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AND THE PACIFIC TSUNAMI WARNING CENTER (PTWC) ENHANCED PRODUCTS
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Tsunami Travel Time Forecasting – Methods, Limitations, Uncertainty, and Sensitivities

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USAID
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Methods of Tsunami Travel Time (TTT) Computation

For tsunami warning purposes, it is important to know the expected/estimated tsunami arrival times (ETAs), which are included in PTWC messages for threat messages.

Method 1: Huygens Principle ("optical method"):

Wave travels from point A to Point B takes the path that requires the least amount of time.

TTT can be computed in real time (PTWC's approach) or from a pre-computed database (e.g., using each tide station as a point source).

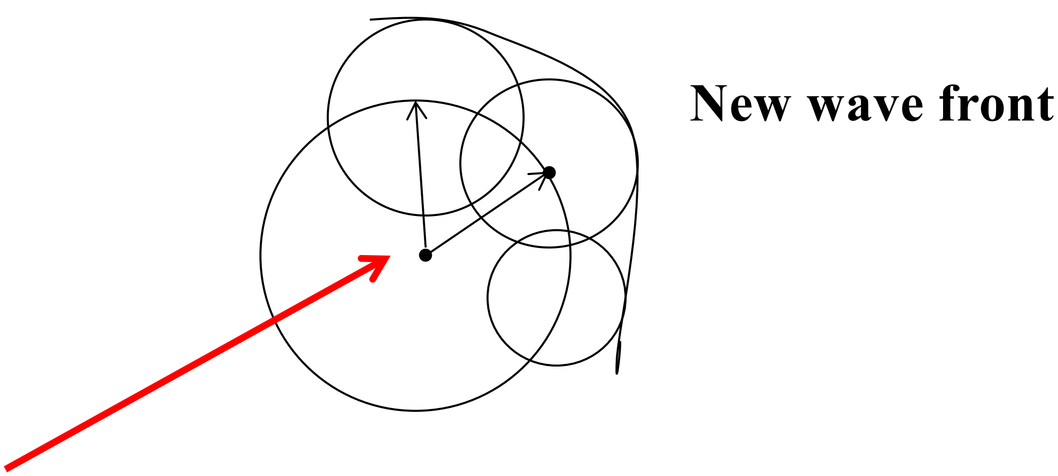
Method 2: Tsunami forecast models (real-time or database based)

ETA is defined as some relative amplitude threshold (e.g., time when wave reaches 5% of the maximum wave amplitude).

Method 1: Huygens Principle ("optical method"):

Every point on the wave front of a point source is also a point source.

tsunami travel time $\frac{dt}{dx}$=C, where C= $\sqrt{gh}$, (wave speed), h is water depth, and g is gravitational acceleration



Travel time from the epicenter to a coastal point: the shortest possible time of all possible wave paths from the epicenter to the coastal point.

GEOWARE TTT software by Paul Wessel

- Epicenter of the earthquake (EQ) is assumed to be the location of the initial point source. *If the epicenter of the earthquake is on land, the nearest ocean point is assumed to be the initial point source* (or searching for a nearest ocean point in deep water, e.g., 250 m).

- The estimated tsunami arrival times (ETA) listed in PTWC's bulletins are computed in real-time using the GEOWARE TTT (tsunami travel time) software http://www.geoware-online.com/tsunami.html) with the GEBCO 30-arc-second bathymetry (http://www.gebco.net

- For speed of computation, a lower resolution is usually used (such as at 10 arc-min.). The computation typically takes a few seconds at 10-min arc-min. resolution for the Pacific basin.

- If an EQ is inland or over very shallow water, an offshore point at water depth > 250 m will be used if it is within 5 degrees.

Reference: Wessel, P. (2009), Pure and Applied Geophysics

Limitations/Uncertainties of ETA computations

- If the bathymetry data is of poor quality, the travel time can be in error, especially in shallow water.

- Earthquake/Tsunami source is finite, not a point source, the actual tsunami arrival time could be sooner than computed (e.g., Sumatra 2004). Although finite source can be used in the TTT software, this option is currently not used at PTWC, as the point source approach works well most of the time, Even for a large earthquake.

- The actual tsunami arrival can also be earlier or later than the predicted. Recent research showed that elasticity of the seafloor and compressibility of seawater also affect tsunami speed (e.g., Tsai et al 2013, Watada et al. 2014, Wang 2015).

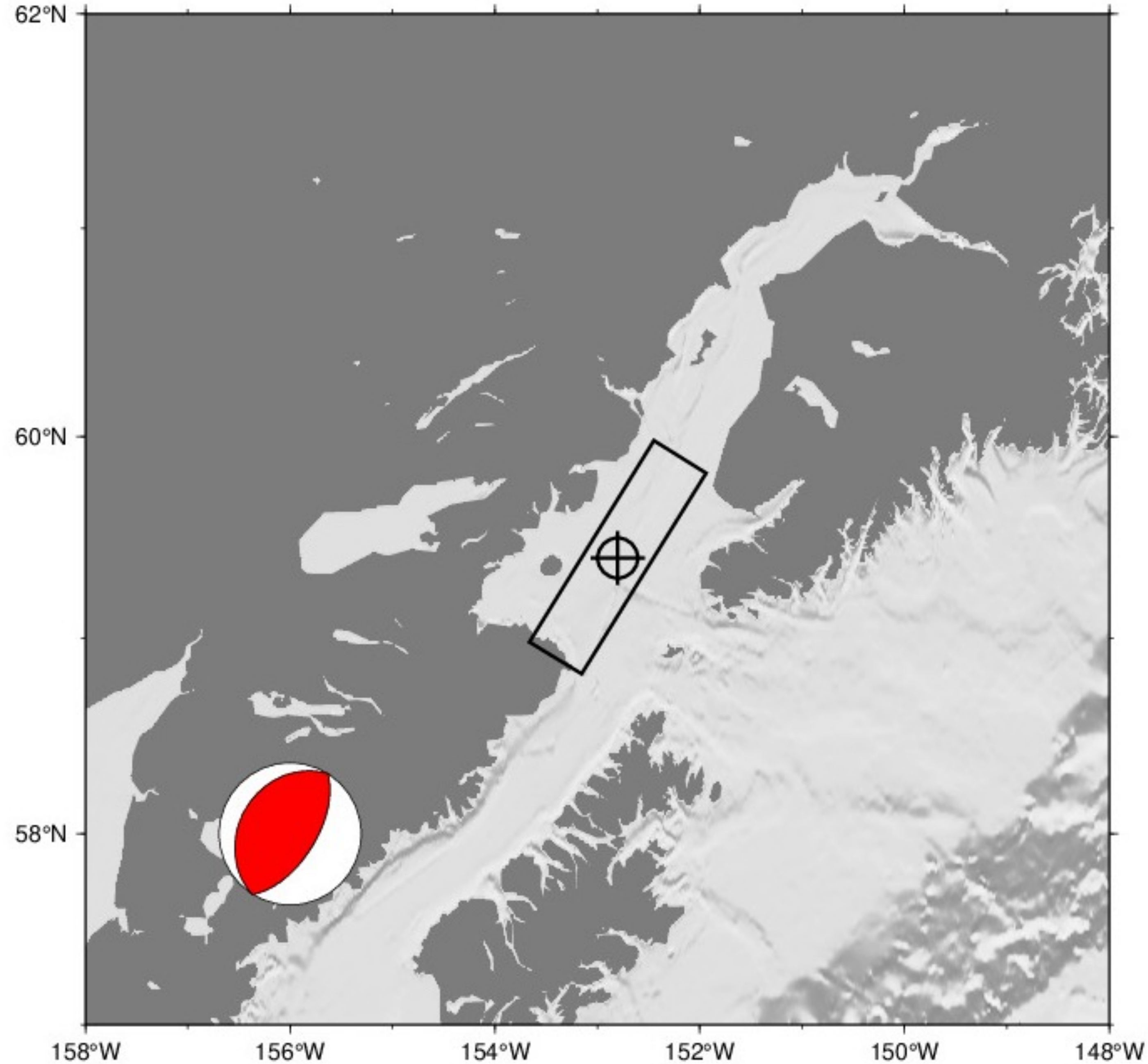
- Tsunami arrival time does not mean the time of maximum wave height. The actual maximum wave height can occur much later.

- Point source for ETA computation can result in very unrealistically long ETAs, because it will take a long time for waves to reach deep water. Very large EQs with finite fault area can cause instantatenous deformation of the seafloor over deeper water, thus ETAs will be sooner than the prediction using a point source.

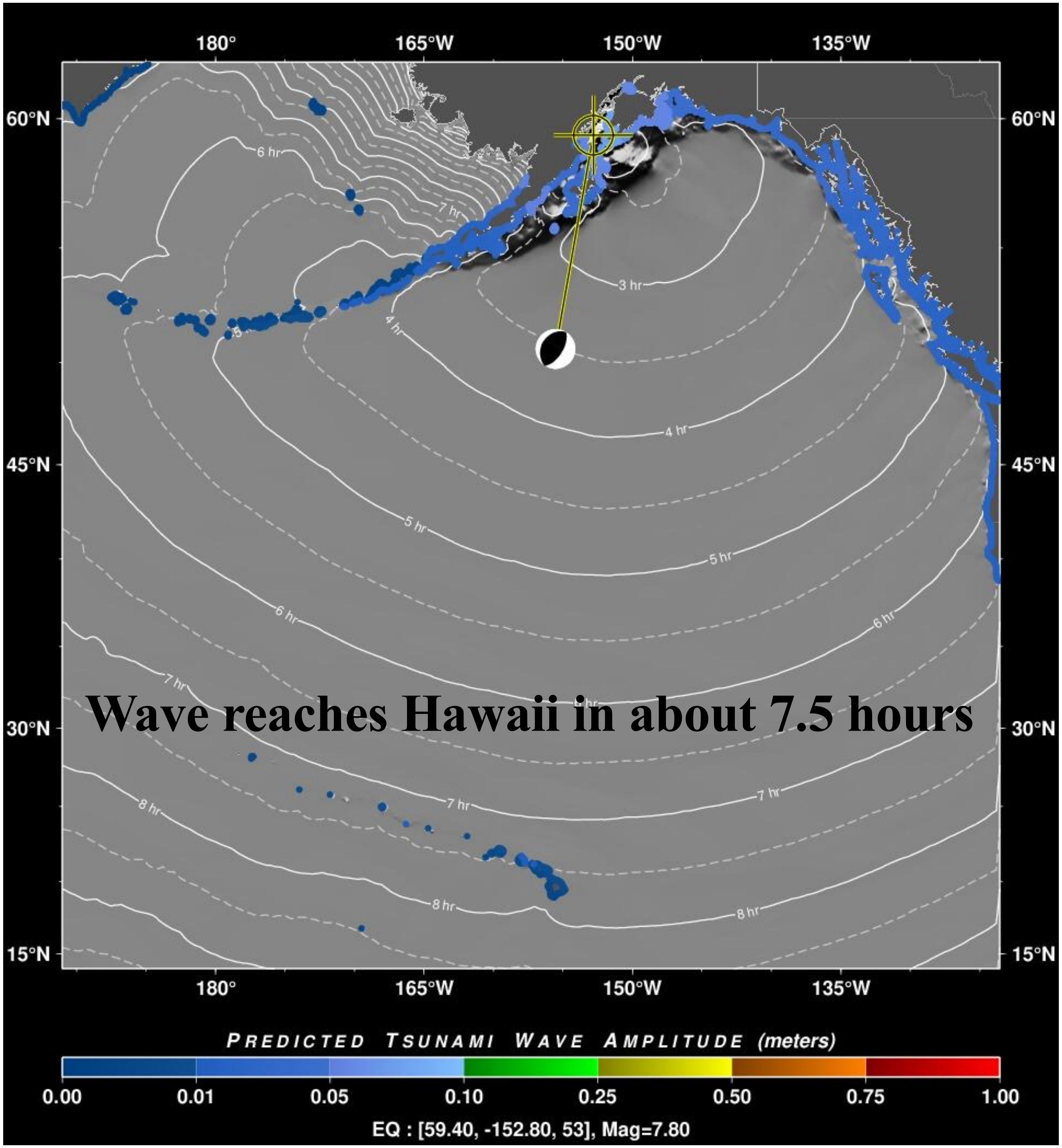
ETA Geoware TTT, line source

Epicenter: Cook Inlet, Alaska

y=59.40, x=-152.80, z=54 km, m=7.80, strike=212, dip=29, rake=90, L=131,W=39 (total L=131)



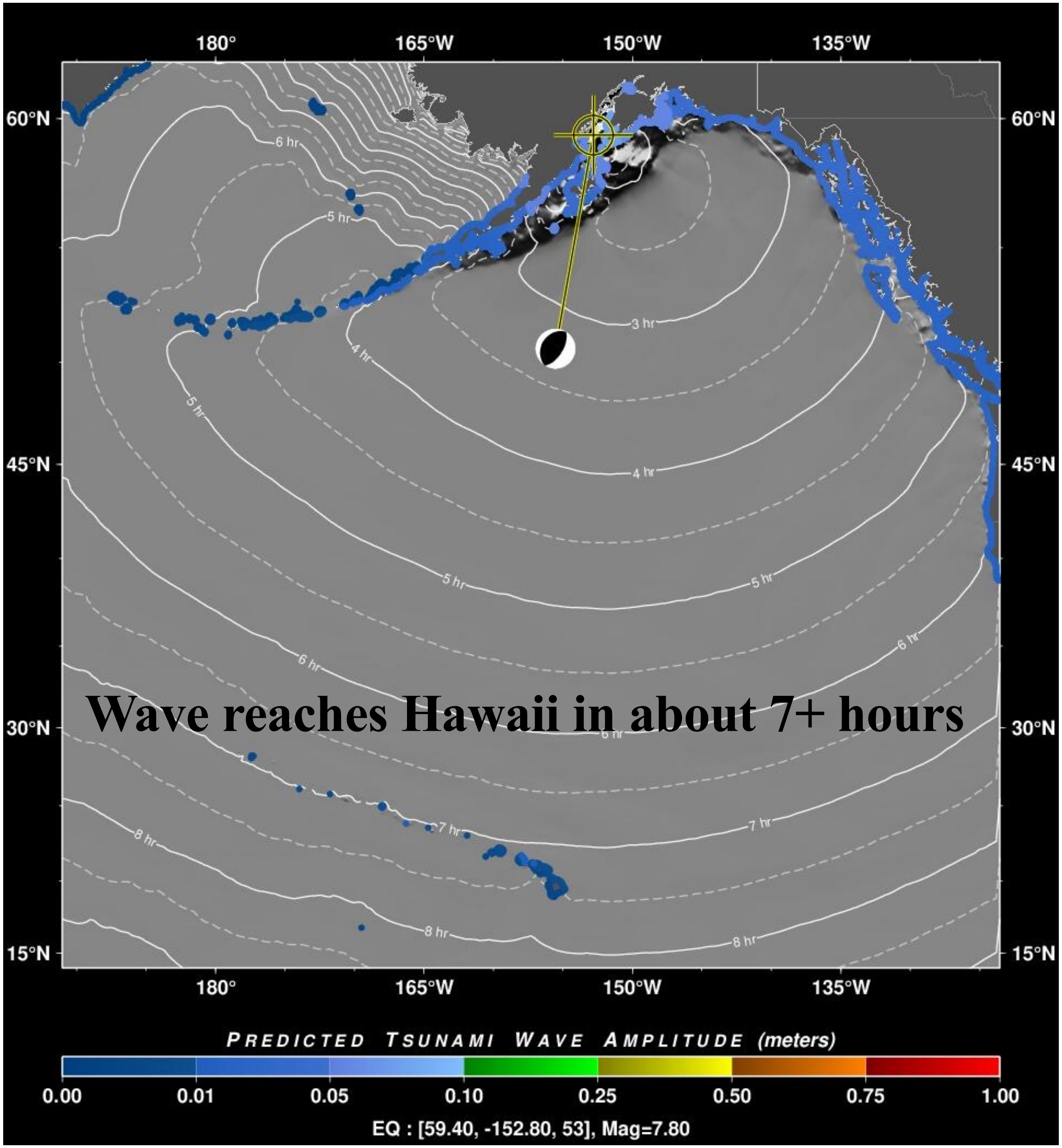
ETA Geoware TTT, point source



Epicenter:
Cook Inlet, Alaska

Tsunami Travel Times are not computed from RIFT but ETAs can be measured from the time series at give model grid points (tide stations).

ETA Geoware TTT, line source (using fault boundaries)



Epicenter:
Cook Inlet, Alaska

ETAs did not change much because the fault size is relative small for a M7.8 EQ, such that the entire fault is still under shallow water.

wave arrivals from RIFT agree with SIFT results for Hawaii, i.e., ETAs are about 5 hours.

Note that ETAs in PTWC enhanced product maps are from Geoware TTT calculation using point sources.

The ETAs in PTWC bulletins are also computed using point sources, but a nearest ocean point in deep water (>250 m, within 5 degrees) are used if the epicenter in shallower water or inland. So one should rely on ETAs in the PTWC bulletins, rather than the PTWC product maps.

In the future, we need to come up with a better method in computing ETAs in product maps (line/finite sources or model results).

ETA from tsunami models

Tsunami travel time can also be computed from tsunami forecast models (slower than the optical method if done in real-time).
This method usually works well for the deep ocean (DARTs).
Uncertainties still exist. Sometimes models can generate absurd tsunami travel times (e.g., intersecting travel time contours, later arrival contours inside closed contours of early arrivals—physically impossible).

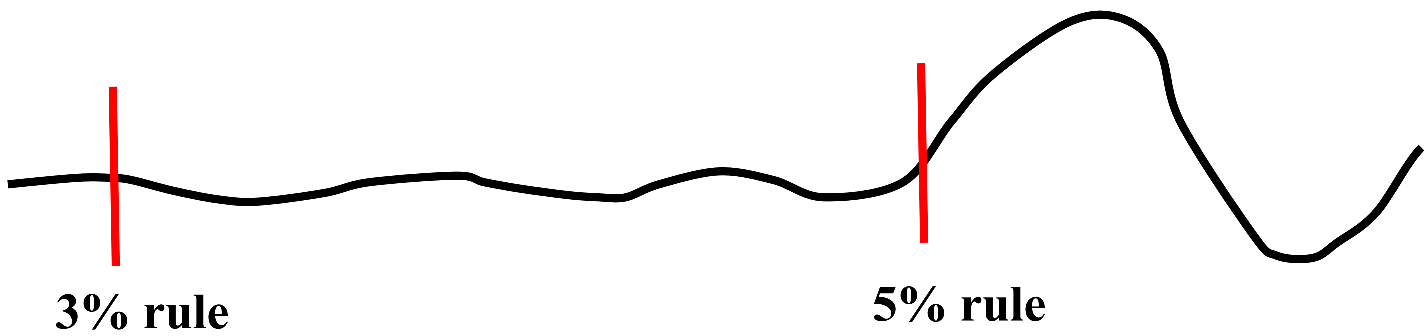
In theory, ETAs from tsunami models are more accurate than those from the TTT software/method. In practice, it has difficulties:

It is difficult to come up with a robust/consistent definition of tsunami arrival time from tsunami wave forms that apply to all situations.

Possible thresholds:
1. Time when waves reached a certain threshold, say 1 cm or 1 mm.
(bad practice, only works for large tsunamis).

2. Time when waves reached a certain % of the max wave amplitude, say 5%. The result might be sensitive to the threshold chosen.

ETAs might be sensitive to the definition

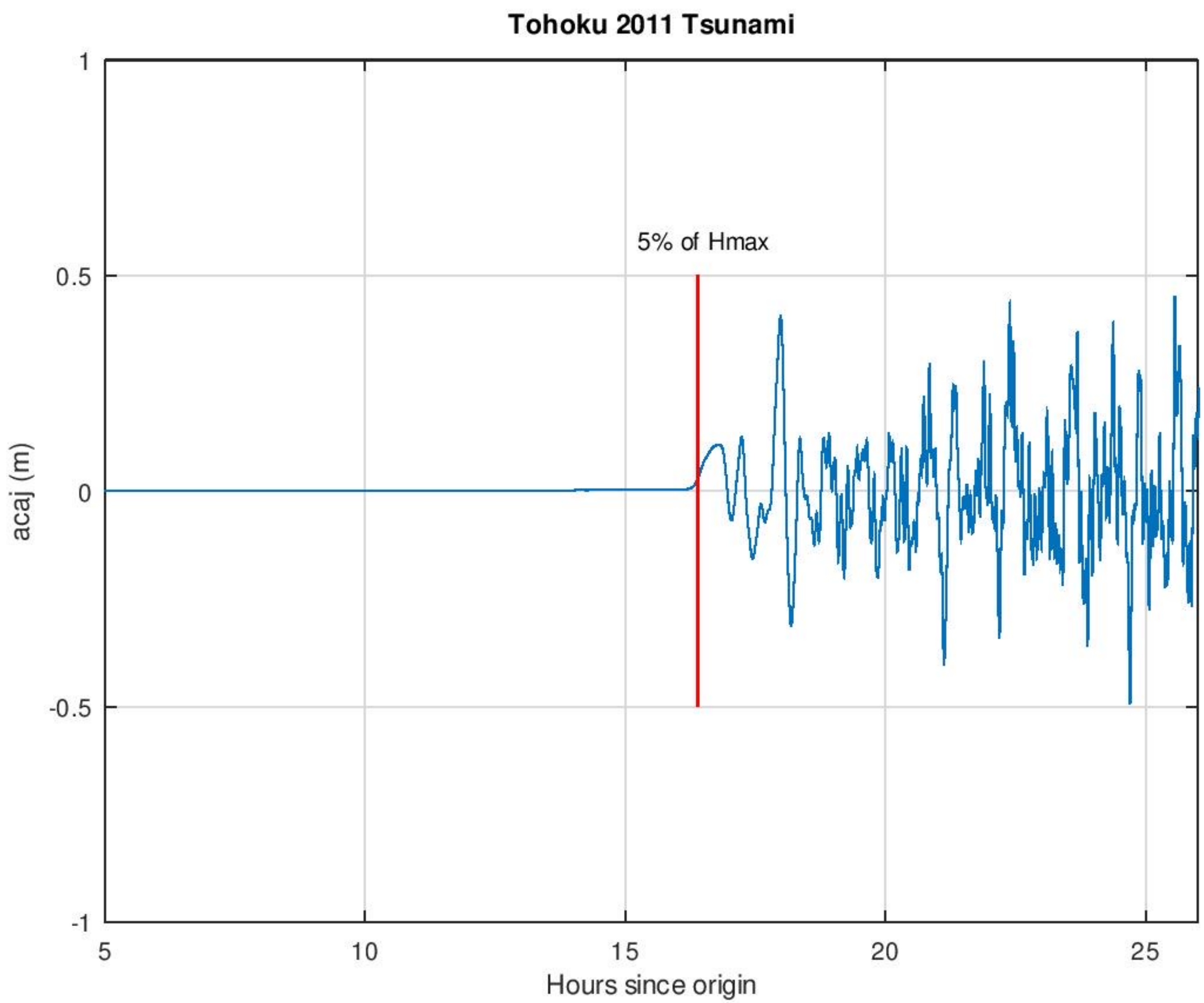


Difficult to apply such a method to observed data

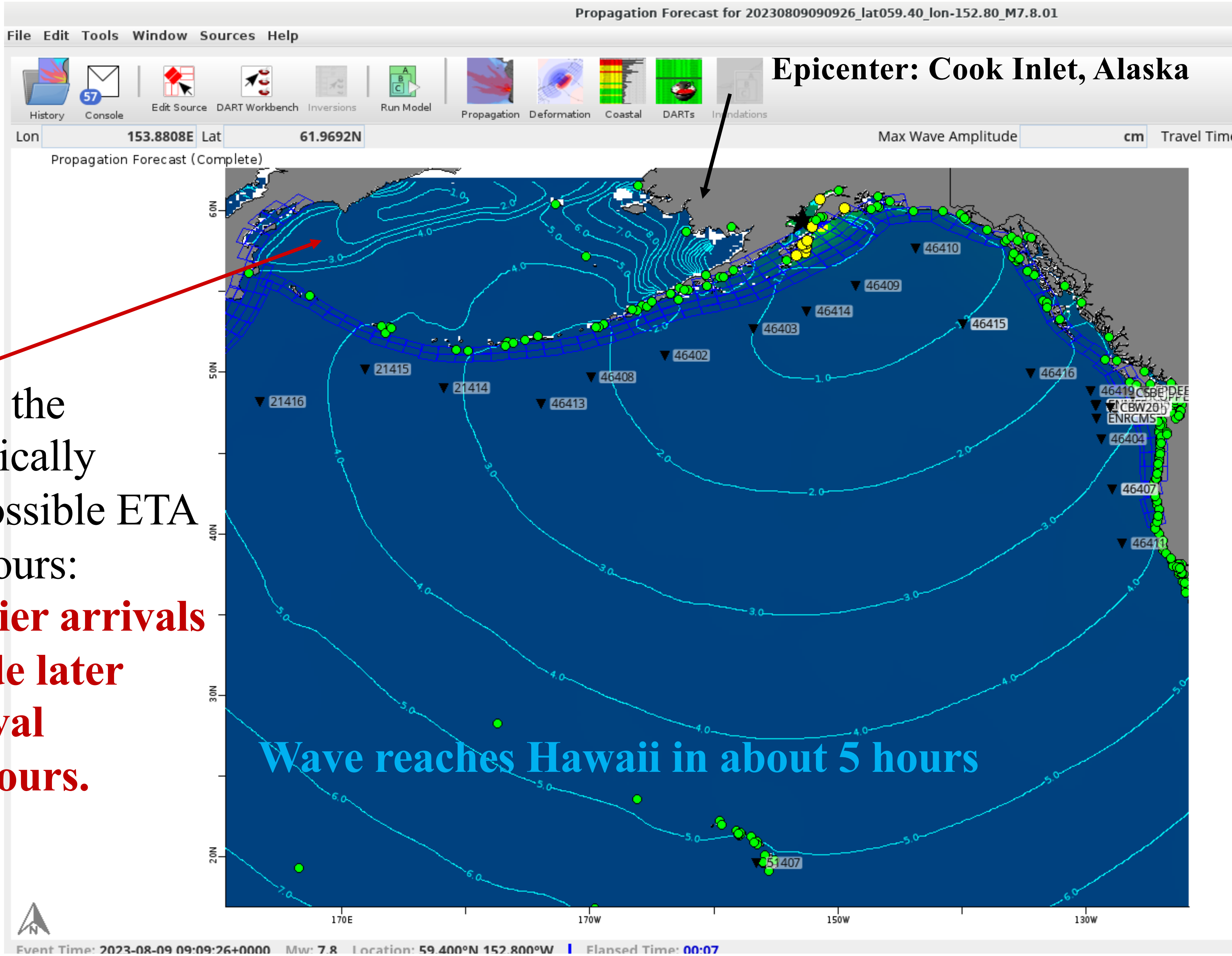
There can be unexpected be problems with this approach from models.

Measuring Tsunami Arrival Times

1. **From models: time at which wave amplitude reaches 5% of the max amp. (actual application is a bit more complex: initial deformation, etc.).**
   This method does not work well for observations!



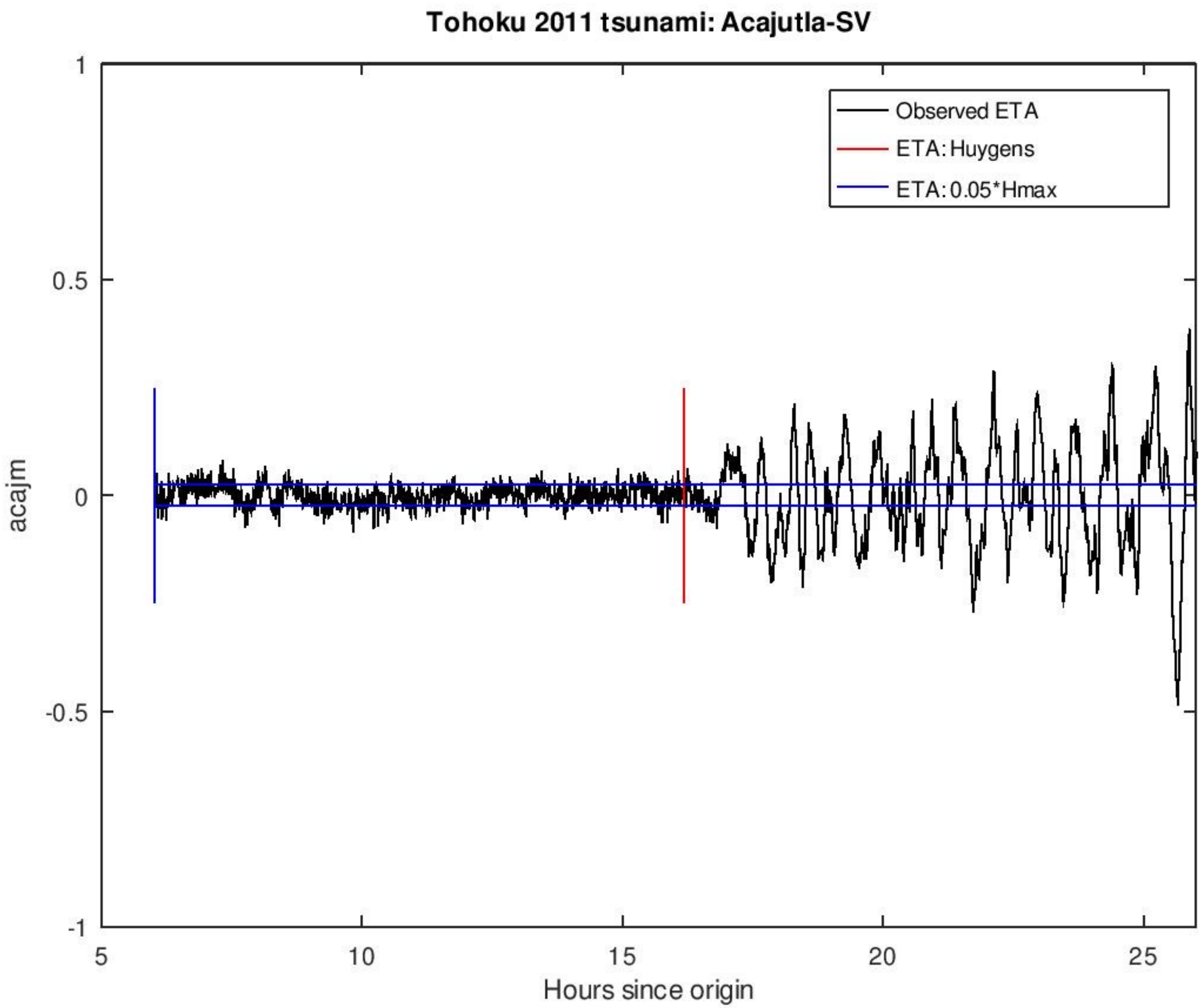
ETA from tsunami models (SIFT propagation database)



Note the physically impossible ETA contours:
Earlier arrivals inside later arrival contours.

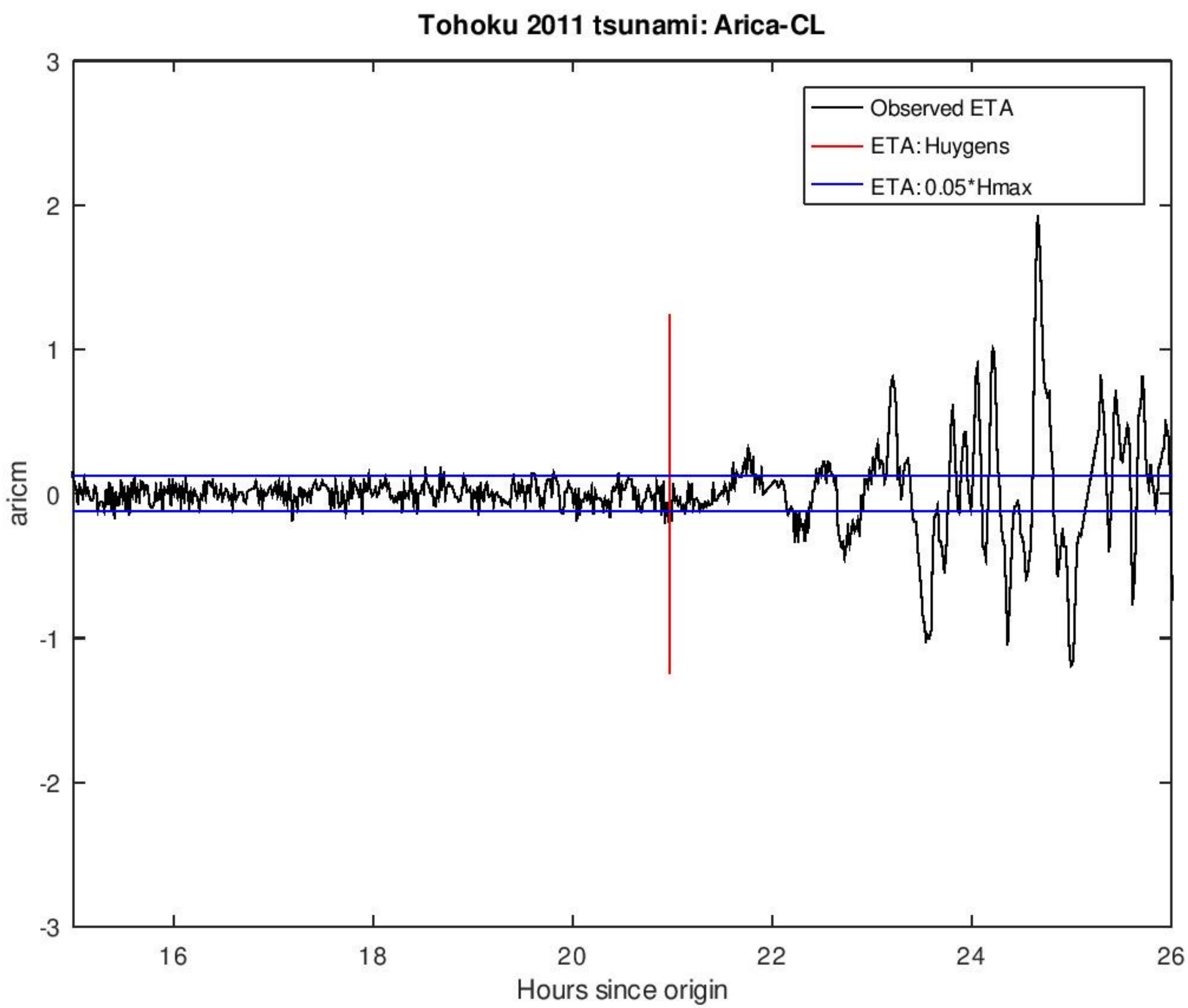
Measuring Tsunami Arrival Times

2. From observations: you know it when you see it (manual).



Measuring Tsunami Arrival Times:

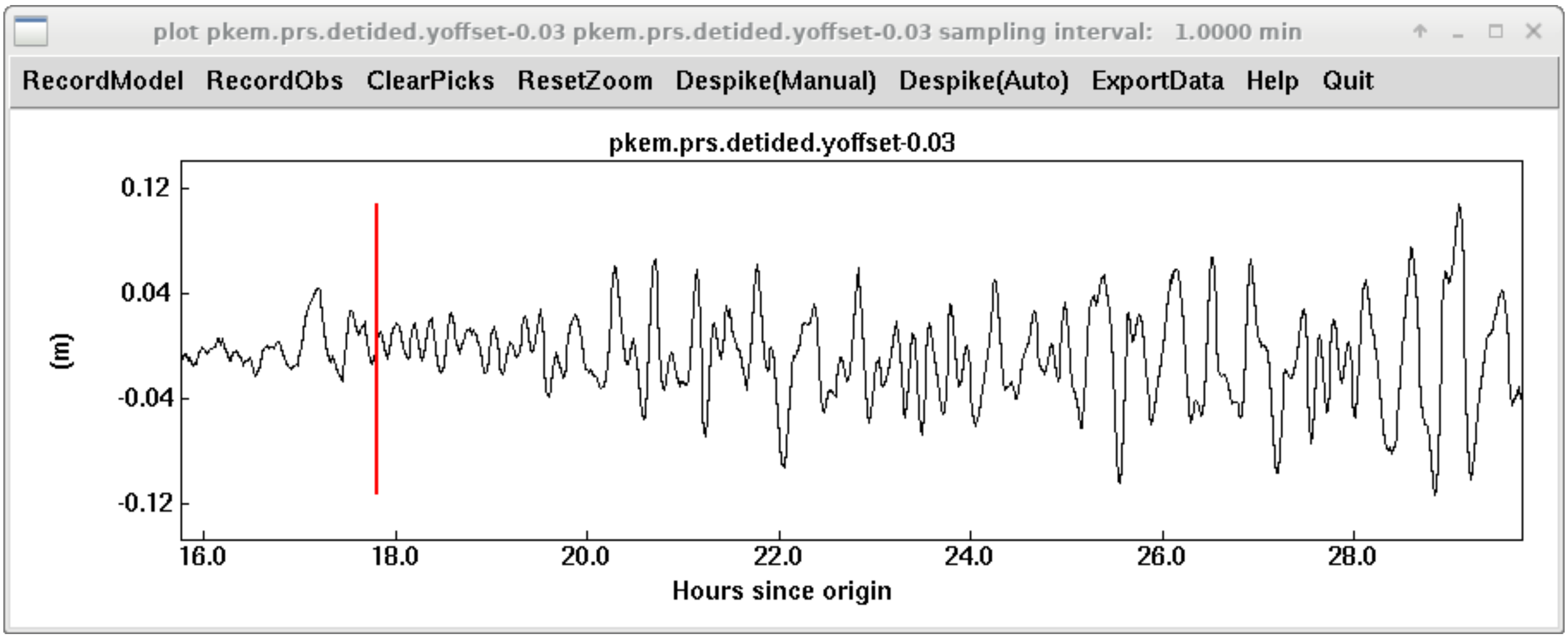
From observations: you know it when you see it, sort of.



Measuring Tsunami Arrival Times:

What you see can be deceiving. Where is the tsunami arrival time below?

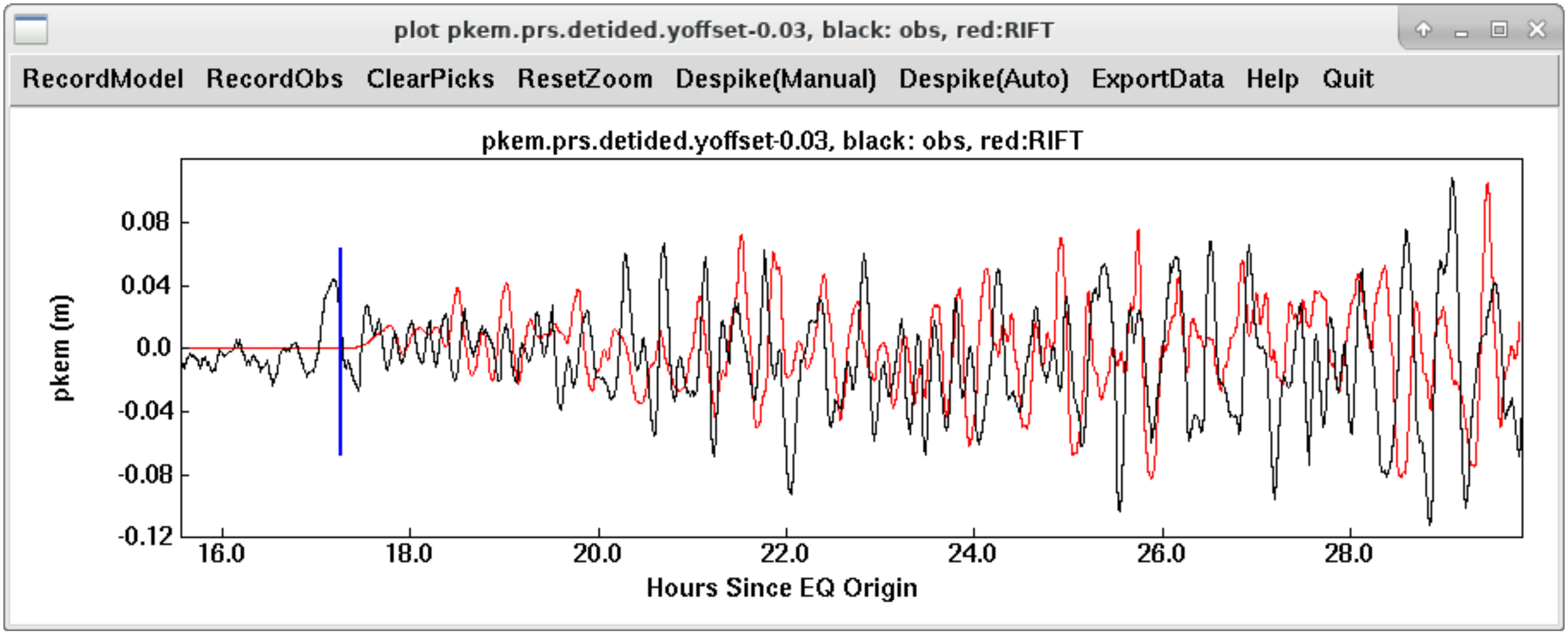
Chile 2014 M8.2 Tsunami. Red line: ETA from TTT software.



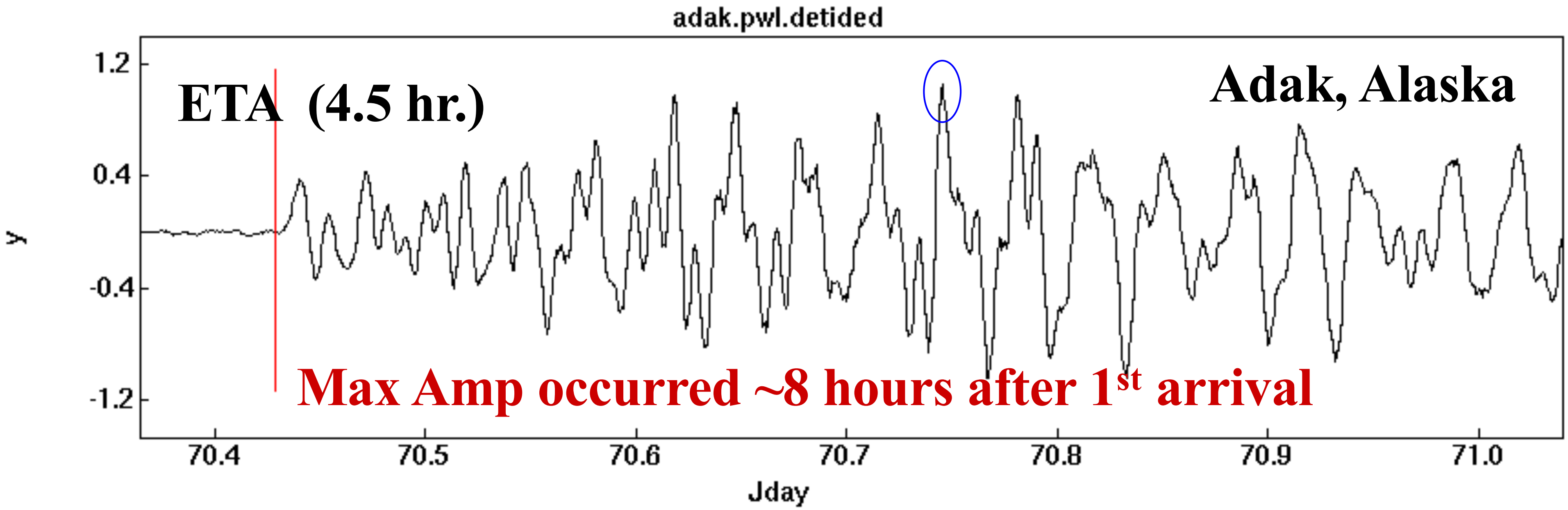
Measuring Tsunami Arrival Times:

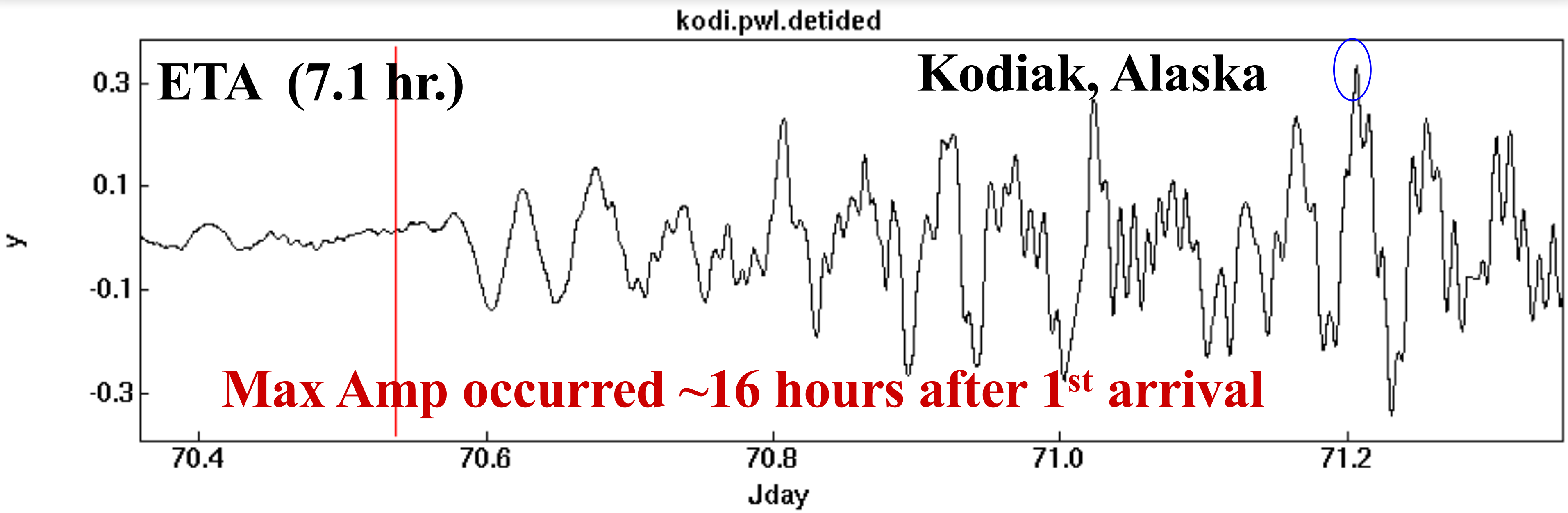
It is not always obvious when tsunami has arrived.

Chile 2014 M8.2 Tsunami.



2011 Tohoku Tsunami



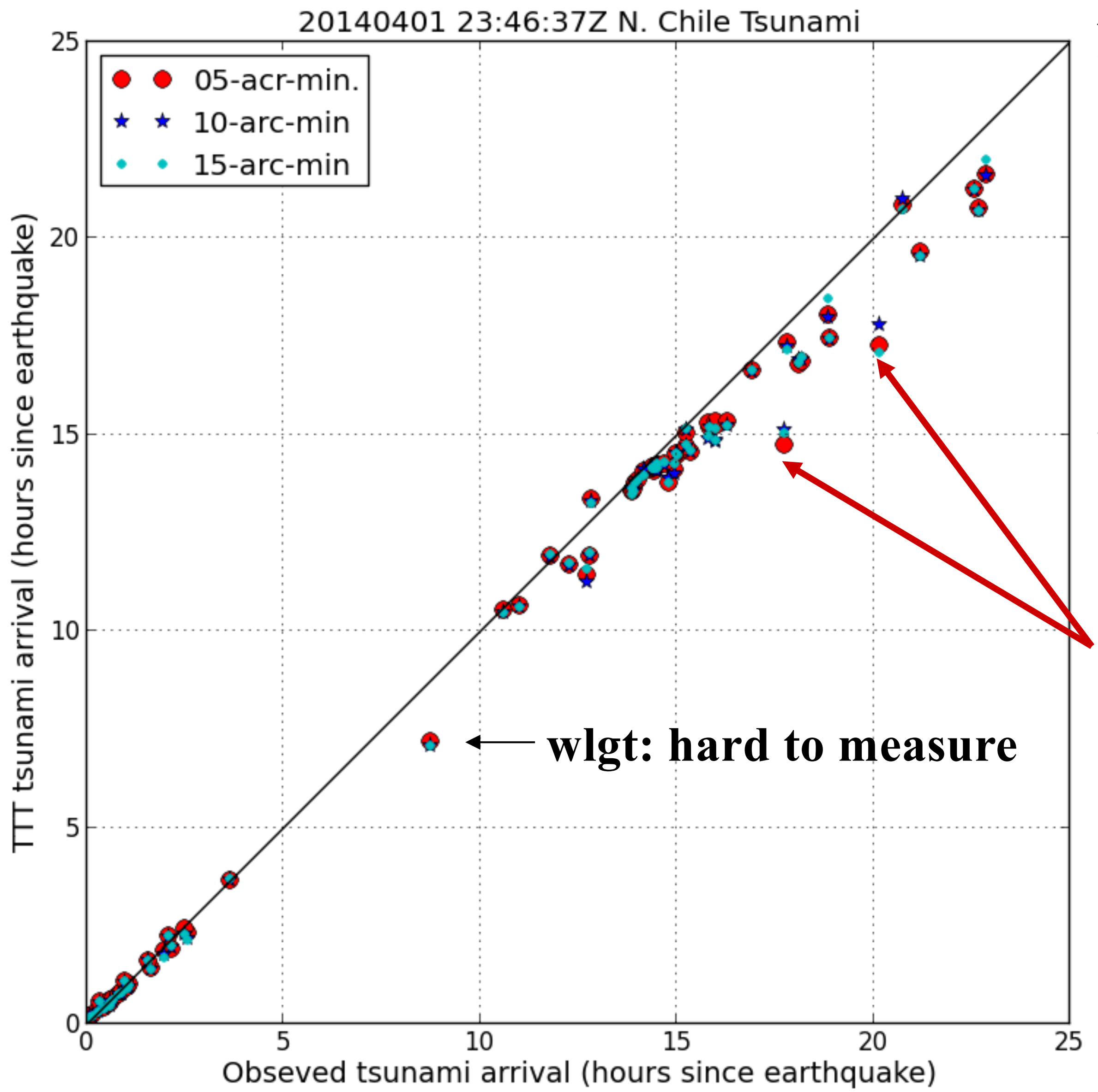


2004 Sumatra Tsunami: point-source ETAs fail!

Rupture length 1300-1500 km
Rupture lasted about 8-10 min.

Using the epicenter (red target) as a point source for ETA computation would result in tsunami arrivals up to 2 hours late.

Tsunami arrived at Andaman Islands 30 min. after the origin, but ETA is about 2 hrs after the origin.



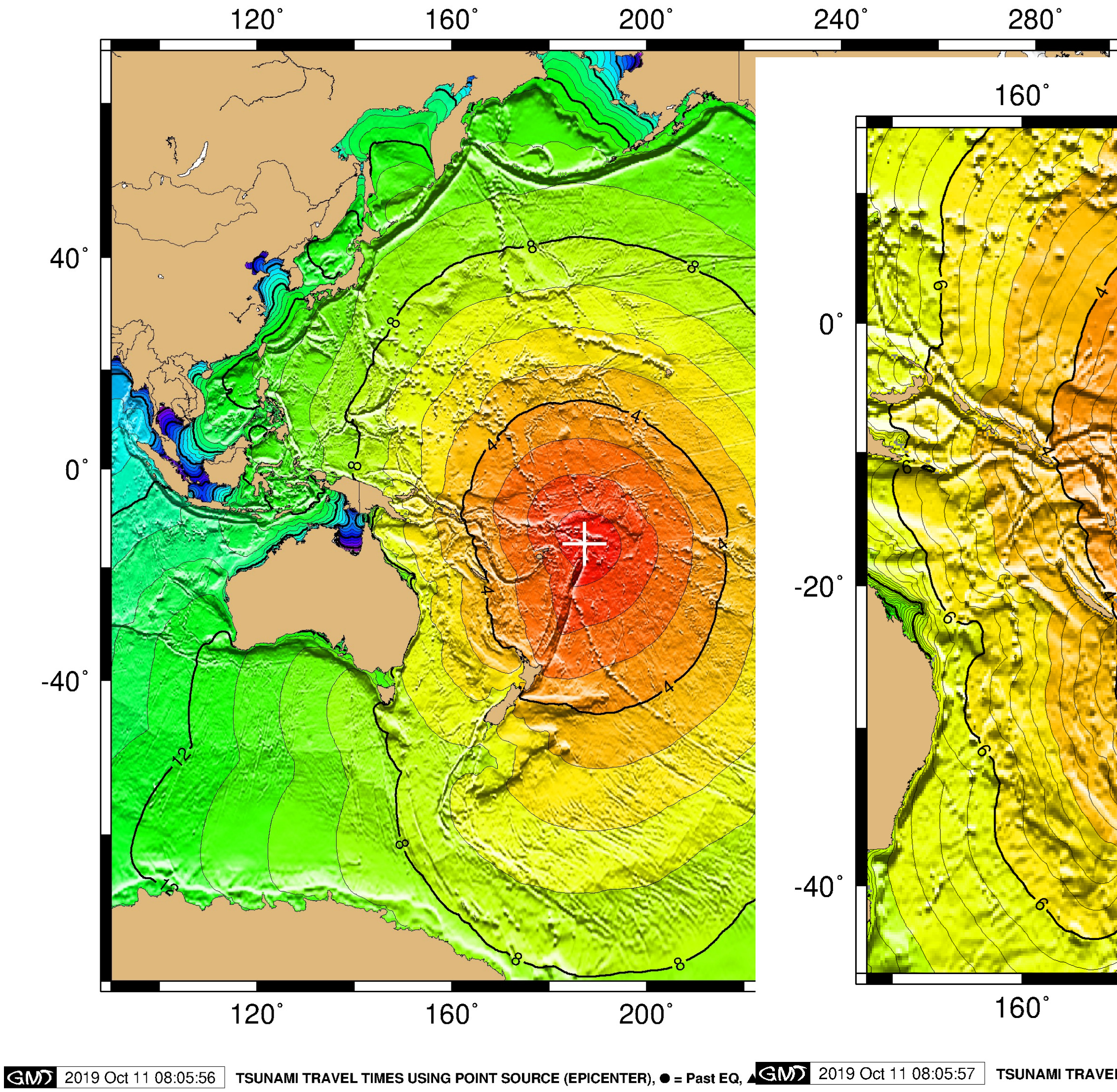
April 1, 2014
M8.2 Chile Tsunami

Computed ETAs vs. the observed (manually/visually measured from tide records).

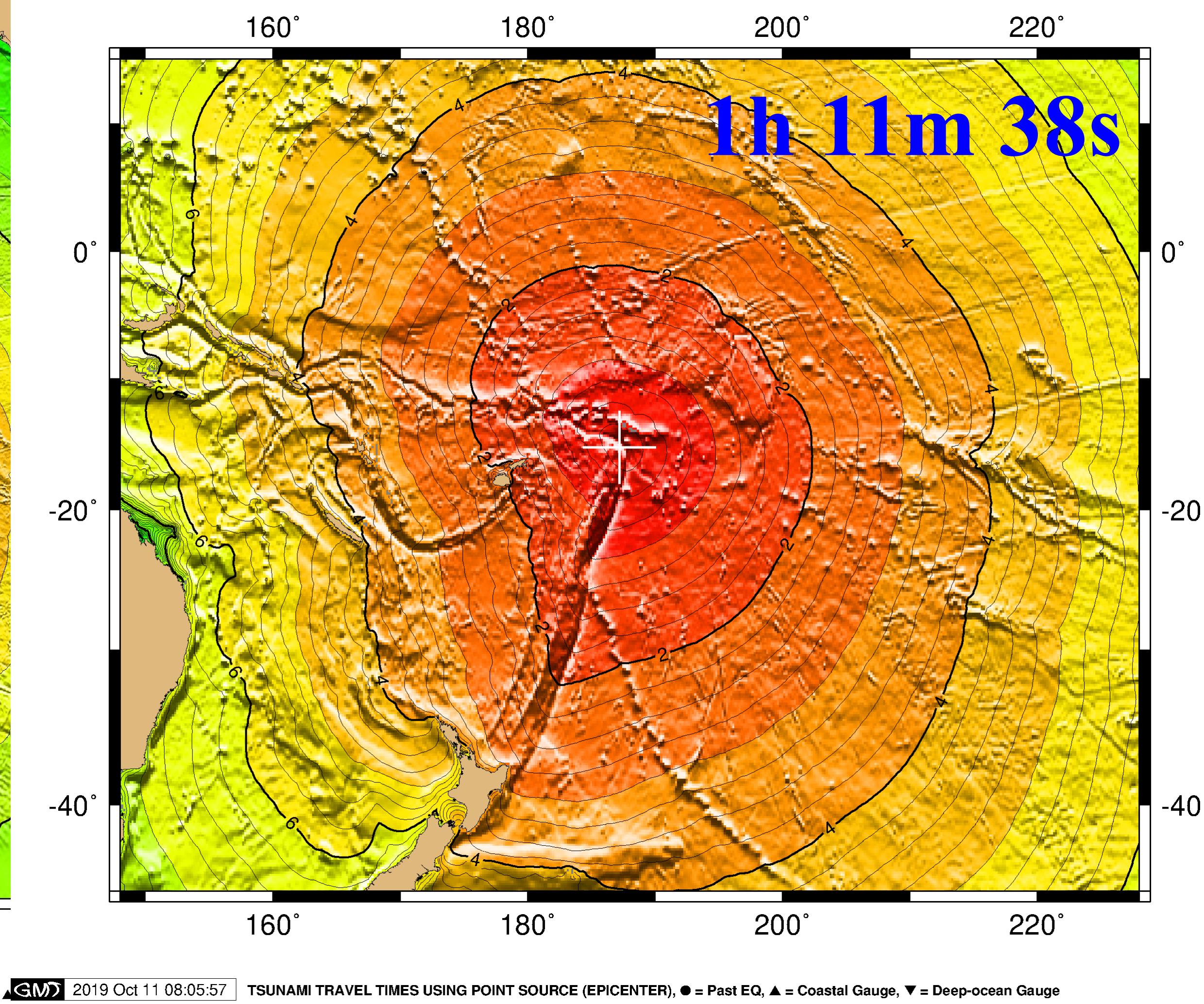
There is not much sensitivity between 5, 10, 15 arc-min. resolutions.

kush and pkem: Incorrectly measured from observations. Actual arrivals are much sooner than shown.

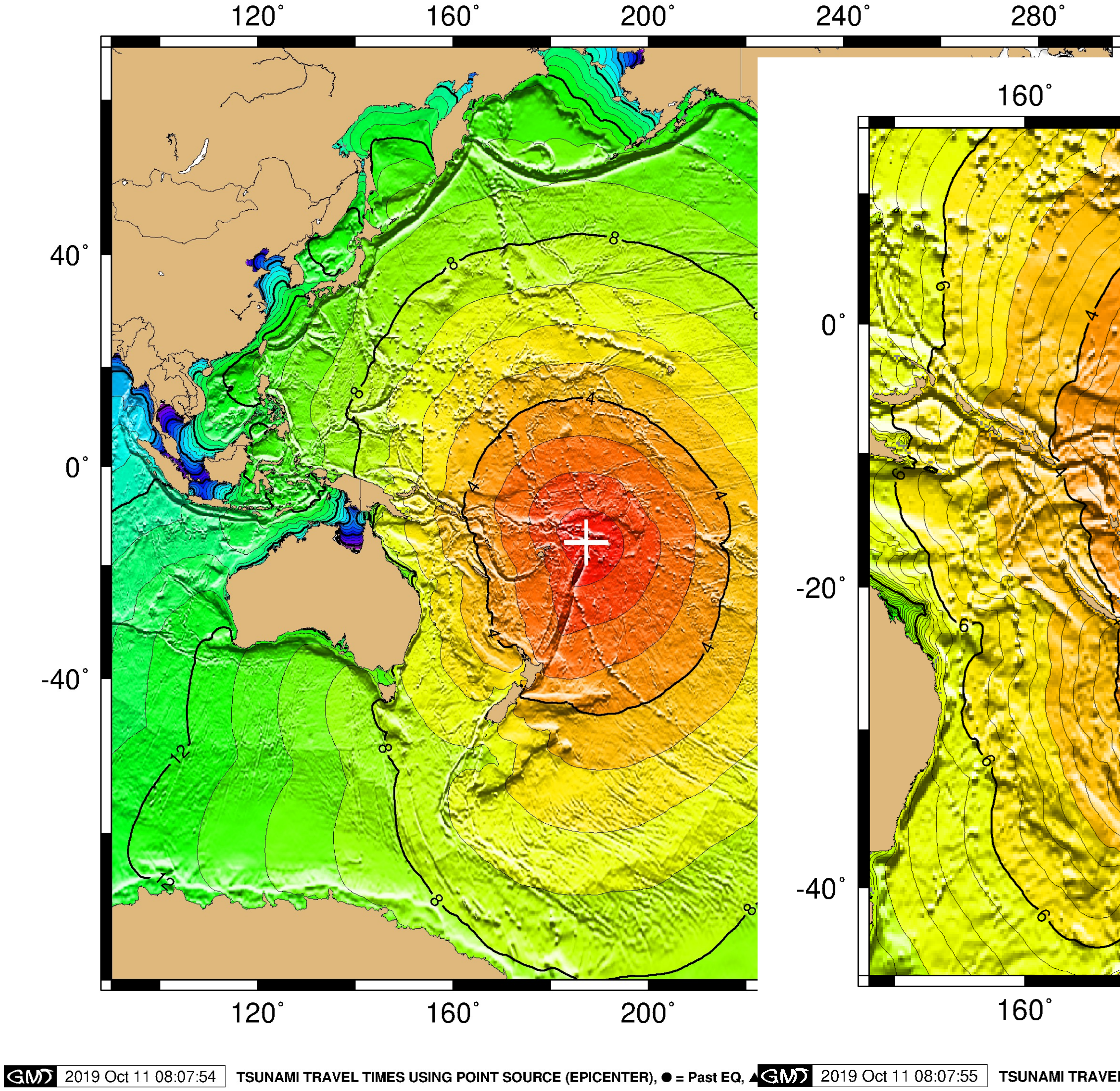
ETA to Nuku'alofa from Samoa tsunami 2009 location



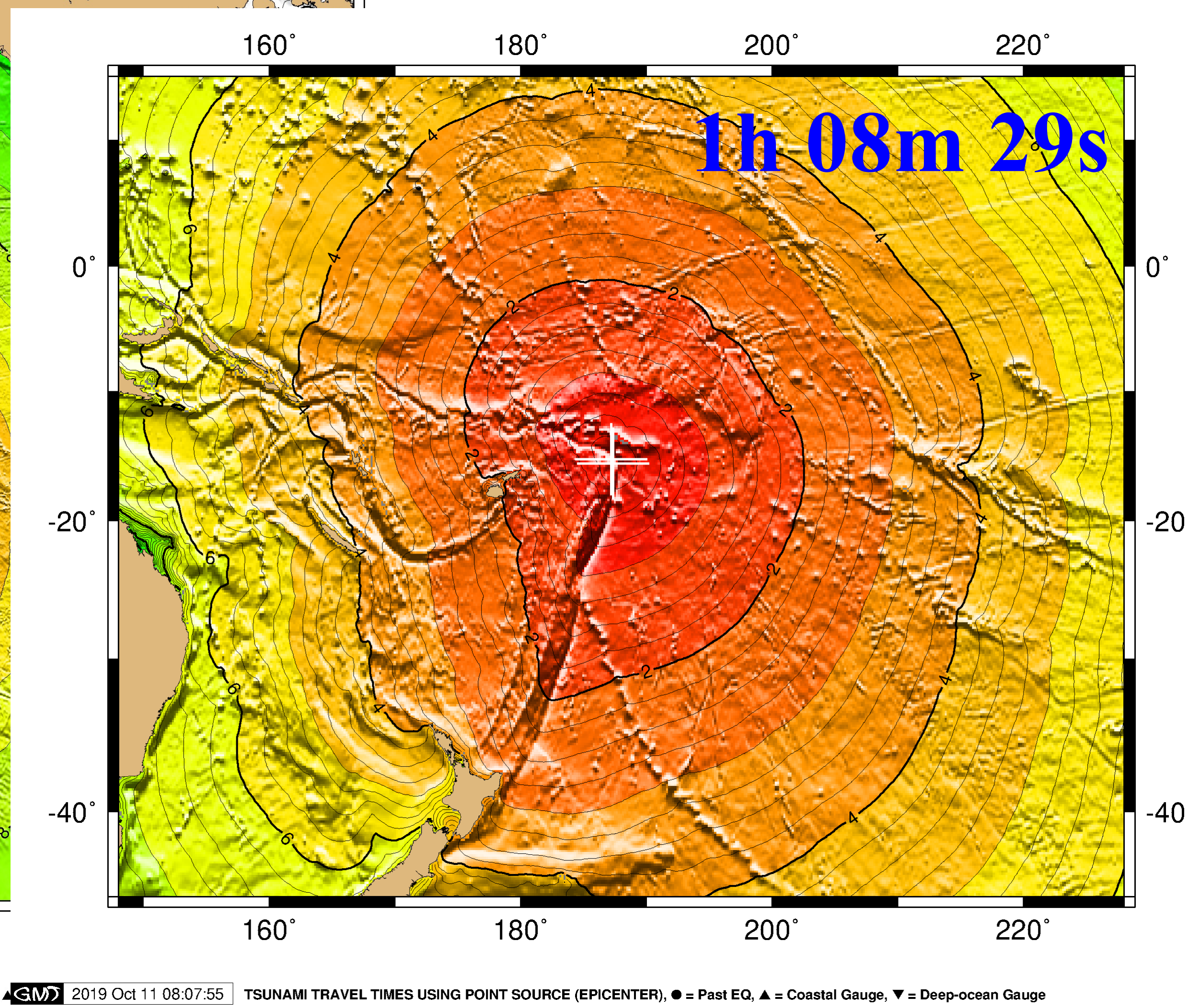
Point source



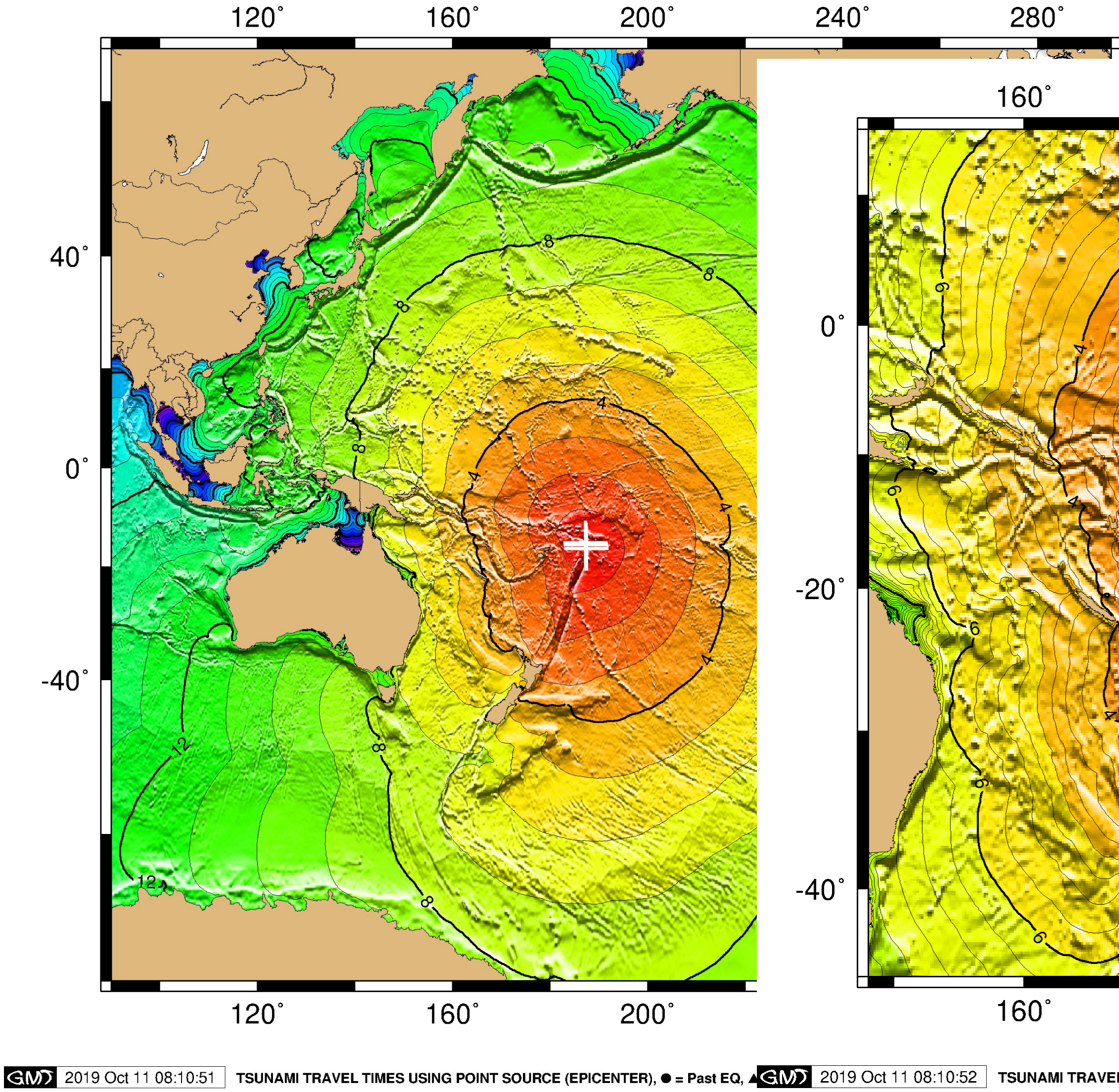
ETA to Nuku'alofa



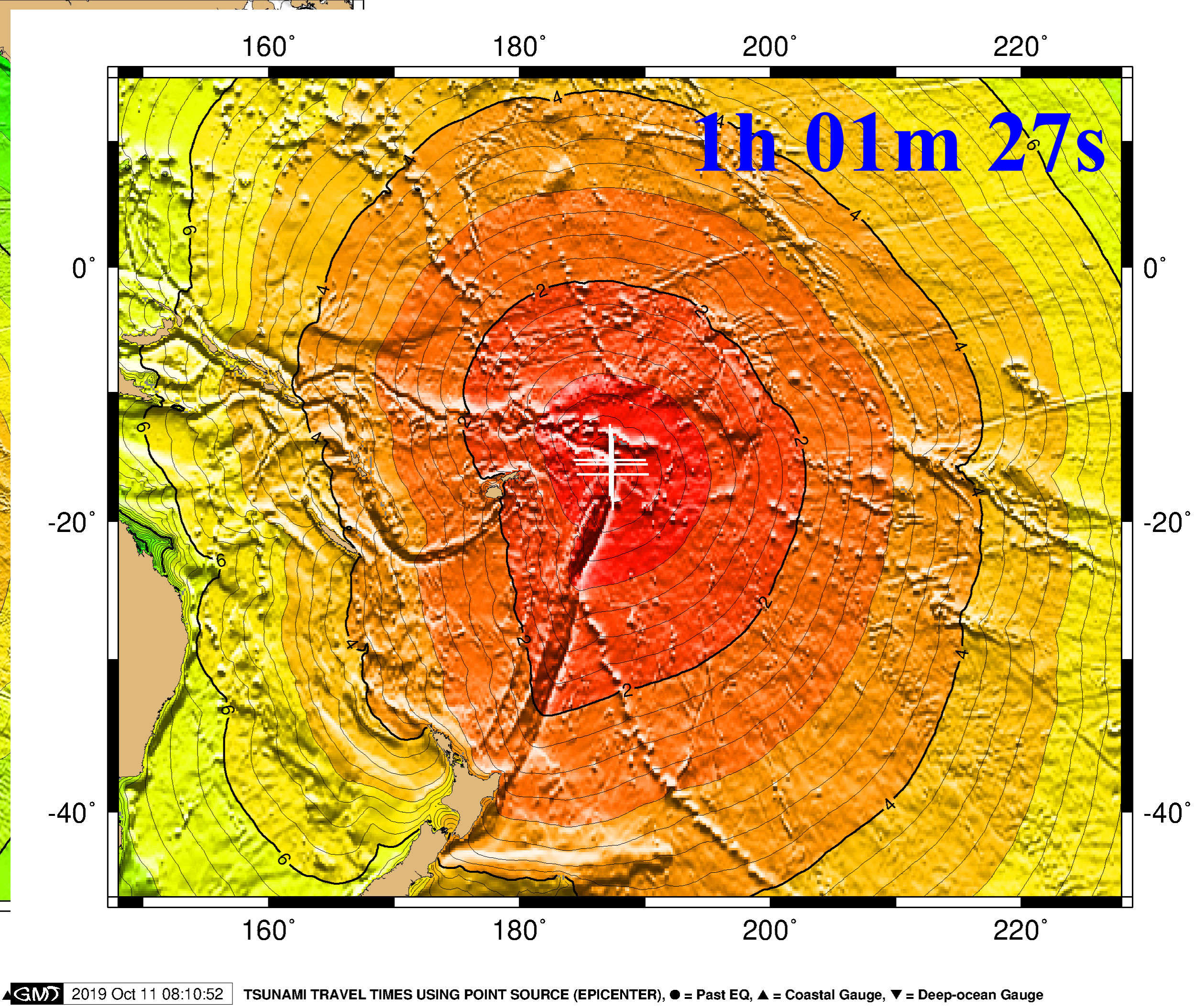
Two sources



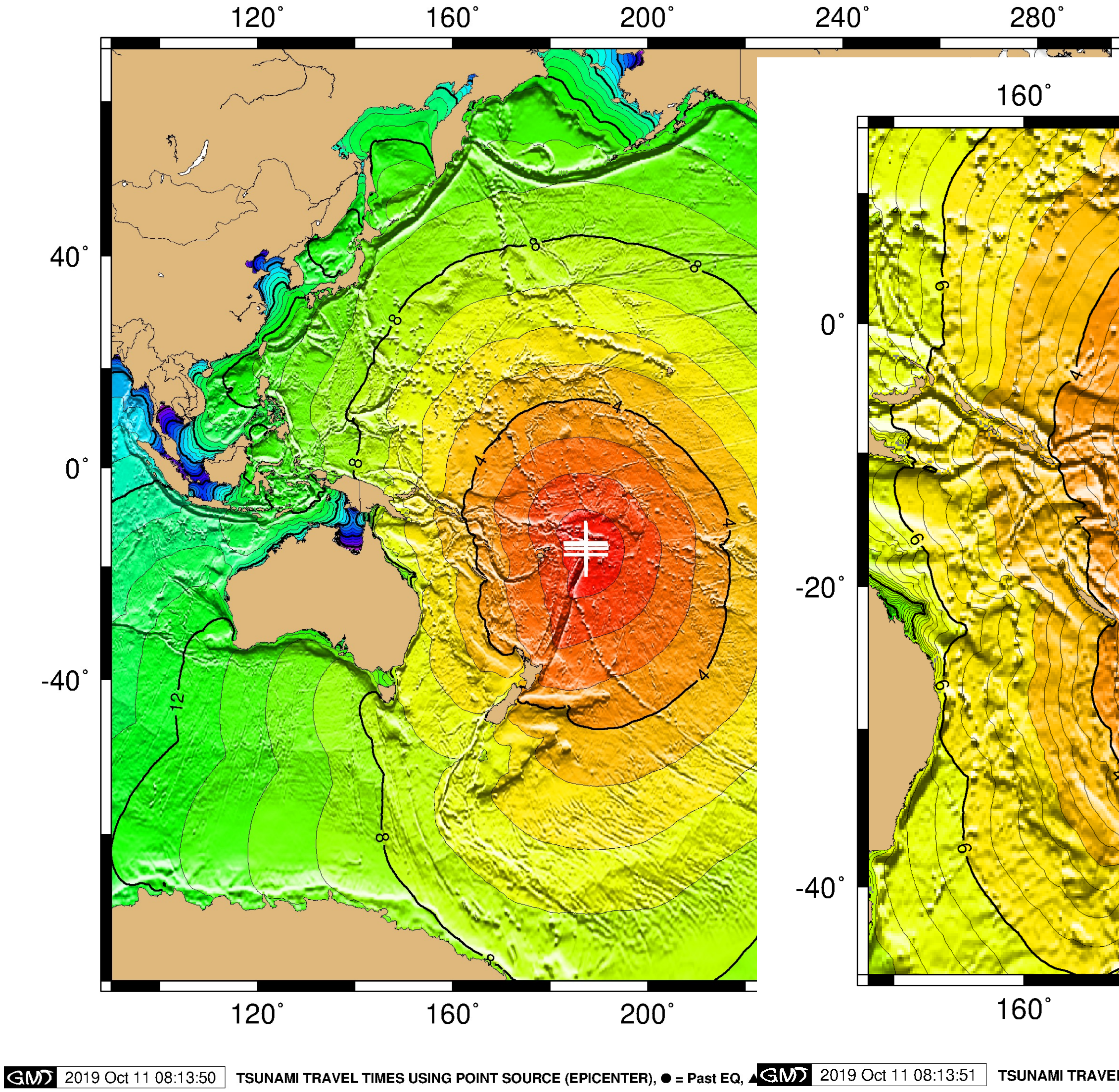
ETA to Nuku'alofa



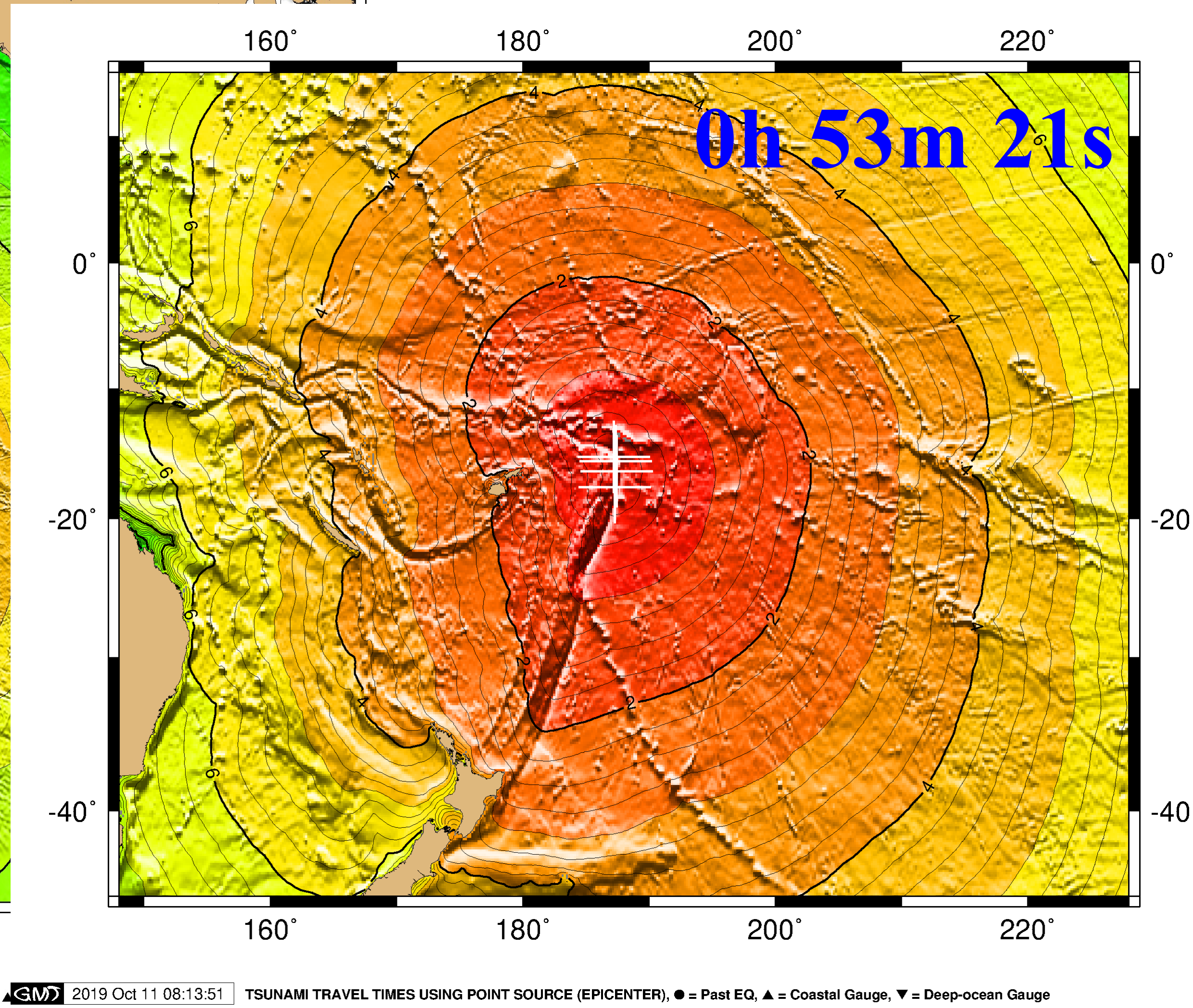
Three sources



ETA to Nuku’alofa

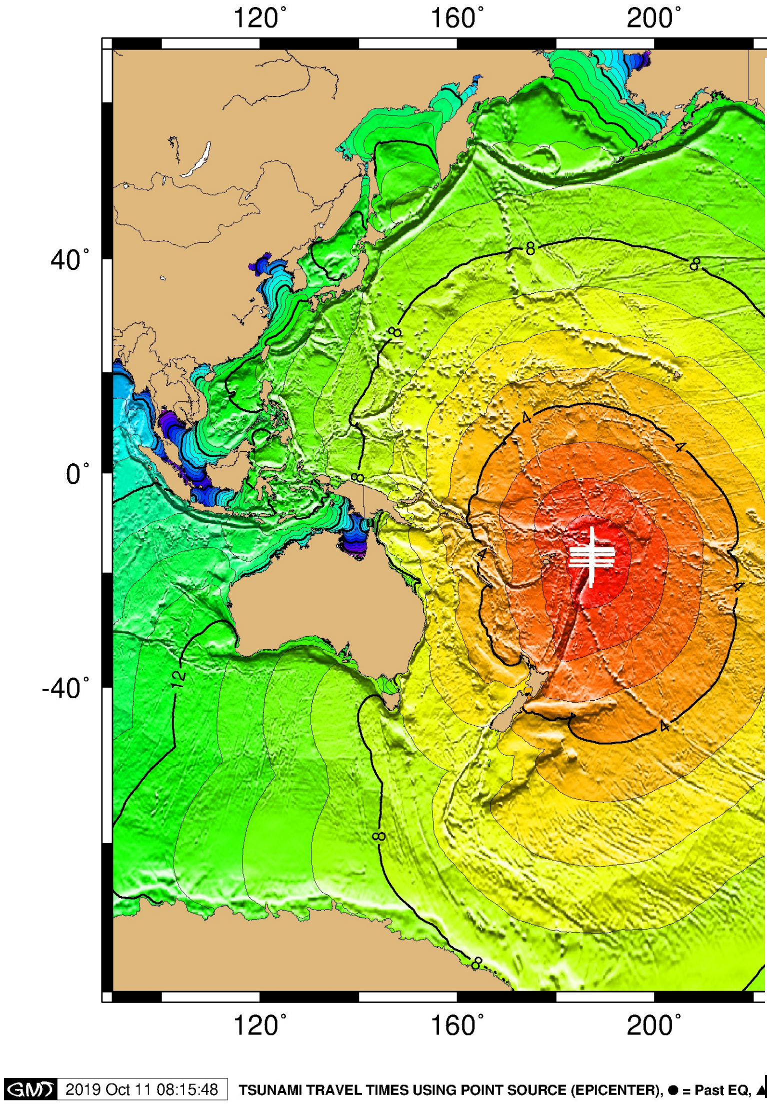


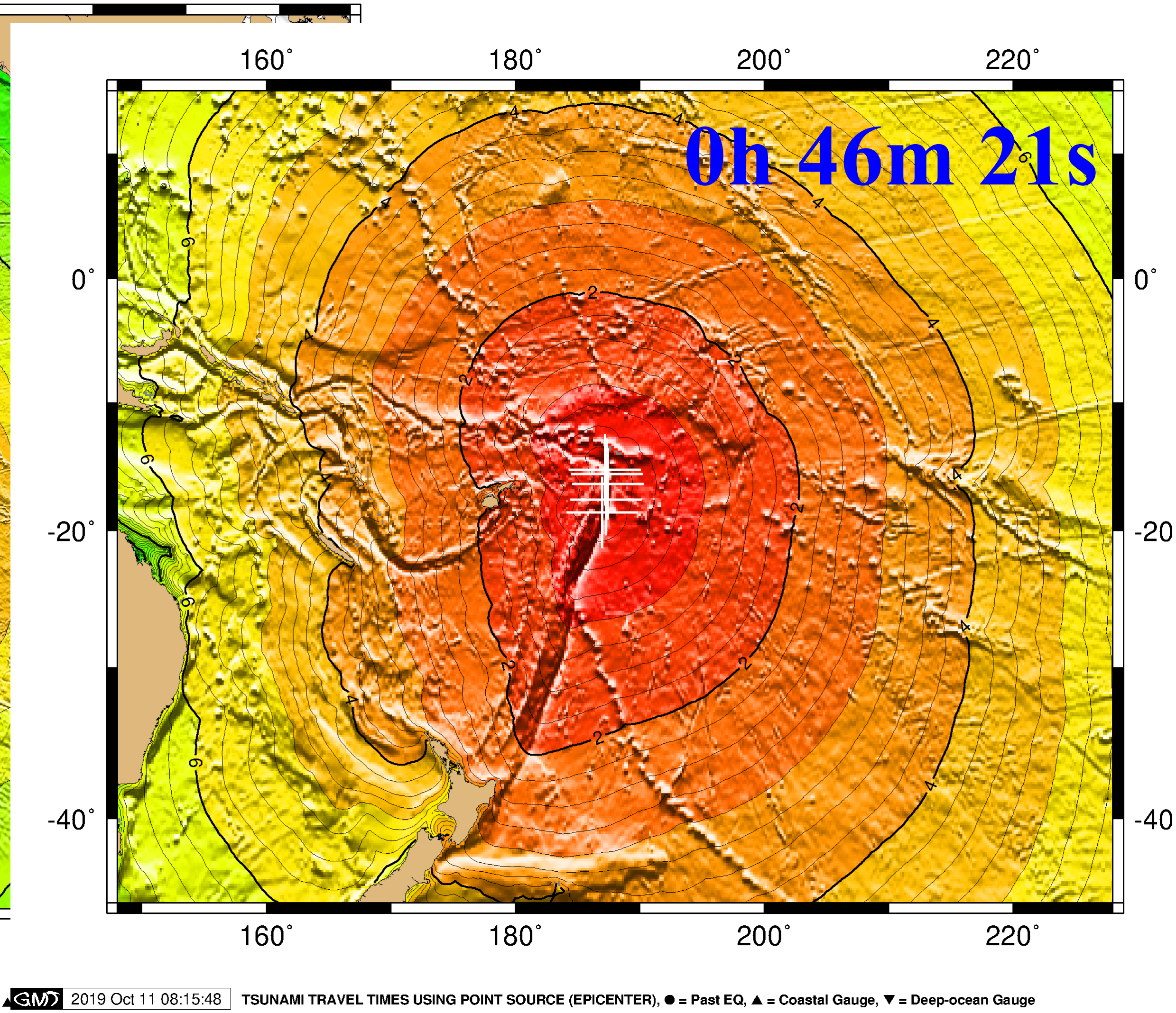
Four sources



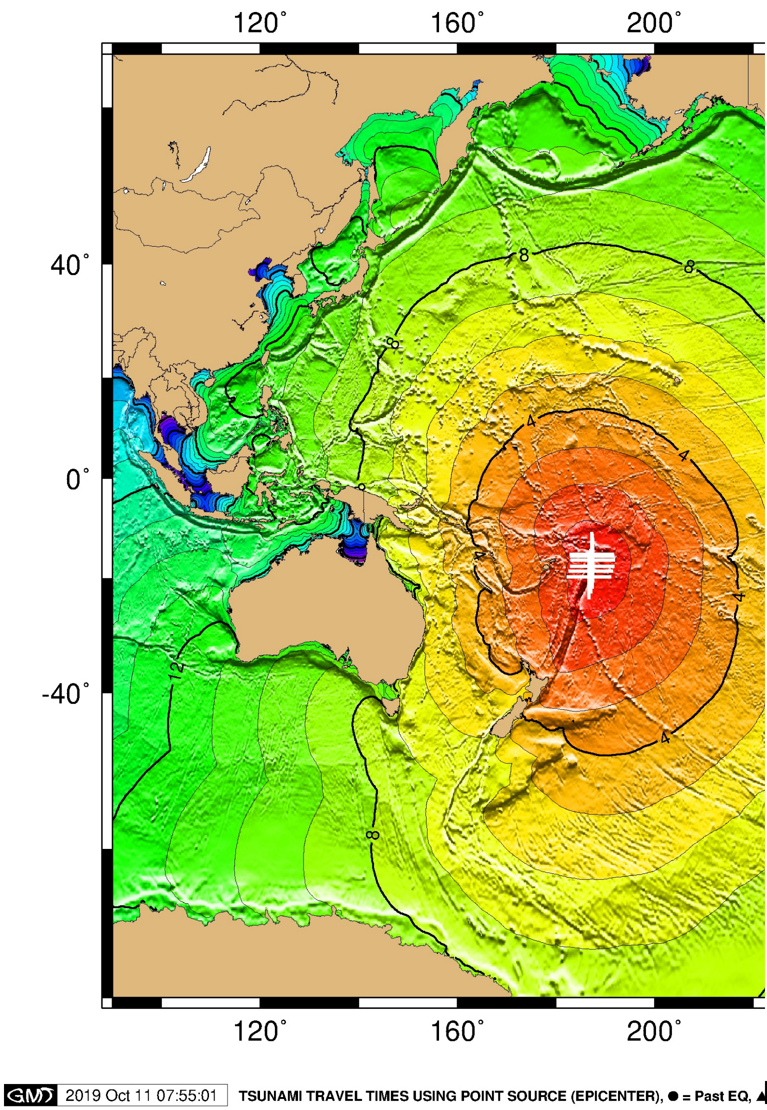
ETA to Nuku'alofa

Five sources (~300 km fault length)

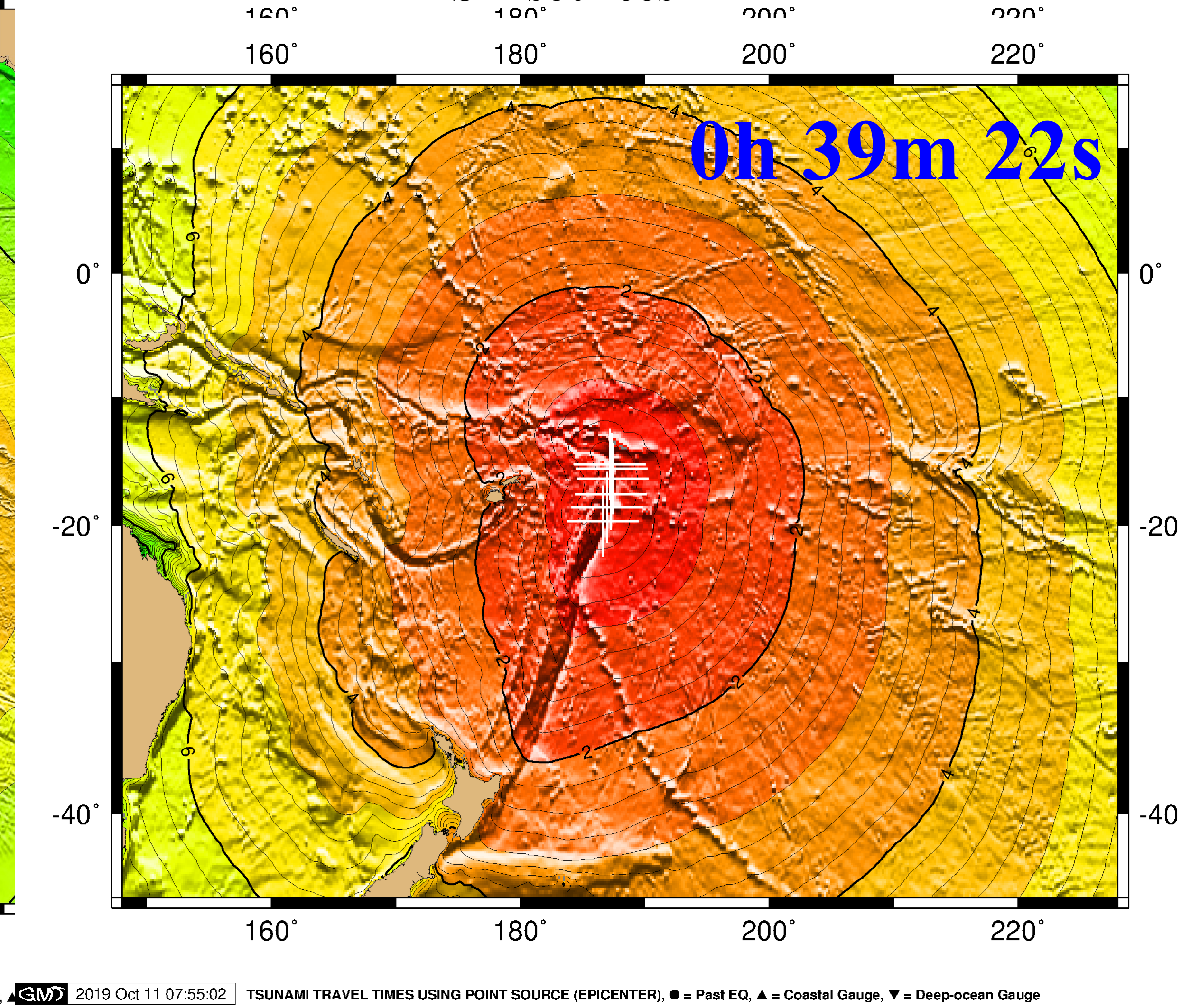




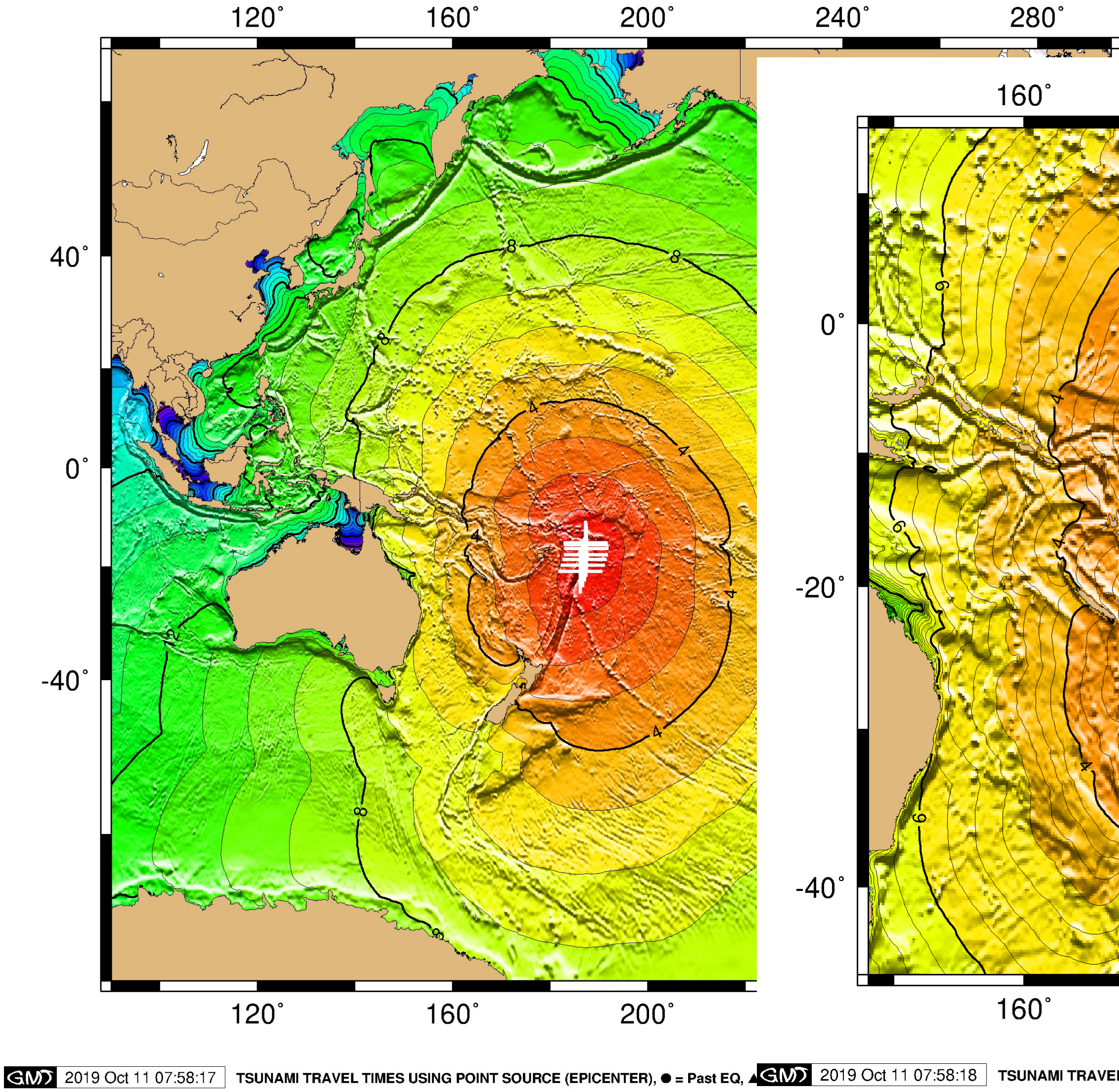
ETA to Nuku'alofa



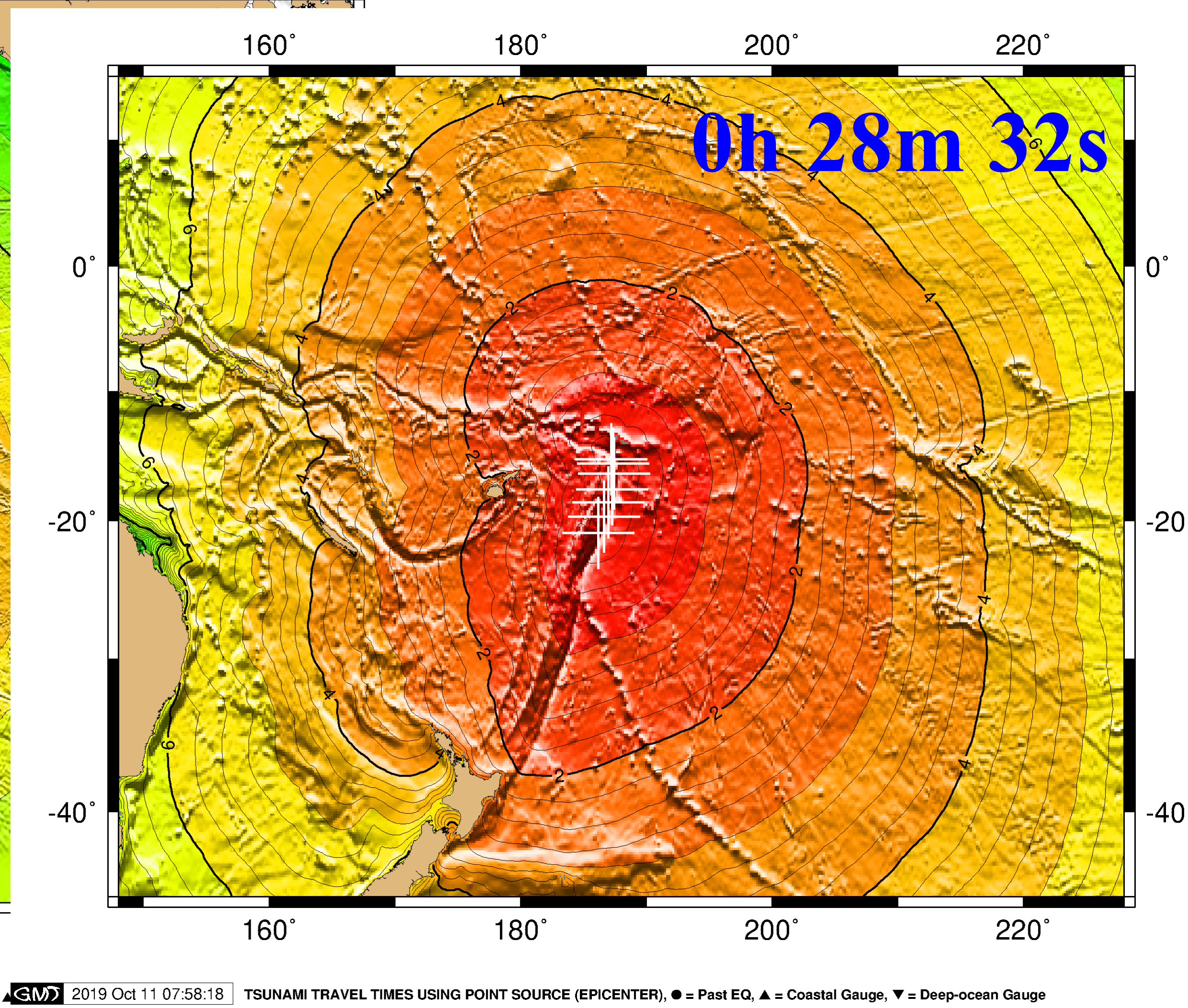
Six sources



ETA to Nuku'alofa

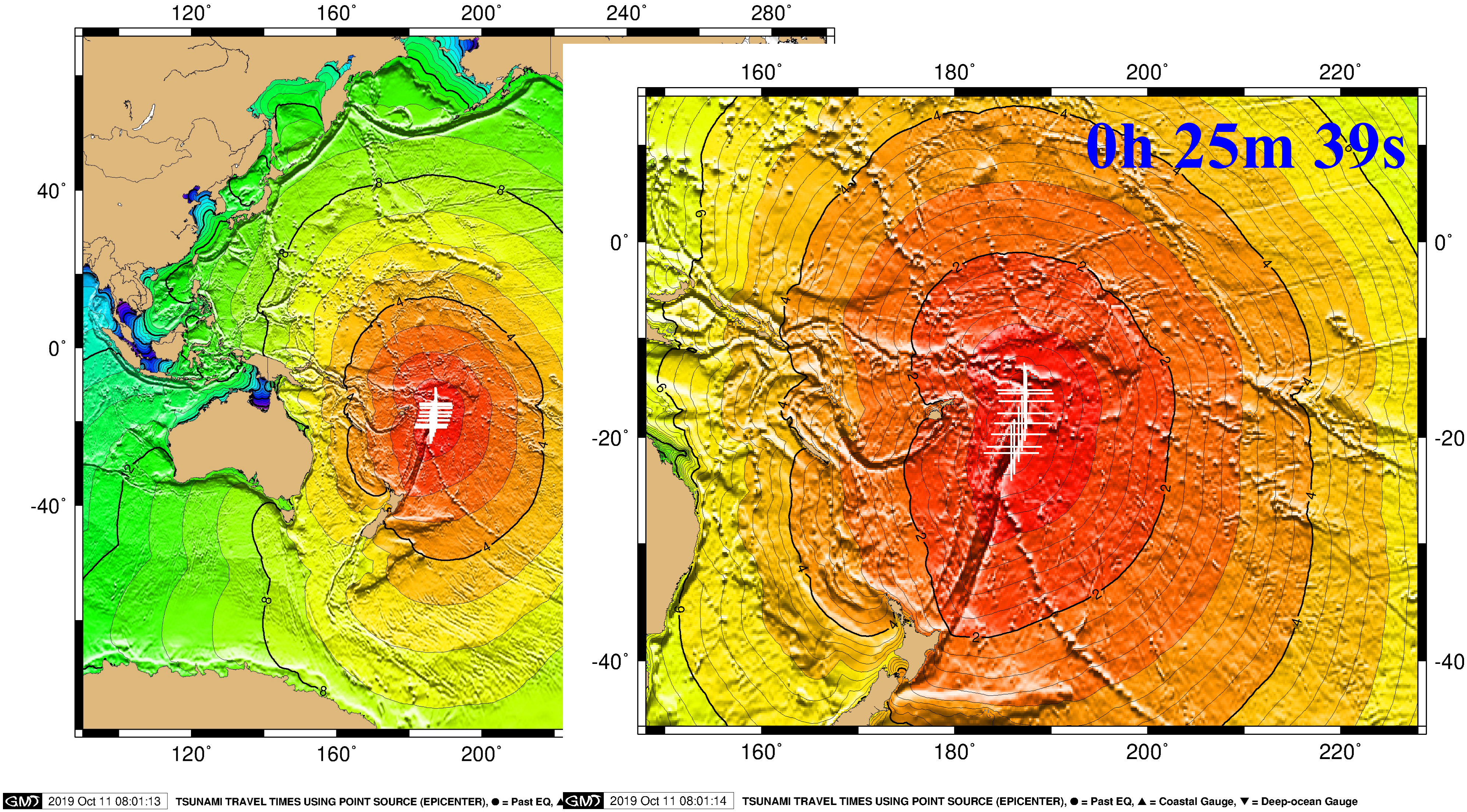


Seven sources



ETA to Nuku'alofa

Eight sources (~600 km fault length)

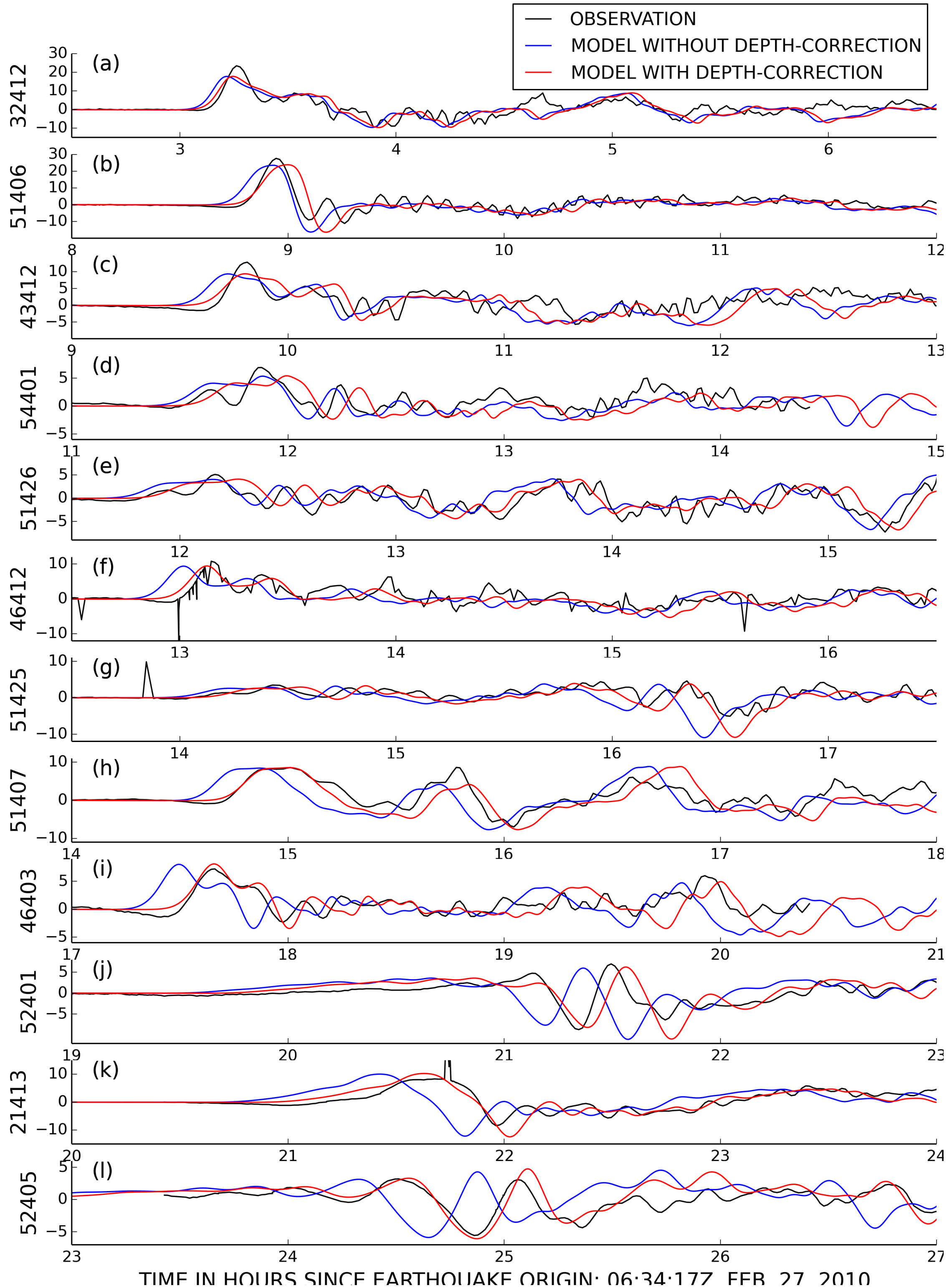


Summary

1. **Geoware TTT method using point sources work most of the time**

2. **Line/finite sources can be used to improve the accuracy of Geoware TTT for large earthquakes.**

3. **ETAs from models work well for the deep ocean but can be unphysical at times for locations of complex bathymetry.**



Chile 2010 tsunami

ETAs at DARTs from Huygens principle do not show as large errors as at tide stations, but ETAs can be up to 15-20 min. sooner than the observed.

← RIFT model vs DARTs

Compressibility of seawater slows down tsunami waves

Compressibility is modeled via a depth correction by Wang 2015 (implemented in the RIFT model).

Modeled and observed waves are out of phase without the depth correction.

Mahalo!