Preparing for Seismic Observation with *Dragonfly*: What Seismology will look like on Titan?

And what can we learn from the upper structure?

Lorraine Delaroque[1], *T. Kawamura[1], A. Lucas[1], S. Rodriguez[1], K. Onodera[2], H. Shiraishi[3], R. Yamada[4], S. Tanaka[3], M. P. Panning[5], R. D. Lorenz[6]*

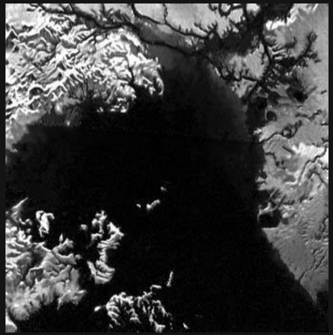
[1]IPGP / U. Paris Cité, CNRS, France, [2]Institute for Planetary Material, Okoyama U., [3]ISAS, JAXA, [4]U. Aizu, [5]JPL, Caltech, [6]Johns Hopkins U. APL

CDD 2026 | IPGP | 31 March 2026

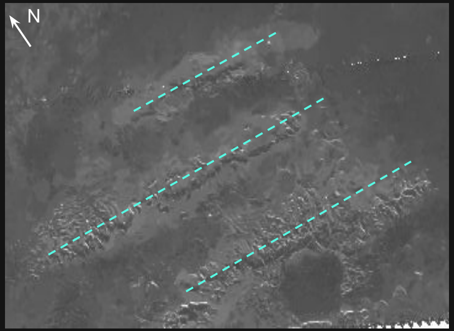
Credit: NASA/JPL/University of Arizona

Some background: what do we know?

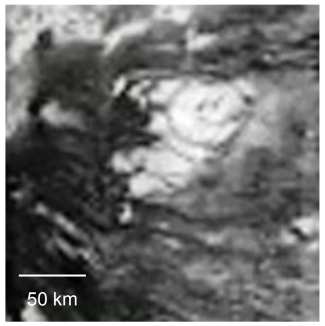
What we observed, we know → Surface features



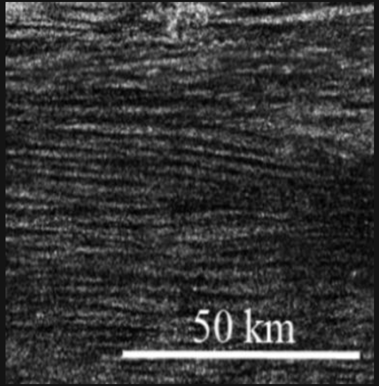
Lakes[1] (NLDSAR)



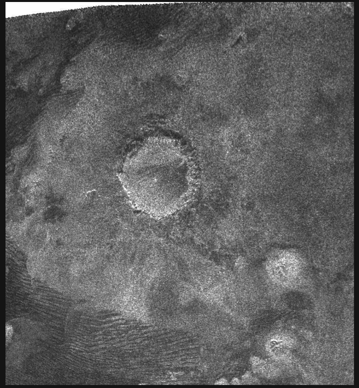
Mountains ridges[1] (NLDSAR)



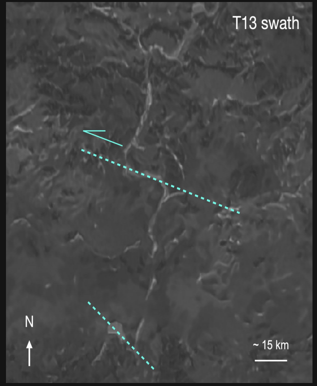
Cryovolcano? (VIMS)



Dune fields[2] (SAR)



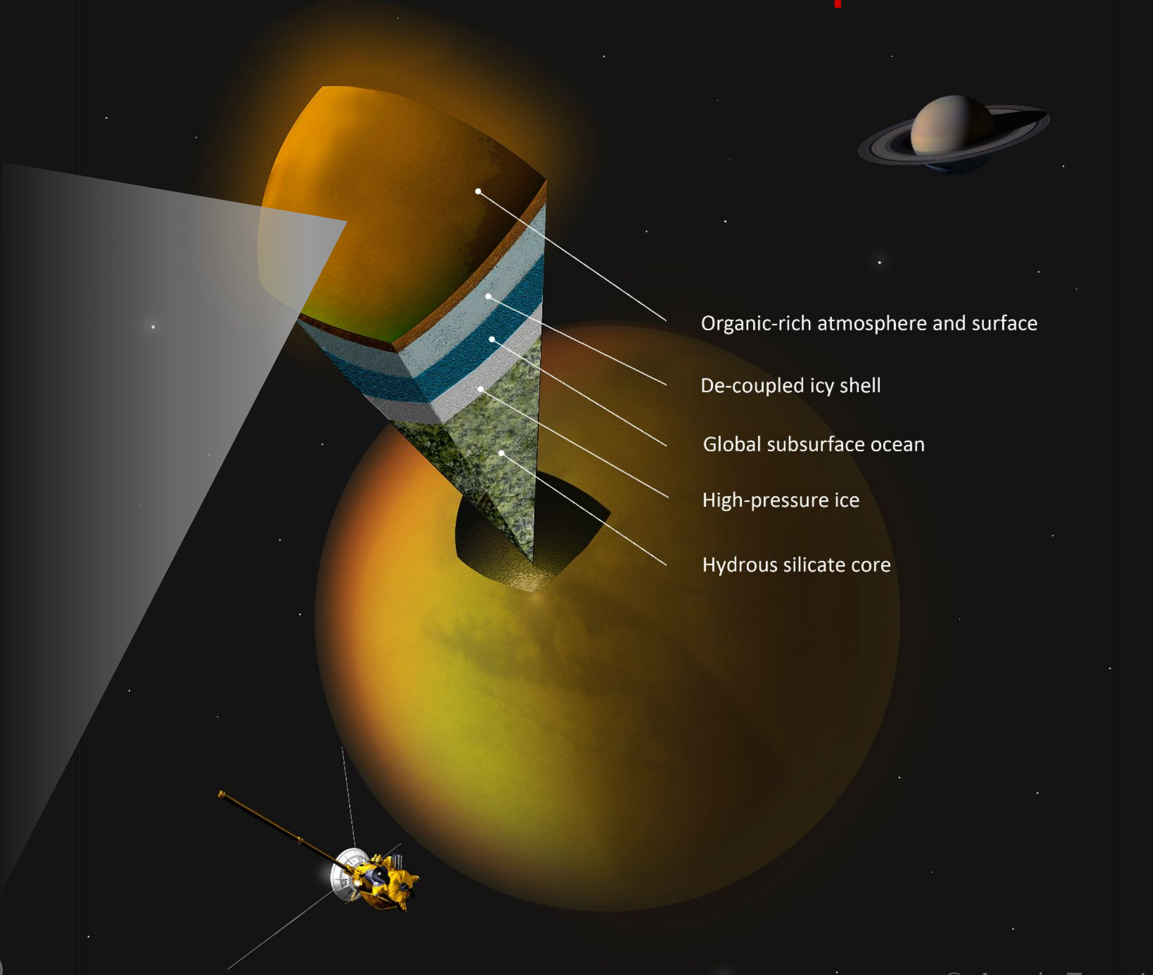
Impact crater (SAR)



Fluvial channel[1] (NLDSAR)

[1] Lucas et al. 2014, [2] Radebaugh et al. 2007

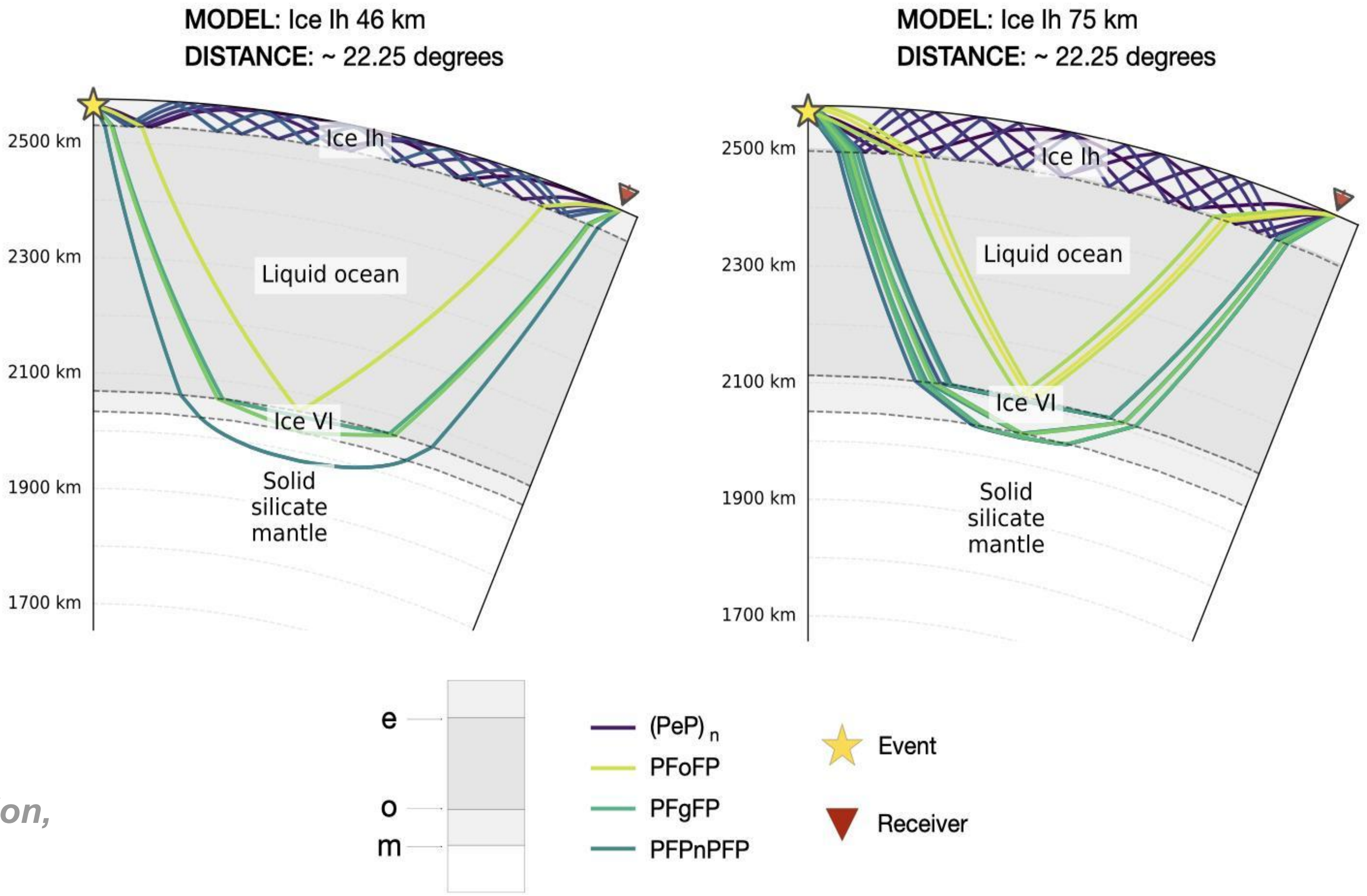
What we're unsure about → Deep structure



© Angelo Tavani

What can seismic data tell us?

- ➔ **Can Titan produce detectable quakes?**
- ➔ **Can P-wave multiple constrain the ice shell thickness?**

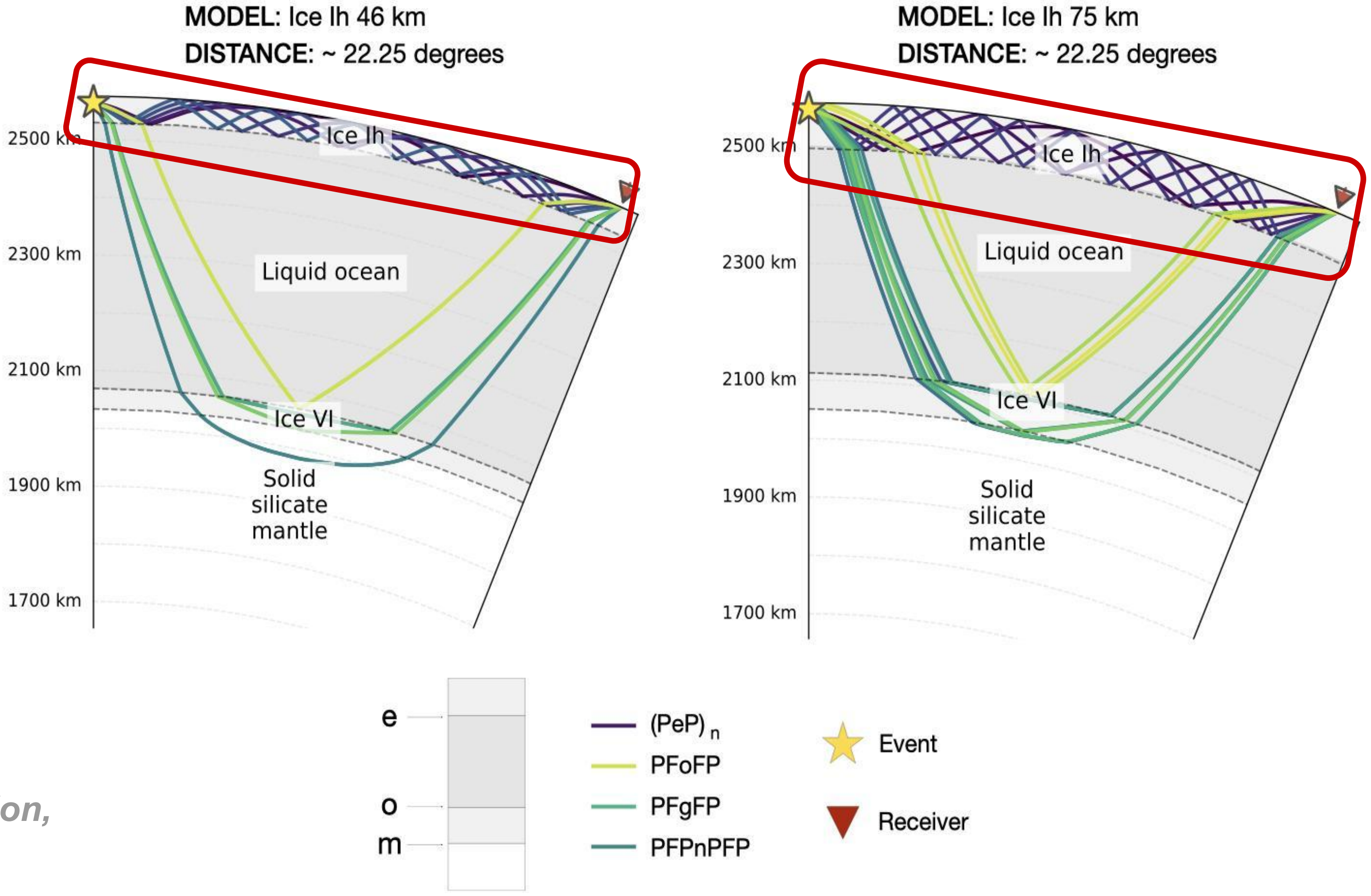


Delaroque et al. 2025 (accepted)

Keywords: Planetary Seismology, Dragonfly Mission, Interior Structure, High-frequency / Body waves

What can seismic data tell us?

- ➔ **Can Titan produce detectable quakes?**
- ➔ **Can P-wave multiple constrain the ice shell thickness?**

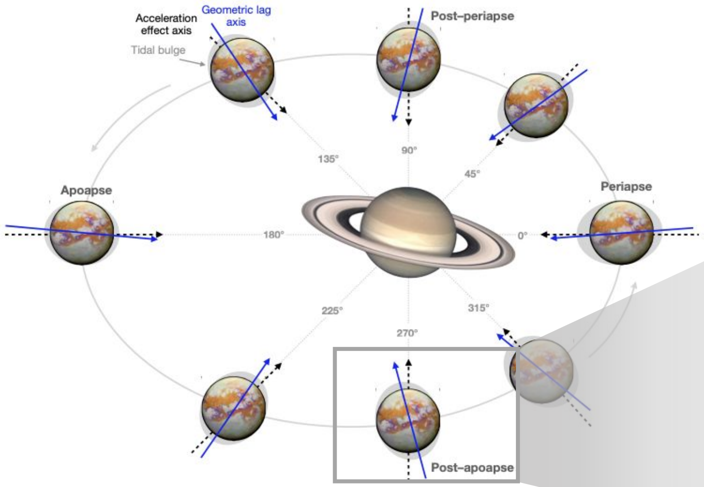


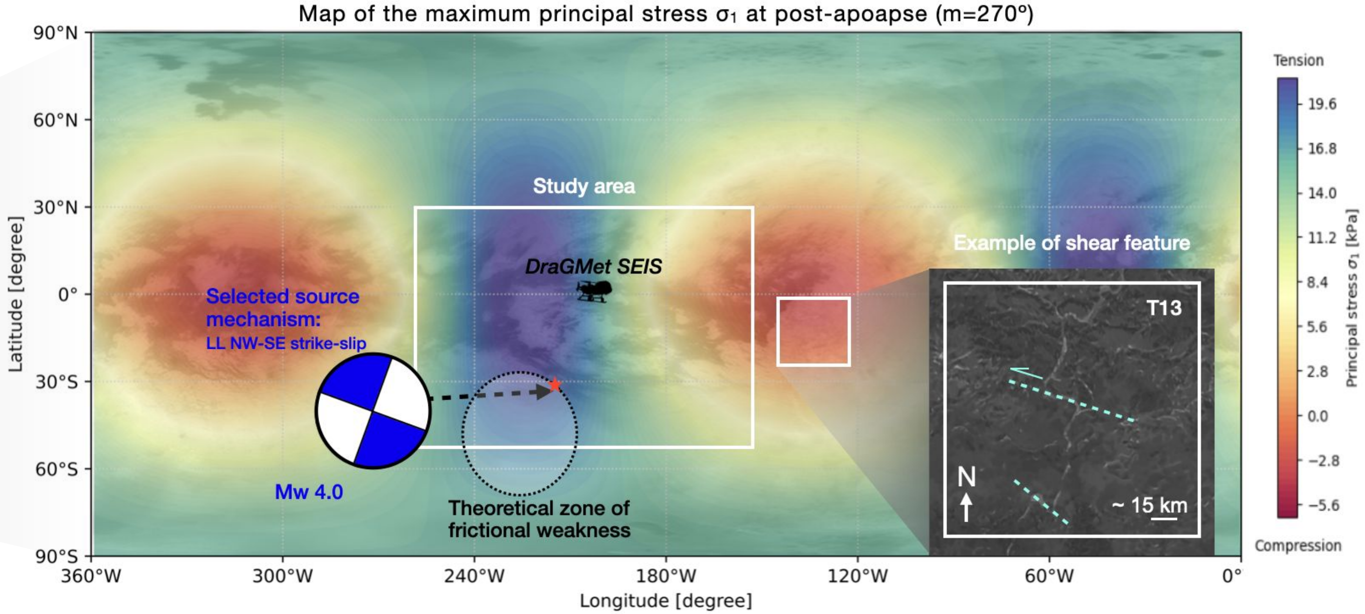
Delaroque et al. 2025 (accepted)

Keywords: Planetary Seismology, Dragonfly Mission, Interior Structure, High-frequency / Body waves

Methods – Defining the source

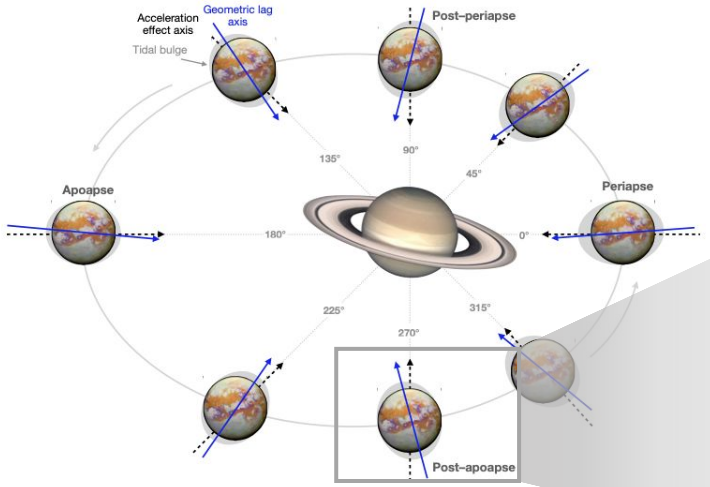
STEP 1: global tidal stress field modeling + fault orientation → resolve normal & shear traction

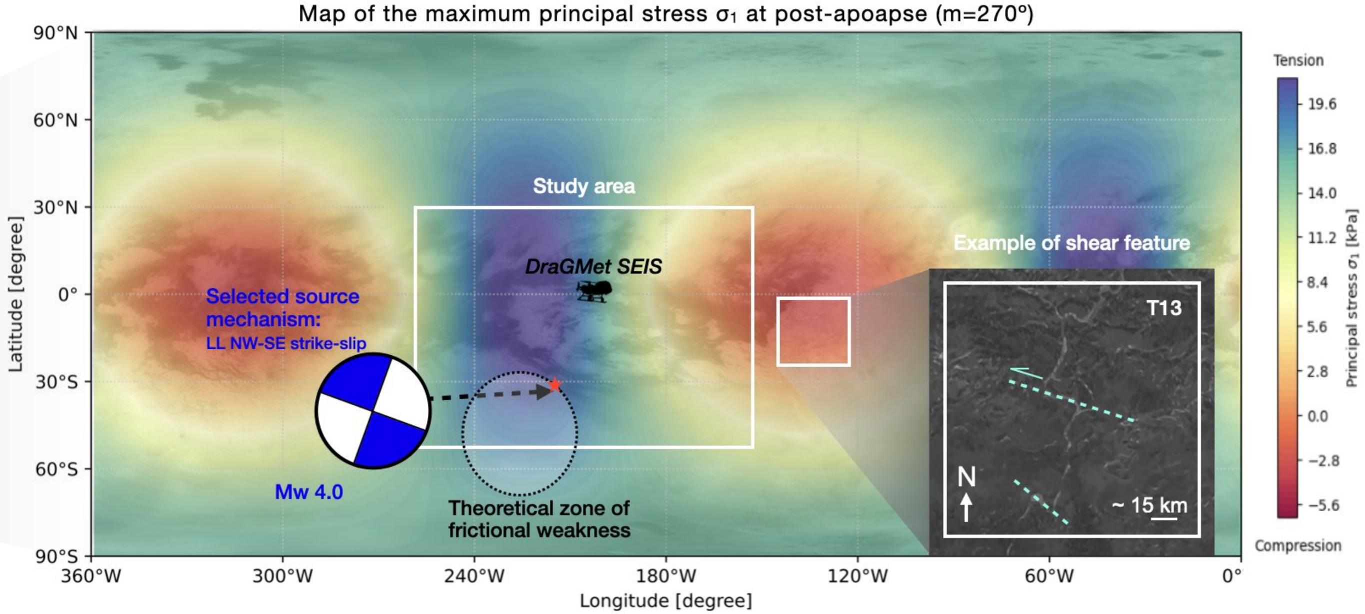




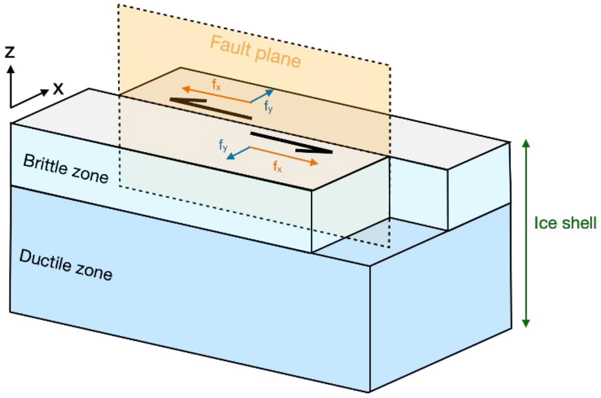
Methods – Defining the source

STEP 1: global tidal stress field modeling + fault orientation → resolve normal & shear traction




Map of the maximum principal stress σ₁ at post-apoapse (m=270°)

STEP 2: Coulomb stress from the resolved tractions

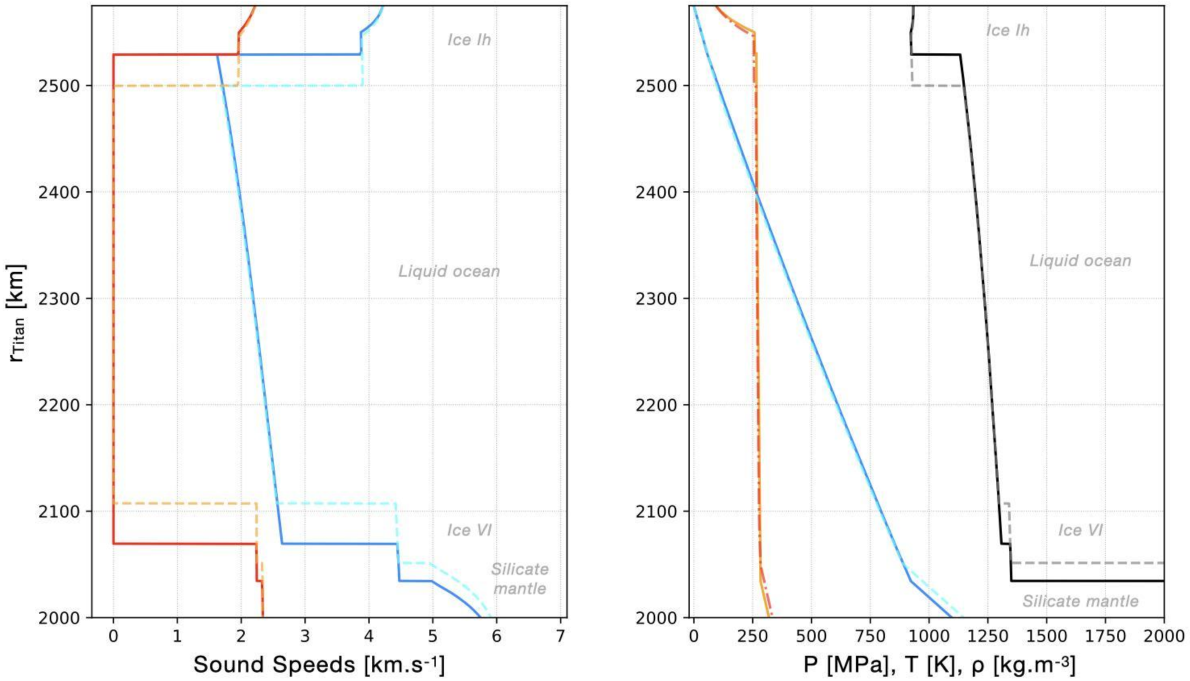


- $\tau_s = \frac{1}{2}(\sigma_{\varphi\varphi} - \sigma_{\theta\theta}) \sin 2\beta + \sigma_{\theta\varphi} \cos 2\beta$
- $\sigma_n = \sigma_{\theta\theta} \cos^2 \beta + \sigma_{\varphi\varphi} \sin^2 \beta + \sigma_{\theta\varphi} \sin 2\beta$
- $\tau_c = \underbrace{|\tau_s|}_{\text{Shear stress}} - \underbrace{\mu_f(\sigma_n + \rho g z)}_{\text{Frictional resist.}} \xrightarrow{\qquad}$ Evaluate the fault stability

Methods – Defining the interior model

- **1D self-consistent model** with *PlanetProfile* software
- **Ice Ih thickness** uncertainty ± 40km! ⇒ <u>test of 2 scenarios</u>
- **Anelastic attenuation** data from experimentations ⇒ <u>test of 3 scenarios</u>

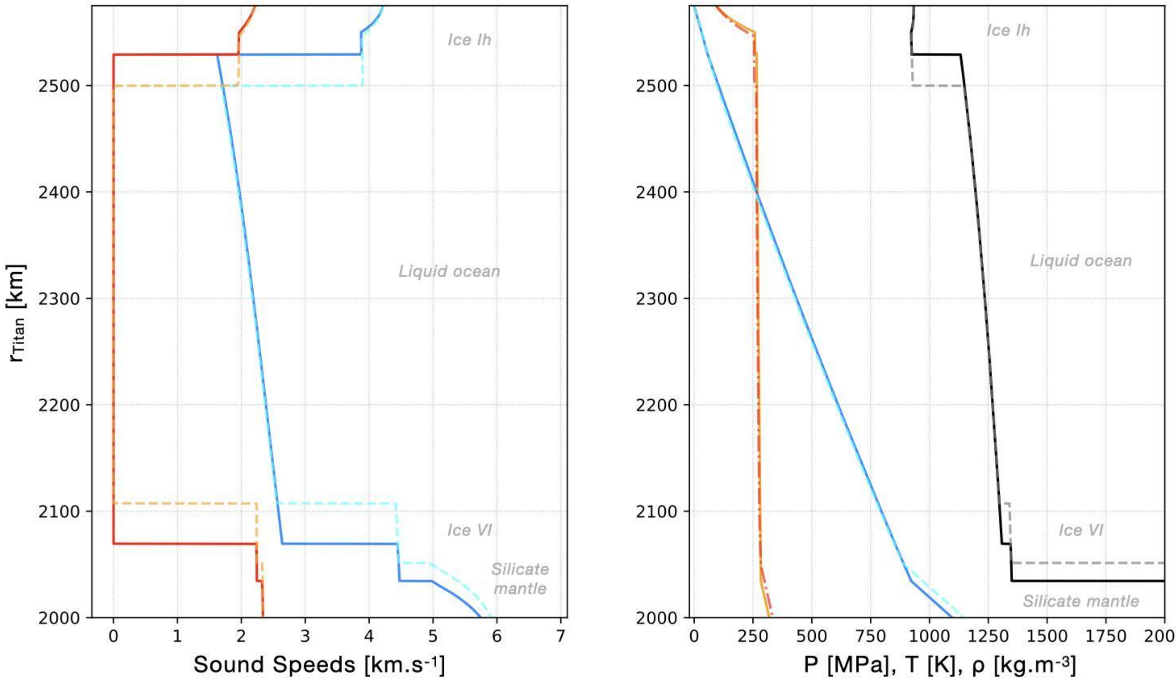
1D Model of parameters (*PlanetProfile,* Vance et al. 2018)



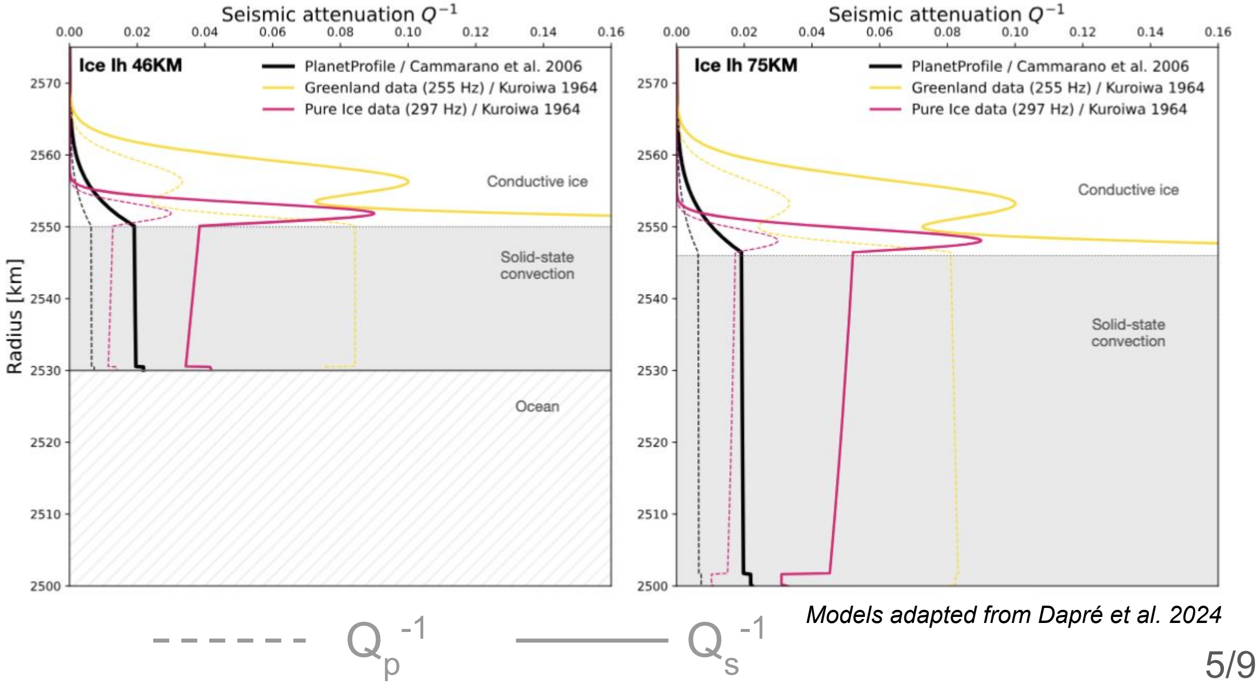
Methods – Defining the interior model

- **1D self-consistent model** with *PlanetProfile* software
- **Ice Ih thickness** uncertainty ± 40km! ⇒ test of 2 scenarios
- **Anelastic attenuation** data from experimentations ⇒ test of 3 scenarios

1D Model of parameters (*PlanetProfile,* Vance et al. 2018)



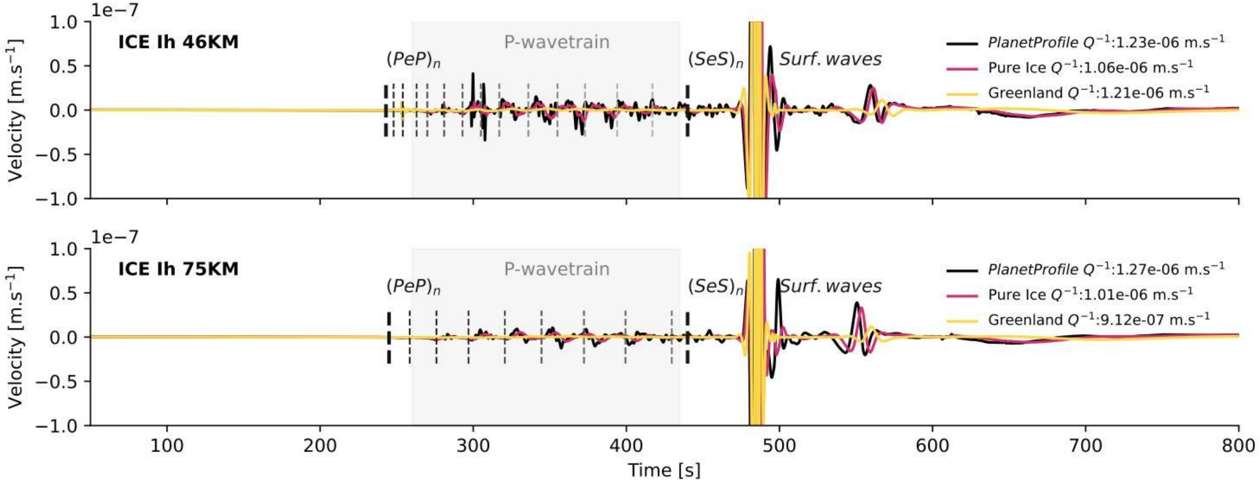
Shear attenuation (experimentation at HF)



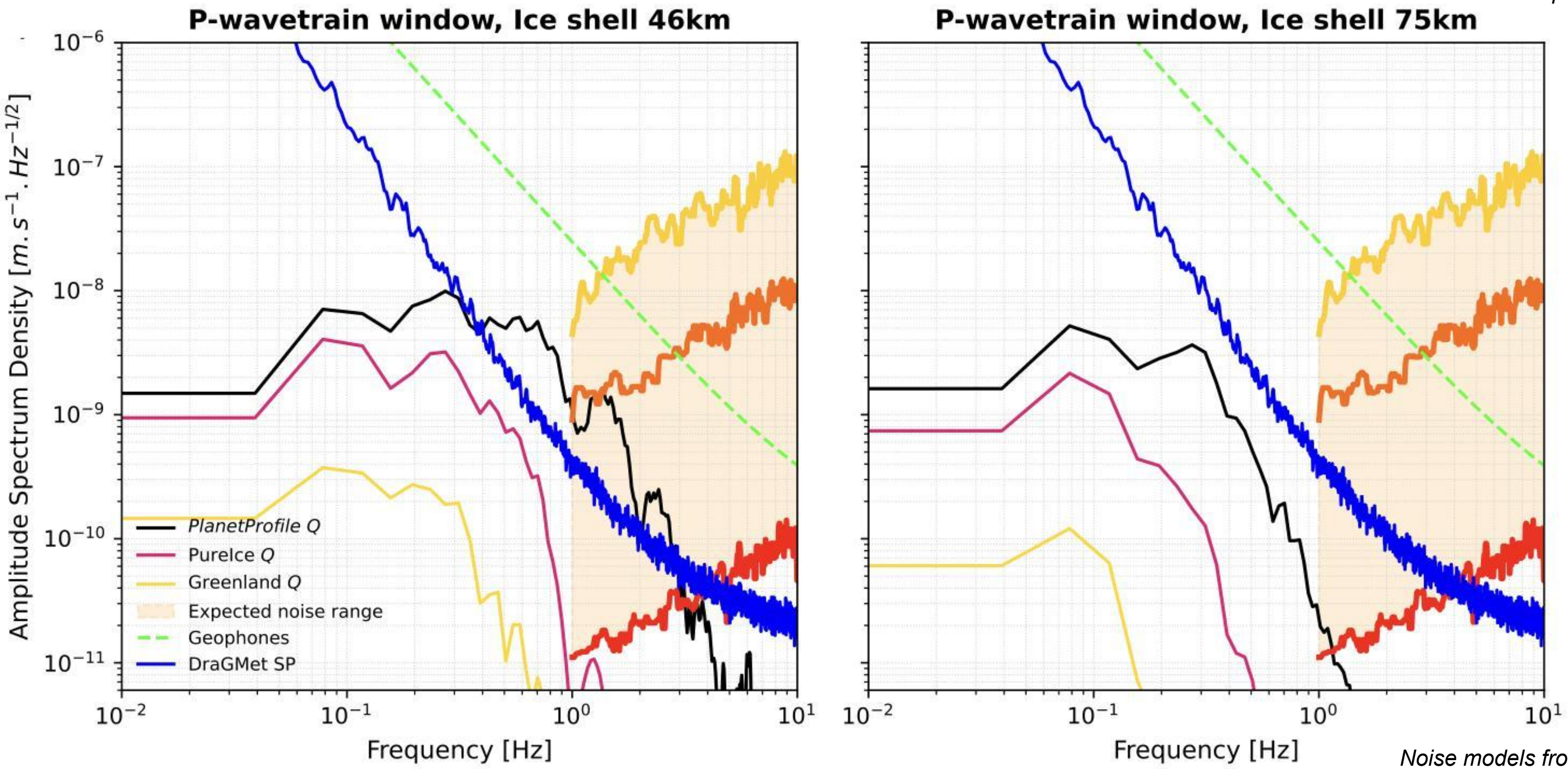
Models adapted from Dapré et al. 2024

Synthetic waveforms

- wavenumber integration method of the CPS → **well performance at HF**
- f ~ up to **10 Hz**
- S-R distance **~ 1,000km**



Delaroque et al. 2025 (accepted)

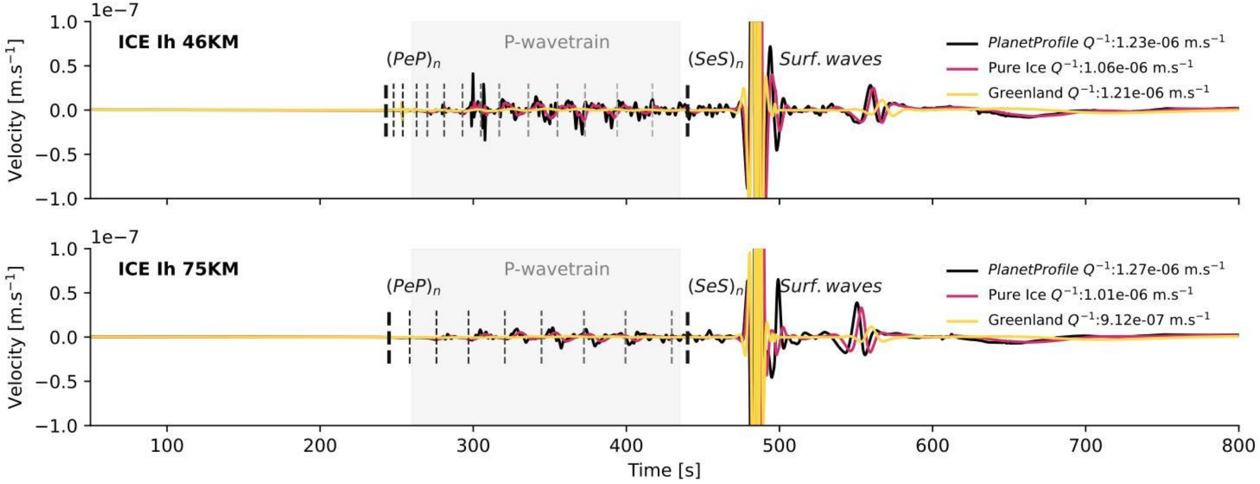


Turbulence noise

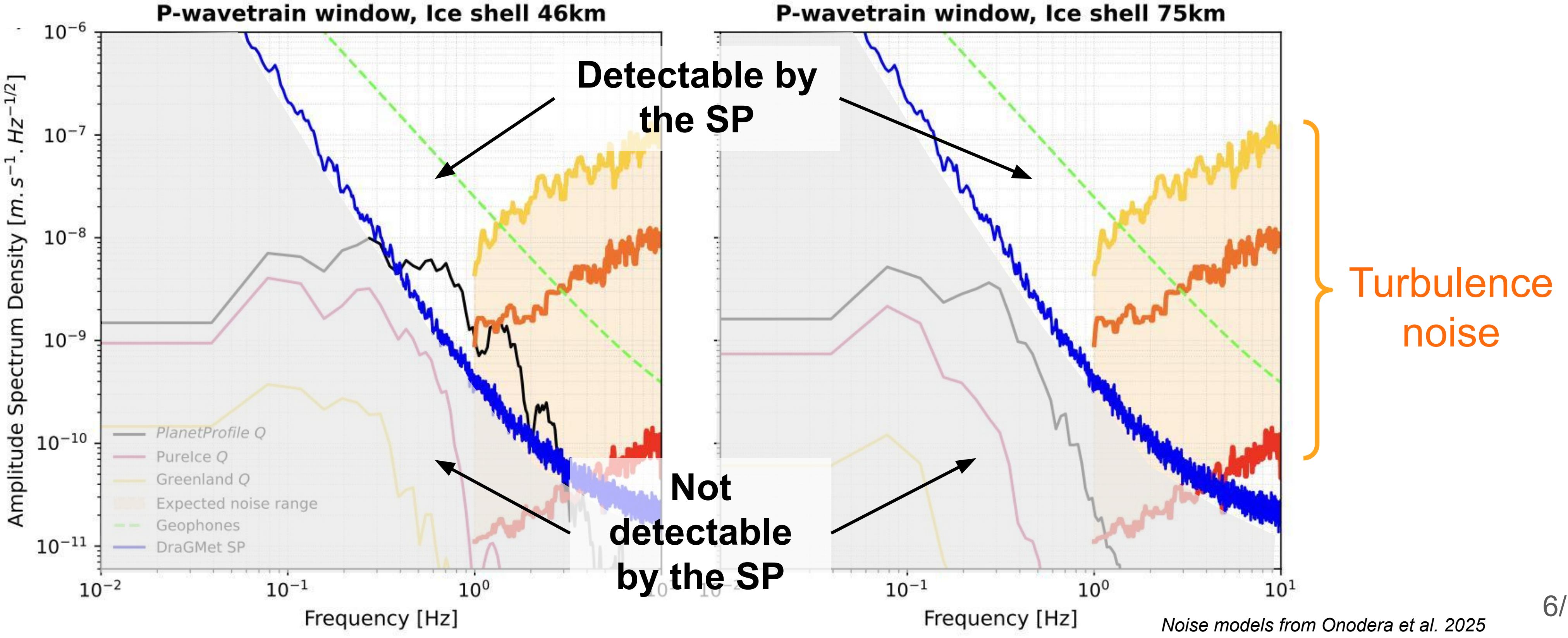
Noise models from Onodera et al. 2025

Synthetic waveforms

- wavenumber integration method of the CPS → **well performance at HF**
- f ~ up to **10 Hz**
- S-R distance **~ 1,000km**



Delaroque et al. 2025 (accepted)



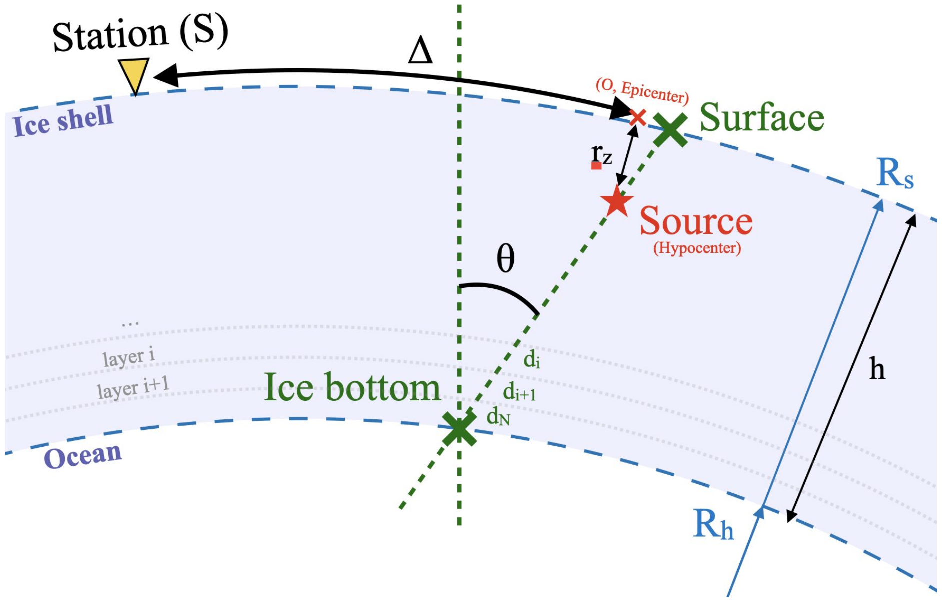
Detectable by the SP

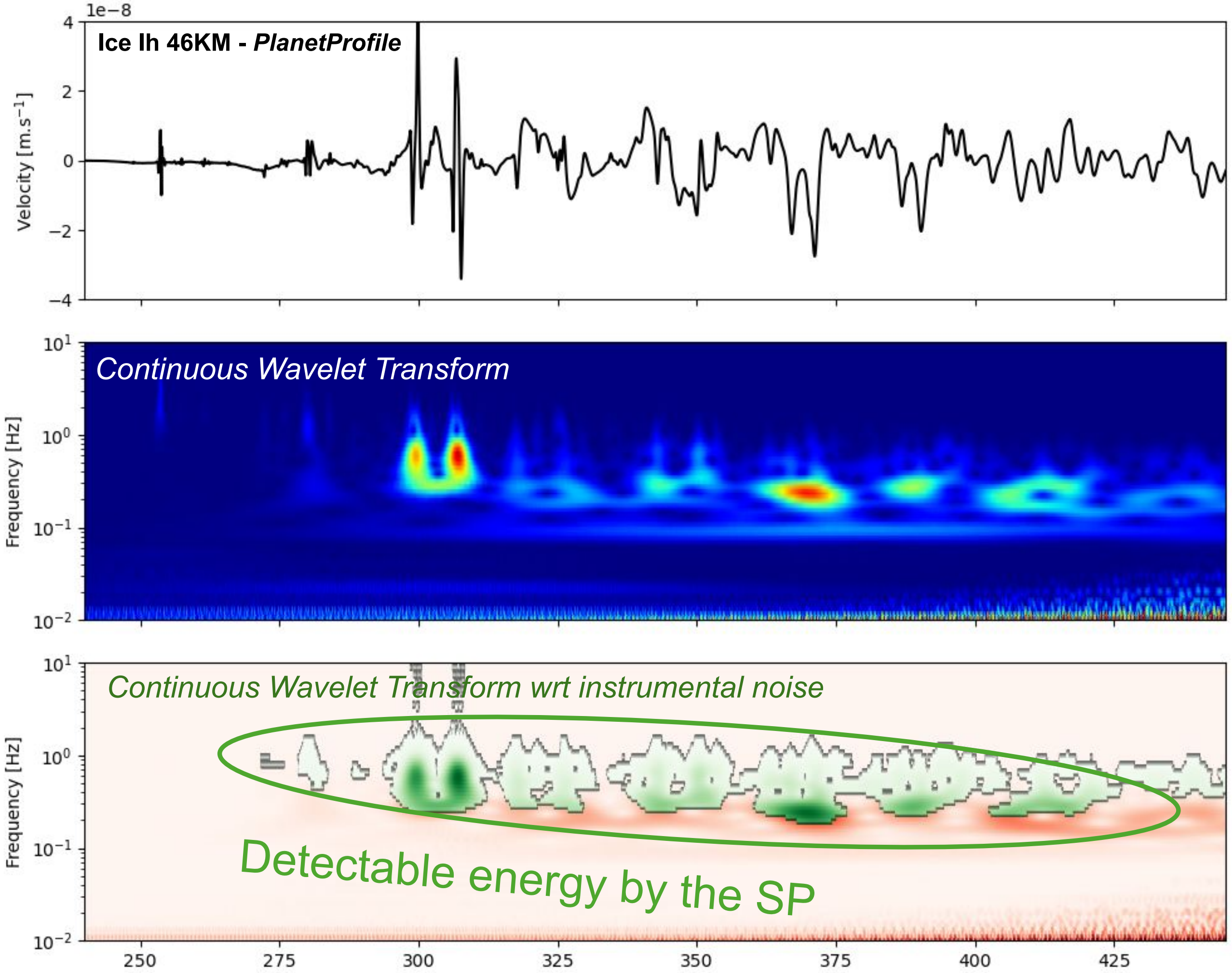
Not detectable by the SP

Turbulence noise

Noise models from Onodera et al. 2025

Retrieving the Outer Ice Shell thickness




Ice Ih 46KM - *PlanetProfile*

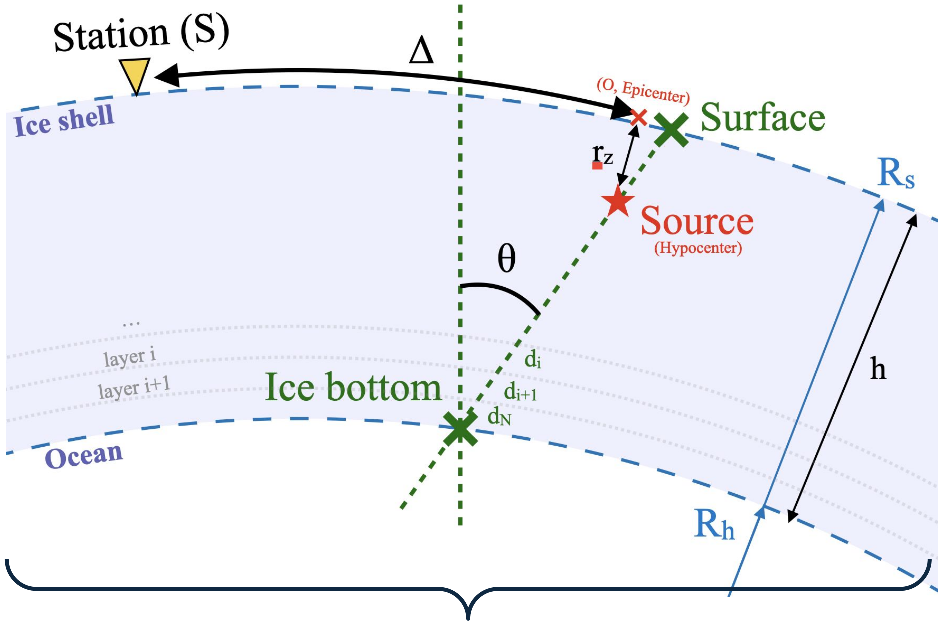
Continuous Wavelet Transform

Continuous Wavelet Transform wrt instrumental noise

Detectable energy by the SP

Delaroque et al. 2025 (accepted)

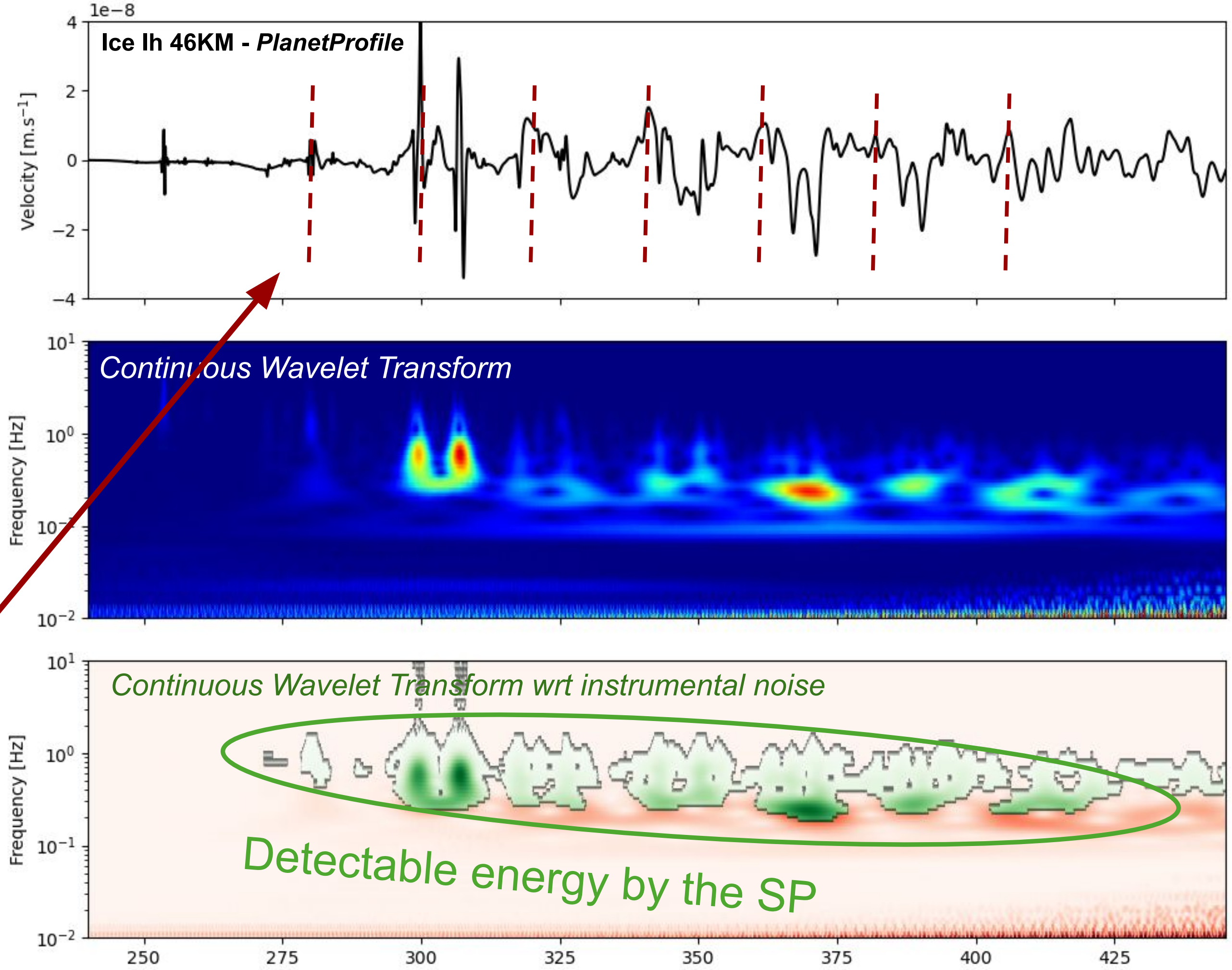
Retrieving the Outer Ice Shell thickness



$$t^{\mathrm{PeP}}(n) = \frac{d^{z\to h} + (2n-1)d^{s\to h}}{V_{p,Ih}},$$

$$d^{i\to j} = \sqrt{R_i^2 + R_j^2 - 2\cdot R_i \cdot R_j \cdot \cos(\theta)},$$

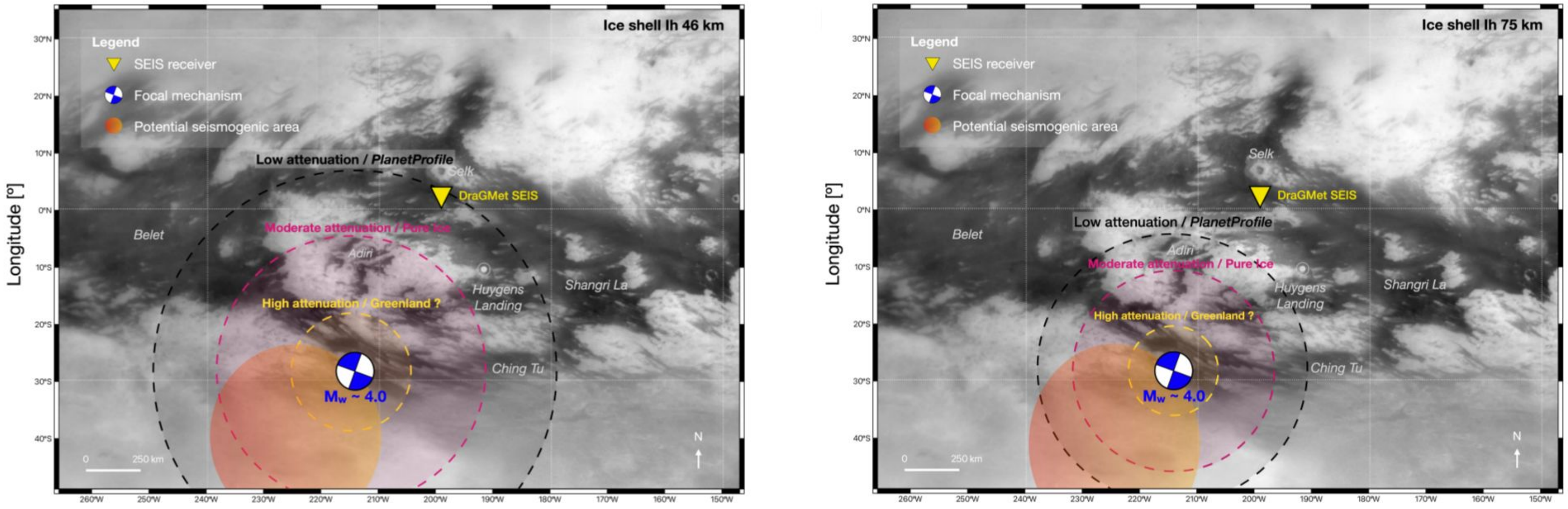
$$i,j \in \{z,s,h\},\ i \neq j, \text{and } \theta = \frac{\Delta_{OS}}{2n}$$



Delaroque et al. 2025 (accepted)

Take-home Messages

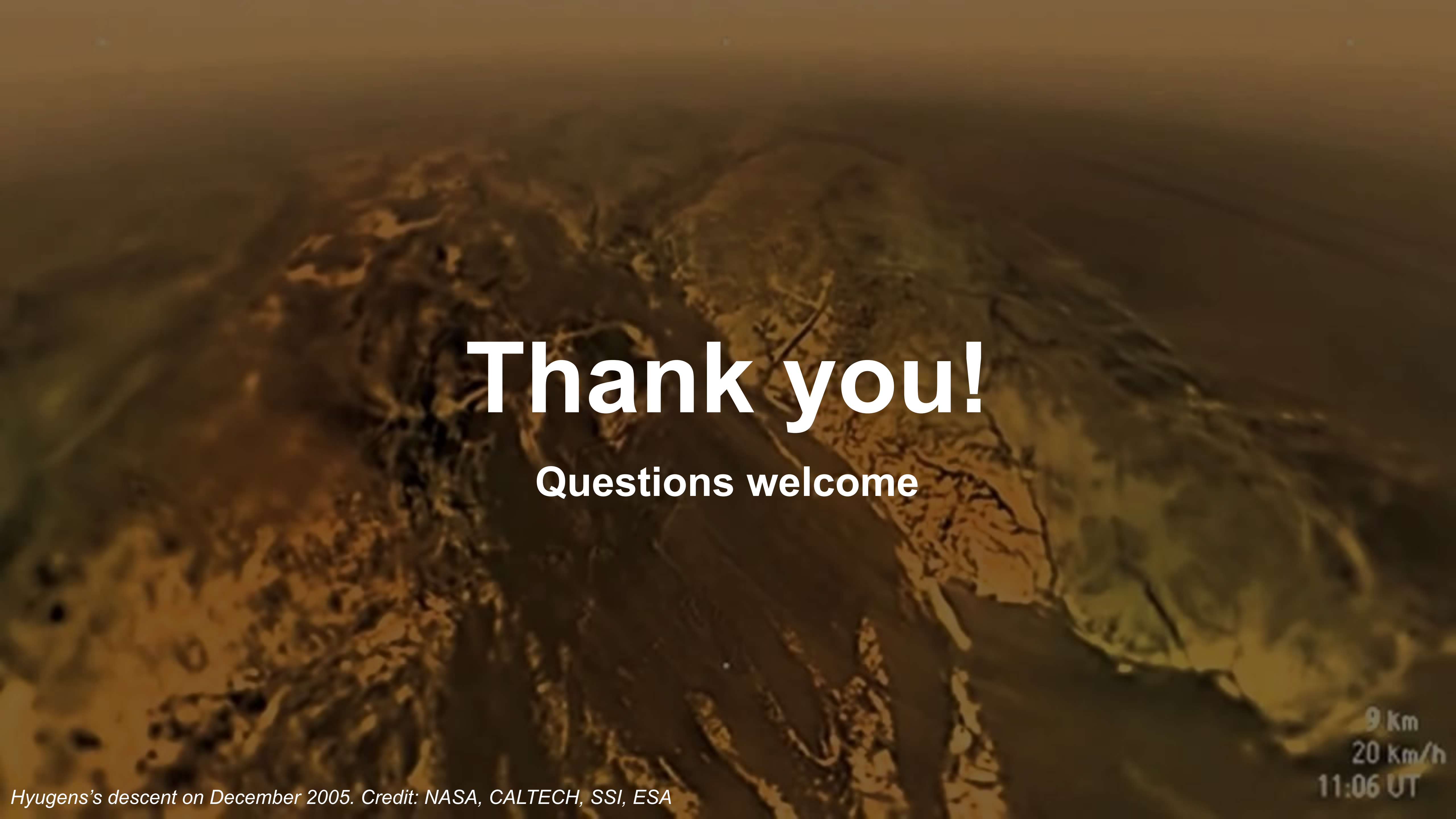
- Detection from potential seismogenic zone with **environmental limits** needs either a **Mw ≥ 4.0**, a **low attenuation** and/or **a closer distance**
- Depending on attenuation, we can detect **from 600–1,000 km**.
- **Time separations** may be useful for **measuring the outer ice shell thickness**



Delaroque et al. 2025 (accepted)

Thank you!

Questions welcome



Hyugens's descent on December 2005. Credit: NASA, CALTECH, SSI, ESA

References (1/2)

J. W. Barnes et al. Science goals and objectives for the Dragonfly Titan rotorcraft relocatable lander. Planet. Sci. J., 2(4):130, 2021. **doi:** 10.3847/PSJ/abfdcf.

L. M. L. Burkhard et al. Strike-slip faulting on Titan: Modeling tidal stresses and shear failure conditions due to pore fluid interactions. *Icarus*, 371:114700, 2022. **doi:** 10.1016/j.icarus.2021.114700.

F. Cammarano et al. Long-period seismology on Europa: 1. physically consistent interior models. *J. Geophys. Res. Planets*, 111(E12), 2006. **doi:** 10.1029/2006JE002710.

H. P. Crotwell et al. The TauP Toolkit: Flexible Seismic Travel-Time and Ray-Path Utilities. *Seism. Res. Lett*. 2(2), 154—60, 1999. **doi:** 10.1785/gssrl.70.2.154.

K. Dapré & J. E. Irving. Global Seismology of Enceladus. *Icarus*, 408, 115806, 2024. **doi:** 10.1016/j.icarus.2023.115806.

L. Delaroque et al. Investigating the Detectability of Body Wave Phases from Tidal Ice Cracking Events on Titan with the Dragonfly Short-Period Seismometer. *ESS Open Archive* . February 25, 2025. **doi:** 10.22541/essoar.174051738.81748171/v1.

R. L. Kovach & C. F. Chyba. Seismic Detectability of a Subsurface Ocean on Europa. *Icarus*, 150(279-287), 2001. **doi:** 10.1006/icar.2000.6577.

D. Kuroiwa. Internal Friction of Ice. Ⅲ ; The Internal Friction of Natural Glacier Ice. In: *Contribution from the Institute of Low Temperature Science*, A. 18(49-62), 1964, **URL:** http://hdl.handle.net/2115/20229.

S. Goossens et al. A low-density ocean inside Titan inferred from Cassini data. *Nature Astronomy*, 8, 846-855, 2024. **doi:** 10.1038/s41550-024-02253-4.

R. B. Herrmann. Computer programs in seismology: An evolving tool for instruction and re search. *Seism. Res. Lettr*., 84:1081–1088, 2013. **doi:** 10.1785/0220110096.

R. D. Lorenz et al. Wind and surface roughness considerations for seismic instrumentation on a relocatable lander for Titan. *Planet. Space. Sci*., 206:105320. **doi:** 10.1016/j.pss.2021.105320.

A. G. Marusiak et al. Exploration of Icy Ocean Worlds Using Geophysical Approaches. Planet. Sci. J., 2:150 (14pp), 2021. **doi:** 10.3847/PSJ/ac1272.

G. Mitri et al. Mountains on Titan: modeling and observations. *J. Geophys. Res. Planets*, 115(E10), 2010. **doi:** 10.1029/2010JE003592.

References (2/2)

K. Onodera et al. Assessment of atmospheric-driven ground noises for Dragonfly’s seismic observation on titan. In *SSA*, 2024.

K. Onodera et al. Developing a short-period Seismometer for Dragonfly: The Instrumental Noise Assessment of Engineering Model. In *56th LPSC*, 2025. **Retrieve from:** **https://www.hou.usra.edu/meetings/lpsc2025/pdf/1145.pdf**.

L. E. Peters et al. Seismic Attenuation in Glacial Ice: A Proxy for Englacial Temperature. *J. Geophys. Res.,* 117, FE2008, **doi:** **10.1029/2011JF002201**.

H. Shiraishi et al. Status update of seismometer package for Dragonfly relocatable lander. In *JpGU*, 2024.

C. Sotin et al. Titan’s interior structure and dynamics after the Cassini-Huygens mission. *Annu. Rev. Earth Planet. Sci.*, 49(1):579–607, 2021. **doi:** **10.1146/annurev-earth-072920-052847**.

S. D. Vance et al. Vital signs: Seismology of ocean worlds. Astrobiology, 18:37–53, 2018a. **doi:** **10.1002/2017JE005341**.

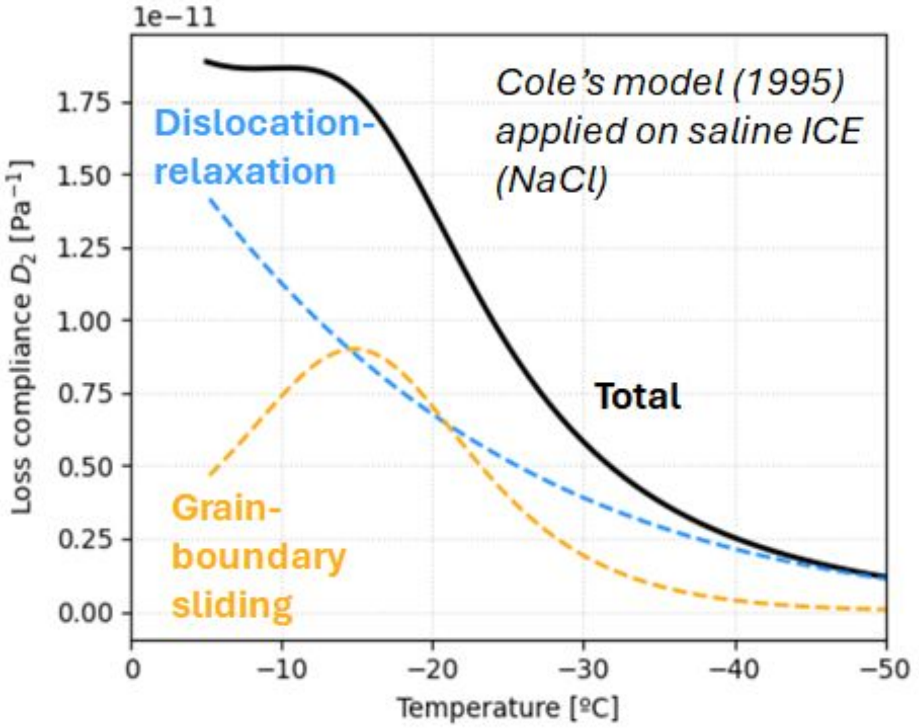
S. D. Vance et al. Geophysical investigations of habitability in ice-covered ocean worlds. *J. Geophys. Res. Planets*, 123:180–205, 2018b. **doi:** **10.1002/2017JE005341**.

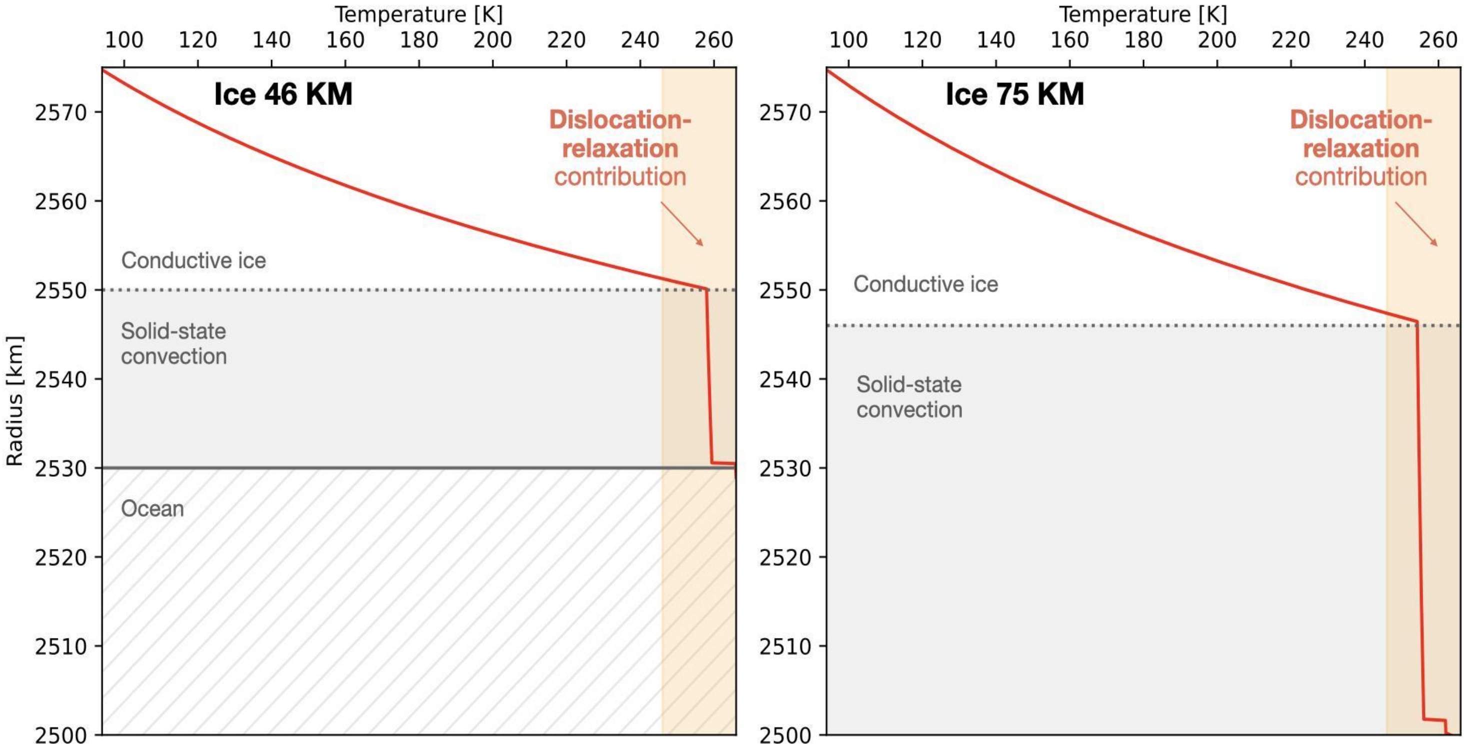
Appendices

Credit: Getty/Stocktrek Images

Anelastic Attenuation Models

Attenuation model extrapolation at seismic frequencies -> **Dislocation-relaxation mechanism** non-negligible at **LF (1 Hz)** and **HT (<-30ºC)**





Detectability Mapping

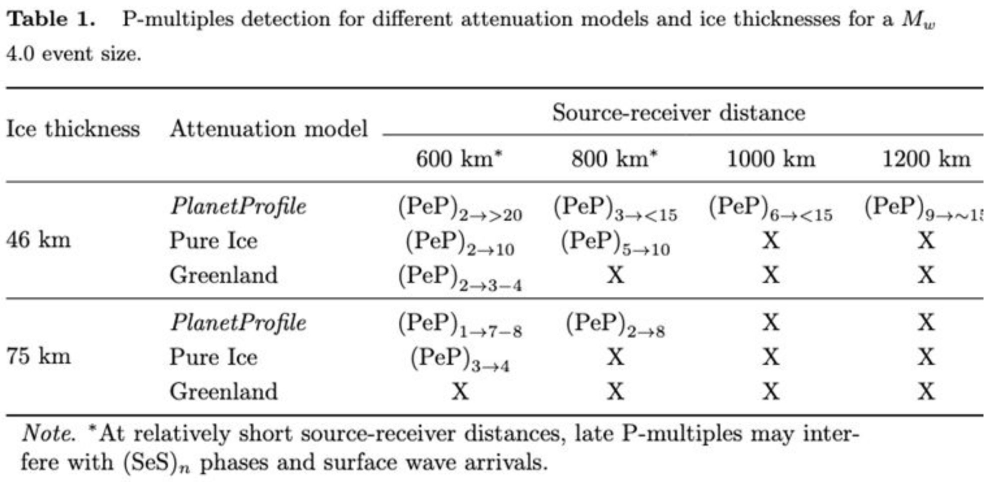
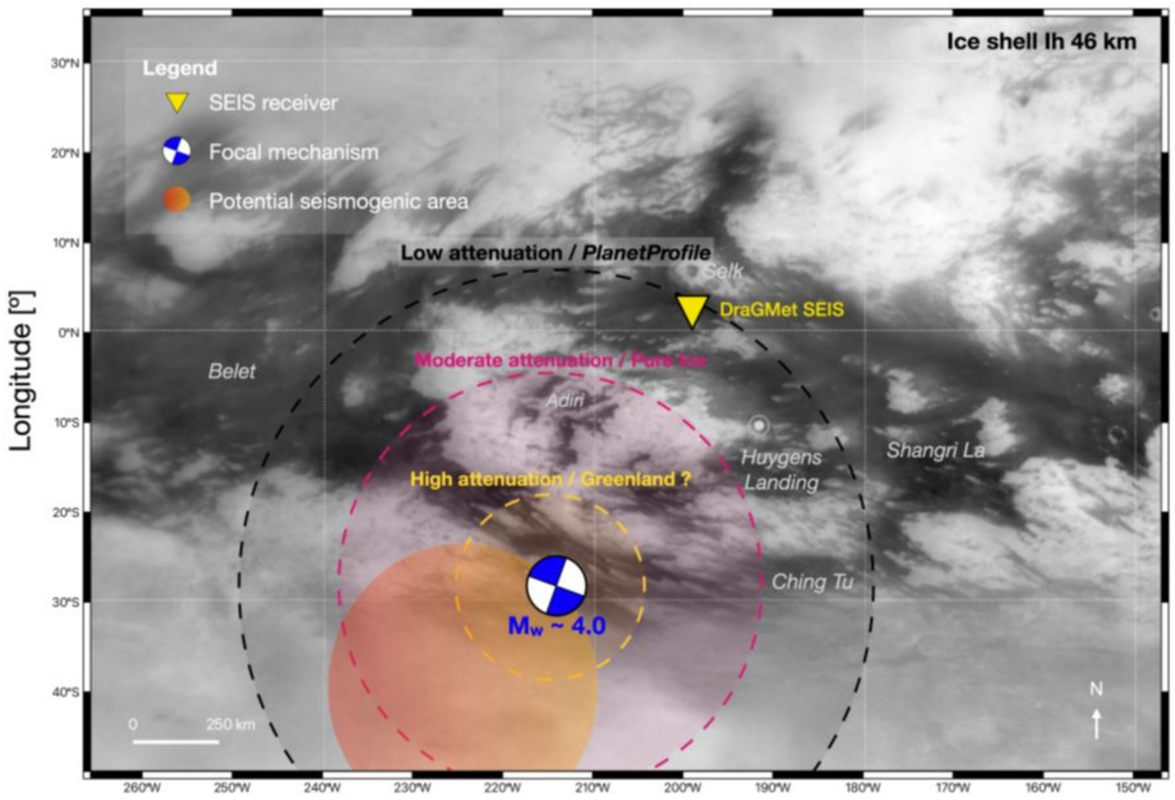
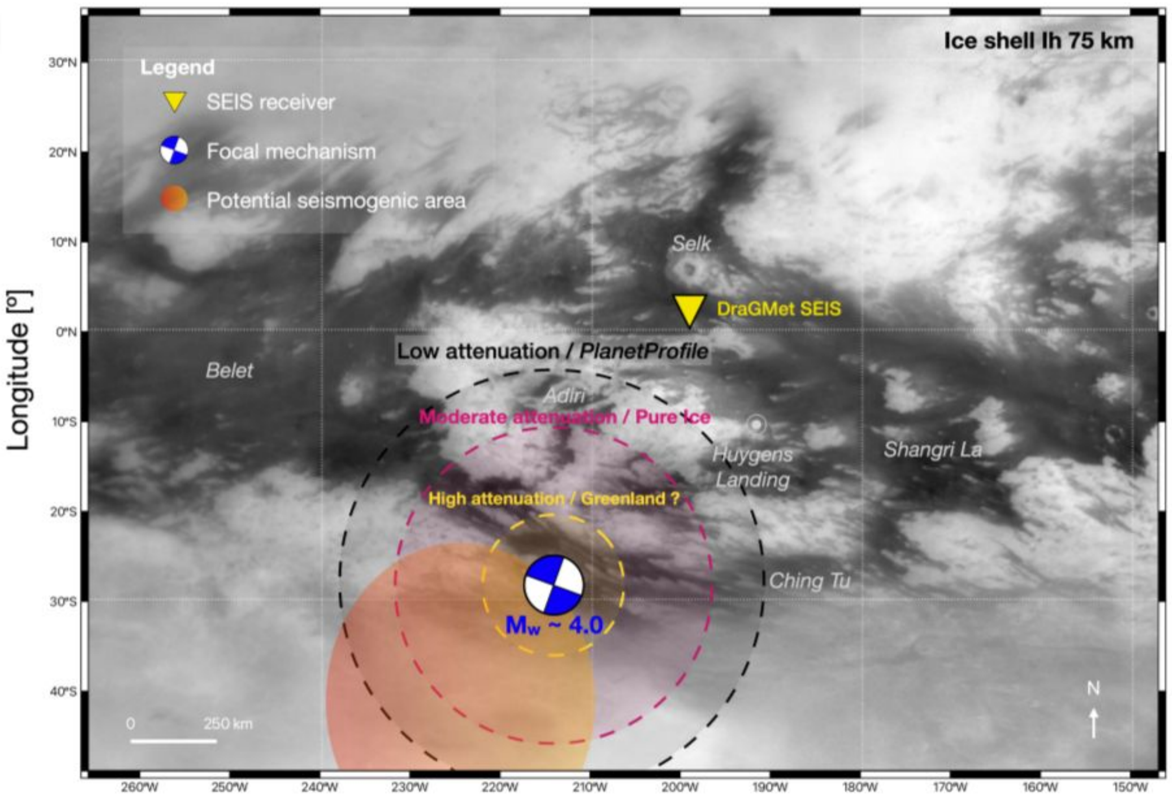


Table 1. P-multiples detection for different attenuation models and ice thicknesses for a M_w 4.0 event size.

Ice thickness	Attenuation model	Source-receiver distance			
		600 km*	800 km*	1000 km	1200 km
46 km	*PlanetProfile*	$(\mathrm{PeP})_{2\to>20}$	$(\mathrm{PeP})_{3\to<15}$	$(\mathrm{PeP})_{6\to<15}$	$(\mathrm{PeP})_{9\to\sim1}$
	Pure Ice	$(\mathrm{PeP})_{2\to10}$	$(\mathrm{PeP})_{5\to10}$	X	X
	Greenland	$(\mathrm{PeP})_{2\to3-4}$	X	X	X
75 km	*PlanetProfile*	$(\mathrm{PeP})_{1\to7-8}$	$(\mathrm{PeP})_{2\to8}$	X	X
	Pure Ice	$(\mathrm{PeP})_{3\to4}$	X	X	X
	Greenland	X	X	X	X

Note. *At relatively short source-receiver distances, late P-multiples may interfere with $(\mathrm{SeS})_n$ phases and surface wave arrivals.





Source – Choice of the Event Size (1/2)

Objectives: What are the expected event sizes?

- Determine the **seismic energy release** (*Gutenberg & Richter, 1944*)
- Link the **observed number of events** as a function of **magnitude**
- Need to define 3 parameters: the **b-value**, the **cumulative seismic moment** ΣM_0, the **largest event** $M_0^\star$ expected

Gutenberg & Richter, 1944

(1) $$\log_{10} N(M_w) = a - bM_w$$

Golombek et al. 1992

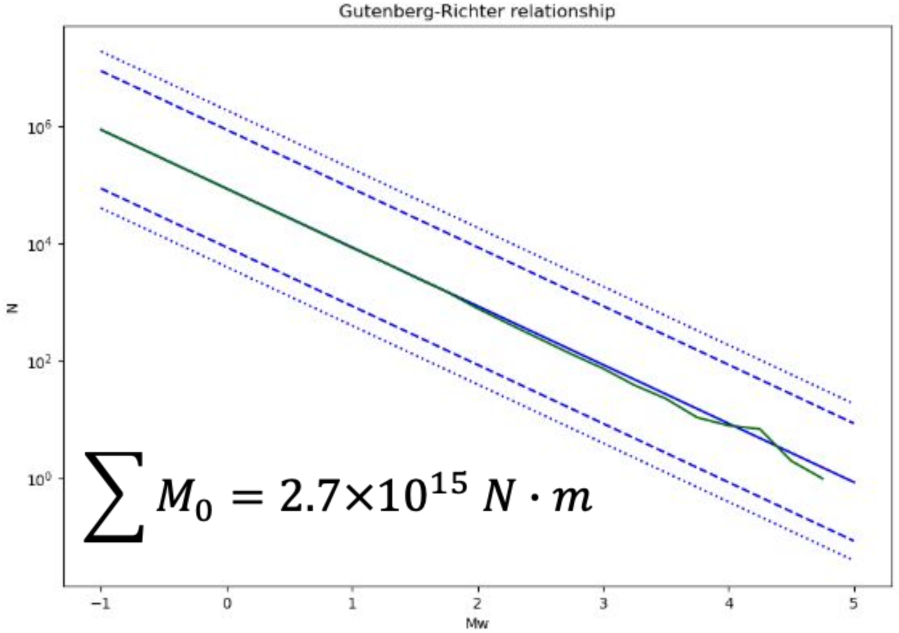
(2) $$N(M_0) = AM_0^{-B} \longrightarrow$$

$$\log_{10} M_0 = 1.5M_w + 9.1$$

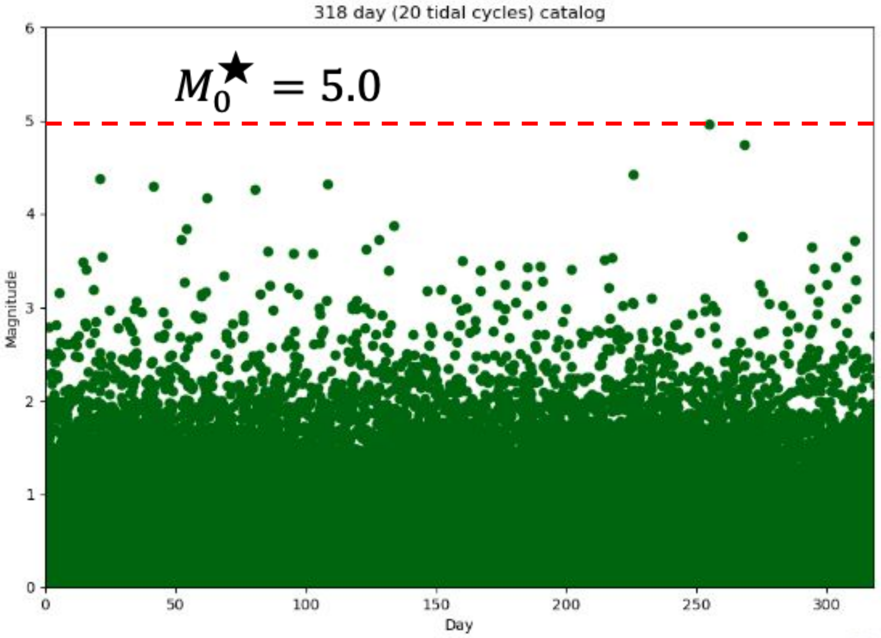
$$a = \log_{10} A - 9.1B$$

$$b = 1.5\ B$$

(3) $$\boxed{\sum M_0 = \frac{AB}{1-B}\left(M_0^\star\right)^{1-B}}$$



$$\sum M_0 = 2.7\times10^{15}\ N\cdot m$$



$$M_0^\star = 5.0$$

Panning et al. 2021

Source – Choice of the Event Size (2/2)

Objectives: Is the stress drop consistent with tidal models?

- The **seismic moment** M_0 linked to the moment magnitude M_w by *Kanamori, 1977*
- **Static stress drop** for a regular crack model (i.e. $L \gg w$) from *Kanamori & Anderson 1975* expressed in terms of M_0

Kanamori, 1977

(1) $$\log_{10} M_0 = \frac{3}{2} M_w + 9.1$$

$$\begin{cases} M_w\ 4.0 \longrightarrow 1\times10^{15}\ N\cdot m \\ M_w\ 3.0 \longrightarrow 4\times10^{13}\ N\cdot m \end{cases}$$

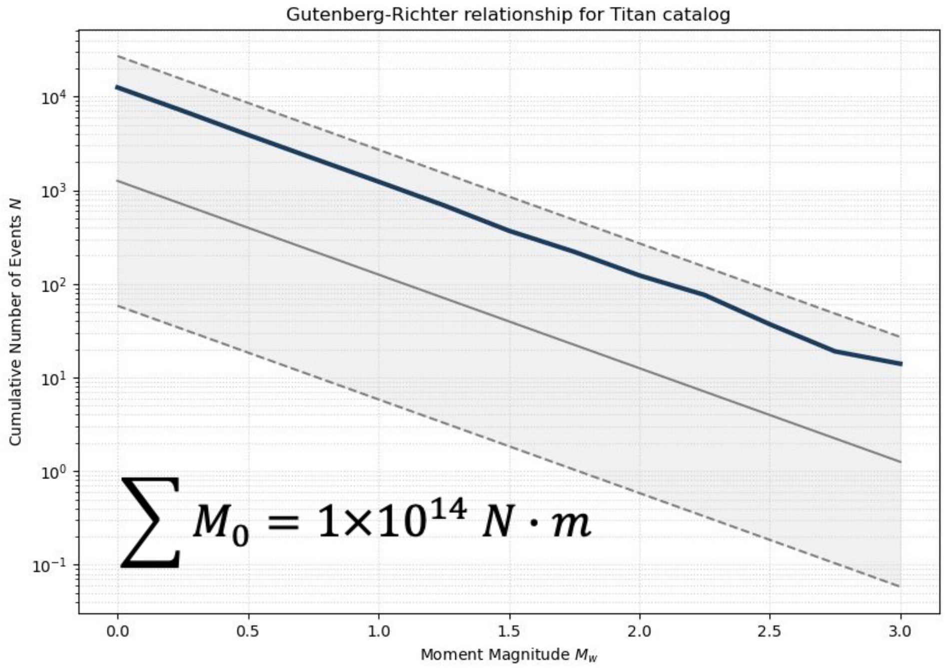
Kanamori & Anderson 1975

(2) $$\Delta\sigma = \frac{2}{\pi}\frac{M_o}{Lw^2}$$

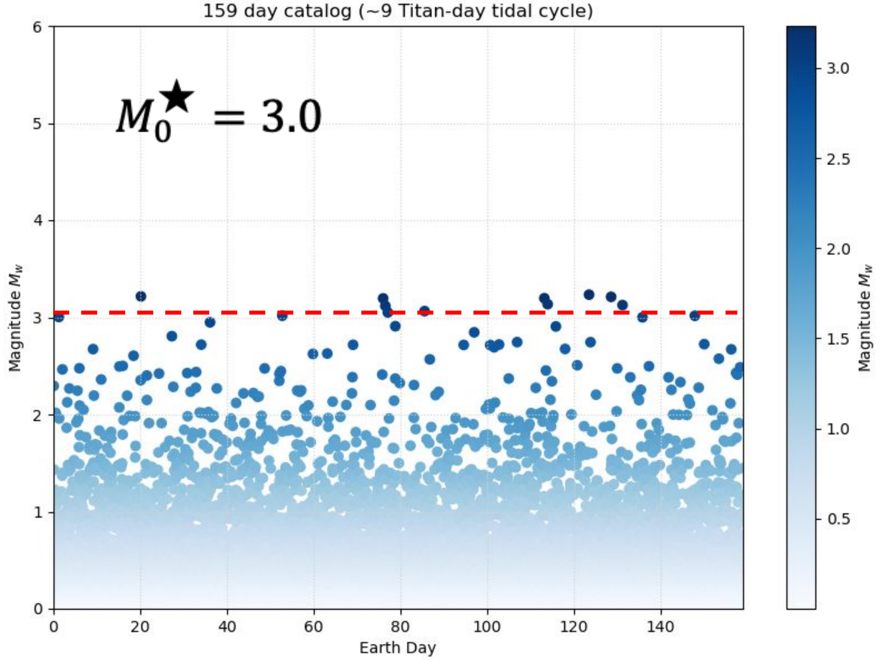
Tidal stress models ⟶ ~ 25 kPa

$M_w\ 3.0 \longrightarrow w \sim 20\ m, L \sim 1\ km \quad \sim 25 kPa$

$M_w\ 4.0 \longrightarrow w \sim 80\ m, L \sim 2\ km \quad \sim 50 kPa$



$$\sum M_0 = 1\times10^{14}\ N\cdot m$$



$$M_0^{\bigstar} = 3.0$$

Here I've updated the values from Panning et al. 2018 & Panning et al. 2021 (see slide before)

Source – Tidal dissipation rate: what do we rely on?

As the k_2 value has been updated, the tidal dissipation rate used for seismicity catalog predictions should change too! Therefore, some updates are needed.

According to *Hurford et al. 2020*, the total energy dissipated in a given time period T is given by:

$$E_T = \left(\frac{k_2}{Q}\right)\left(\frac{21}{2}e^2\right)\left(\frac{GM_P^2nR^5}{a^6}\right)\int_0^T (1 - 0.143\cos(2nt))dt$$

Which becomes

$$\boxed{E_T = \left(\frac{k_2}{Q}\right)\left(\frac{21}{2}e^2\right)\left(\frac{GM_P^2nR^5}{a^6}\right)\left[T - 0{,}143\,\frac{\sin(2nt)}{2n}\right]}$$

The parameters to “choose” are mainly k_2 and Q

With the orbital parameters:

- e: orbital ellipticity
- G: gravitational constant
- M_P: mass of Saturn
- R: Radius of Titan
- P_{orb}: Period of revolution
- n: mean motion $n = \frac{2\pi}{P_{orb}}$

Now, the cumulative moment (i.e. characteristic timescale for moment balance) can be expressed as:

$$\sum M_0 = \eta \cdot \left(\frac{k_2}{Q}\right)\left(\frac{21}{2}e^2\right)\left(\frac{GM_P^2nR^5}{a^6}\right) \cdot T$$

The largest predicted seismic event is written as:

$$M_C = f \cdot \sum M_0$$

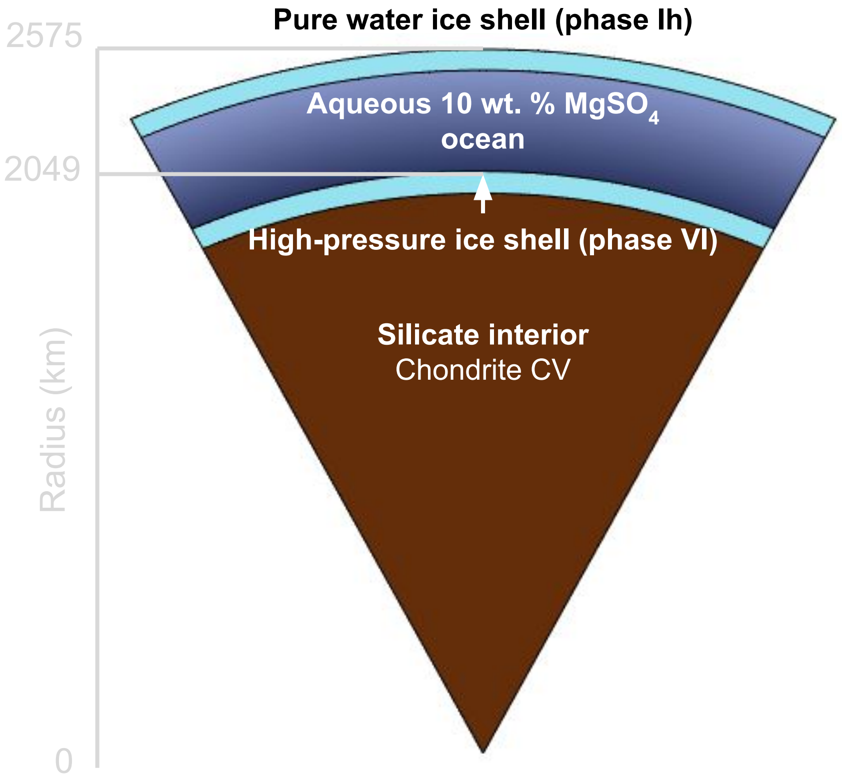
With f the fraction of the “total moment release captured in the largest seismic event”, and η the “conversion factor between total energy dissipated and total seismic moment release” according to *Hurford et al. 2020*.
The conversion of M_0 to M_w based on *Kanamori et al. 1977*:

$$M_{w,C} = \frac{2}{3}(\log_{10} M_C - 9.1)$$

Where does actually the Q value come from? See the new paper of Downey et al. 2025!!

Models – Details on the Interior Structure used

T_b = 262 K



Old values

C/MR^2 = **0.3414** ± 0.0005 (*Fortes et al. 2007, Iess et al. 2010*) → **0.345** ± 0.01

k_2 ∈ [**0.589** ± 0.15; **0.637** ± 0.224] (*Iess et al. 2012*) → **0.375** ± 0.06

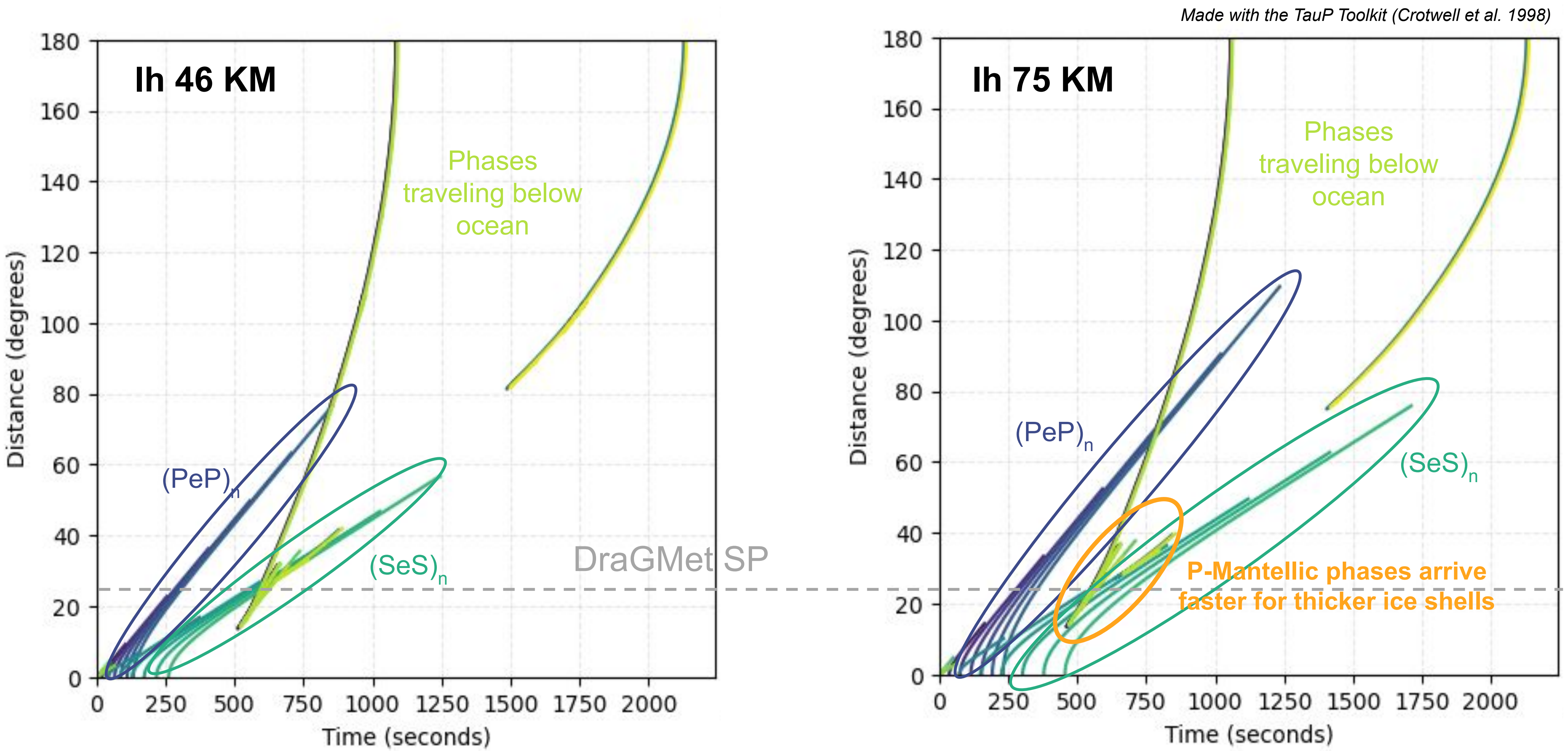
New values (*Goossens et al. 2024*)

Parameter	Titan's oceanic composition of 10 wt. % MgSO4	
	Ice Ih 46 km	Ice Ih 46 km
ρ_{rock} moy. [kg.m^{-3}]	3625	3622
T_b* [K]	266.0	262.0
D_{Ih} [km]	46.0	75.0
D_{ocean} [km]	463.0	369.0
D_{VI} [km]	35.0	82.0
D_{mantle} [km]	2031	2049

* Temperature (Tb) between the ice shell and the ocean values from *Vance et al. 2018*. D is the layer thickness

Delaroque et al. 2025 accepted (Supp. Mater.)

Waveforms – Theoretical Ray-paths



P-Mantellic phases arrive faster for thicker ice shells

Made with the TauP Toolkit (Crotwell et al. 1998)