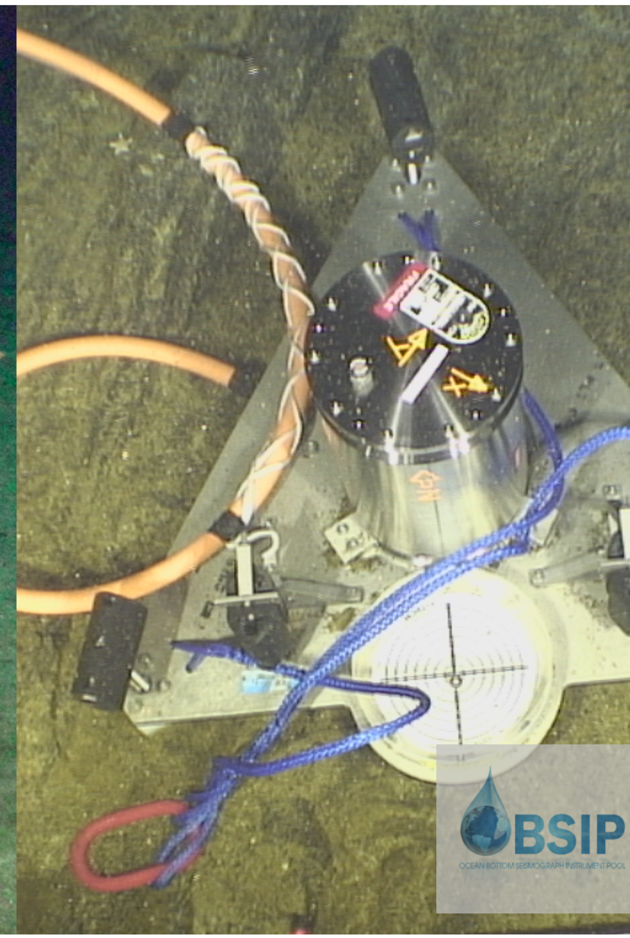
# mizing seafloor pressure sensor networks for the ction of slow slip earthquakes in Cascadia and bey

drickson[1], William Wilcock[1], David Schmidt[1], Parker MacCready[1], Emily Roland[1],
ler Kurapov[2], Mark Zumberge[3], Glenn Sasagawa[3]

of Washington, [2]NOAA Coast Survey Development Laboratory, [3]Scripps Institution of Oceanography

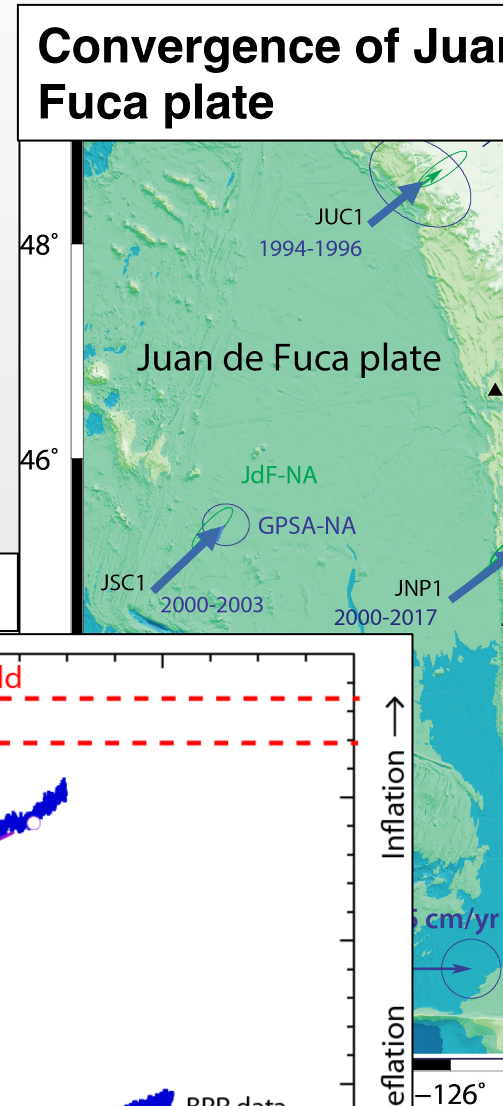
# utline

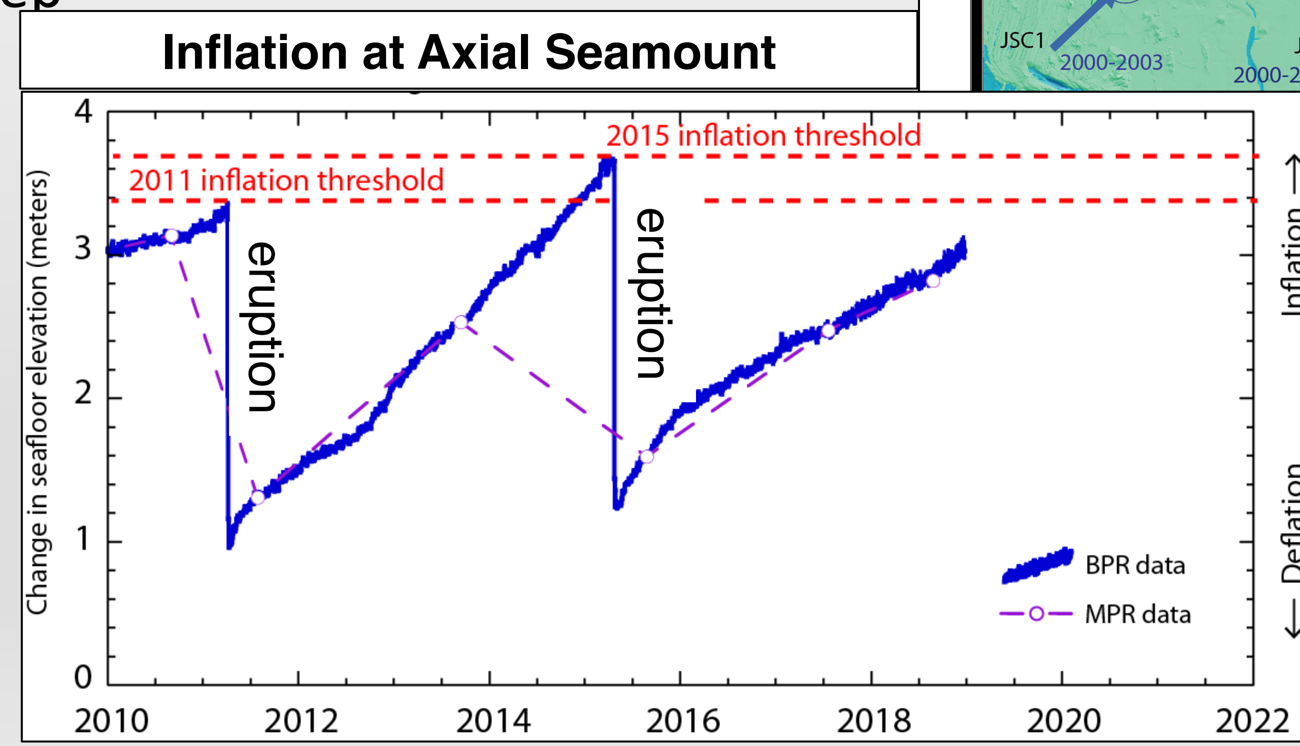
- What can we learn from seafloor geodesy?
- eafloor pressure geodesy in Cascadia
- volving methods for highly accurate pressure measurements
- Other geodetic tools/measurements in the ocean

# hat can we learn om seafloor geodesy?

- bduction zones
  - Interseismic strain
  - Transient fault slip and creep
  - Strain partitioning
- dge/Transform systems
  - Spreading/Slip rates
  - Volcanic deformation
- traplate
  - Plate motion
  - Rigidity and flexure

David Chadwell

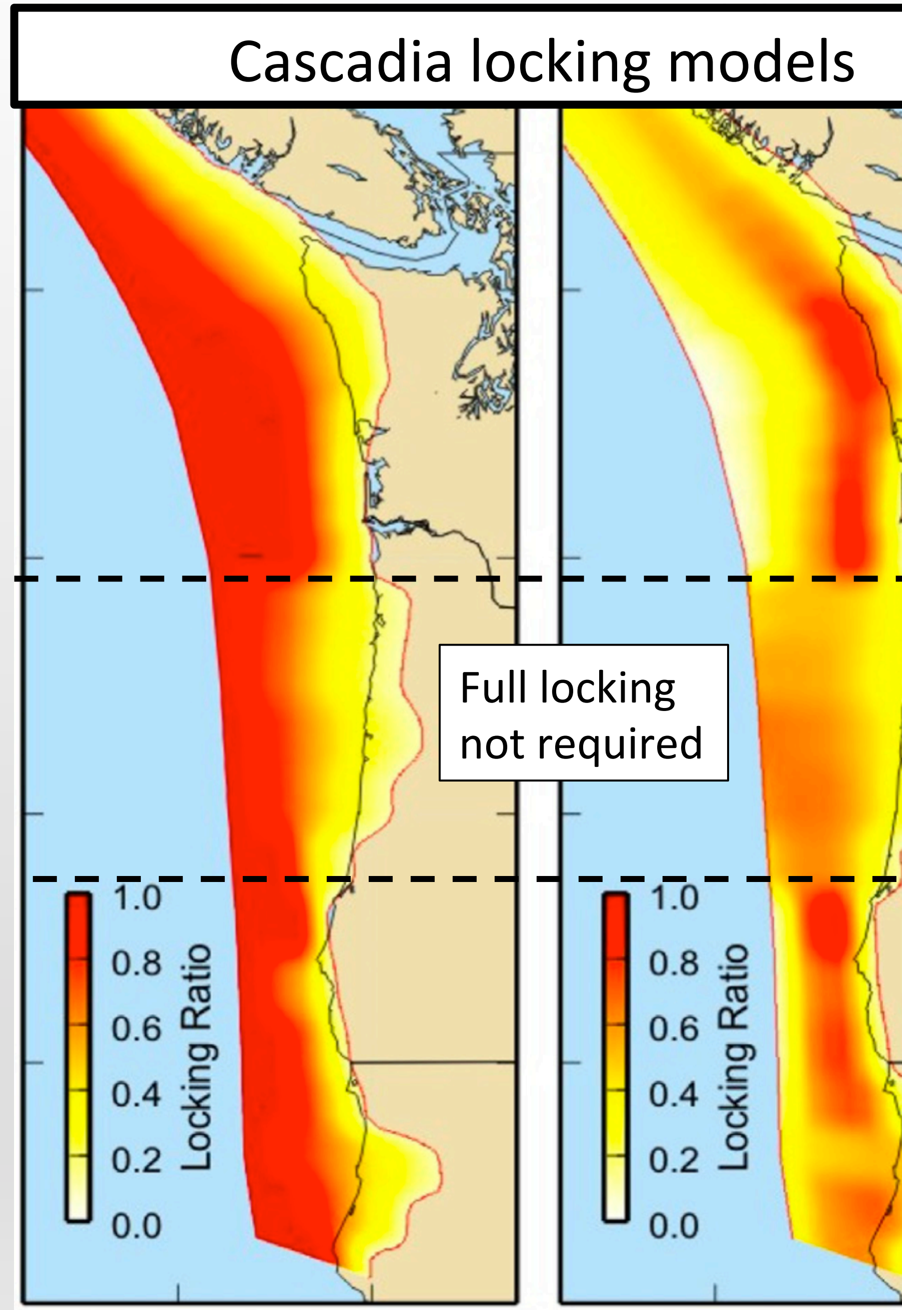



Bill Chadwick, https://www.pmel.noaa.gov/eoi/axial_

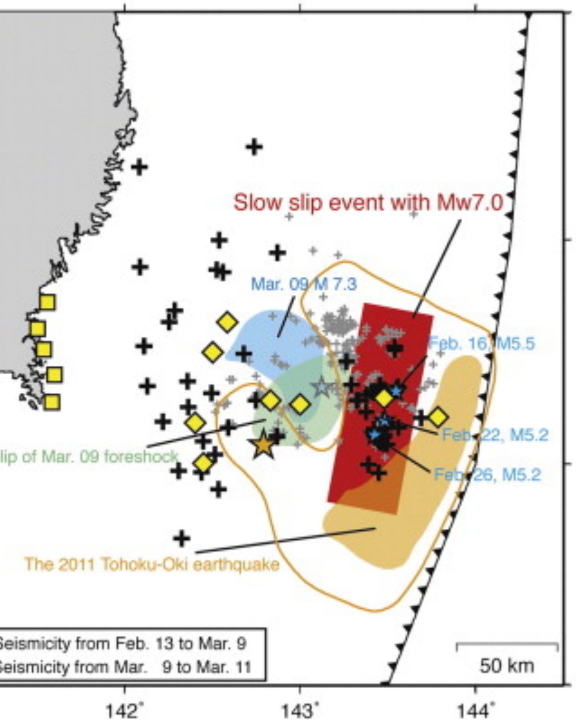
# afloor pressure geodesy Cascadia

- omalously low seismicity near the egathrust
- rge distance from shoreline to trench
- rtial locking inferred off central OR



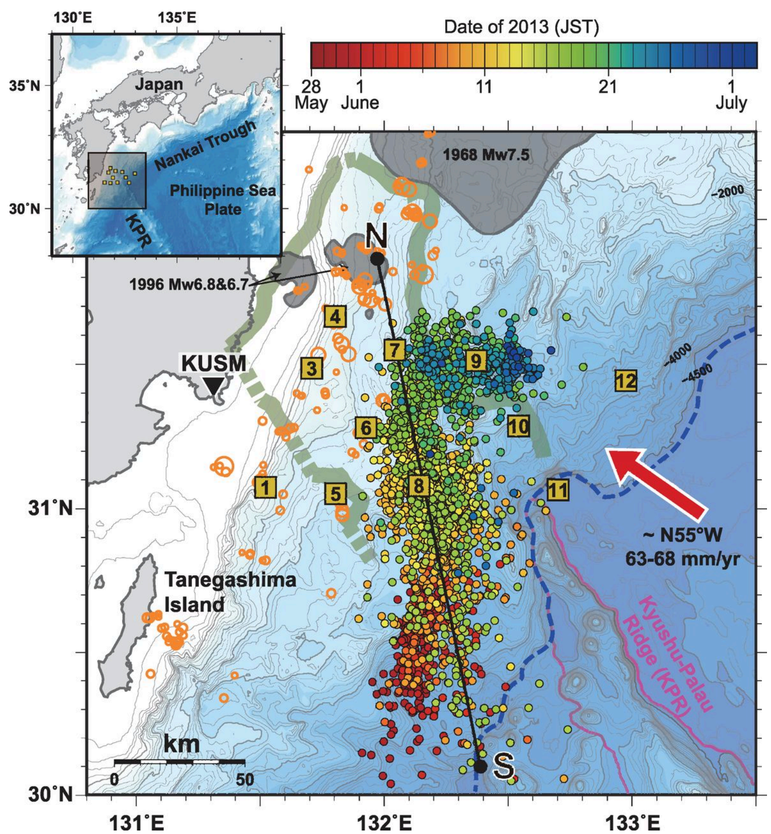

Schmalzle et

# ar-trench slow slip and tremor observed in any settings. Occurring in Cascadia?



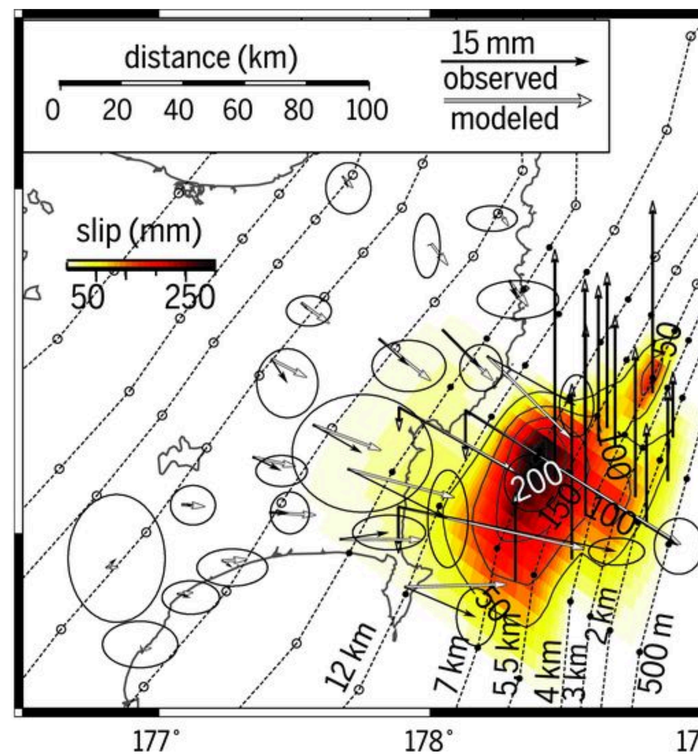

**an Trench 2008**

Ito et al., 2013




**Nankai 2013**

Yamashita et al., 2015




**Hikurangi 2015**

Wallace et al., 2016

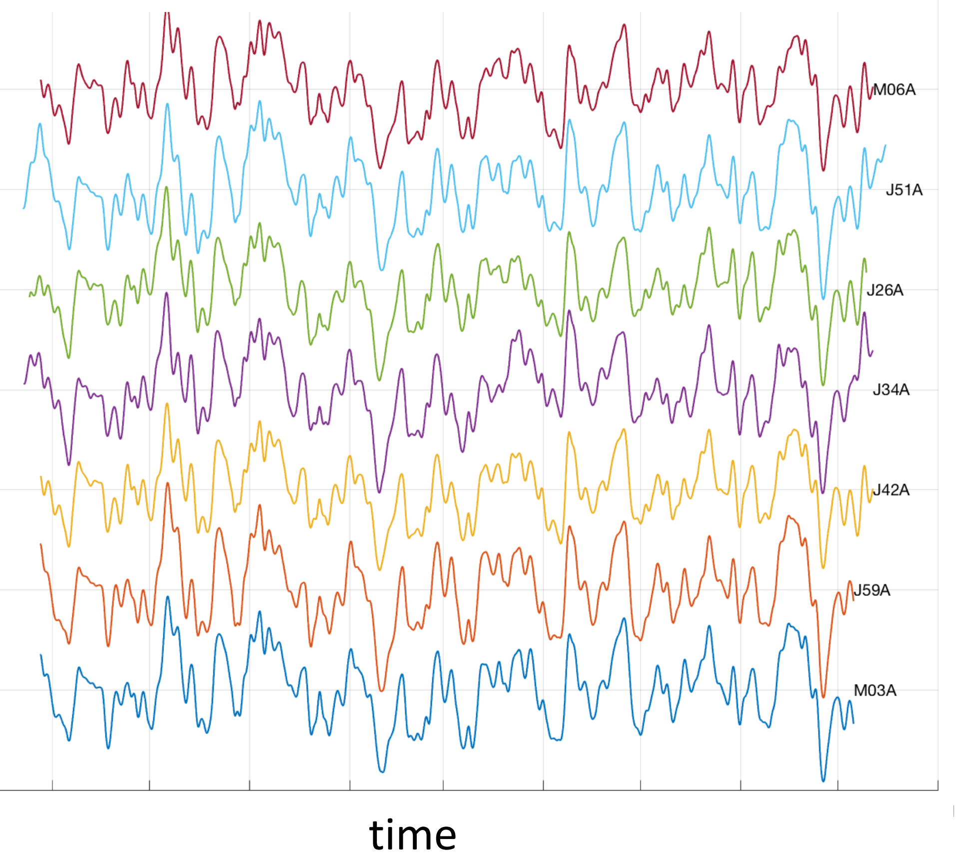
# afloor pressure for detecting offshore formation

$$P(t) = P_0 + P_{tidal} + P_{drift} + P_{ocean} + P_{geodetic}$$

# afloor pressure for detecting offshore formation

$$P(t) = \sout{P_0 + P_{tidal} + P_{drift}} + P_{ocean} + P_{geodetic}$$

Filtered pressure w/ synthetic SSE



# afloor pressure for detecting offshore formation

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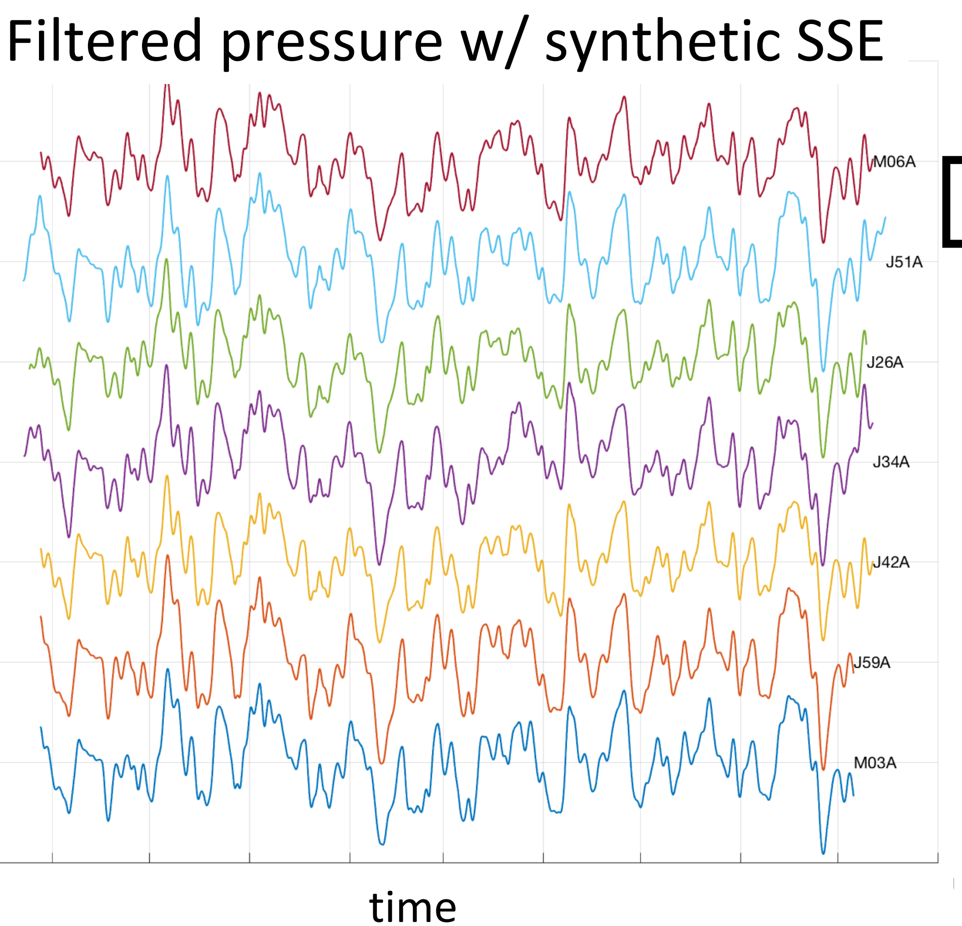
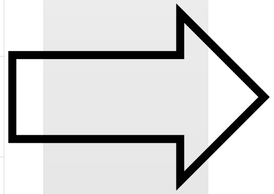
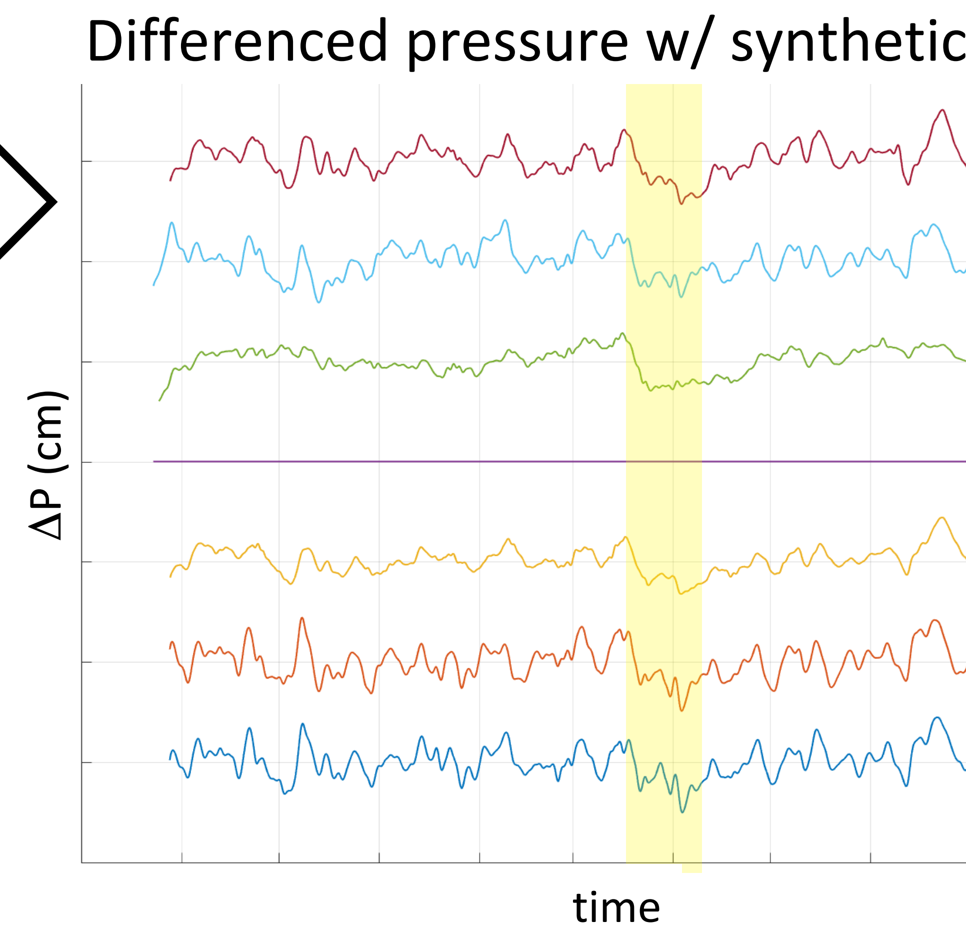




# otivating Questions

an oceanographic signals be effectively removed from seaflo
ressure data?

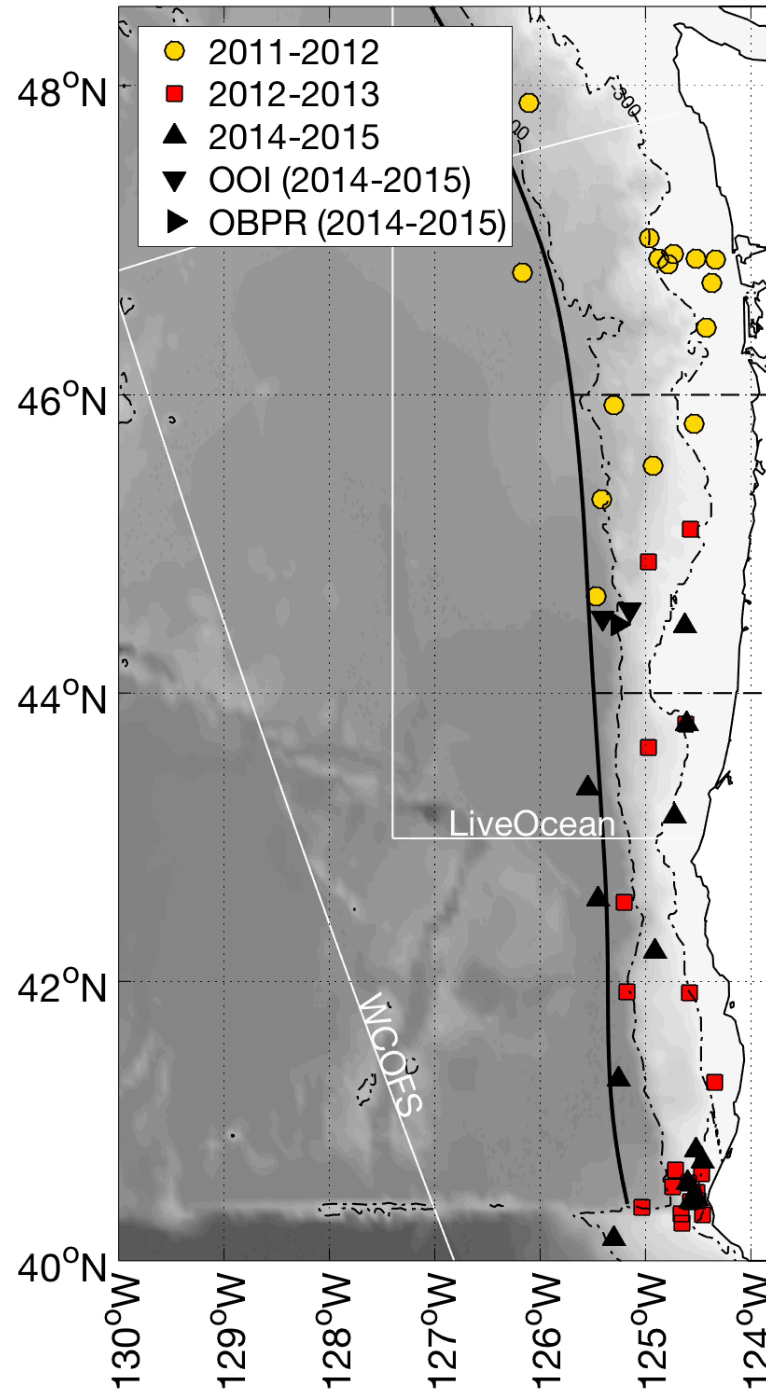
- We find that differencing of depth-matched instruments can reduce signals RMS from >3 cm to <1 cm
- Oceanographic models don't work as a correction, but can be used to understand regional oceanographic processes

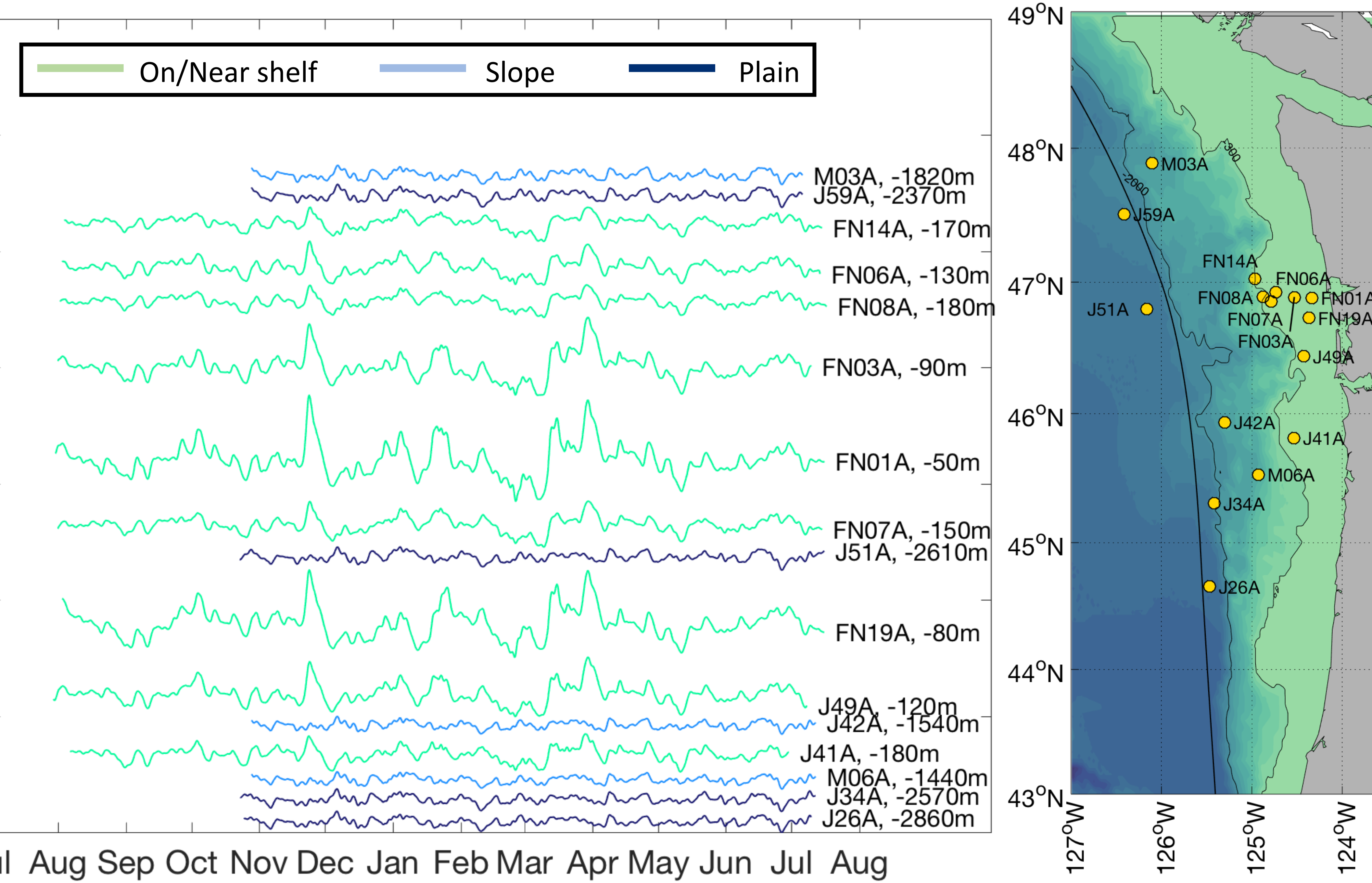
/hat is the detectability of shallow slow slip earthquakes usin
eafloor pressure?

- A number of $M_w$>5.7 SSE scenarios predicted to produce detectable signals
- Optimized network geometry utilizes lines of depth-matched sensors

# essure data in Cascadia

- 11-2015 Cascadia Initiative experiment
  - Absolute pressure gauges (APGs) on some instruments
  - Alternate north and south each year
- pplemented by Cabled Array APGs and e benchmark instrument off Oregon
- gh quality pressure data counts
  - 2011-2012: 16
  - 2012-2013: 19
  - 2013-2014: 0
  - 2014-2015: 17

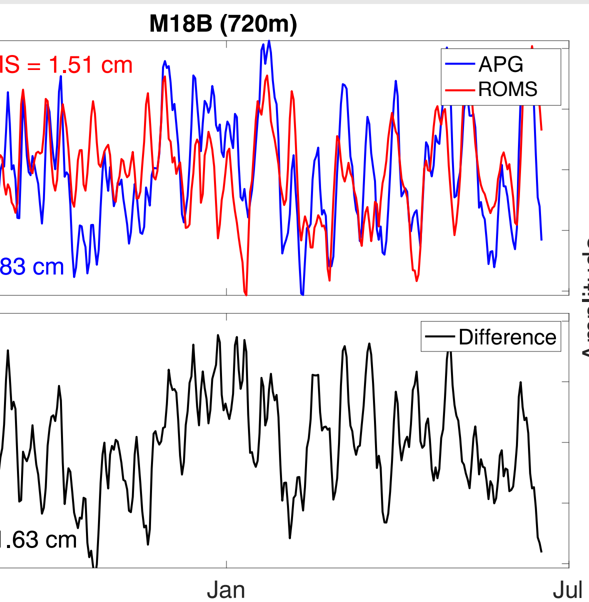


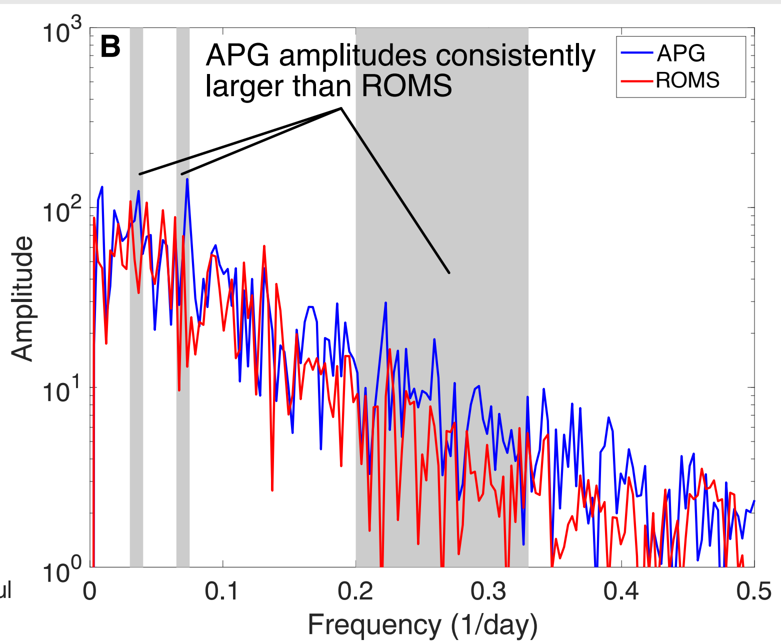


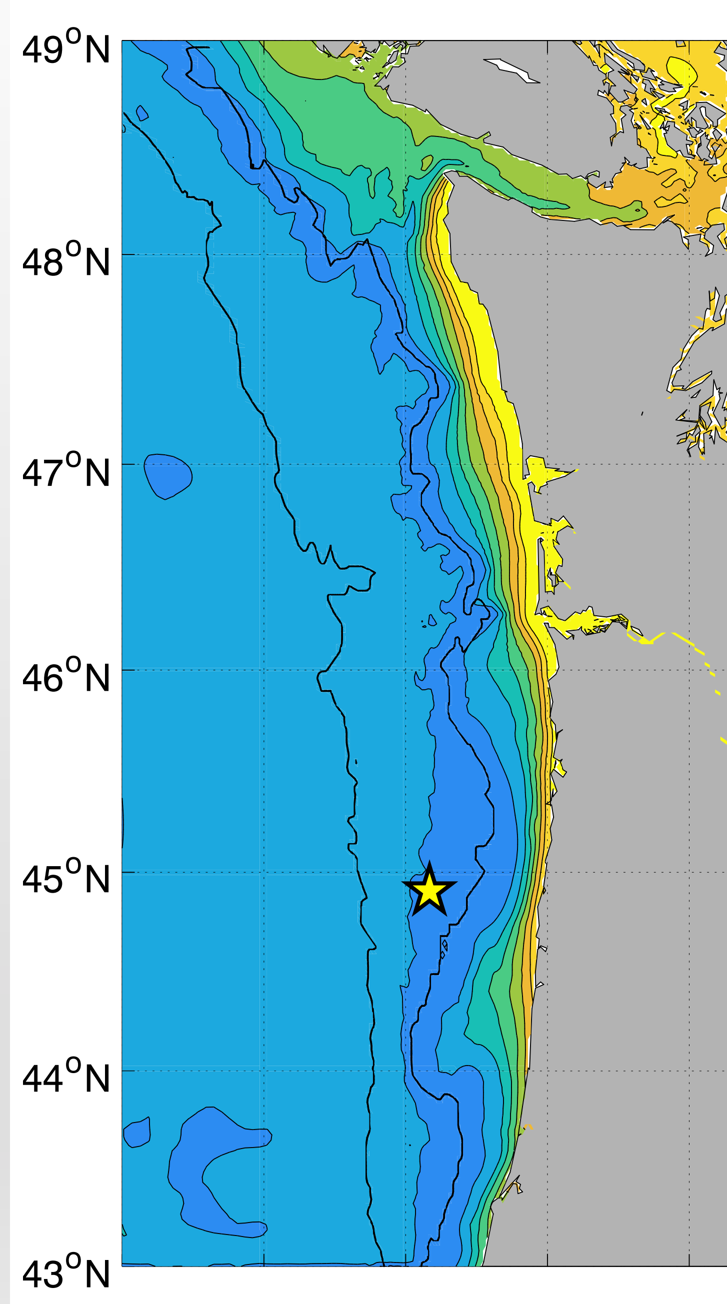
On/Near shelf
Slope
Plain
M03A, -1820m
J59A, -2370m
FN14A, -170m
FN06A, -130m
FN08A, -180m
FN03A, -90m
FN01A, -50m
FN07A, -150m
J51A, -2610m
FN19A, -80m
J49A, -120m
J42A, -1540m
J41A, -180m
M06A, -1440m
J34A, -2570m
J26A, -2860m
Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug
49°N
48°N
47°N
46°N
45°N
44°N
43°N
127°W
126°W
125°W
124°W
M03A
J59A
FN14A
FN06A
FN08A
FN01A
FN07A
FN19A
FN03A
J51A
J49A
J42A
J41A
M06A
J34A
J26A

# afloor pressure from ocean
# culation models

- edict many signals seen in APG records
- oser agreement on shelf than at depth
- ot sufficiently accurate to serve as
  eanographic correction

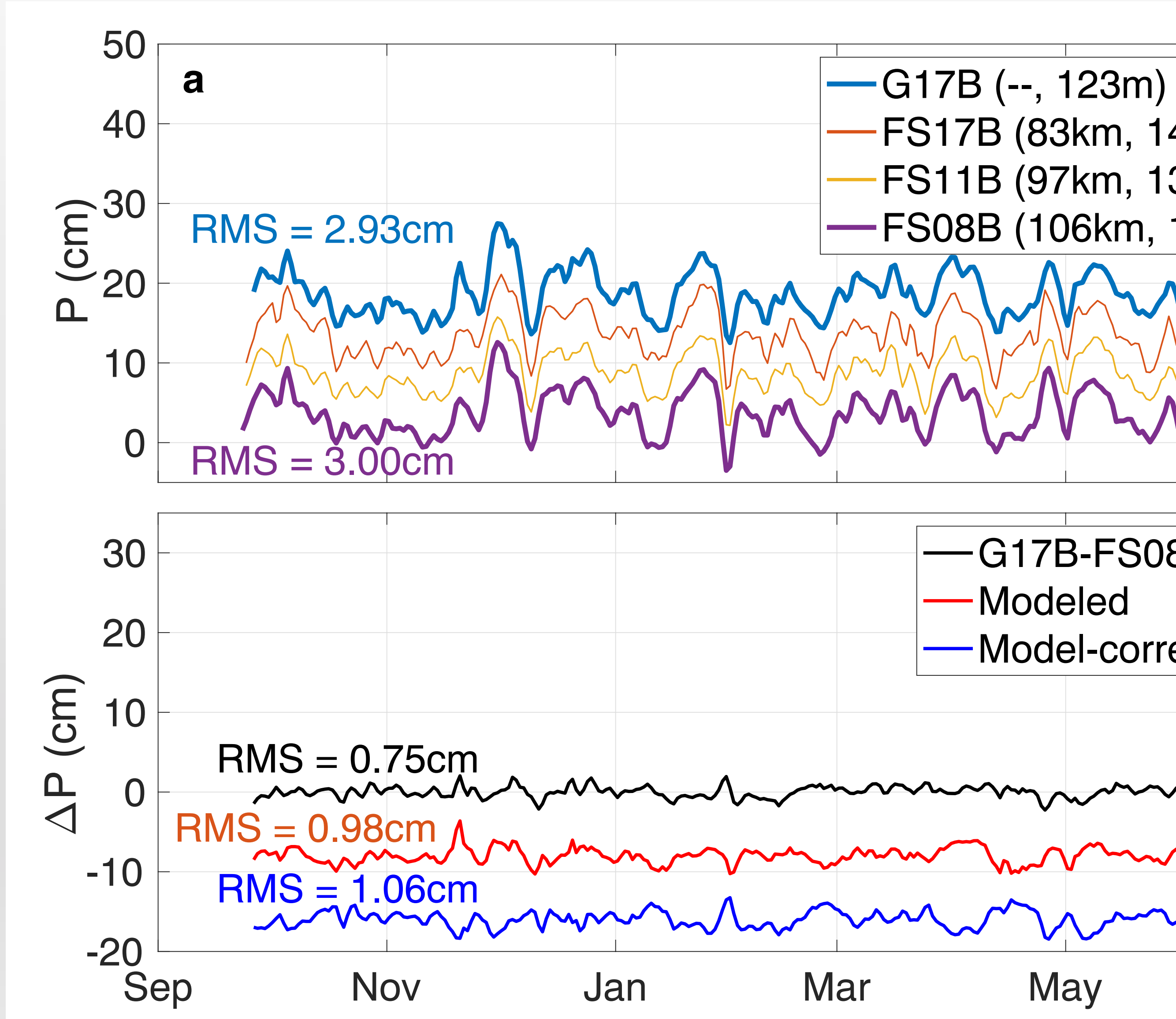


# ferencing applied to Cascadia

- b-centimeter RMS nplitudes from depth atched differencing
  - Deeper than 1400 m can vary in depth by 100s of meters over >100 km
  - Shallower requires <50 m depth matching and <100 km separation



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- b-centimeter RMS
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  - Deeper than 1400 m can vary in depth by 100s of meters over >100 km
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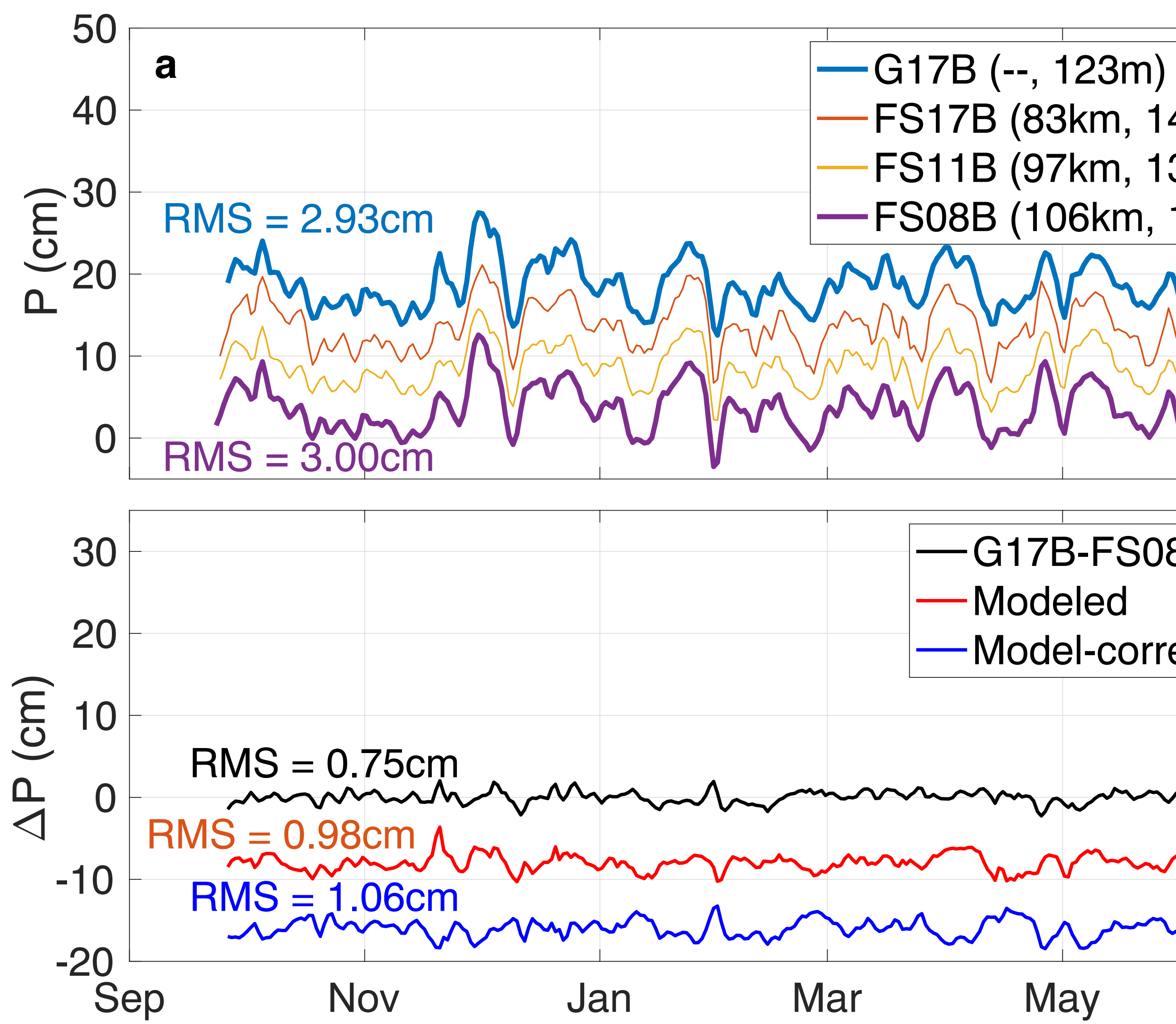
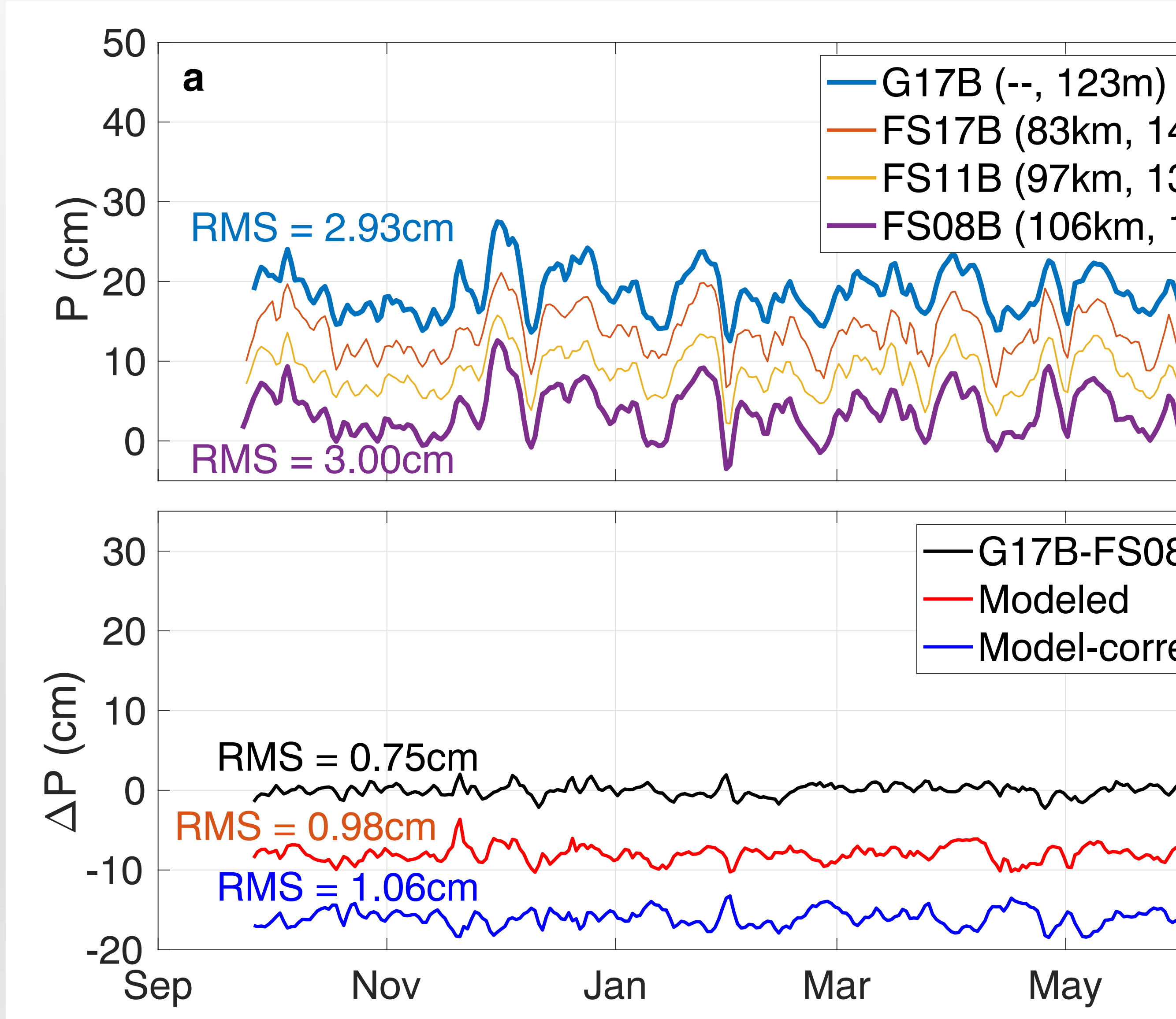
- offsets indicative of
Es found
- eanographic models in
reement



# ferencing applied to Cascadia

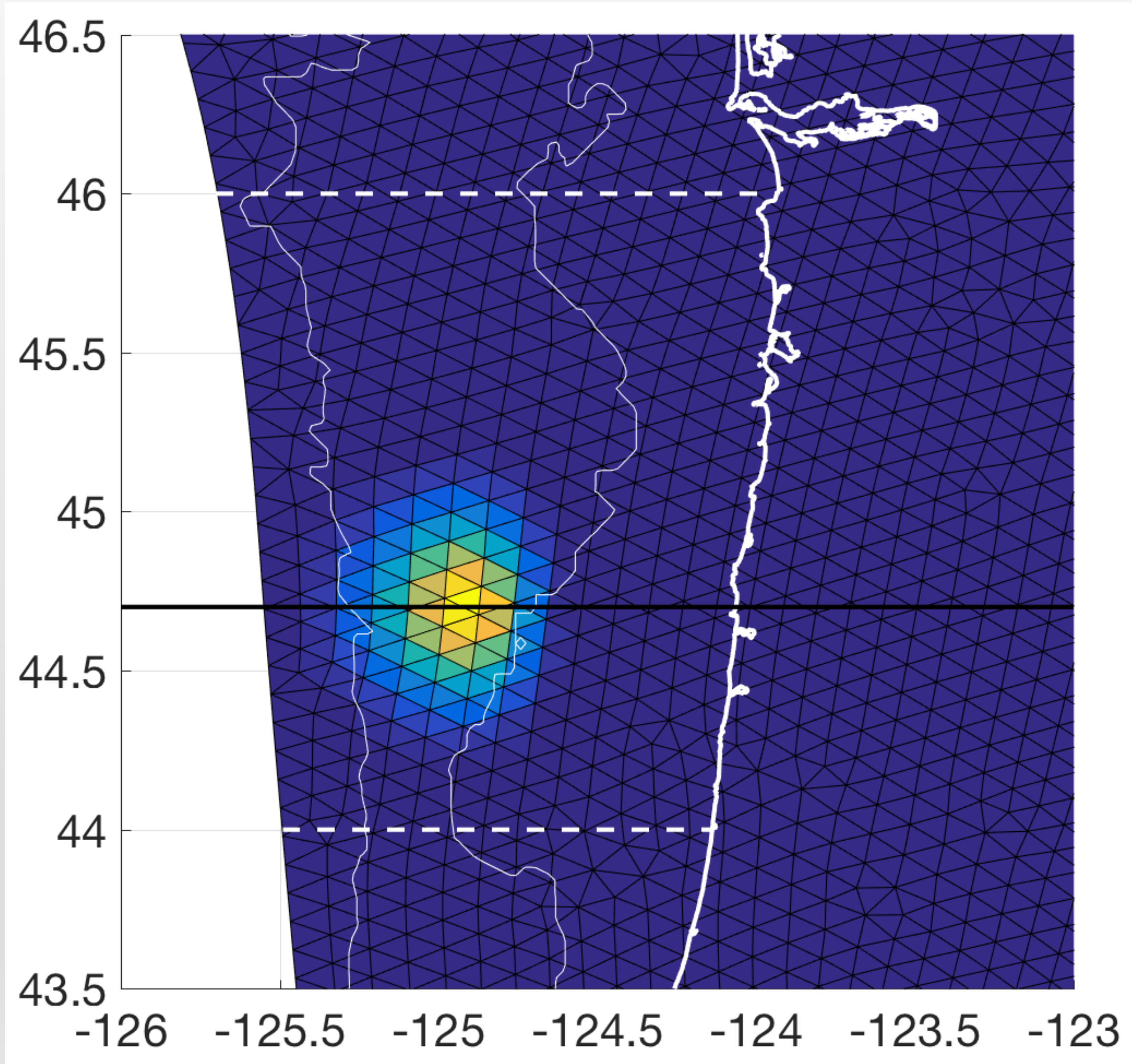
**1.5 cm threshold** for ambiguous detection of SSE signal (2σ offset)



# stic half space model

- p centered beneath
  ntinental slope offshore
  egon
- = 10 GPa, σ = 0.38
- ussian slip distribution in y and
  depth
- riable magnitude and stress
  op

$M_w$ 6.3, $\Delta\sigma$ = 0.06 MPa

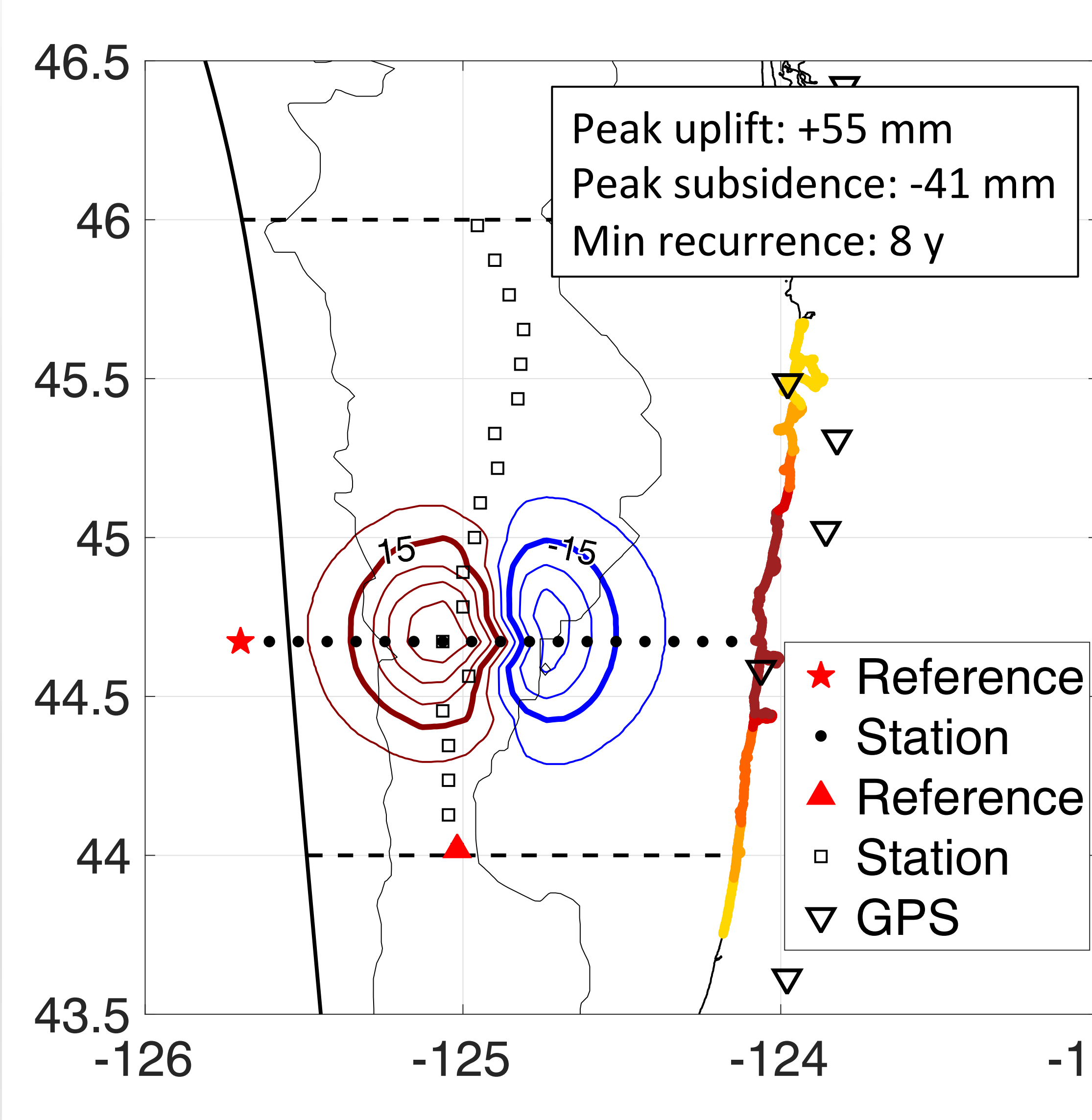


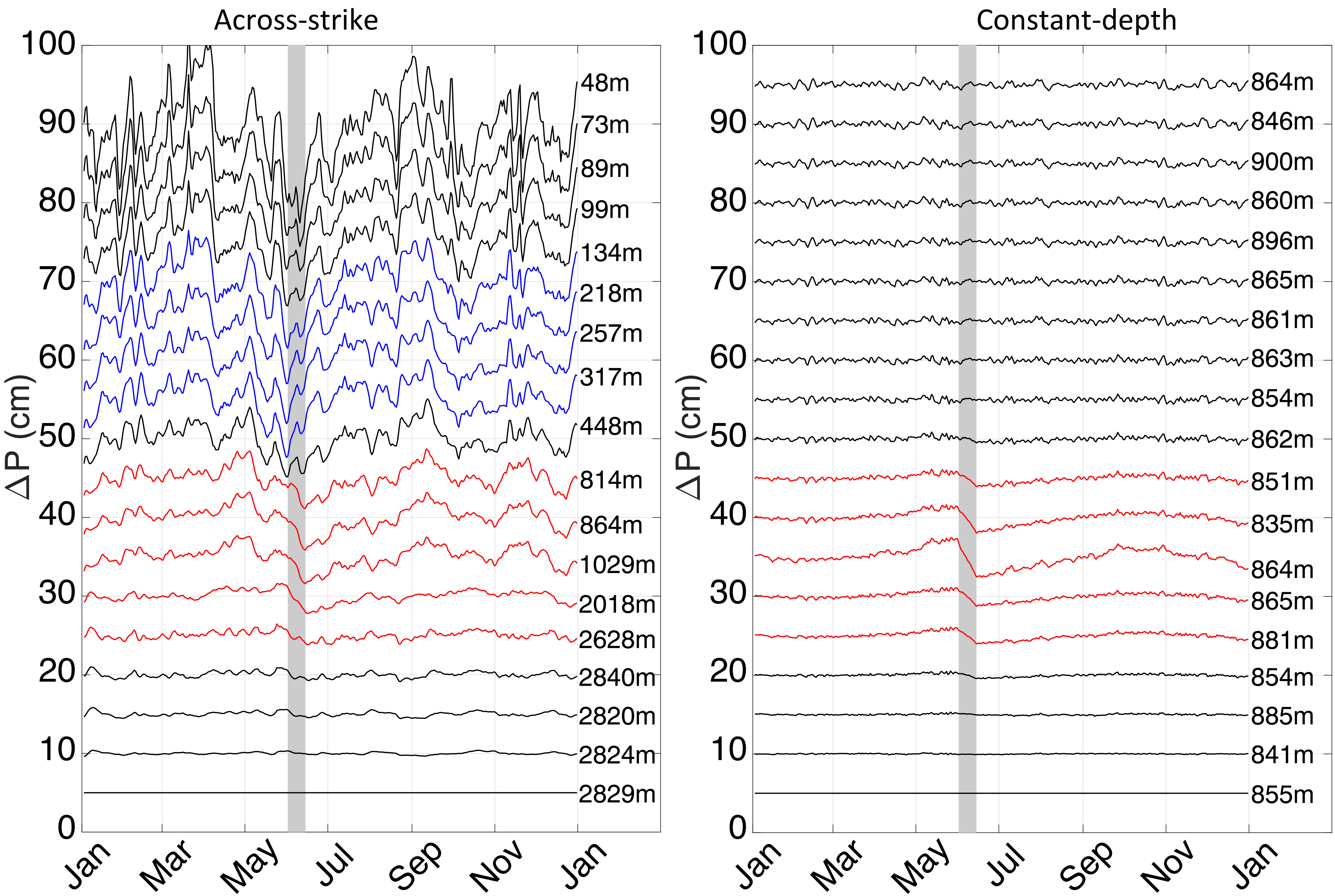

Fault geometry from McCrory e

# nthetic SSE detection

- nplistic station lines at ~10km
  acing overlying deformation
  - Pressure time series from
    oceanographic models
- d predicted deformation
  early over 14 days
- oose reference station at end
  each line for differencing

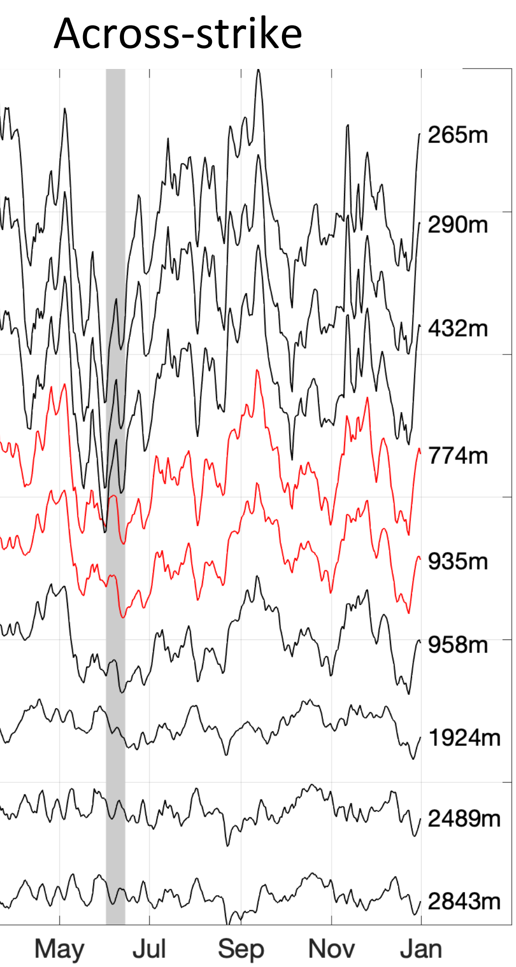
$M_w$ 6.3, $\Delta\sigma$ = 0.06 MPa

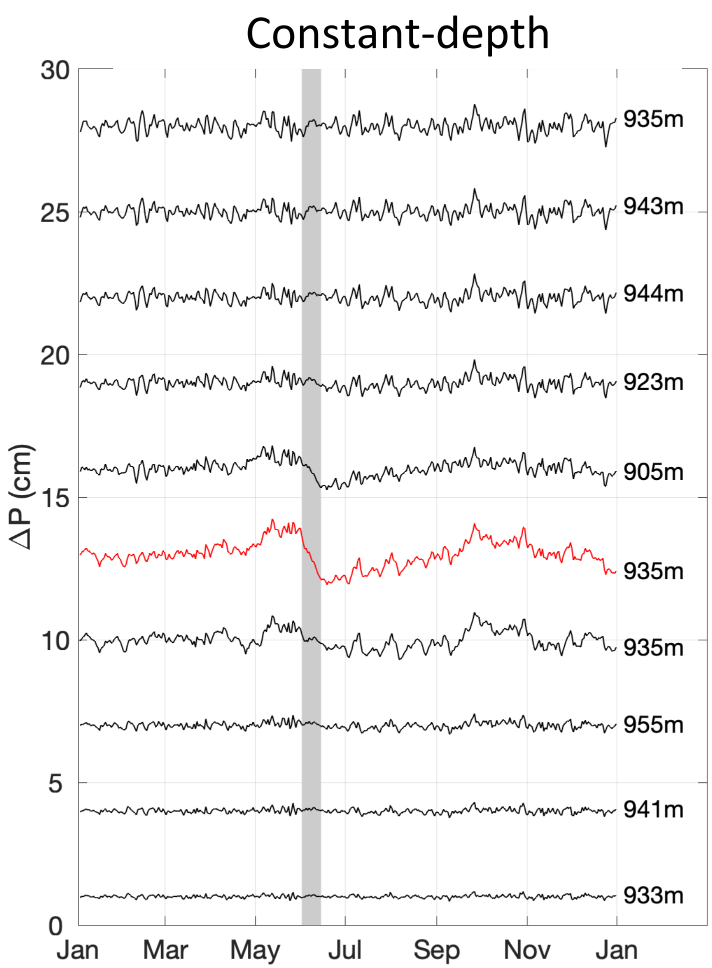


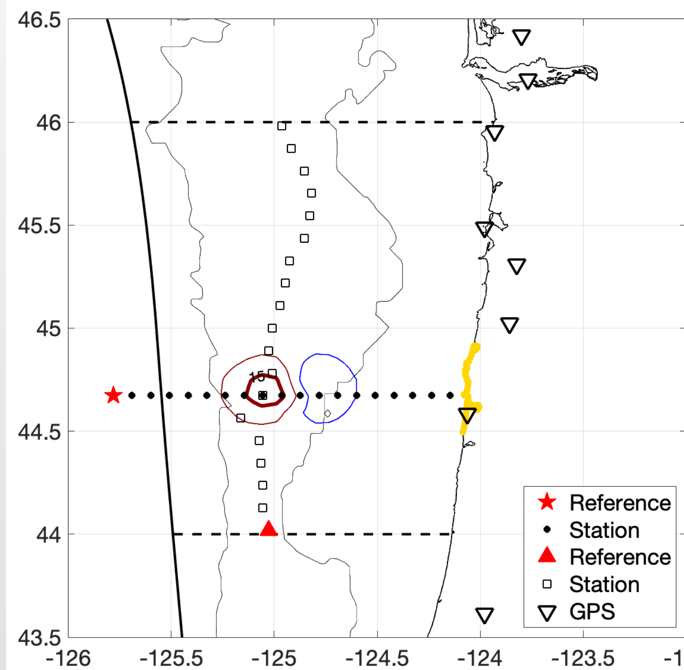


Across-strike
Constant-depth
ΔP (cm)
ΔP (cm)
100
90
80
70
60
50
40
30
20
10
0
48m
73m
89m
99m
134m
218m
257m
317m
448m
814m
864m
1029m
2018m
2628m
2840m
2820m
2824m
2829m
864m
846m
900m
860m
896m
865m
861m
863m
854m
862m
851m
835m
864m
865m
881m
854m
885m
841m
855m
Jan
Mar
May
Jul
Sep
Nov
Jan

# w magnitude model, $M_w$5.7



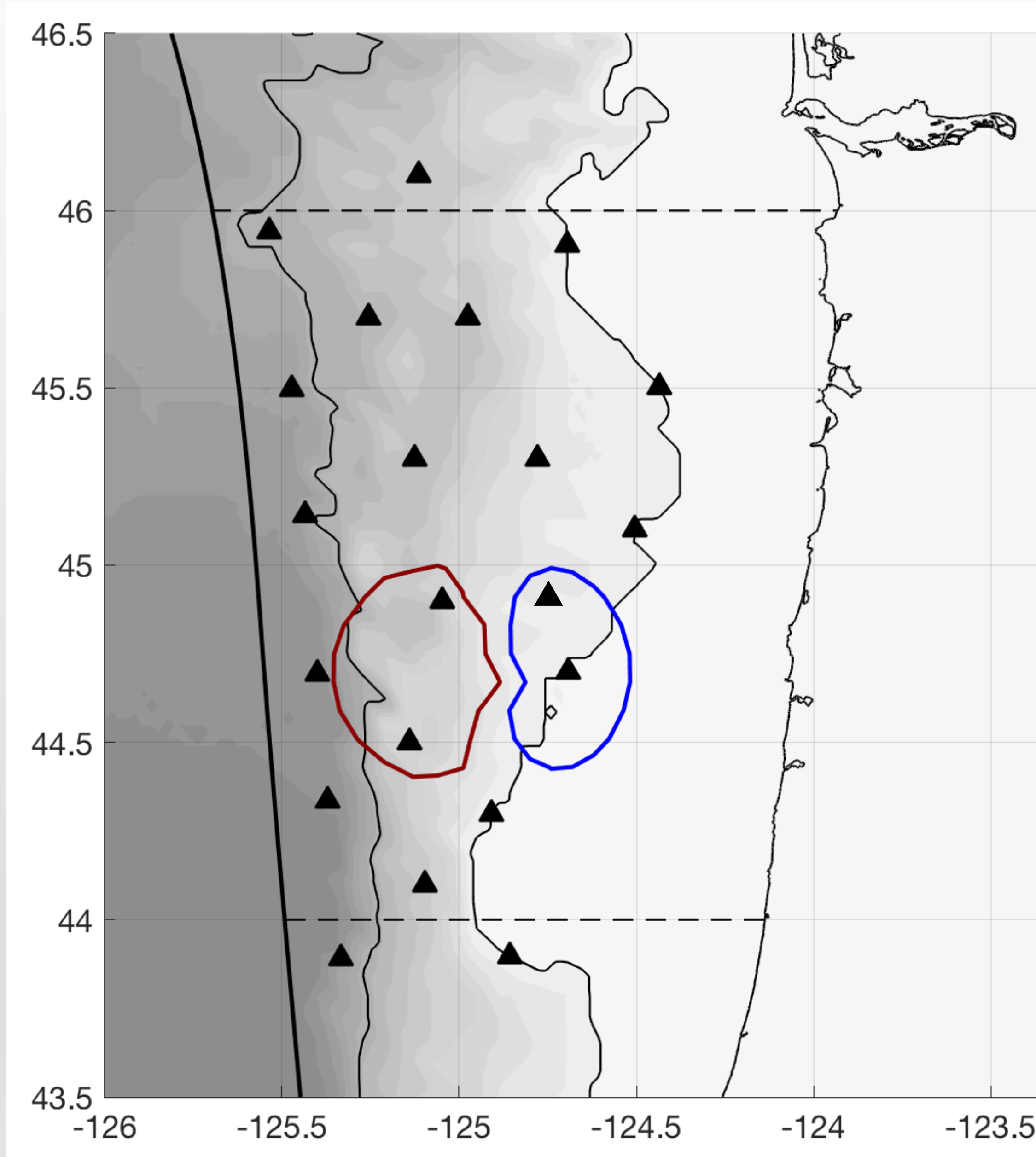




Peak uplift: +22 mm
Peak subsidence: -14 mm
Min recurrence: 4 y

# ealized network for
# E detection

- Instruments, grouped along
obaths
- km N-S spacing
- med at detecting a $M_w$ 6.3 with
oderate $\Delta\sigma$, or larger event
- ecadal-scale observation
- ecreasing detection threshold to
cm greatly increases area of
eformation



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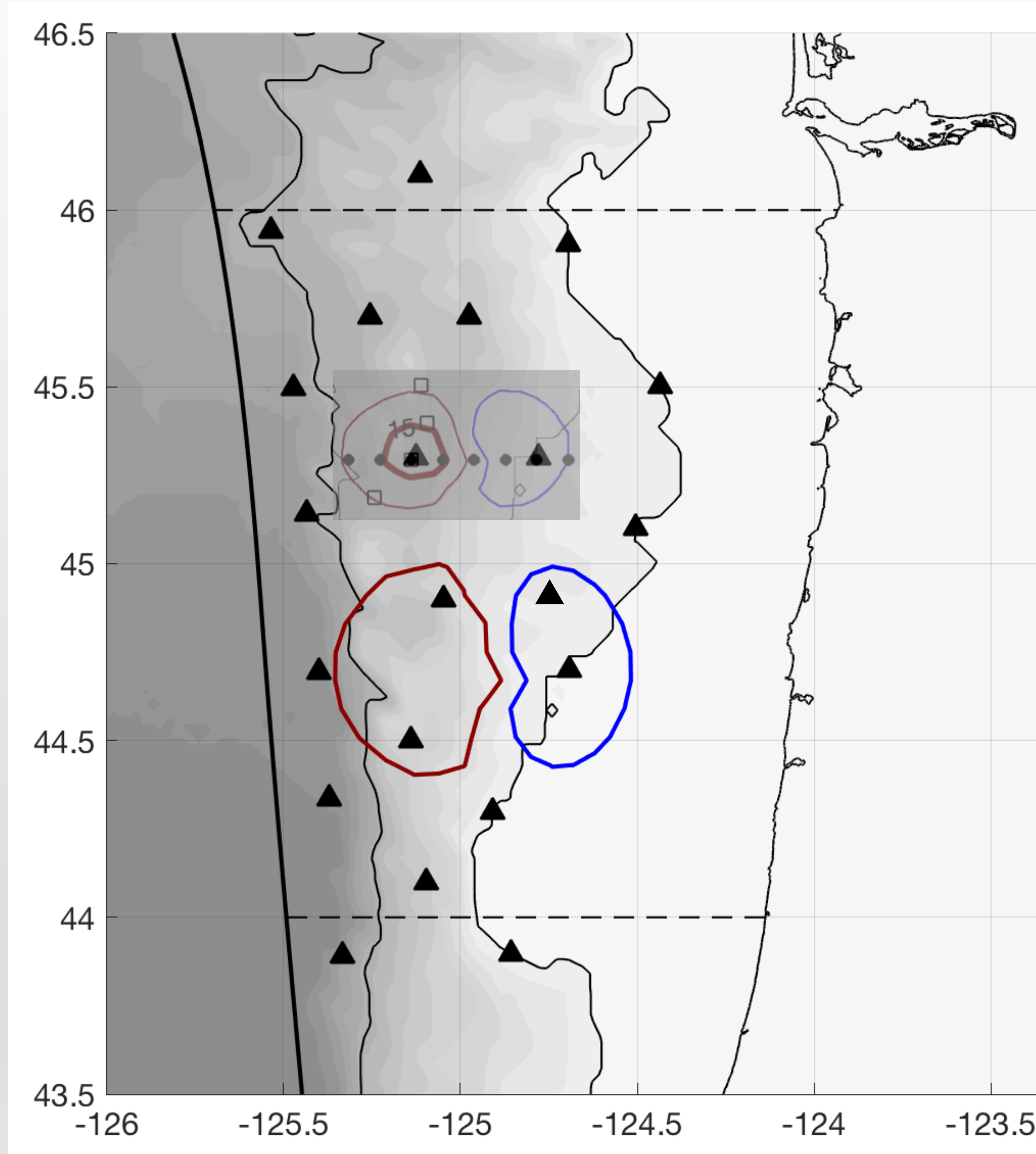


# tline

Vhat can we learn from seafloor geodesy?

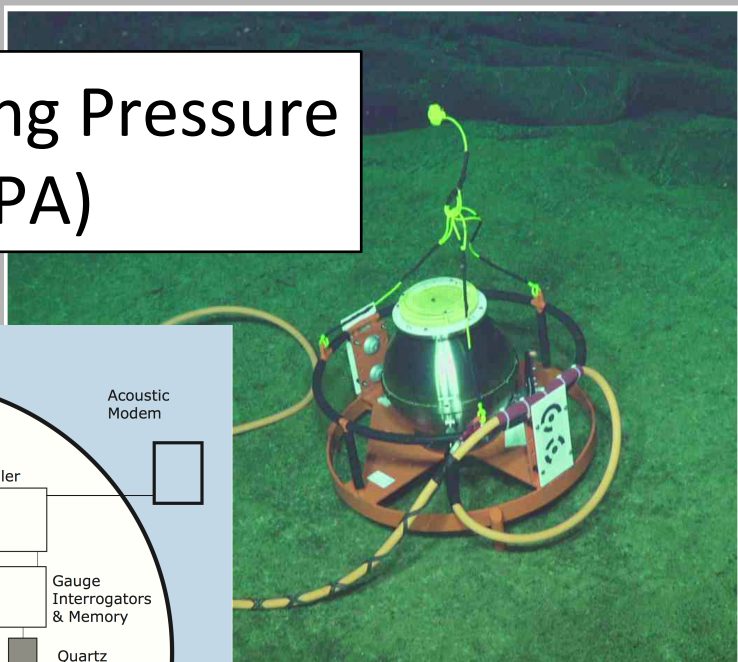
eafloor pressure geodesy in Cascadia

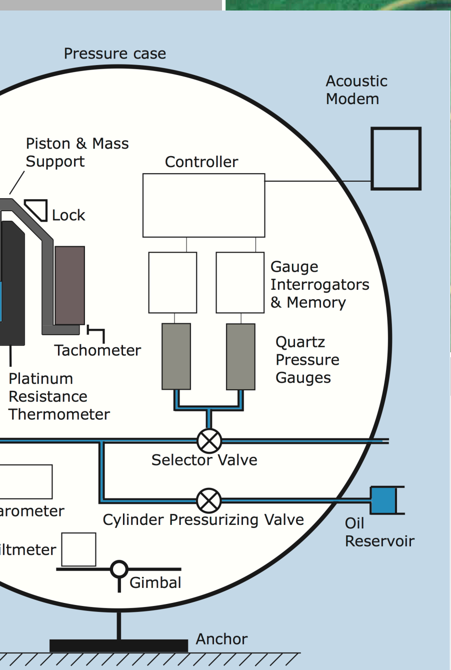
volving methods for highly accurate pressure measurements

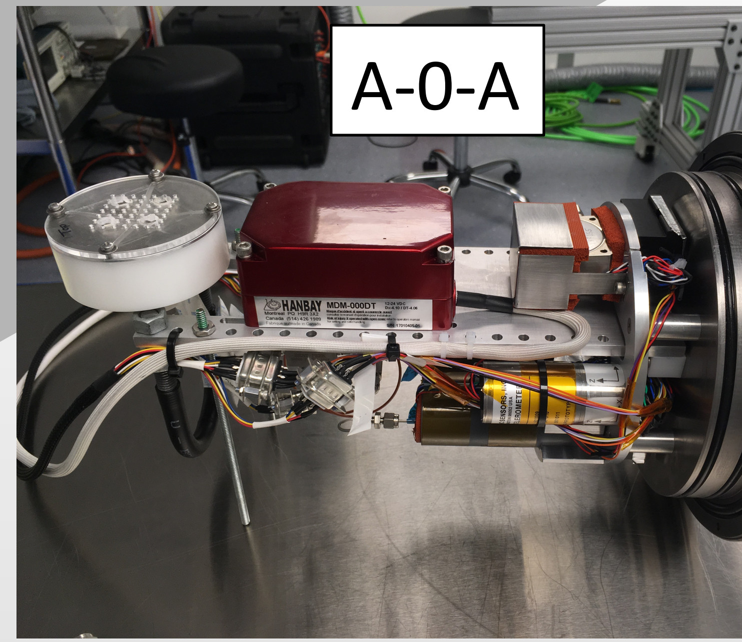
Other geodetic tools/measurements in the ocean

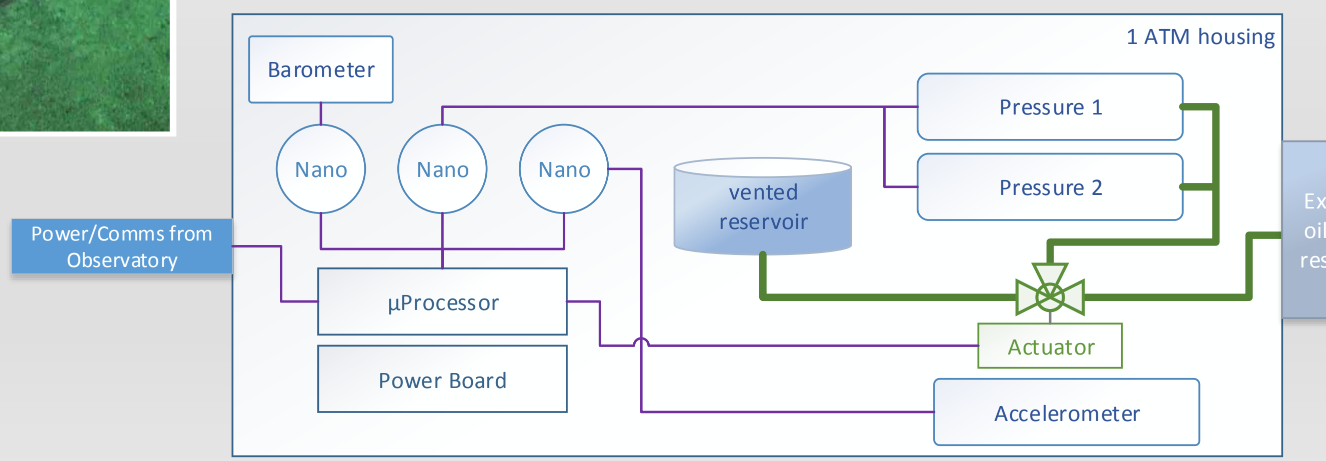
# strumental drift correction in seafloor essure measurements

## alibrating Pressure der (SCPA)





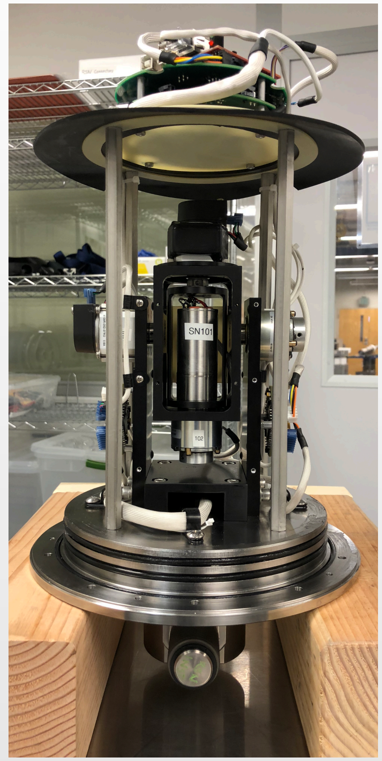



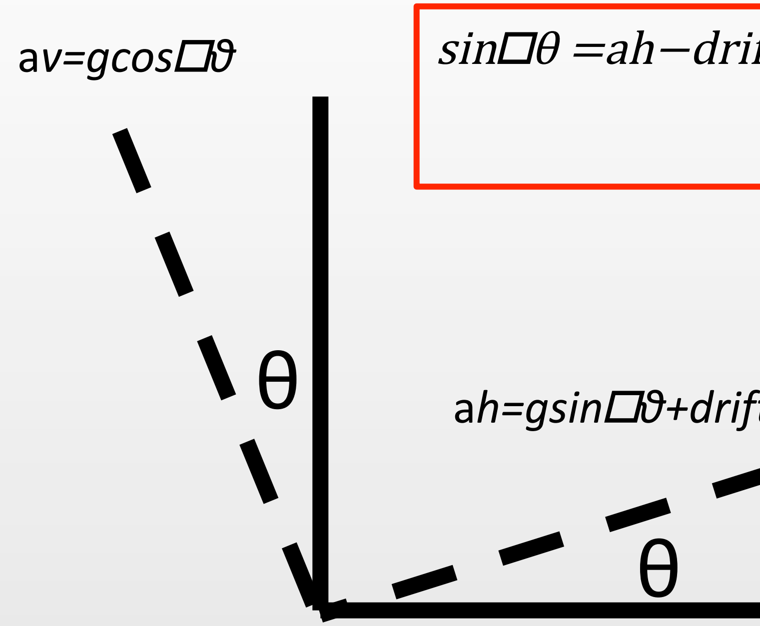

nberge, Glenn Sasagawa

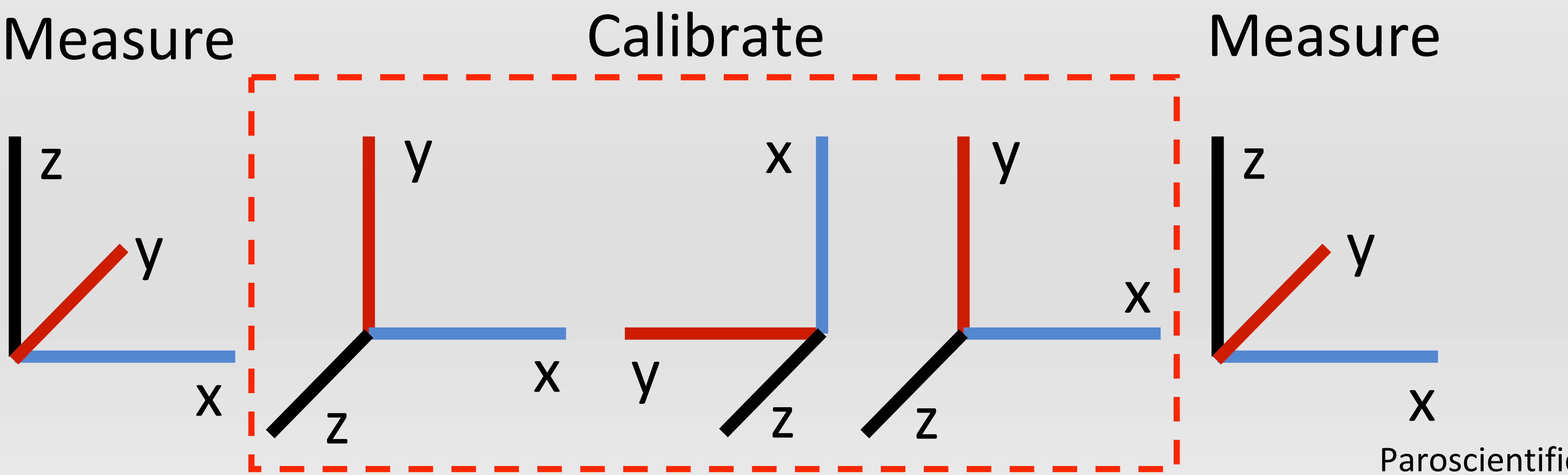
Paroscientifi

# lf-Calibrating Tilt celerometer

- mponent accelerometer
- zontal channels measure tilt as
- ical channel measures
- brated against combined g vector

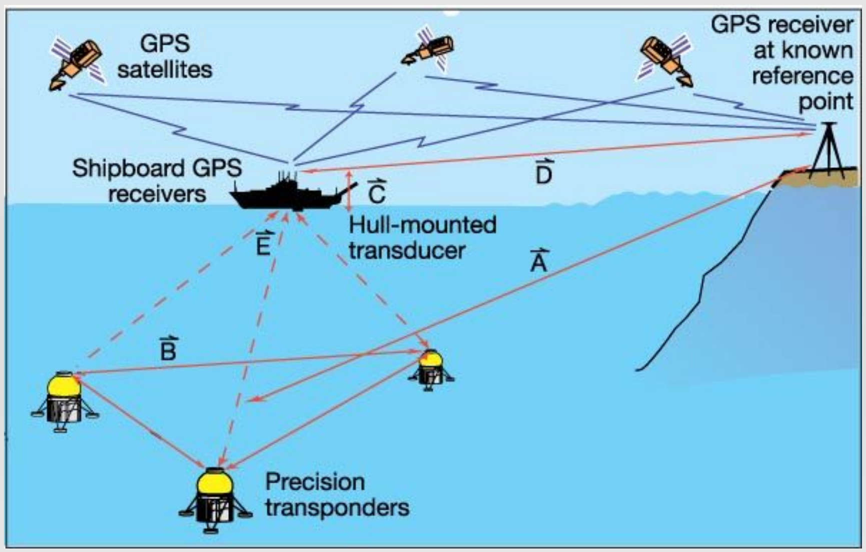




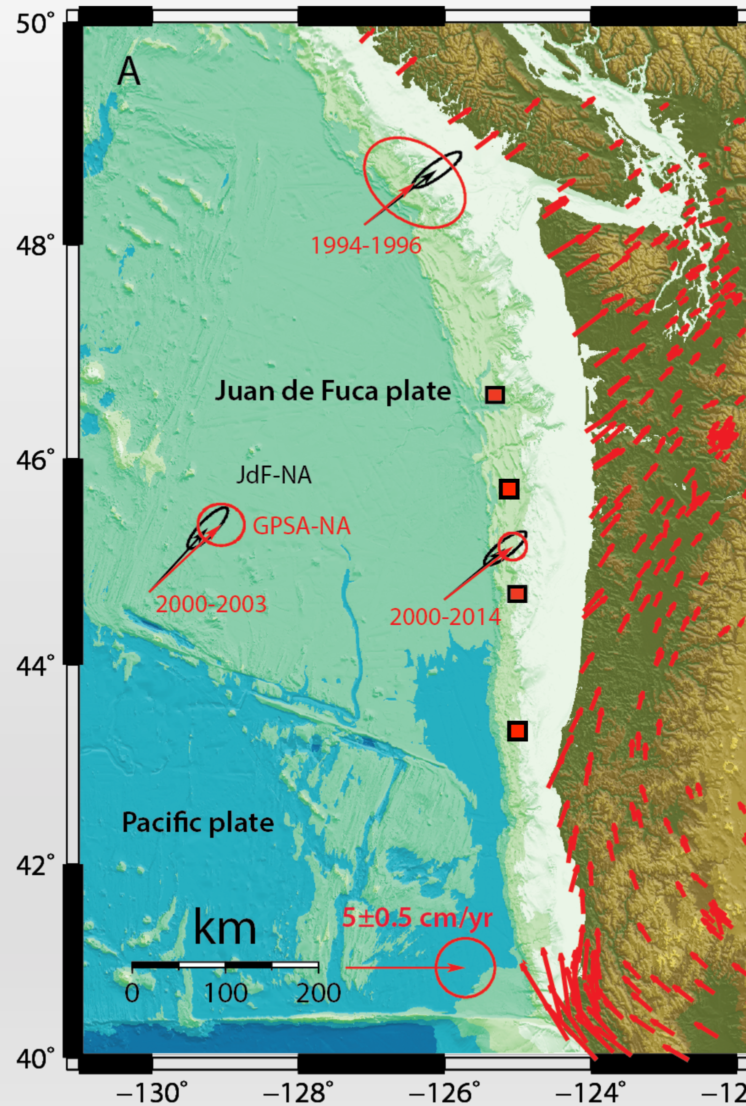



# S-A for seafloor horizontal displacement

- afloor transponders
- ip or glider to take campaign style
  easurements
- n precision



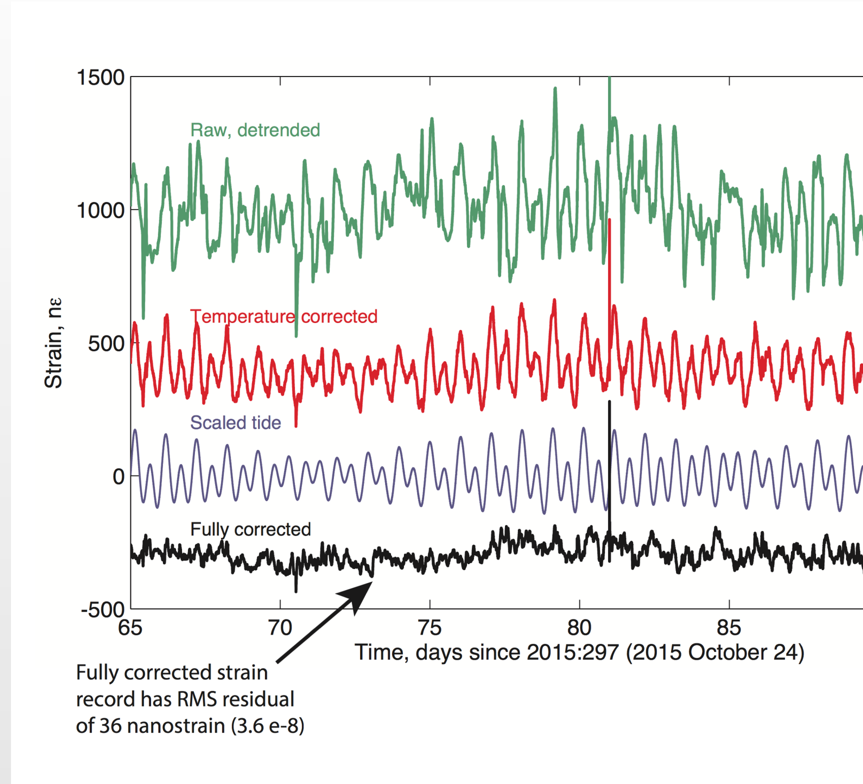

Gagnone et al., 2005

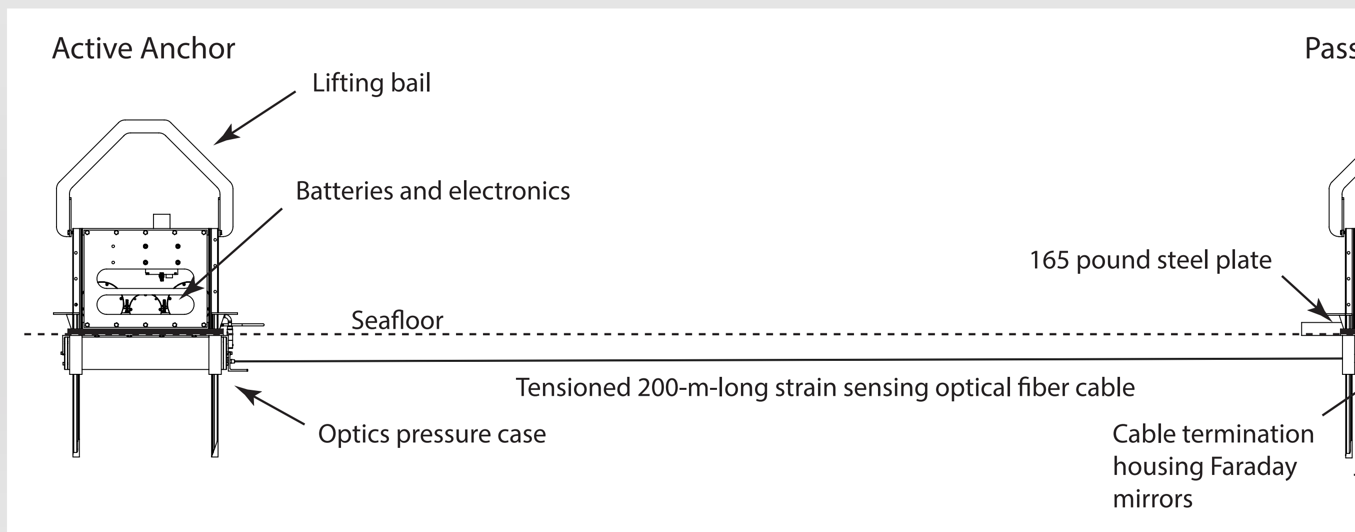



David Schmidt and Dave Cl

# ptical fiber strainmeters

- terferometry to precisely easure length
- eriod-dependent sensitivity etter of 10s of microstrain or etter

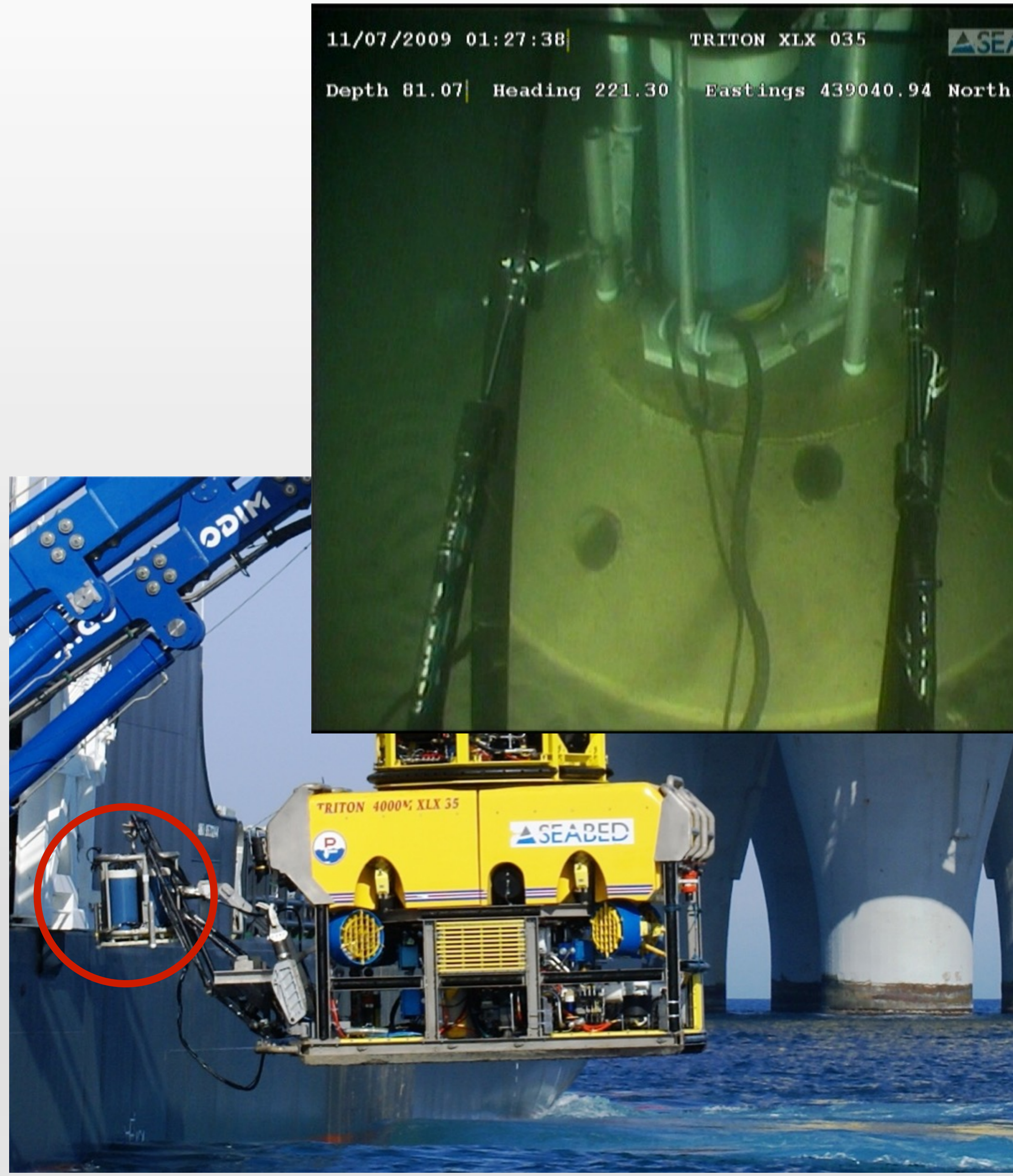



Mark Z

# afloor gravimetry

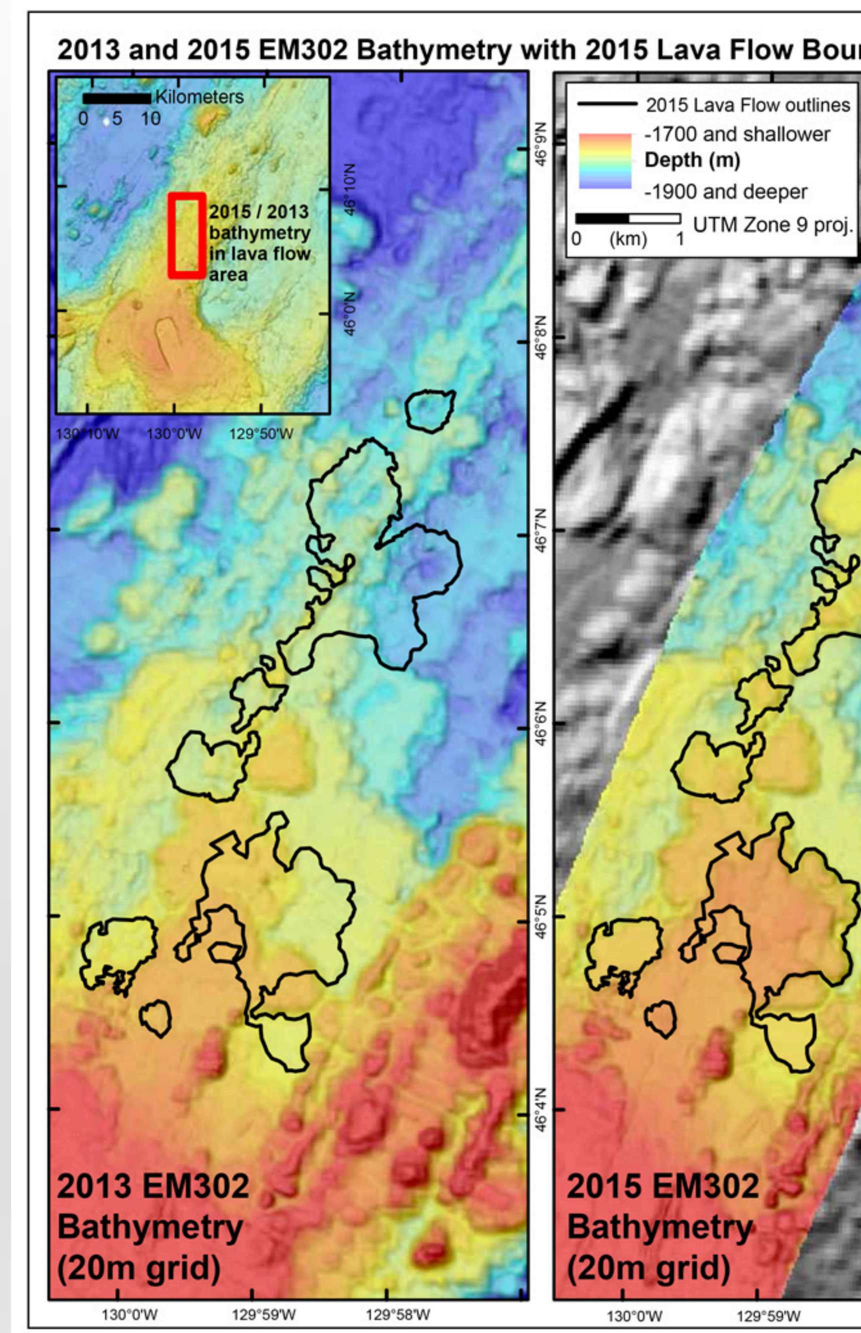
- mpaign/Benchmark style easurements
- .01 mGal precision
- onitor reservoir changes, ap intrusive layers, etc.




Mark Zumberge & Glenn

# fferential Bathymetry

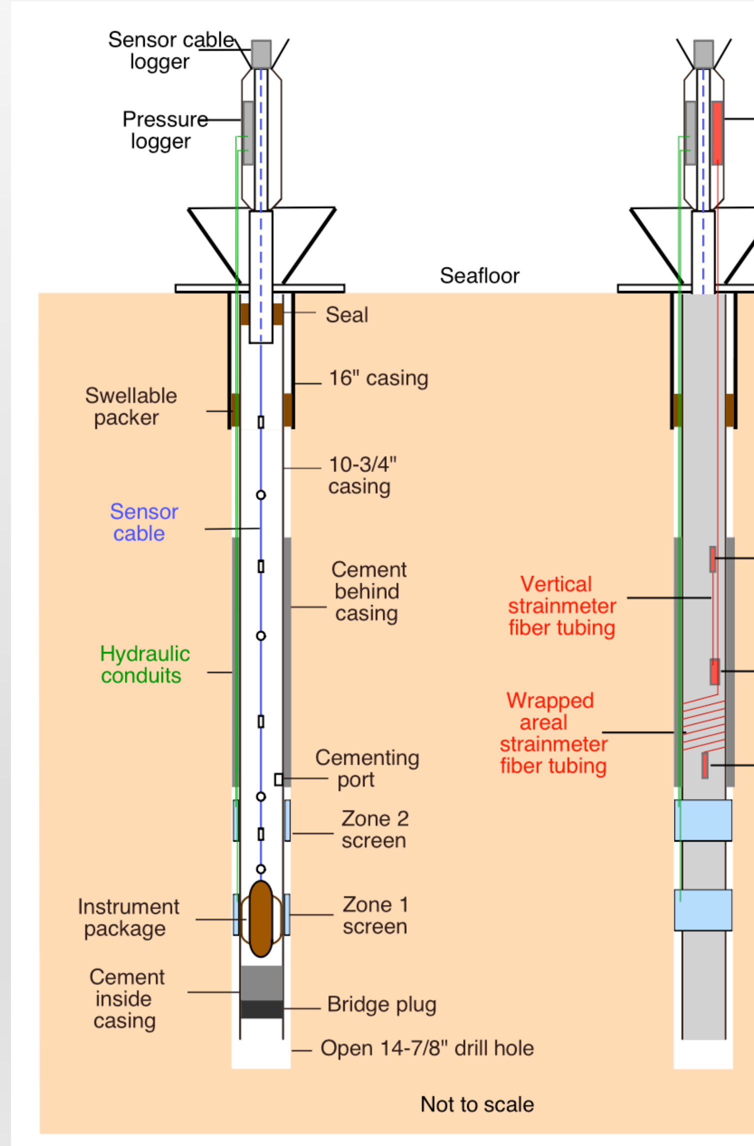
- de scan sonar, multibeam, c.
- epeat surveys
- riable resolution, depending n technique




Susan Merle, NO

# rehole Observatories, CORKS

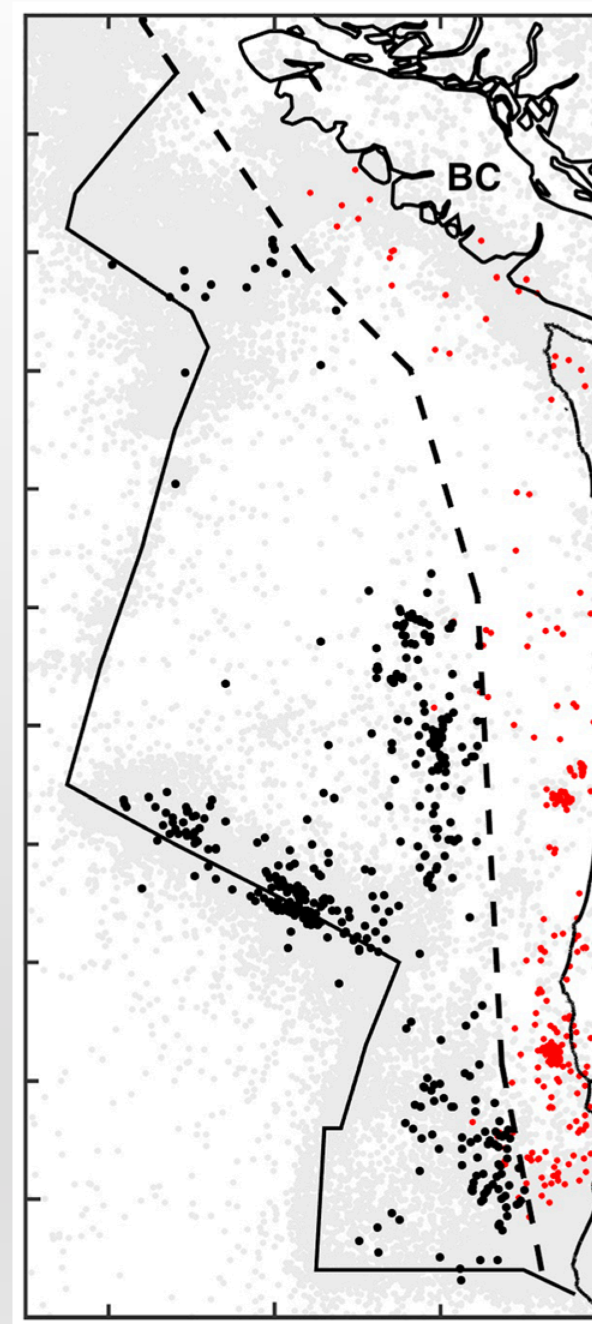
- ismic and geodetic
  strument packages
- rmation pressure
- uid sampling



# Thank you!

# afloor pressure geodesy
# Cascadia

- omalously low seismicity near the egathrust
- rge distance from shoreline to trench




Stone et

# otivating Questions

an oceanographic signals be effectively removed from seafloo
ressure data?

Over what scales are oceanographic signals comparable within a sens
network?

Can oceanographic circulation models be used to remove/understand
these signals?

# otivating Questions

an oceanographic signals be effectively removed from seafloo
ressure data?

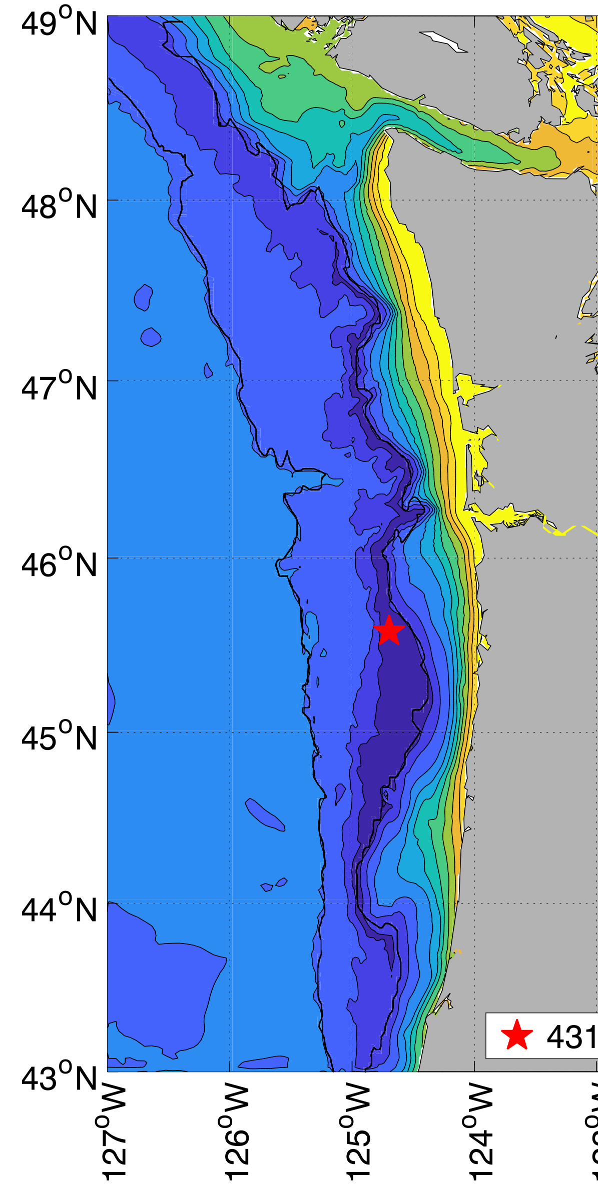
- Explore spatial scale of oceanographic comparability between pressu
sensors
- Use oceanographic circulation models to understand these signals

Vhat is the detectability of shallow slow slip earthquakes usin
eafloor pressure?

- Model expected amplitudes and dimensions of deformation
- Present optimal geometry for the detection of SSEs

# odels suggest regional continuity

- eanographic models in agreement with tterns identified in APG differences
- ggest larger separation, lower RMS may be ssible from precisely matched depths



# odels suggest regional continuity

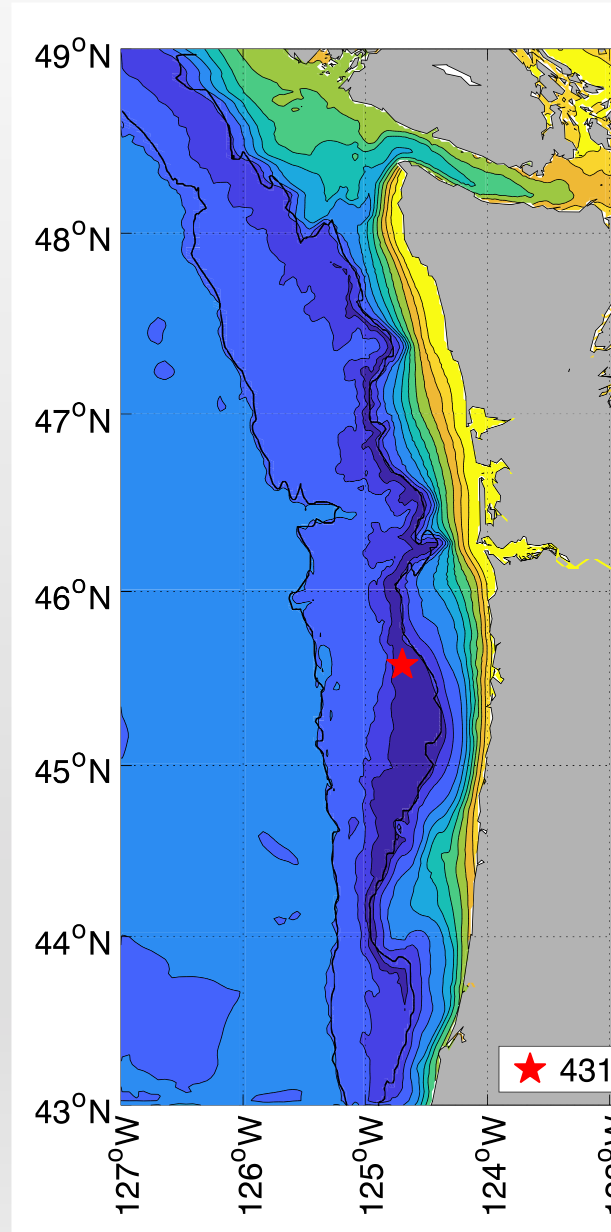
eanographic models in agreement with
tterns identified in APG differences

ggest larger separation, lower RMS may be
ssible from precisely matched depths

n residual noise:

**1.5 cm threshold** for unambiguous detection of SSE signal

(2σ offset)



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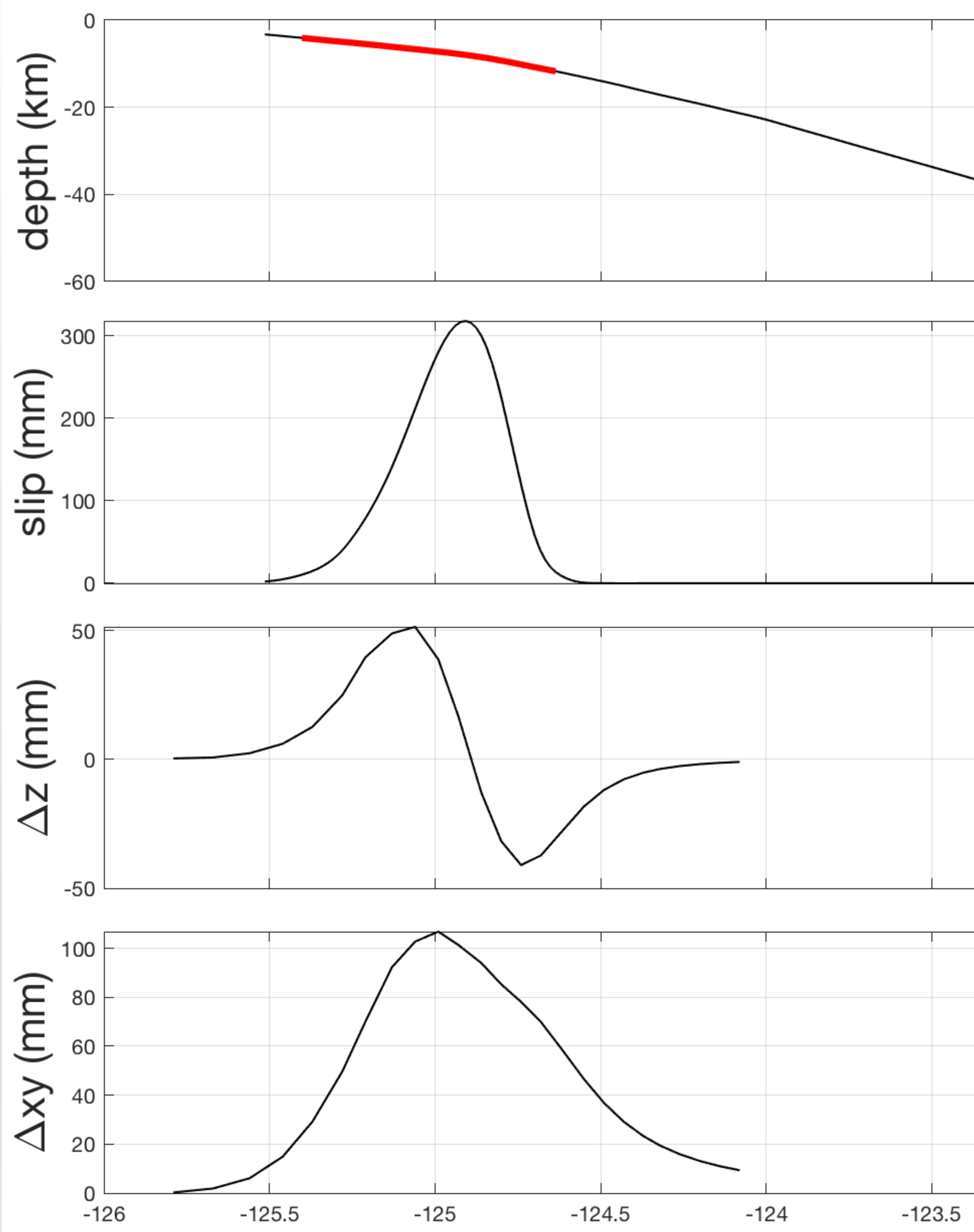
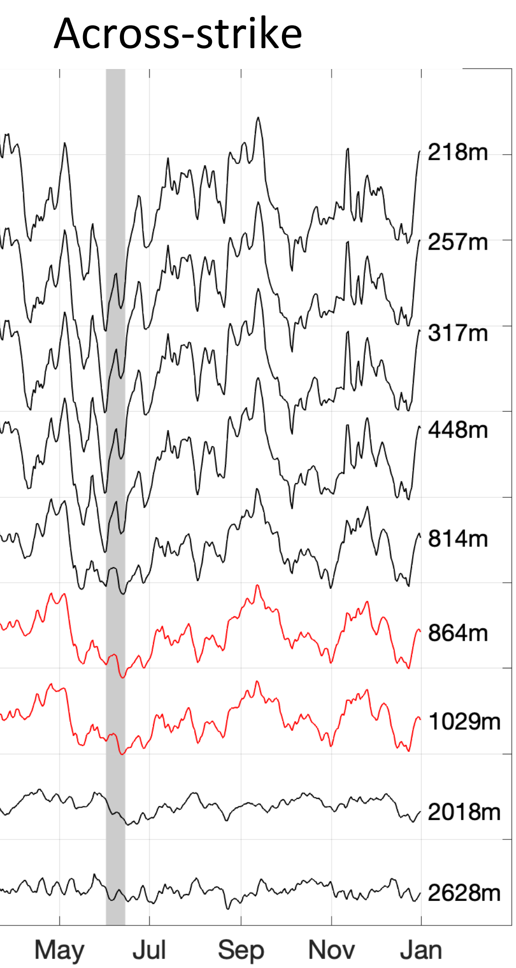
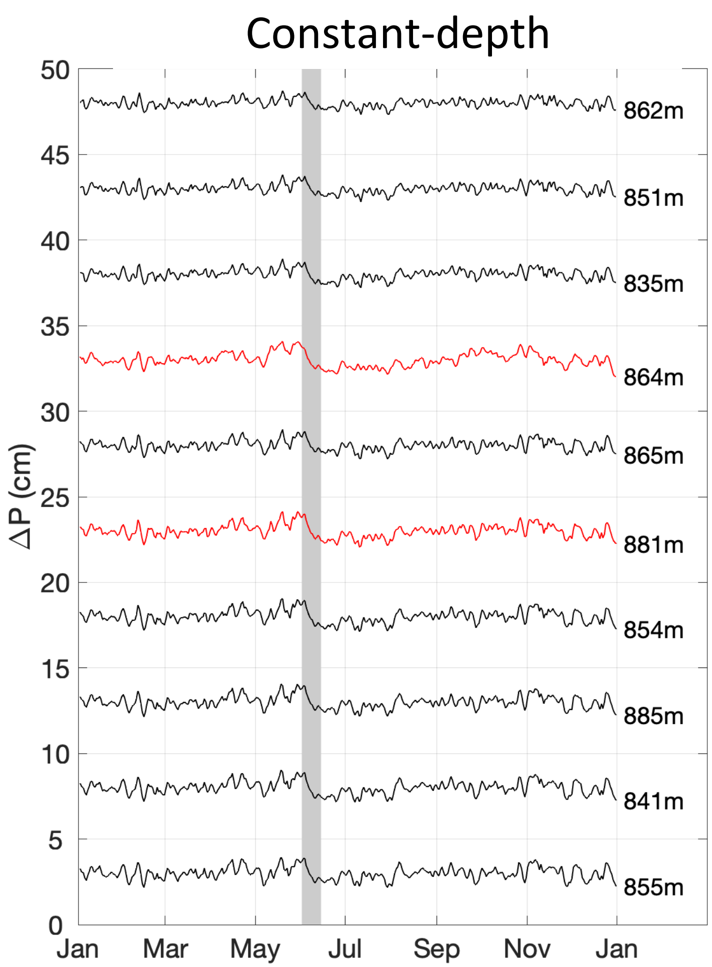
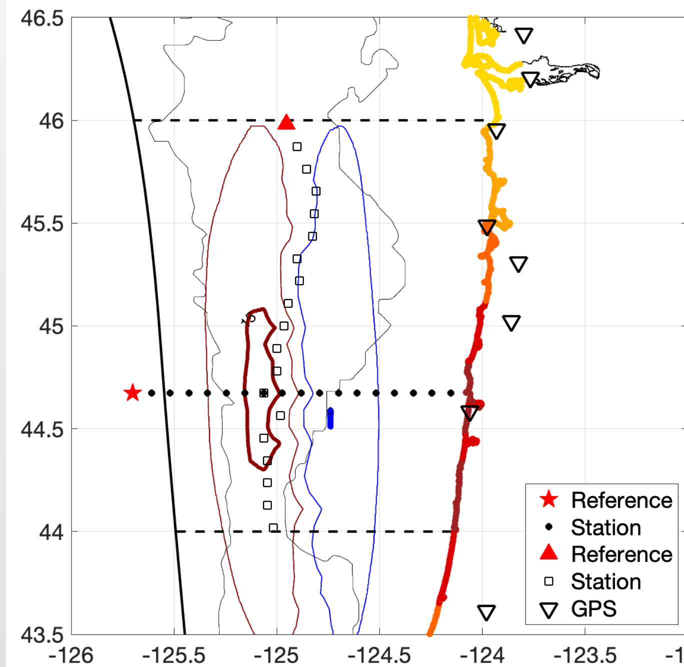
- $_w$ 6.3, $\Delta\sigma$ = 0.06 MPa



# w stress drop model $\Delta\sigma$ = 0.01 MPa



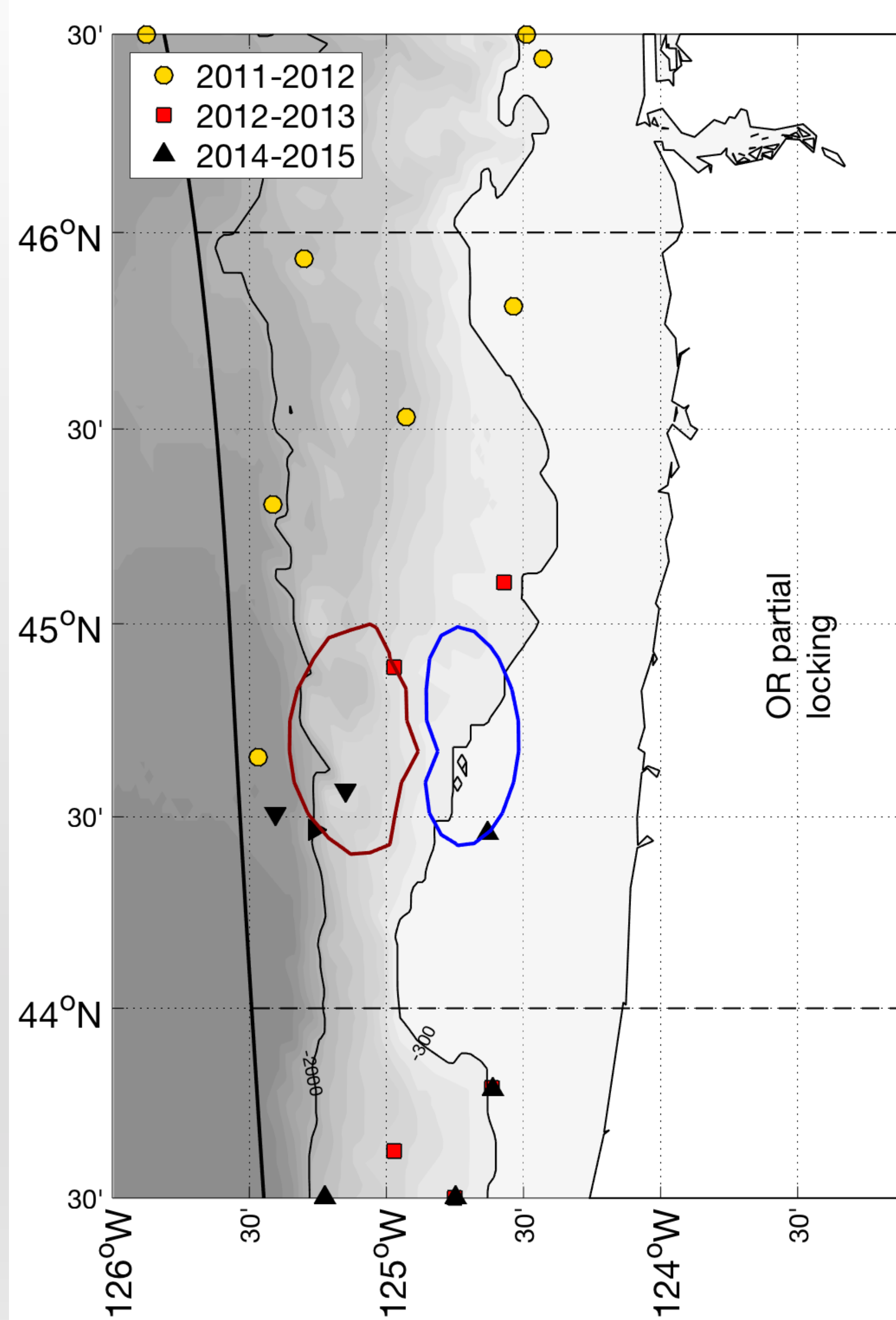




Peak uplift: +18 mm
Peak subsidence: -15 mm
Min recurrence: 2.5 y

# aluating Cascadia APG taset

- sufficient instrumentation to liably detect SSE
  - Instrument migration between years
- mited depth-matching
- periment duration too short
  - <1 year at given location



# ealized network for
# E detection

- . Instruments, grouped along
obaths
- 5 km N-S spacing
- med at detecting a $M_w$ 6.3 with
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- ecadal-scale observation
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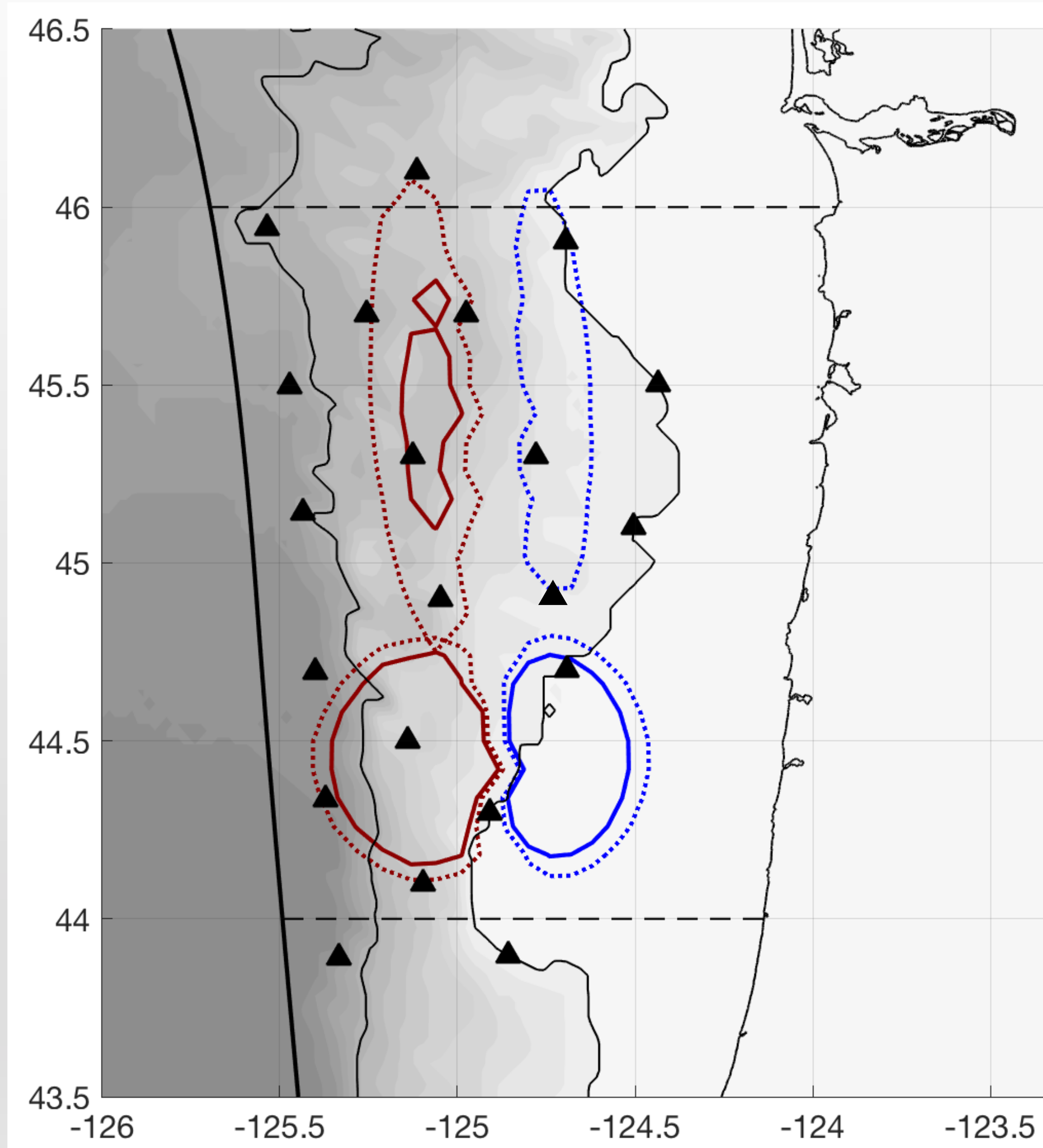
cm greatly increases area of
eformation



# nclusions

- Oceanographic signals can be effectively removed with
pth-matched differencing
  - <1 cm RMS over ~100 km separation
  - Detection threshold of 1.5 cm
  - Oceanographic models suggest further reduction possible
- $M_w$6.3 SSEs detectable with a modest network
  - Cascadia APG data insufficient for SSE detection
  - A decadal experiment off central Oregon utilizing depth matched geometry may be required
  - Threshold reduction to 1 cm improves ability to detect smaller SS