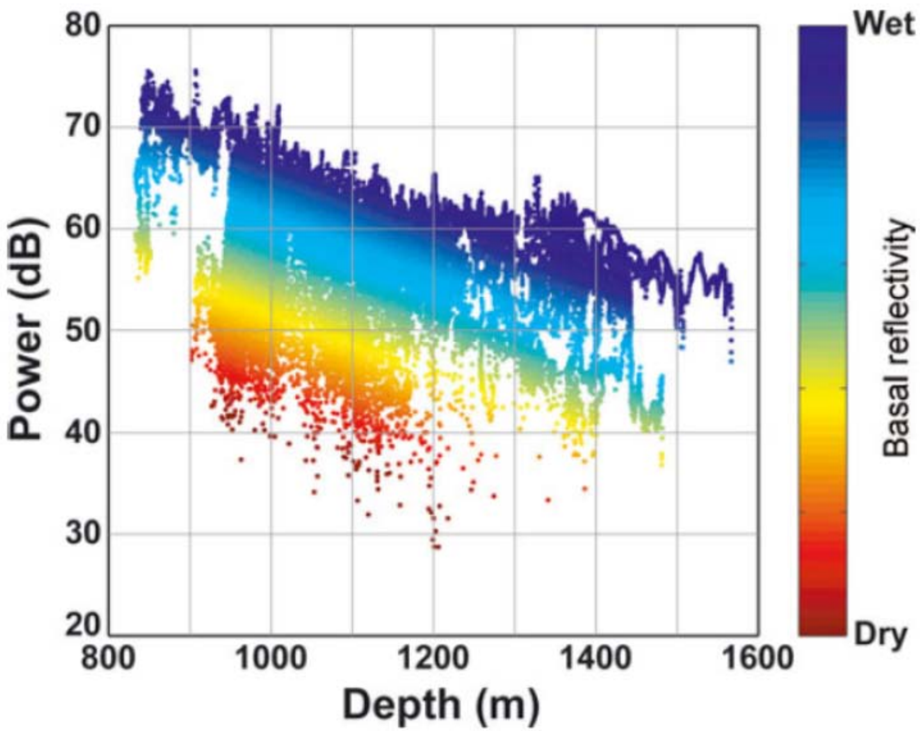
The bed returned power is more controlled by attenuation rather than bed reflectivity

Matsuoka (2011) *GRL*

Conventional radar algorithm

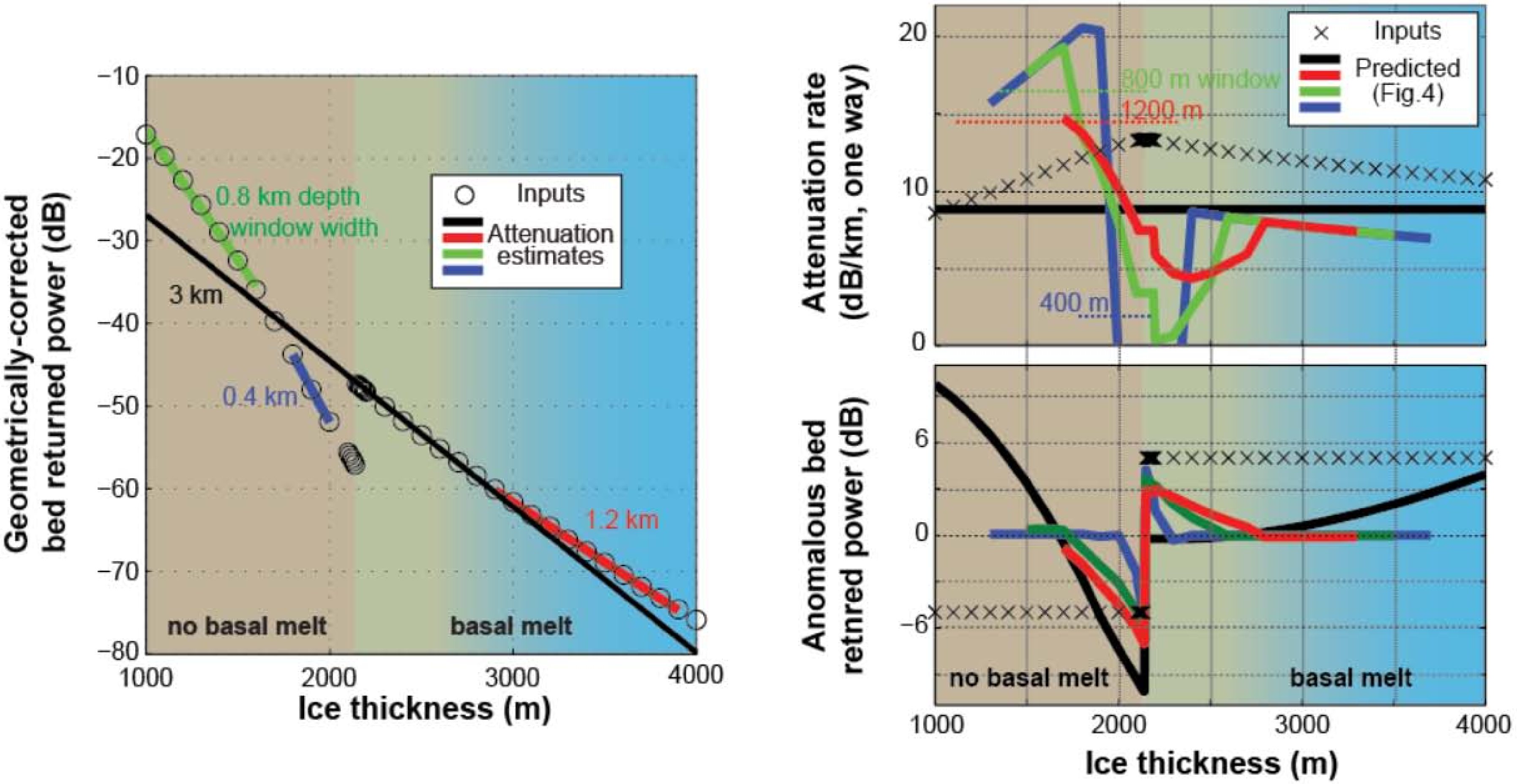
Attenuation rate is assumed to be uniform in the study area so that attenuation is proportional to the ice thickness





Jacobel et al. (2009) *Ann Glaciol.*

False estiamtes of attenuation



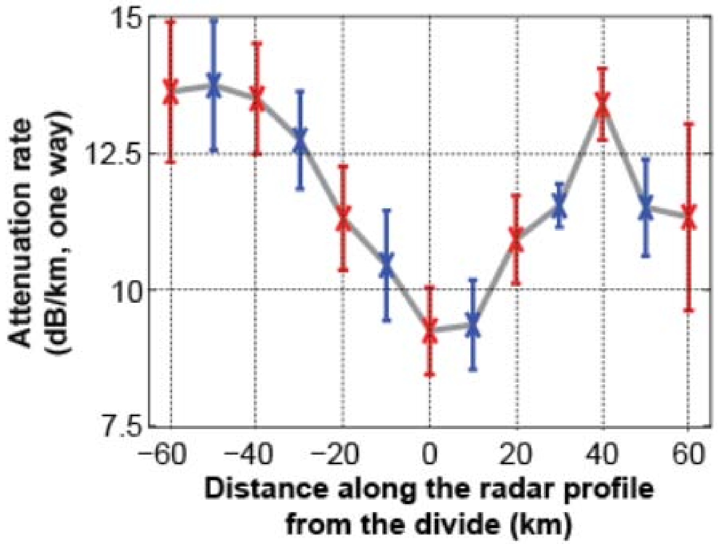
Matsuoka (2011) *GRL*

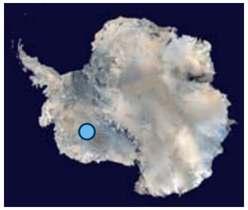
Attenuation estimates from radar data

$$\left\langle \frac{d\left[P^c\right]_{\mathrm{dB}}}{dz} \right\rangle_{z_1}^{z_2} \approx \left\langle \frac{d[R]_{\mathrm{dB}}}{dz} \right\rangle_{z_1}^{z_2} - \left\langle \frac{d[L]_{\mathrm{dB}}}{dz} \right\rangle_{z_1}^{z_2}$$

$$\left\langle \frac{d[L]_{\mathrm{dB}}}{dz} \right\rangle_{z_1}^{z_2} = \frac{[L(z_2)]_{\mathrm{dB}} - [L(z_1)]_{\mathrm{dB}}}{z_2 - z_1}$$

$$= 2\frac{\left[\int_{z_1}^{z_2} N(z)\,dz\right]_{\mathrm{dB}}}{z_2 - z_1} = 2\langle N \rangle_{z_1}^{z_2}$$

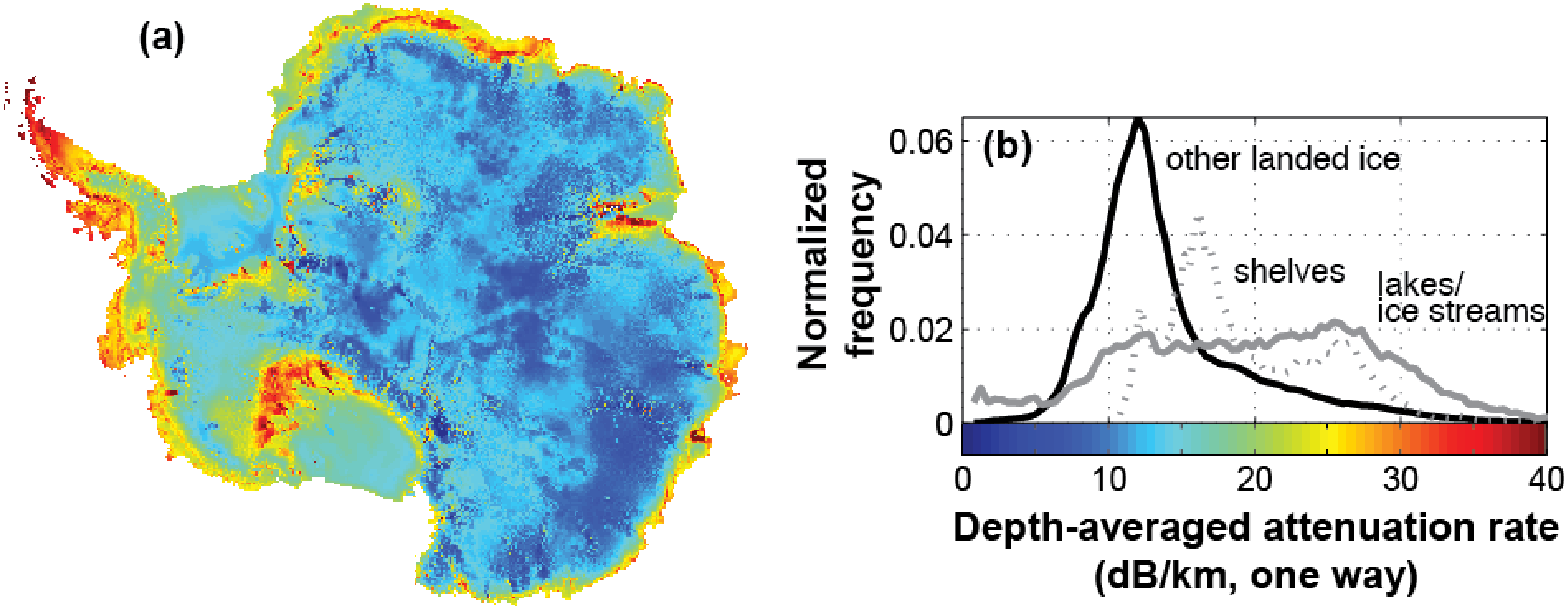




Returned power from the bed beneath 3-km-thick ice varies by 27 dB, regardless of the bed conditions.

Matsuoka et al. (2010) *JGR Earth Surface*

Continental attenuation estimates



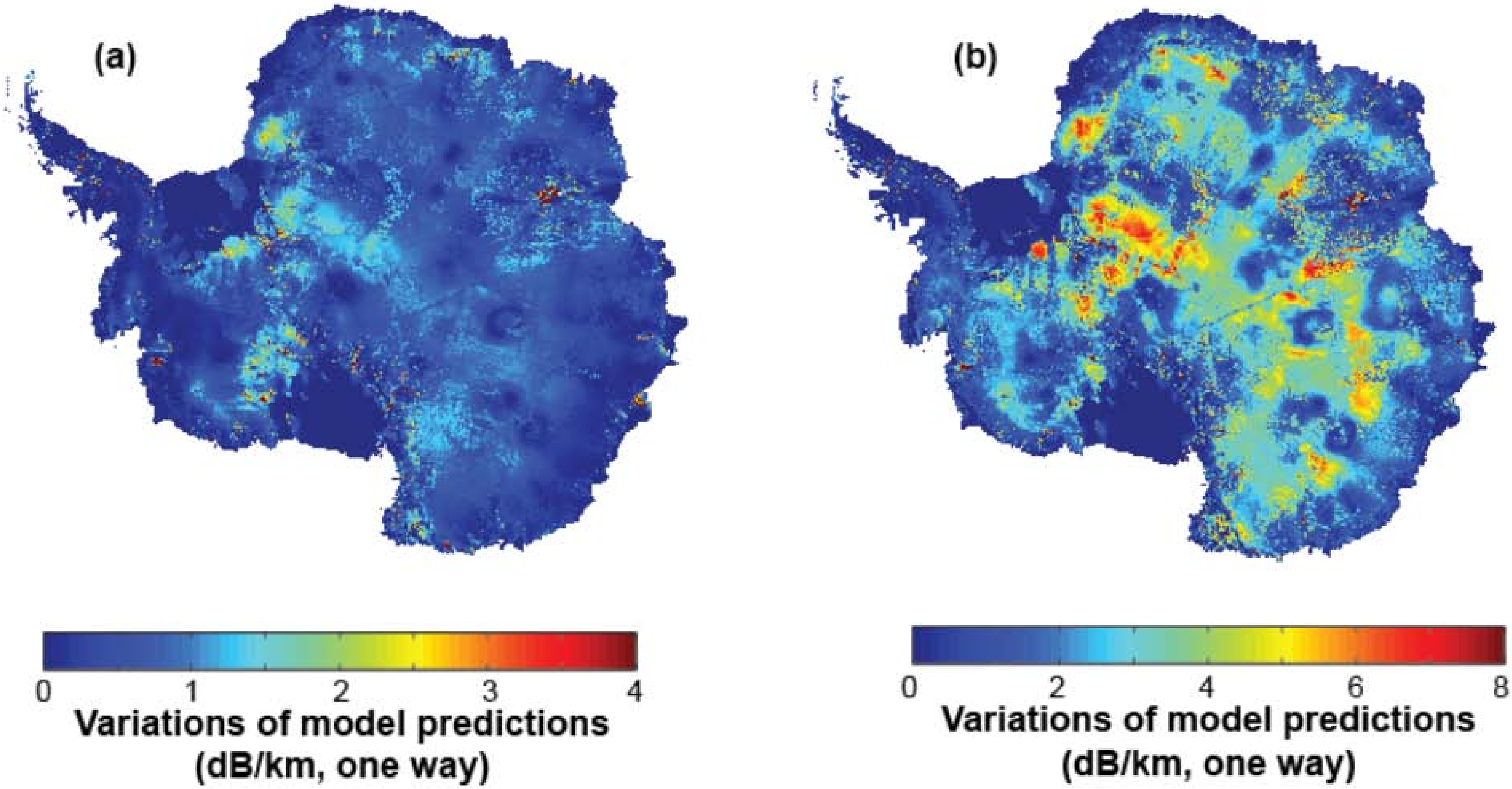
Geothermal flux is tuned using ice temperature from deep bore holes and locations of known subglacial lakes [Pattyn, 2010, EPSL].

Matsuoka, Pattyn, MacGregor (in prep)

Attenuation variations between model ensembles

Upper half of the ice sheet

Lower half of the ice sheet

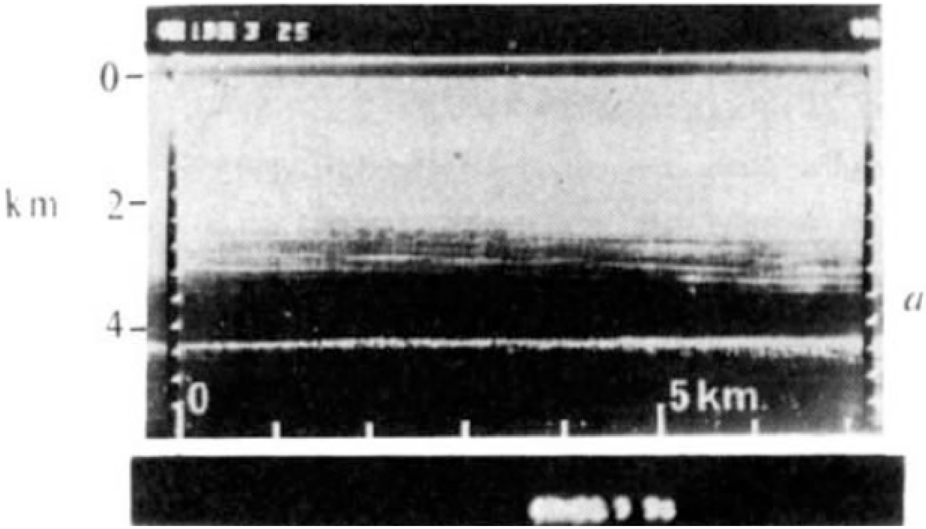


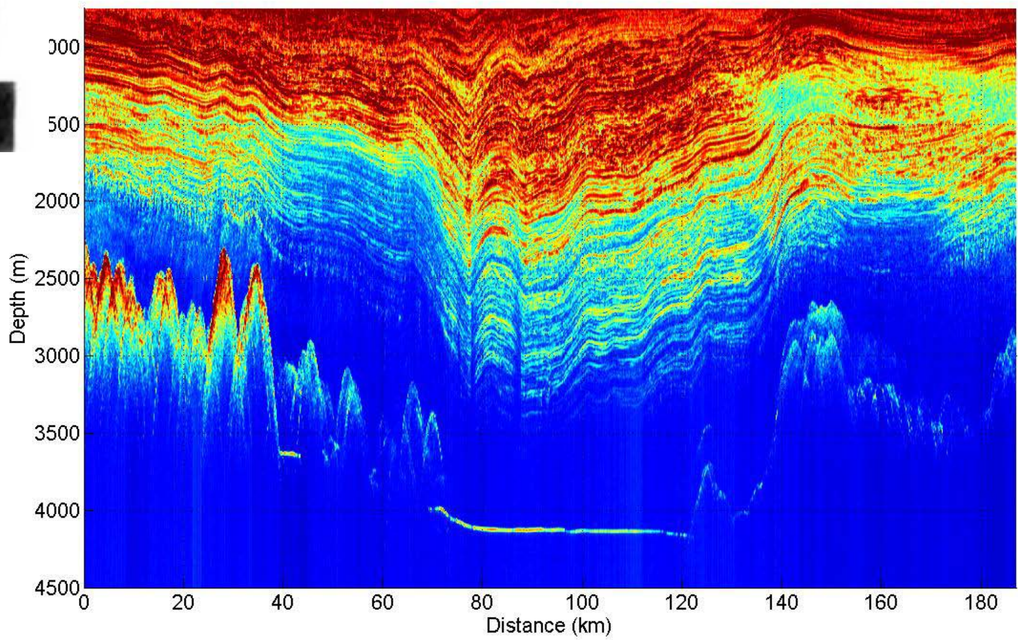
Matsuoka. Pattyn, MacGregor (in prep)

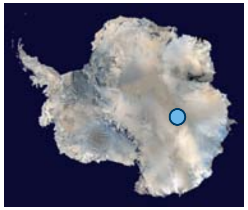
What should we do?

- Routinarly use multi-frequency/polarimetry sensors and collect coherent data
- More rigorous data-interpretation models
  - Understand the all properties of the radar data altogether.
  - More tightly couple ice-core and borehole-logging studies with the radar studies.
    - Low depth-resolution data for birefringence and attenuation
    - High depth-resolution data for reflection

40 years in radioglaciology



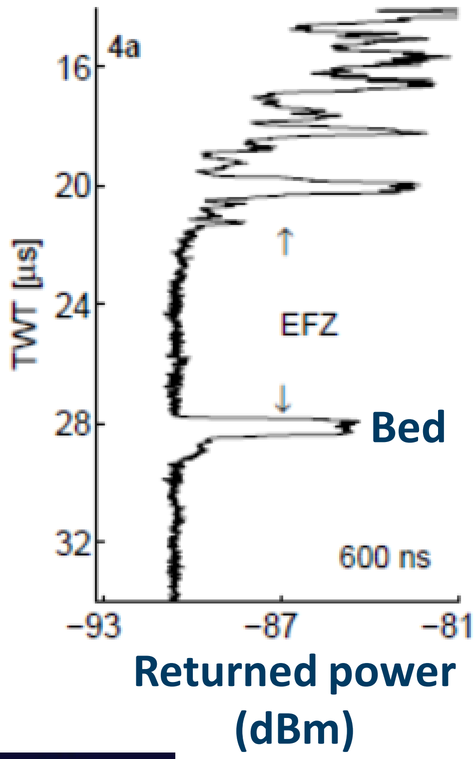


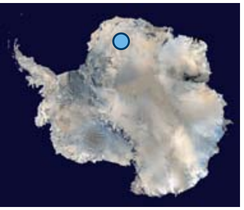


Oswald and Robin (1973) *Nature*; Data courtesy: SOAR

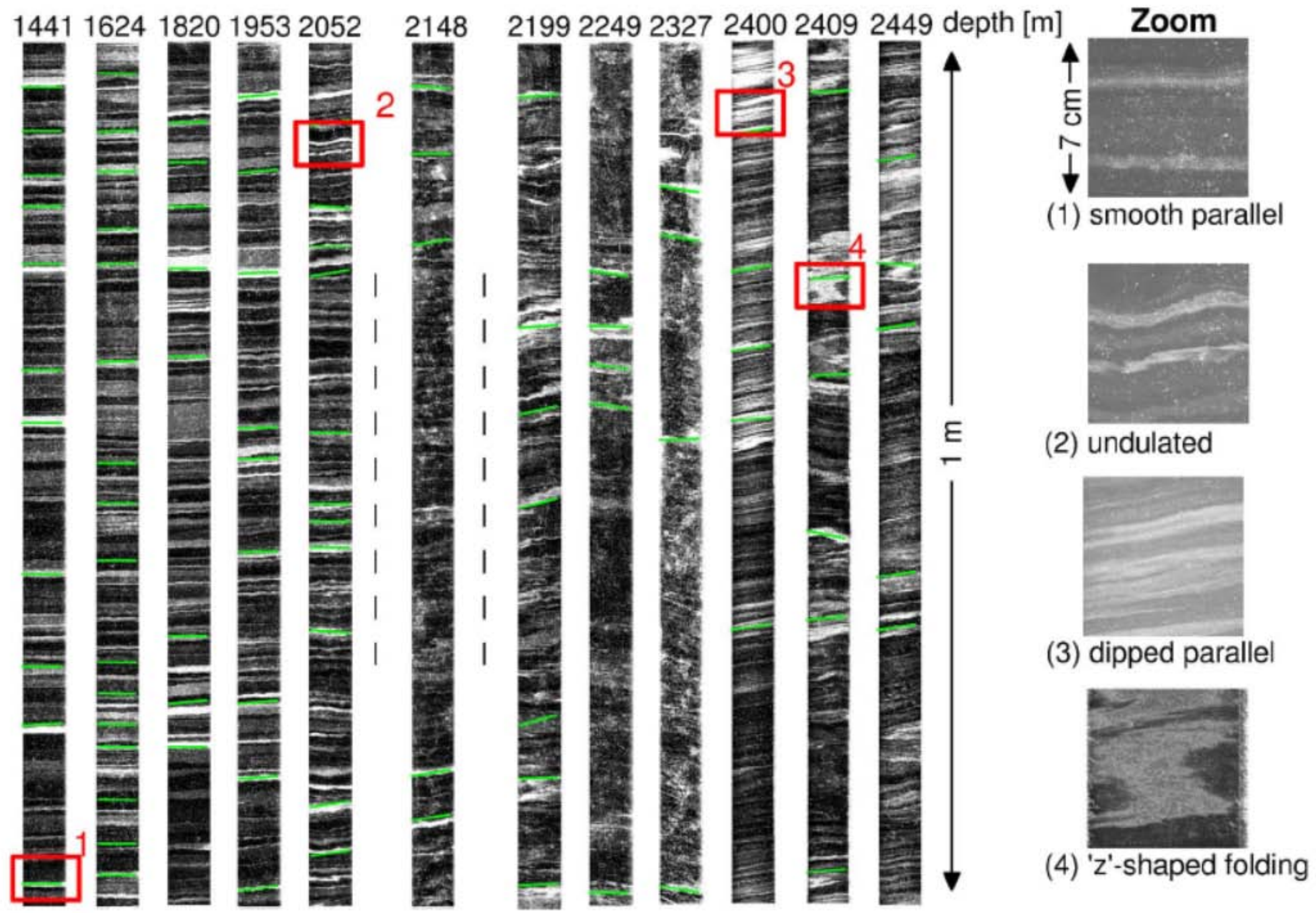
Unlock the secrets in the deep ice

Echo-Free Zone (EFZ)





Optical scan images of the ice core



Drew et al. (2009) The Cryosphere

Thank you

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