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Time reverse imaging of tsunami sources to improve tsunami warning

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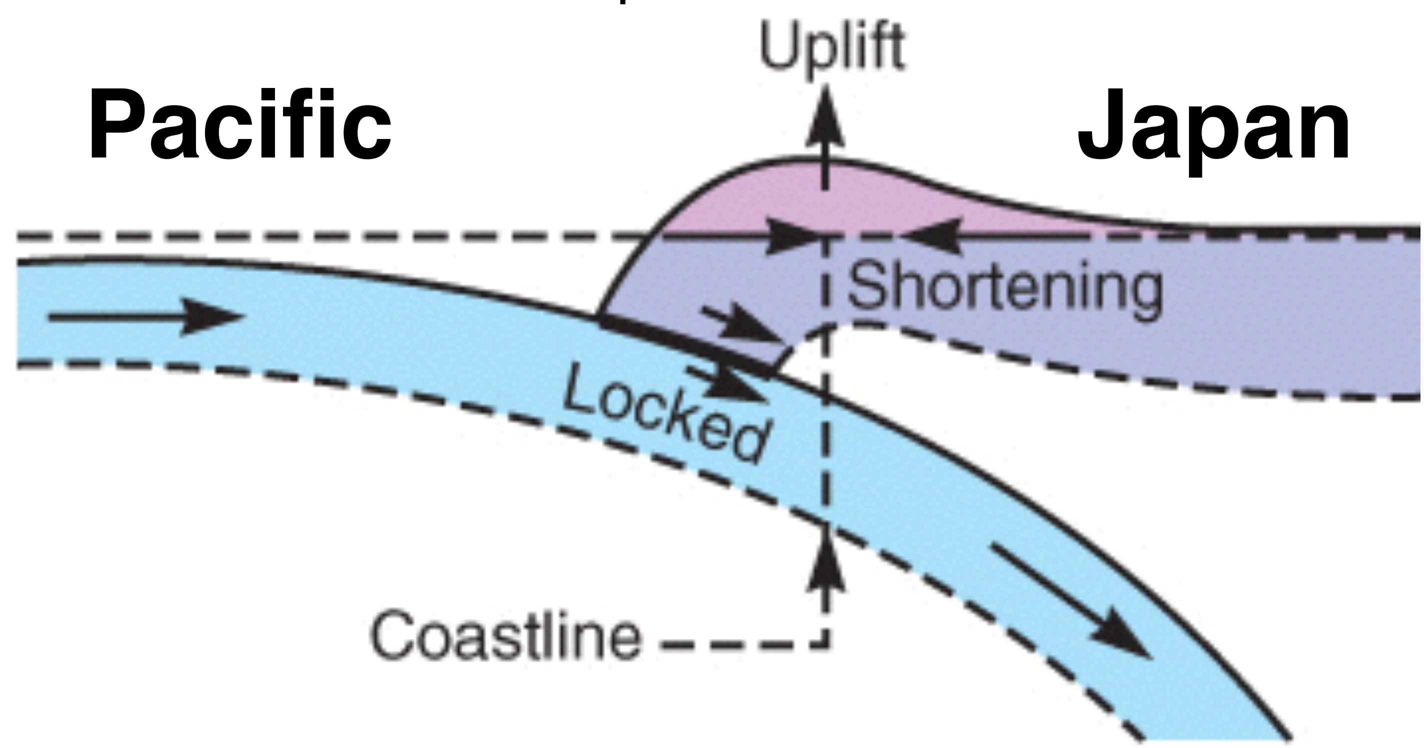
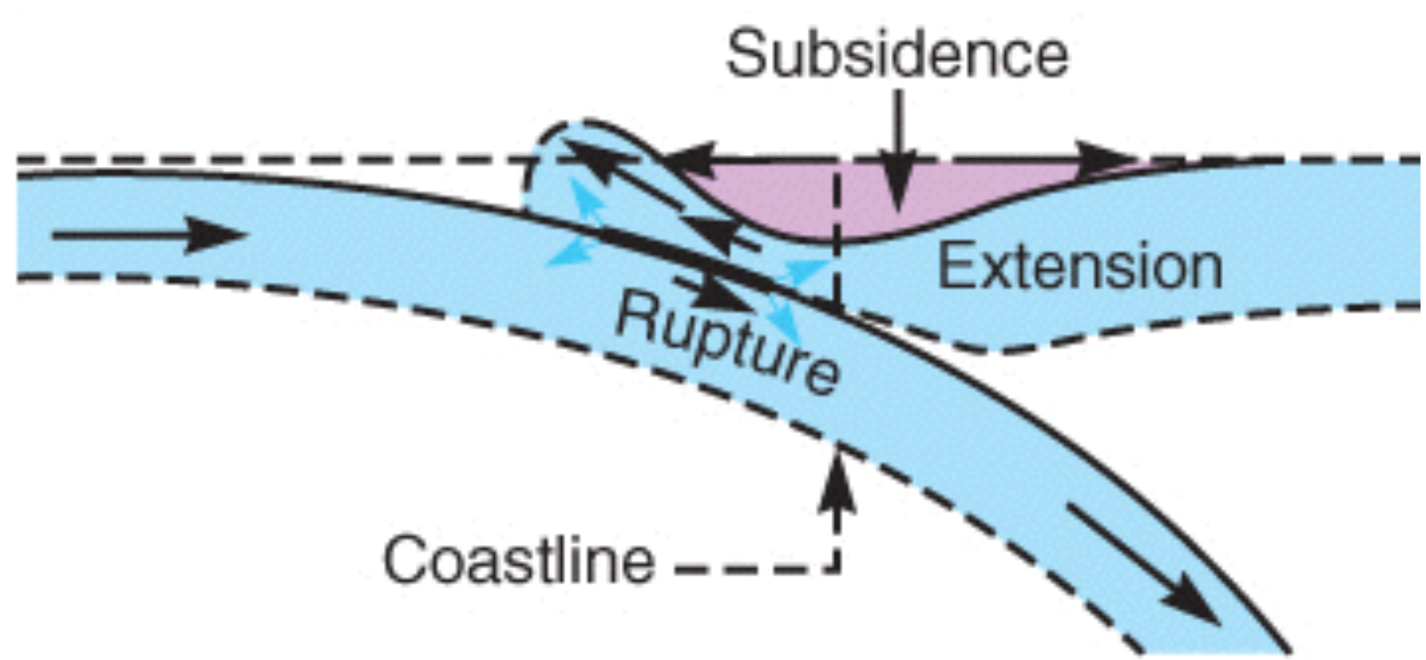
Tsunami cause: Excitation by elastic seafloor deformation during great/giant earthquakes

- Tsunami: Caused by seafloor uplift during earthquake
- Other causes: Submarine landslides, complex geology
- Many warning systems ignore the other causes (a strong assumption)
- Many other subjective choices are also required

Between earthquakes:



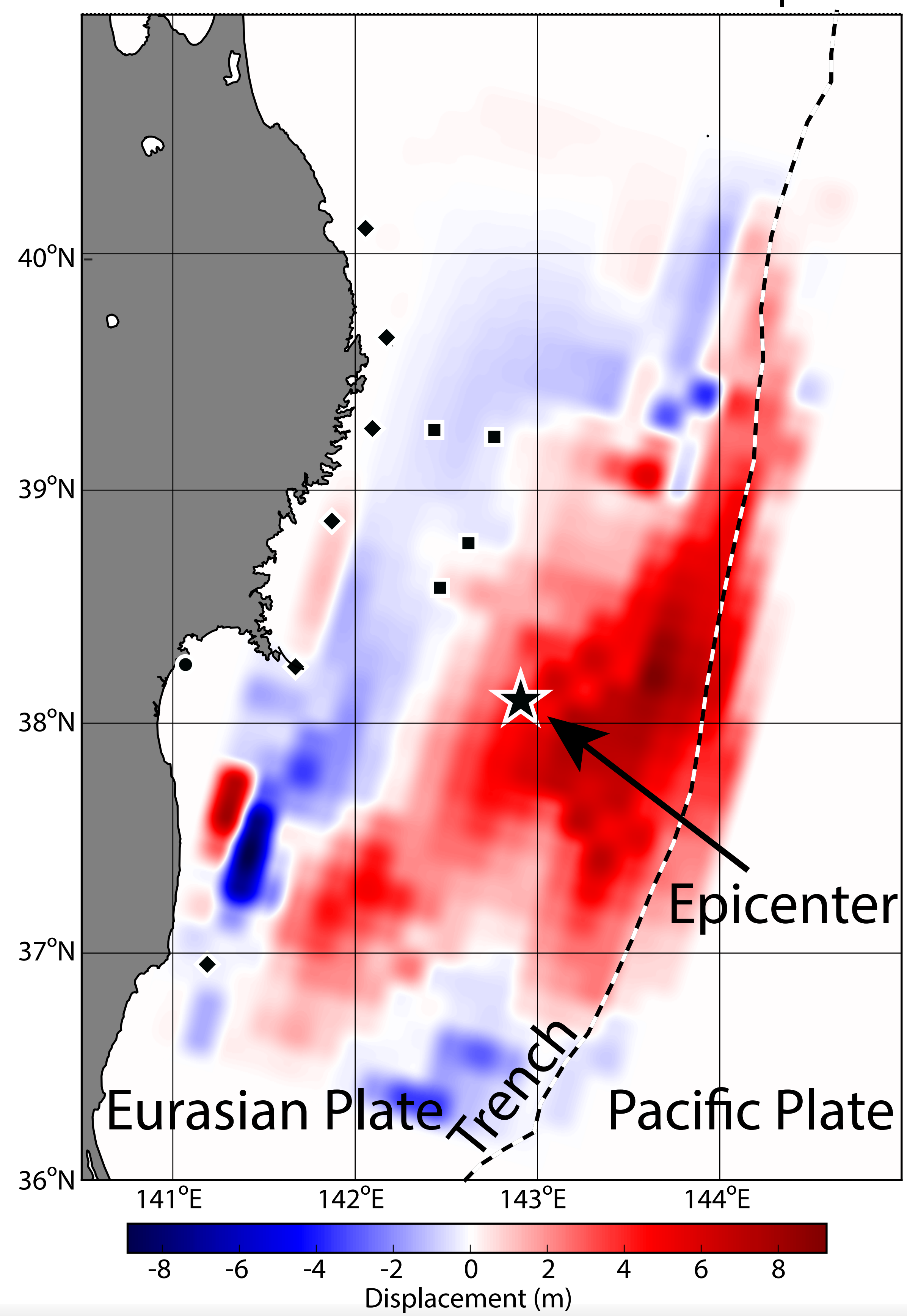
During Earthquake:



Limitations of current warning systems

- Typically based on “point source” and empirical scaling
- Many are based on “scenarios” which are used to rapidly compose tsunami
- While more source complexity is desirable to predict tsunami effects better, it’s currently not feasible
- Our method is step towards including complex sources by rapid estimation based on new sensors

Best estimate for 2011 Japan



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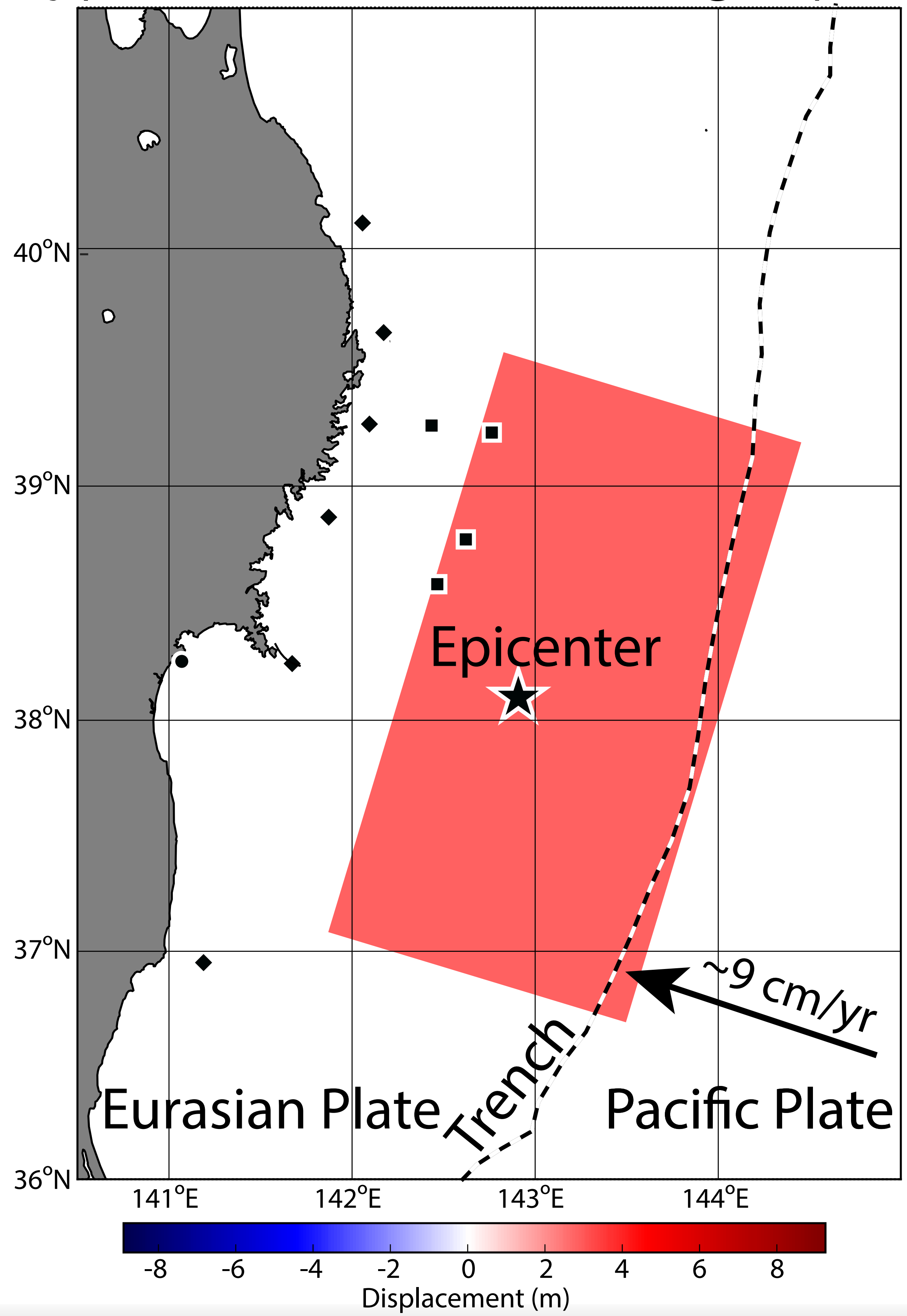
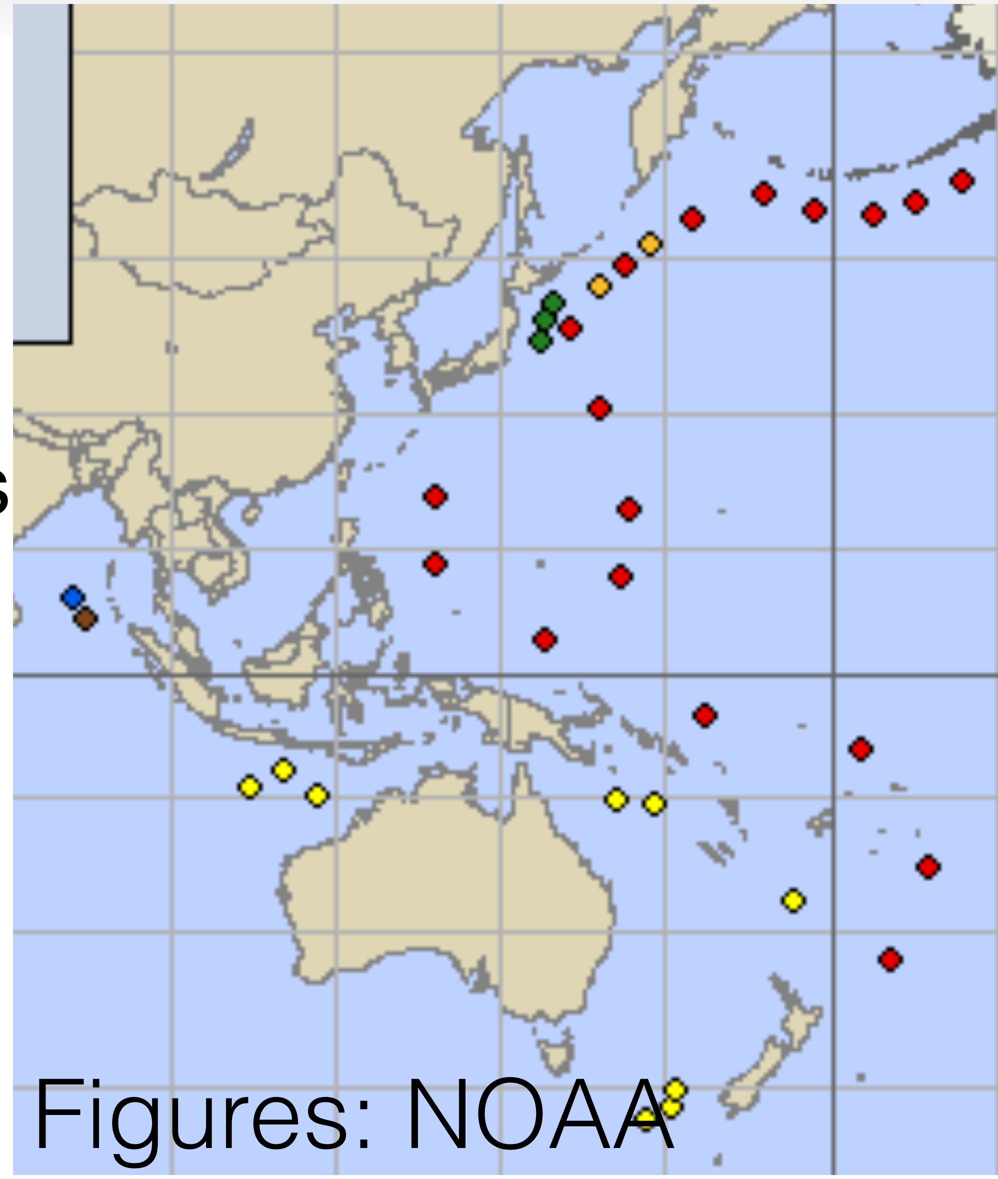
Typical tsunami-warning input

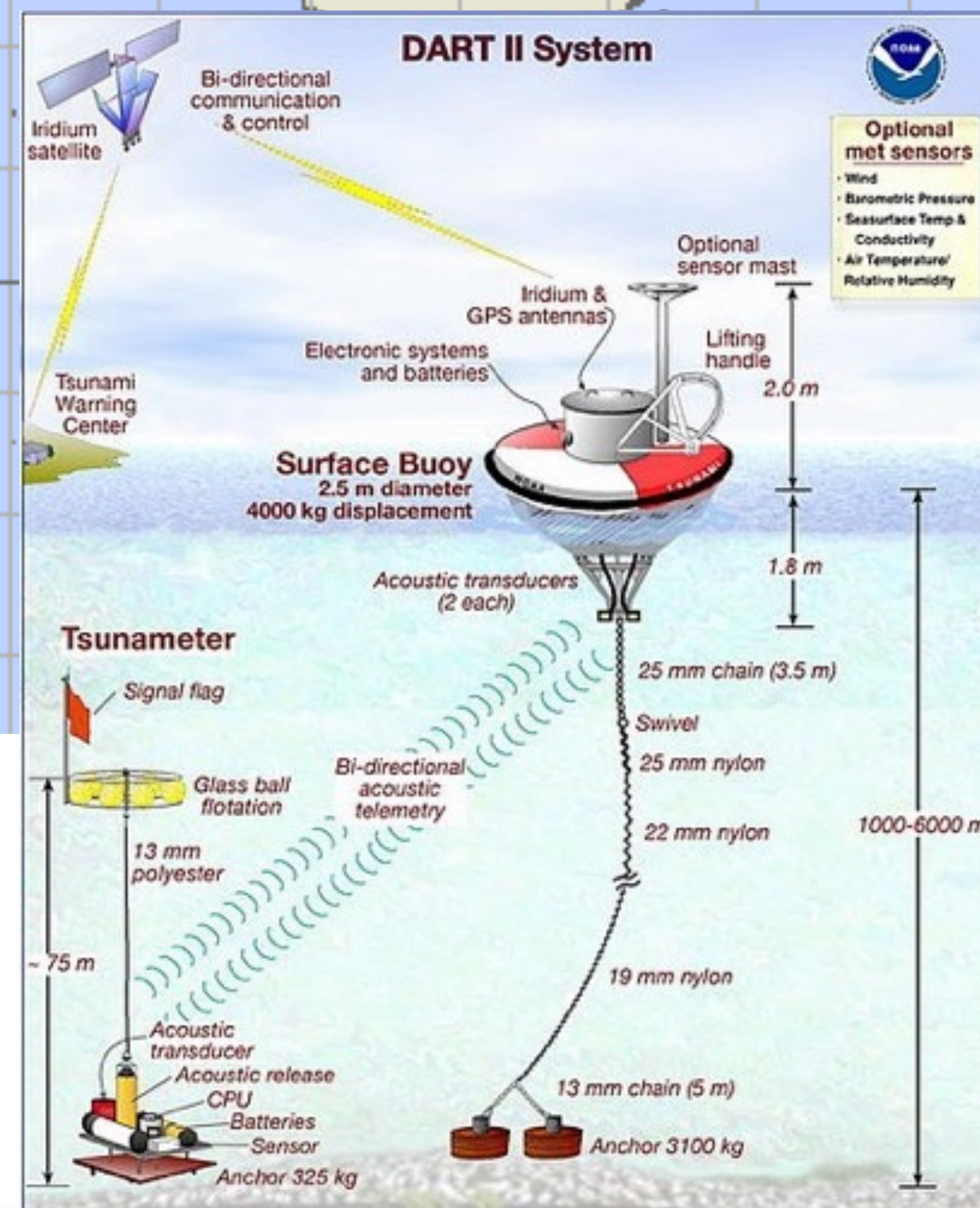


New Frontiers in Tsunami Observation: Global DART Buoy Network and Friends

- Like hard-rock seismometers, deep-ocean tsunami measurements suffer only benign path effect
- They give much clearer picture of the tsunami source than coastal tide gauges.
- The new global network of buoys can revolutionize tsunami source imaging



Figures: NOAA



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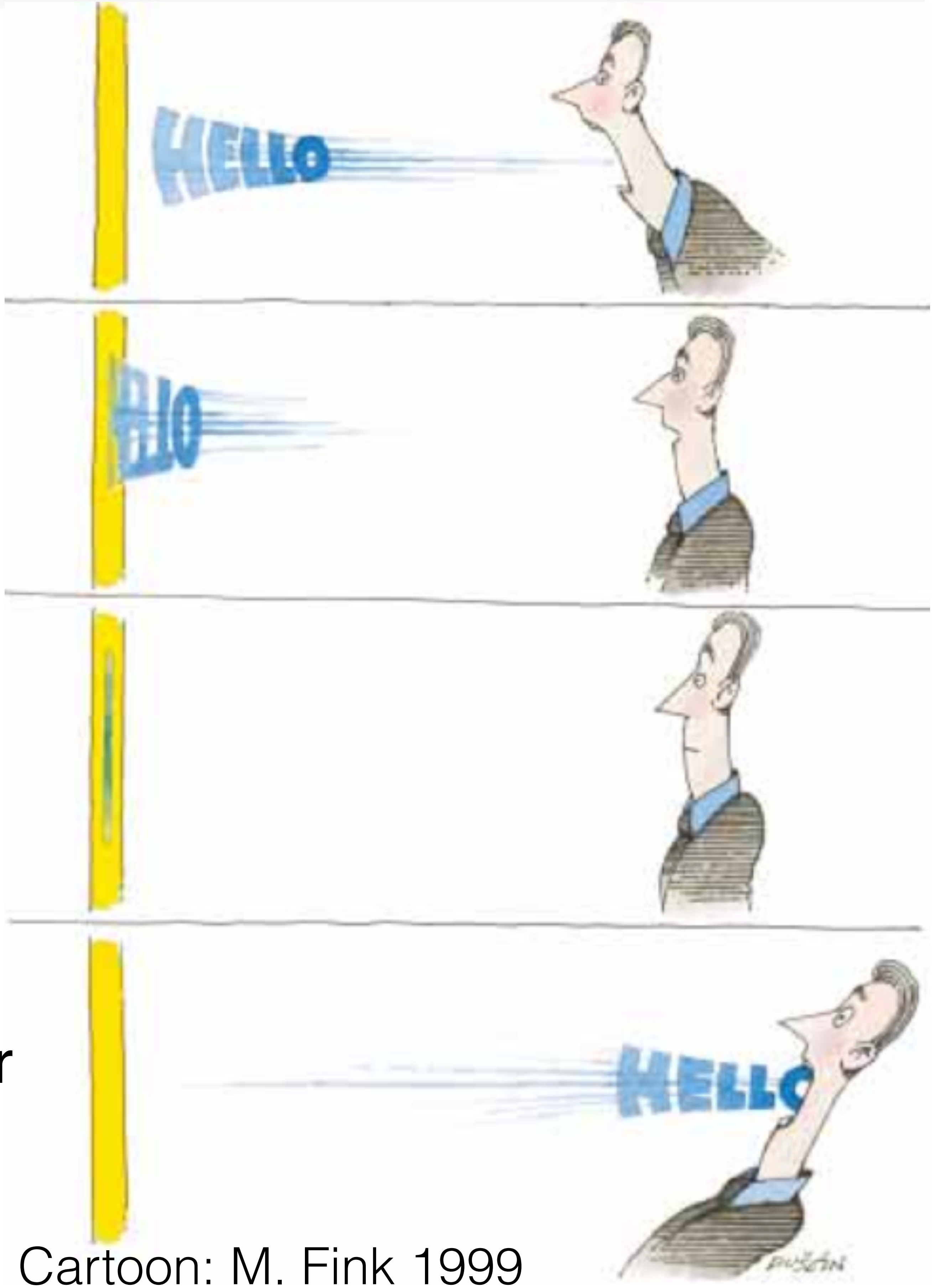
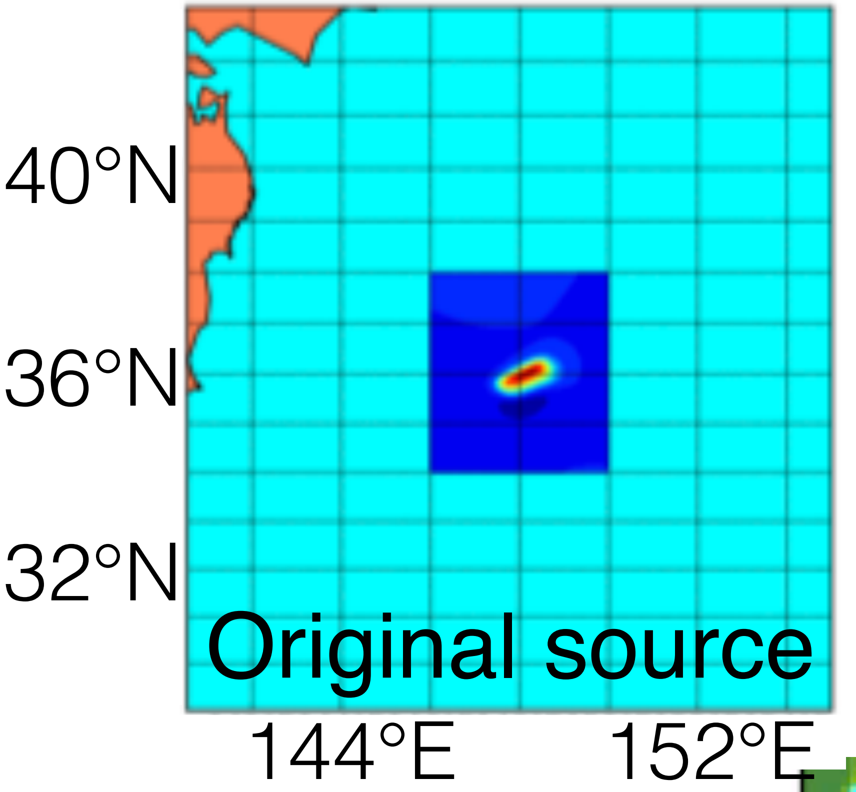
Time reverse imaging (TRI) can reproduce source

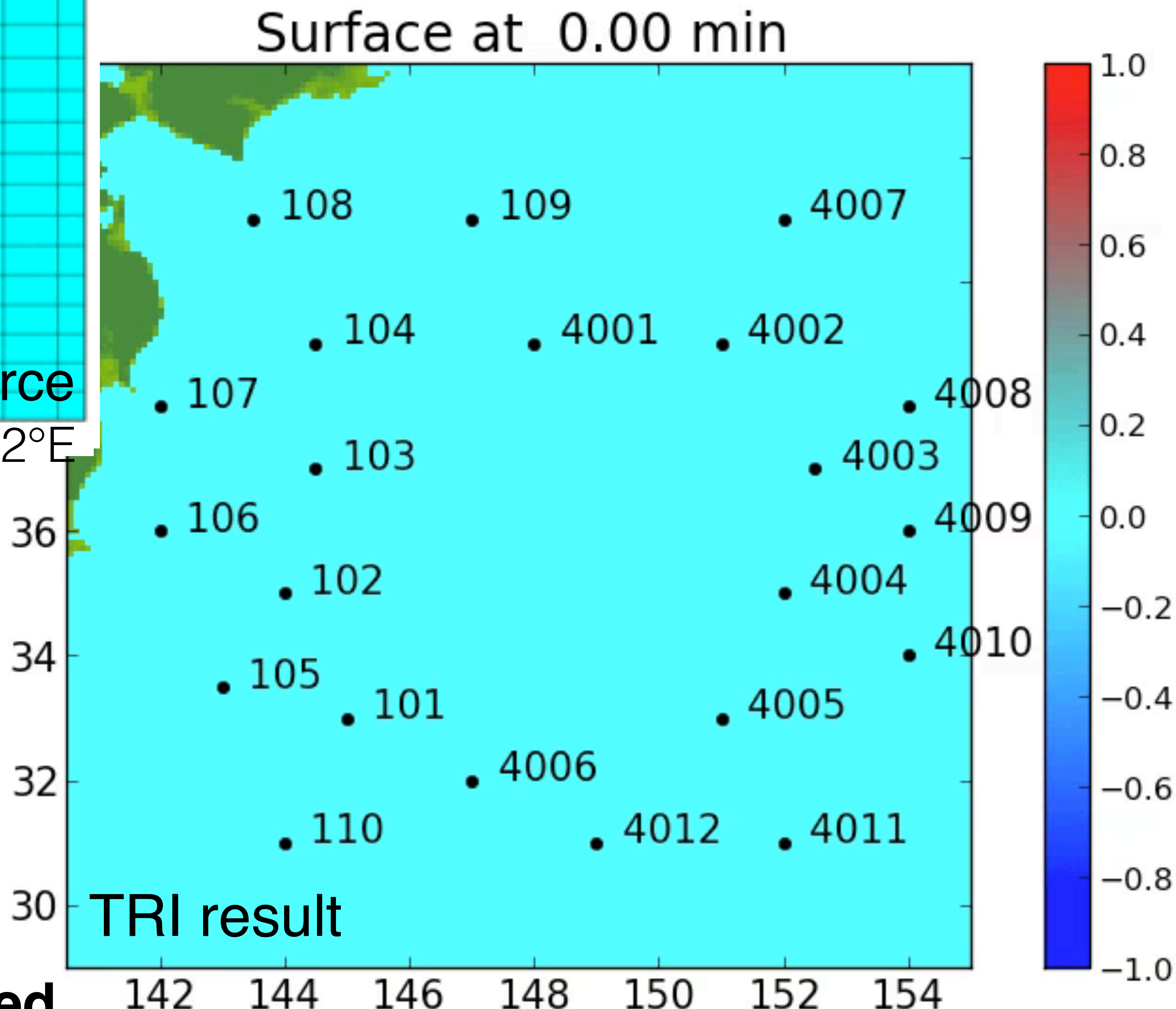
- Common in acoustics, medical science, material science… (long distance communication, destruction of tumours & kidney stones, detection of material defects)
- Basis: **The physical processes underlying wave propagation are unchanged if time is reversed**
- Time-reversed signal: Refocuses @ location of original source regardless of the complexity of the propagation medium, with a similar shape (depending number of sensors)



Cartoon: M. Fink 1999

Our work: Apply TRI to obtain rapid, objective source image



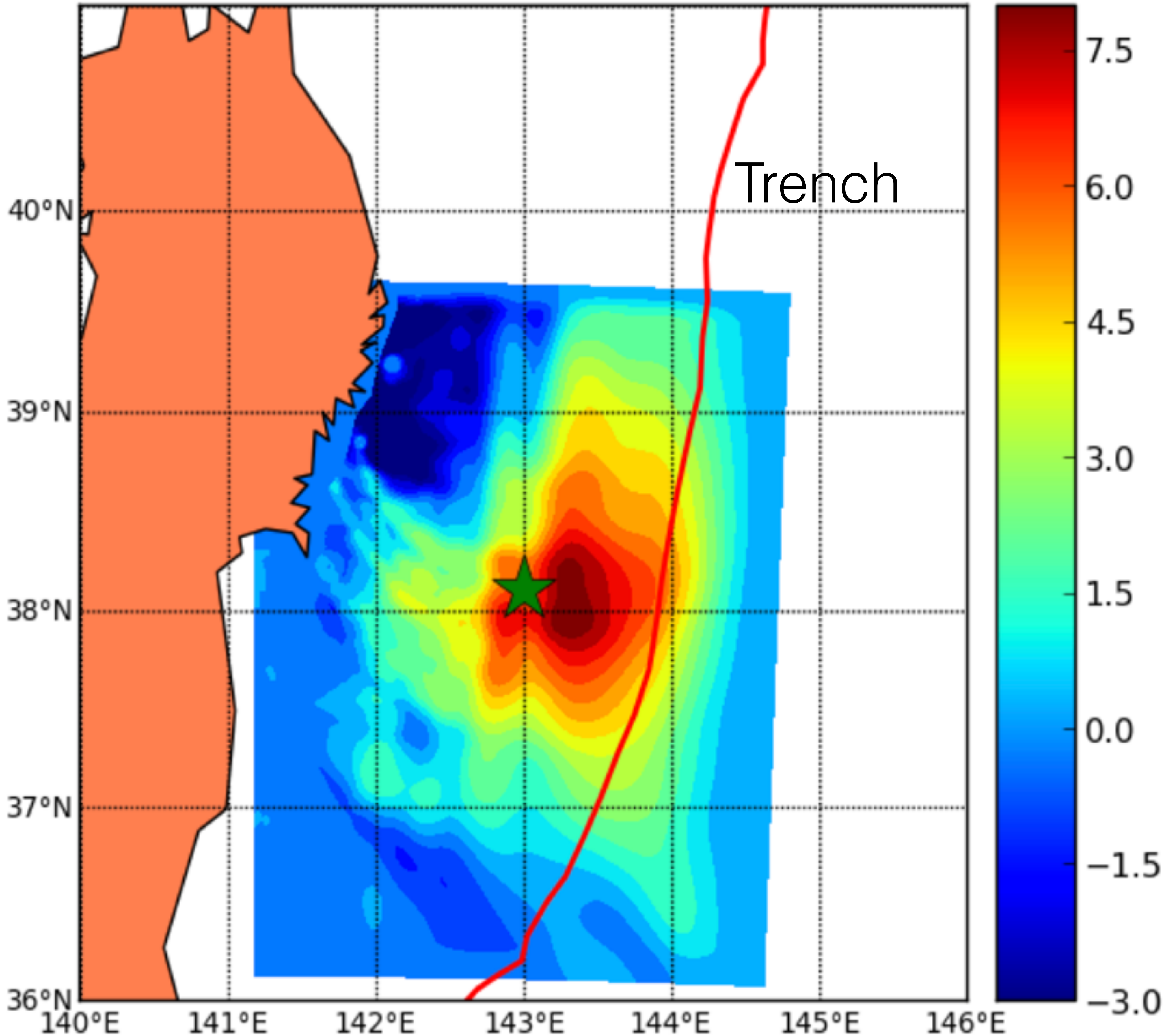


Simple, simulated illustration works…

Problem: Real tsunamis much more complicated

TRI applied to Japan tsunami: Crude estimate

Problem: Real tsunamis much more complicated



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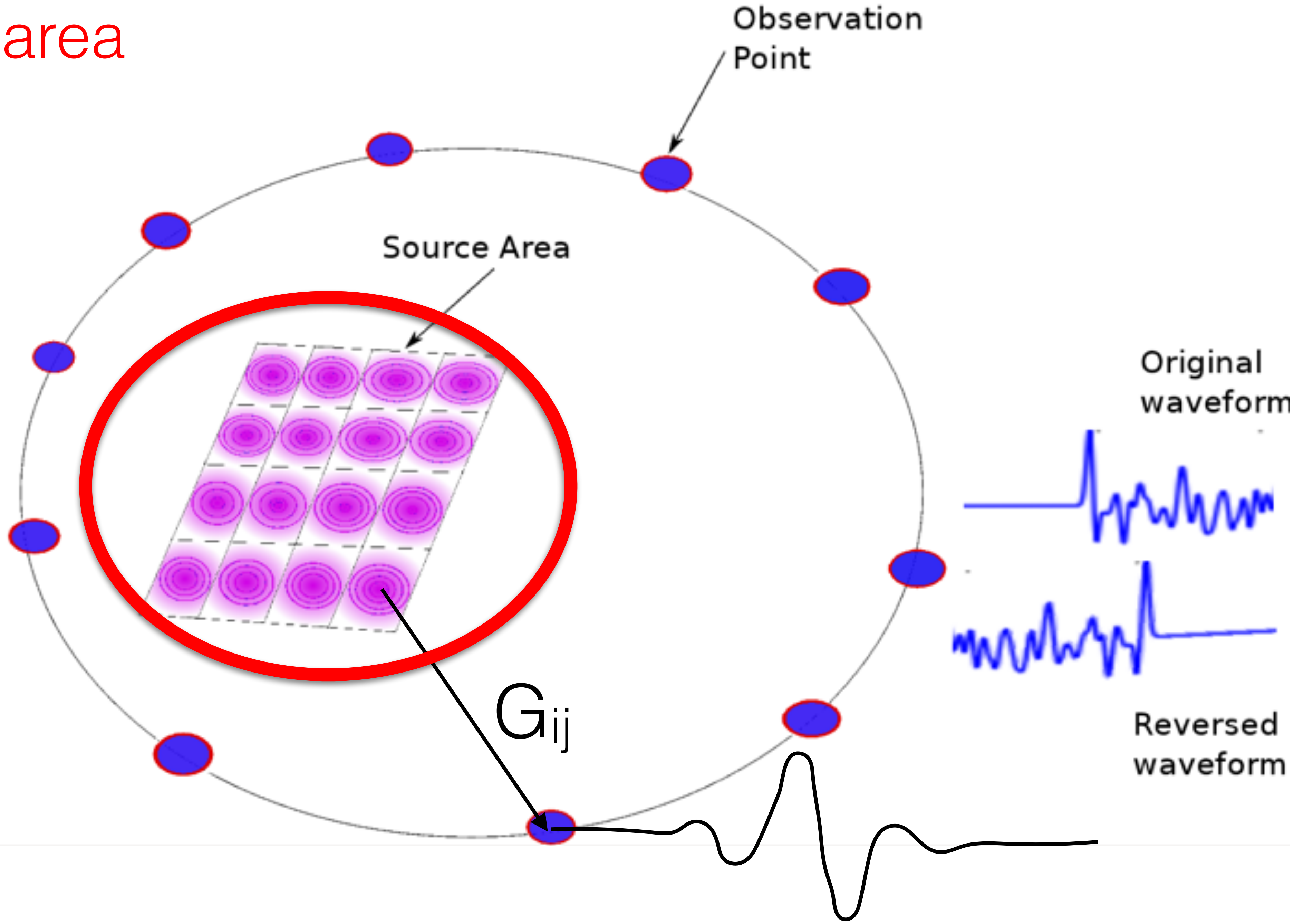
TRI with Green's function scaling

- Divide the source area into subregions



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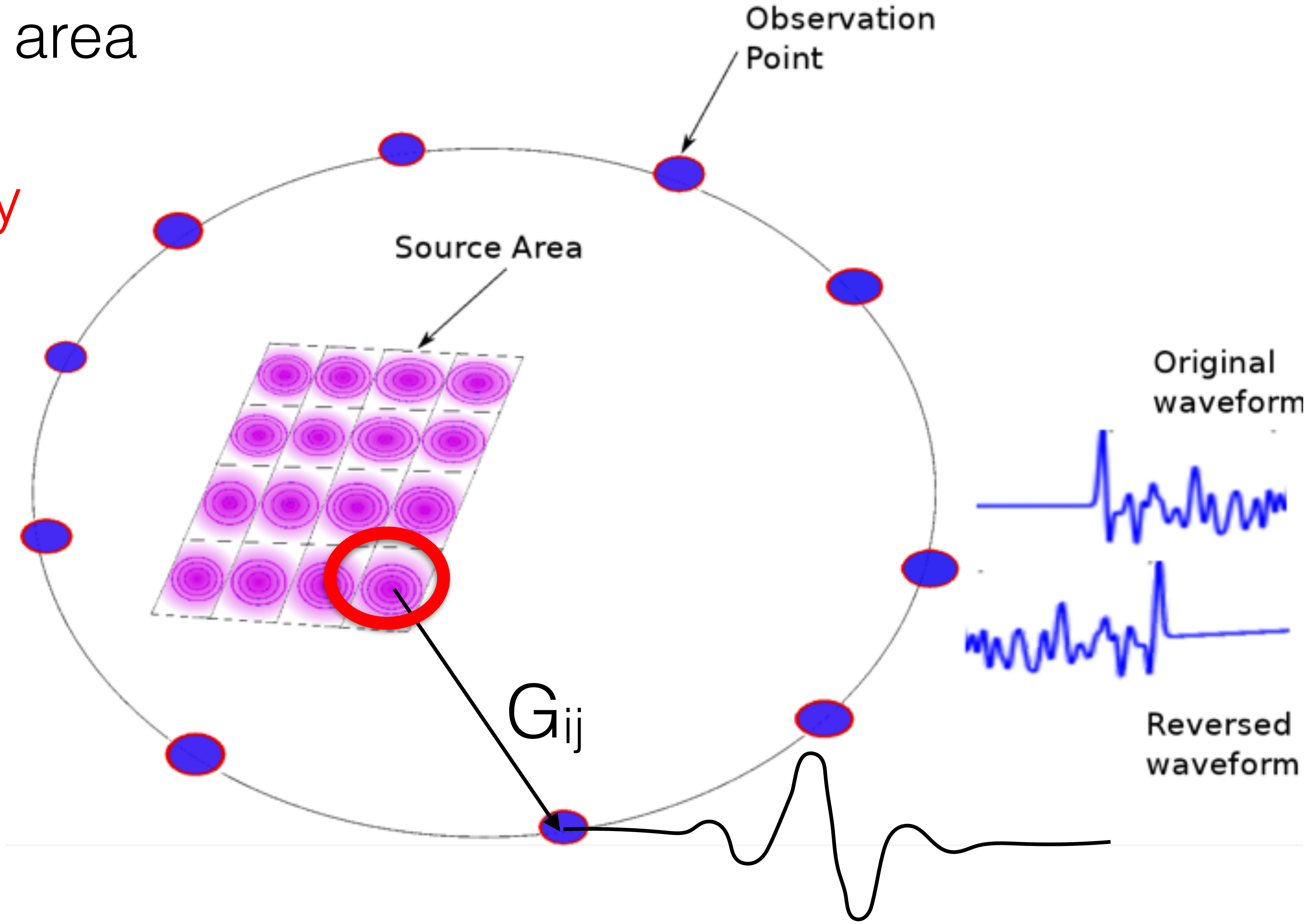
TRI with Green's function scaling

- Divide the source area into subregions.
- Create elementary source over each subregion



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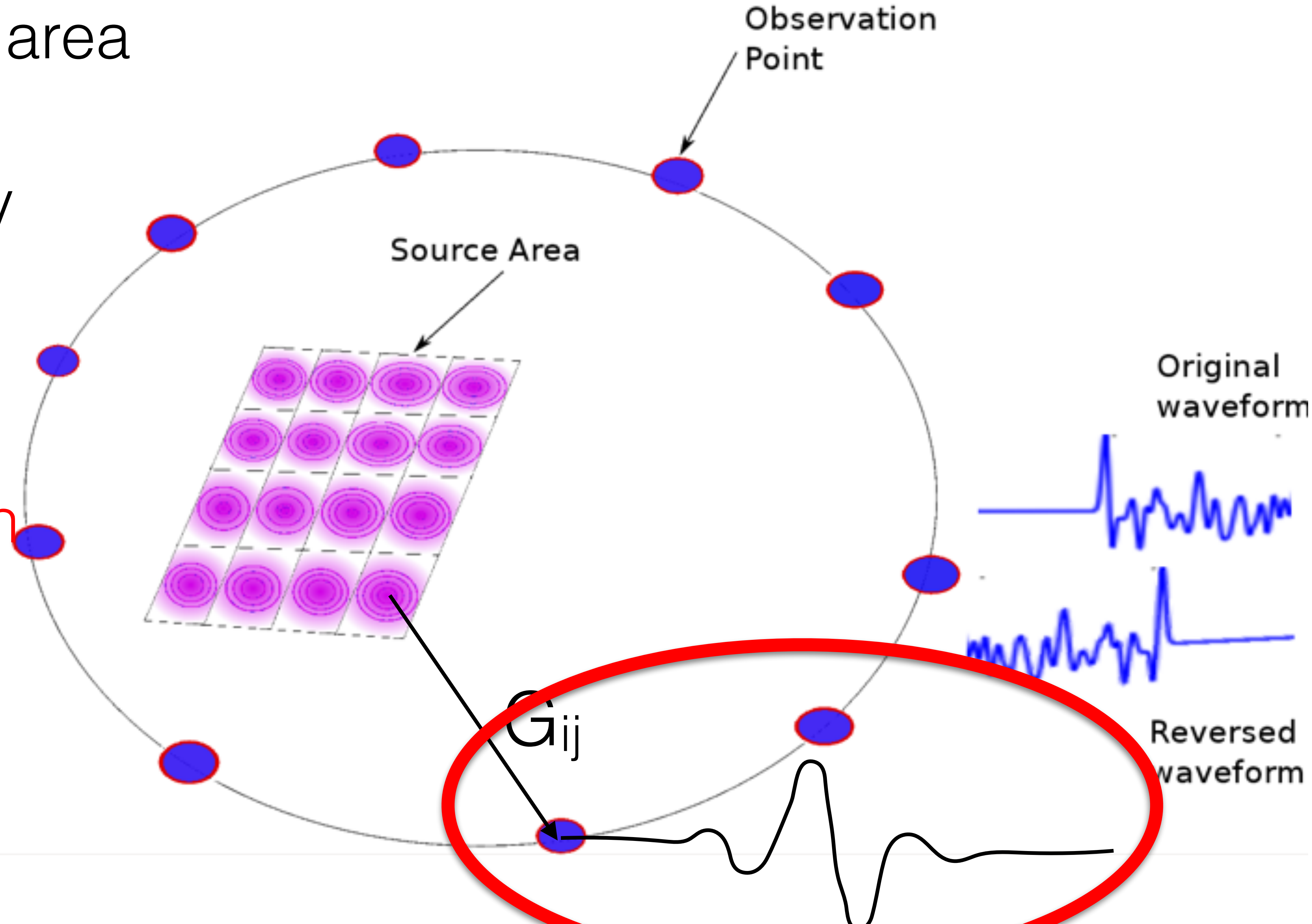
TRI with Green's function scaling

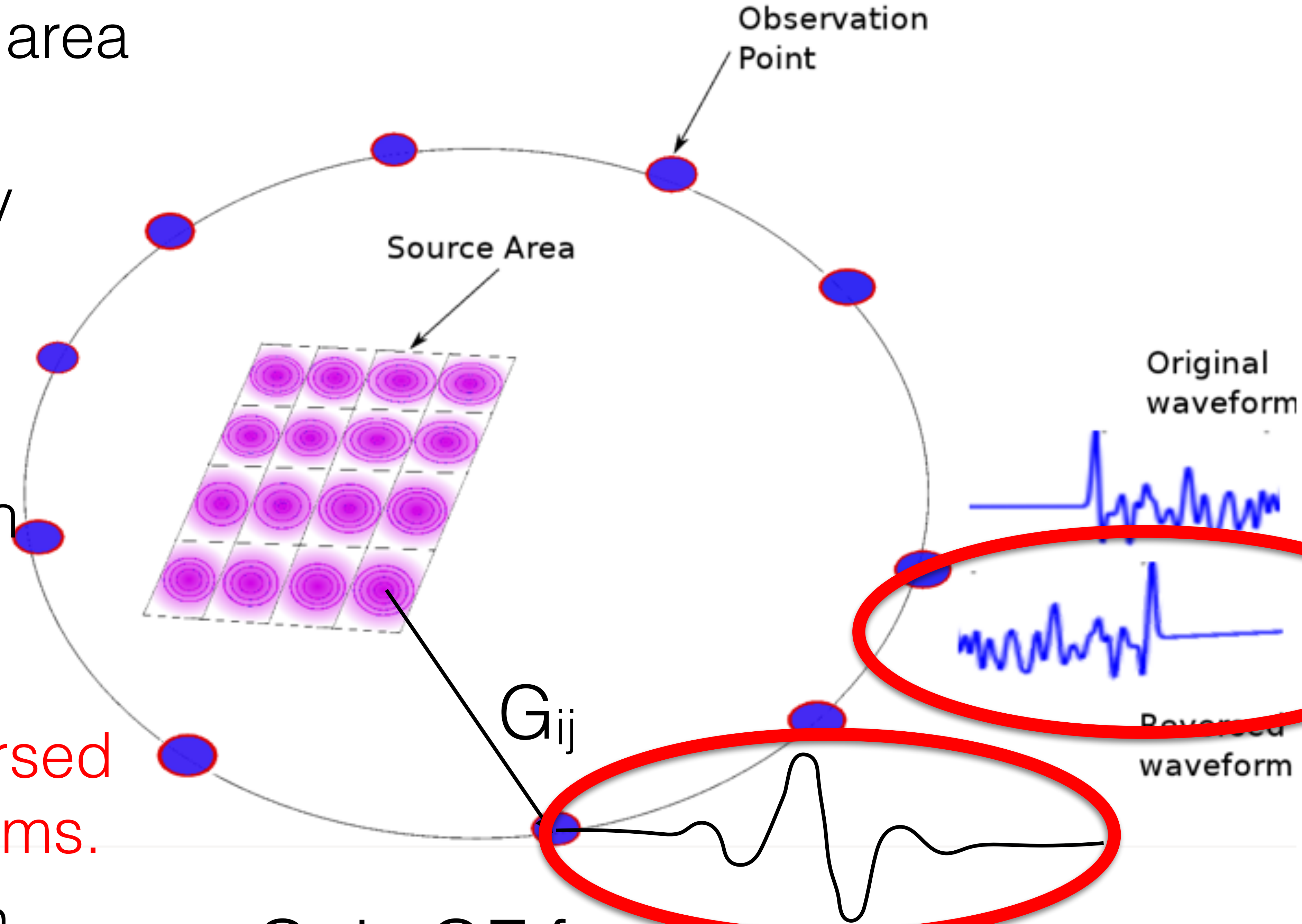
- Divide the source area into subregions.
- Create elementary source over each subregion
- Compute Green's function from each subregion



G_{ij} is GF from source i to receiver j (describe tsunami propagation from i to j; depend on seabed topography)

TRI with Green's function scaling

- Divide the source area into subregions.
- Create elementary source over each subregion
- Compute Green's function from each subregion
- Convolve Green's function with reversed observed waveforms.
- Amplitude at each subregion: Scaled wave height at the final time



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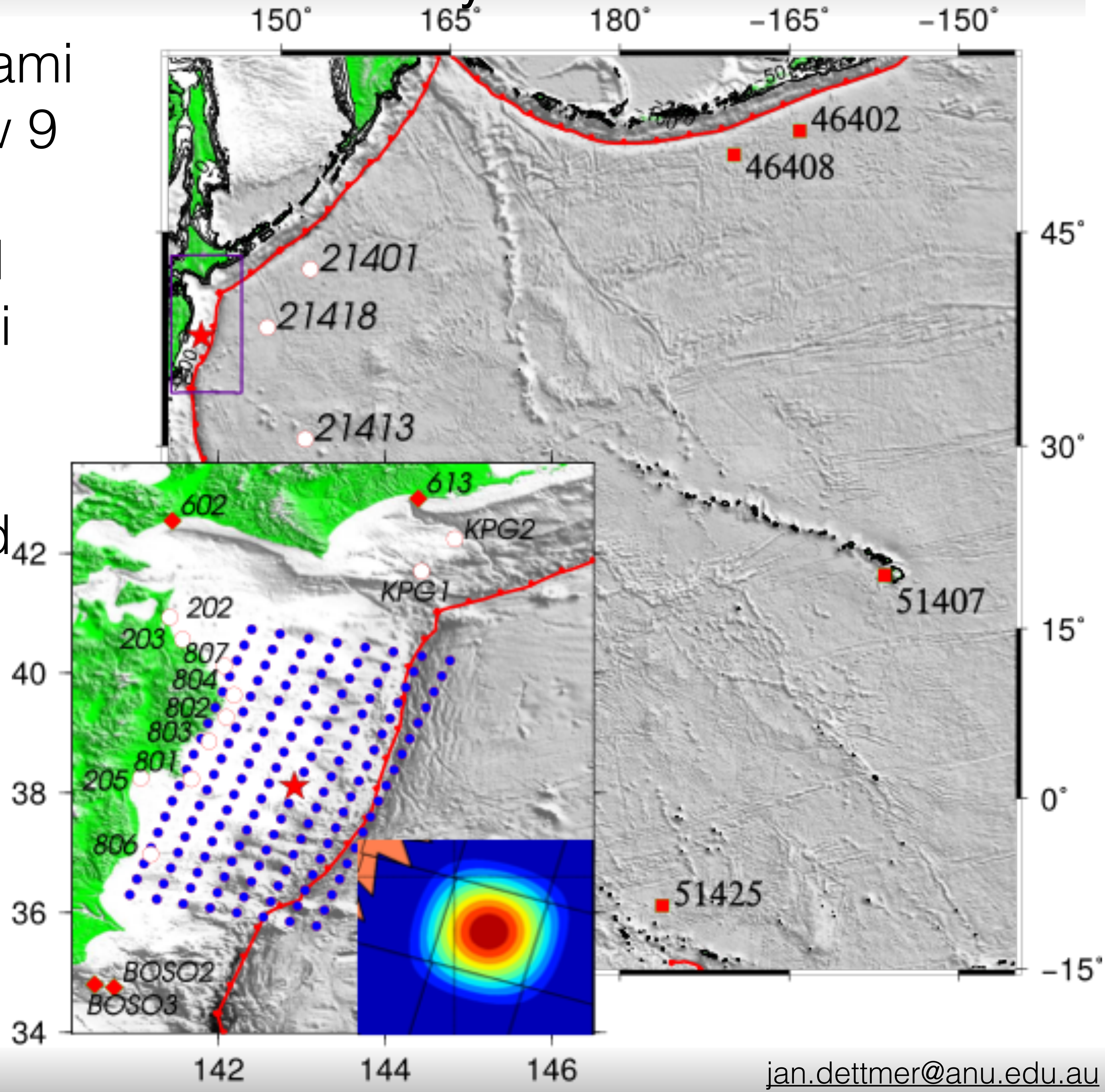
2011 Japan tsunami: Ideal case study

- Very large tsunami due to giant Mw 9 earthquake
- Unprecedented array of tsunami observations available
- Many published source models for comparison



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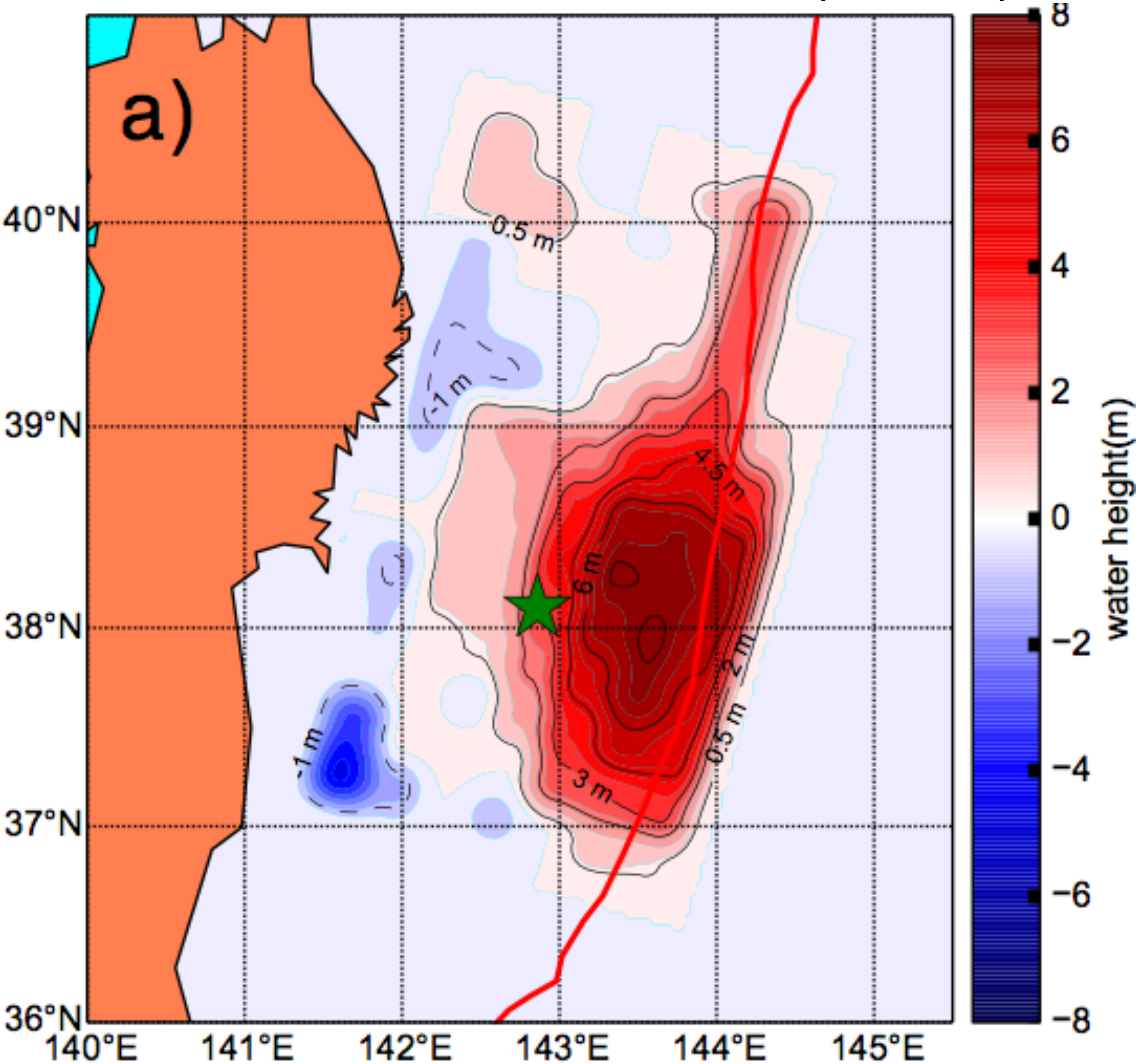
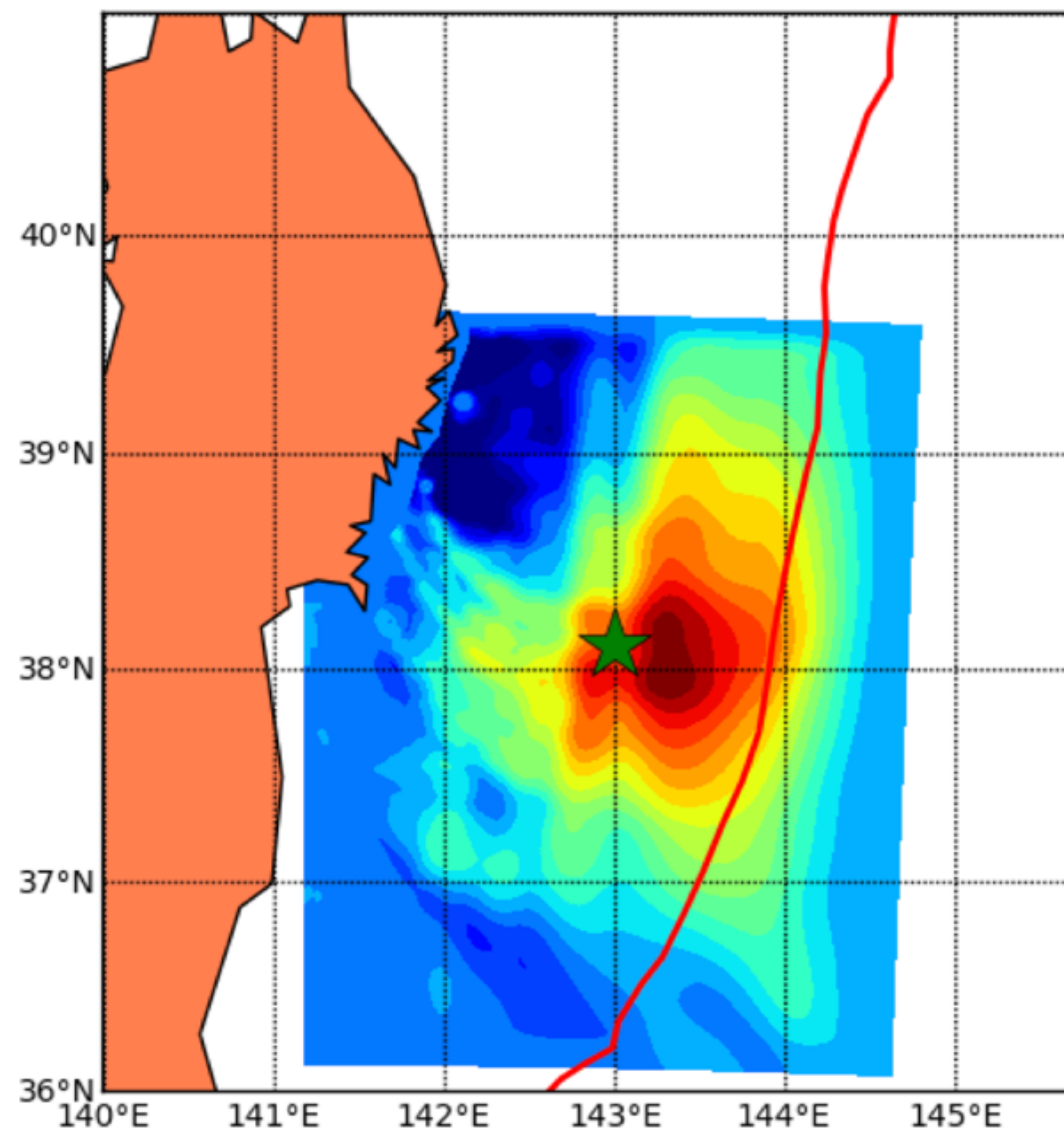
New approach: Similar resolution;
Fraction of computational cost, fewer subjective choices

GF-TRI Hossen et al. (2015)

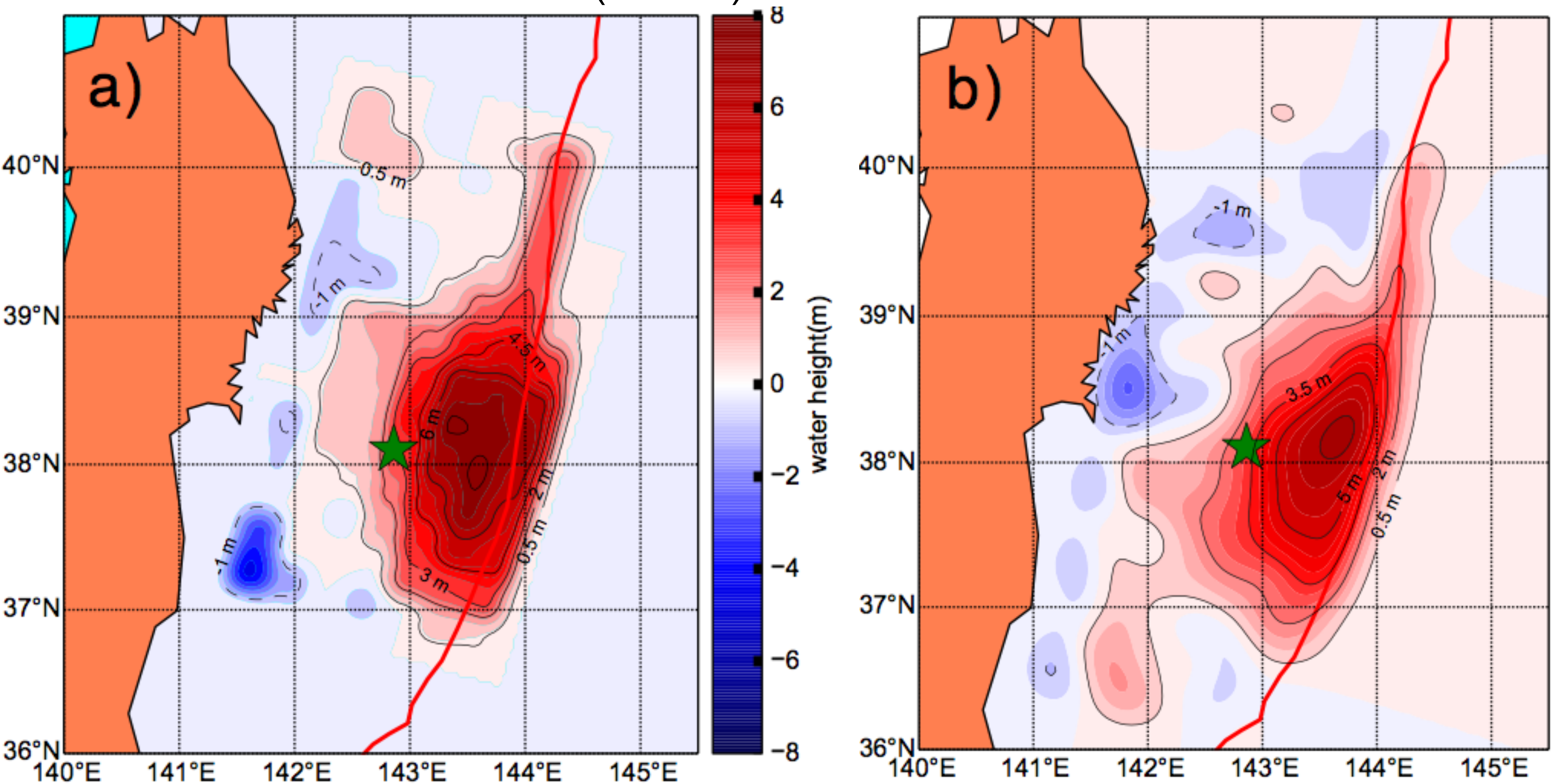


Previous TRI



New approach: Similar resolution; Fraction of computational cost, fewer subjective choices

GF-TRI Hossen et al. (2015) | Conventional method



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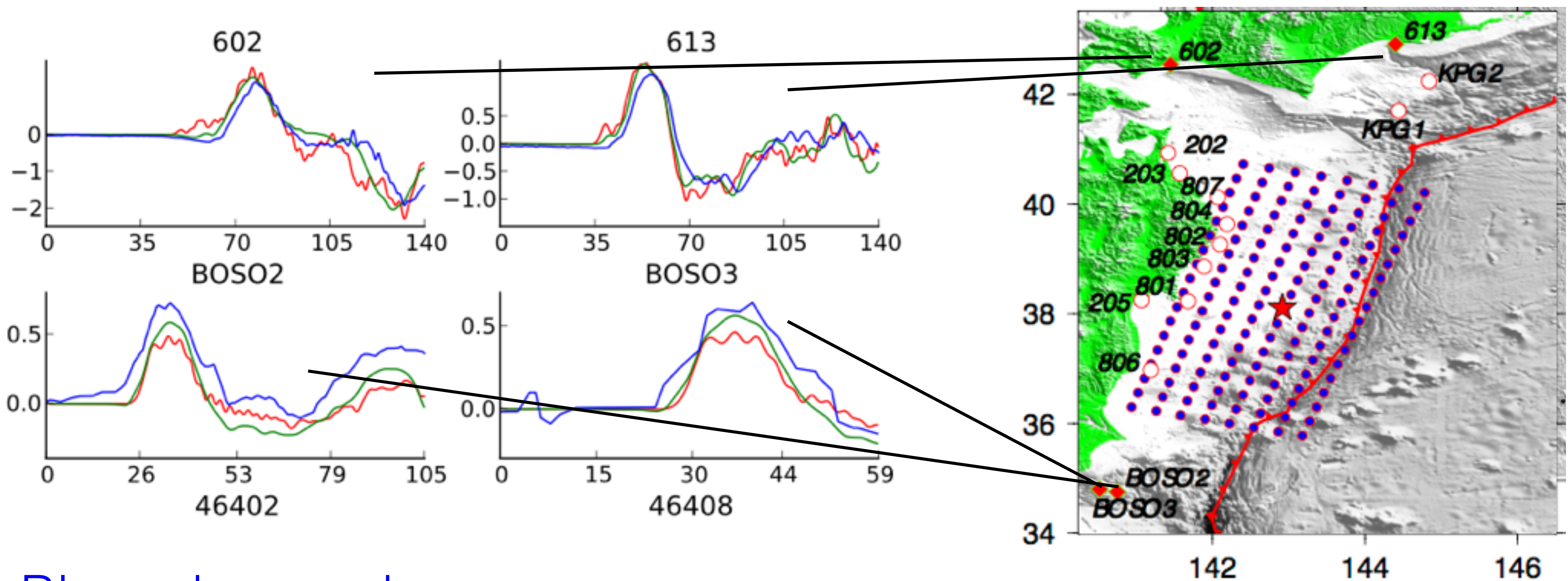
Predictive power near field:
Similar to conventional but much faster & more objective



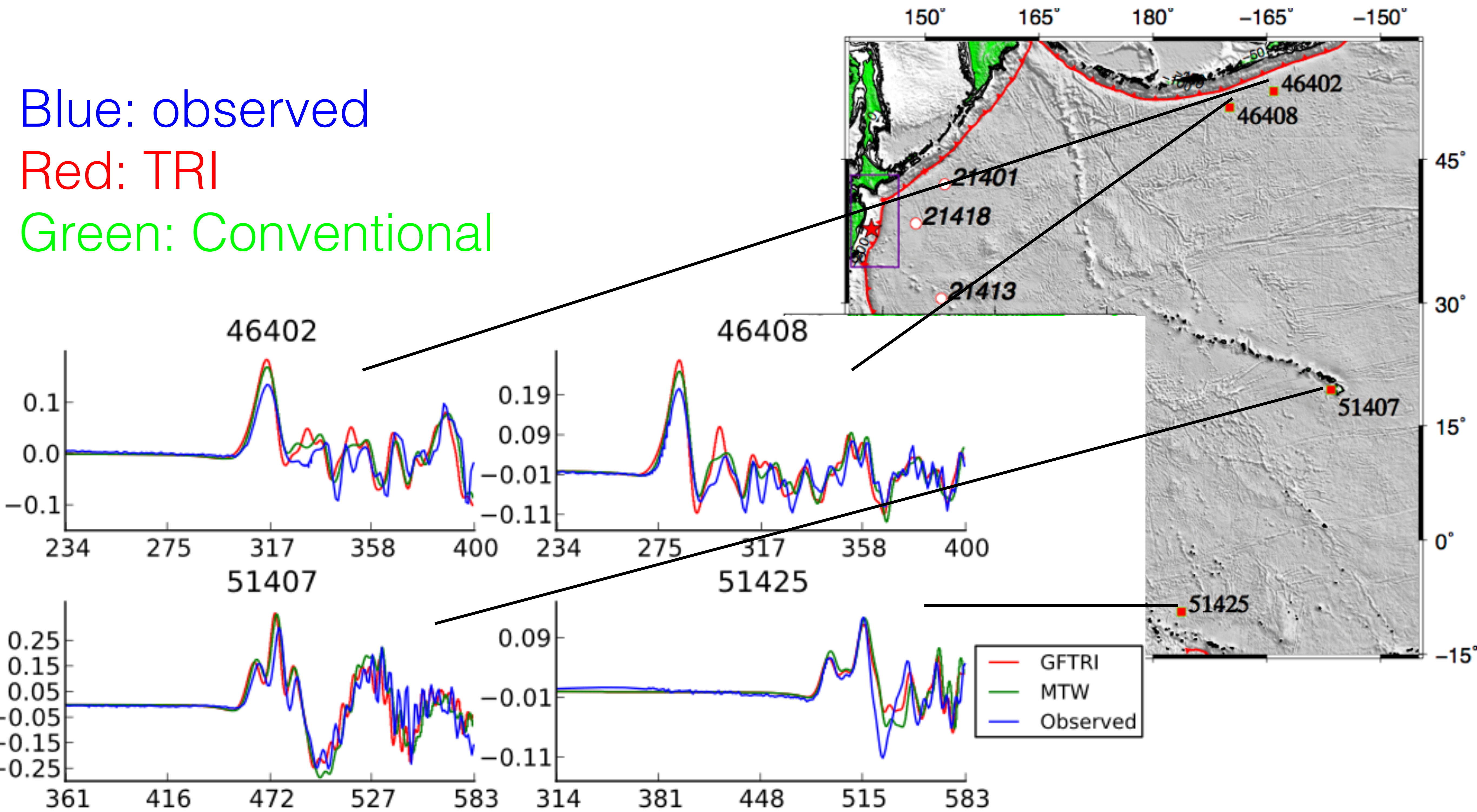
Blue: observed

Red: TRI

Green: Conventional

Predictive power far field: Excellent

Blue: observed
Red: TRI
Green: Conventional



Importance/future impact: Tsunamis & harbour resonance

- Coastal populations already warned of far-field tsunamis & can escape
- Effects on ports persist for many hours & depend on subtle waveform features that may excite harbour resonance
- Example: Resonance excited in the harbour at Geraldton, Western Australia, by the 2004 Indian Ocean Tsunami

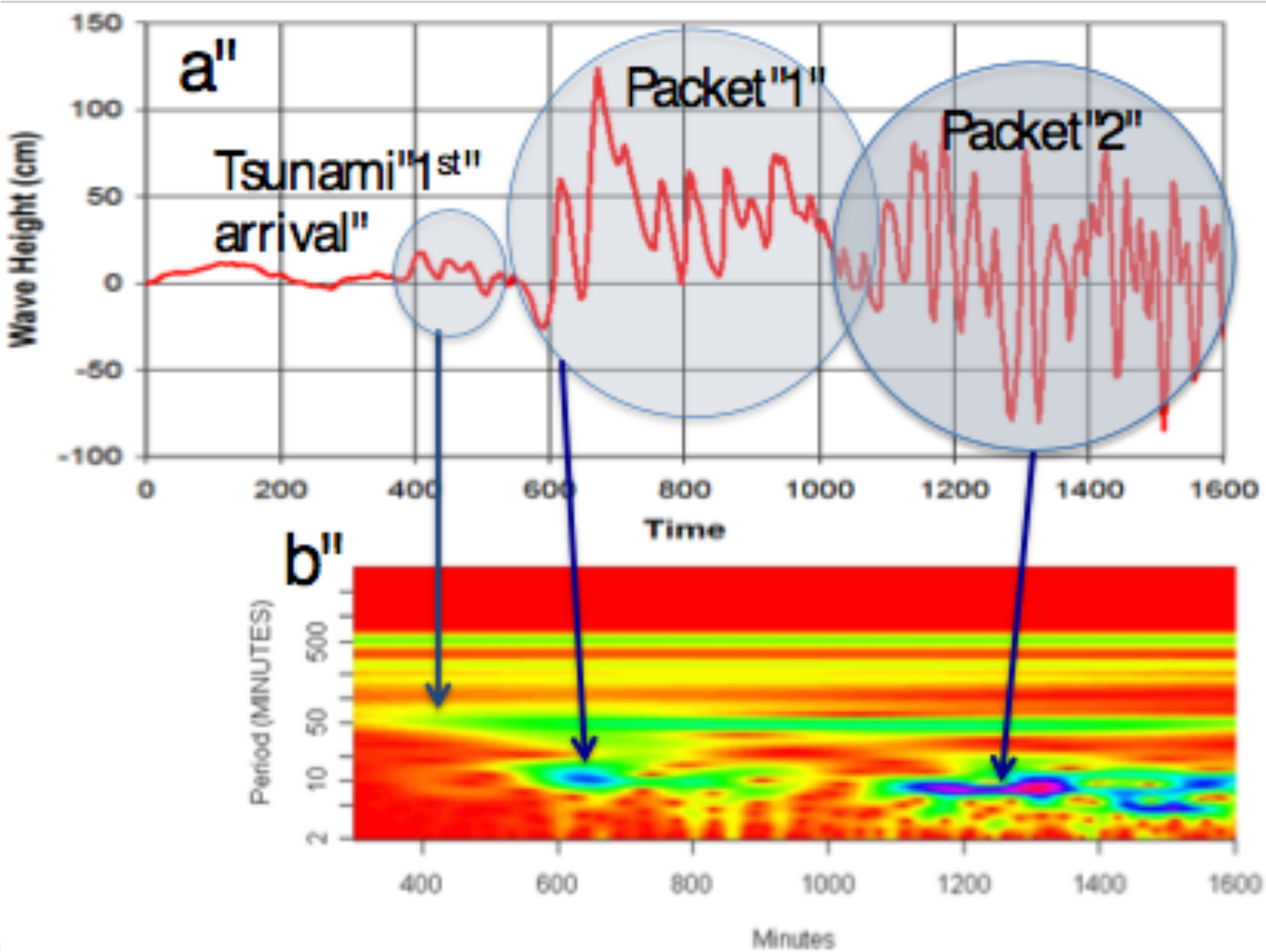


Figure: Geoscience Australia

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Summary

- New sea level sensors can be used for time reverse imaging of large tsunami sources
- Tsunami TRI is simple: Average observed waveforms convolved with Green's functions pre-calculated for an array of source points (i.e. no real-time tsunami simulation necessary to estimate source)
- Prediction of far-field waveforms using TRI-determined source is excellent
- Current warning systems work well for alerting distant coastal communities, ports are more difficult to protect:

  Resonances excited by late-arriving phases require better tsunami source estimates which may be forecast effectively using TRI

References:
- Hossen et al., (2015). Geophysical Research Letters, 42. doi:10.1002/2015GL065868
- Hossen et al., (2015). Pure and Applied Geophysics, 172, 969-984. doi:10.1007/s00024-014-1014-5

Both available upon request.

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Appendix

Earthquake rupture & tsunami knowledge: Helps early warning & disaster response

Recent tsunamis reminder of devastating consequences:

2004 Sumatra-Andaman (250,000+ deaths)

2010 Maule (500+ deaths)
2011 Tohoku (18,000+ deaths)

2011 Japan tsunami damage:


SH-60B helicopter over Sendai, US Navy


2011 tsunami, Tohoku coast, NOAA/NGDC image

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Source knowledge key to prediction

Sumatra 2004

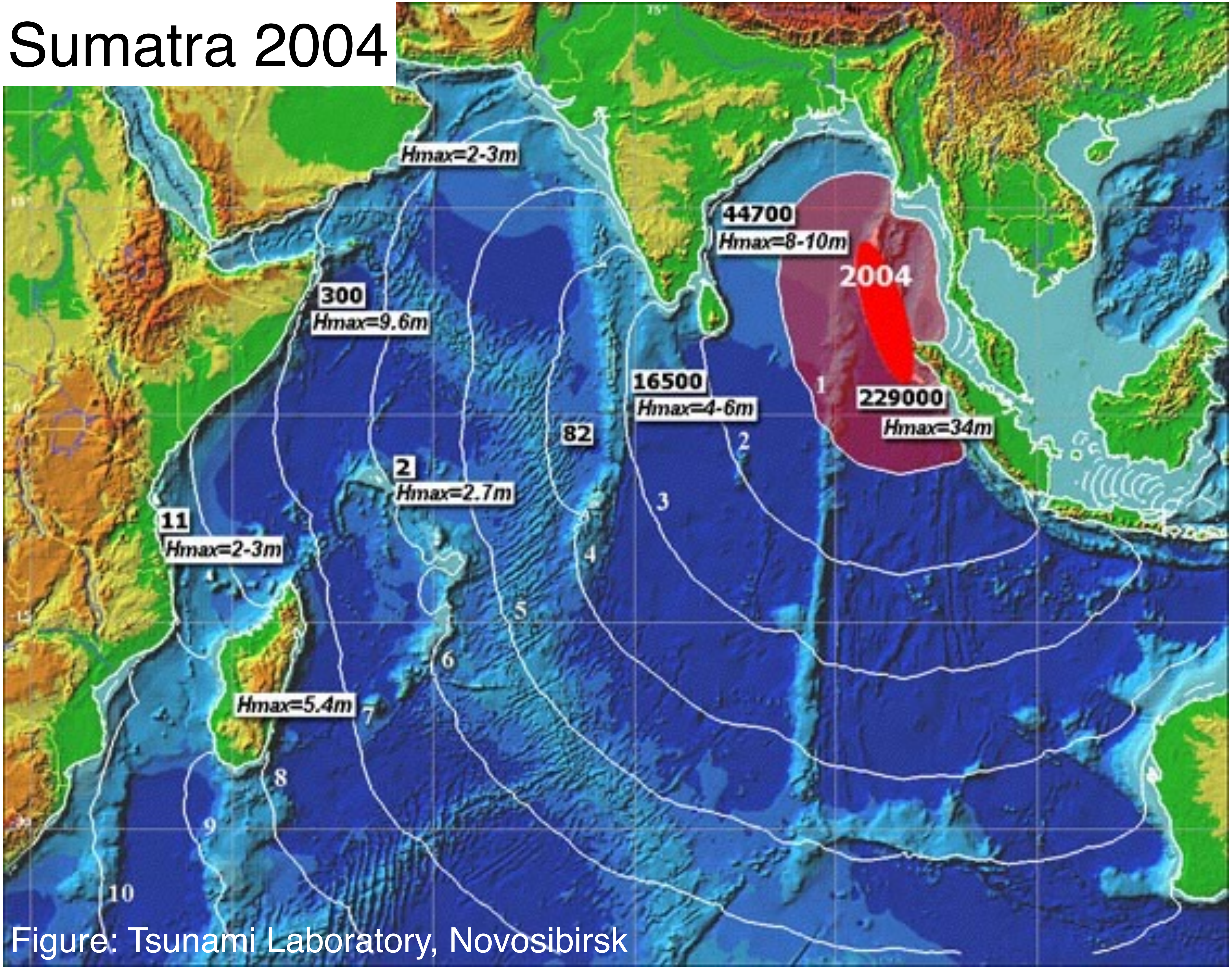

Figure: Tsunami Laboratory, Novosibirsk

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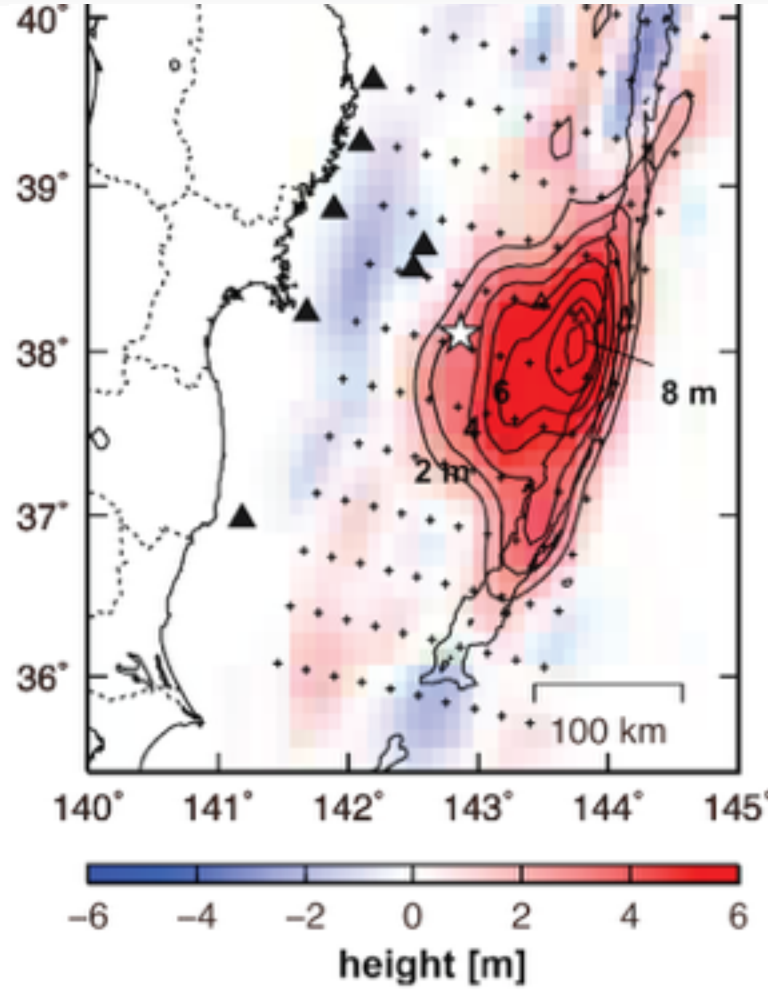
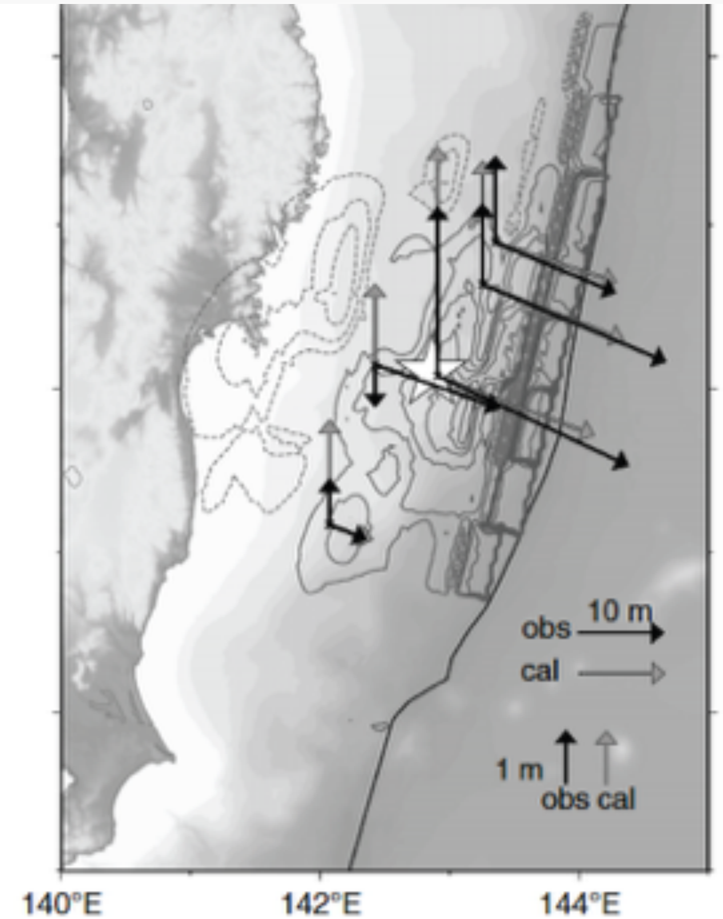
2011 Tohoku: Source image changes with assumptions

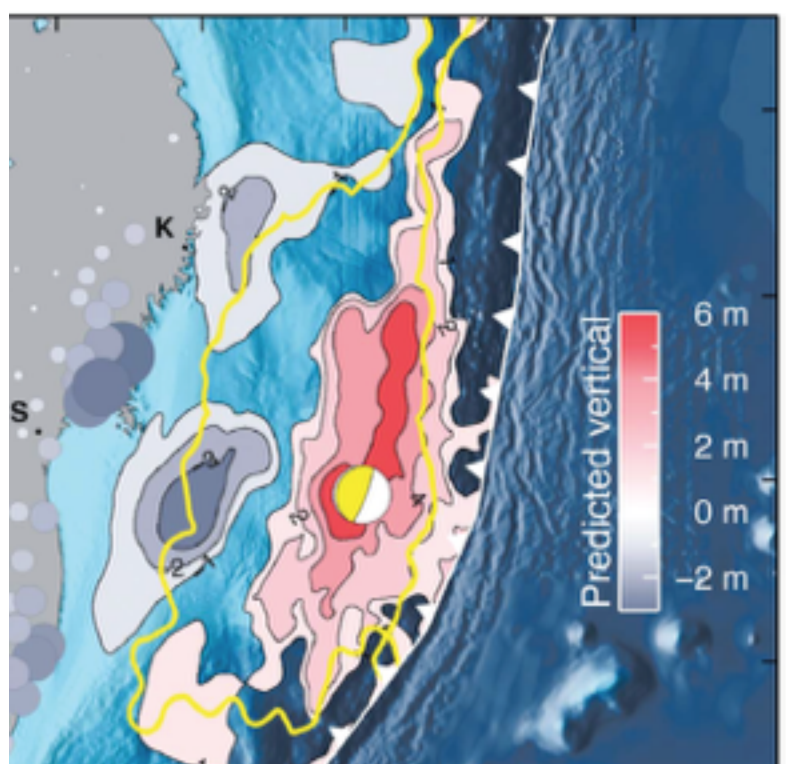
Saito et al.
EPS 2011



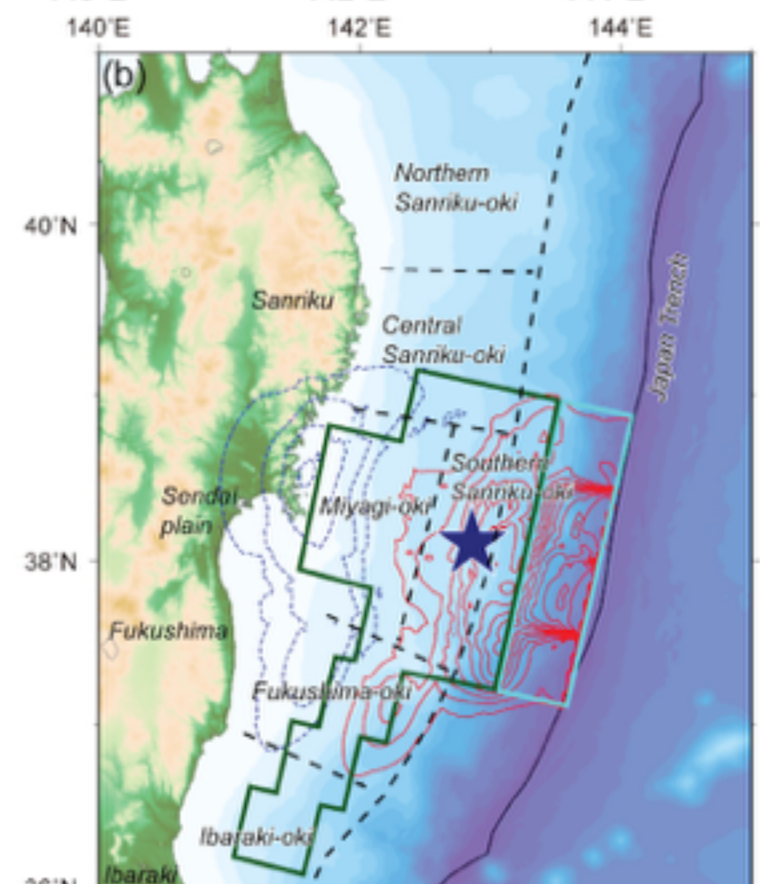
Satake et al.
BSSA 2013



Simons et al.
Science 2011



Fuji et al.
EPS 2011



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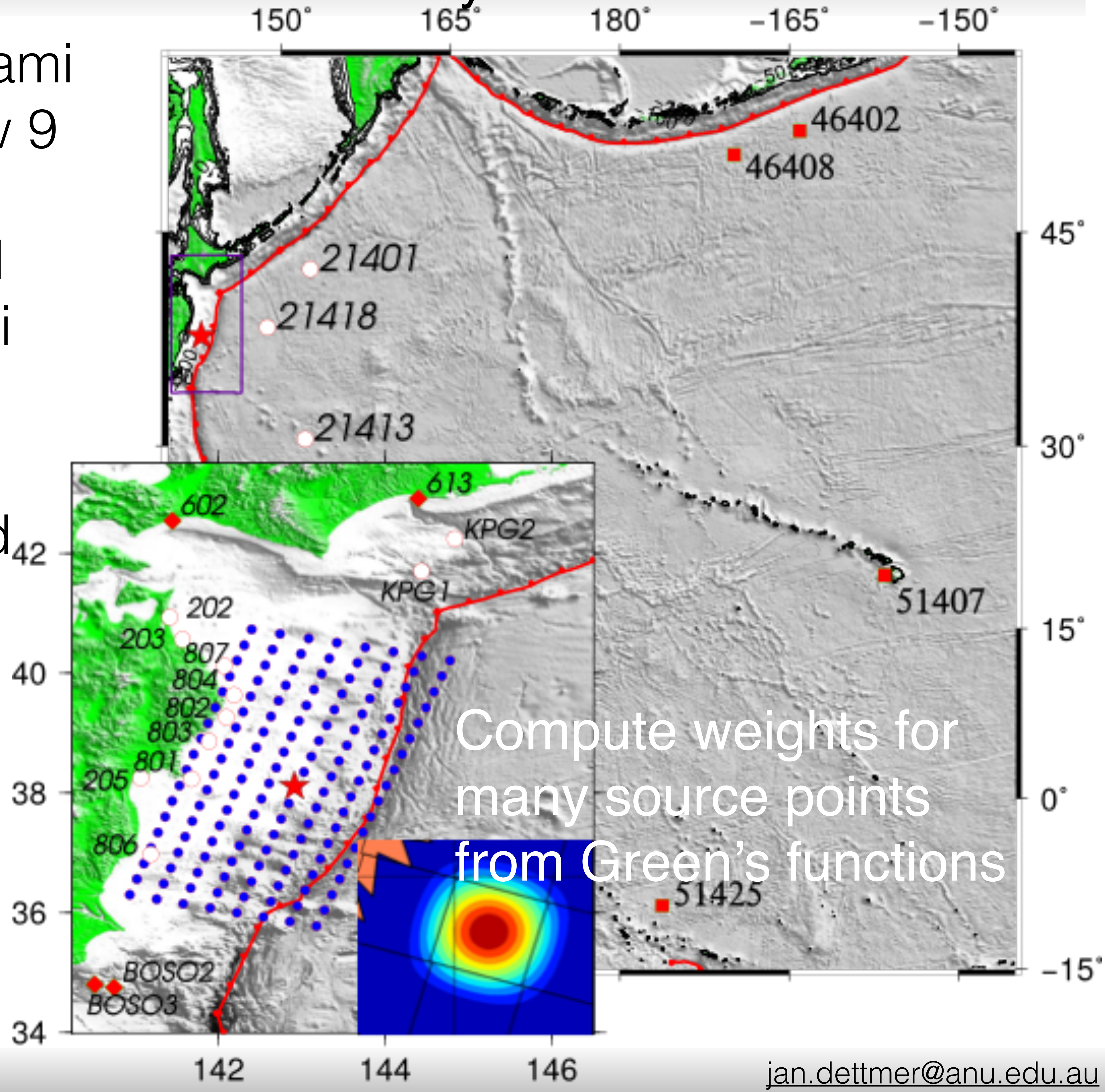

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