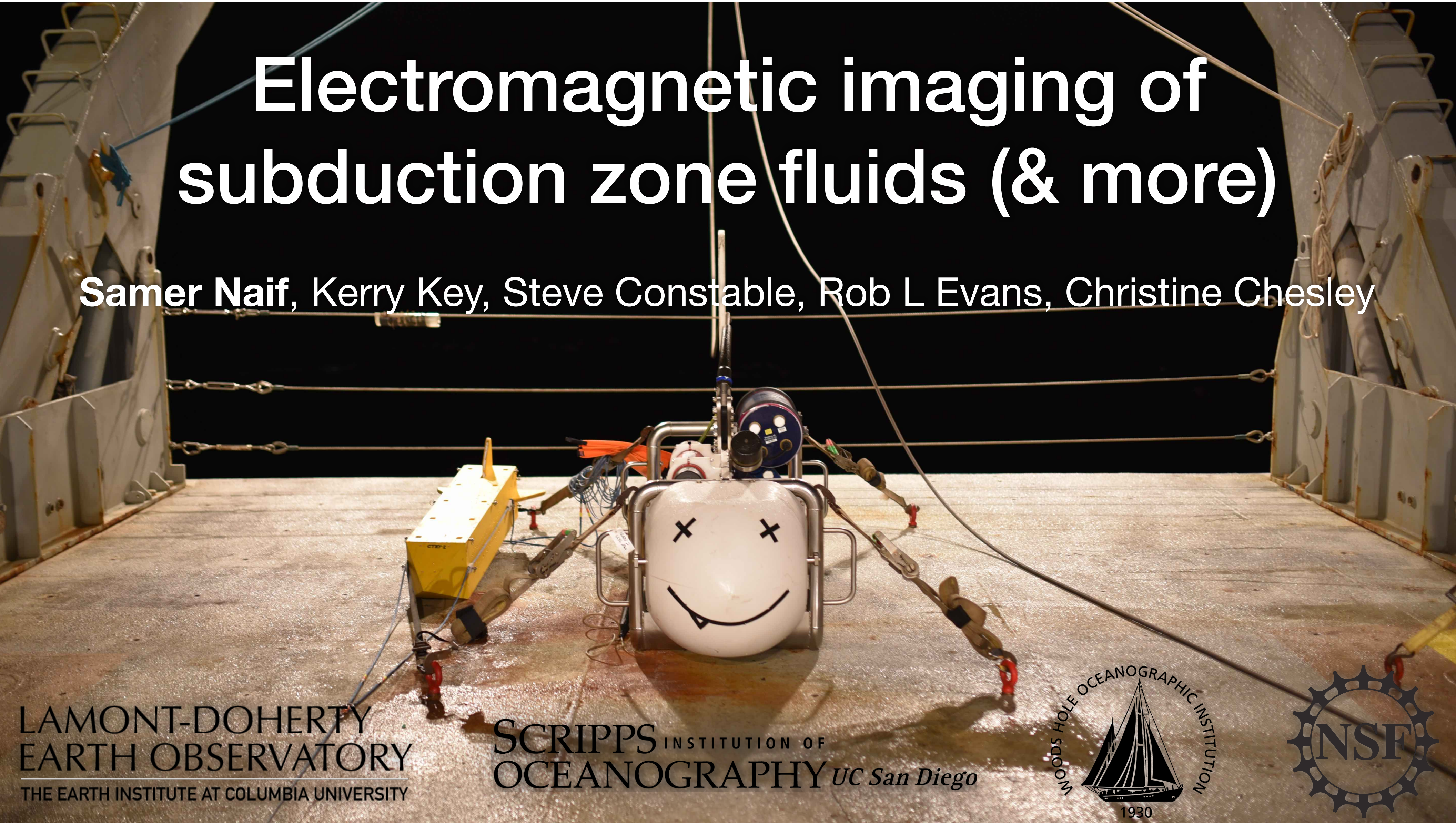
Electromagnetic imaging of subduction zone fluids (& more)

Samer Naif, Kerry Key, Steve Constable, Rob L Evans, Christine Chesley



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THE EARTH INSTITUTE AT COLUMBIA UNIVERSITY

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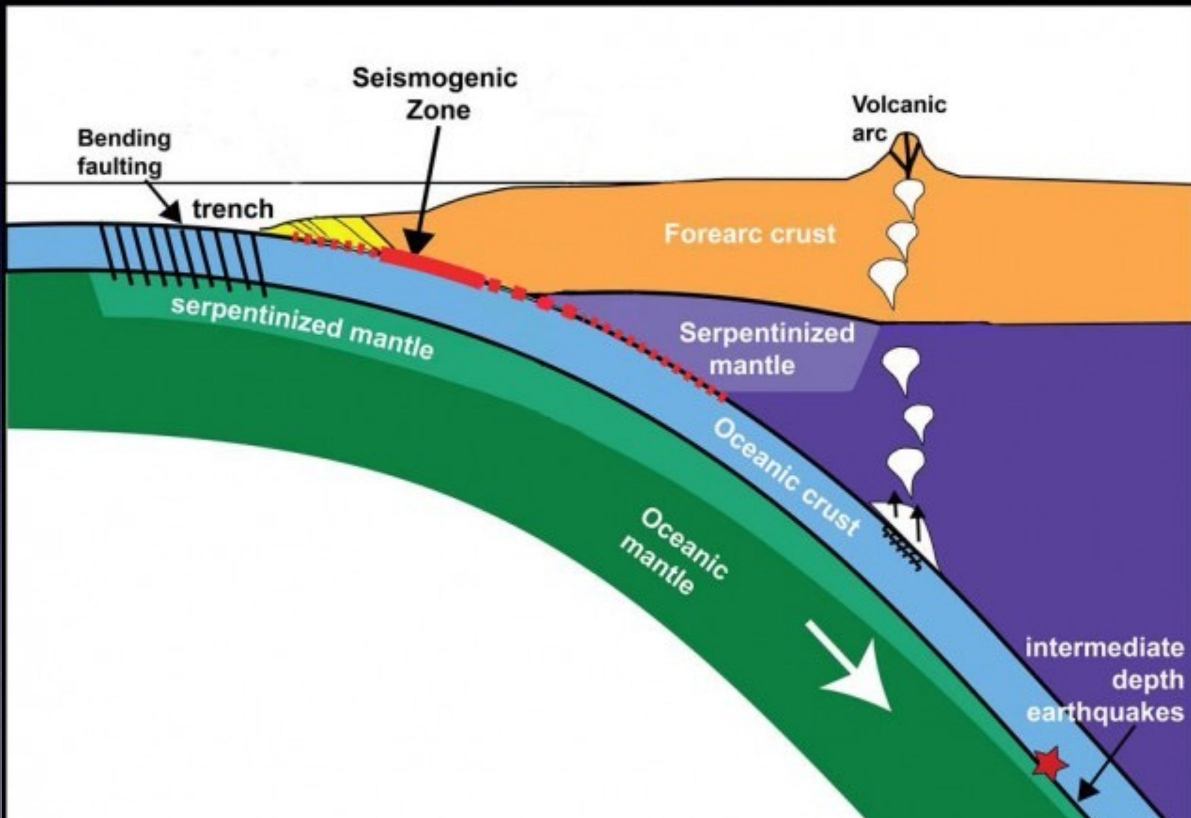
NSF

Subduction zones & fluids



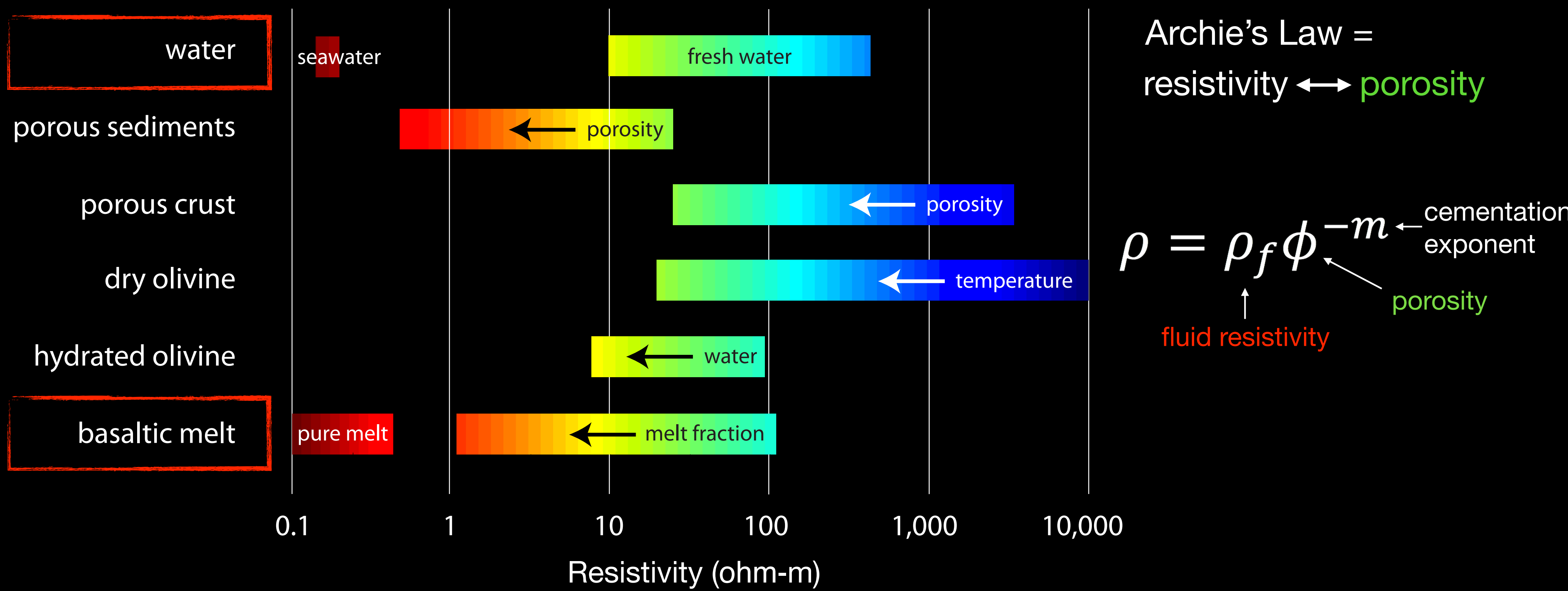
Shillington, modified from Oleskevich et al. (1999)

Slabs transport & release fluids at subduction zones

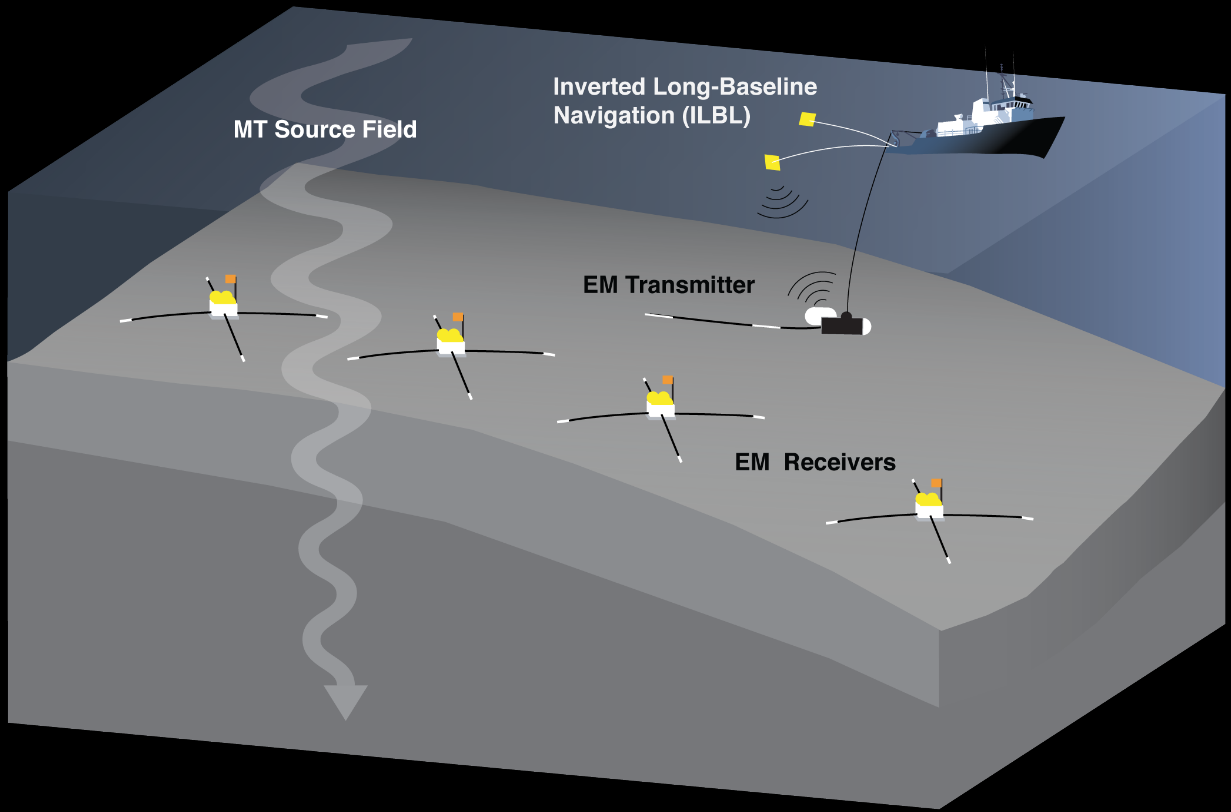
- Fluids weaken the plate interface, modulate megathrust seismicity
- Released H_2O promotes melting and drives of arc volcanism
- Stored H_2O is recycled to deep mantle, important for understanding water cycle

Electrical resistivity (ρ) of oceanic plates

is sensitive to porosity, temperature, and hydration



Marine EM methods image resistivity



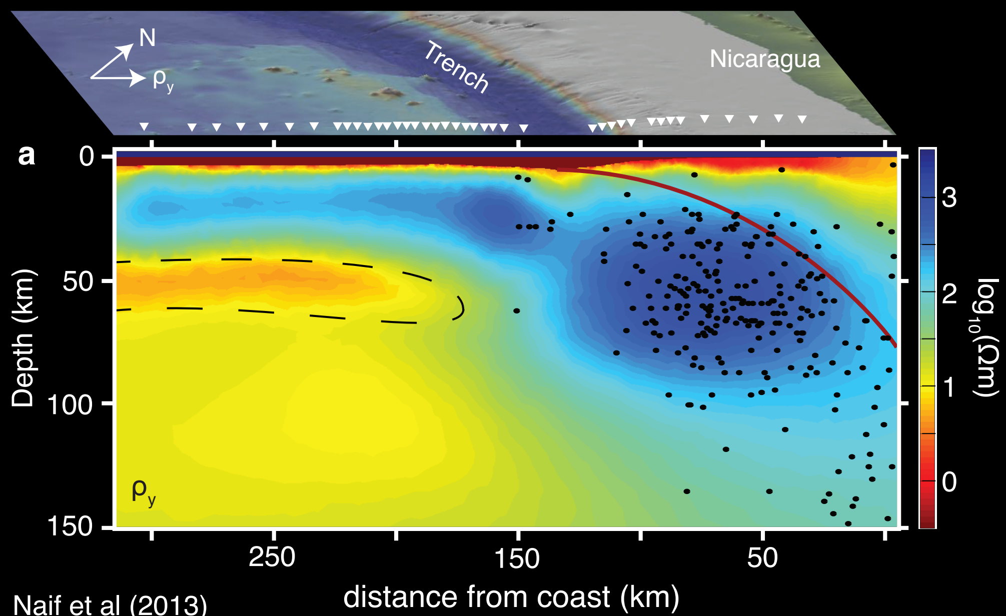
Magnetotellurics (MT)

- Natural source low-frequency method
- Ideal for mapping conductors
- Greater depth sensitivity
- Lower resolution

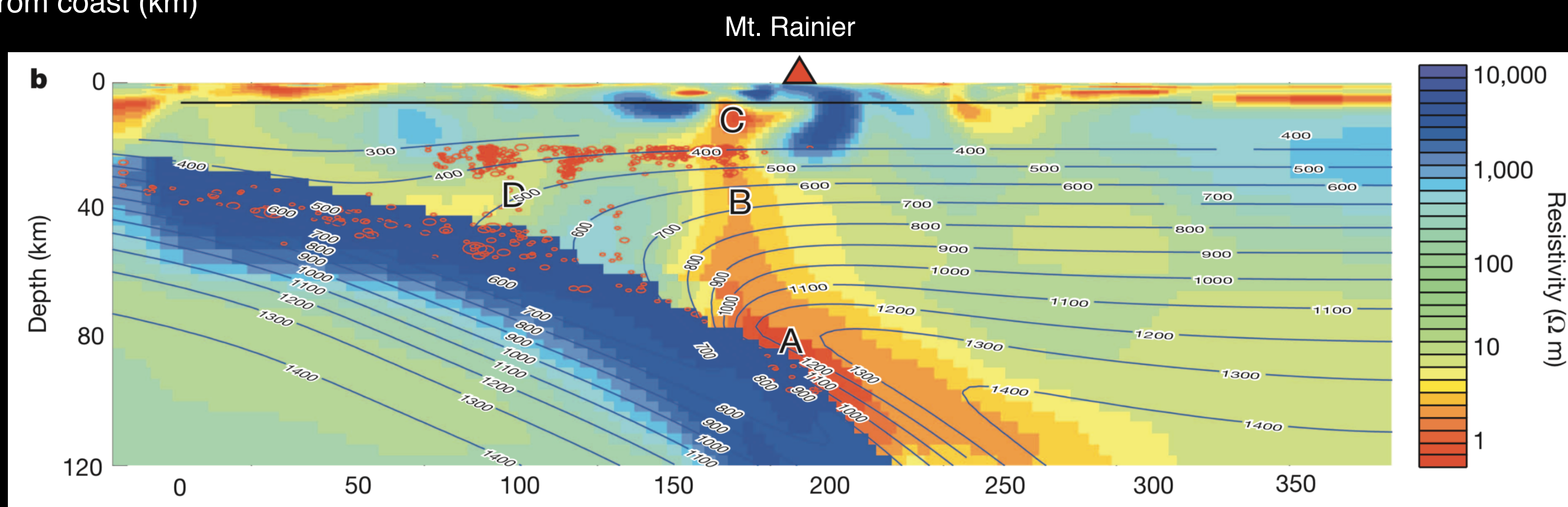
Controlled-Source EM (CSEM):

- Dipole source transmitter
- Ideal for mapping shallow structure
- Higher resolution
- Requires transmitter navigation

Brief aside:
example MT observations



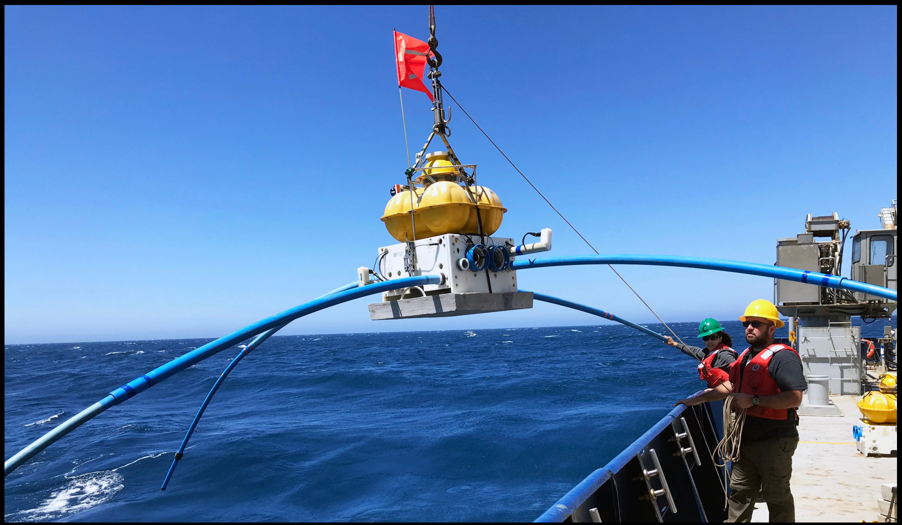
Naif et al (2013)



McGary et al (2014)

Operations & Time

- 30 minutes to assemble and deploy each receiver
- Transmitter deep-towing at 1.5-2.0 knots
- 200 km profile of MT+CSEM = 10 to 12 days ship time



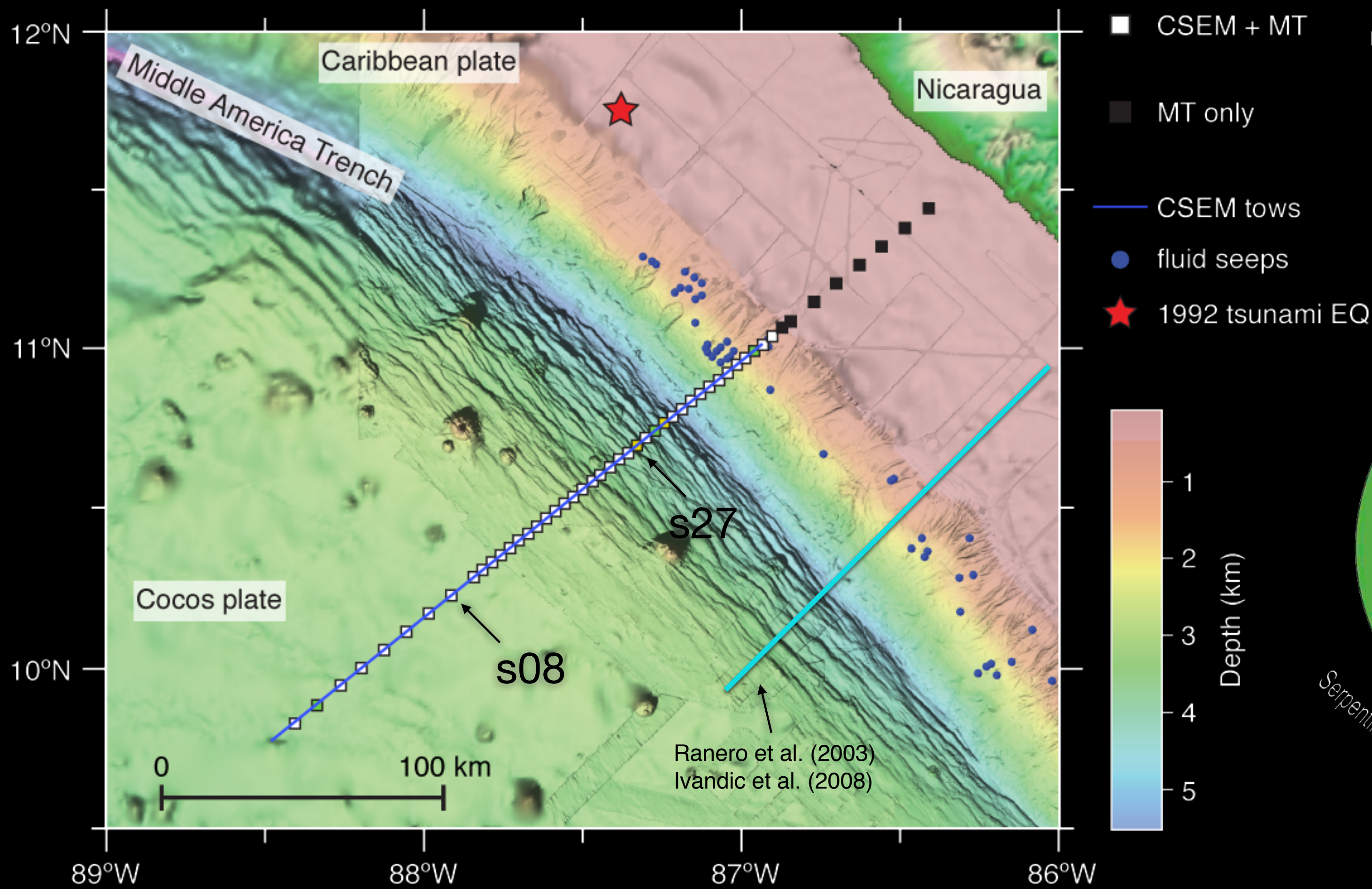
Step 1: deploy Scripps broadband receivers

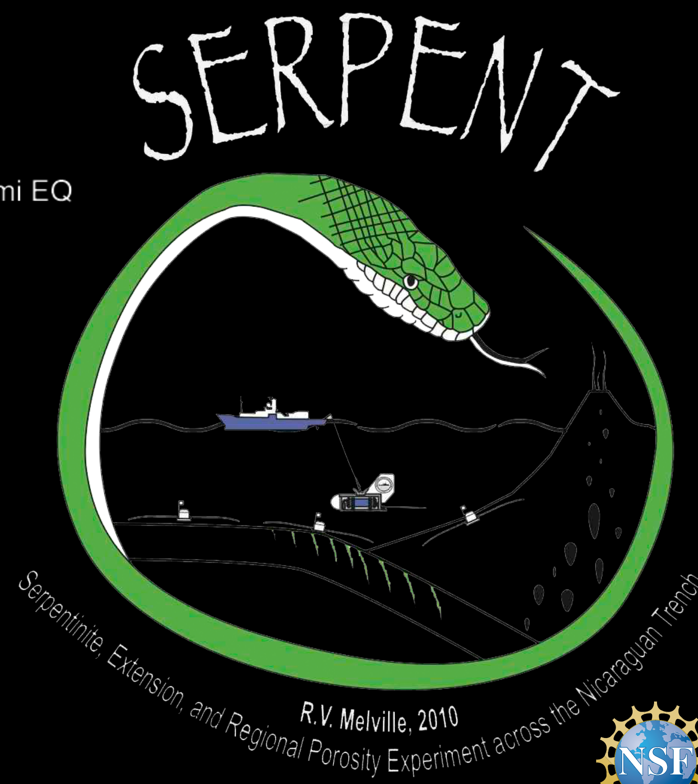
Step 2:
deploy, deep-tow, &
nav Scripps transmitter

Step 3: Recover and repeat

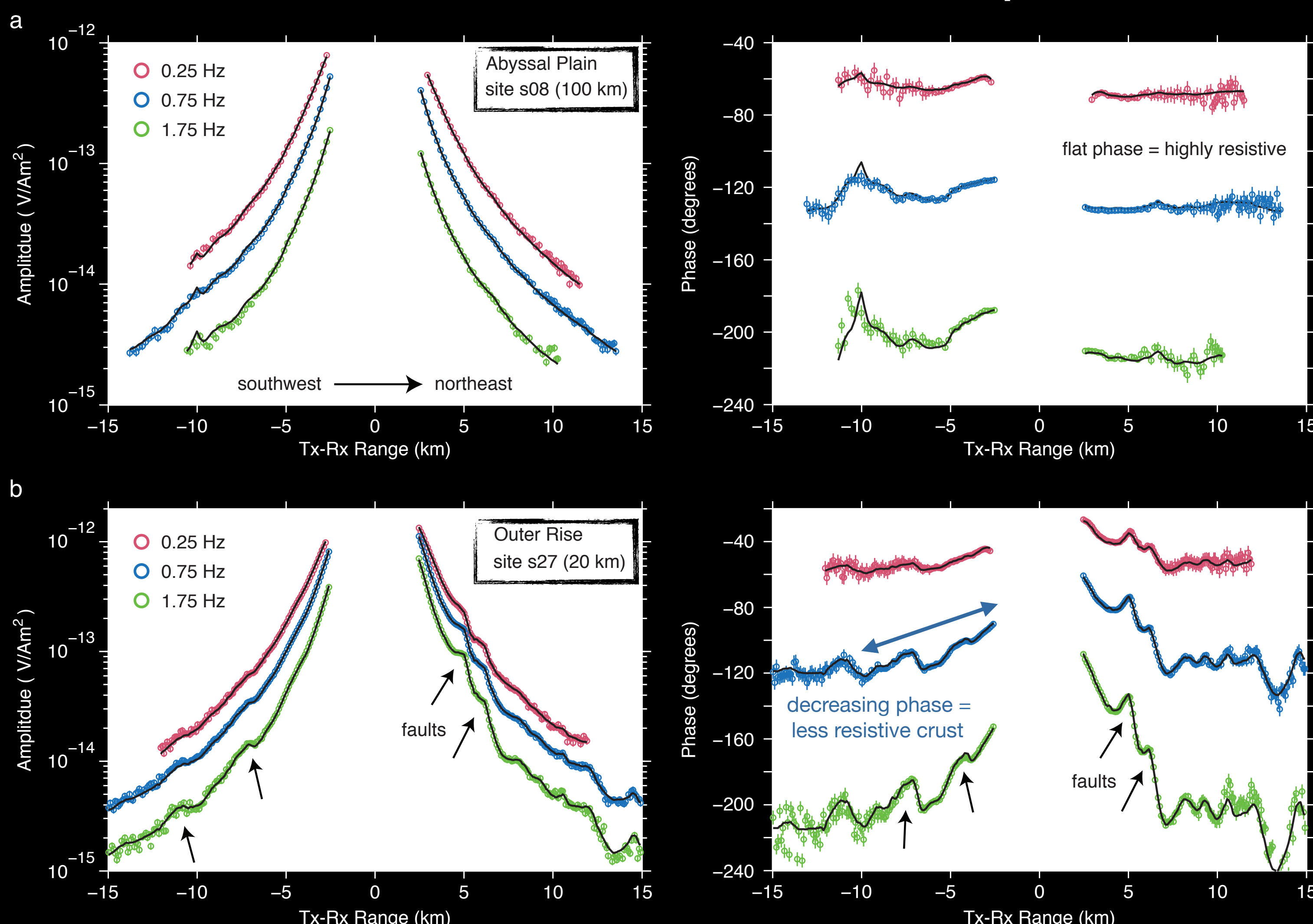
First marine CSEM survey at a subduction zone

- ➡ Single cruise (28 days)
- ➡ 54 broadband receivers
- ➡ 800+ line-km CSEM

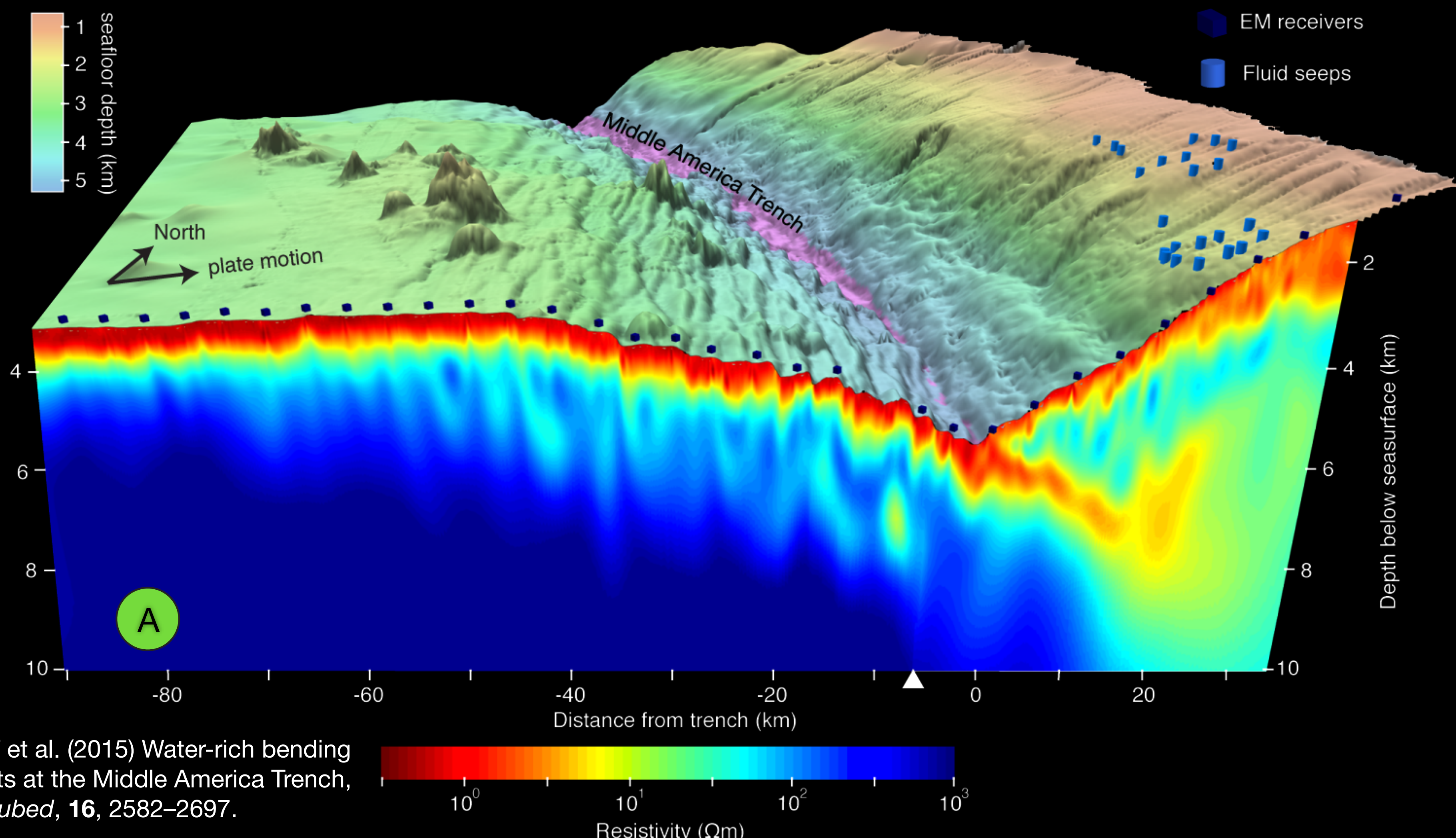




SERPENT CSEM data examples



CSEM Result data fit to RMS 1.0 @ 2% error floor



A Naif et al. (2015) Water-rich bending faults at the Middle America Trench, *G-cubed*, **16**, 2582–2697.

Electrical resistivity of the solid Earth (is porosity dependent)

Archie's Law = resistivity ⟶ porosity

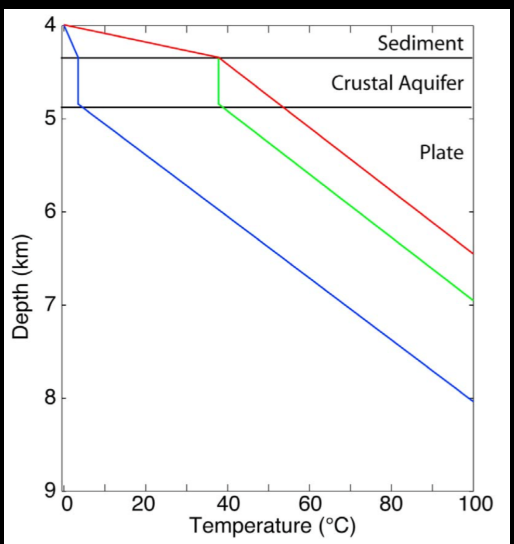
$$\rho = \rho_f \phi^{-m}$$

← cementation exponent
m = 2.0

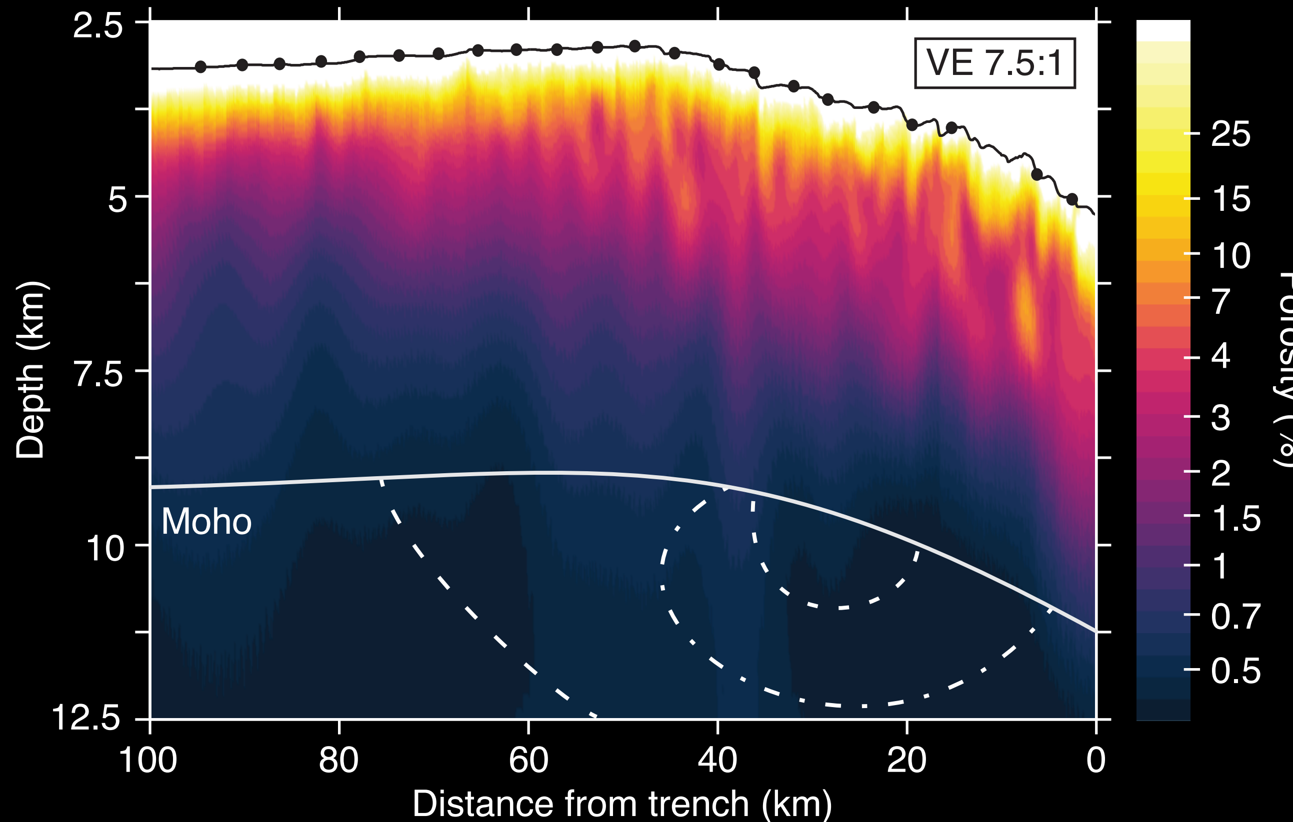
Seawater resistivity is temperature dependent

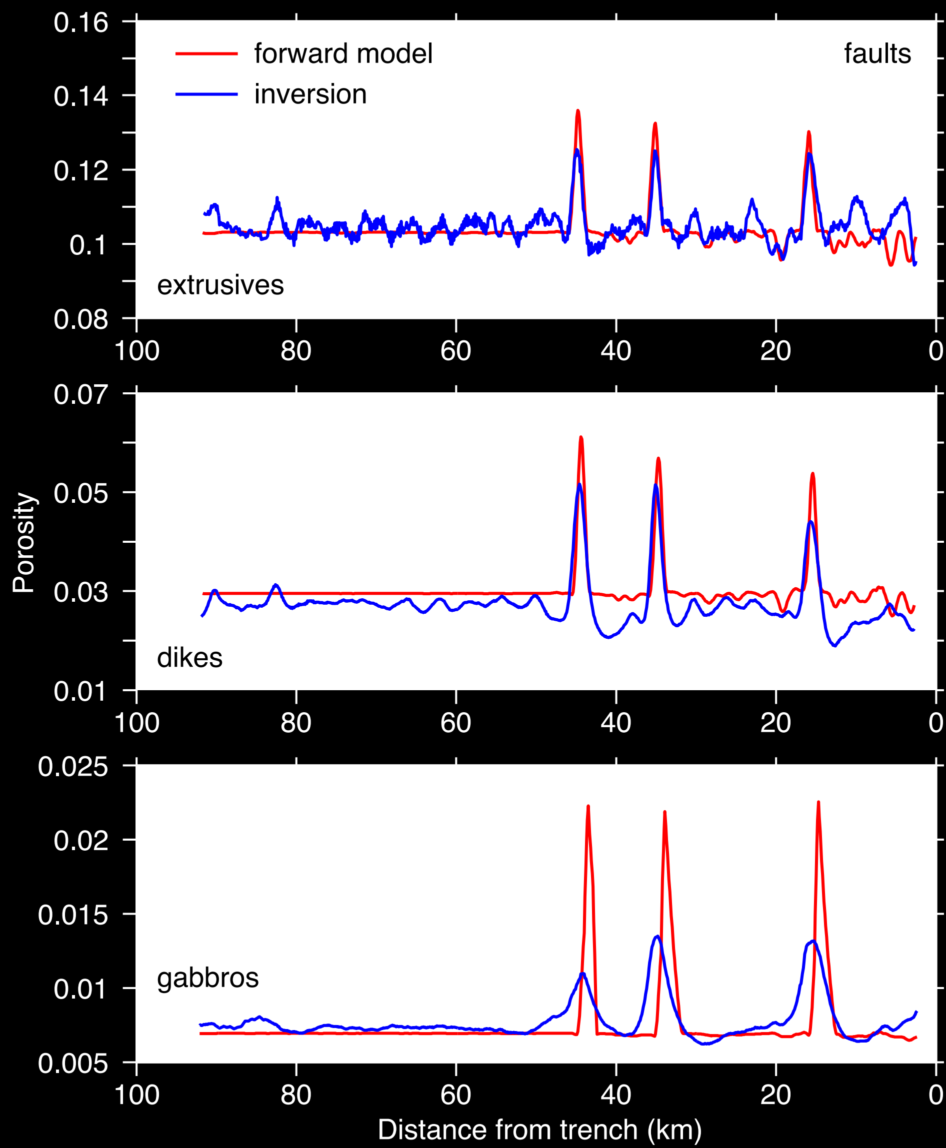
↓

$$\rho_f(T) \approx \frac{1}{3 + 0.1T}$$



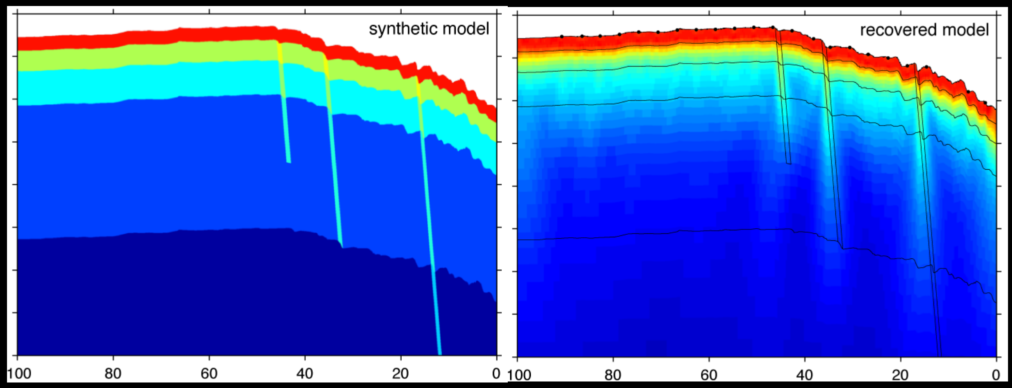
from Harris et al. (2010)



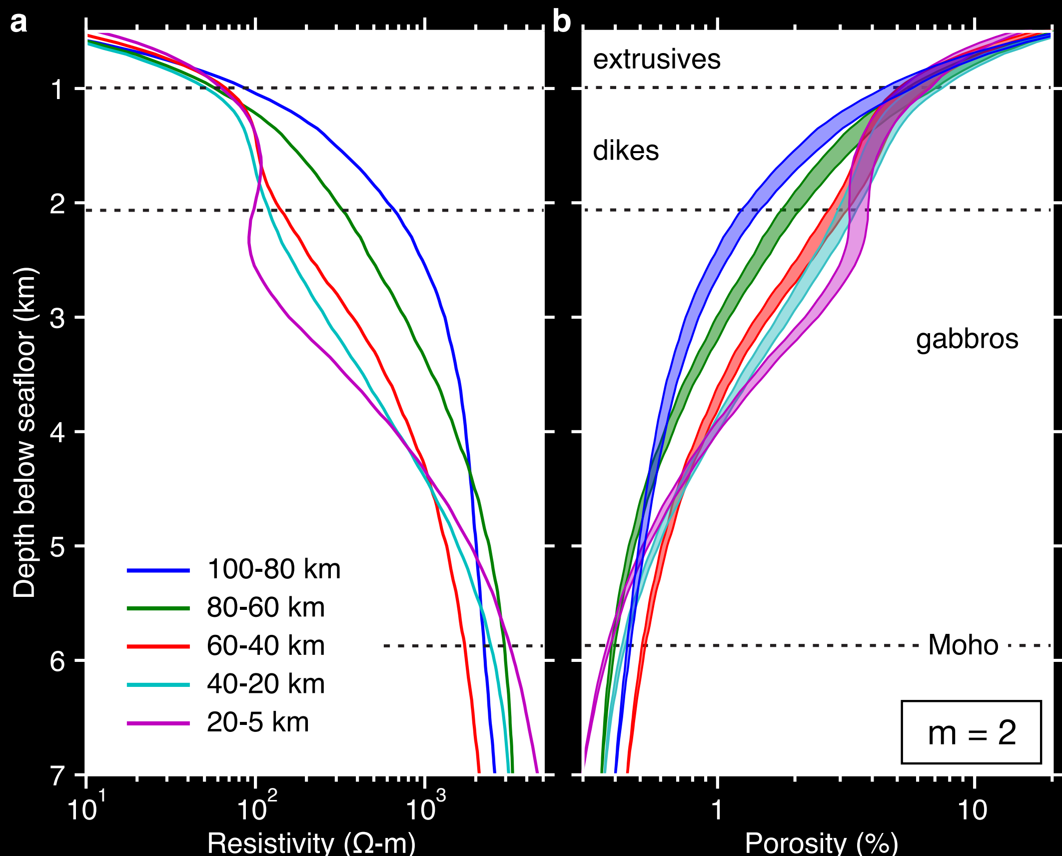


Synthetic model porosity

- Porosity estimates of synthetic fault model
- Fwd and inverse models agree in extrusives & dikes
- Gradually lose resolution in the gabbros (>3.5 km depth)
- Laterally integrated porosity is conserved



Incoming plate porosity



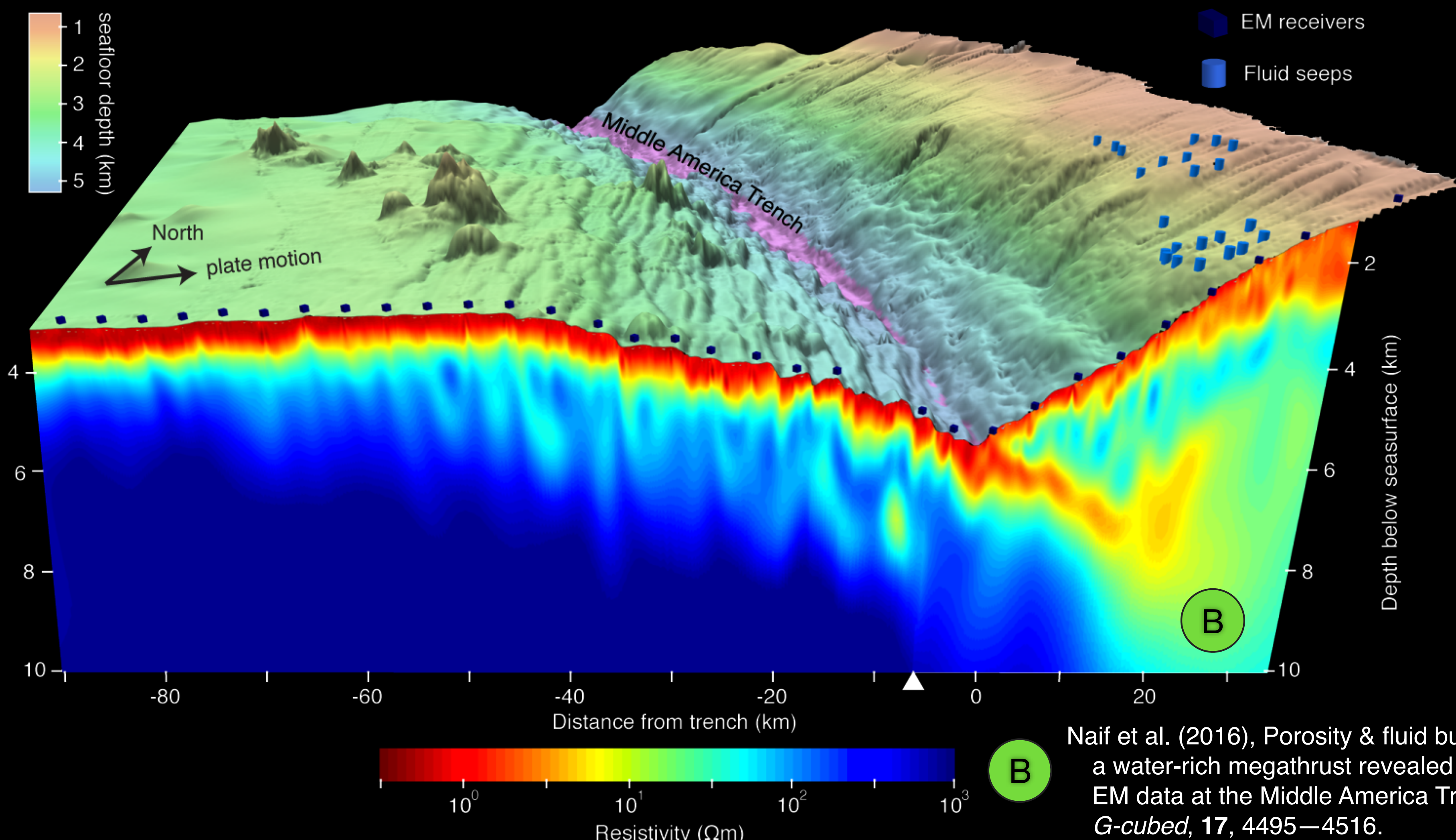
- Since integrated porosity is conserved, we laterally average 20 km windows
- Crust progressively becomes more porous with proximity to trench

	Typical crust*	100–80 km	20–5 km
Extrusives	0.104	8–12%	9—14%
Dikes	0.03	0.027	0.048
Gabbros	0.007	0.007	0.017

* from Jarrard's (2003) ocean drilling compilation study

Significantly more crustal H_2O subducted than currently thought

CSEM Result data fit to RMS 1.0 @ 2% error floor



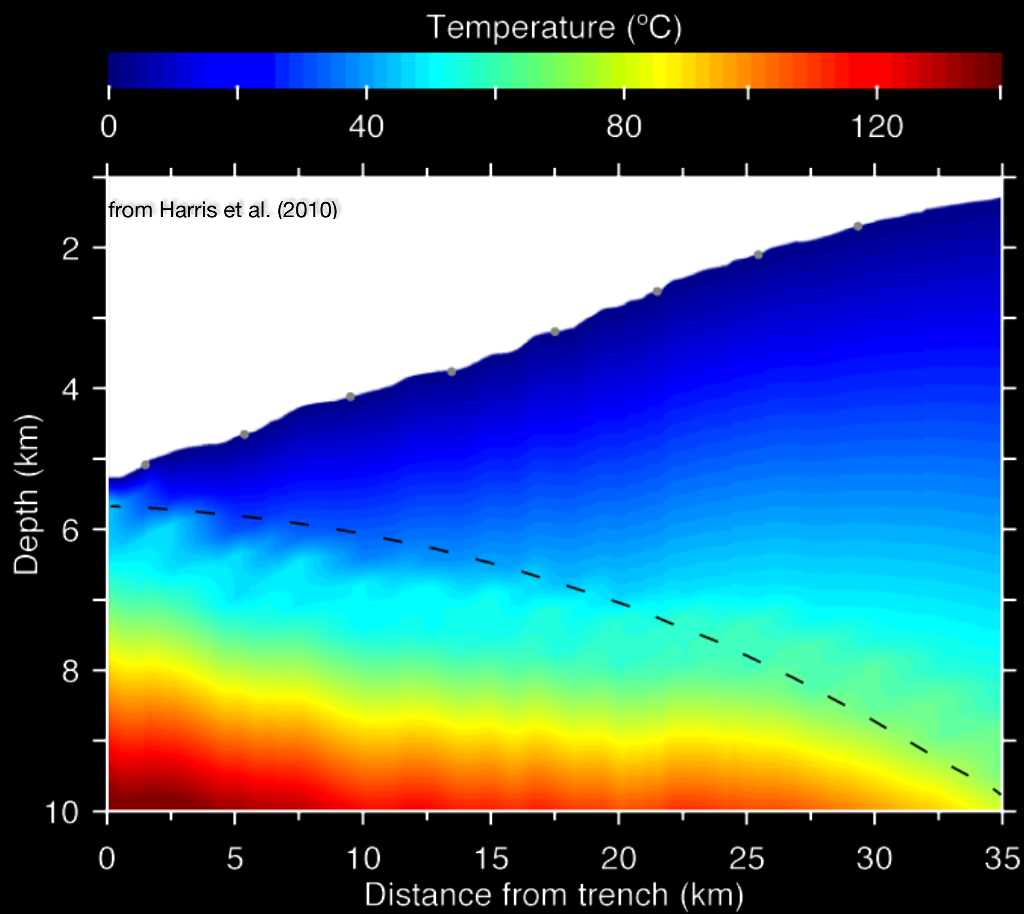
B

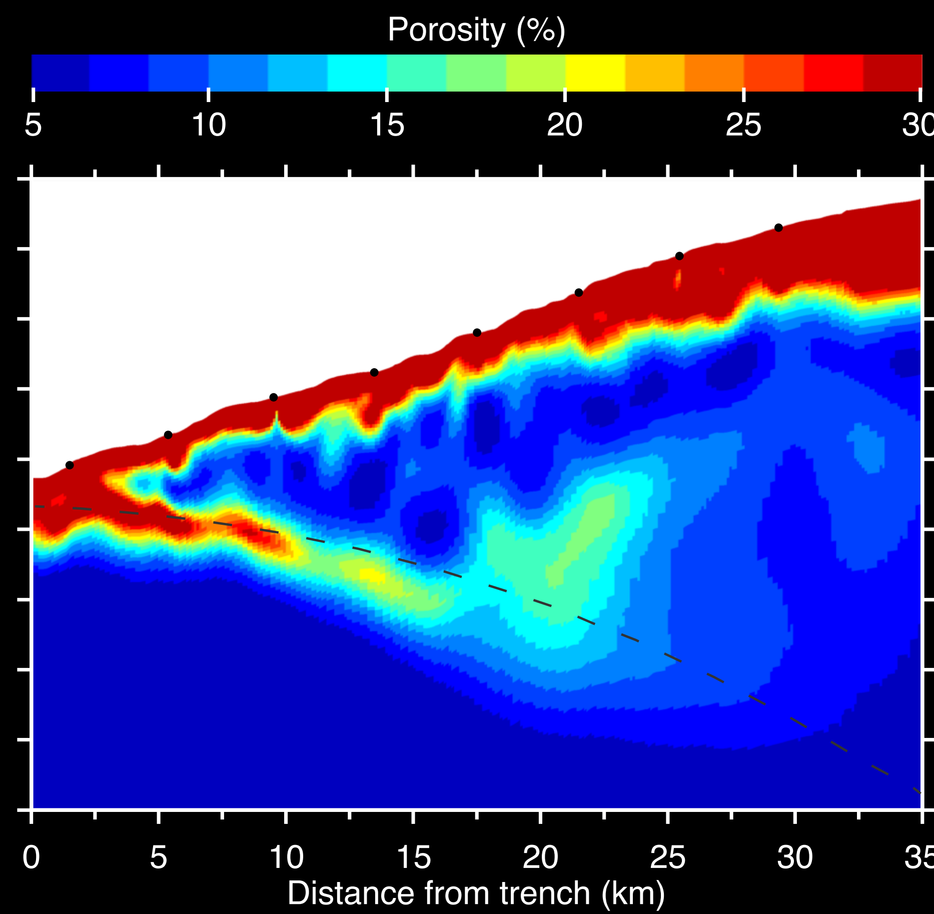
Naif et al. (2016), Porosity & fluid budget of a water-rich megathrust revealed with EM data at the Middle America Trench, *G-cubed*, **17**, 4495—4516.

Archie's Law = resistivity ⟶ porosity

$$\rho = \rho_f \phi^{-m}$$

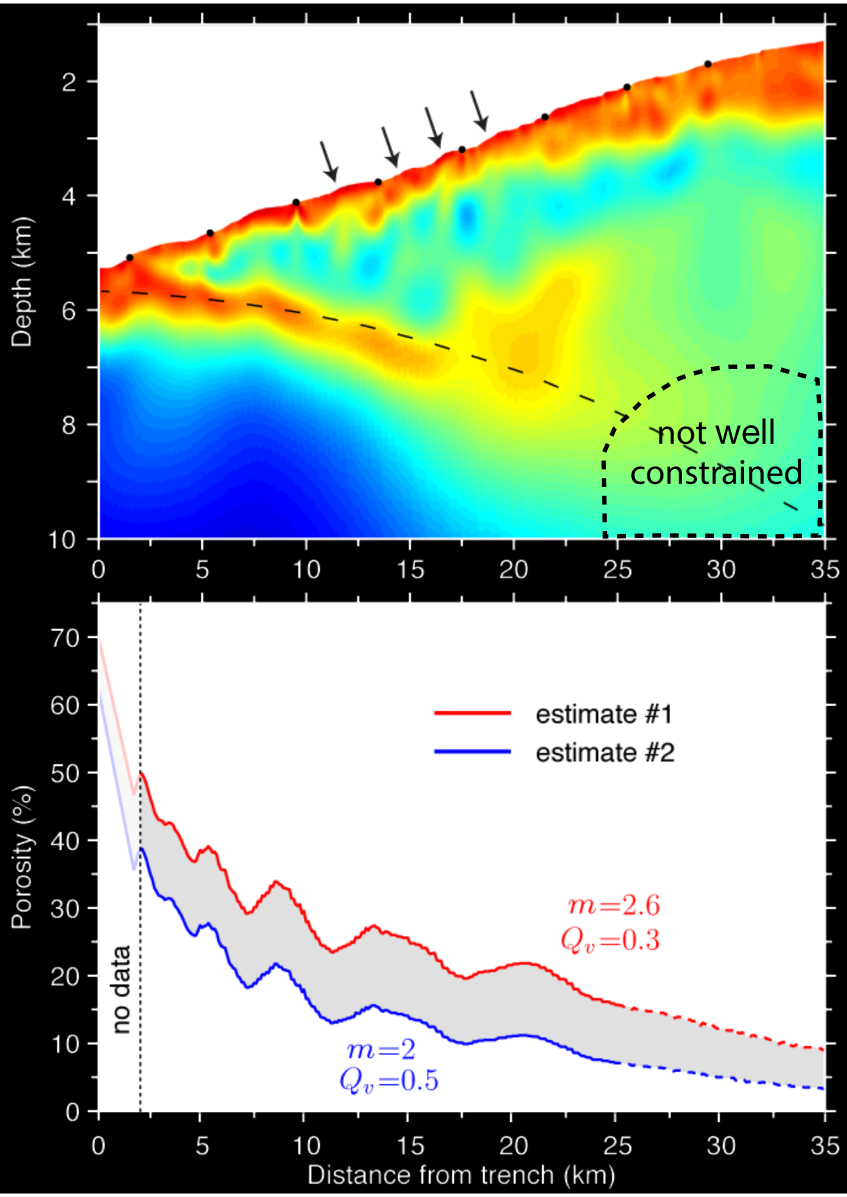
← cementation exponent
m = 2.0



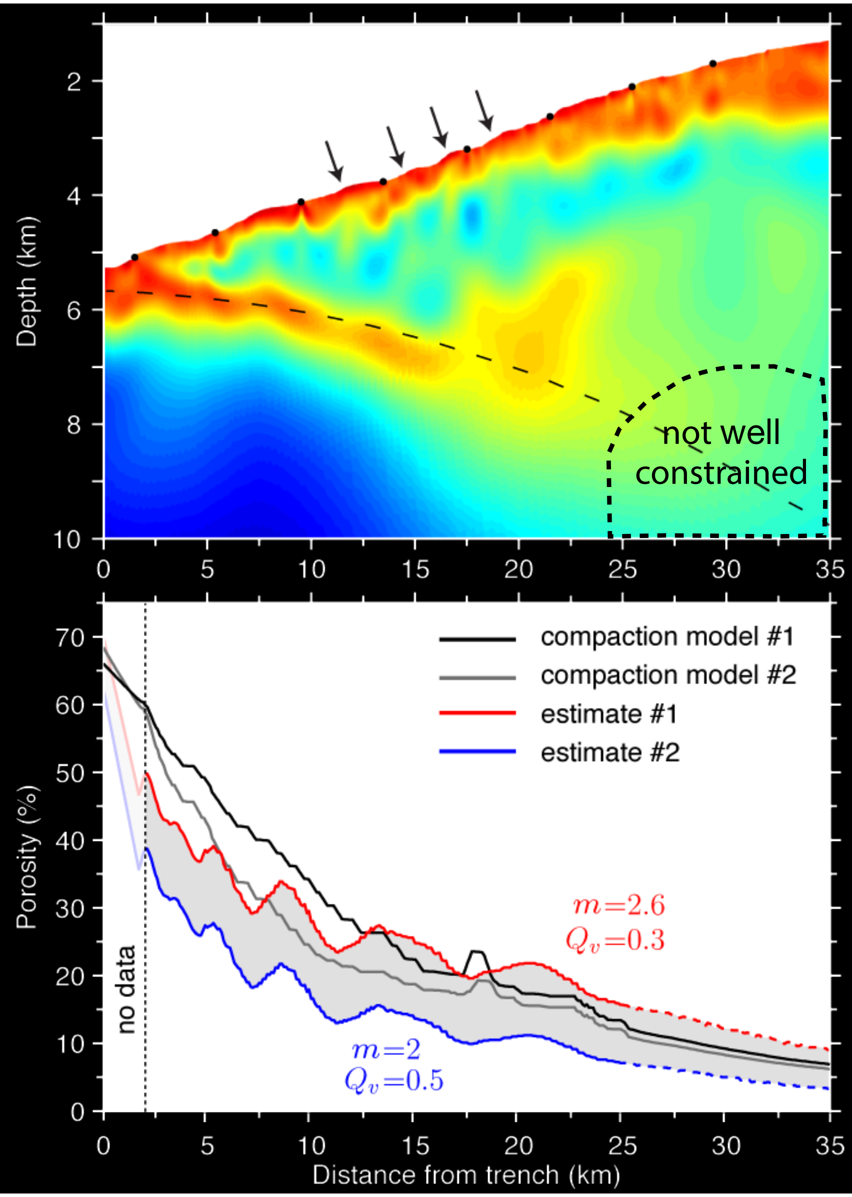


*Note: Archie's Law is not appropriate for clay-bearing sediments

Megathrust porosity



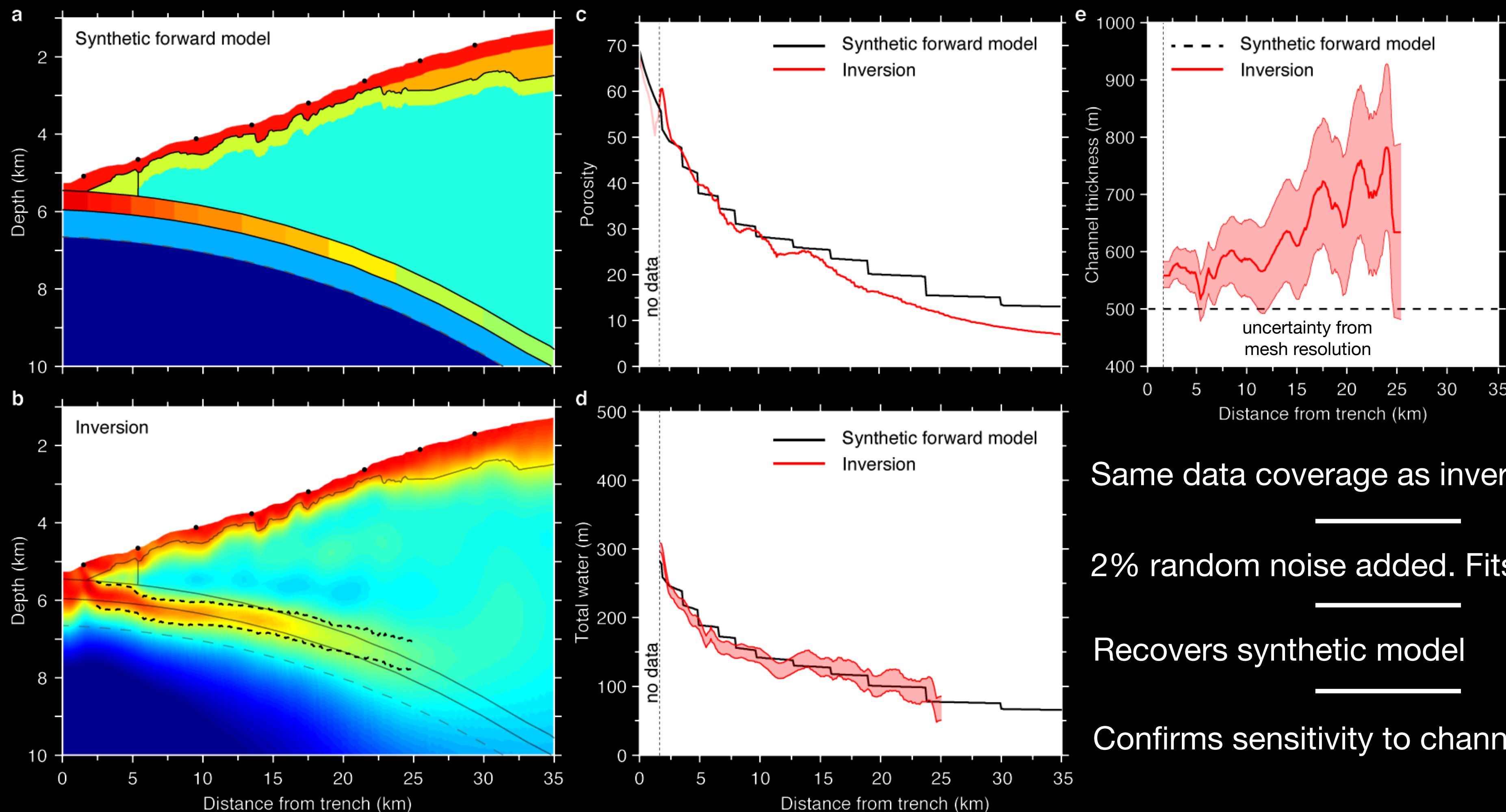
- Sediment porosity estimated with empirical relationship appropriate for clay-bearing sediments



Megathrust porosity

- Sediment porosity estimated with empirical relationship appropriate for clay-bearing sediments
- Agrees well with porosity predictions from experiments and drilling data

Synthetic tests



Same data coverage as inverted data

2% random noise added. Fits to RMS 1.0

Recovers synthetic model

Confirms sensitivity to channel

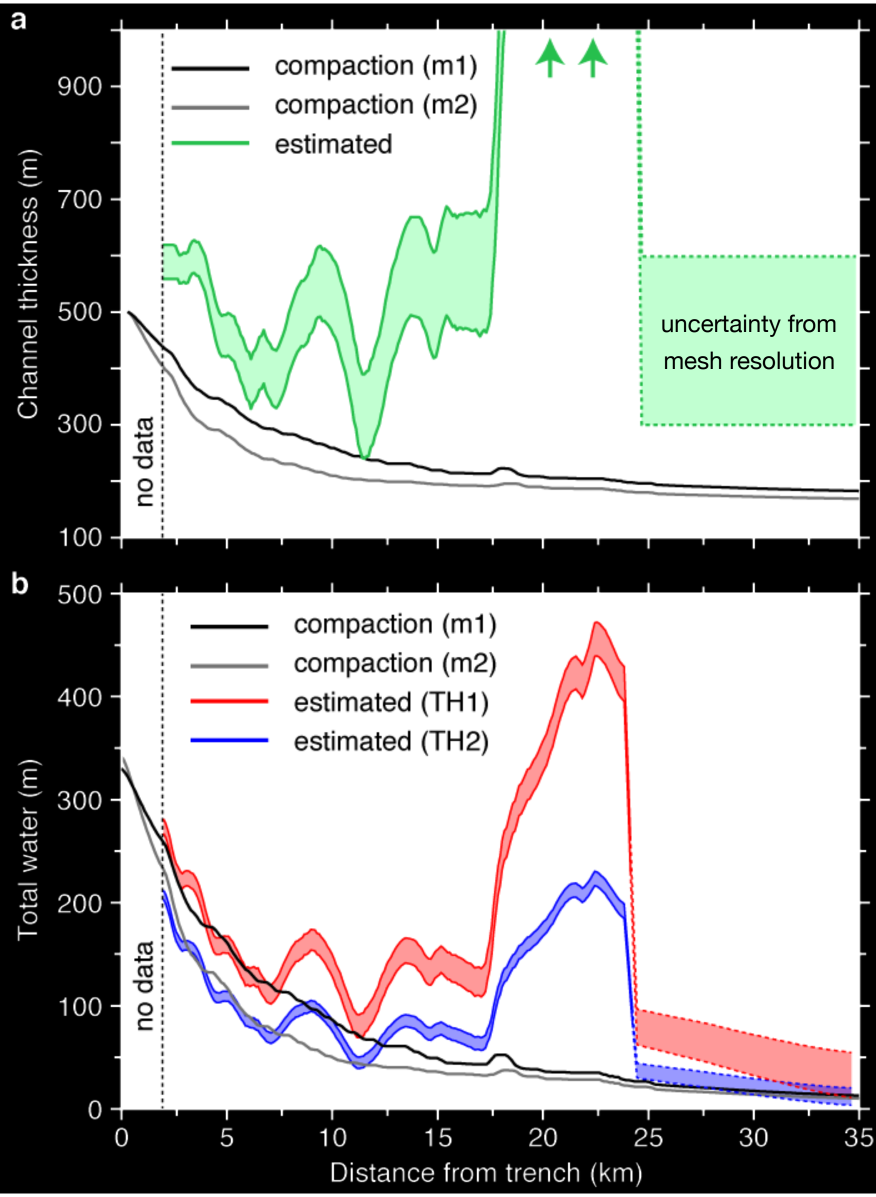
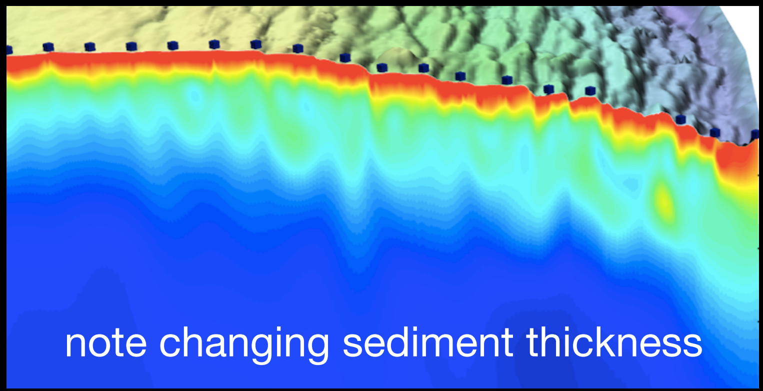


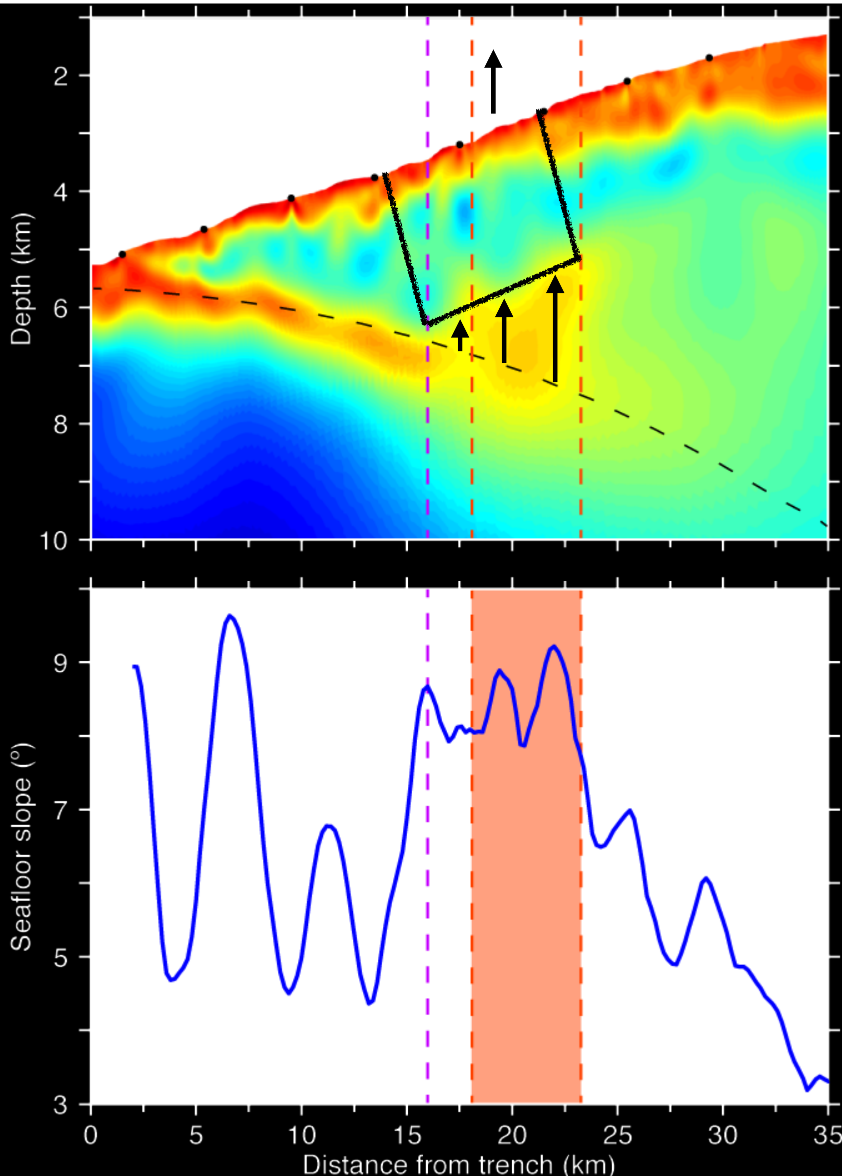
Plate interface water budget

- Define channel thickness to estimate water budget
- Estimates consistent with compaction of 500 m seds
- Large budget @17—23 km from conductive anomaly

➡ Suggests anomaly is part of upper plate

- Lateral variability due to subducting topography (synthetic tests confirm this)



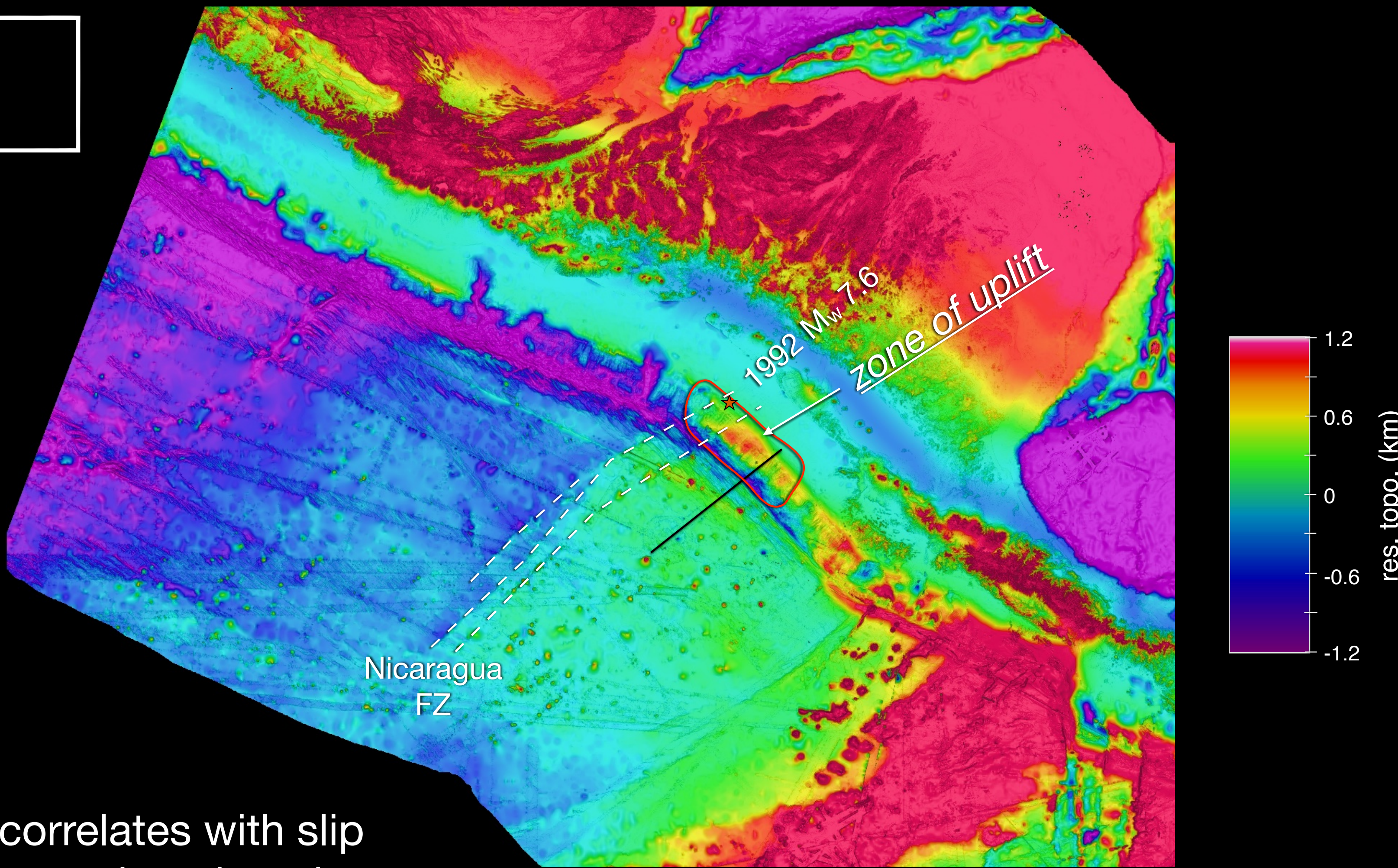


Cause of upper plate anomaly?

- Steep slope correlates with upper plate anomaly
- ~~Hydrofracturing would lead to compaction and subsidence~~
  - inconsistent with spatial scale and porosity of conductor
- Only alternative is uplift

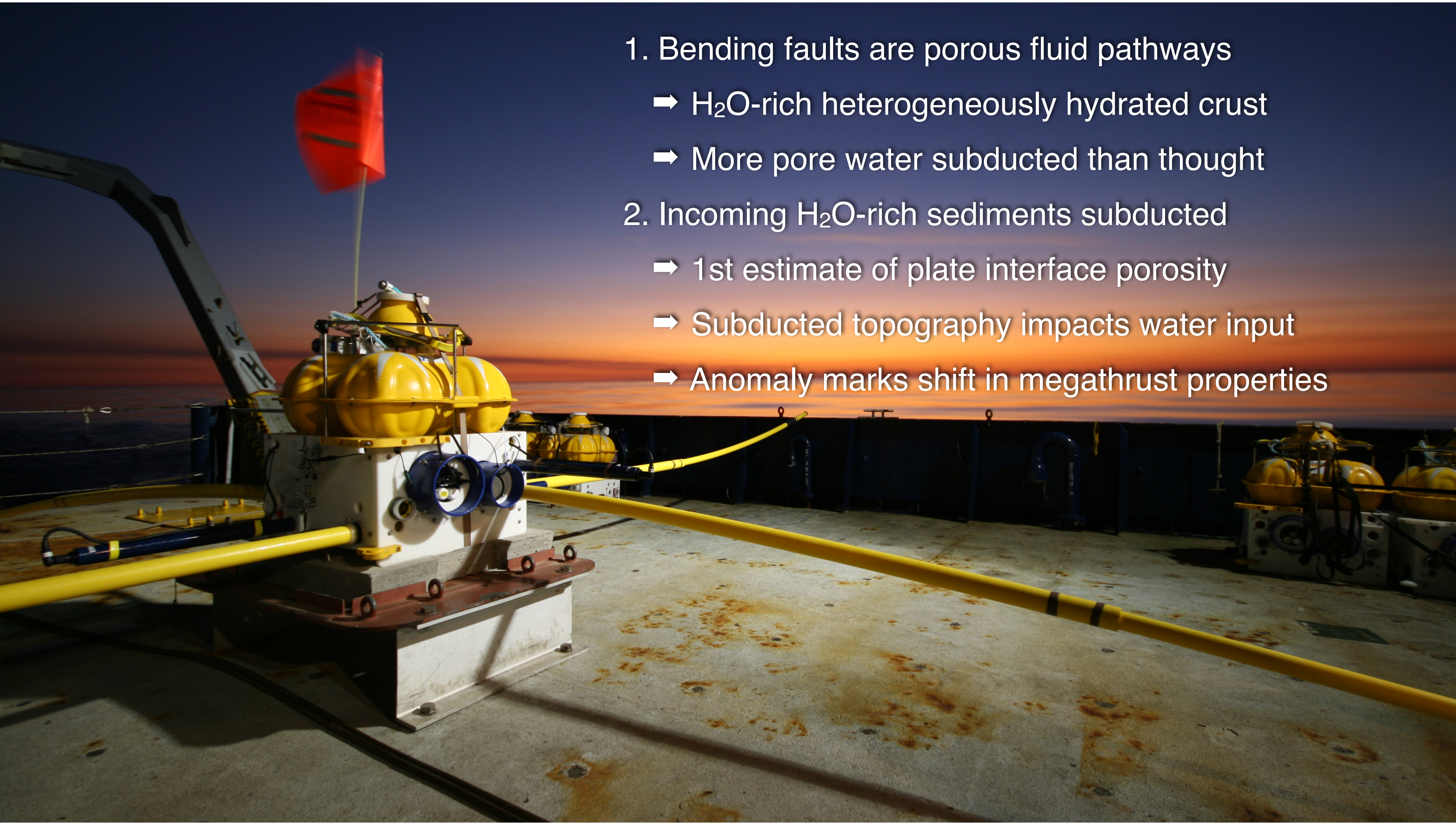
Underplated sediments?
Subducting topography?
Active faults?

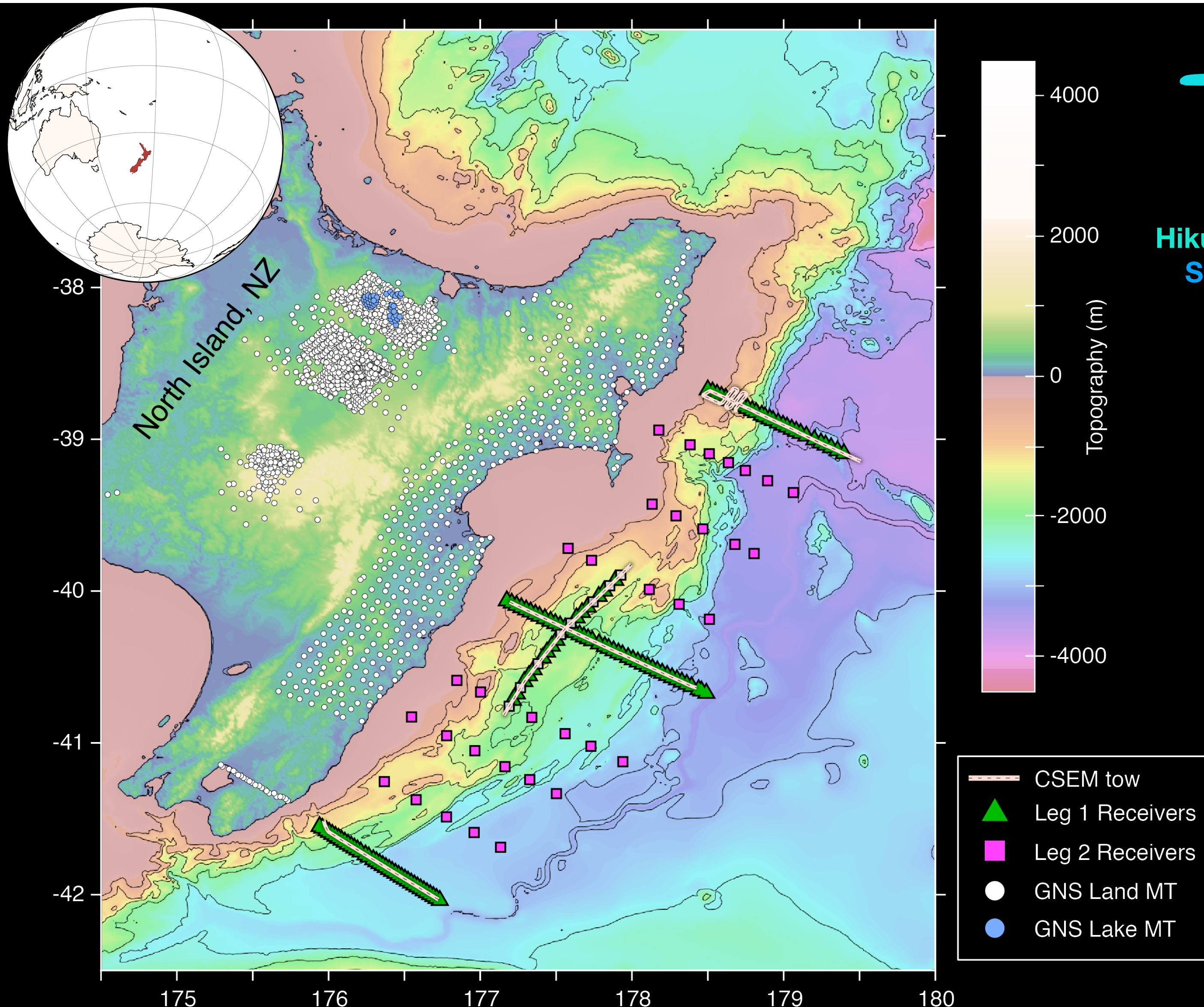
Residual Topography



Uplifted forearc correlates with slip patch of 1992 tsunami earthquake

Naif & Bassett (in prep)


1. Bending faults are porous fluid pathways
➡ H_2O-rich heterogeneously hydrated crust
➡ More pore water subducted than thought
2. Incoming H_2O-rich sediments subducted
➡ 1st estimate of plate interface porosity
➡ Subducted topography impacts water input
➡ Anomaly marks shift in megathrust properties



RESIST

Hikurangi Trench Regional Electromagnetic Survey to Image the Subduction Thrust

R/V Revelle 2018/2019

➡ 170 OBEM sites

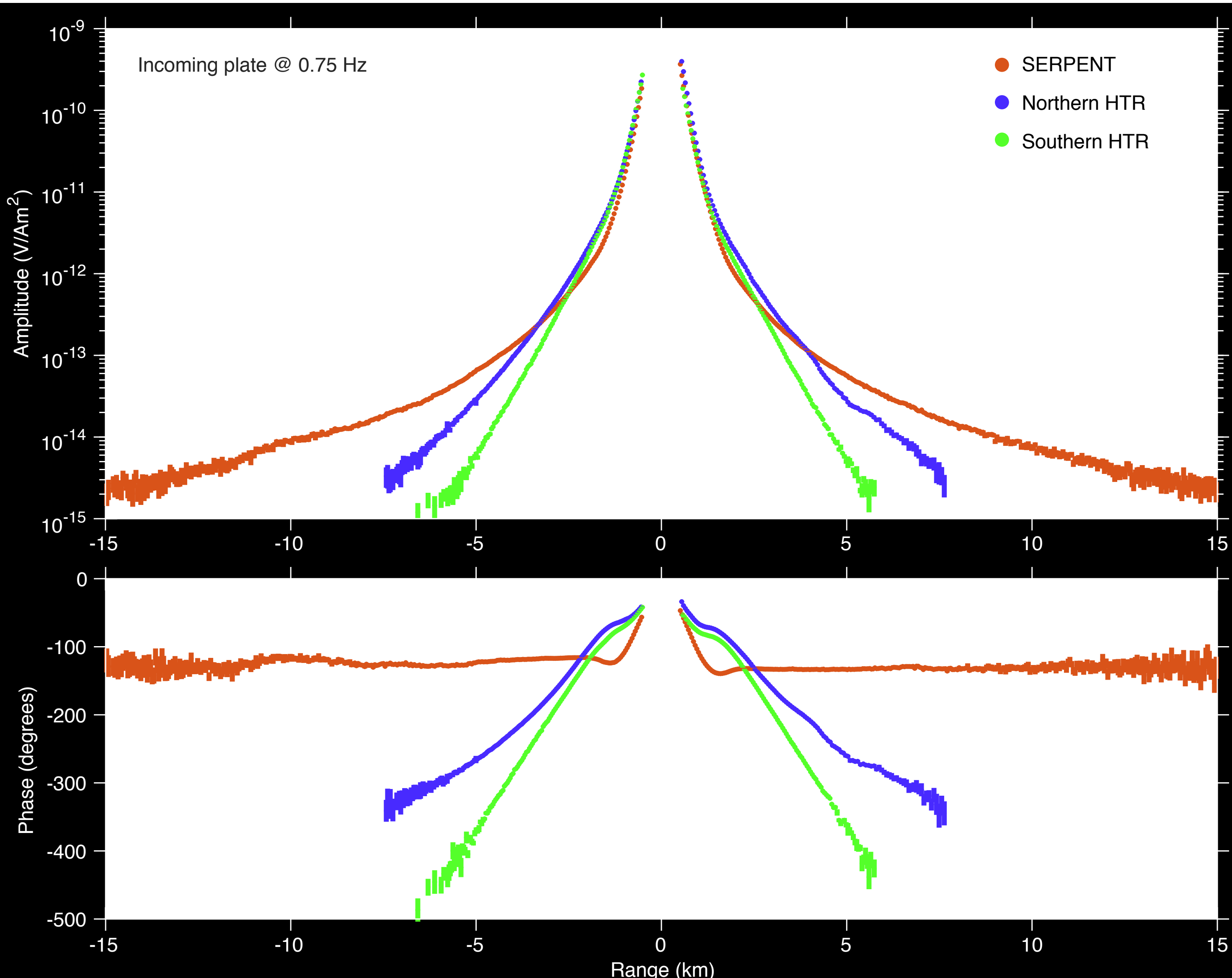
➡ 500+ line-km CSEM

Leg One (29 days)

- Deployed 170 receivers
- Collected 4 CSEM lines
- Recovered 128 receivers

Leg Two (8 days)

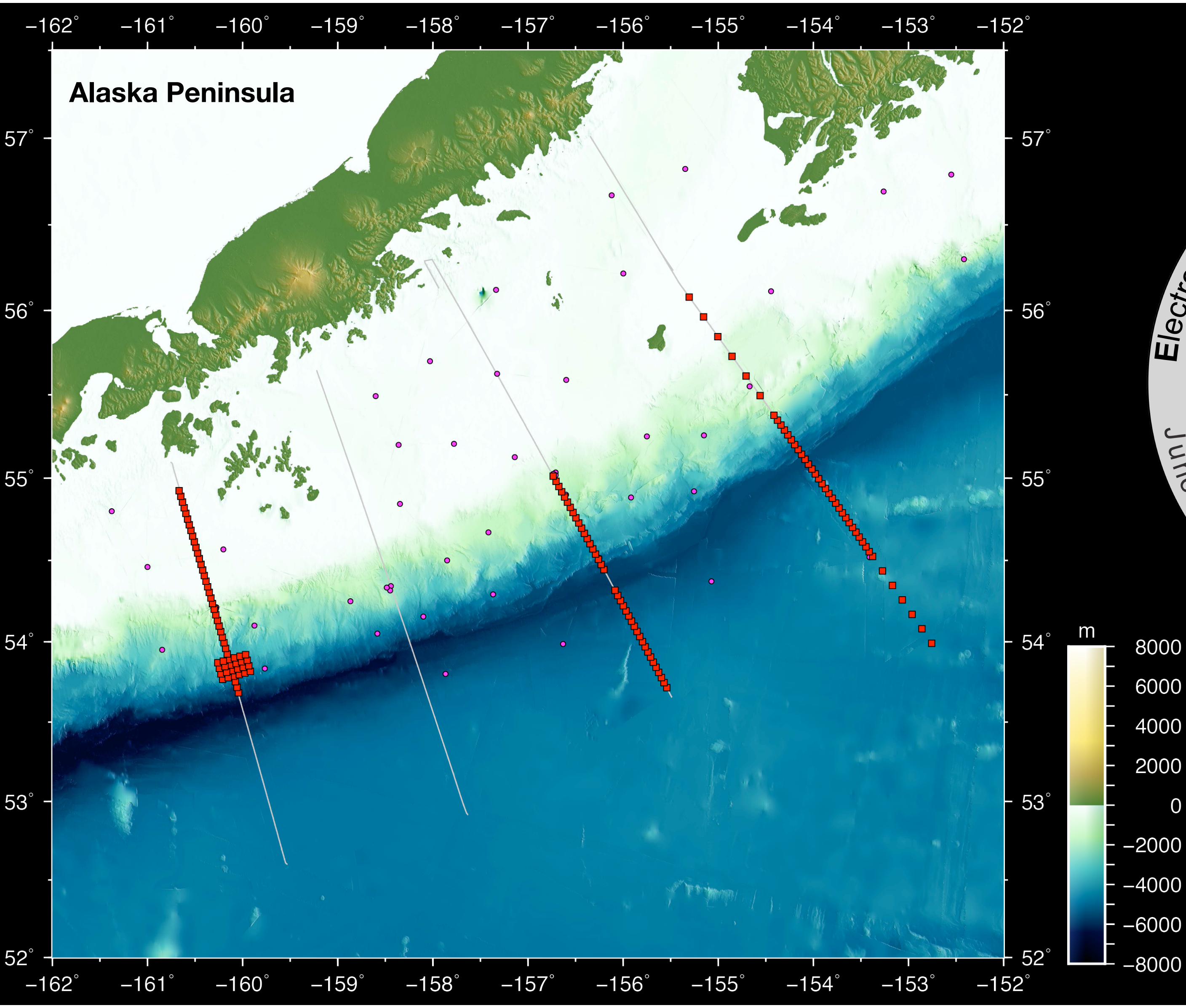
- Recovered 42 receivers



Preliminary results to be presented at AGU:

T41C-03 & T54D-05

E-MAGE



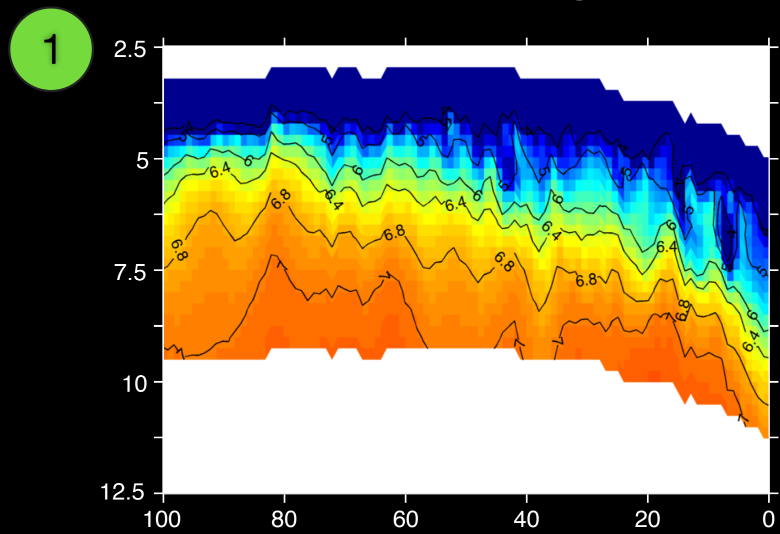
Electro-Magnetic Alaskan GeoPRISMS Experiment
June 2019
LDEO - SIO - WHOI

Single Cruise (33 days)

- ➡ 159 OBEM sites
- ➡ 600+ line-km CSEM
- ➡ R/V Sikuliaq


Thank You

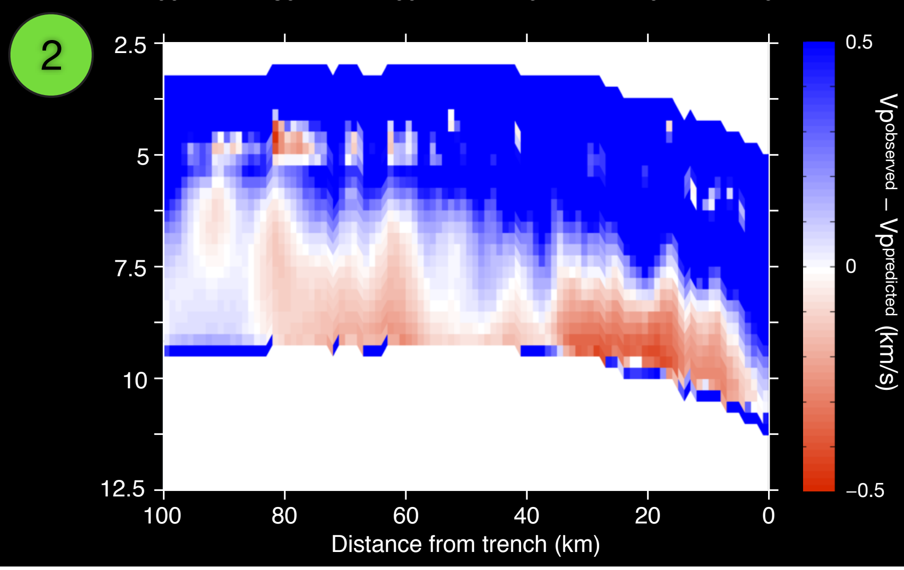
Estimating crustal alteration w/ joint seismic-EM

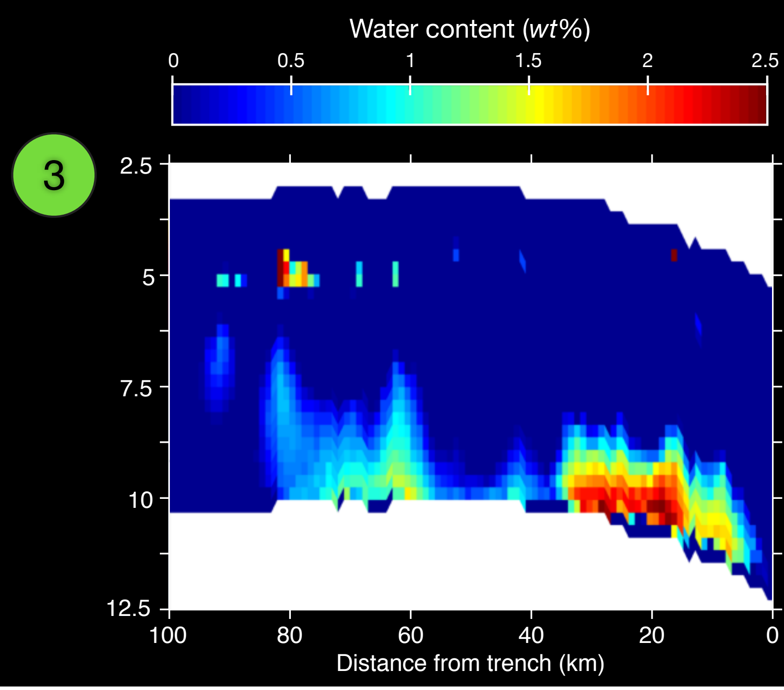


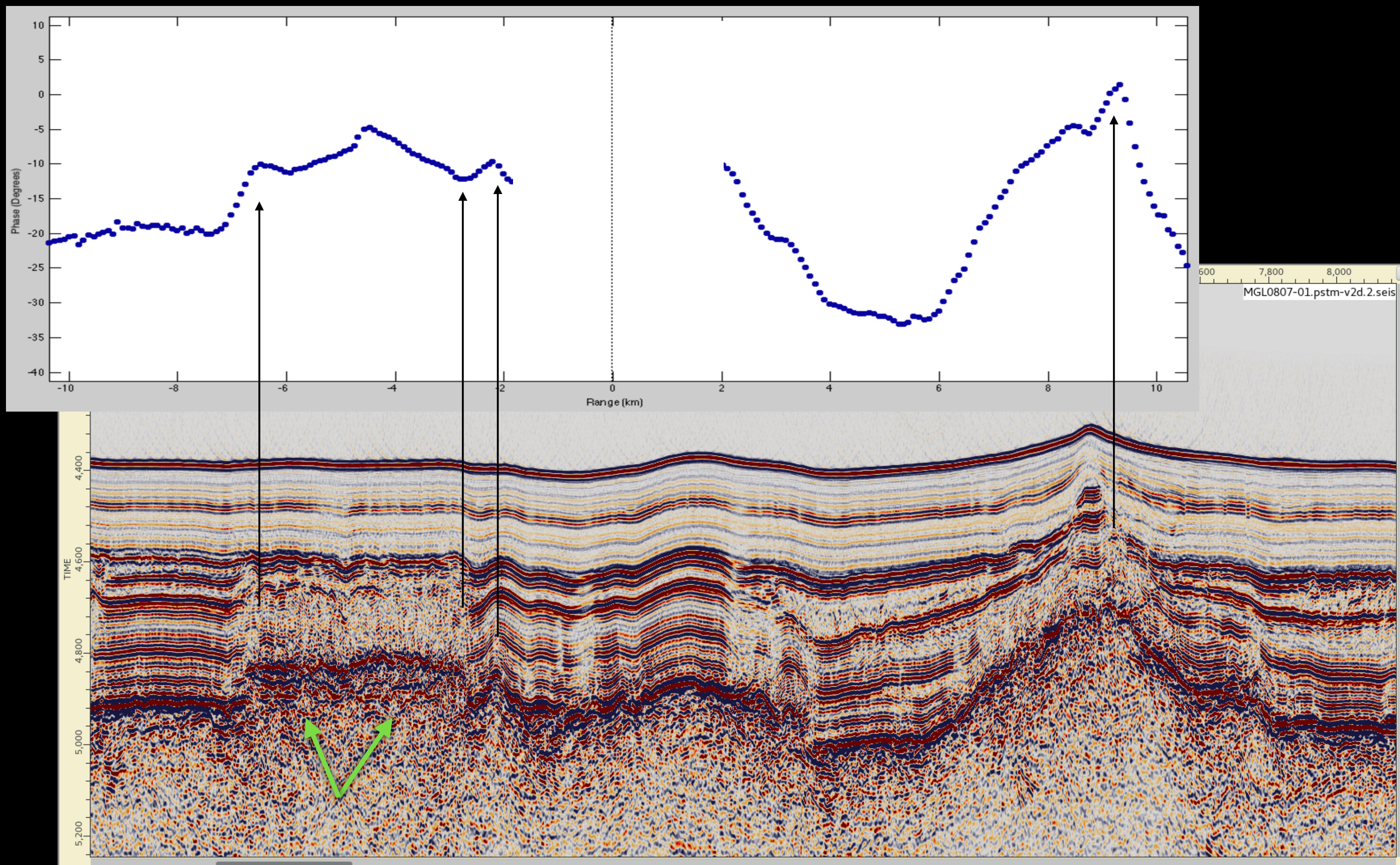
1 resistivity → porosity → predicted Vp

2 predicted minus observed velocity

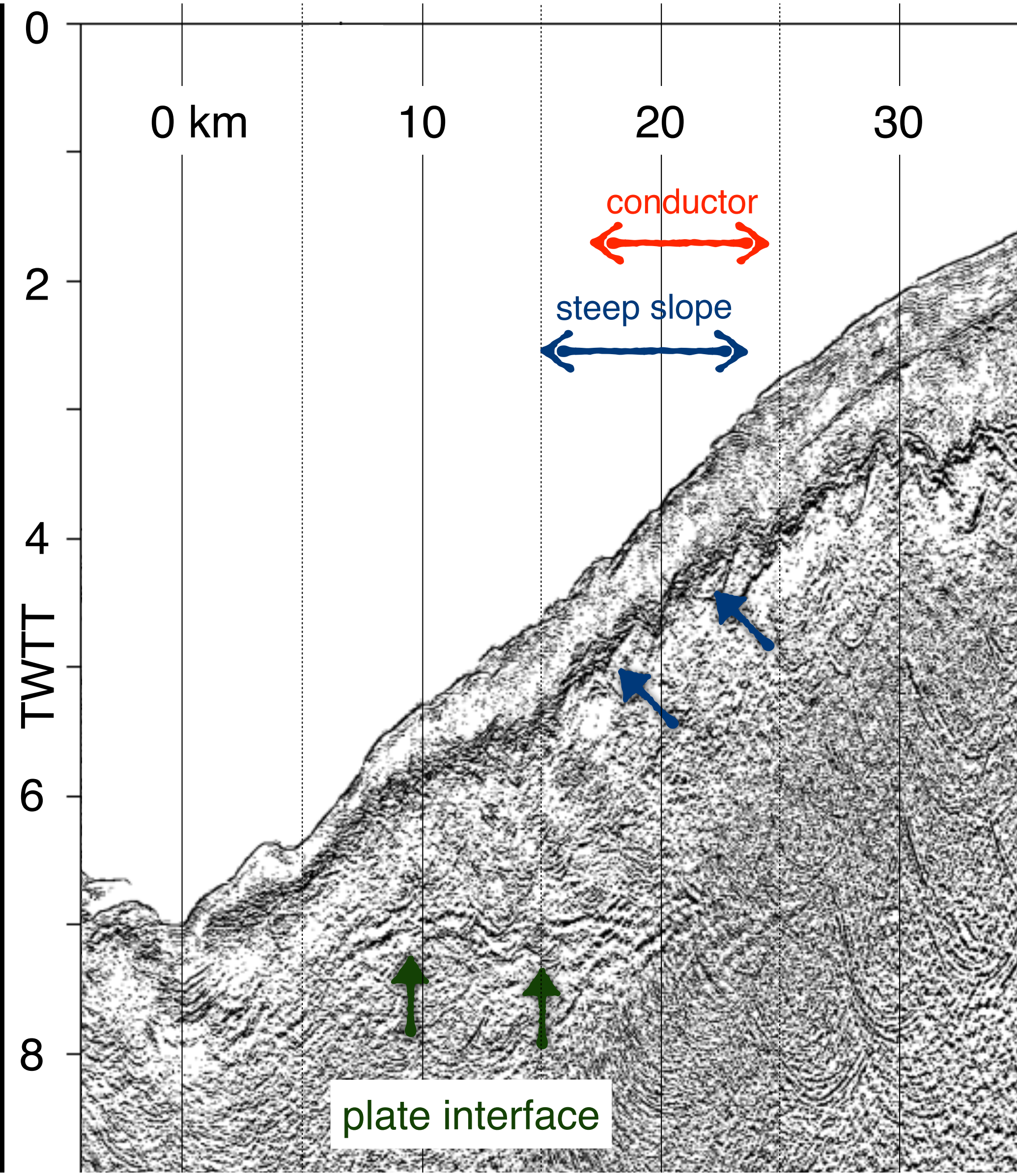
3 ΔVp → %alteration → %water







Intrusive sill eruptions disrupt sediment at time of emplacement



time-migrated MCS

Basement topography shows steepened slope.

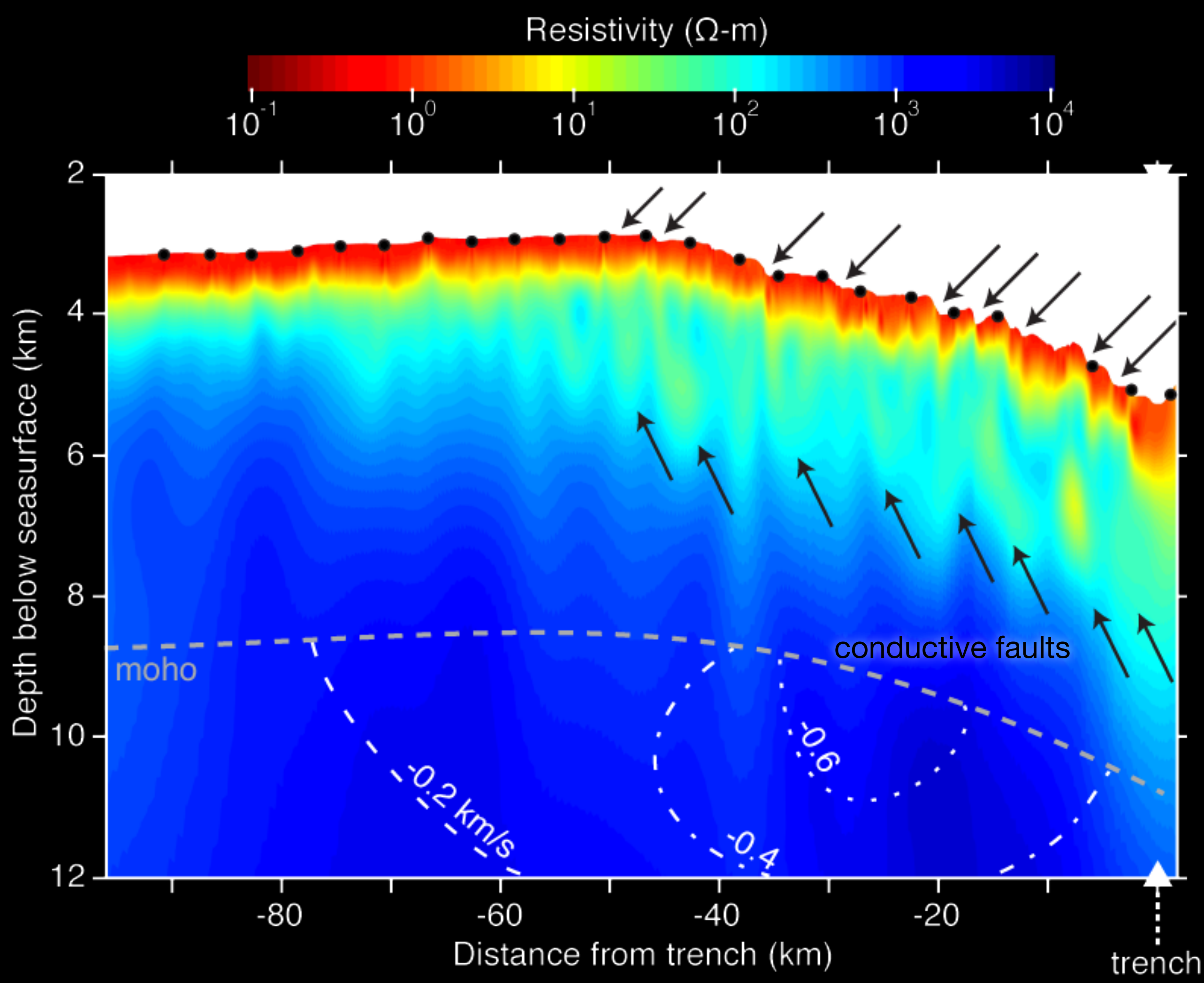
Consistent with uplift

Difficult to discern structure within upper plate

Need depth-migrated MCS to compare and integrate with CSEM (work in progress)

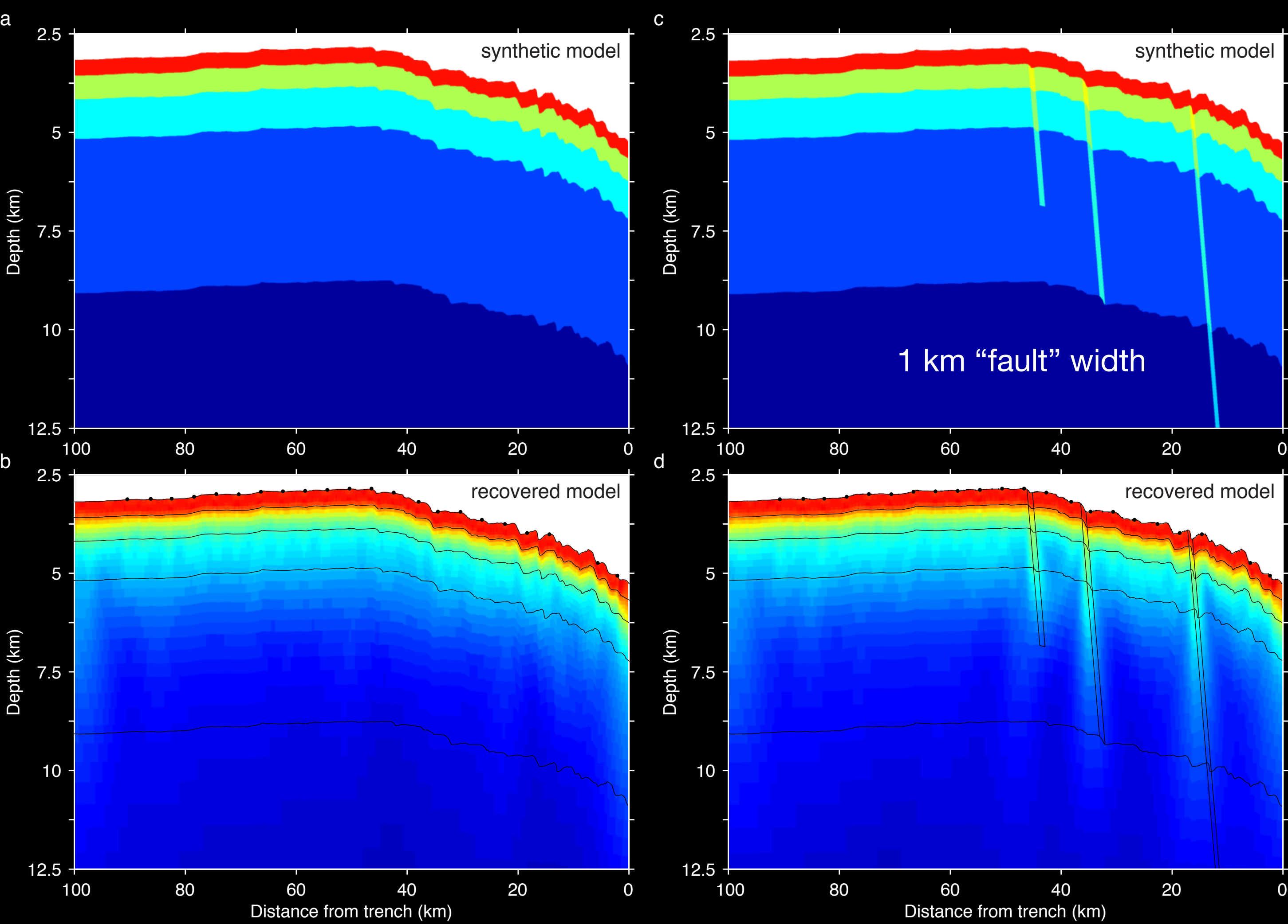
Image from K. McIntosh

Outer Rise

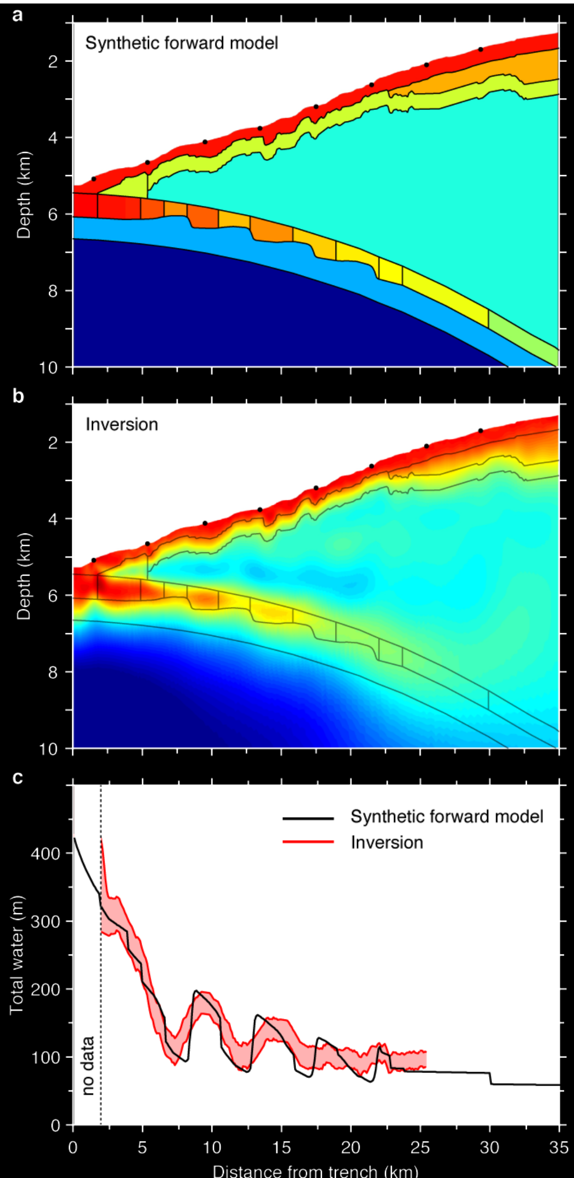


- Fault scarps correlate with steeply dipping conductive channels in the crust
- These are porous channels along the fault trace that drive fluids into the slab
- For the most part, mantle remains resistive

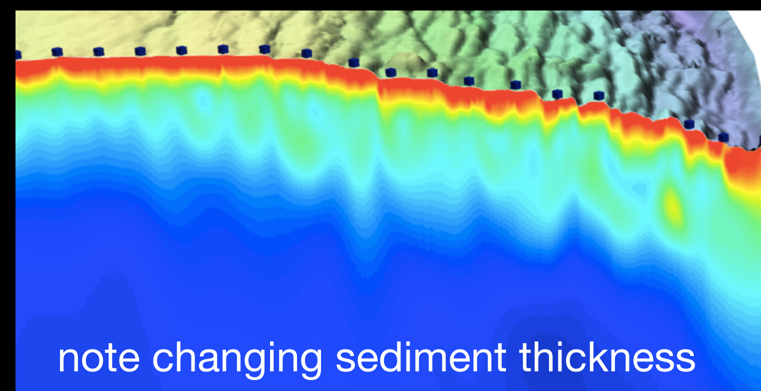
Synthetic Tests



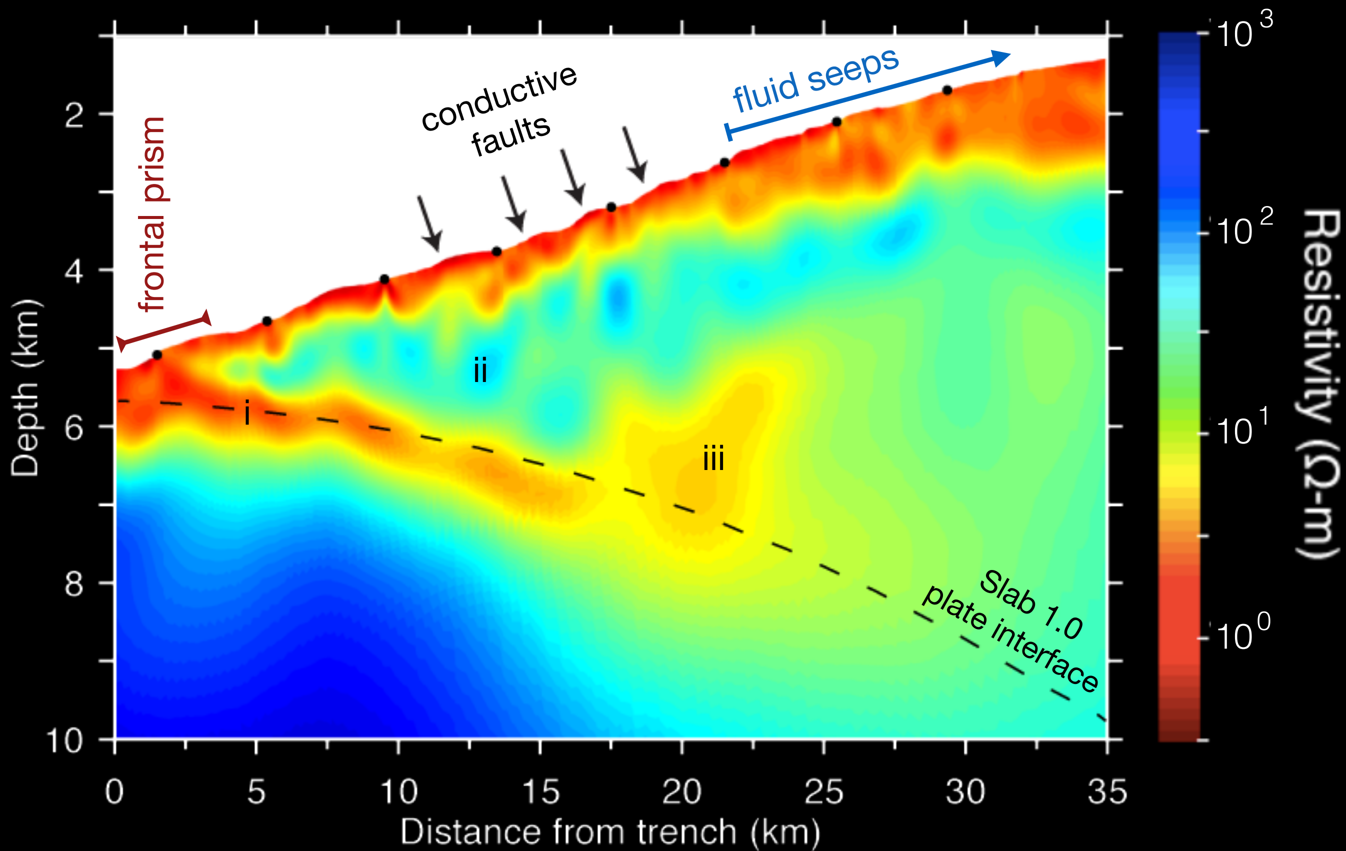
- Same data coverage as inverted data set
- 2% random noise added
- Fits to RMS 1.0
- Recovers synthetic model
- Sensitivity to 6-8 km bsf



Synthetic test of varying sediment thickness



- data sensitive to channel thickness
- consistent with laterally variations due to subducting bending faults



i. Sediment subduction along megathrust plate interface

ii. Upper plate is resistive, suggests with low porosity basement

iii. Conductor extends into upper plate below cluster of seafloor seeps

Navigation matters for CSEM