5th Workshop on "SMART Cable Systems: Latest Developments and Designing the Wet Demonstrator Project"

(Dubai, UAE, 17-18 April 2016)

Benefits and requirements for ocean bottom measurements for tsunami early warning and earthquake science

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Overview “Seismology and tsunami science”

- Tsunami early warning (local sources)
- Local earthquake analysis
- Global earthquake analysis
- Local site monitoring based on ambient noise
- Data management
- Summary and site recommendations

Tsunami early warning

DART system

Deep-ocean Assessment and Reporting of Tsunamis (DART)

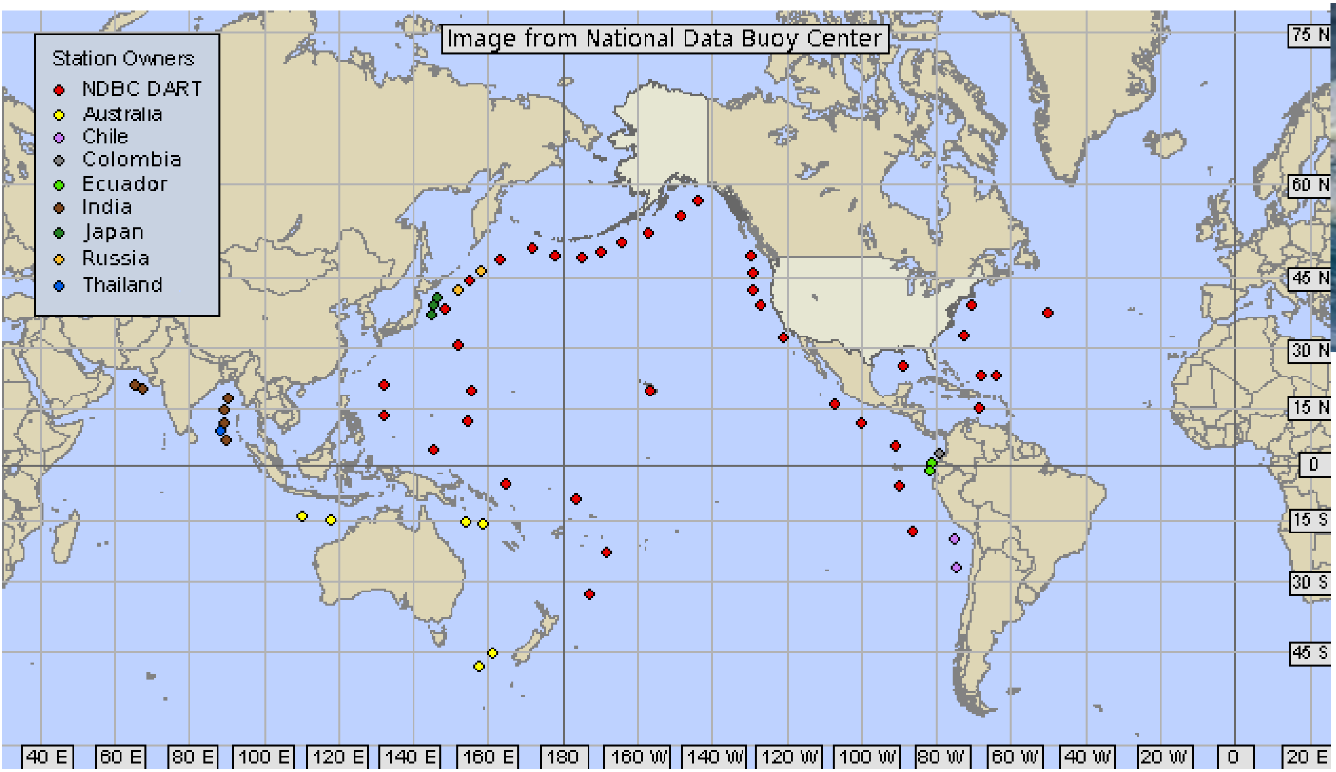
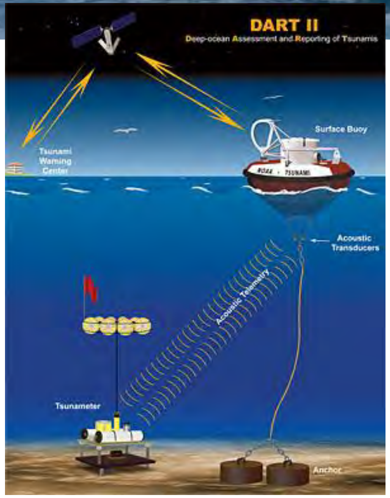


Image from National Data Buoy Center

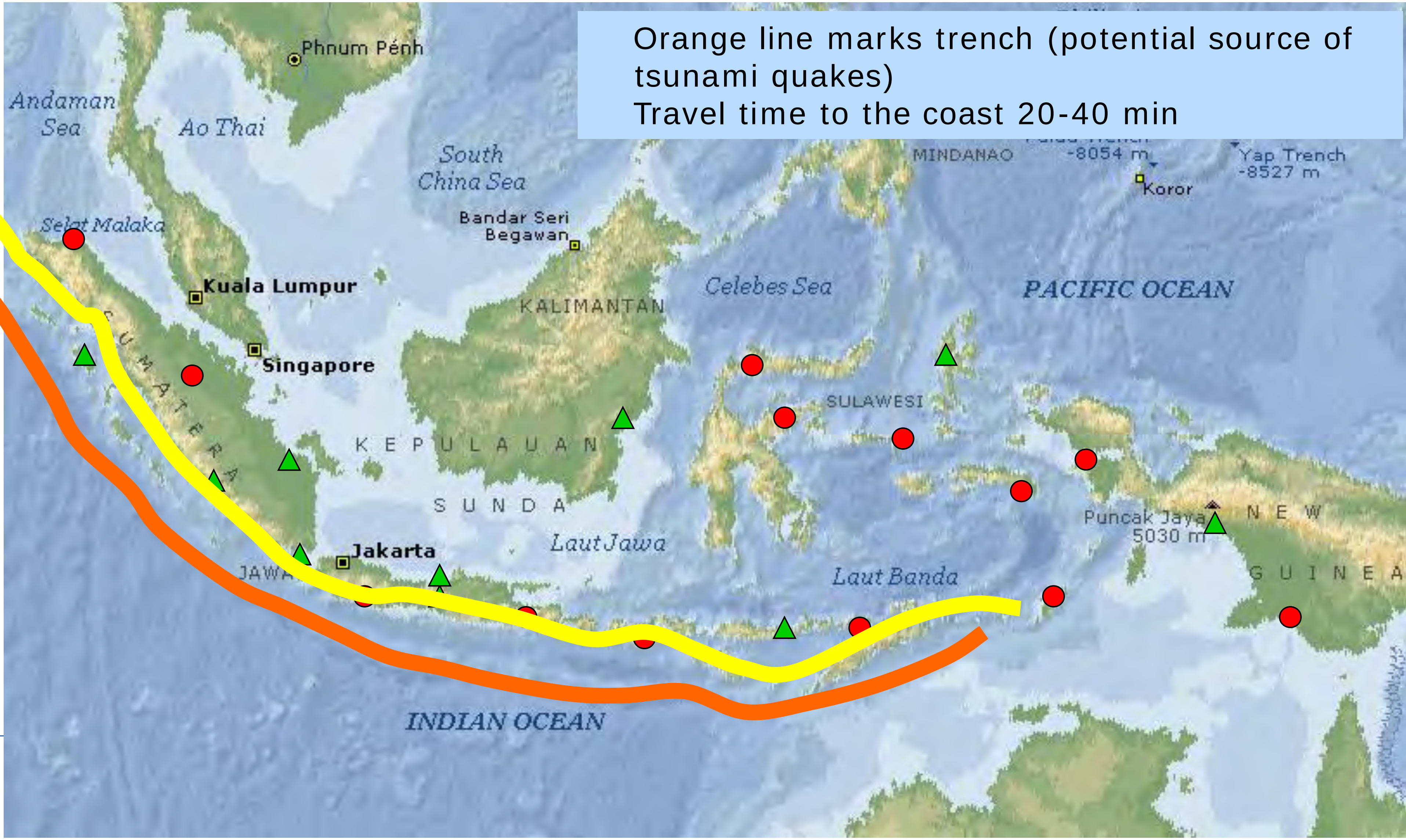


Issues:

- In some regions (Indonesia) frequent losses through vandalism
- Technical limitation to 15 sec sampling in triggered mode
- Sparse coverage (~500 km or less) imposed by high unit costs

Challenge for local sources: Example Indonesia

- Short warning times (Legal mandate in Indonesia: decision 5 min after EQ origin time)

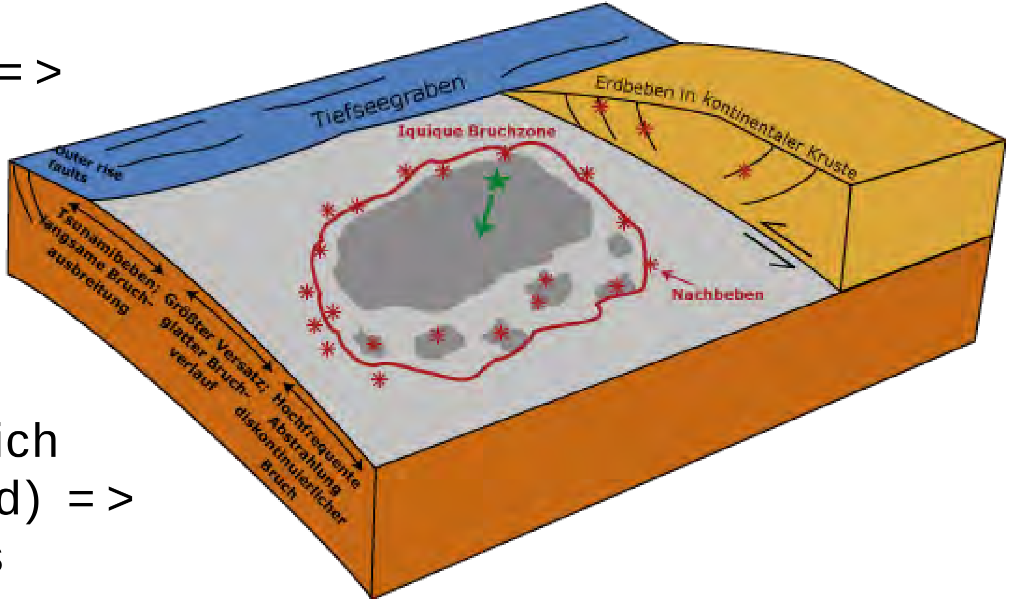


Orange line marks trench (potential source of tsunami quakes)
Travel time to the coast 20-40 min

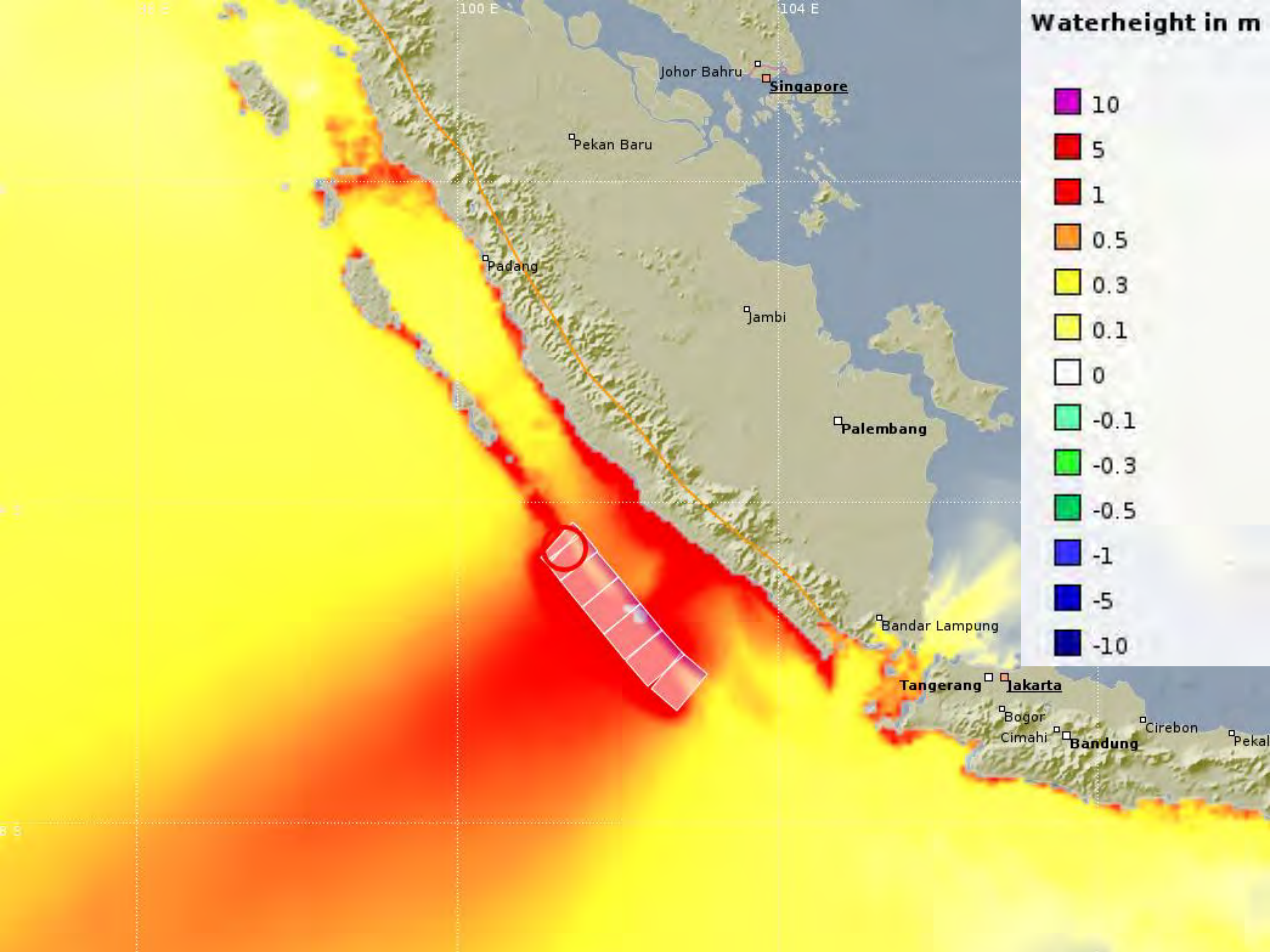
Sources of uncertainty in near-field tsunami assessment

DART data generally not available => need to rely on seismological measurements

- Early seismological magnitudes underestimated for the largest earthquakes (e.g. Japan 2011)
- Along-strike rupture extent (which part of the coastline is inundated) => necessary for targeted warnings



- Along-dip rupture extent. Is the rupture focused on the shallow part of the plate interface?
- What are the material properties (shear modulus m) in the area of peak slip (M_0= *m d A*). Soft material (shallow fault) => larger tsunami for given M_W.
- What is the dip of the fault plane (steeper faults => larger seafloor vertical displacement)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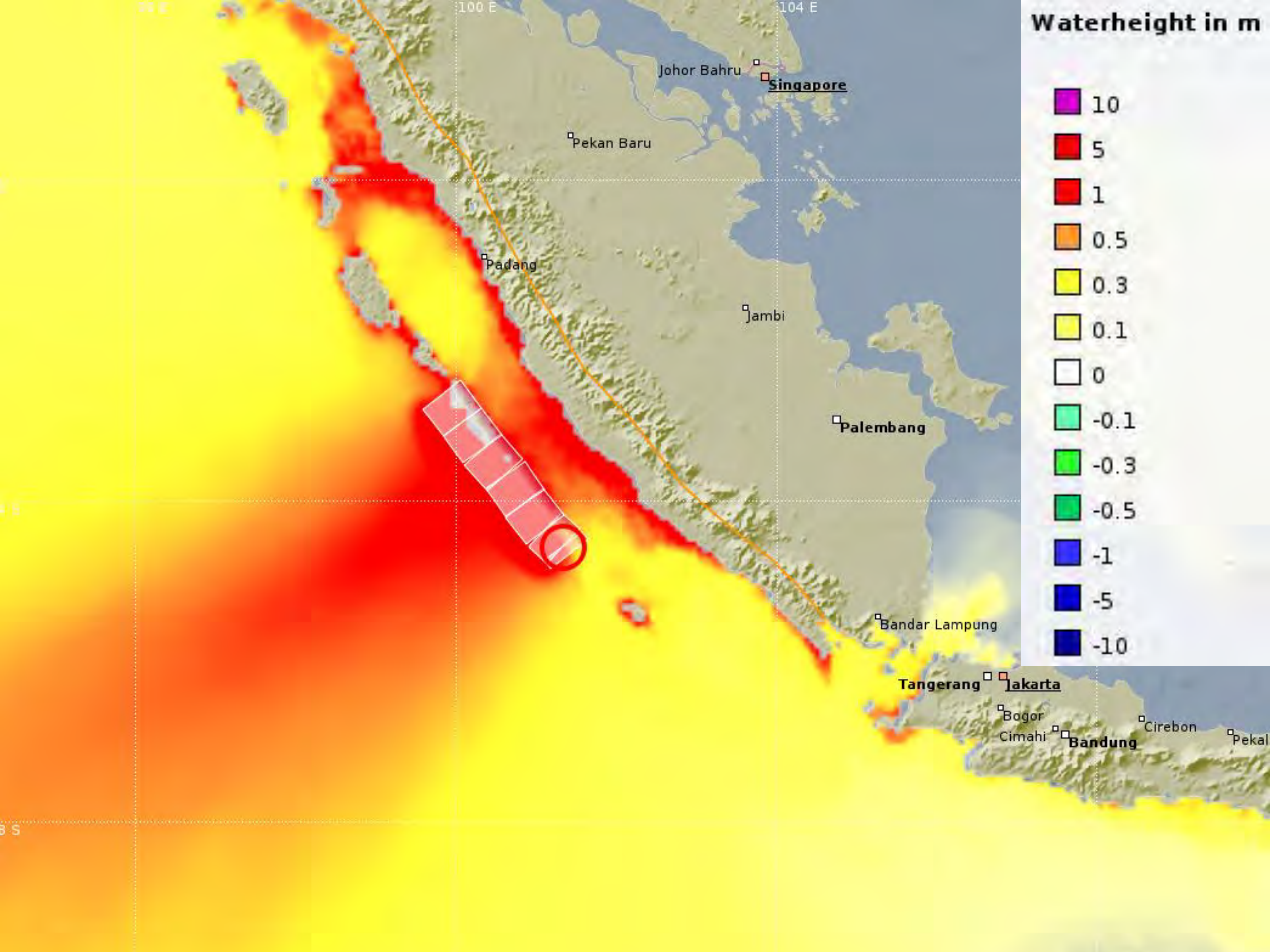
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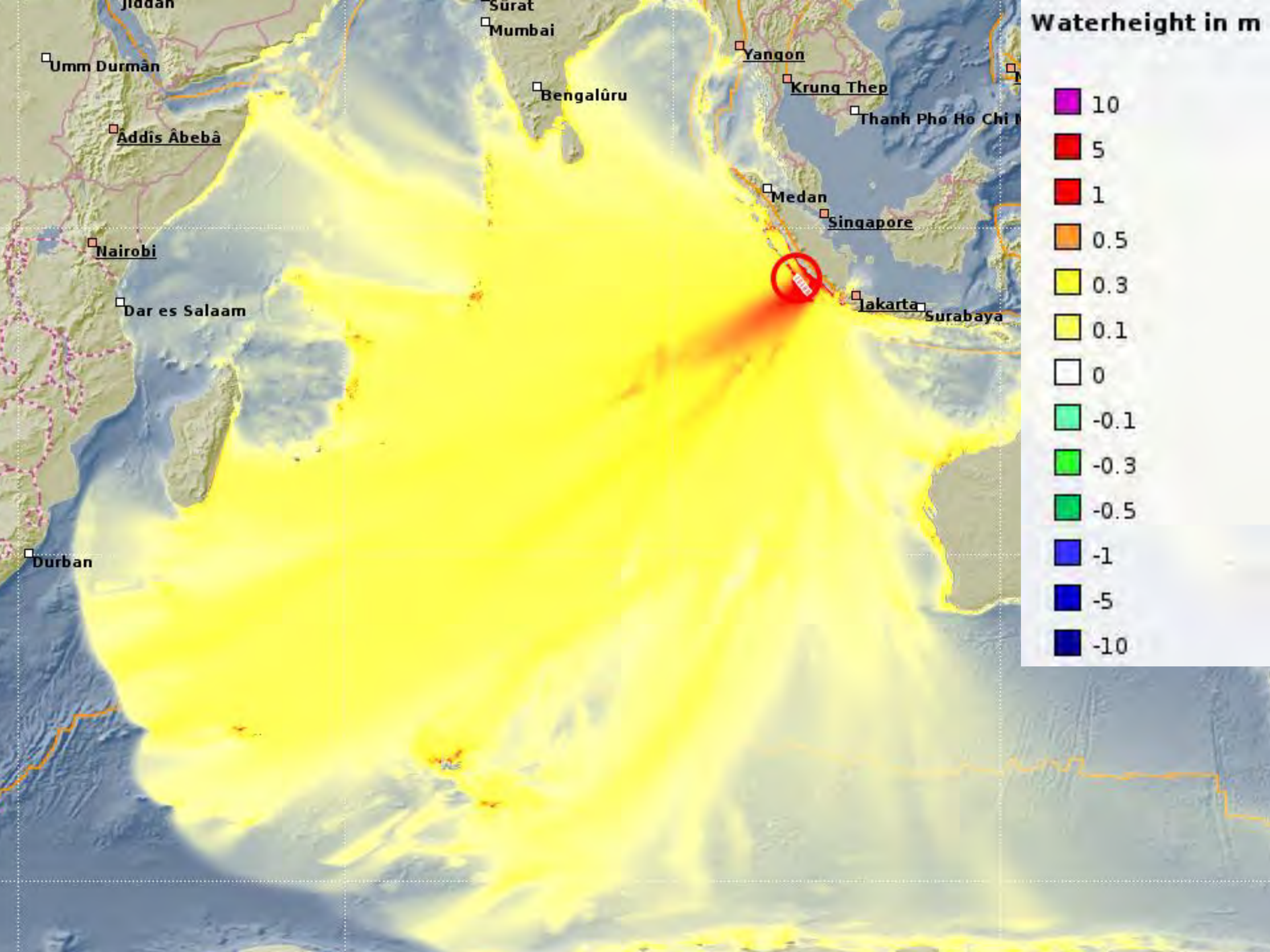
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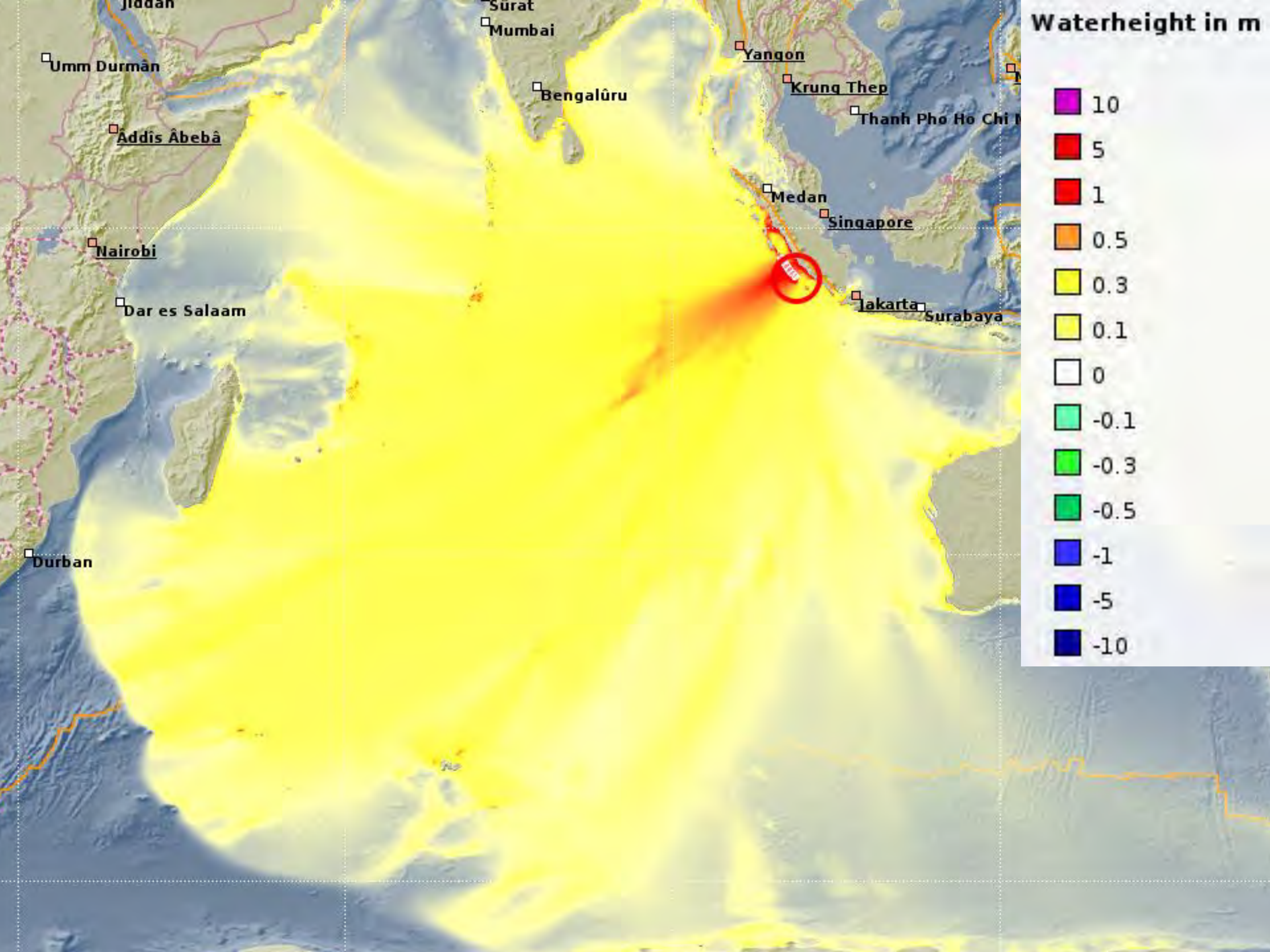
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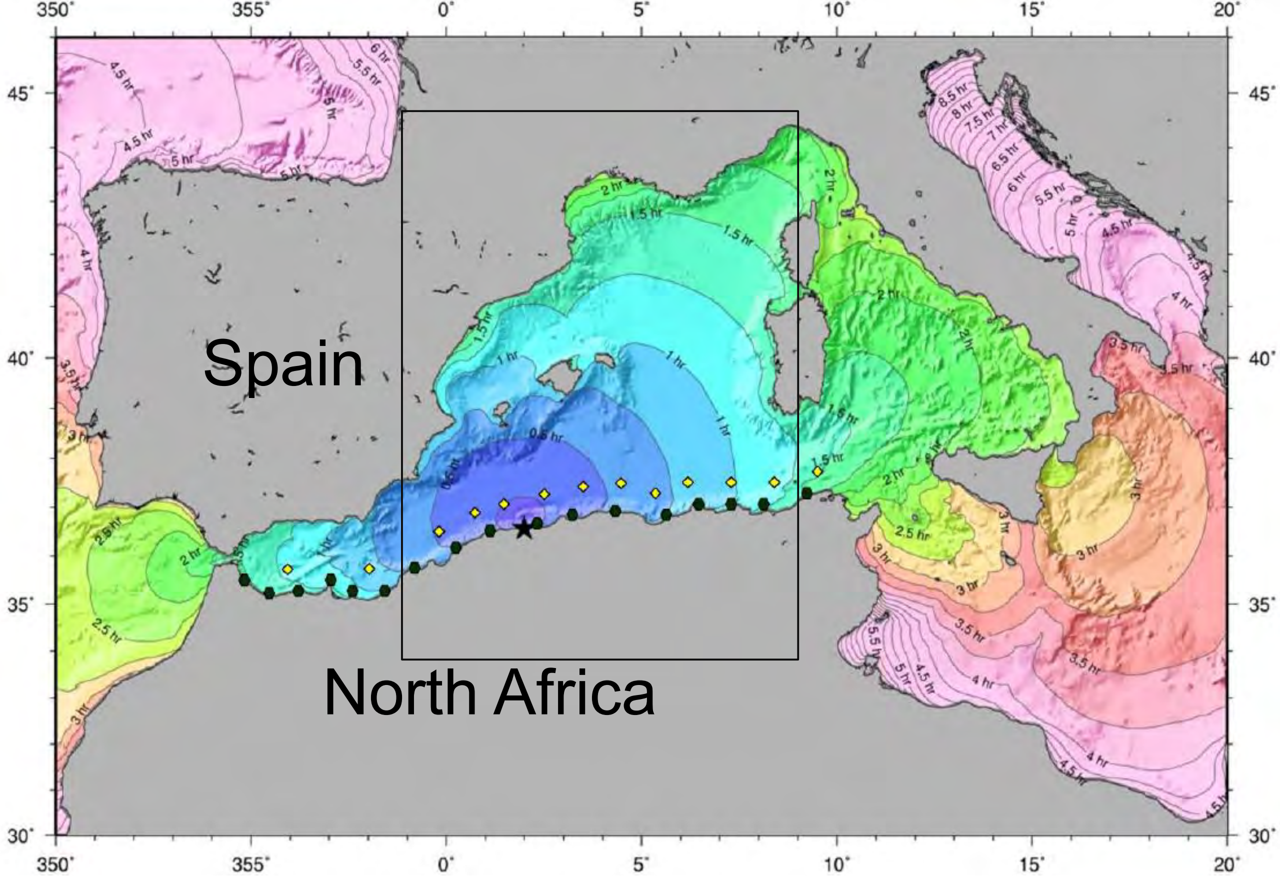
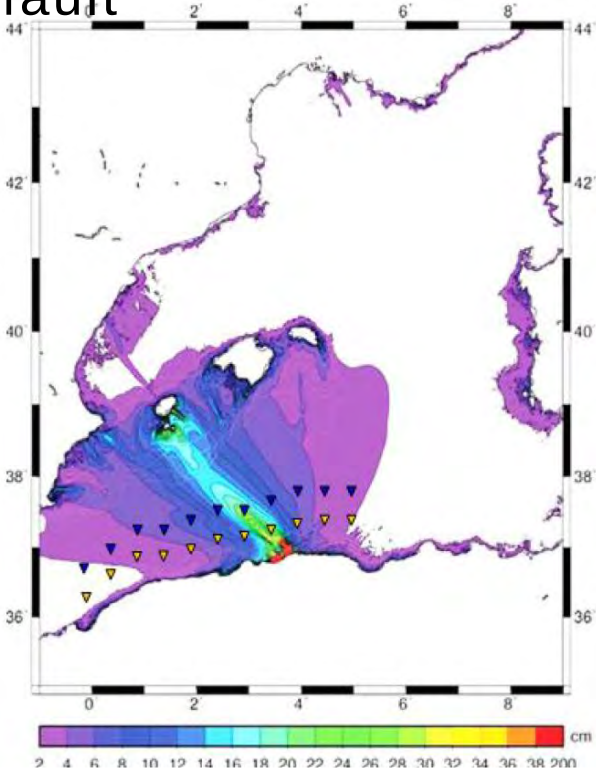
Challenge for local sources: Example Western Mediterranean



Tsunami potential from moderate size EQ (Zemmouri Mw 6.9 causing significant damage on Balearic islands), enhanced by steep fault

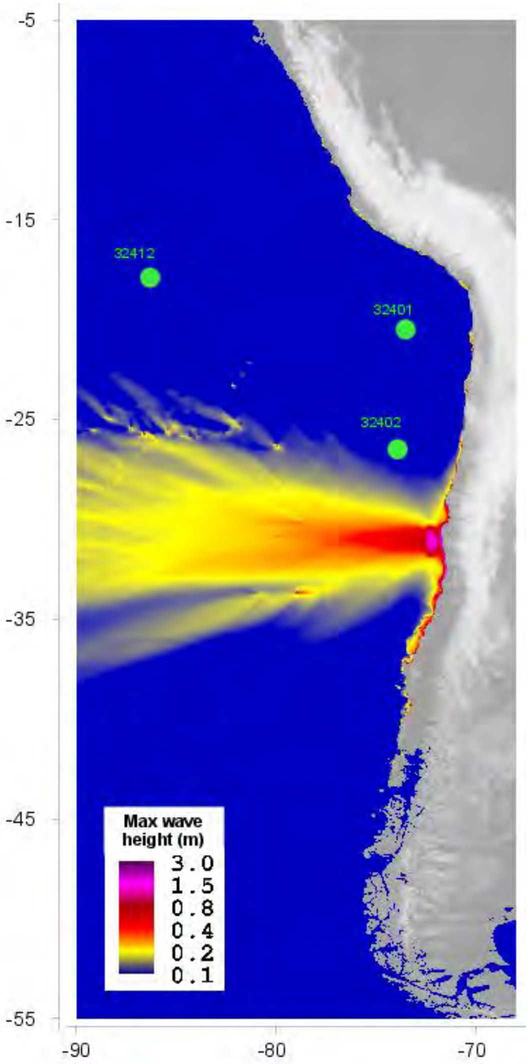


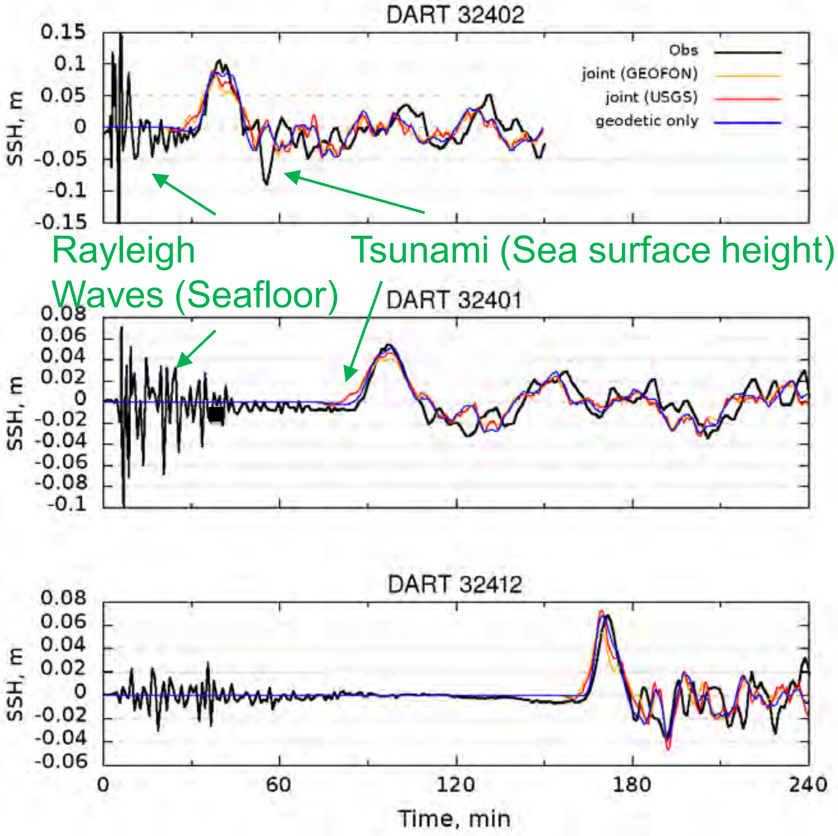
Black dots: potential EQ sources
Yellow dots: required spacing for achieving 15 min warning

Schindelé et al. (NHESS 2008)

Separation of seismic and tsunami signal

Example: 16 September 2015 Illapel Earthquake, Central Chile





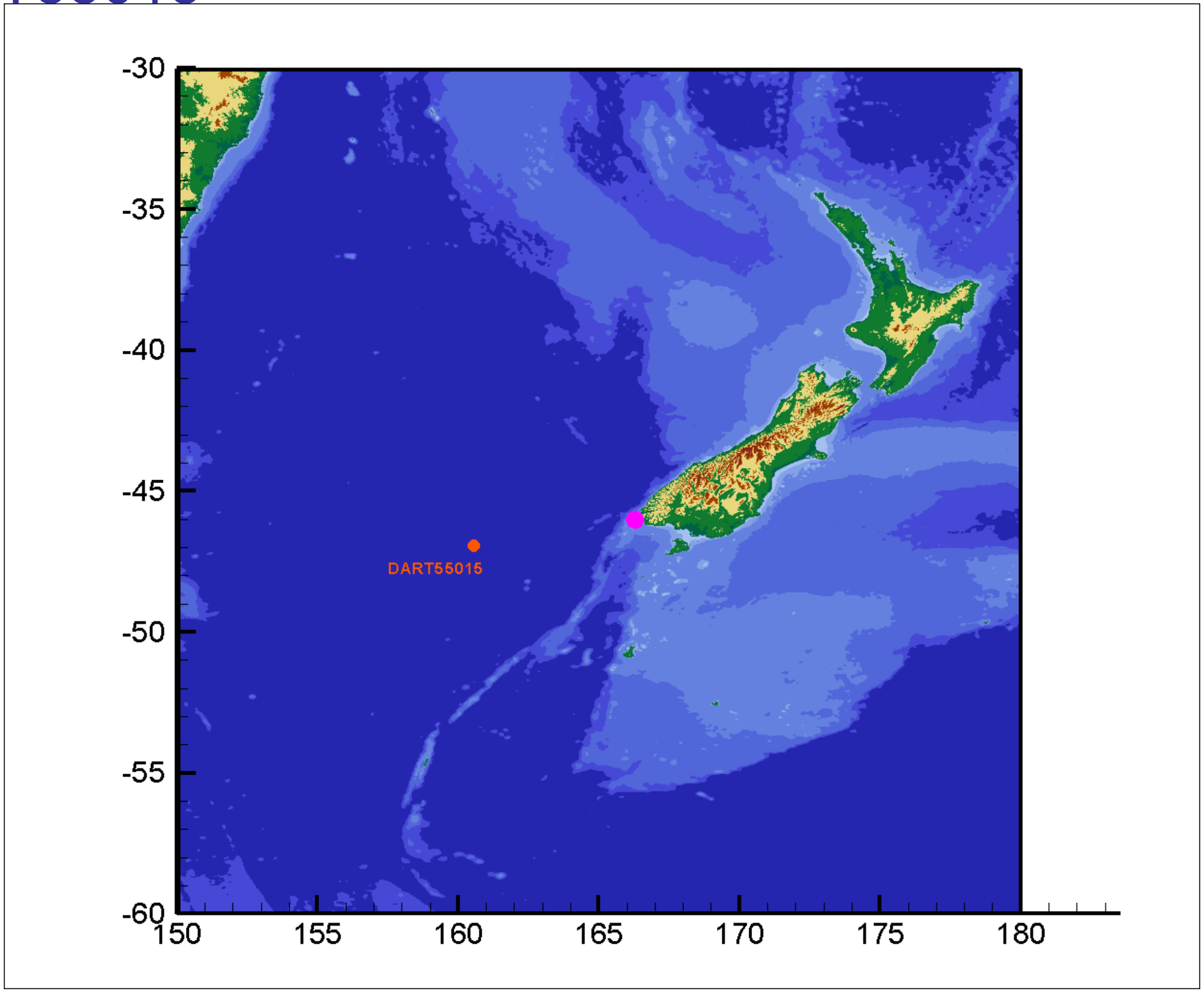
Rayleigh Waves (Seafloor)

Tsunami (Sea surface height)

Tilmann et al. (2016 GRL)

15 July 2009, New Zealand Mw=7.6

DART55015

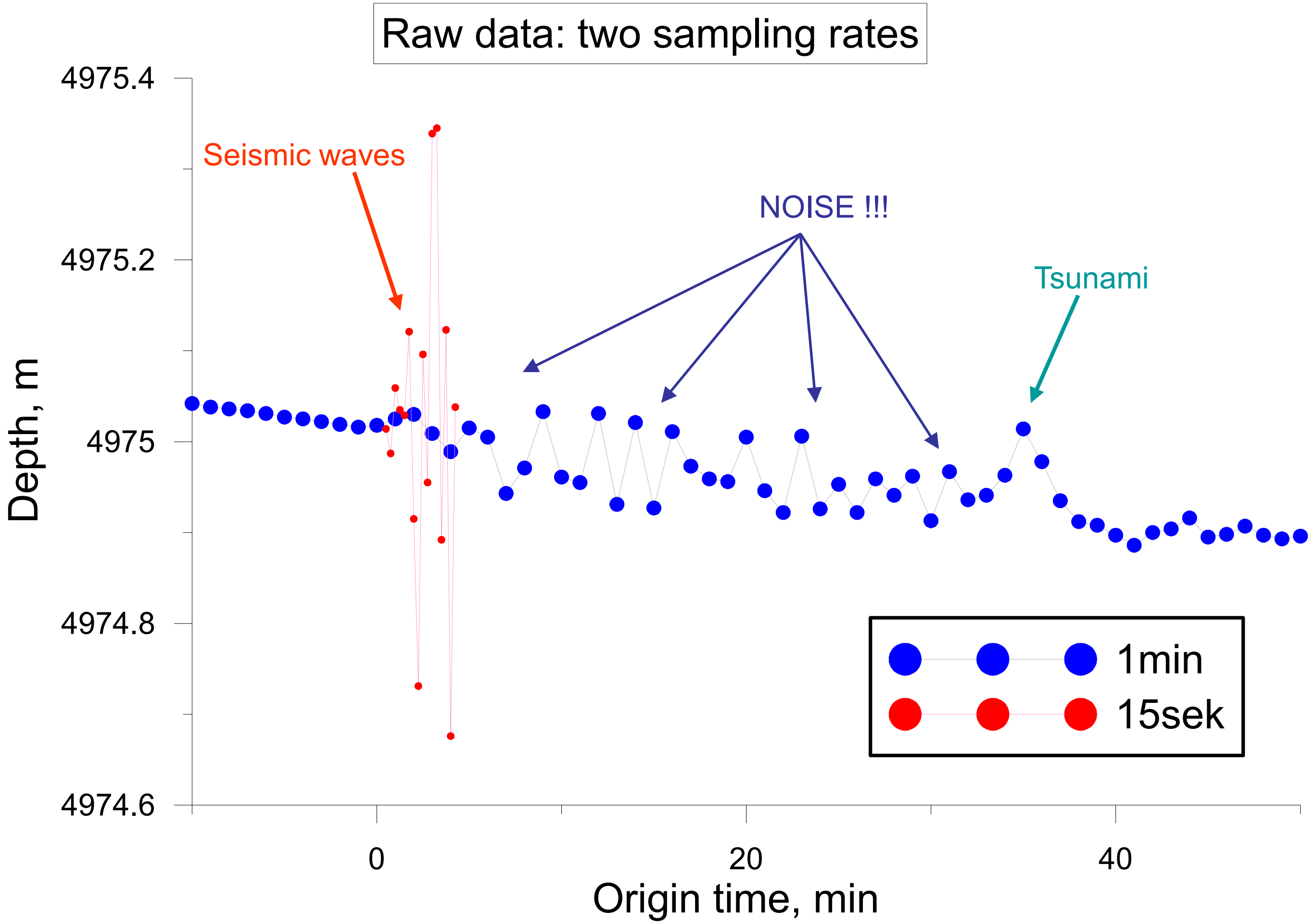


Australian DART55015 buoy is located ca. 500 km from the epicenter (about 30 min tsunami runtime).

A. Babeyko,
Pers comm.

July 2009, New Zealand Mw=7.6

DART55015



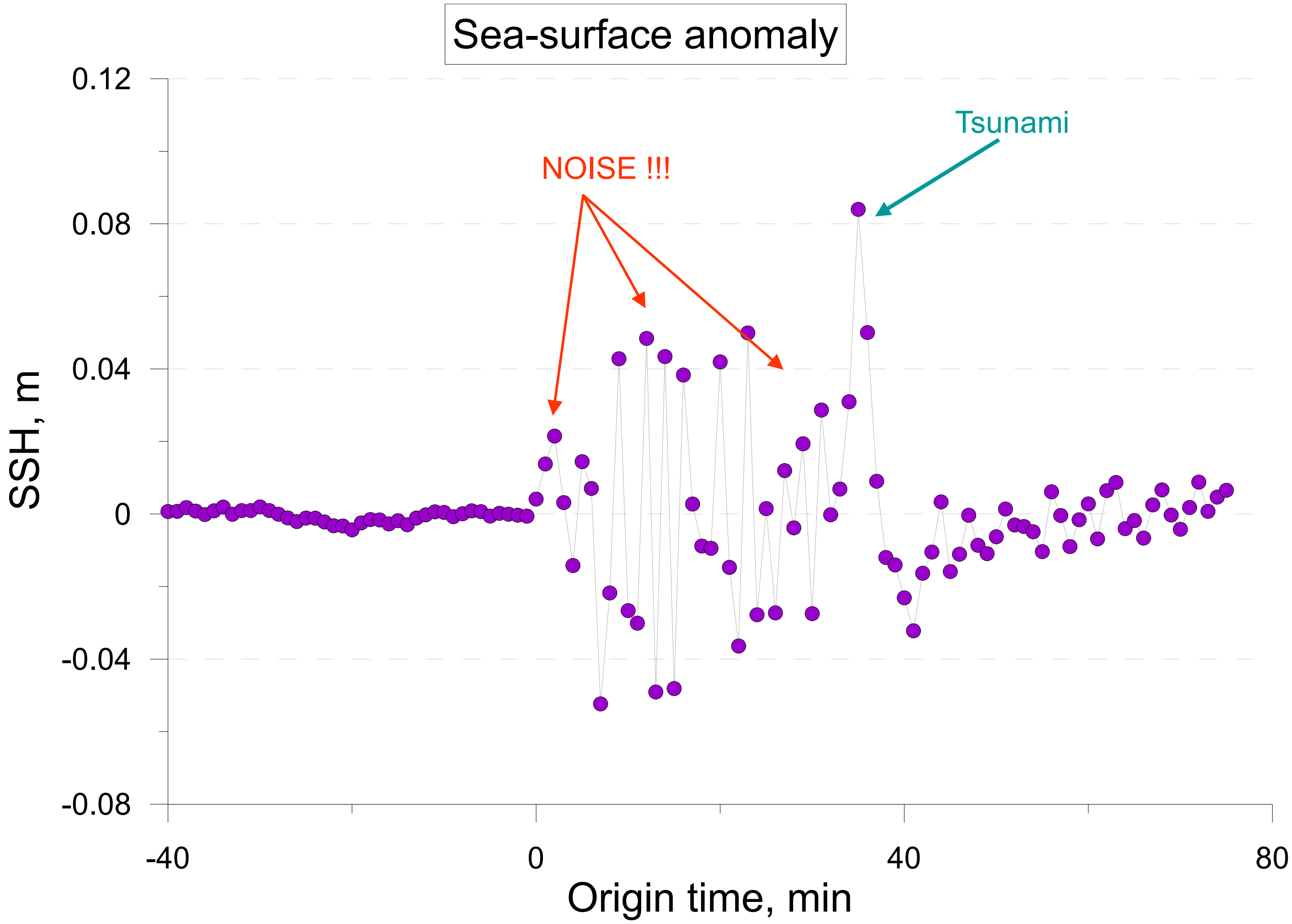
Detided time series. Origin time is time relative to the earthquake (09:23 UTC).

15-sec record series shows first seismic waves. Then – <u>aliased</u> noise, … Till the leading tsunami wave after ca. 30 min.

A. Babeyko, Pers comm.

July 2009, New Zealand Mw=7.6

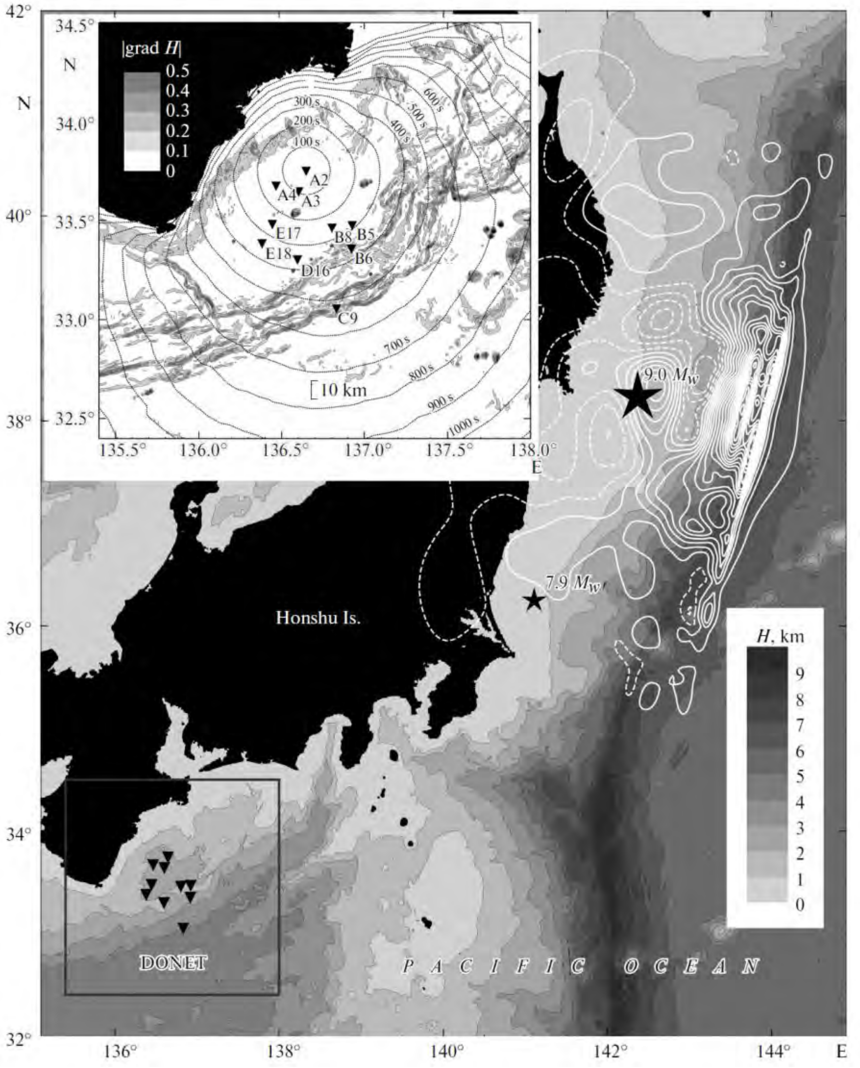
DART55015



Noise amplitude from Mw=7.6 at ca. 500 km distance is comparable to the tsunami signal!

A. Babeyko,
Pers comm.

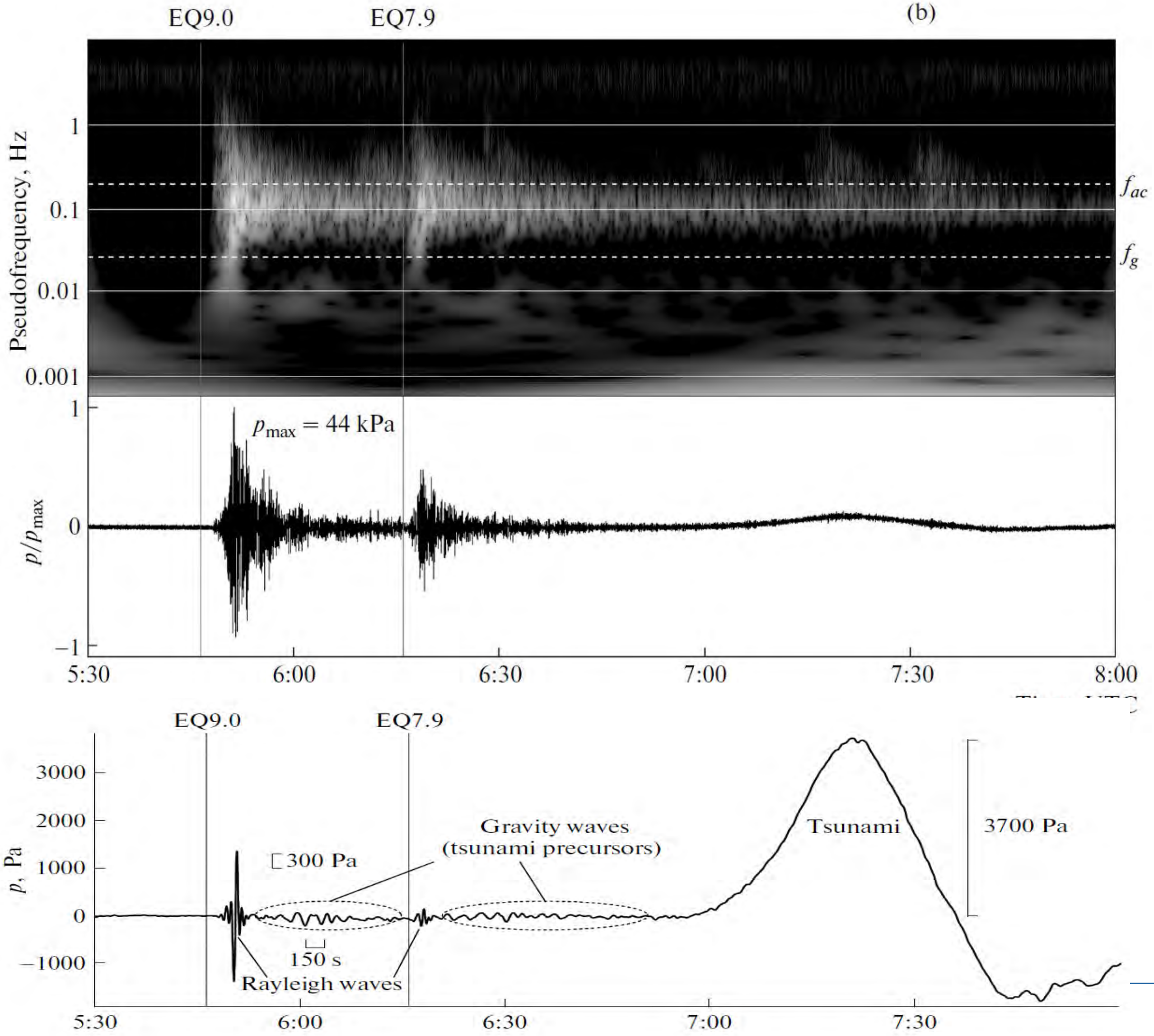
What can we do if high sampling rate recordings are available?



DONET pressure recordings of Japan 2011 EQ with high sampling rate

Nosov et al. (Doklady Earth Sci 2015)

What can we do if high sampling rate recodings are available?



DONET pressure recordings of Japan 2011 EQ

In raw pressure data, seismic signal dominates

Low pass filtering isolates sea surface height signal (but only possible for unaliased data)

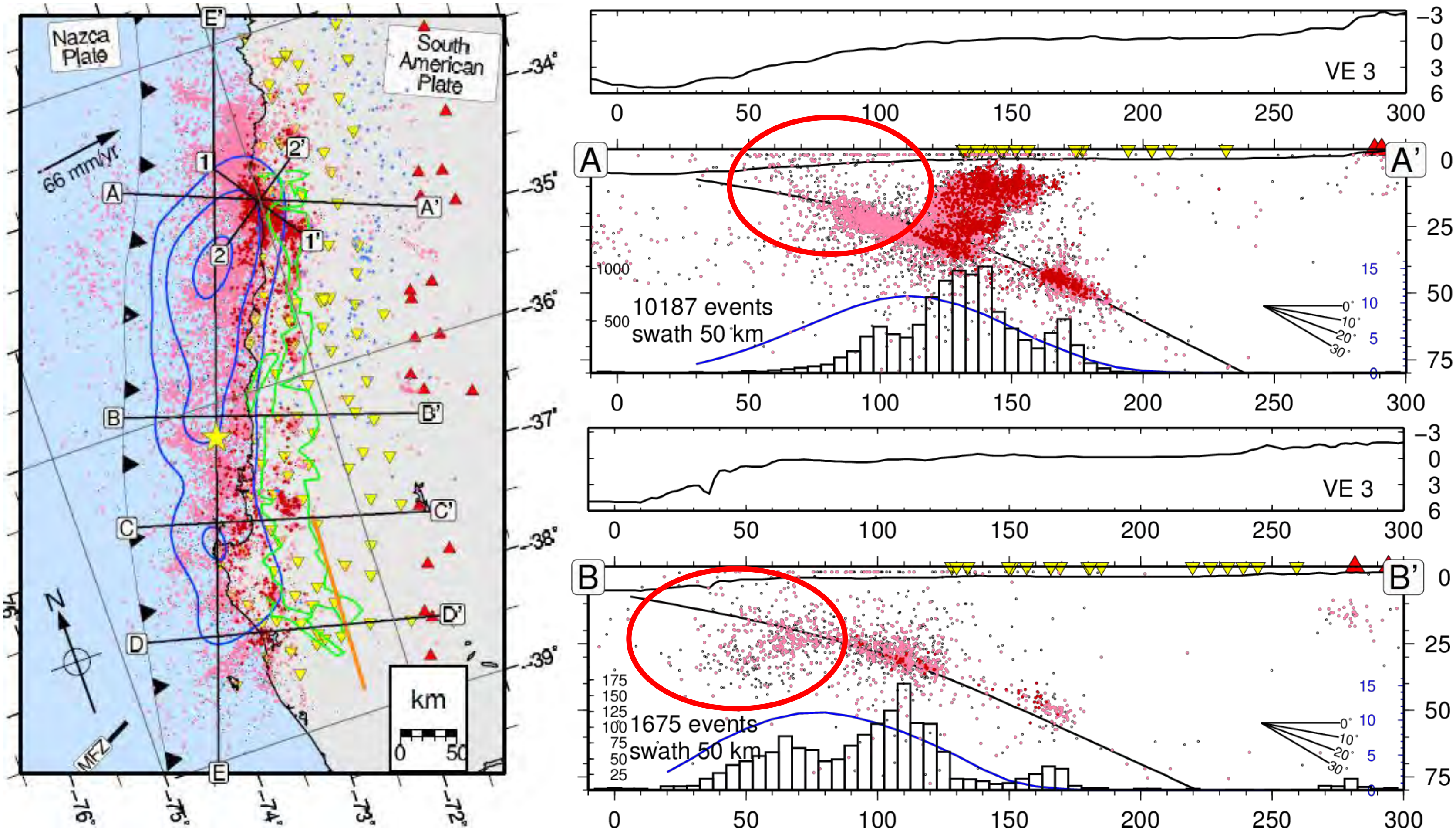
Nosov et al. (Doklady Earth Sci 2015)

Tsunami early warning summary

- Focus on short term warning
- Repeater spacing of ~50 km should be adequate even for high stress drop sources with steep dip, which might only have a relatively small rupture zone
- Benefit from high sampling rate allowing separation of tsunami and seismic signal
- Need to ensure cable not disrupted during earthquake

Local earthquake monitoring

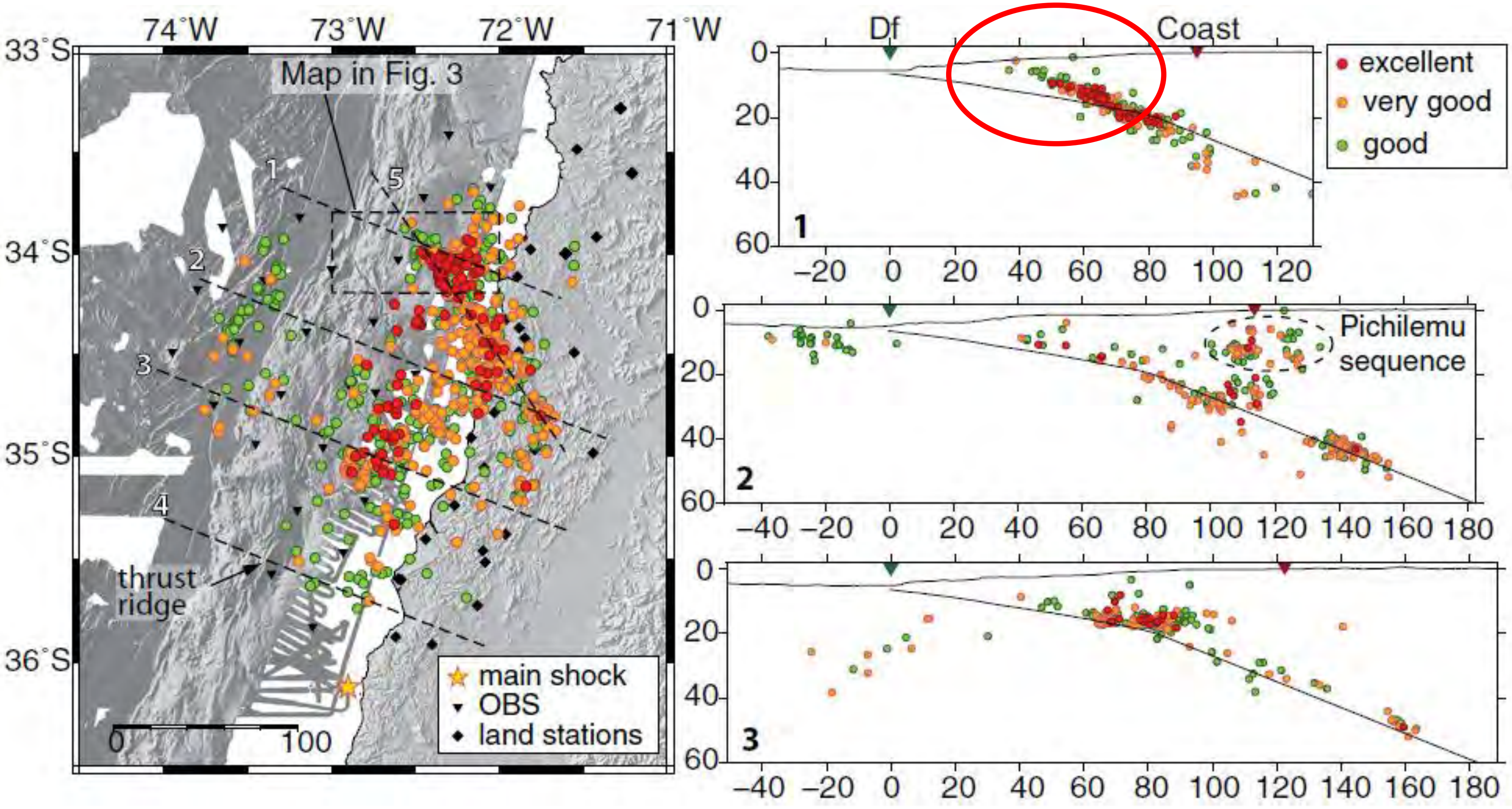
Chile 2010 aftershocks (land stations)



Seismicity defines plate interface and crustal seismicity below land but becomes diffuse below the forearc

Lange et al (GJI 2012)

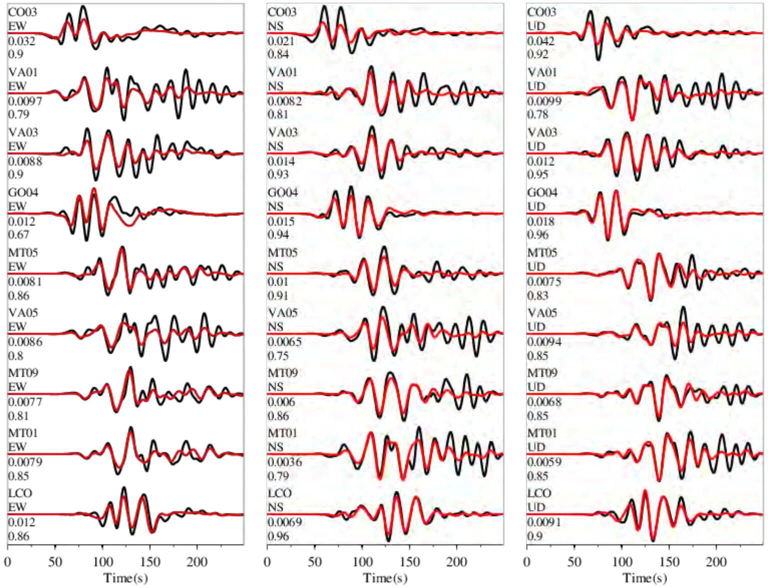
Chile 2010 aftershocks with OBS

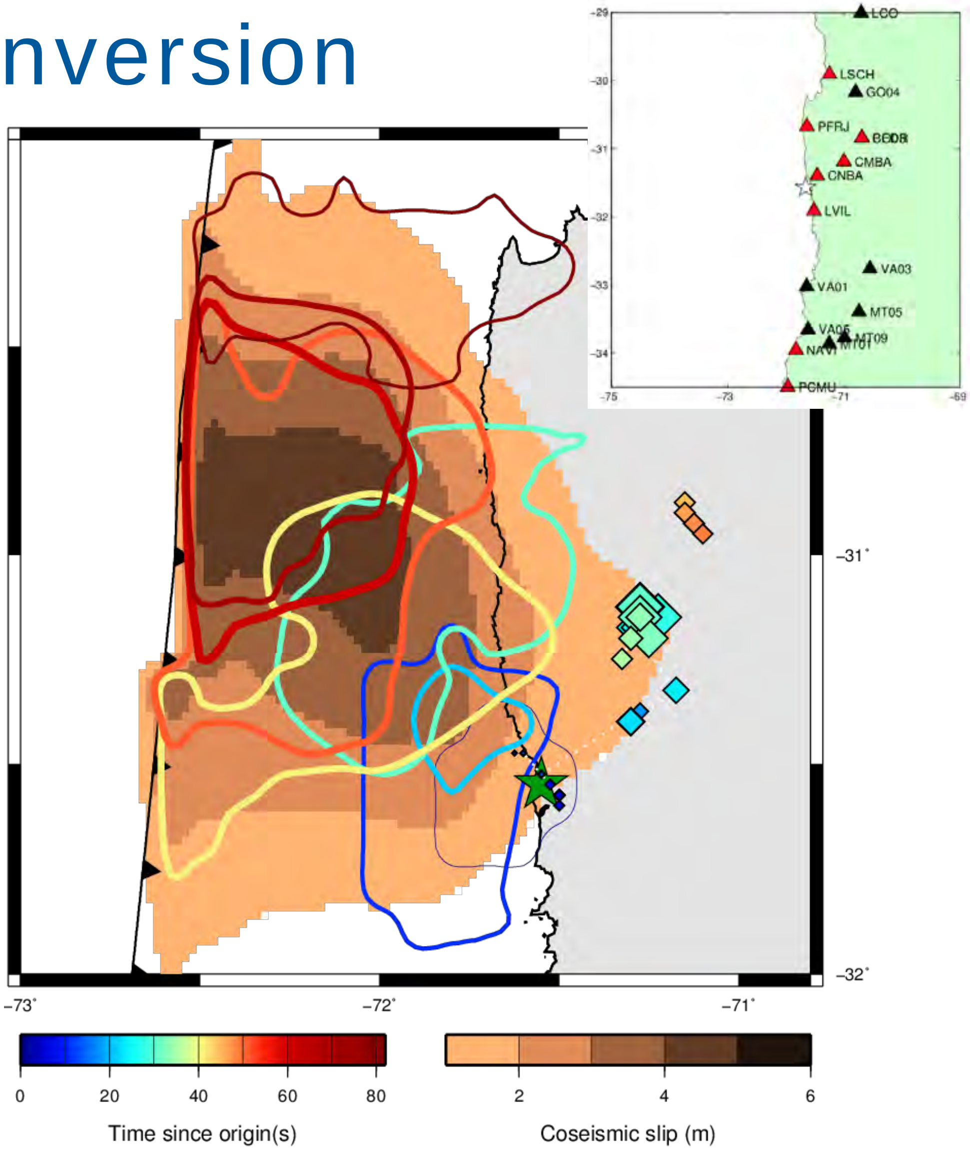


Seismically active splay fault can be clearly identified => steeper dip potentially enhances tsunami if activated during main shock

Lieser et al (Geology 2014)

Central Chile 2014 (Mw8.2): kinematic source inversion

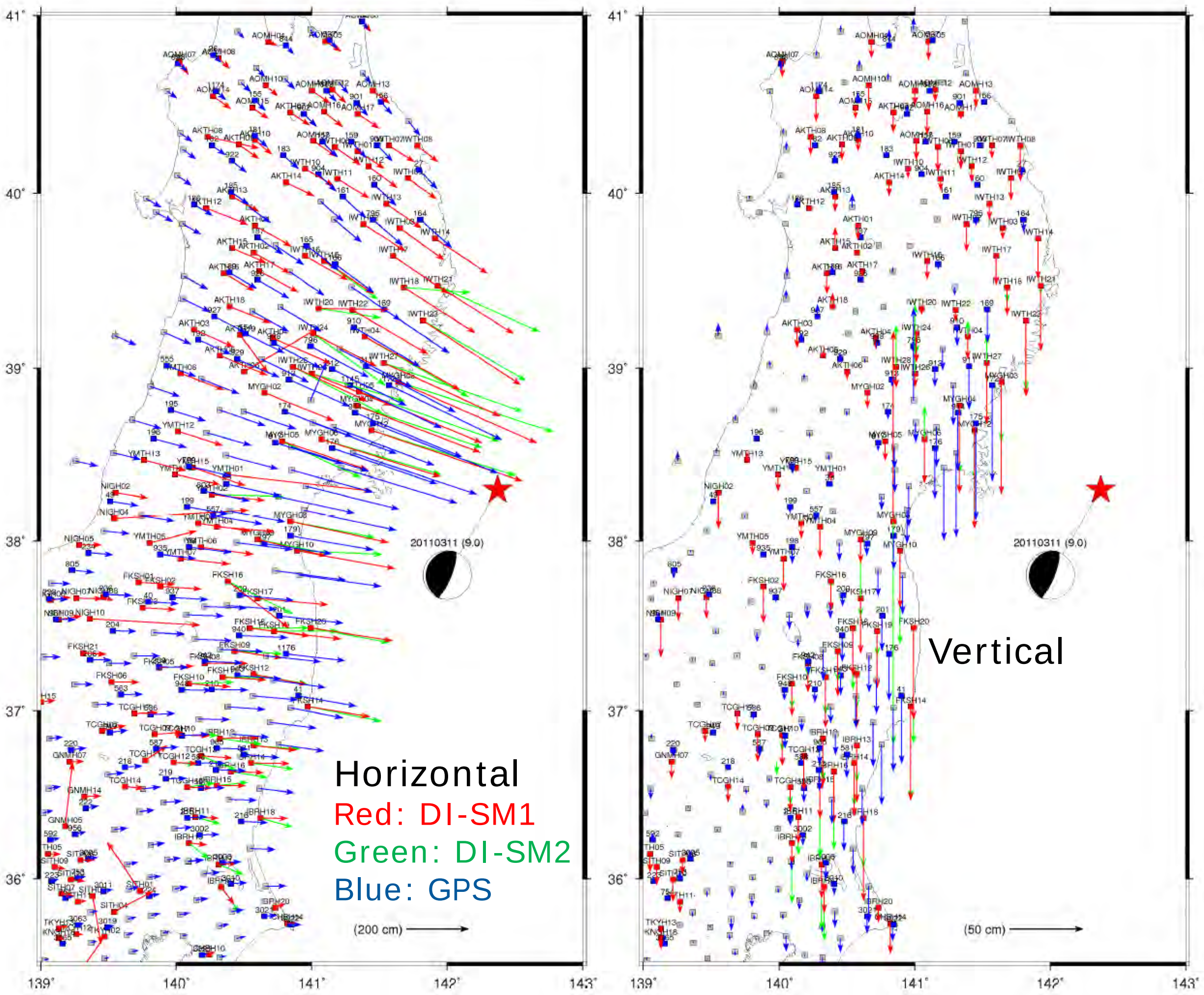




- Reconstruction of rupture evolution requires good azimuthal coverage
- Detection and period measurement for earthquake early warning

Tilmann et al. (GRL 2016), R. Wang, Y. Zhang (pers. Comm.)

Displacement from acceleration



Obtain static displacement through double integration of accelerometer records

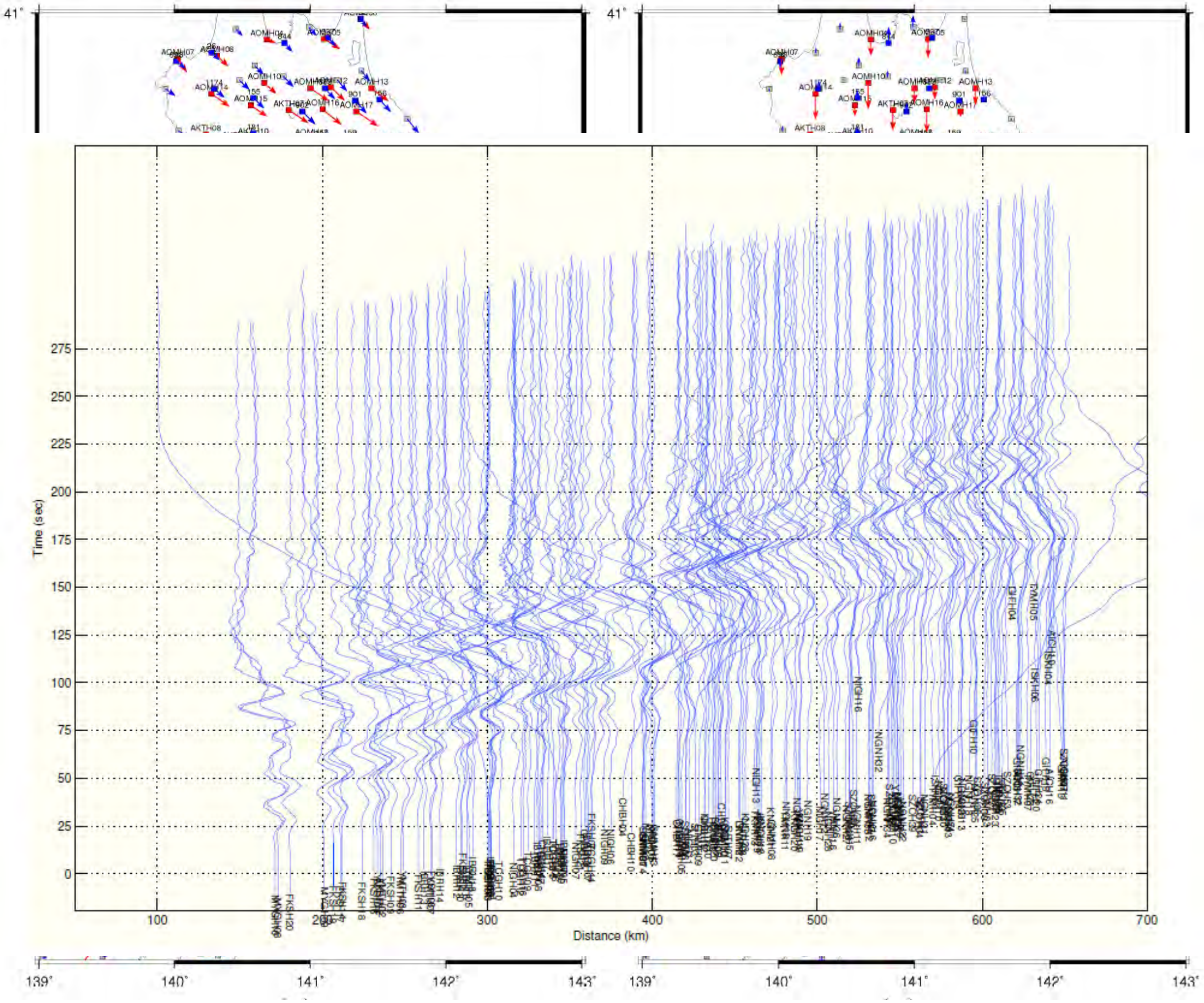
(after correcting for accelerometer drift)

Would be most informative on outer forearc

(of course this puts cable in danger in case of major earthquake)

Muzli Ph thesis (2012)

Displacement from acceleration



Obtain static displacement through double integration of accelerometer records

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Muzli Ph thesis (2012)

Local earthquake

Background seismicity and aftershocks

- Accelerometers less sensitive than seismometers but if coupling similar to land-based accelerometer, events down to magnitude 3 should be recordable across the forearc (range ~100 km)
- Pressure sensors provide complementary recordings of P waves if sampled at sufficiently high freq (> 20 Hz)

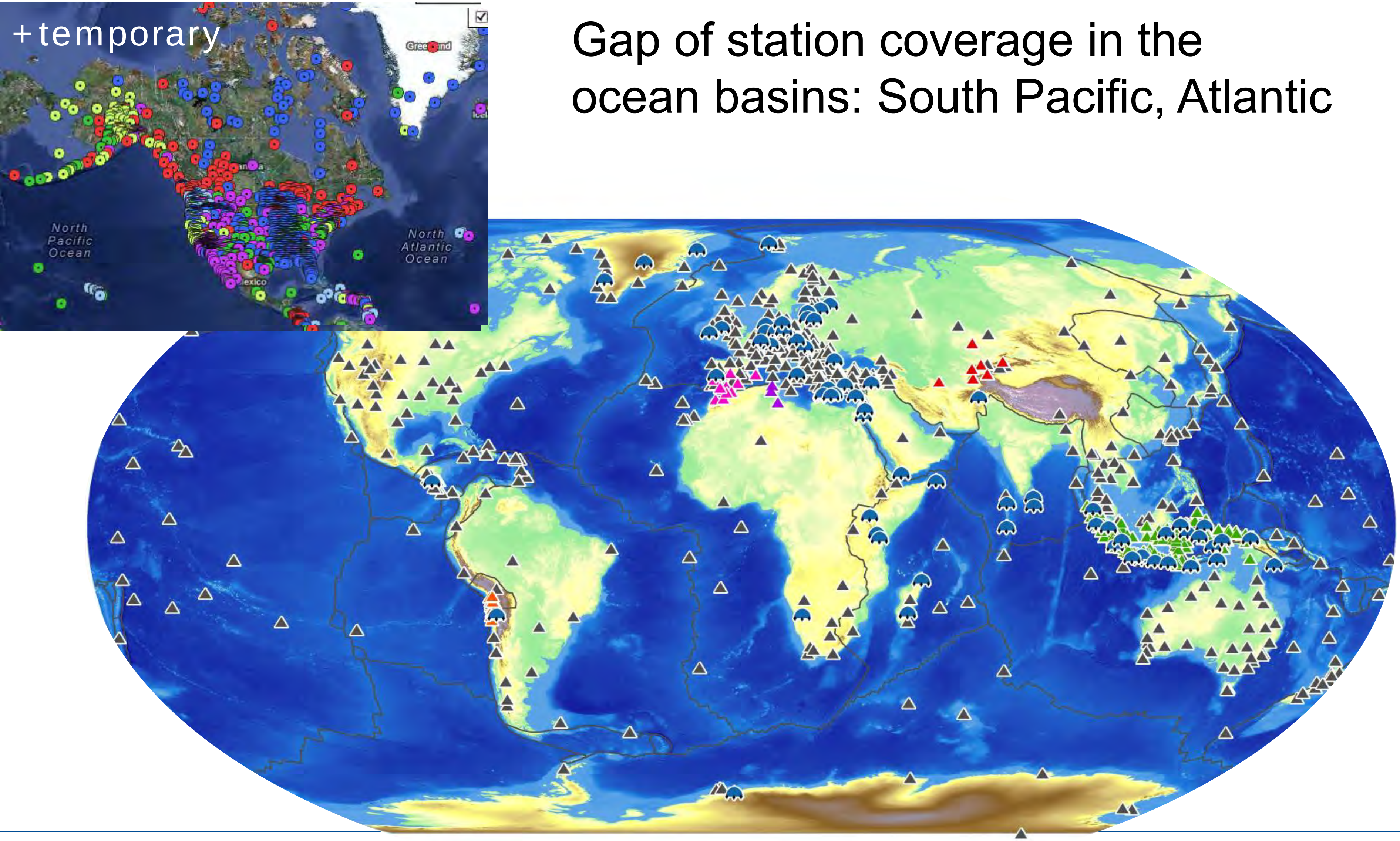
Large earthquakes

- Strong motion data helps to constrain shallow slip kinematics + doubly integrated acceleration gives estimate of static offset
  - Science targets: Frictional property variation along megathrust, splay fault activations
  - Early warning targets: tsunami generation potential
- Potential to increase earthquake early warning times for megathrust earthquakes (cf existing cable networks)

Global earthquake monitoring

Global permanent station coverage

Gap of station coverage in the ocean basins: South Pacific, Atlantic



Only open stations accessible through IRIS or EIDA listed (esp. South America but also Africa has additional stations)

Example Science targets for global network

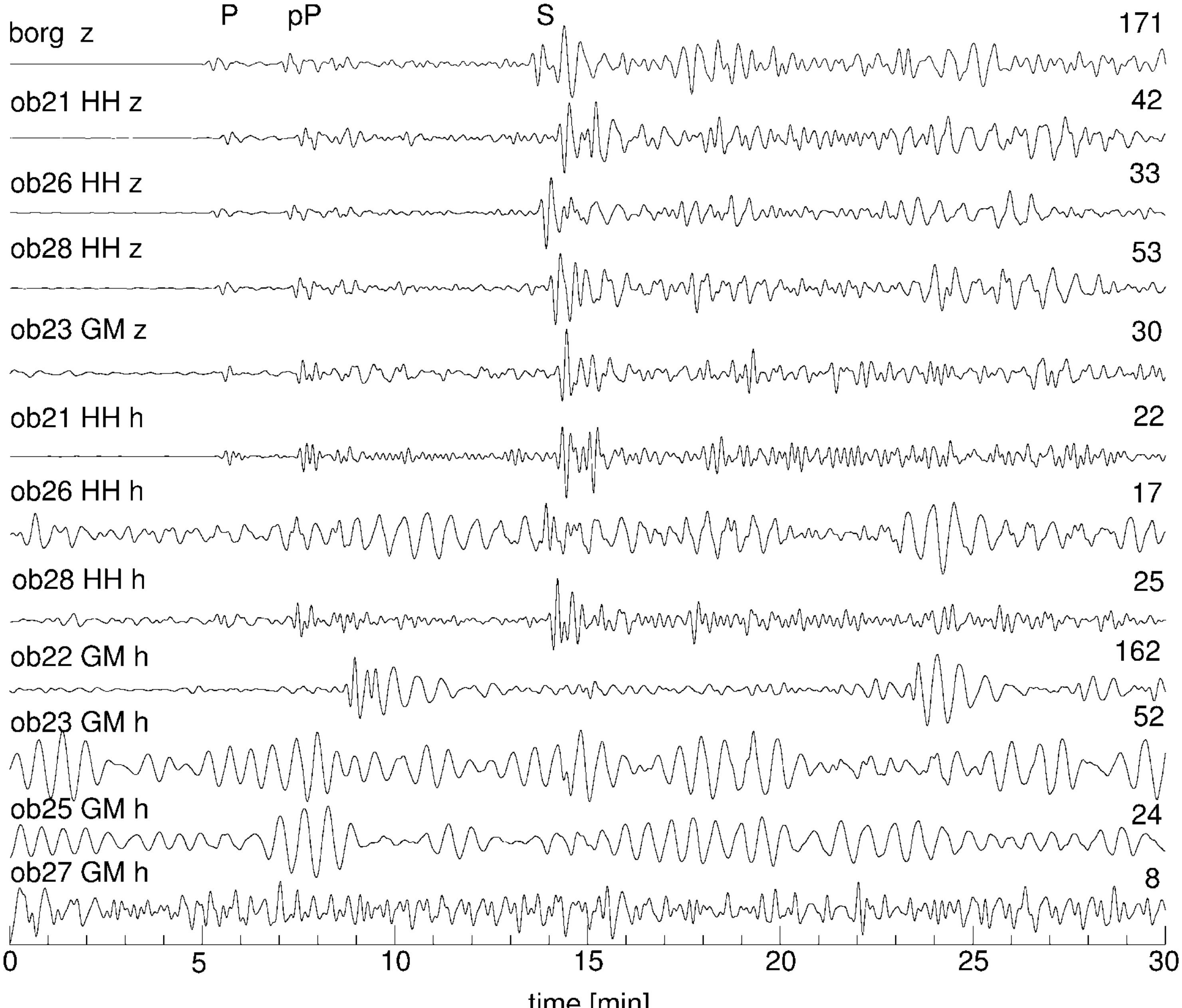
Upper mantle

- Understand the role of different scales of convection in maintaining
- Understand geodynamic sources for minor volcanic activity visible in isolated seamounts (mini-hotspots; chem spots?)

Deep Earth

- Even out coverage for mapping D'' (thin layer above the Earth's core), representing phase change and/or 'slab grave yard'

North Atlantic OBS network



Pressure and broadband seismometers

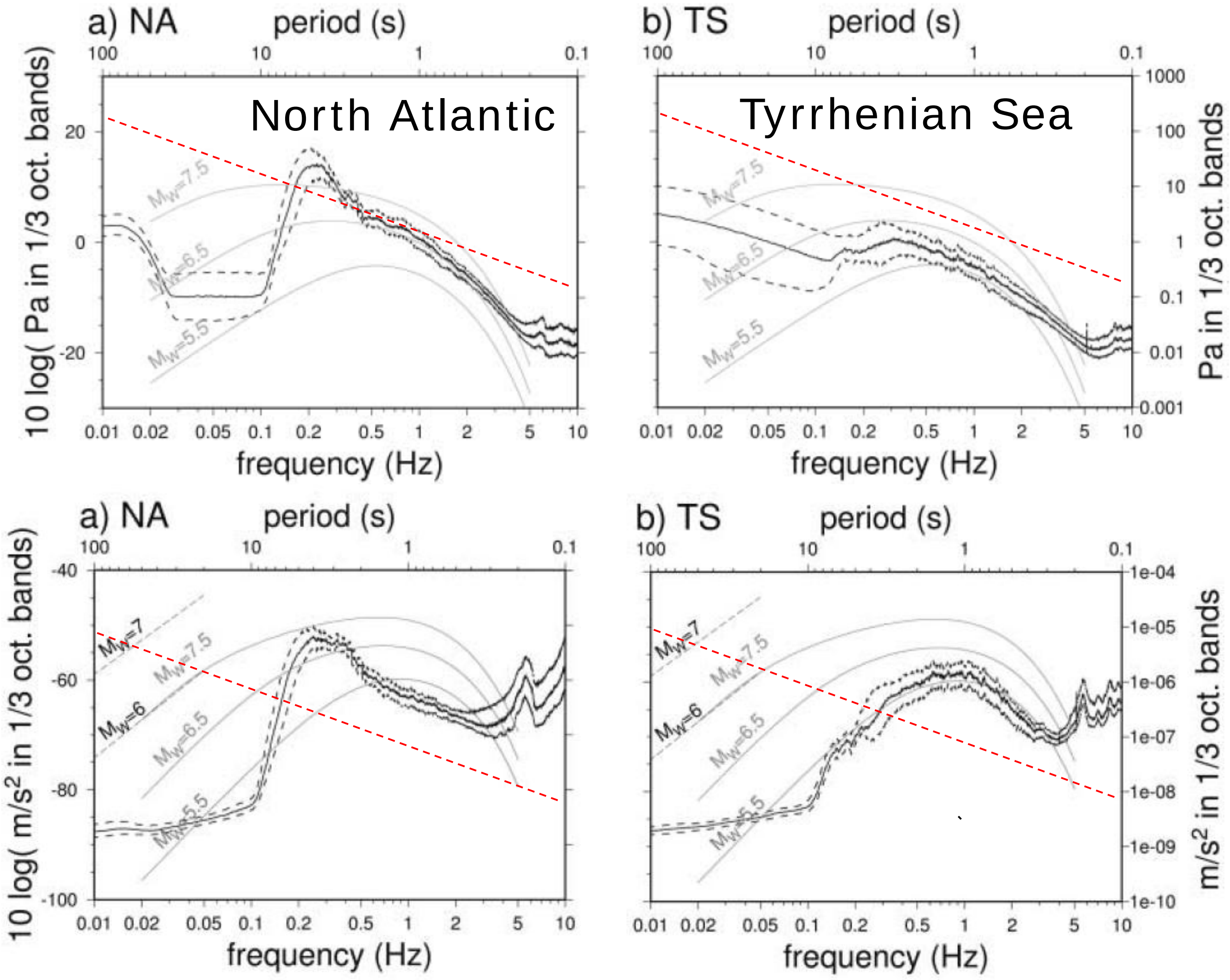
Earthquake Mw7.3 Kamchatka

Dahm et al (2006)

Teleseismic body waves

Examples based on free-fall instrumentation, expected signal levels for P wave arrivals.

Rayleigh surface waves well recorded on pressure records at 15-60s



Pressure

Predicted curves for events at 70° epicentral distance (~7800 km)

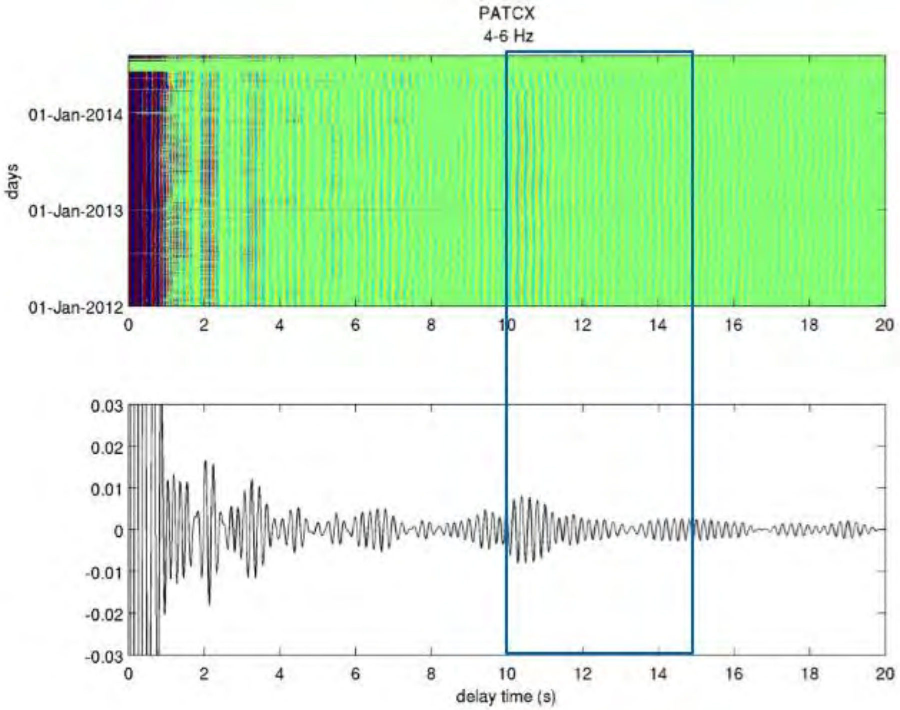
Acceleration

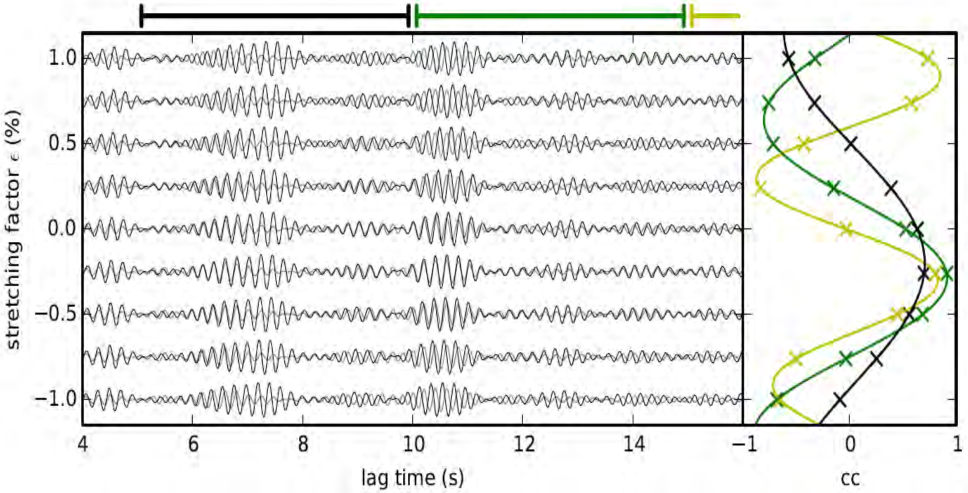
Recommended noise floor in SMART accelerometer (Lentz and Phibbs, 2012)

Dahm et al (BSSA 2006)

Local site monitoring

Local site monitoring - method





Time window: 10-15s

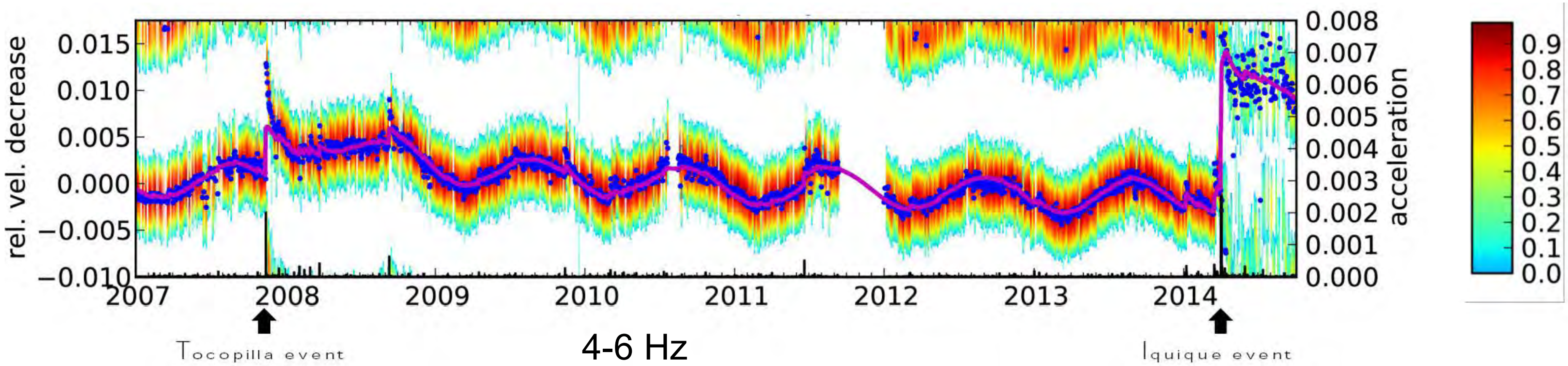
Approach:

1. Calculate daily average cross-correlations
2. Compare codas and bring in alignement by stretching
3. Stretching factor = local %change in velocity

NB: Examples are for land seismometers (not OB accelerometers)

Gassenmeier et al. (GJI 2016), Richter et al. (GJI 2014)

Local site monitoring



- Seasonal variations (~0.4%), probably due to thermal stressing
- Earthquakes cause a pronounced velocity drop (softening) of up to ~2-3% for large earthquakes (e.g. Tocopilla PGA 0.2 m/s^2), followed by exponential or quasi-logarithmic recovery
- Response also found for smaller earthquakes, background shaking, and strongly dependent on site conditions

NB: Examples are for land seismometers (not OB accelerometers)

Gassenmeier et al. (GJI 2016), Richter et al. (GJI 2014)

Local site monitoring – correlation with landslides

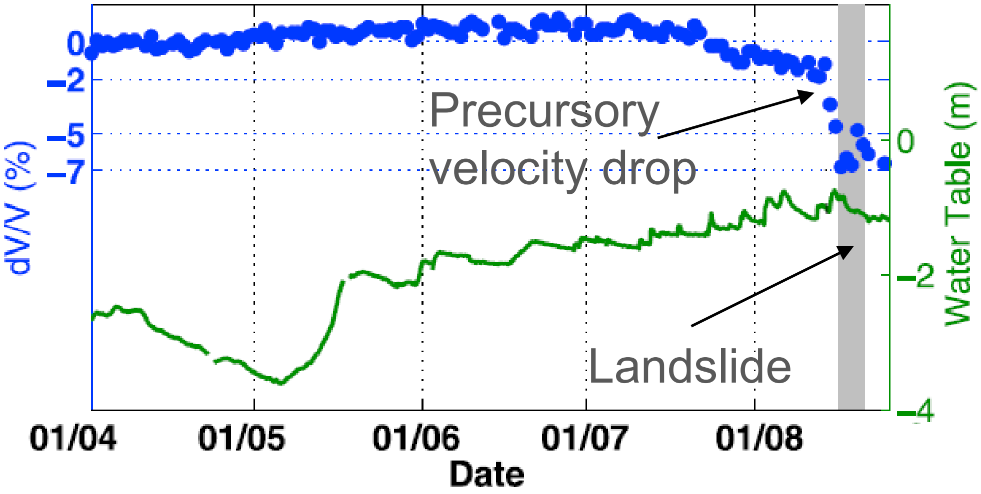


Figure removed as paper under review and only released for oral presentation

Mainsant et al (JGR, 2012):

- Monitoring of clayey landslide in Switzerland
- Velocity drop prior to landslide activation

O. Marc (pers. comm.):

- Enhanced landslide activity after EQs in Japan
- Recovery time scale for landslide activity and vel. changes identical within error

=> Approach needs to be tested in marine environment

Data management in seismology

- **Miniseed**: Established flexible data format for acceleration and pressure time series
- Existing central (**IRIS-DMC**) and federated data centres (**EIDA** – European Integrated Data Archive) able to serve archived and real-time data, and provide long-term safe storage.
- Open data preferred but protocols and technical solutions for delivering embargoed data already in place
- Real-time delivery through **seedlink** protocol
- Typical latency times for real-time data delivery:

Sampling rate (Hz)	Latency (s)
20	14
100	~2

- => Essentially instantaneous for tsunami warning. For earthquake early warning sampling rates ~100 Hz preferred

Summary and siting considerations

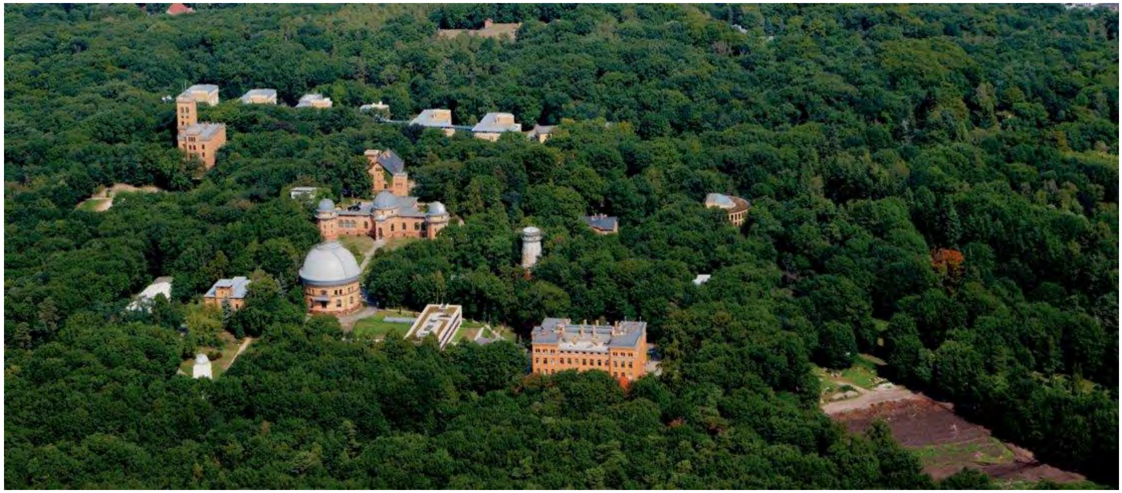
- Optimise expected signal levels and information content
- Minimise risk of failure due to surface deformation / mass flow in major event (where applicable)
- No political or legal considerations taken into account
- Except for global earthquake need to deploy at convergent margin

Summary and siting considerations

Target	Siting 1st preference	Rationale	Min Timing accuracy
Tsunami early warning	Just seaward of trench	Minimise travel time, minimise chance of coseismic failure	1 min
Earthquake early warning	Forearc	Need to be close to likely source (seismogenic megathrust)	A few s
Large earthquake physics	Forearc or seaward of trench	Use strong motion both for kinematic and static inversions	1 s
Local earthquake studies	Forearc and/or seaward of trench	Observe tectonics, faults, mechanical structure	0.1 s
Site monitoring	Forearc slope	Site with soft material able to generate mass failures	Autocorrel: rel. timing 0.01 s, cross-correl: abs timing 0.01 s or better
Global EQ tomography	Abyssal plain	Transoceanic cables to fill gaps in global coverage	0.1 s (Body waves), 1 s (surface waves)

Planned workshop SMART Cables for Earthquake and Tsunami Science and Early Warning

- Date TBA (November?), Venue: Potsdam/Berlin, 2-3 day meeting



- Quantify with model and scenario studies the benefits for early warning and research
- Identify a potential target regions where a first SMART cable deployment would be expected to give the most benefit
- Create further momentum for this initiative internationally and explore avenues of funding