Optimizing Subduction Zone Monitoring

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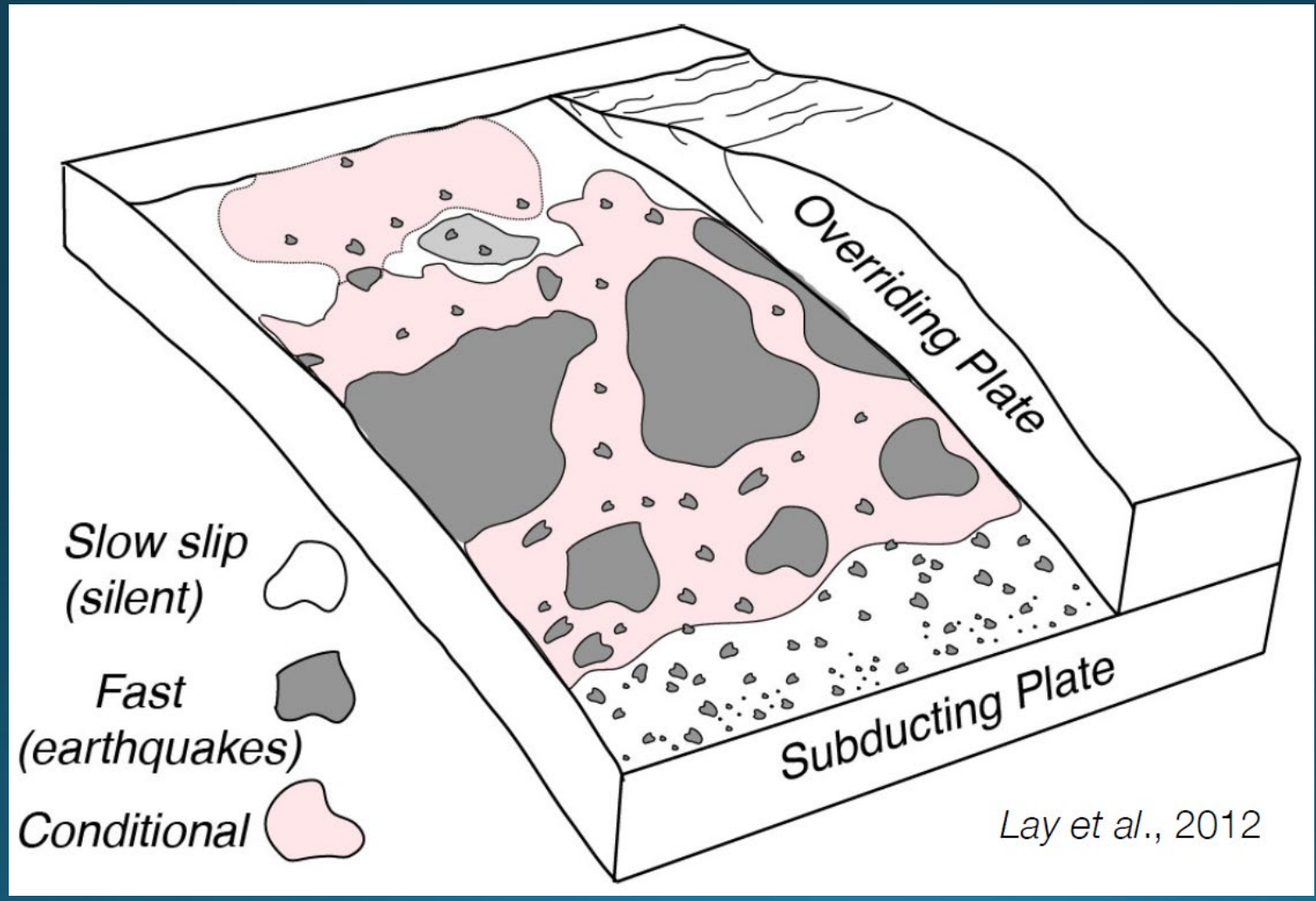
On behalf of Eileen Evans and Ben Brooks

USGS
science for a changing world

CALIFORNIA STATE UNIVERSITY NORTHRIDGE 1958

Locking, slow slip, and in between

$$\dot{s}_{\text{locked}} = \dot{s}_{\text{tectonic}} - \dot{s}_{\text{slow/creep}}$$



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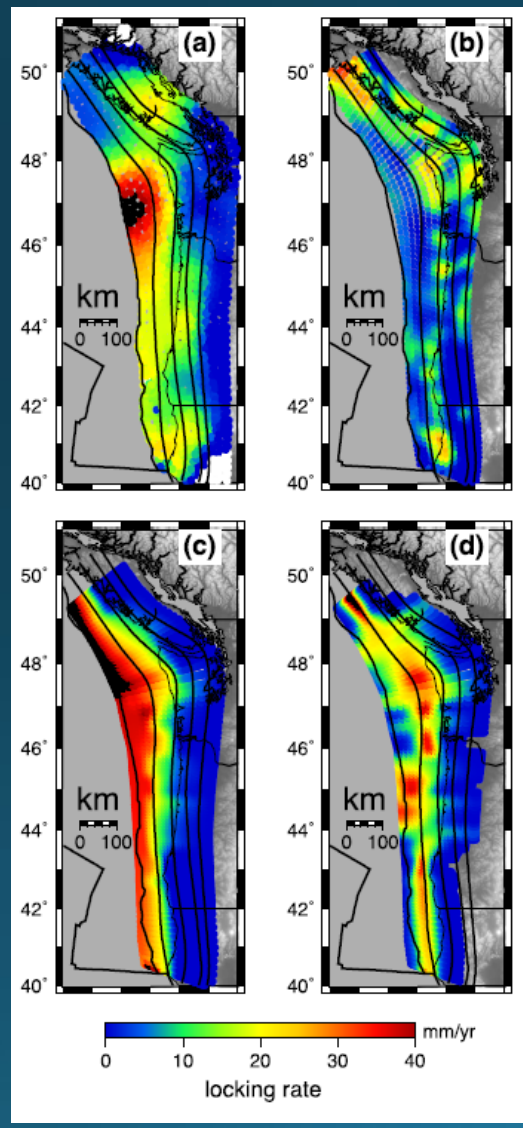
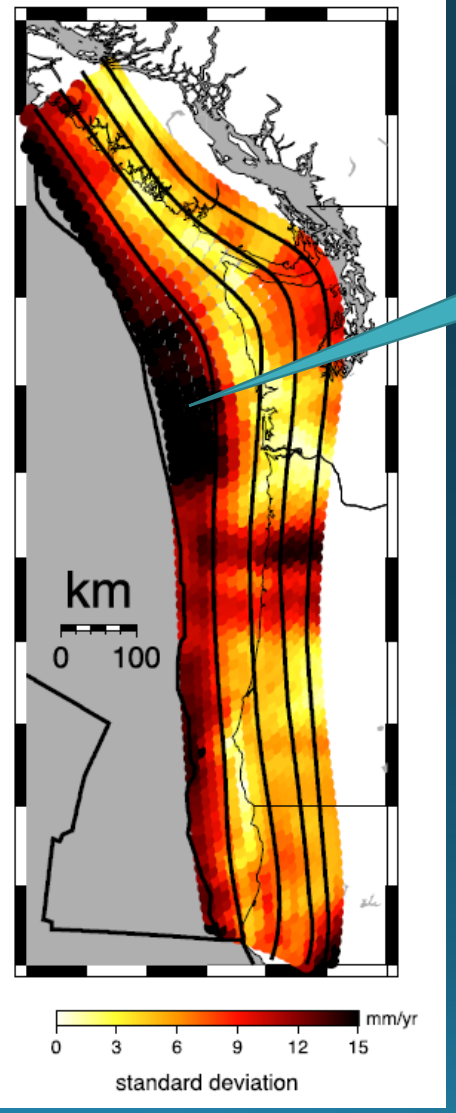
Locking rates from *Pollitz and Evans, 2017*

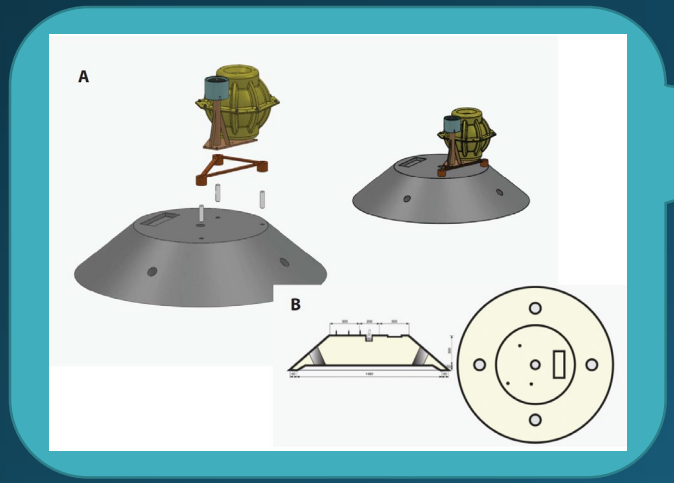
Locking rates from *McCaffrey et al., 2013*

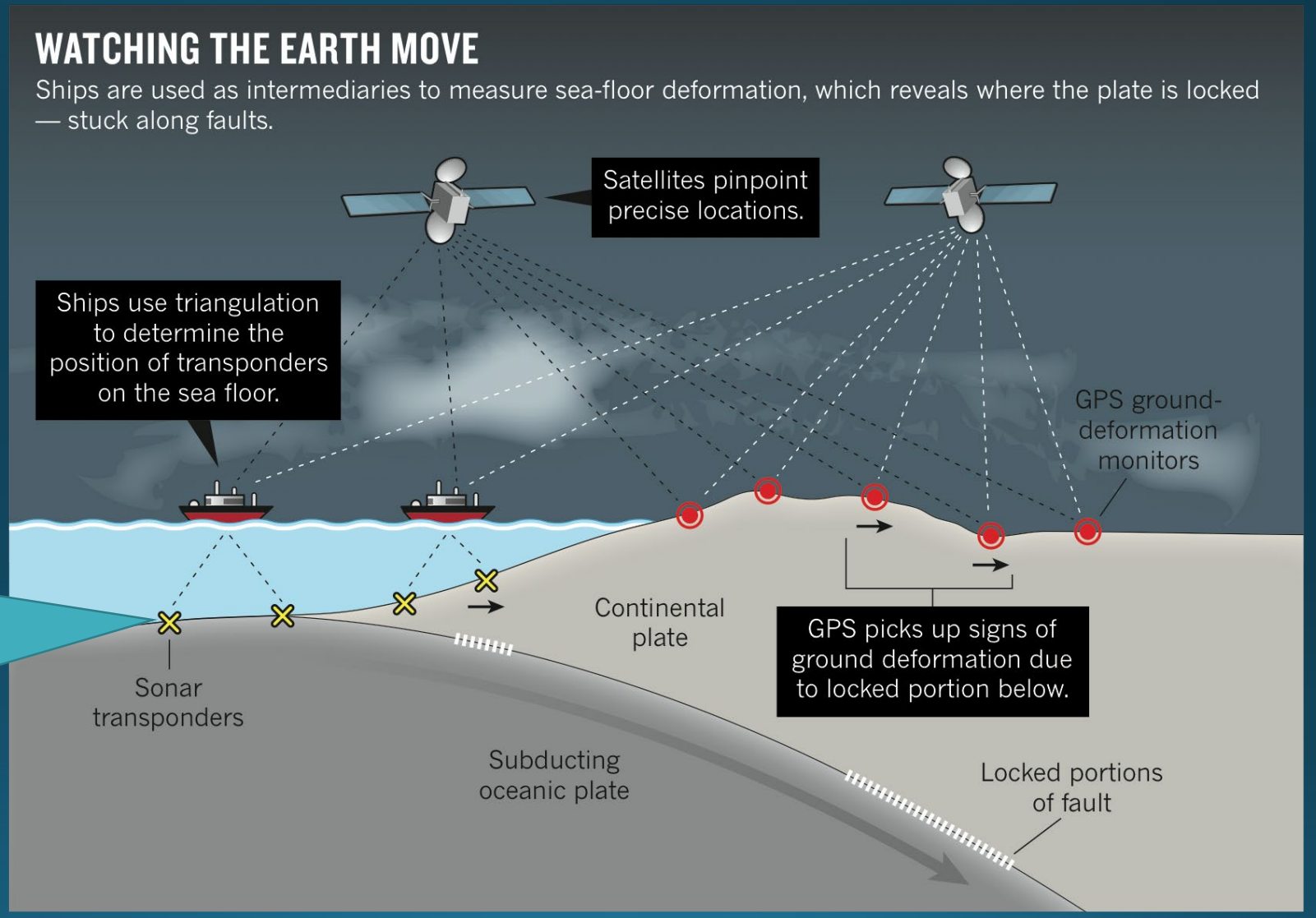




Uncertainty greatest at trench: ±15-20 mm/yr

Seafloor Geodesy – GPS Acoustic (GPS-A)

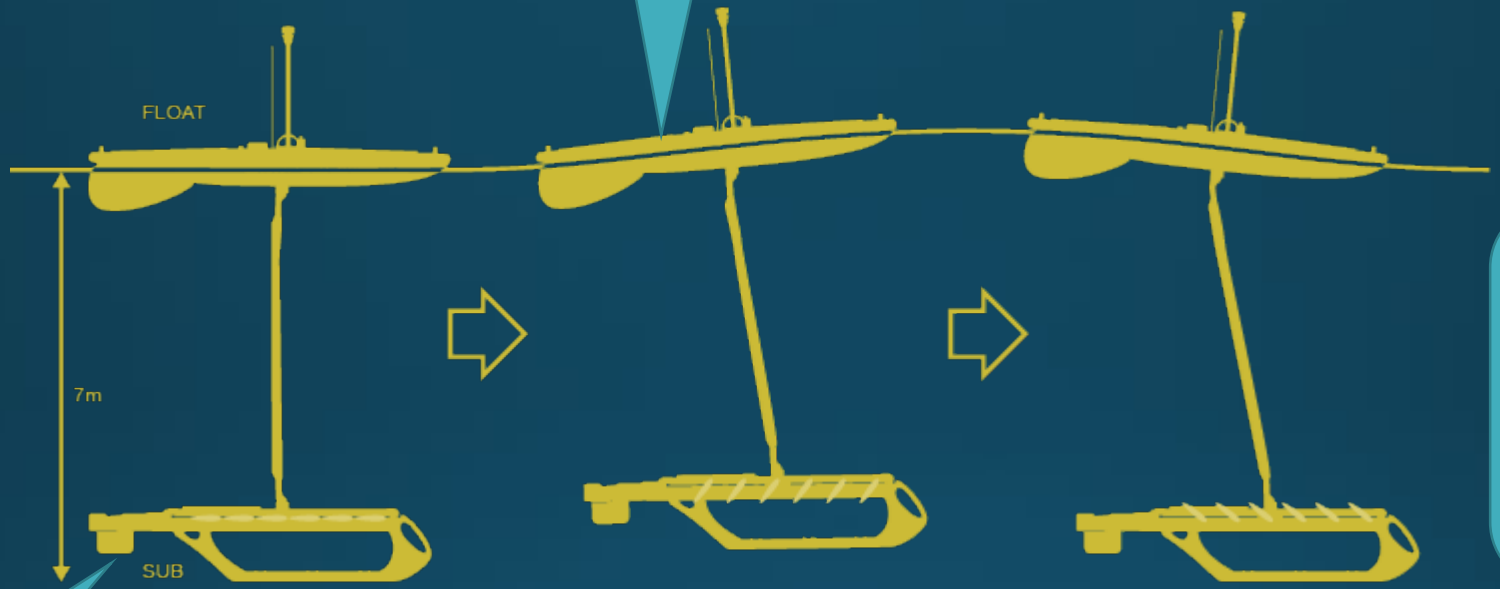




Newman (2011)

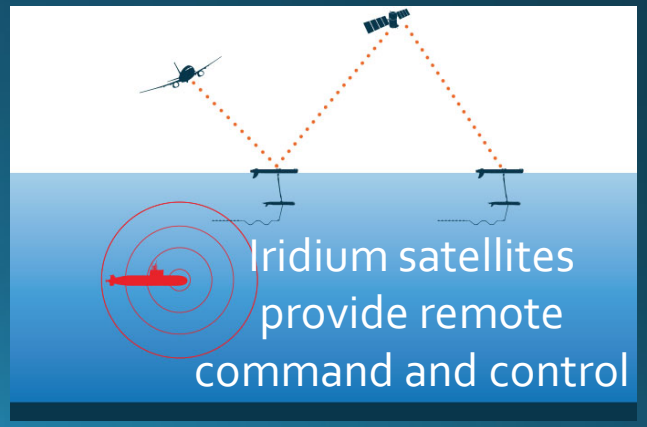
Wave Glider

Solar panels provide power



Differential vertical motion between float and sub propels forward motion (~1 knot)

Active rudder steers course



Iridium satellites provide remote command and control

What can we observe?

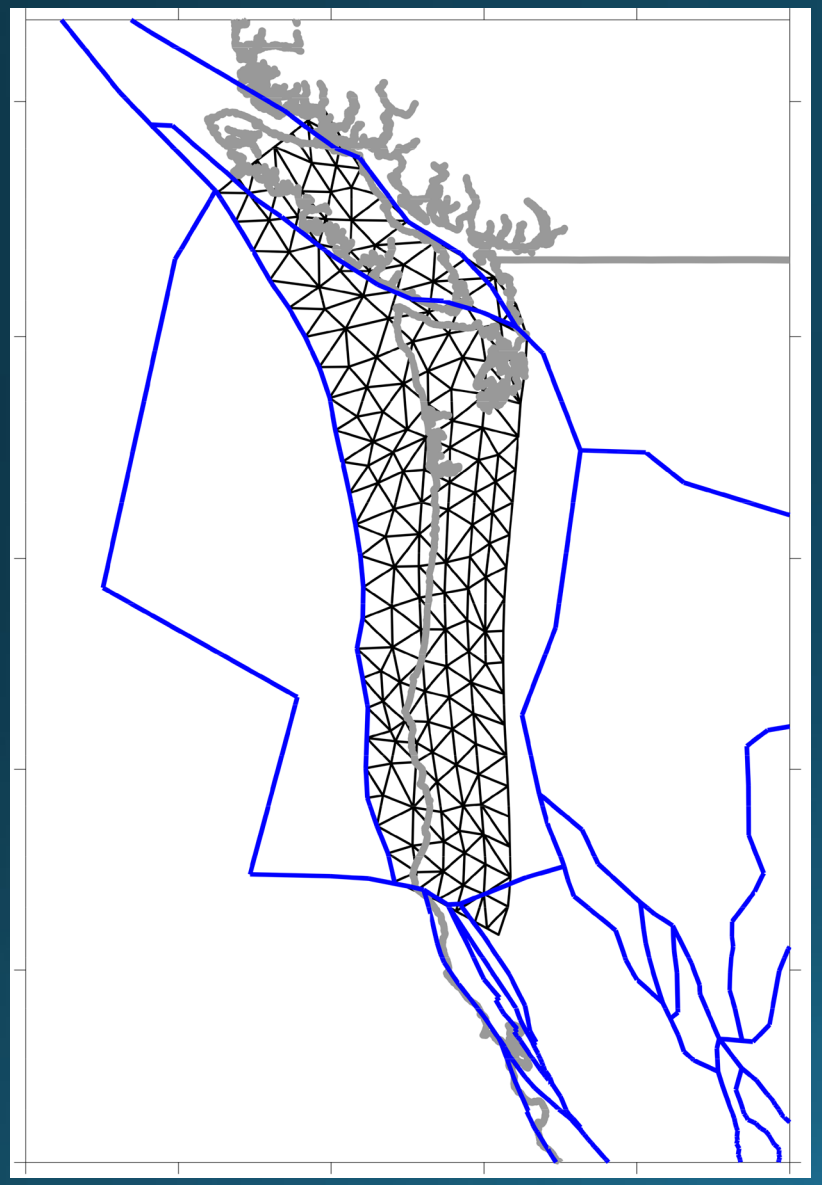
- GPS/A
  - Principally sensitive to horizontal motion
  - Sub-centimeter precision after 3-4 days of observation
- Seafloor pressure gauges
  - Sensitive to vertical motion
  - Centimeter-level precision
- Other sensors in various stages of development (e.g., seafloor strain)
- Modes of operation:
  - Repeat occupation (ship, wave glider)
    - Limited frequency of observation, very expensive
  - Continuous telemetry
    - Requires frequent battery changes, and sometimes additional infrastructure (e.g., buoy), even more expensive
  - Cabled (continuous telemetry and power)
    - So very expensive
      - The mode you choose will determine what kind of transients/precursors (if any) you can observe
- Have to make every observation count
  - Let's try calculating information entropy or differential entropy (Shannon 1948)

Information entropy

- Information entropy (Shannon, 1948) is the amount of missing information about the value of a parameter:
  - $\mathbf{H} = -\int_x f(x) \ln f(x)\, dx$
- For Gaussian statistics/linear inverse problems:
  - $f(x) = \mathcal{N}(x|m^*, \Sigma^*) \rightarrow \quad \mathbf{H} = \frac{1}{2} \ln \det(2\pi e \Sigma^*)$
- **H** is a function of the posterior model covariance matrix, which depends on the inversion design:
  - For determining distributed slip, $\Sigma^* = C_m^* = \left[C_m^{-1} + G^T C_d^{-1} G\right]^{-1}$
  - For determining total moment deficit, $\Sigma^* = \sum_{i=1}^{p} \sum_{j=1}^{p} C_{m\,i,j}^*$
- Goal: Find observation locations that **minimize** entropy

G is model design matrix
C_d is data covariance
C_m is *a priori* model covariance

Entropy in a block model



- Block model
  - Divide crust into microplates bounded by faults (e.g., *Meade & Hager*, 2005)
  - Mesh of triangular dislocations (e.g., *Meade and Loveless*, 2009)
- Constraints
  - Currently: 4213 GNSS velocities (*Kreemer et al.*, 2014)
  - 4000 potential observation locations

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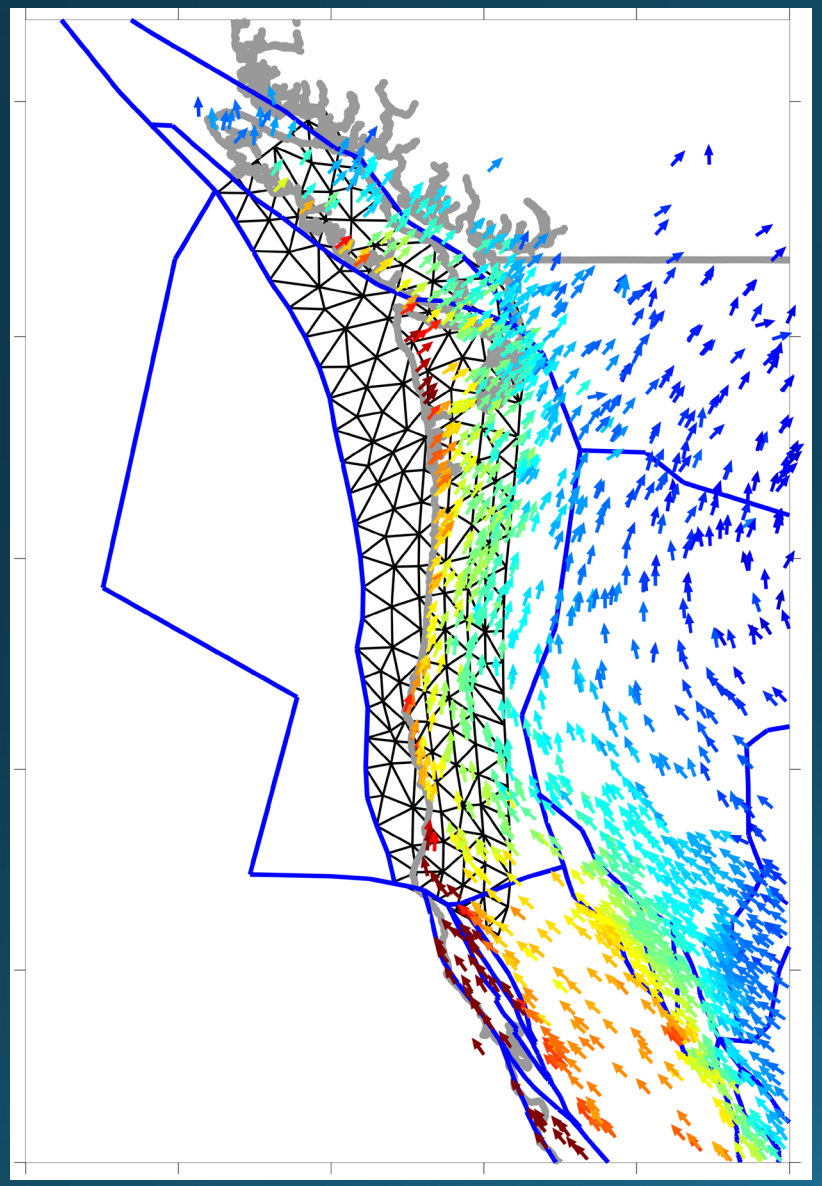

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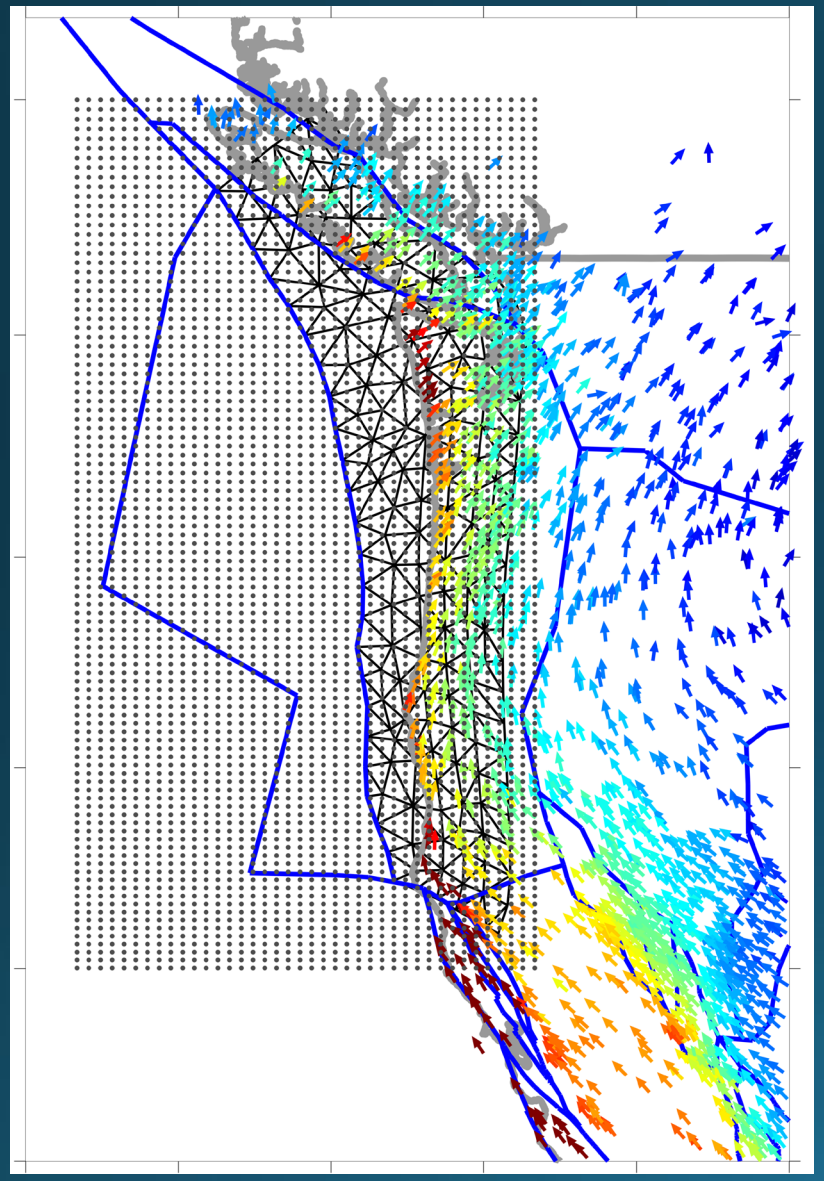

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Which potential observation locations minimize information entropy?

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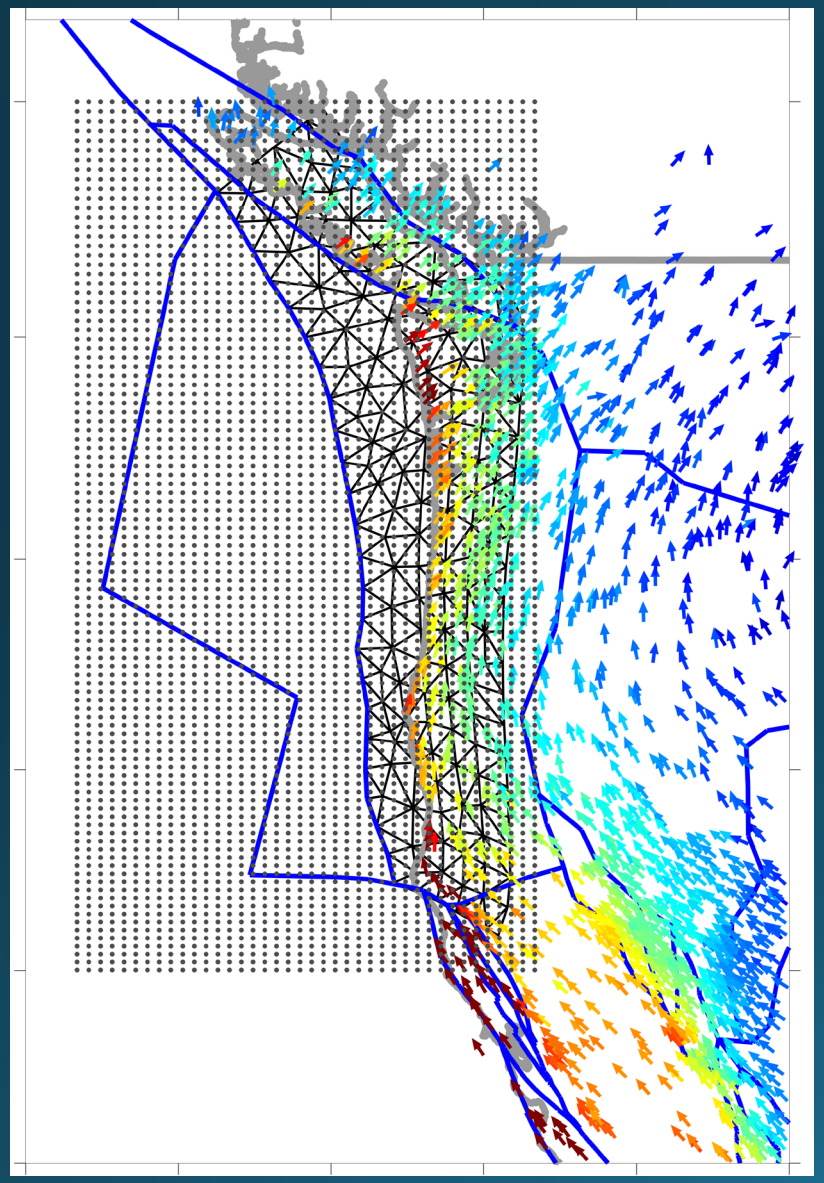
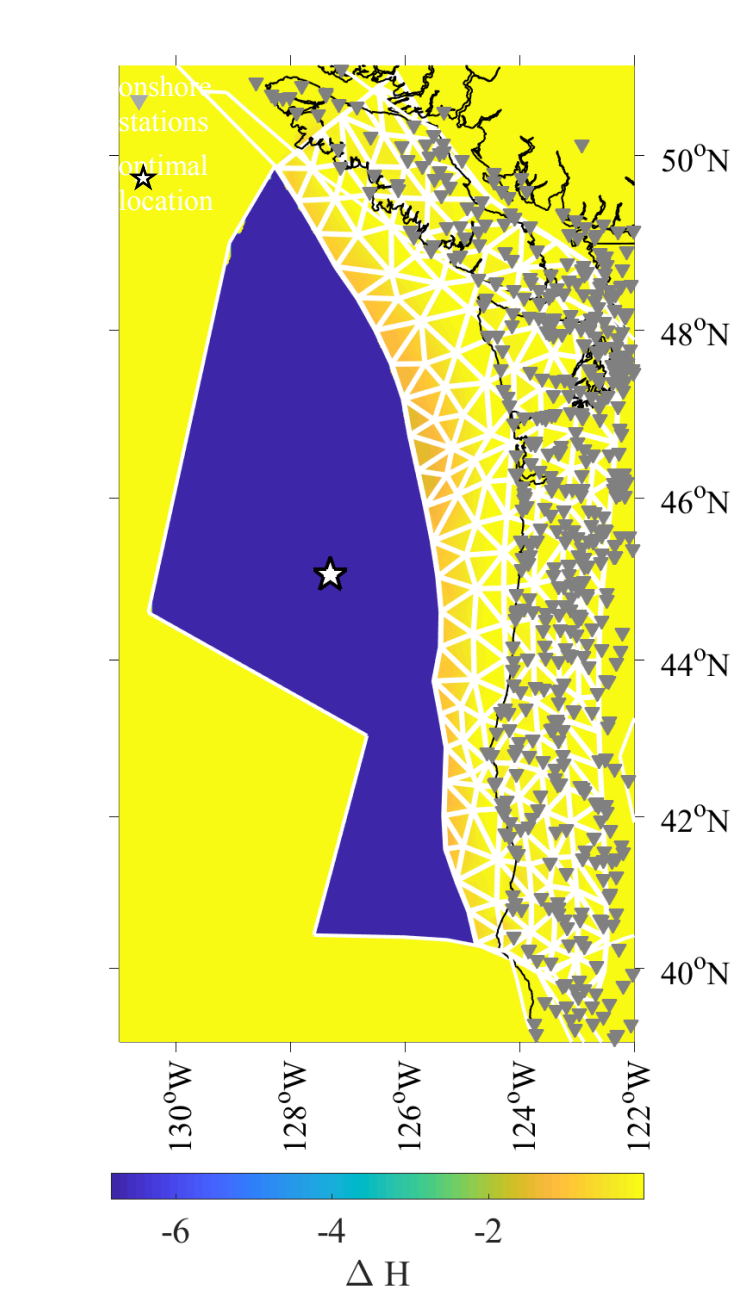


- Data uncertainties:
  - Existing uncertainties as reported (*Kreemer et al*., 2014)
  - New offshore: **±3 mm/yr** (*Chadwell and Spiess*, 2008)
  - New onshore: **±0.85 mm/yr** (mean of existing uncertainties)
- Model uncertainties
  - Euler pole: **±0.1°** Lat, Lon
  - Triangular slip distribution: **±20 mm/yr**
  - Laplacian smoothing

Identifying observation locations



- $\Delta\mathbf{H} = \mathbf{H}_{new} - \mathbf{H}_0$, relative to current onshore network
- First minimum $\Delta\mathbf{H}$ (most new information) on Juan de Fuca plate
  - This is for understanding inter-seismic coupling. If, e.g., we asked what is the total moment deficit, we could get a different answer.
- Subsequent stations along trench
- First onshore location after **21** offshore
- Distribution depends on model assumptions, previously selected locations

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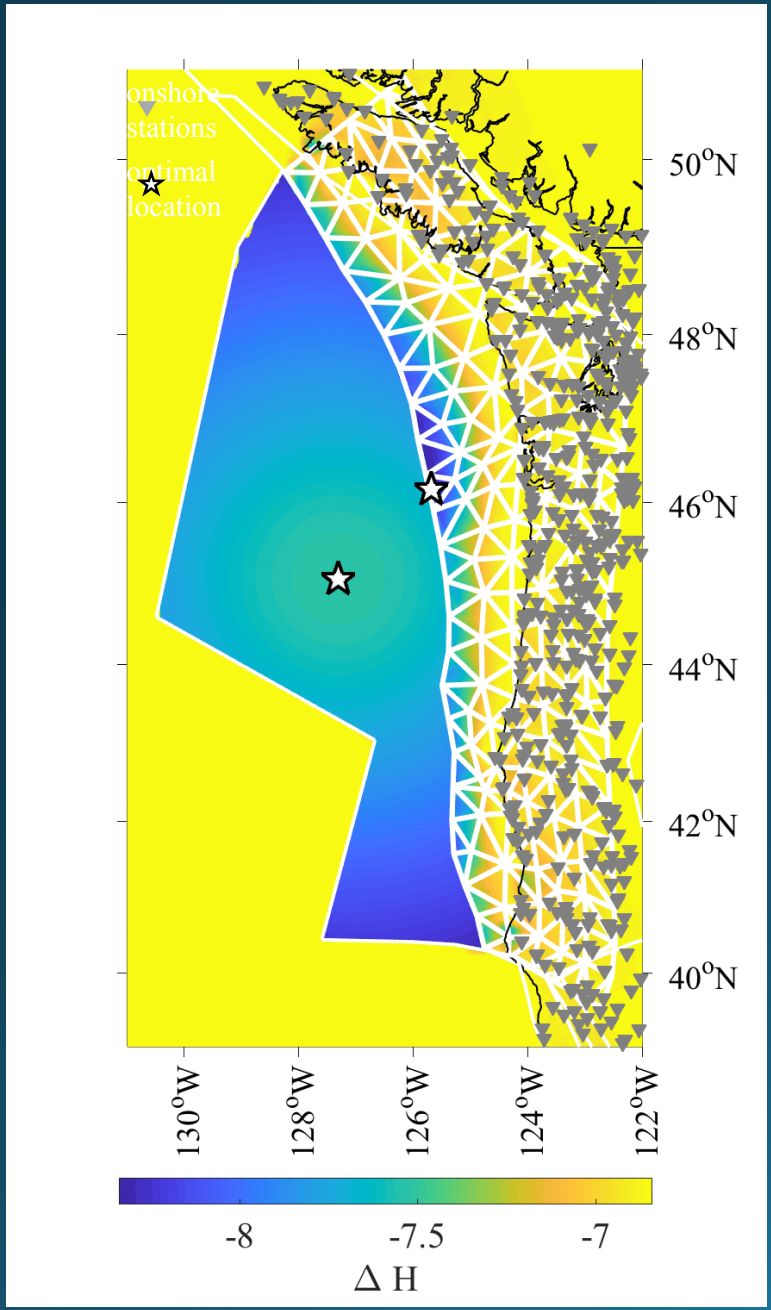

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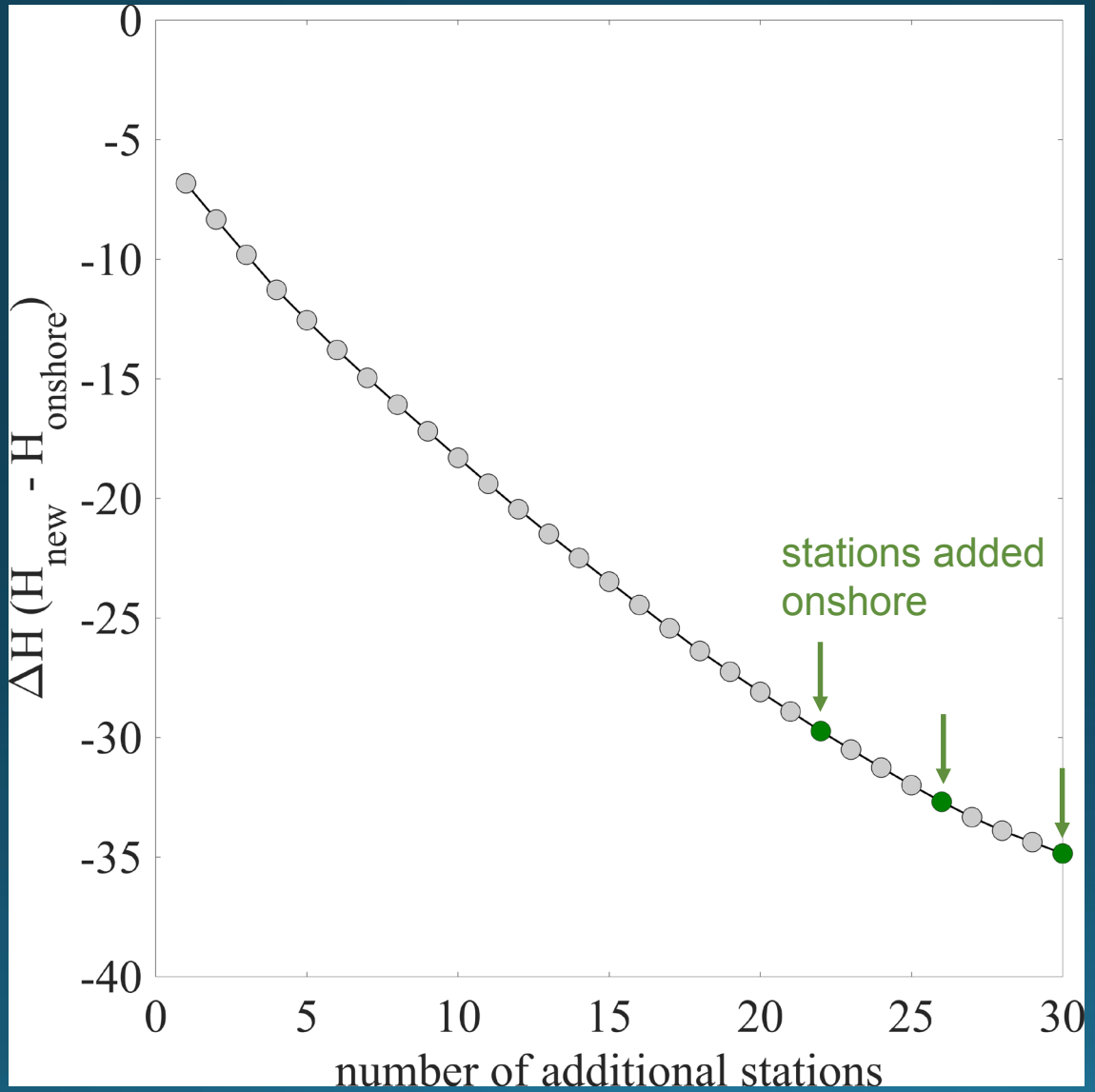

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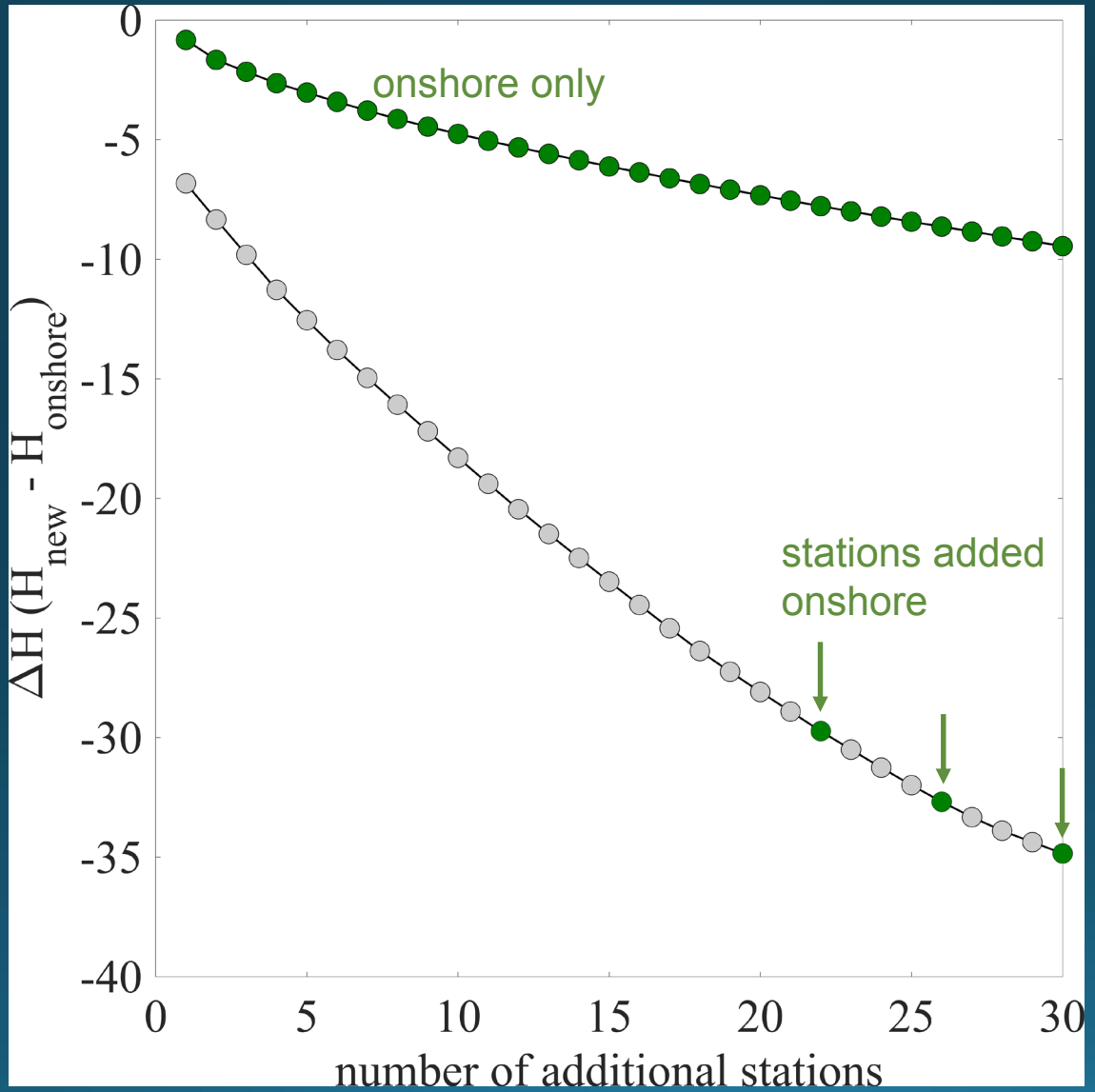

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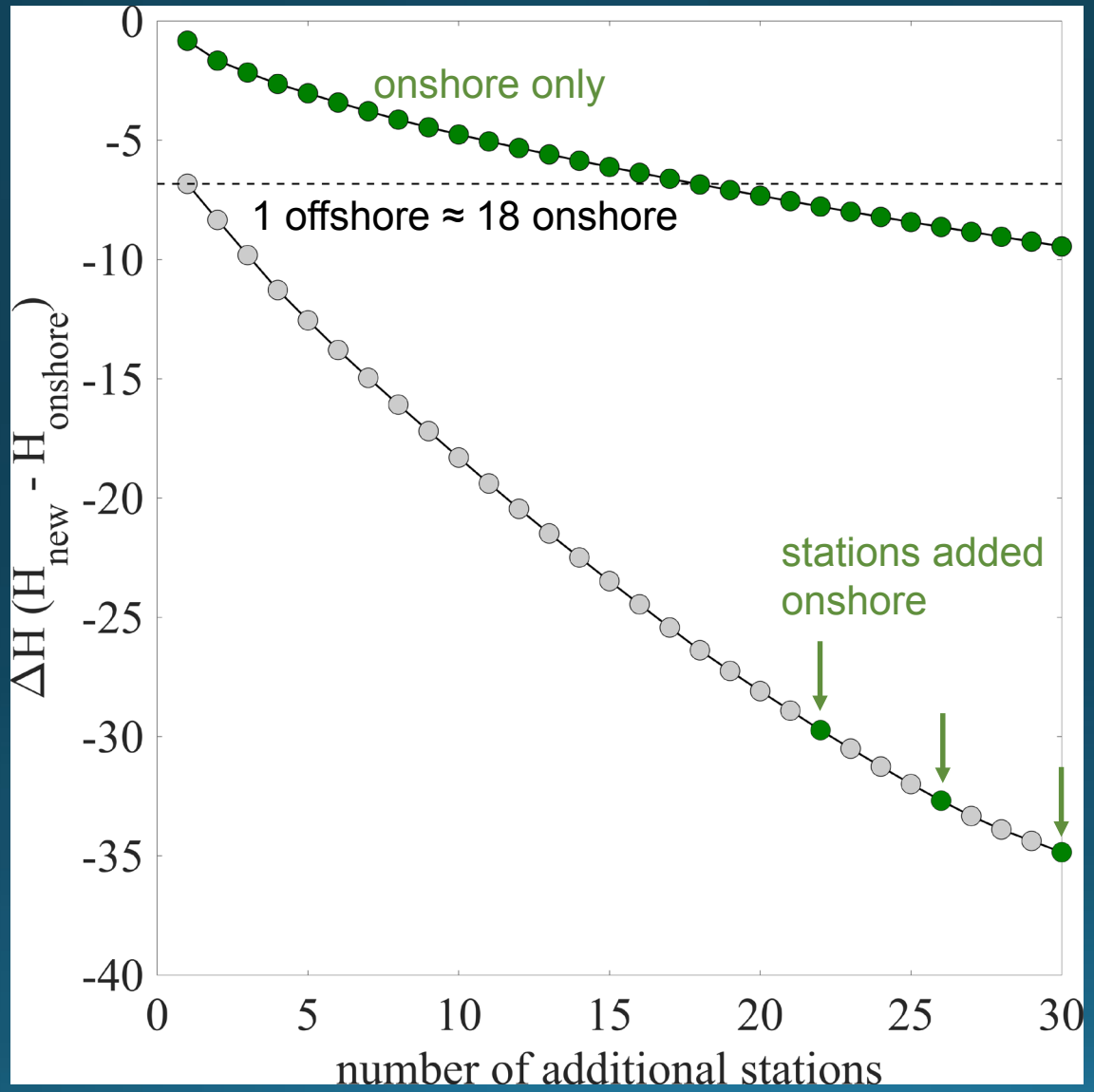

Summary

- **27** of first **30** optimal observation locations are offshore
- Single offshore station provides information gain of **18** onshore stations

Considerations

- What is the entropy reduction per $?
- What is the cost of obtaining a seafloor GPS/A reading vs. traditional telemetered onshore GPS stations?
- How often and for how long would we need to visit transponders to be able to observe transitory seismic precursors with desired accuracy?