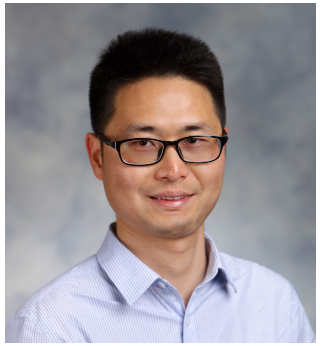


DALHOUSIE UNIVERSITY

Accurate Earthquake Location Using Single-Station Waveforms: A Case Study

Miao Zhang

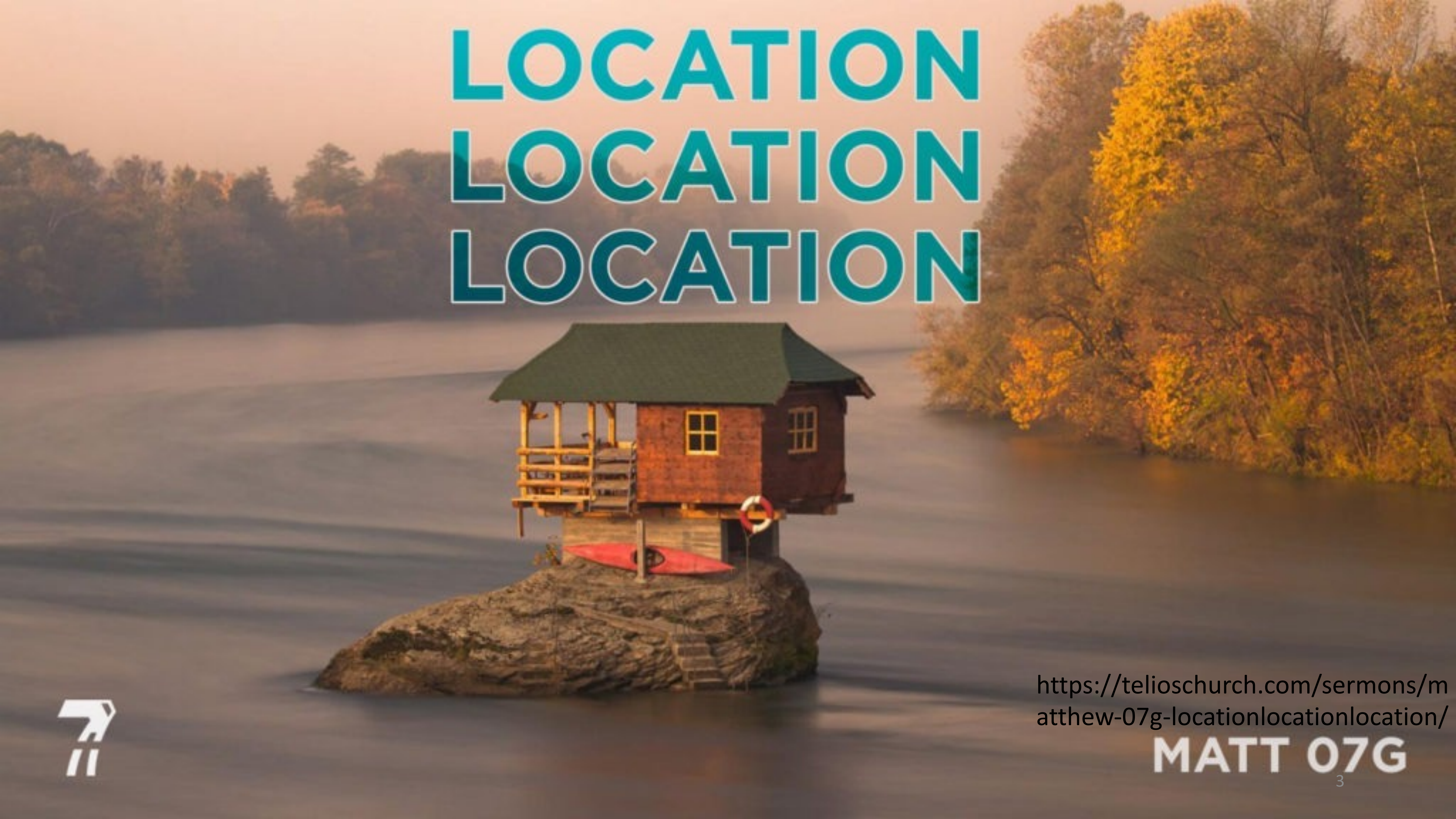
Dalhousie University

USTC, Hefei, China

Mar. 2021

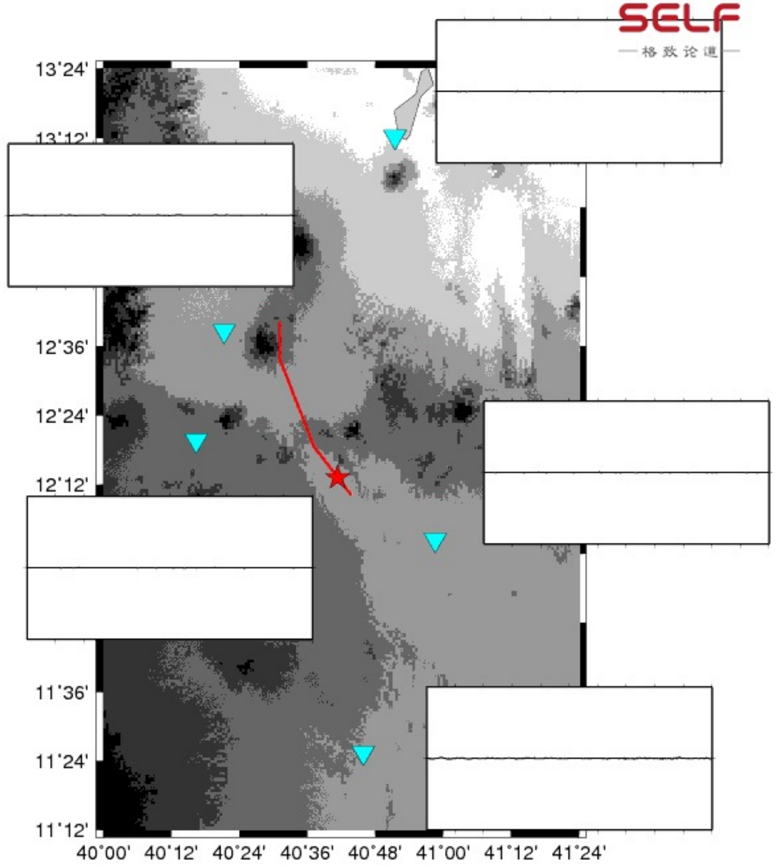
Outline

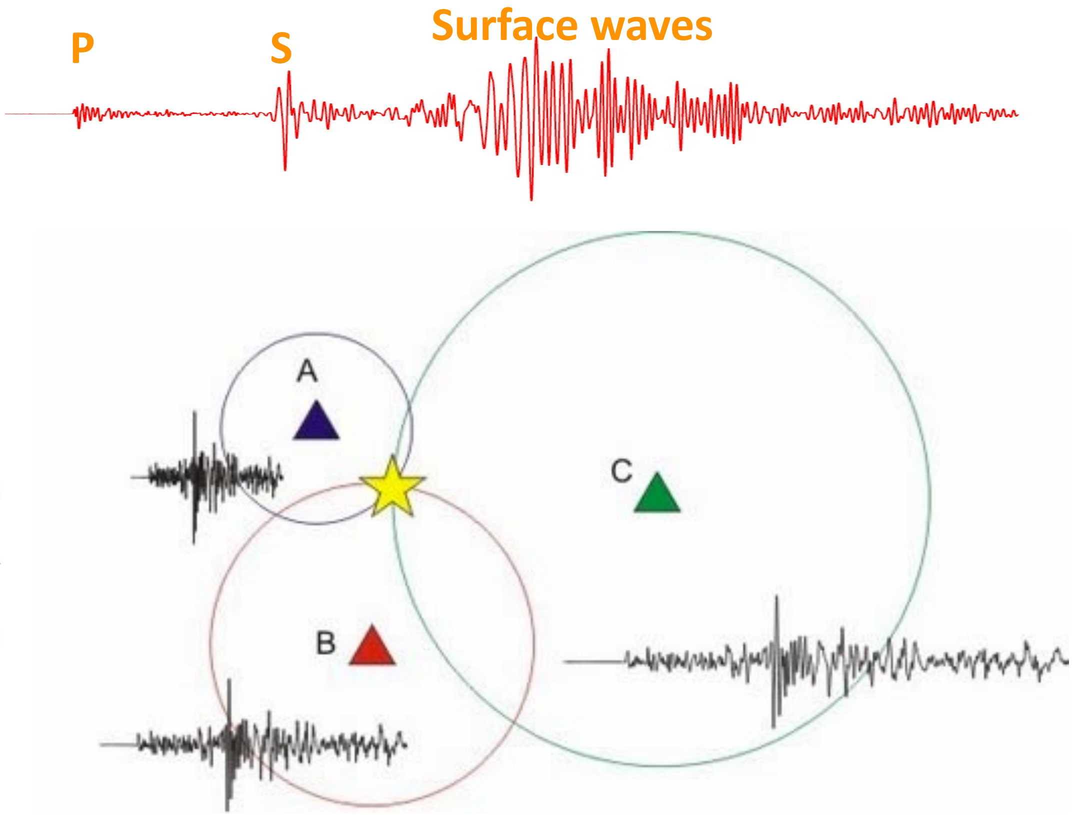
- Background
- Review of single-station location methods
- Source characterization for two small earthquakes in Dartmouth, NS
- Summary



https://telioschurch.com/sermons/matthew-07g-locationlocationlocation/

Earthquake Location





Phase picking -> Phase association -> Event location

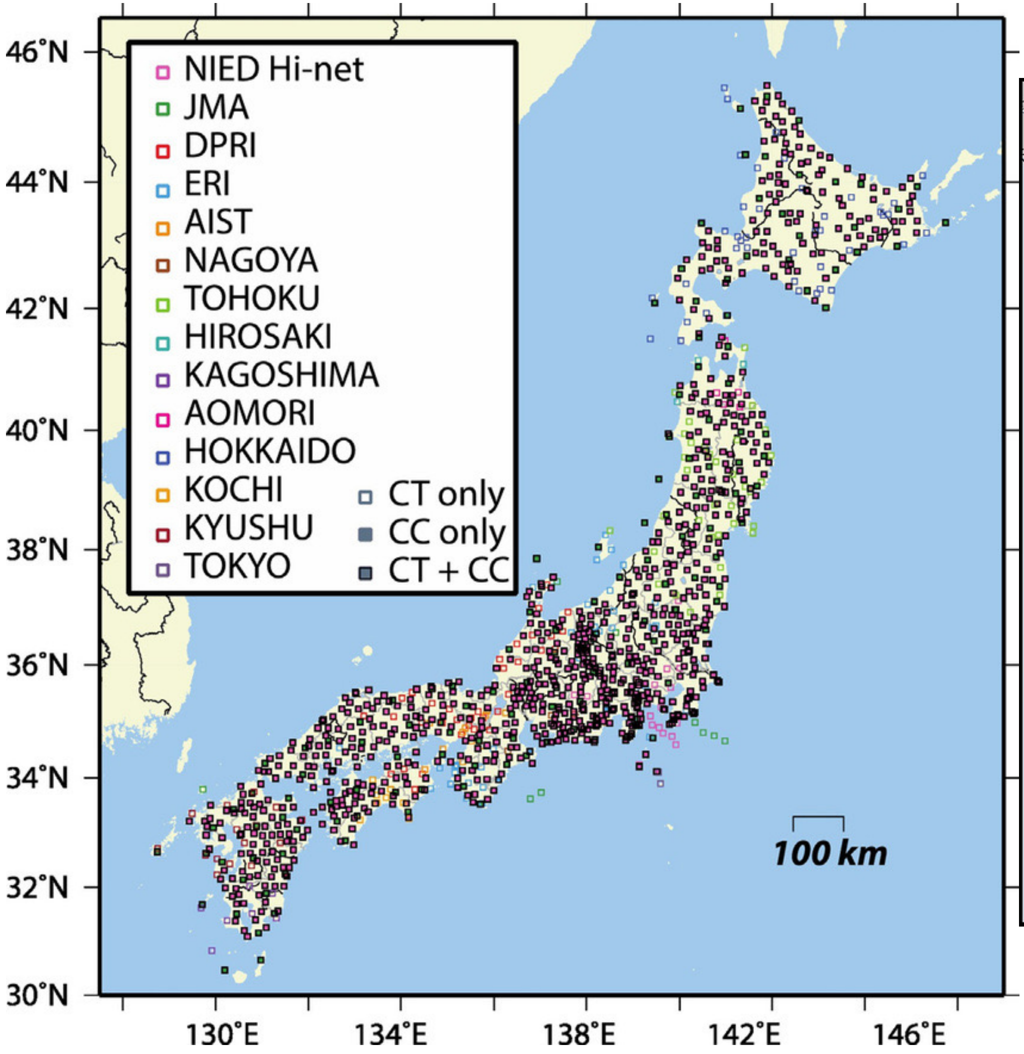
Pick-based methods

VS.

Waveform-based methods

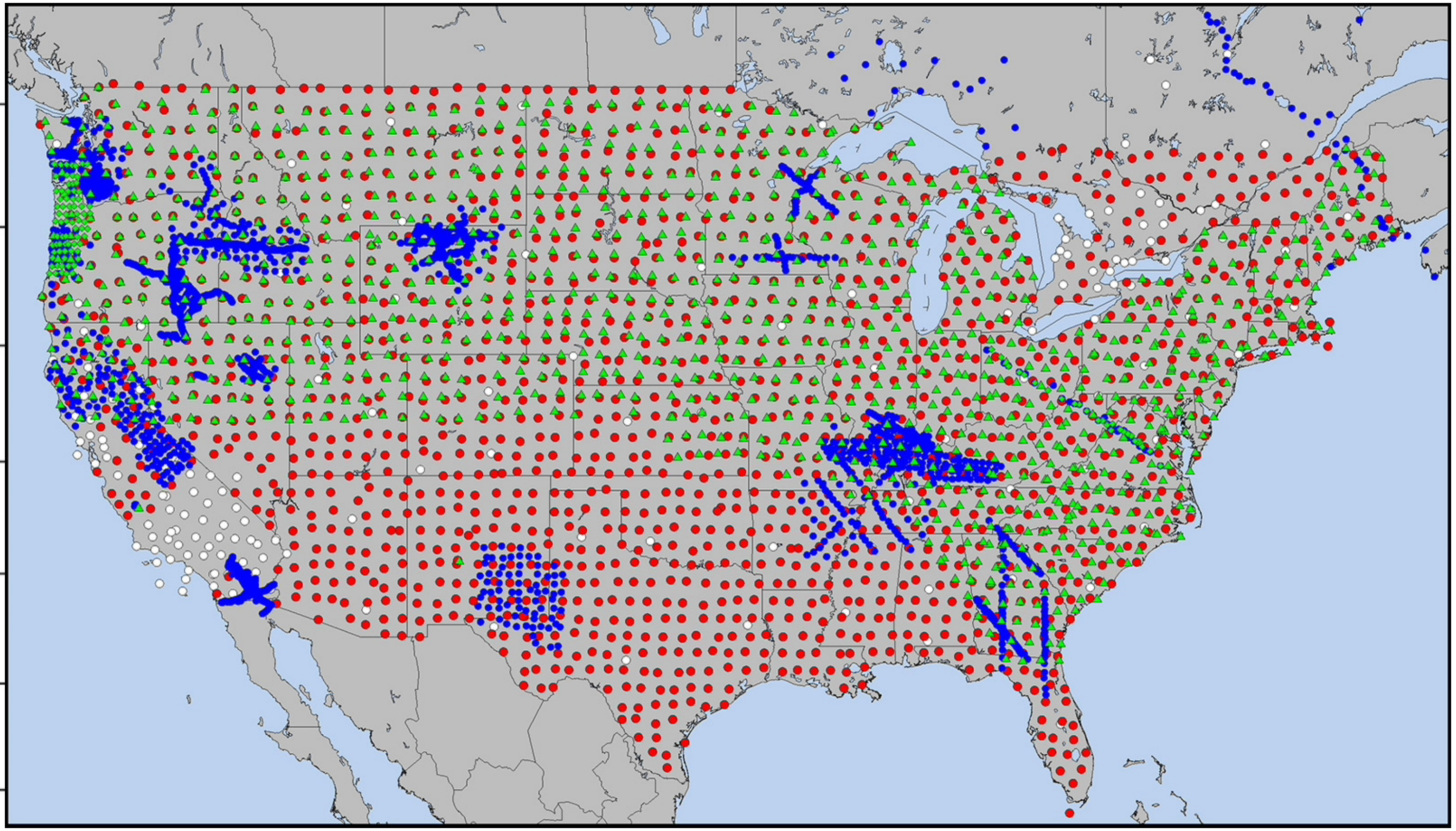
All in one single step (delay-and-sum) & waveform simulation/matching

Hi-net (Japan)



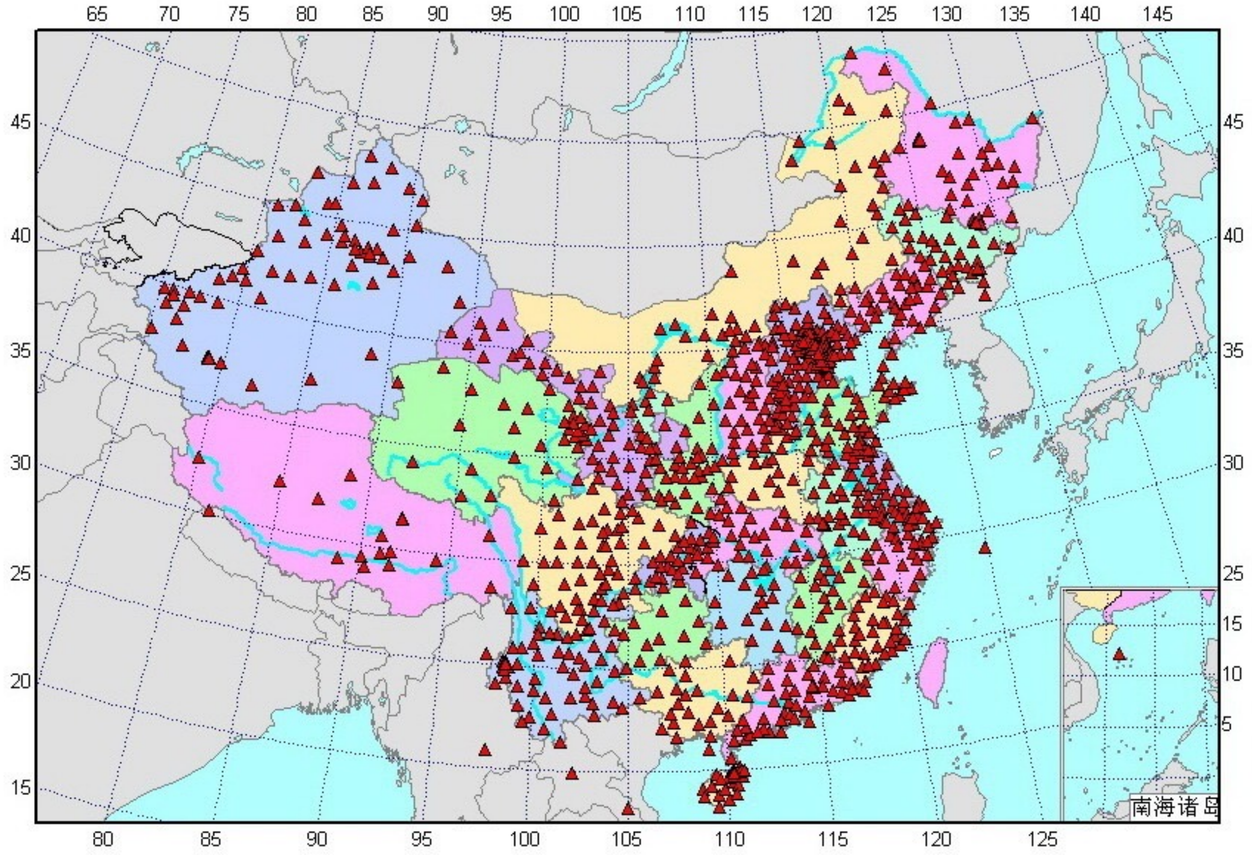
Station spacing: 20~ 30 km

US Array (USA)



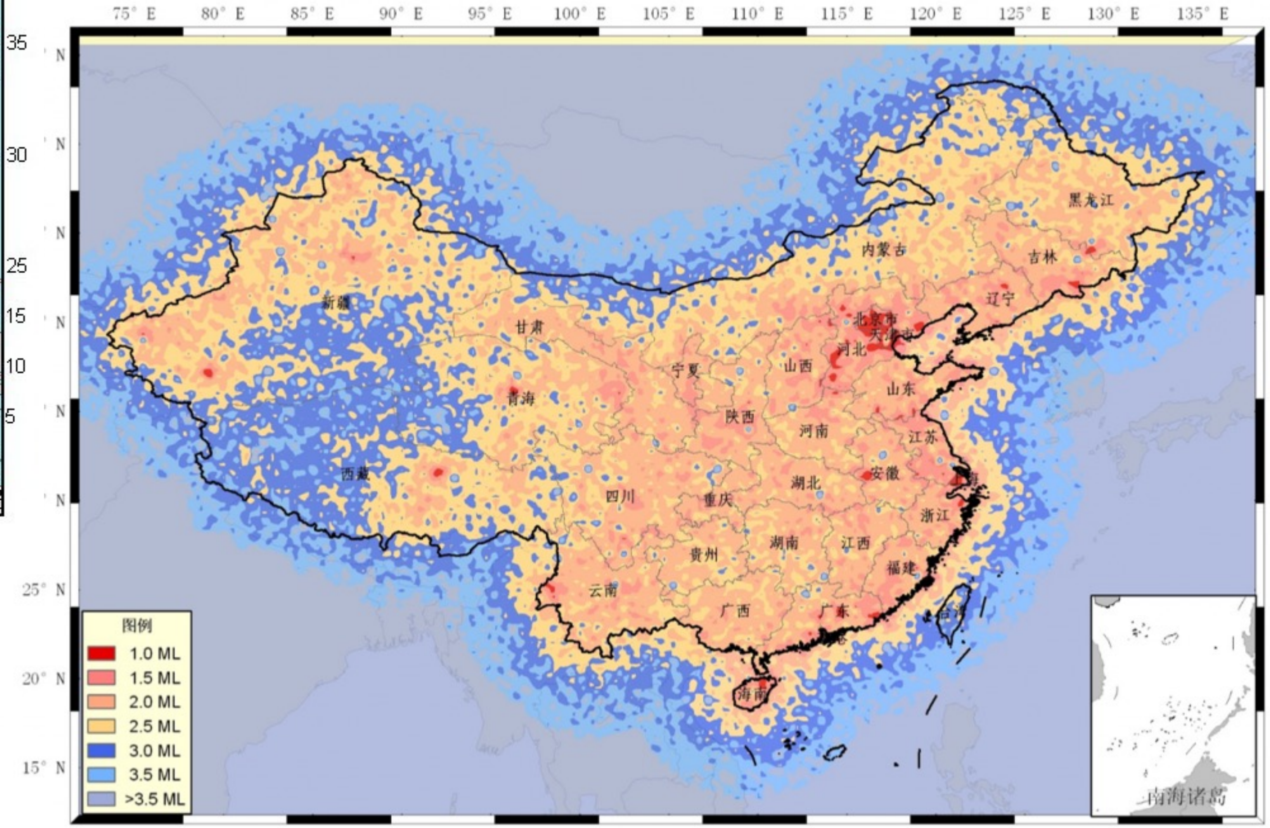
Station spacing: 70 km

Seismic Station Distribution in China



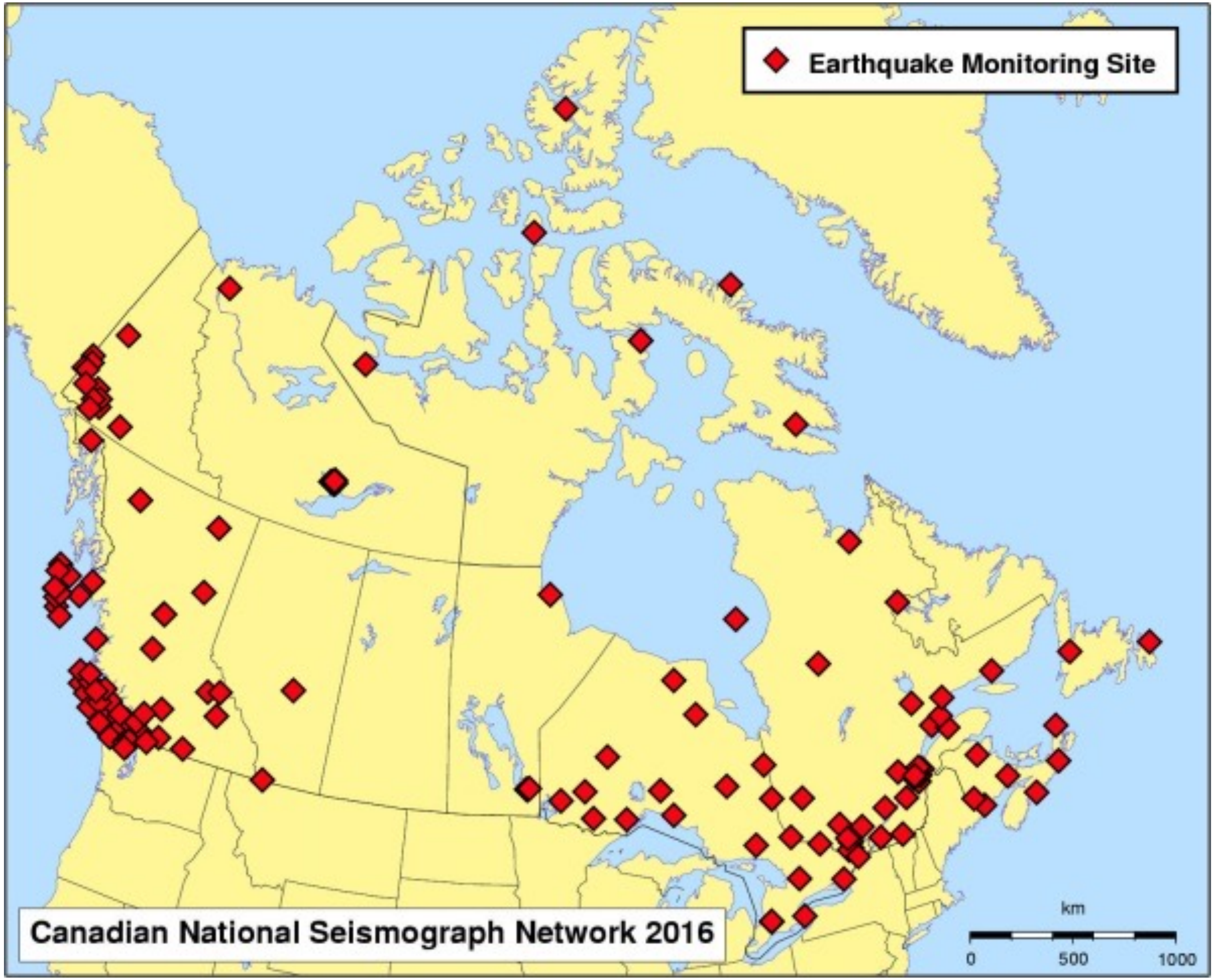
https://data.earthquake.cn/

Earthquake Monitoring Ability

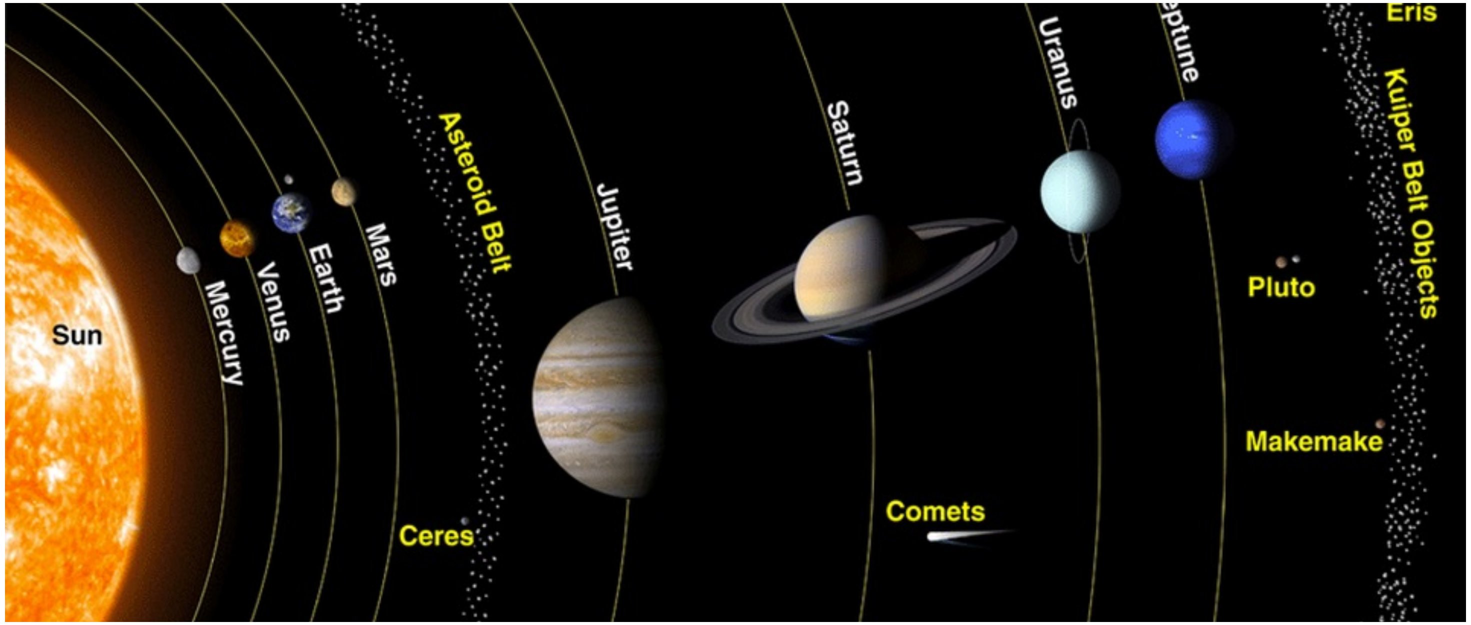


http://chinageorefmodel.org/

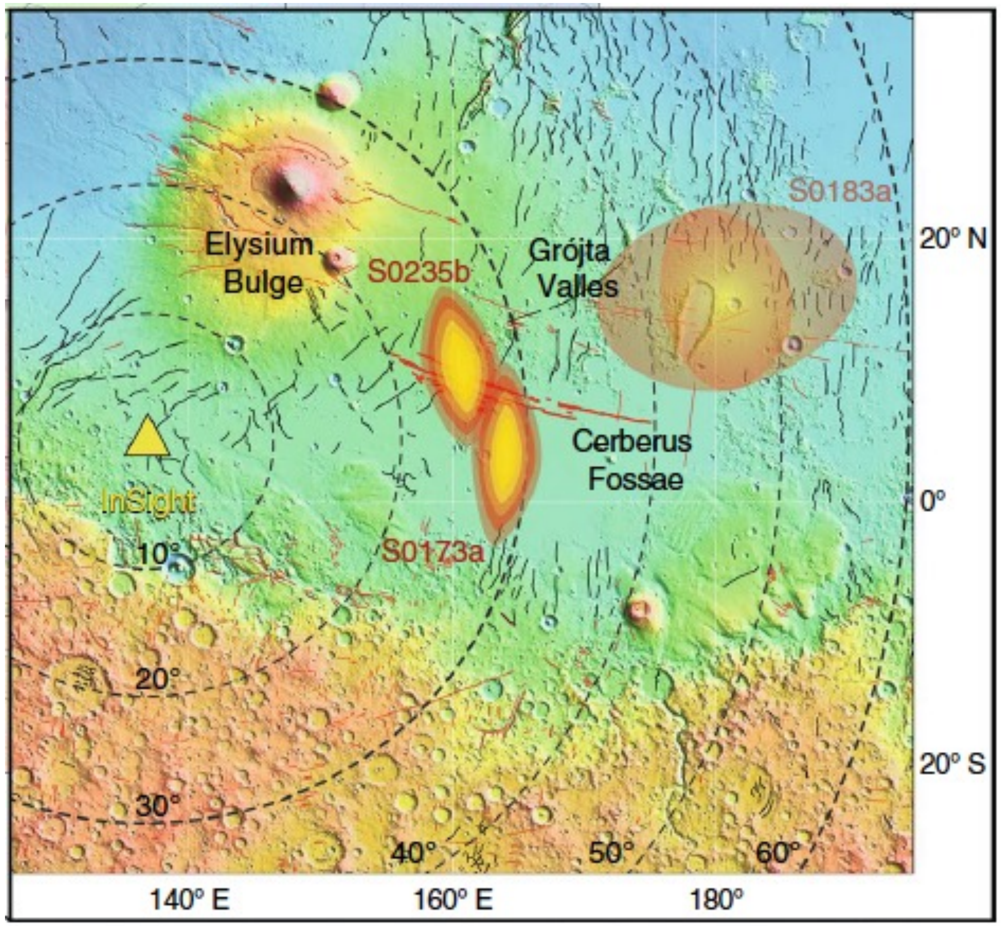
Canadian National Seismograph Network



Quake location on other planets



Seismicity of Mars



Giardini et al., Nat. Geosci., 2020

Outline

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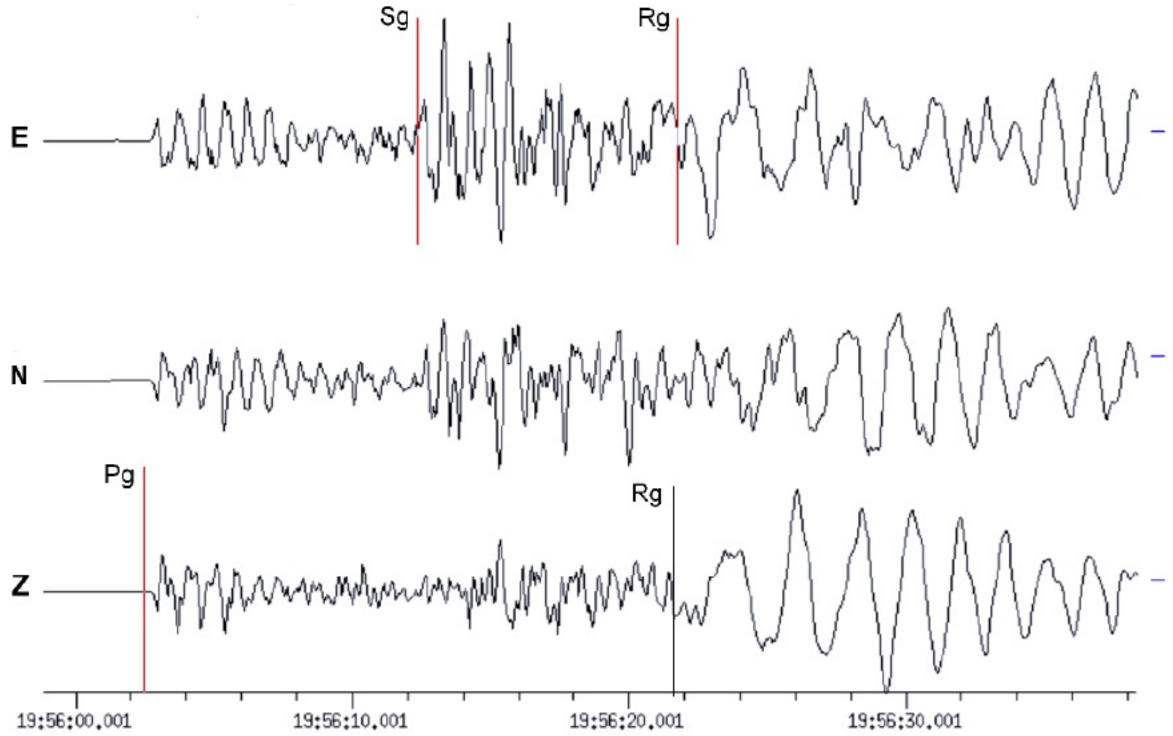
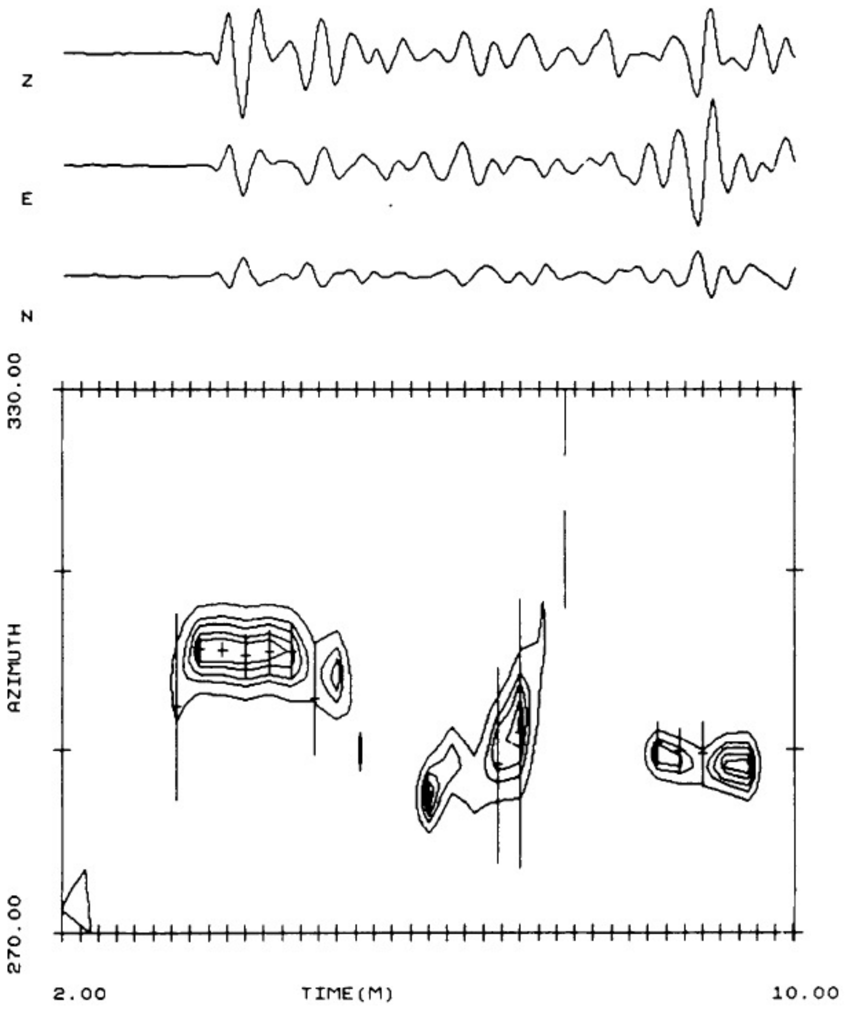
Single-station location:
1. epicentral distance (Tp-s) + back azimuth (polarity)



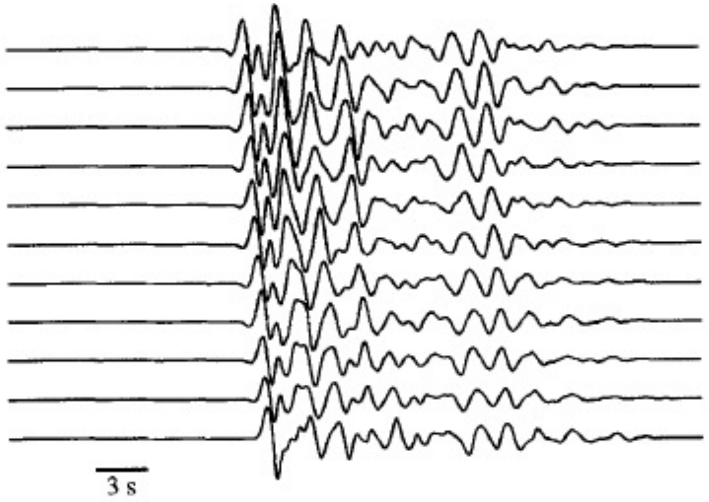


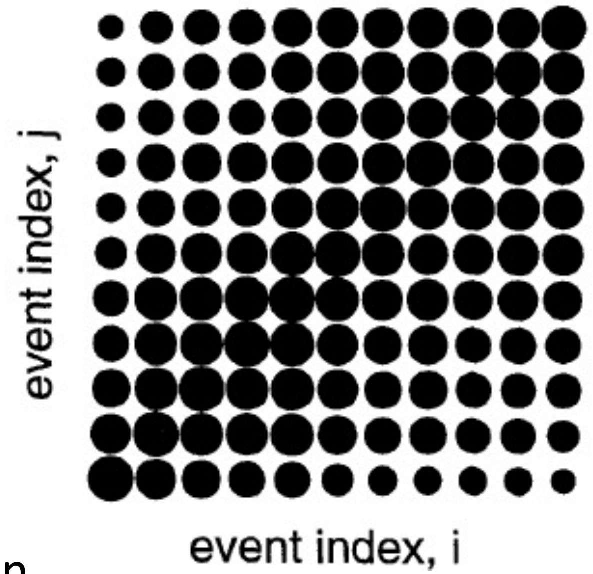
Roberts et al., Geophysical Journal, 1989

Single-station location:
2. using waveform similarity

$$C_{ij}^{\mathrm{pre}} = \exp(-r_{ij}/s);\ r_{ij} = |\mathbf{x}^{(i)} - \mathbf{x}^{(j)}|$$

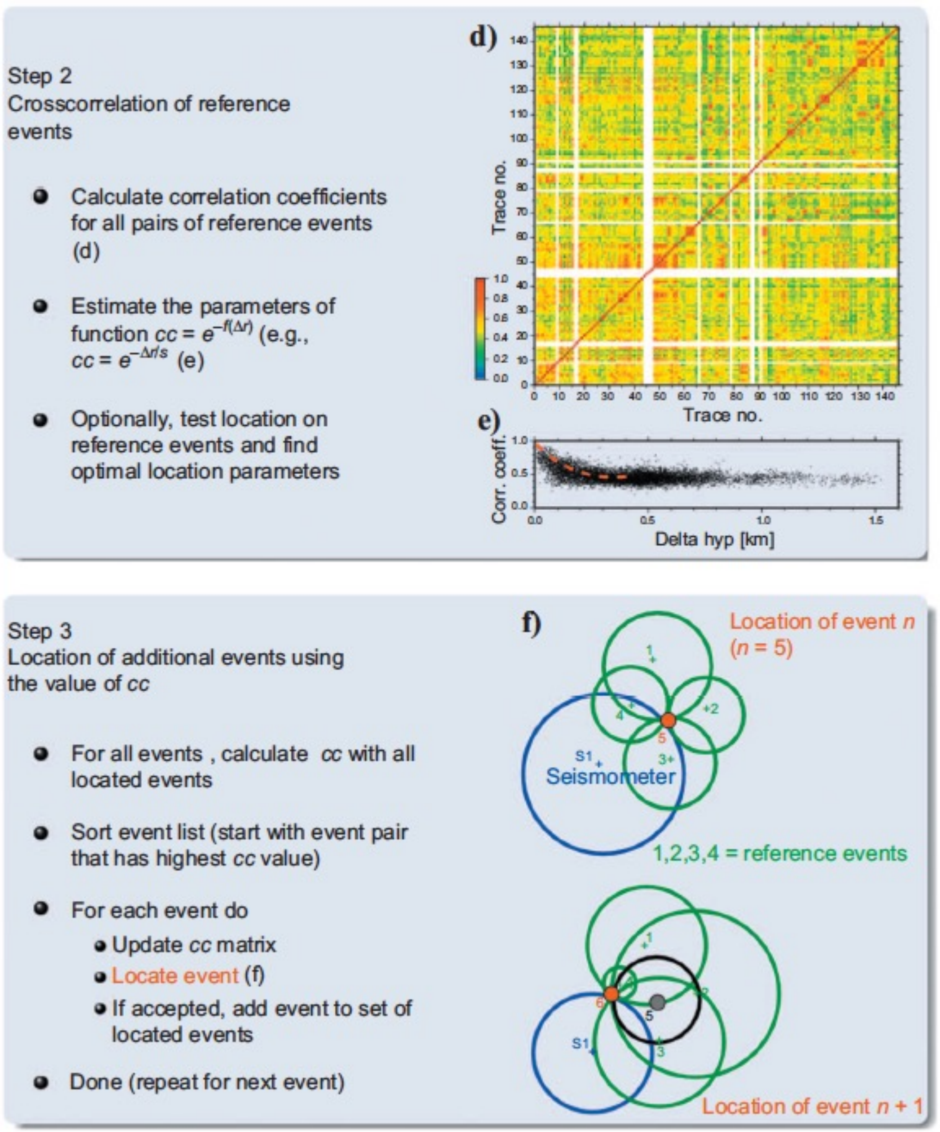
$$E = \sum_i \sum_j |C_{ij}^{\mathrm{obs}} - C_{ij}^{\mathrm{pre}}|.$$





Only recover relative distribution

Menke et al., BSSA, 1999

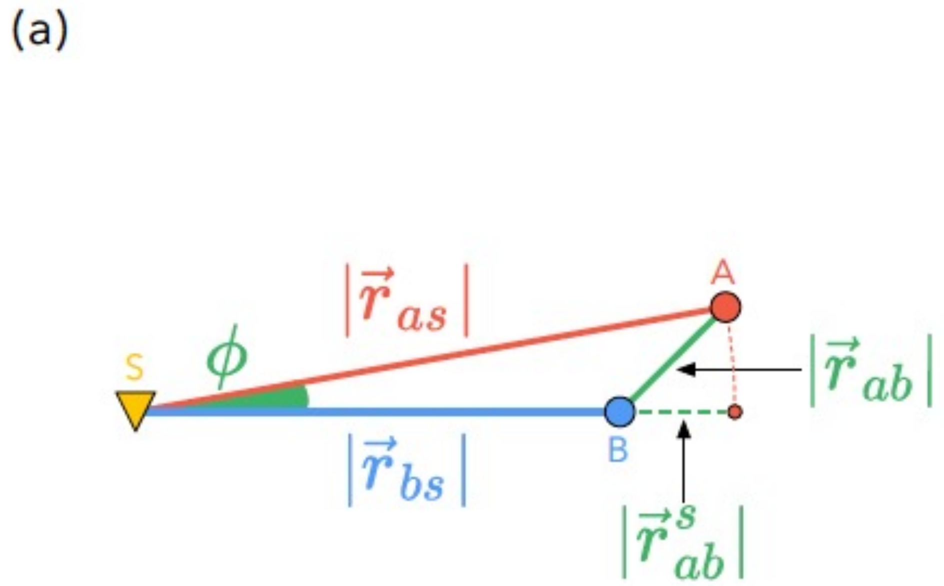


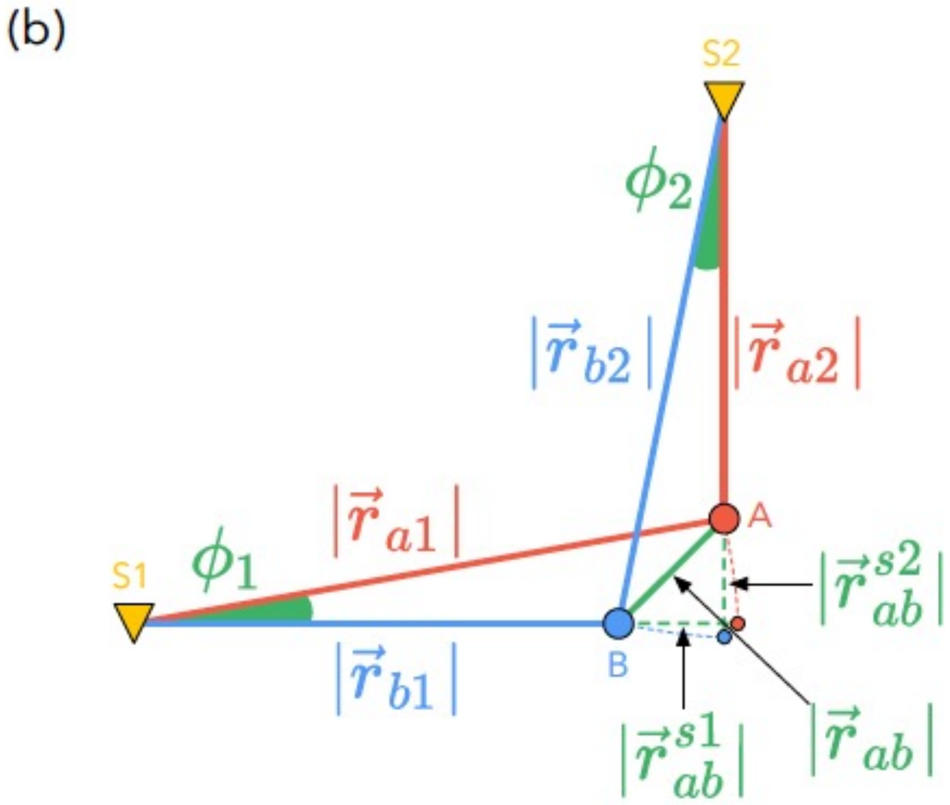
Absolute location: CC + Ts-p

Kummerow, Geophysics, 2010

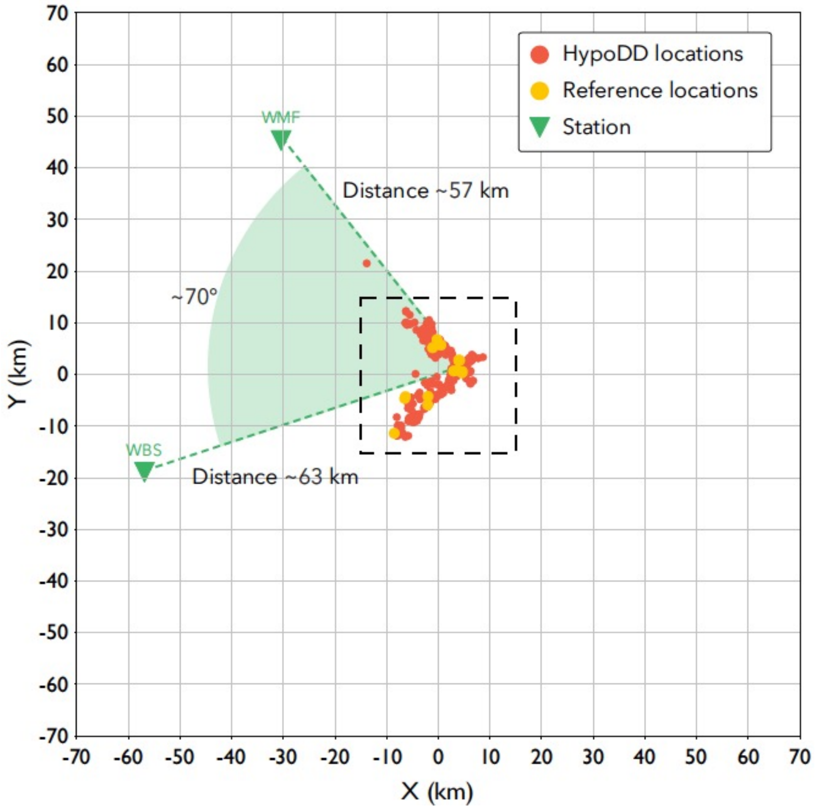
Single-station location:
3. distance-geometry-based method

$$||\mathbf{r}_{ab}||^2 = ||\mathbf{r}_{as}||^2 + ||\mathbf{r}_{bs}||^2 - 2\,||\mathbf{r}_{as}||\,||\mathbf{r}_{bs}||\cos\phi.$$



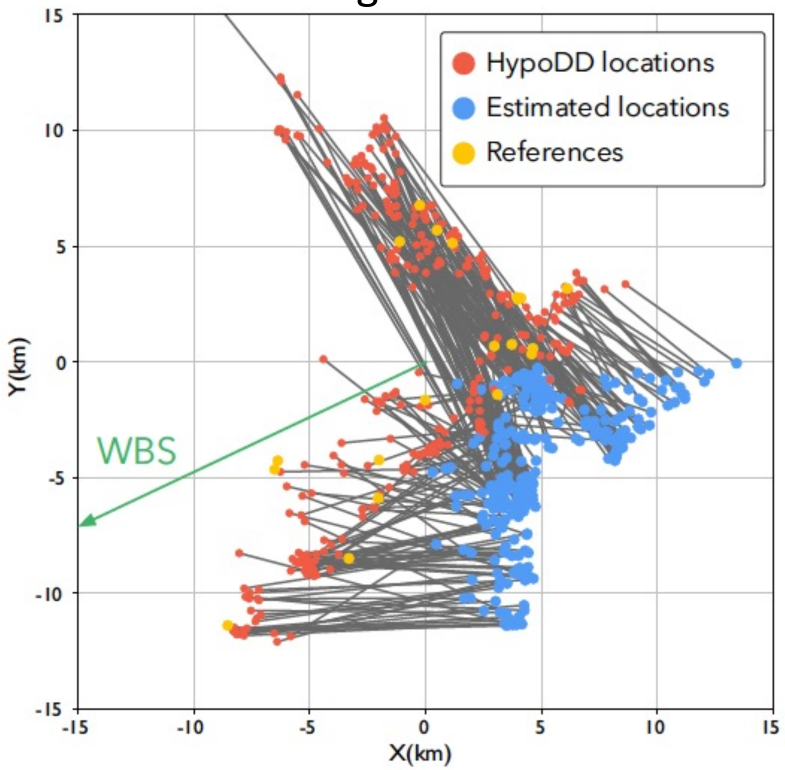


Grigoli, Ellsworth, Zhang et al, GJI, 2021

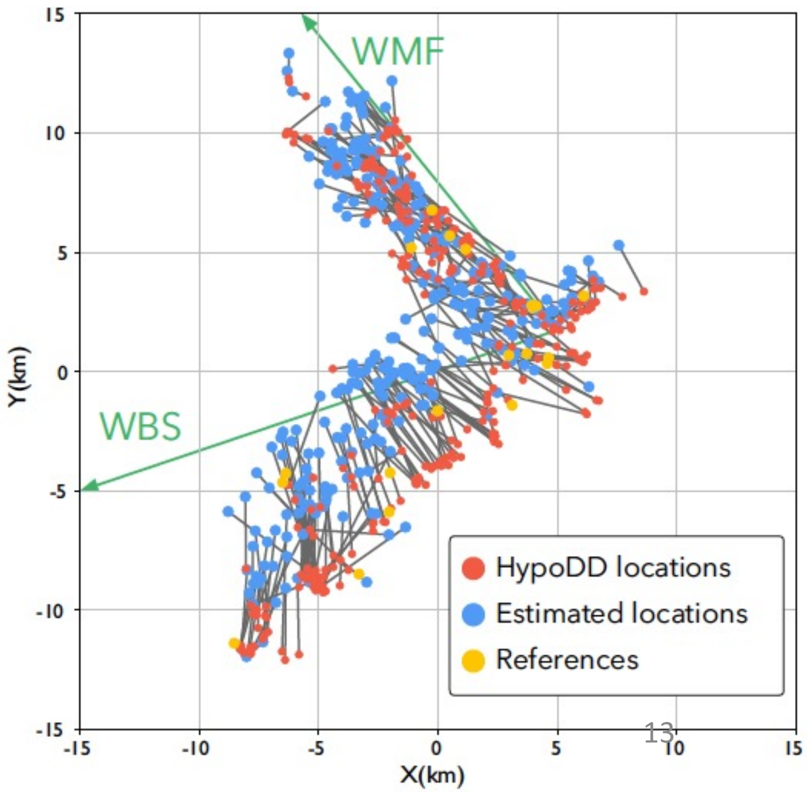


320 aftershocks of the 2019 Mw 6.4 Ridgecrest earthquake (20 first-hour aftershocks as references)

Single station



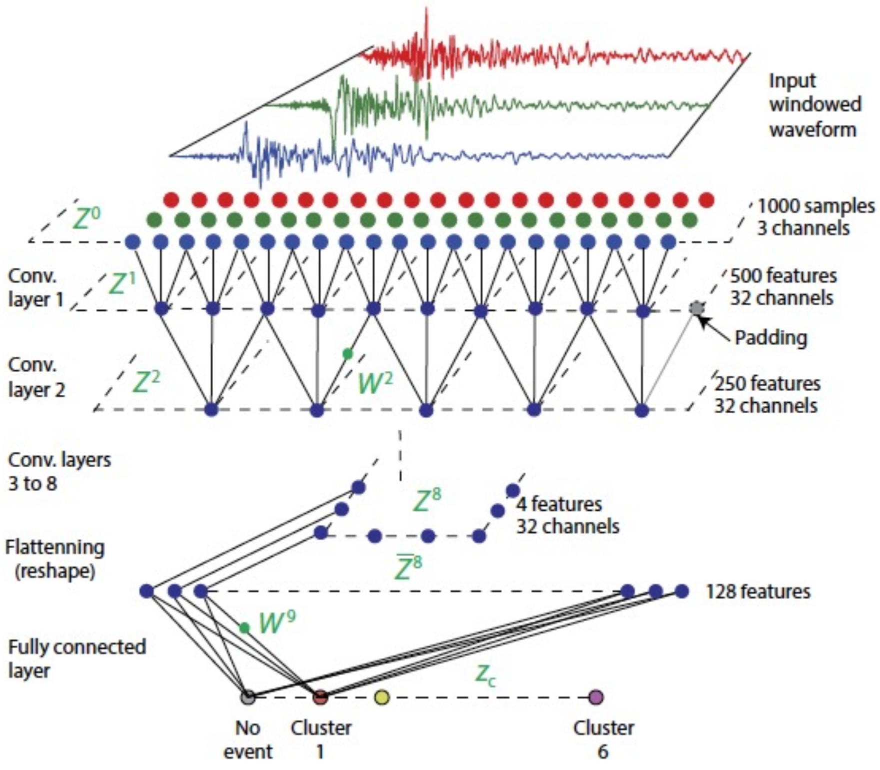
Two stations

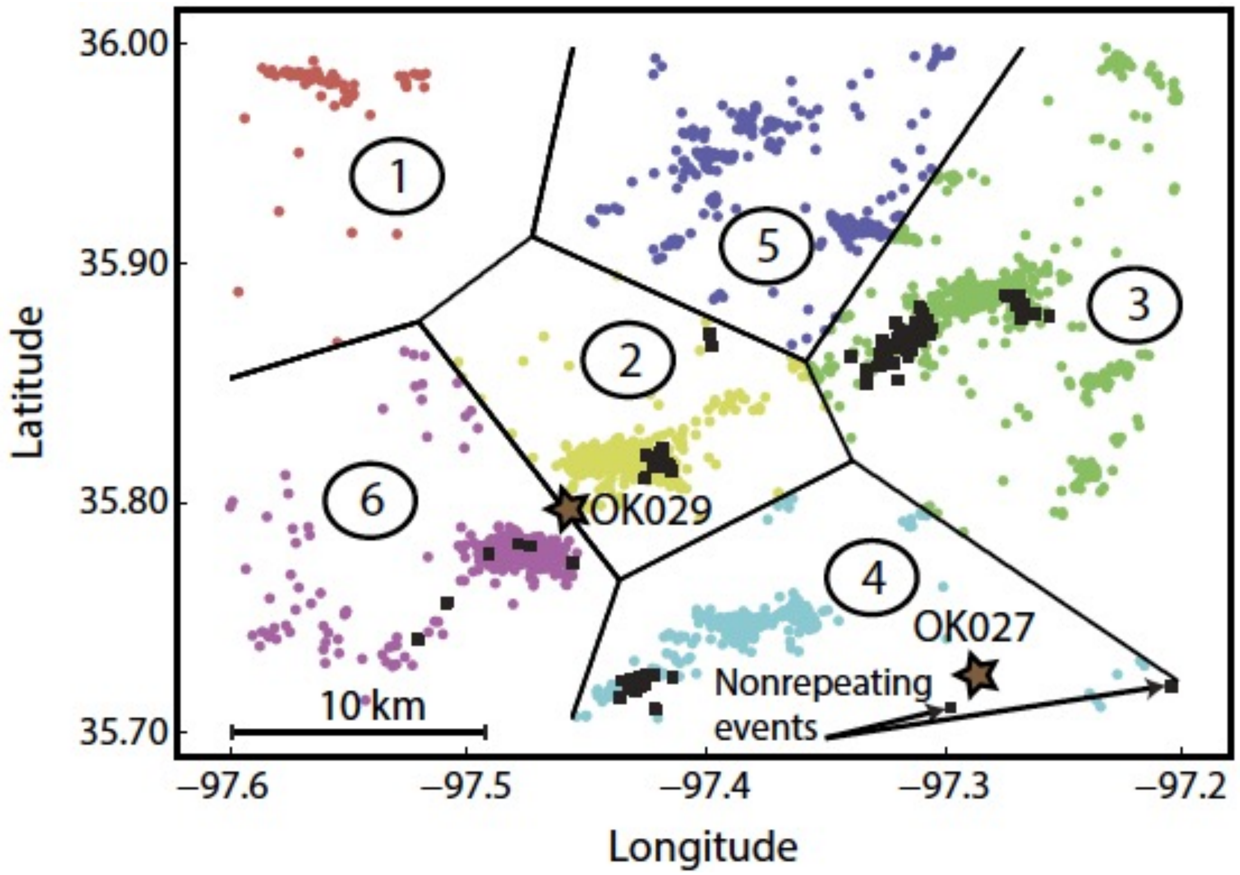


Grigoli, Ellsworth, Zhang et al, GJI, 2021

Single-station location:
3. machine-learning method

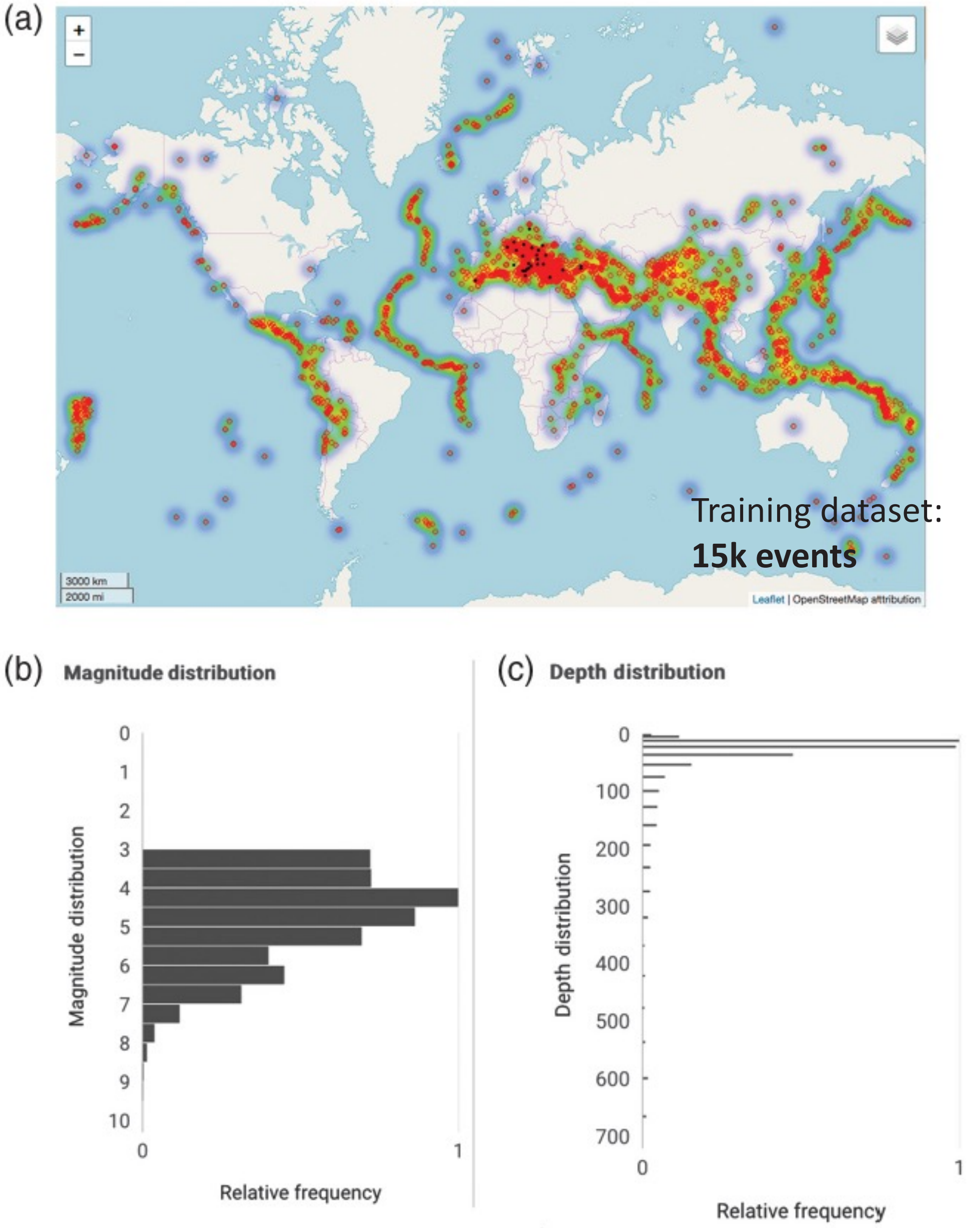
Detection + Classification



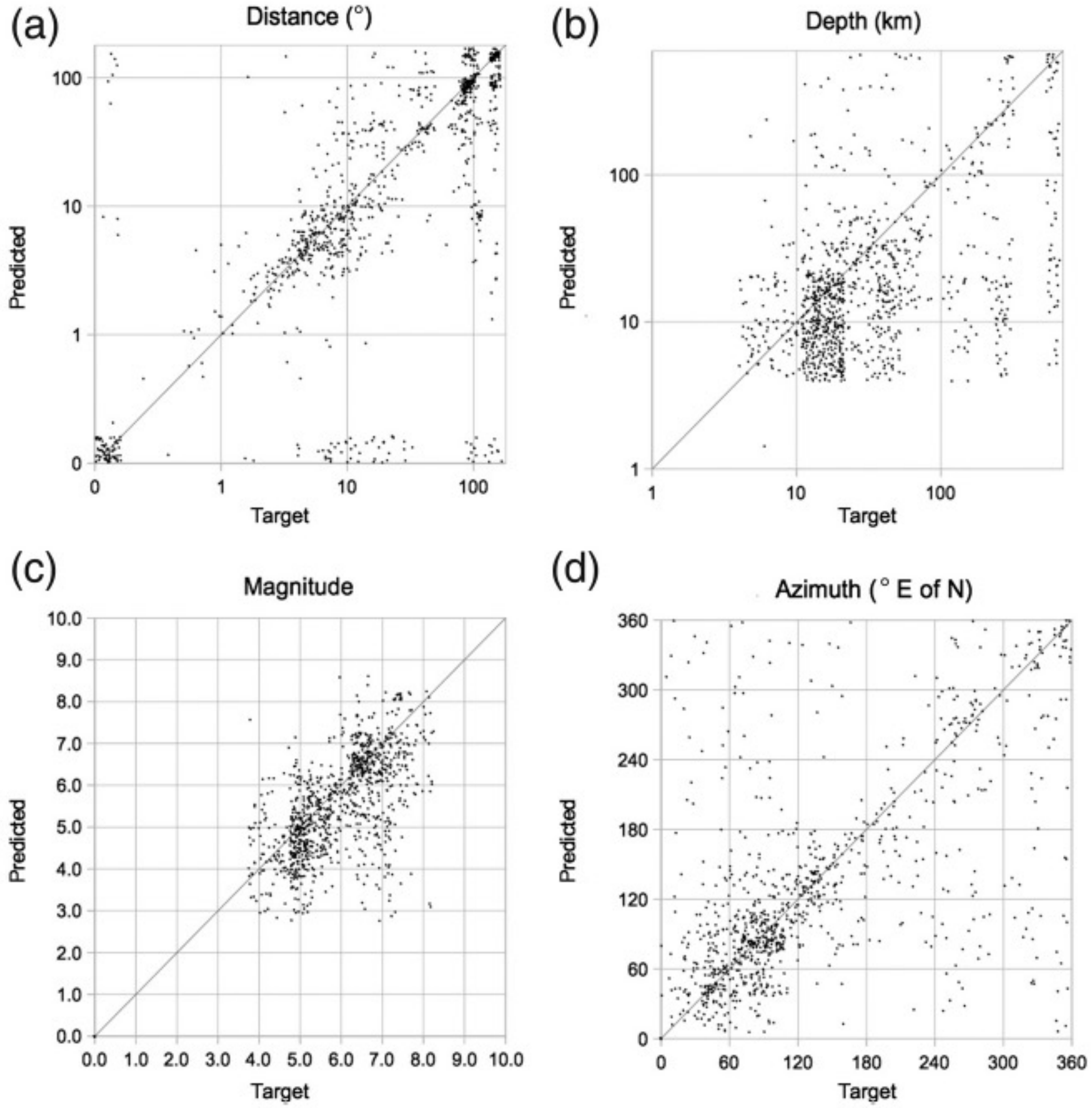


Perol et al., Sci. Adv., 2018

Detection + Classification (multiple parameters)



Training dataset:
15k events

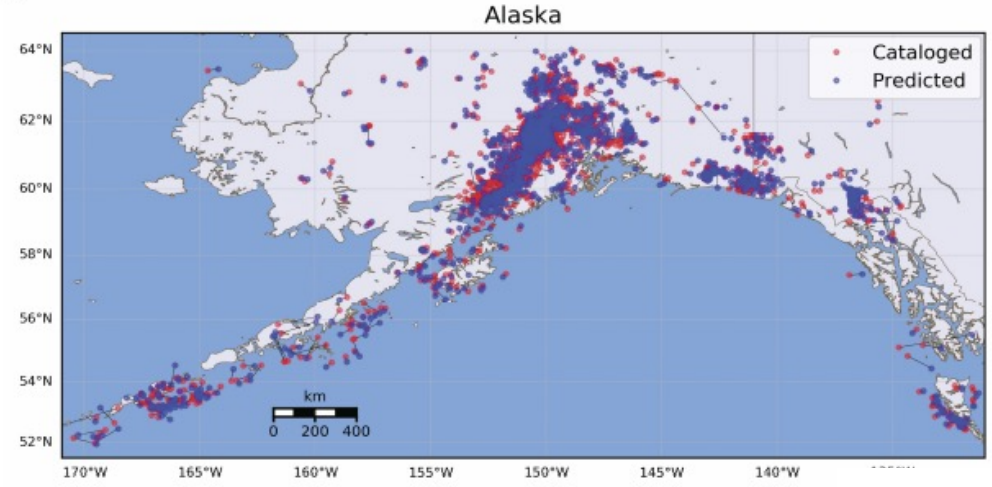


Station-event distance (0°–180°)
Station-event azimuth (0°–360°)

Event magnitude (0–10)
Event depth (0–700 km)

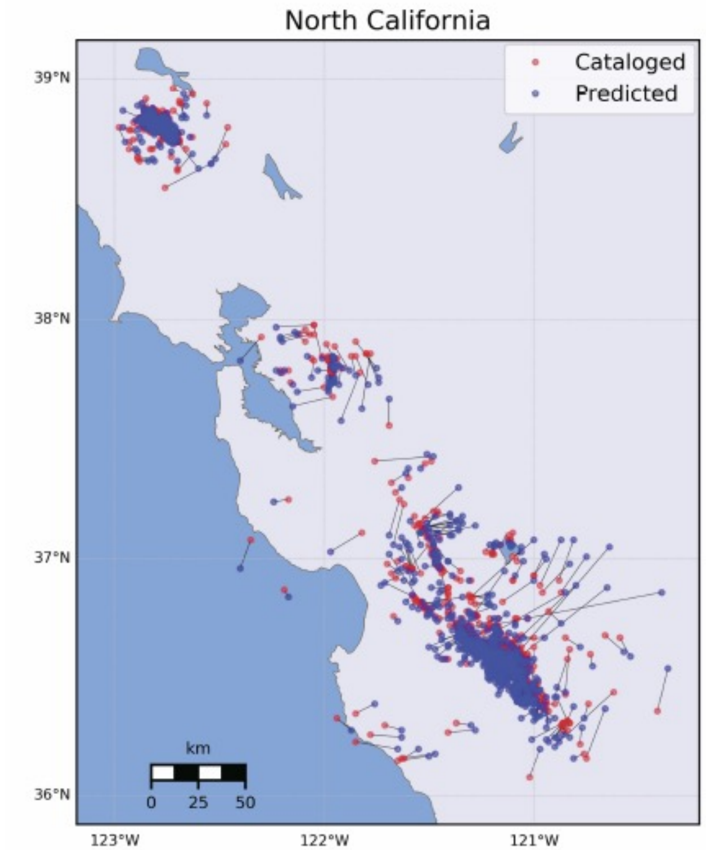
Lomax et al., SRL, 2019

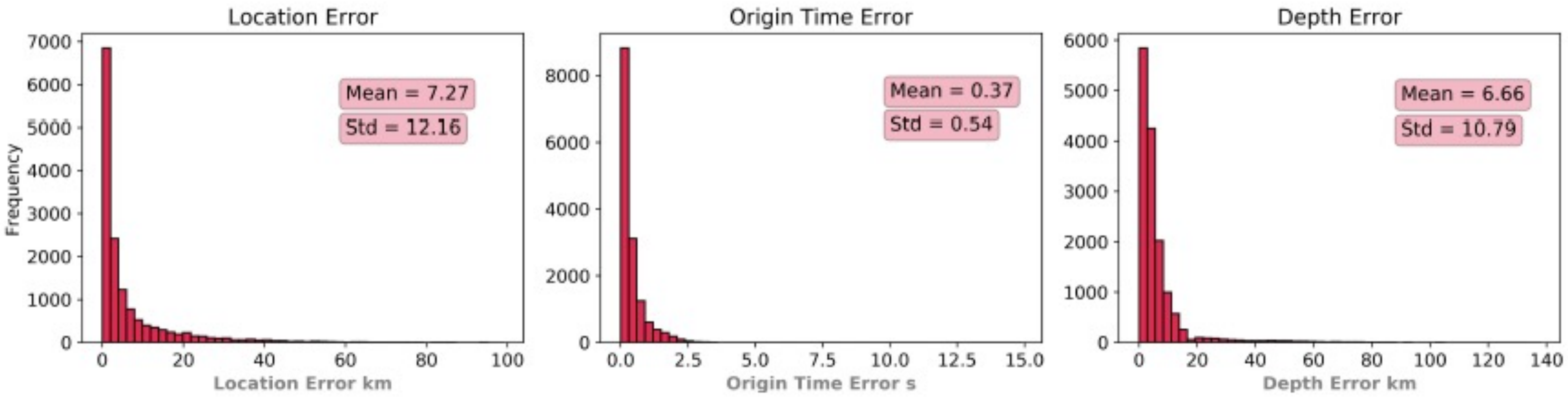
a)



Epicentral distance + back-azimuth + P travel time

b)





Training dataset

STanford EArthquake Data Set (STEAD)

450k events

Uncertainties:

Epicenter: 7.3 km

Origin time: 0.4 sec

Depth: 6.7 km

Mousavi and Beroza, IEEE, 2020

Accurate Depth Determination

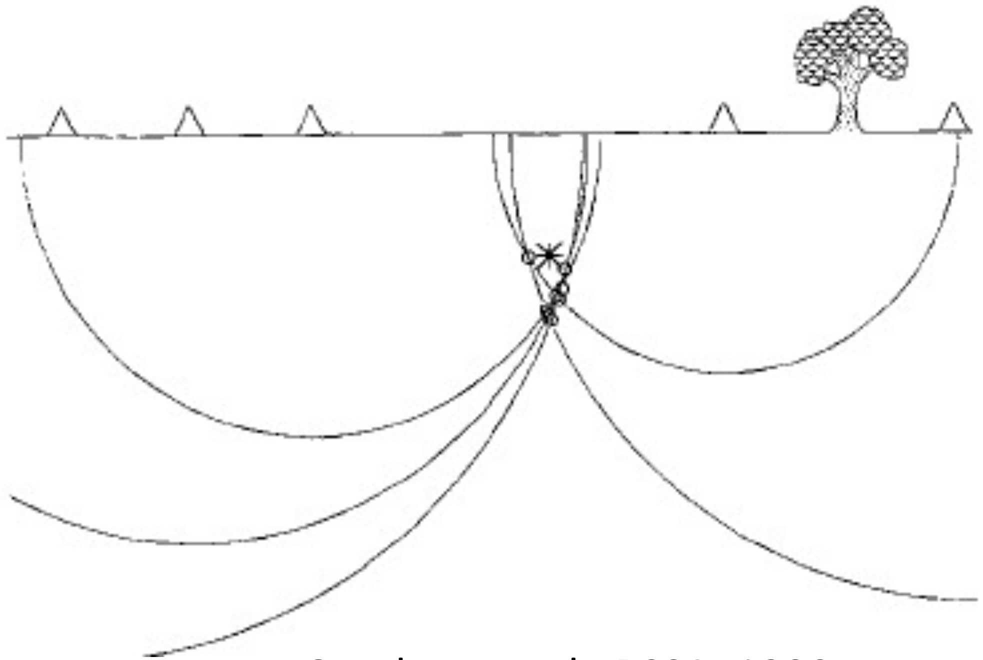
Bulletin of the Seismological Society of America, Vol. 80, No. 6, pp. 1605–1628, 1990

THE EFFECT OF *S*-WAVE ARRIVAL TIMES ON THE ACCURACY OF HYPOCENTER ESTIMATION

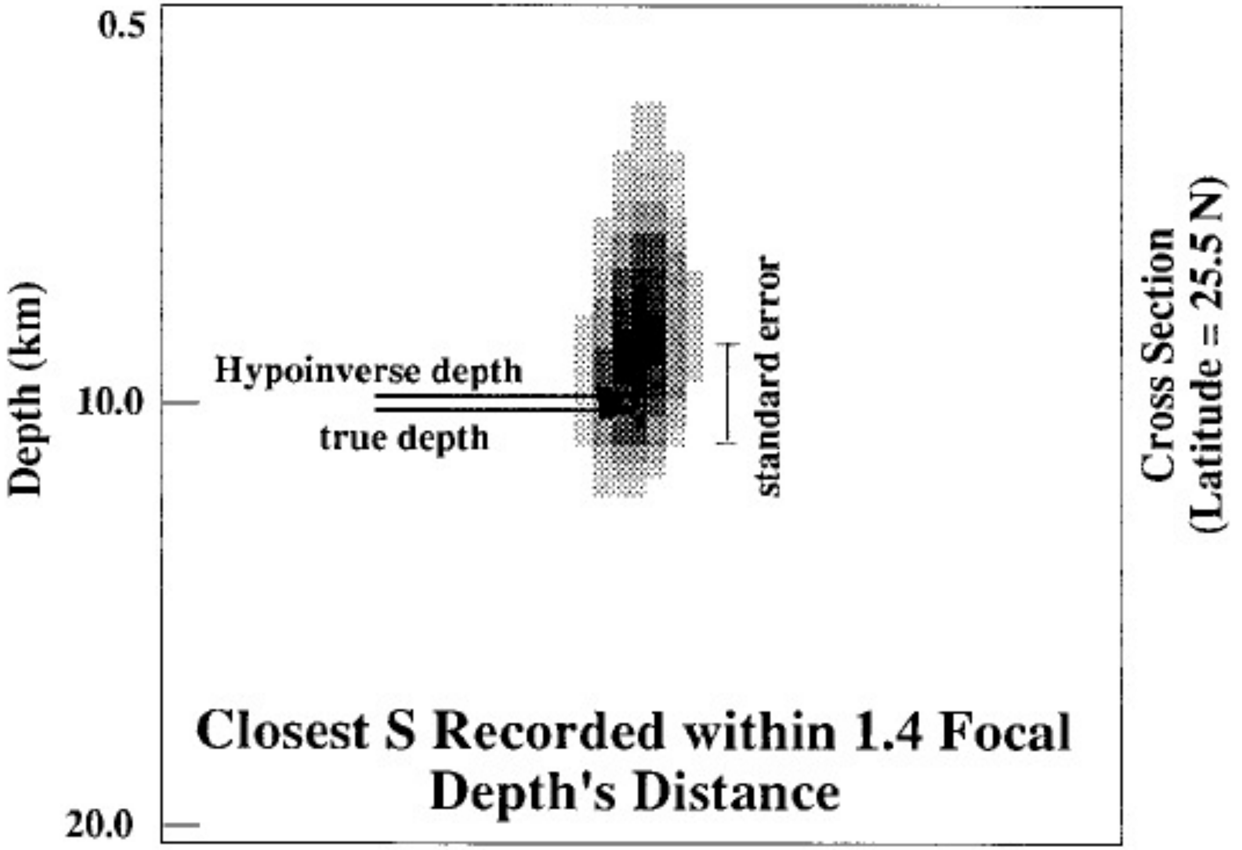
BY JOAN S. GOMBERG, KAYE M. SHEDLOCK, AND STEVEN W. ROECKER

ABSTRACT

Well-constrained hypocenters (latitude, longitude, depth, and origin time) are required for nearly all studies that use earthquake data. We have examined the theoretical basis behind some of the widely accepted "rules of thumb" for obtaining accurate hypocenter estimates that pertain to the use of *S* phases and illustrate, in a variety of ways, why and when these "rules" are applicable. Results



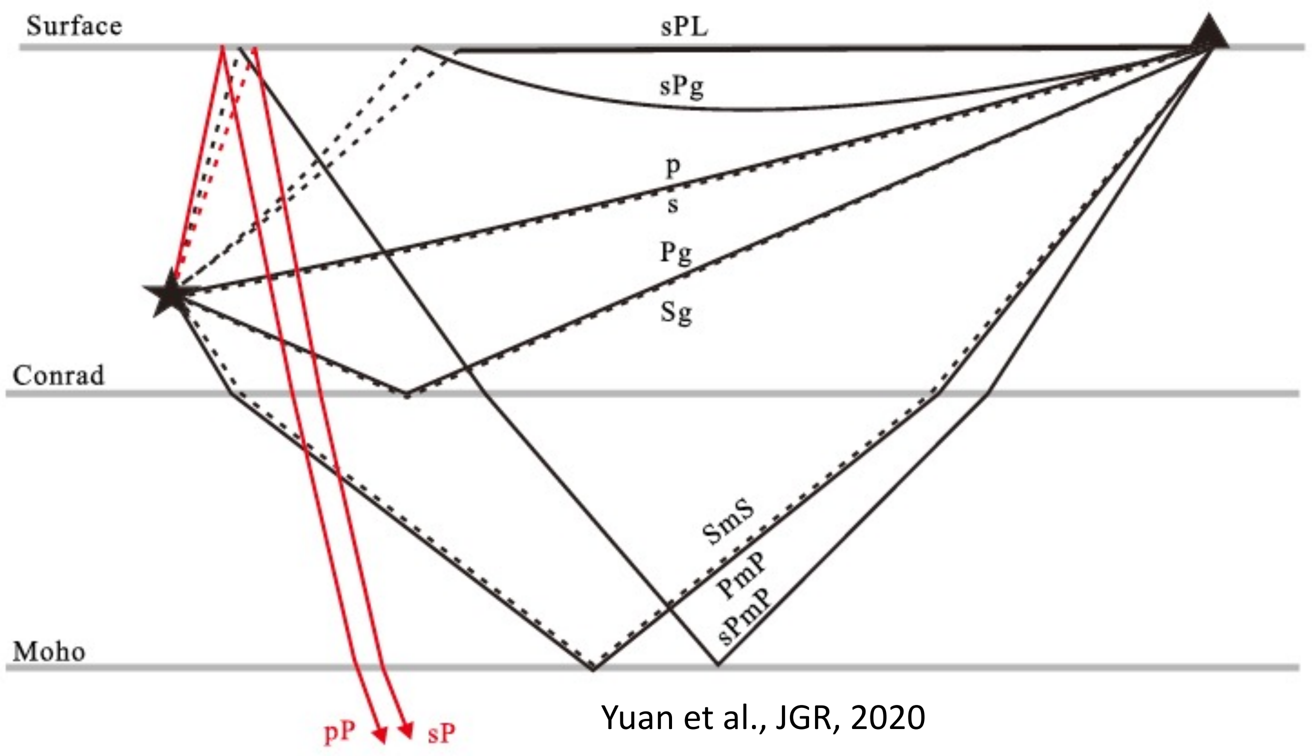
Gomberg et al., BSSA, 1990



At least one S phase is confidently picked at stations within distances of < ~1.4 times the depth

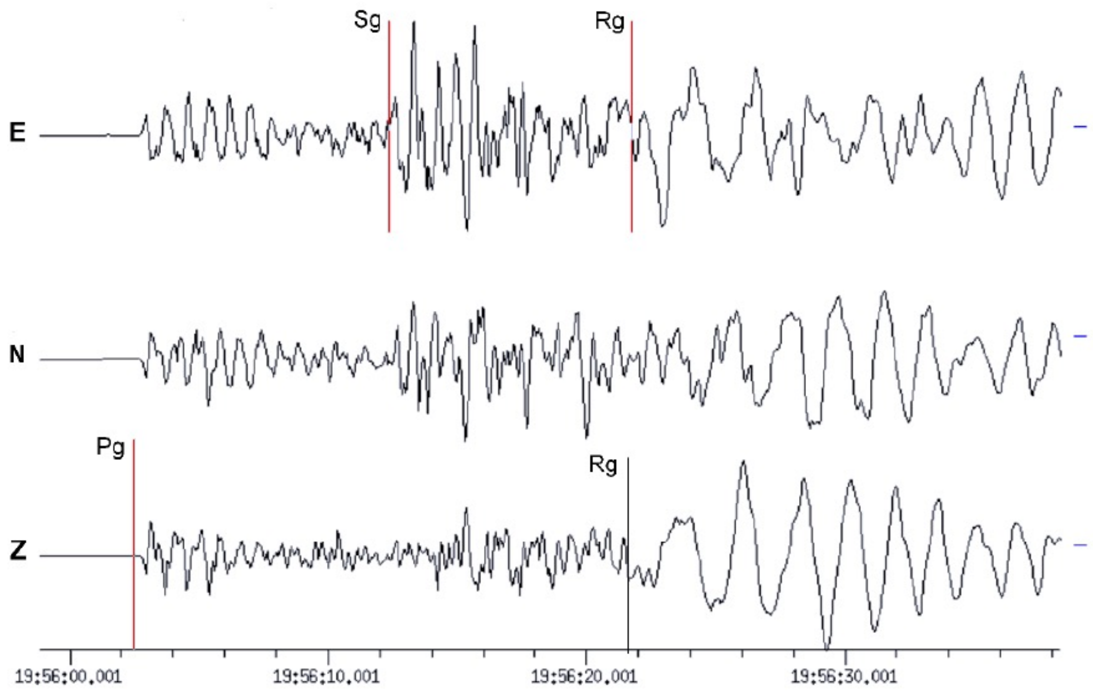
How to determine depth accurately?

Depth phases



Yuan et al., JGR, 2020

Surface waves (e.g., Rg)

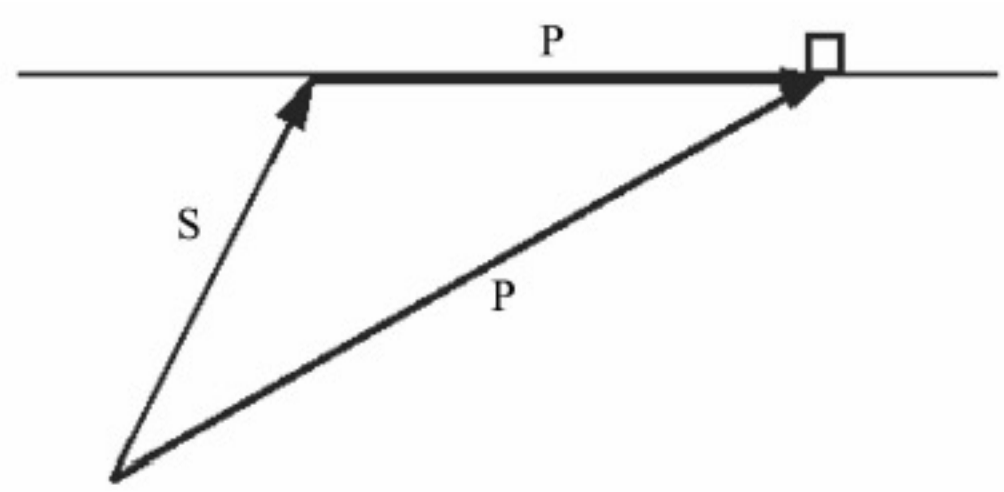


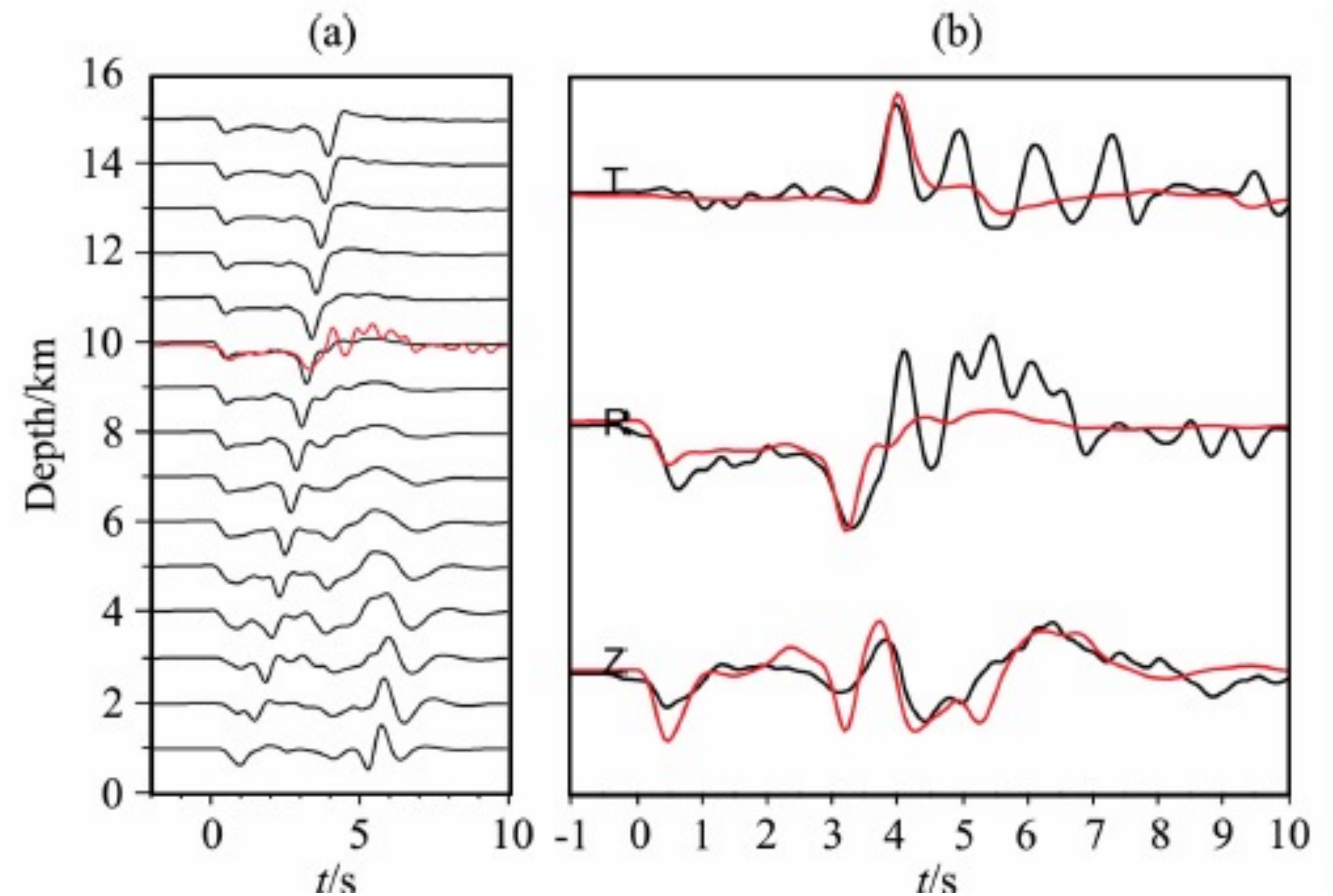
D = 80 km, h = 1 km, M_l = 3.7

Local and regional region: sPL, sPg, sPn, SmS, sSmS, PmP, sPmP, etc.
Global region: pP, sP, pwP, swP, W phase, etc

- Very sensitive to source depth
- Distance: > ~5 times source depth;
- Strong Rg wave when depth < 5~8 km.

Depth Phase: sPL



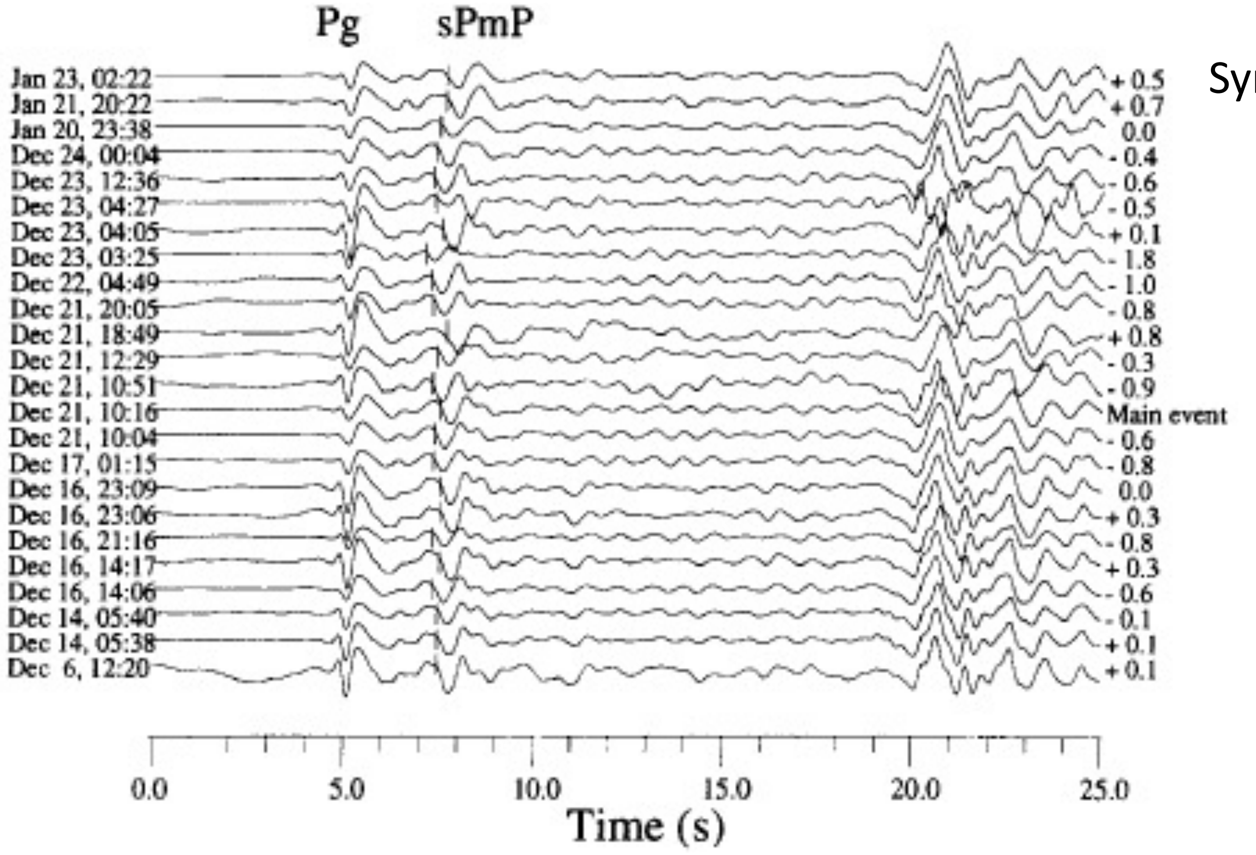


sPL phase

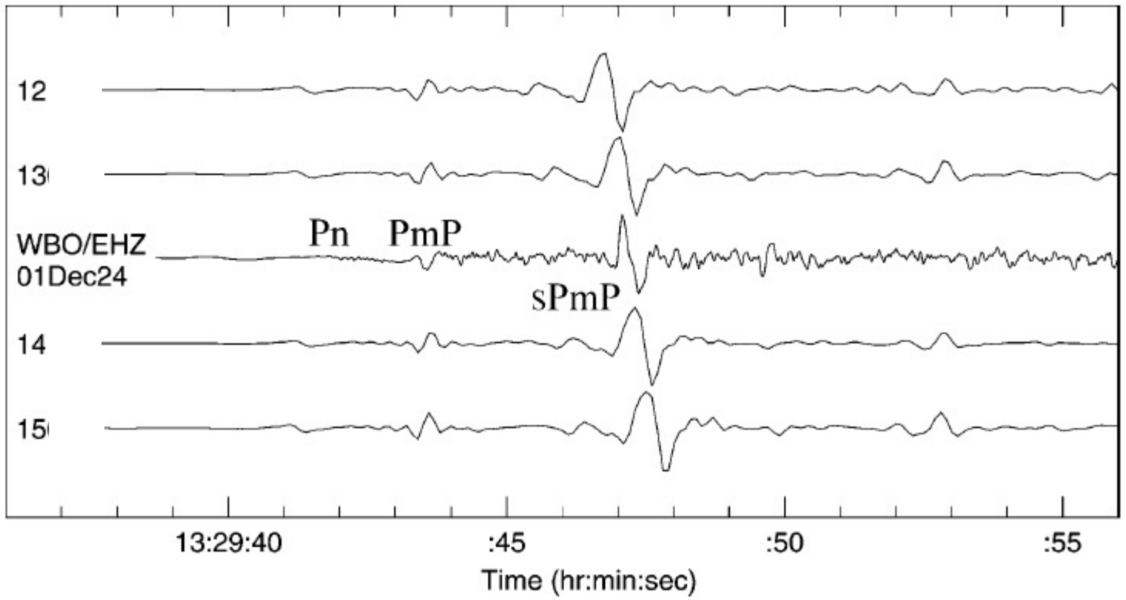
Distance range: 30 ~ 50 km

Chong et al., Chin. J. Geophys., 2010

Depth Phase: sPmP



Syn. Depth (km)

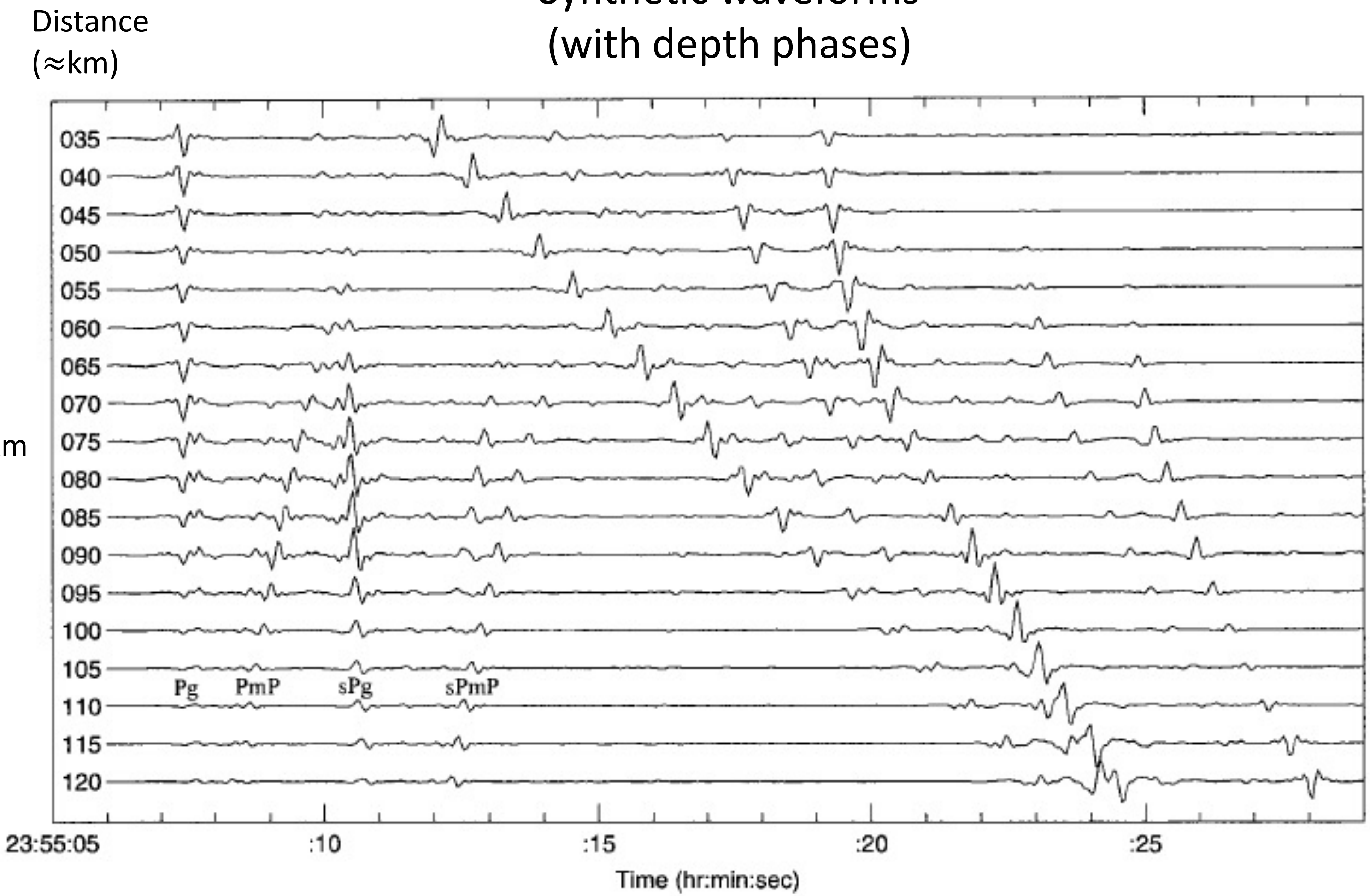


Bock et al., Tectonophysics, 1996

Ma and Atkinson, BSSA, 2006

Synthetic waveforms (with depth phases)

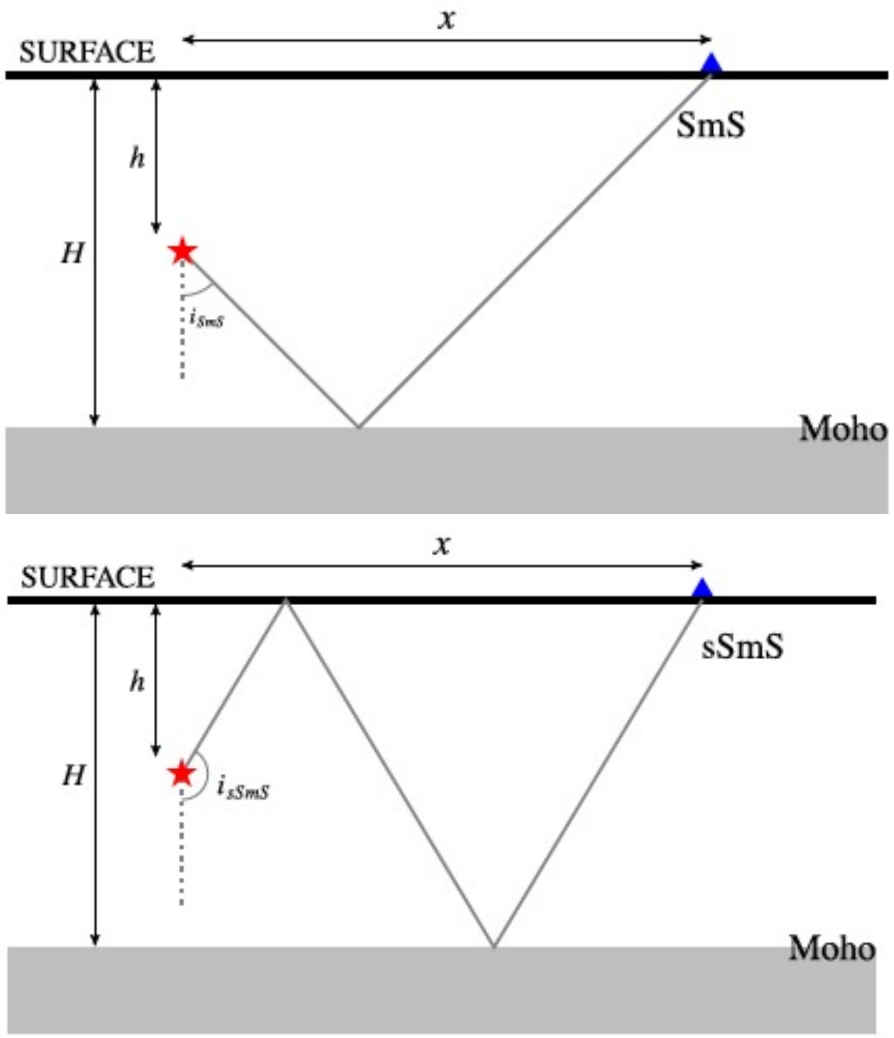
Depth: 12 km

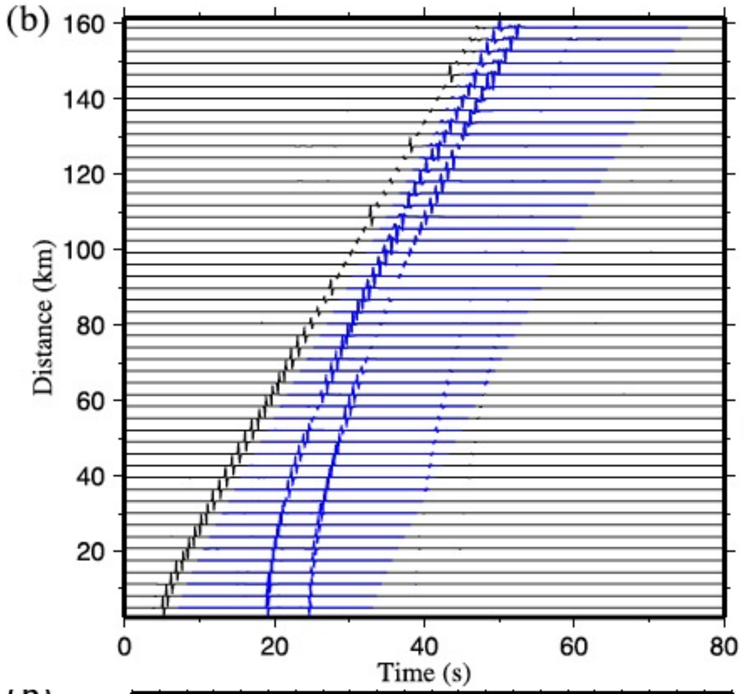


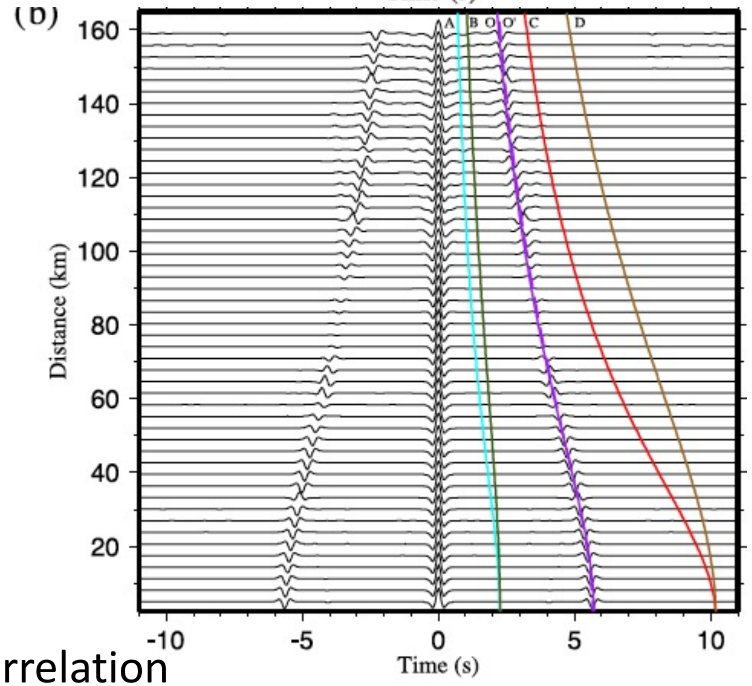
Different depth phases have different recording distances.

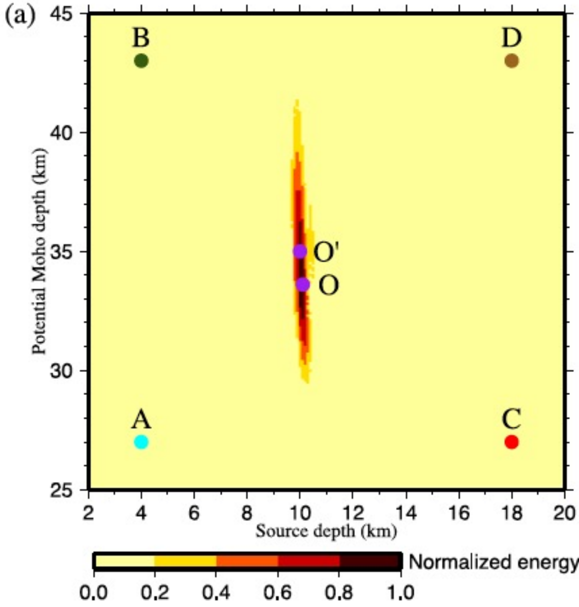
Ma and Atkinson, BSSA, 2006

Depth information extraction: Autocorrelation + Stacking



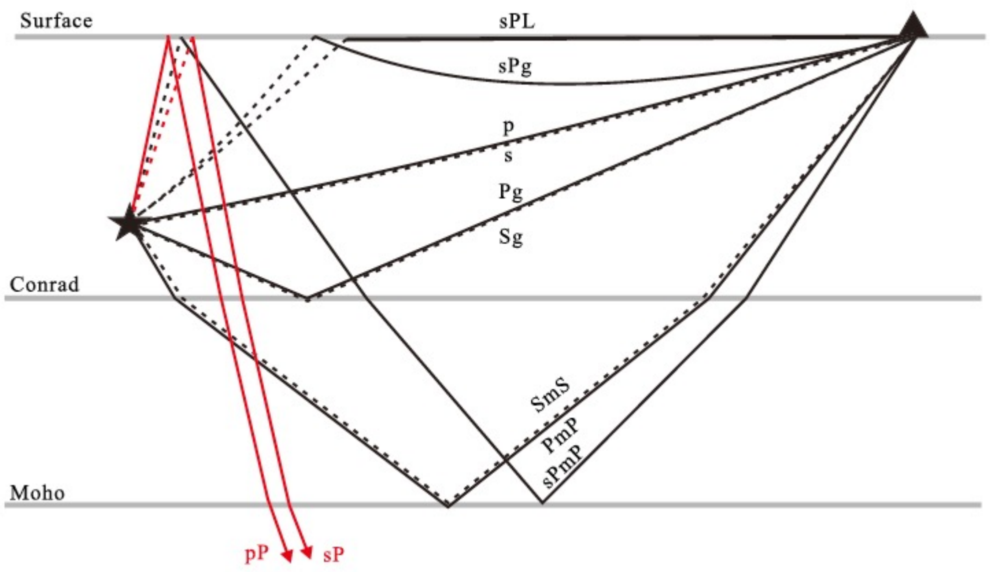




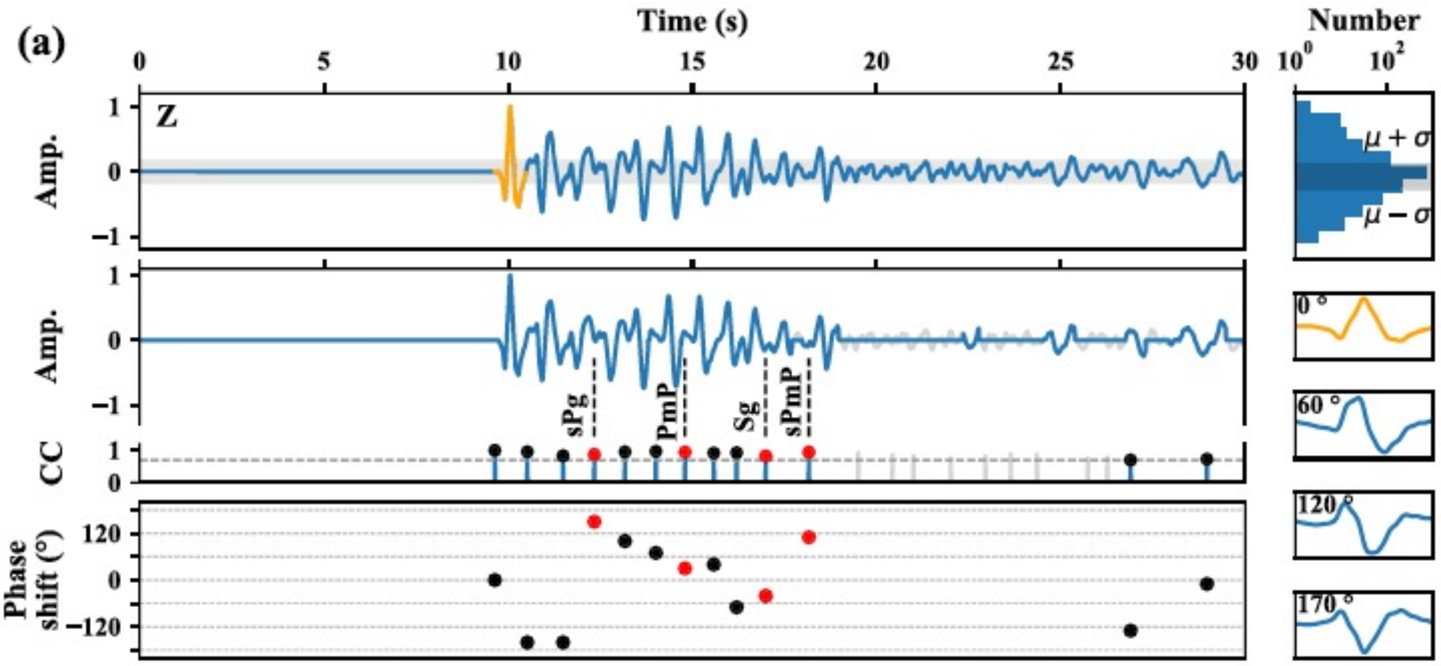


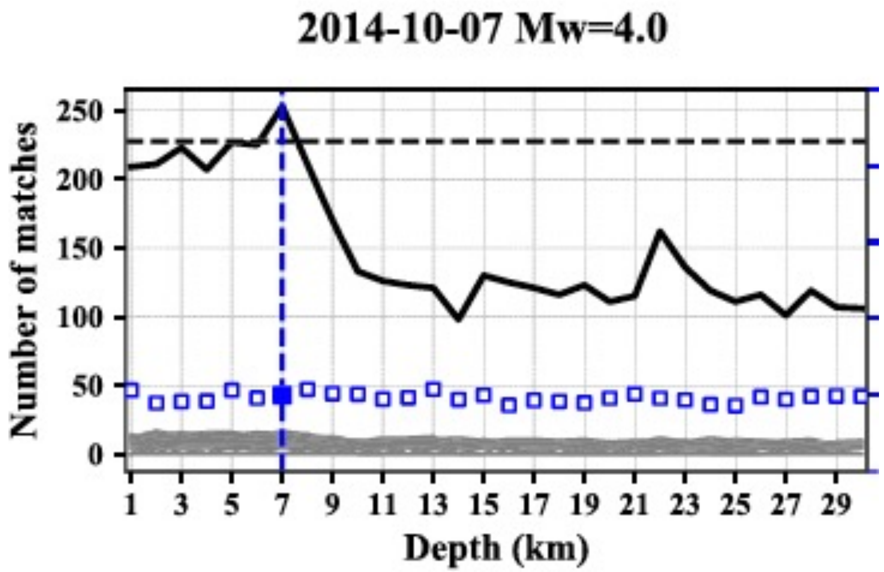
Zhang and Wen, GJI, 2014

Body wave autocorrelation



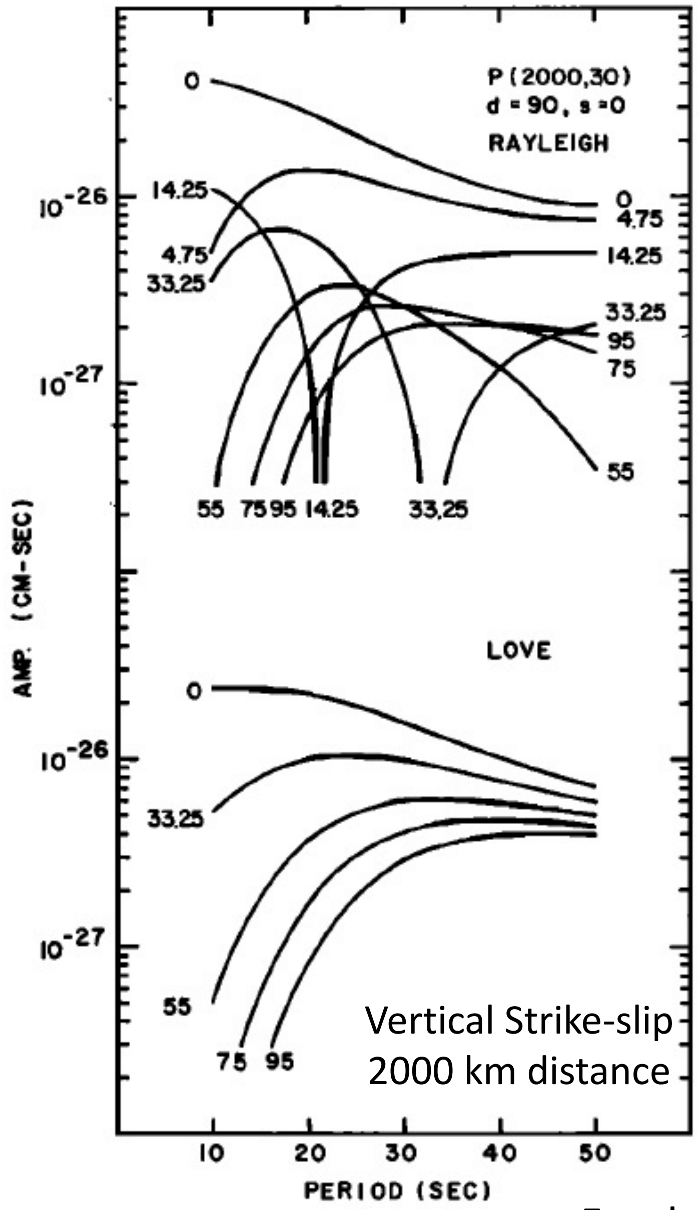
Depth-Scanning: Scan all potential depth phases

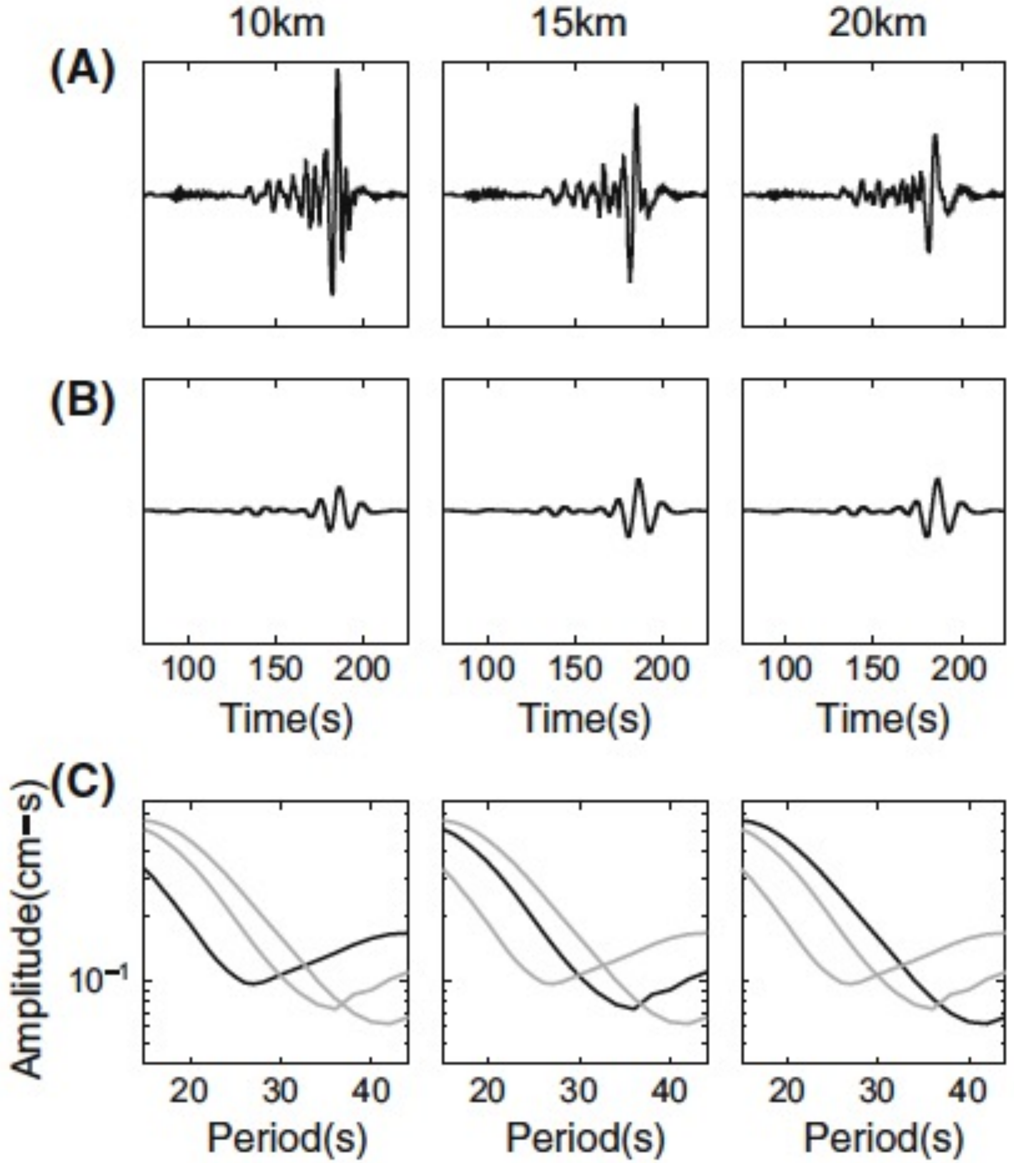




Yuan et al., JGR, 2020

Surface waves: Rayleigh wave amplitude spectral



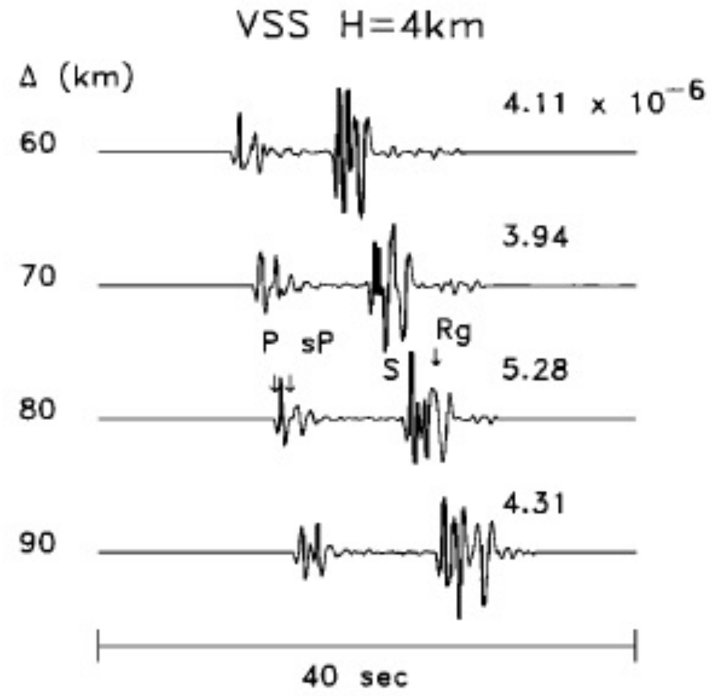


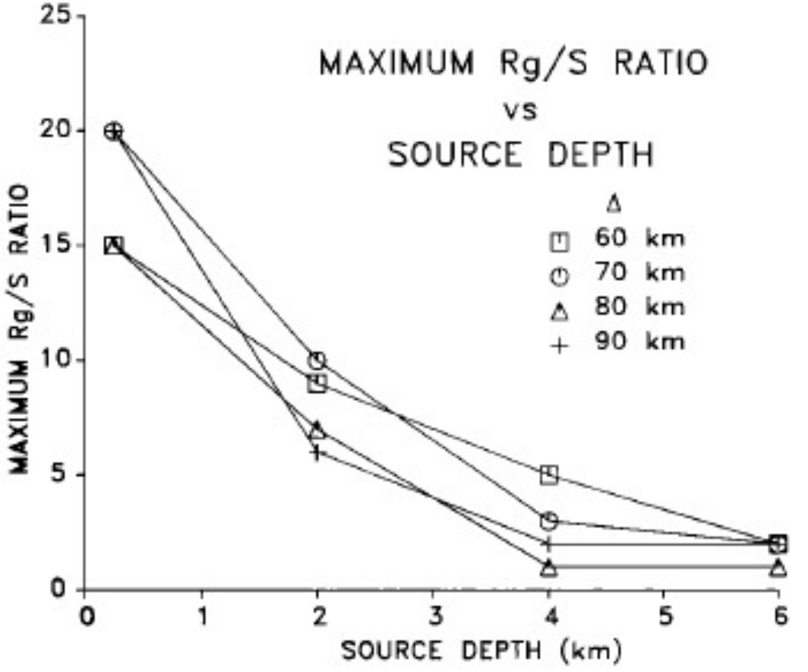
Tsai and Aki, JGR, 1970

Fundamental mode Rayleigh wave: 10–50 sec

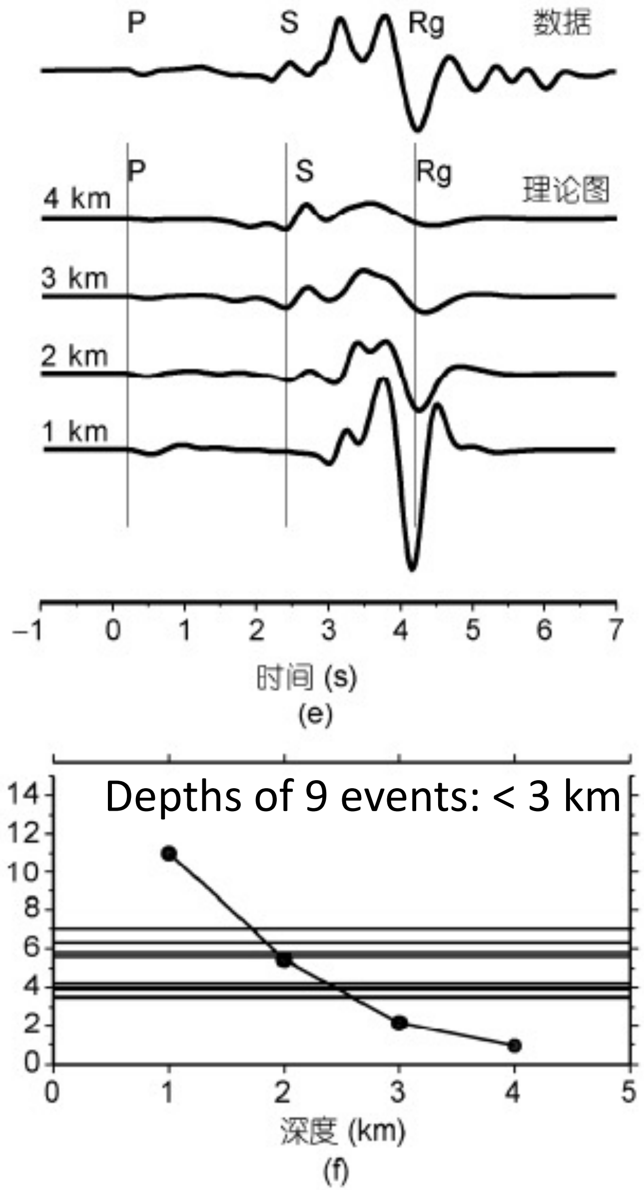
Jia et al., Pure Appl. Geophys., 2017

Surface wave/body wave amplitude ratio (e.g., Rg/S)





Langston et al., JGR, 1987



Luo et al., Sci China Ser D-Earth Sci, 2010

Unknows:
e.g., velocity, focal mechanism, etc.

Outline

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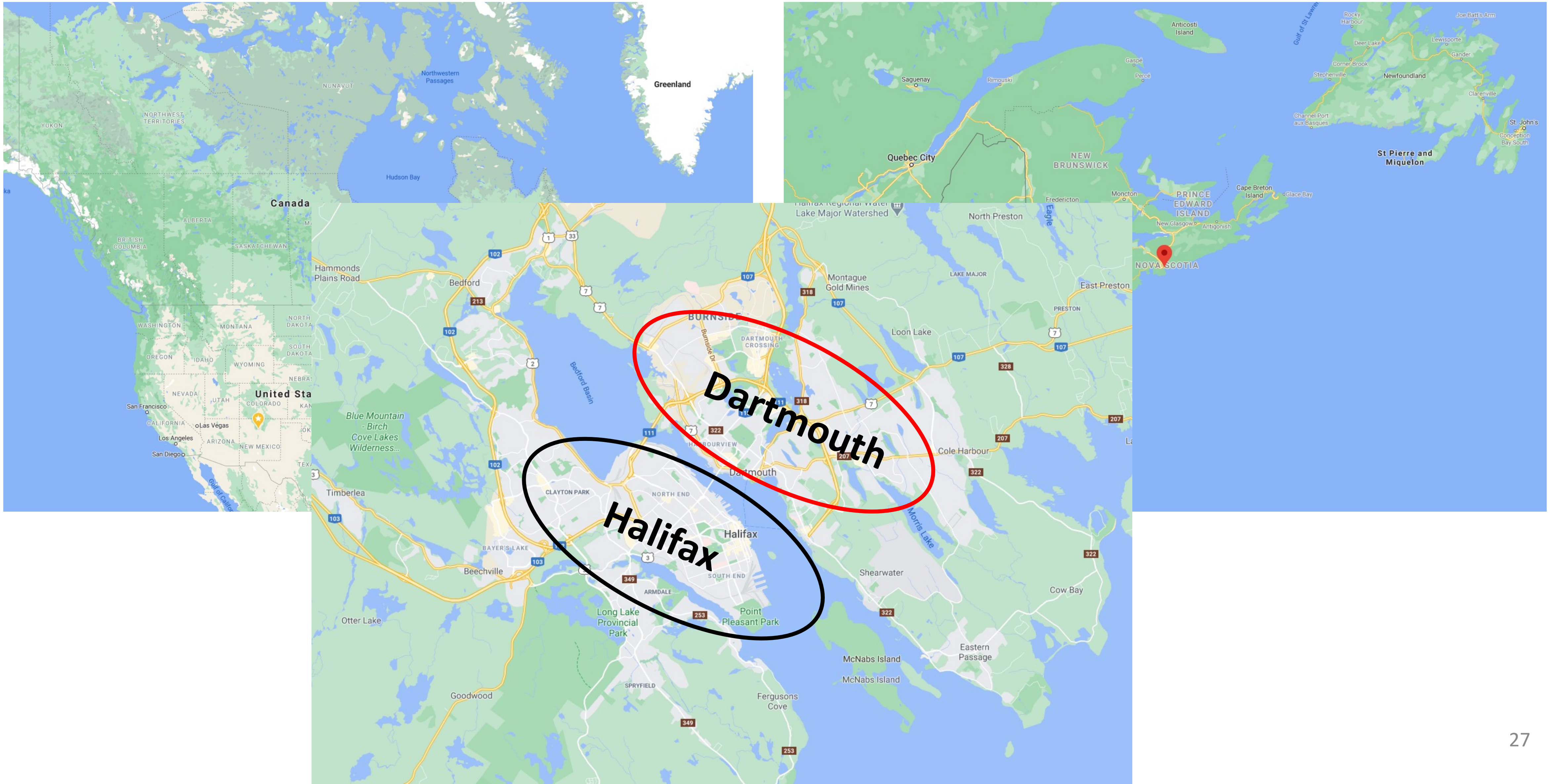
- Source characterization for two small earthquakes in Dartmouth, NS
- Summary

Where is Dartmouth, Nova Scotia, Canada?



First earthquake: Mar. 1, 2020 at 8:40 pm (local time)

Magnitude: M_N 2.4 (Earthquakes Canada, M_L 1.5 - USGS)
Depth: 2 km (Earthquakes Canada)

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(Final catalog M_N 2.4)

Magnitude 2.6 earthquake jolts parts of Dartmouth

Some Dartmouth residents were jolted by a minor earthquake on Sunday night.

Halifax Regional Police said numerous reports came in around 8:40 p.m. from people who felt their homes shaking and heard an "extremely loud noise" that lasted several seconds.

The reports came from the area north east of Lake Mic Mac, including Waverley Rd., Montebello Dr. and Caledonia Rd.

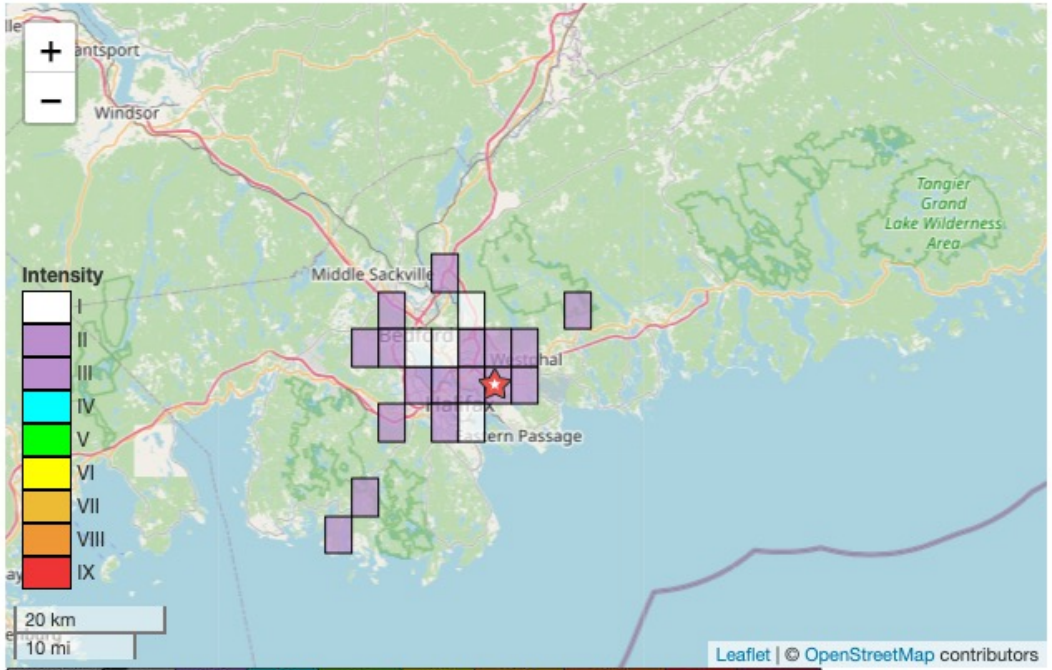
According to Nick Ackerley, a seismologist with Earthquakes Canada, the earthquake was a small magnitude 2.6.

"That is very small, well below the threshold of something that might cause damage," explained Ackerley.

https://www.halifaxtoday.ca/local-news/magnitude-26-earthquake-jolts-parts-of-dartmouth-2131000

Did you feel it?

Intensity	Reports
I	26
II	508
III	50
IV	10
V	0
VI	1
VII	1
VIII	0
IX	0
Total	596



INTENSITY	I	II - III	IV	V	VI	VII	VIII	IX	X+
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy

☆ epicentre

https://earthquakescanada.nrcan.gc.ca/recent/2020/20200302.0038/dyfi-en.php

- No reported damages and injuries
- But widely felt by residents with loud noise

Second earthquake: Mar. 3, 2020 at 00:42 am (local time)

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Aftershock shakes parts of Dartmouth, says Earthquakes Canada

Earthquakes Canada says an aftershock struck the Westphal and Montebello areas of Dartmouth early Tuesday morning.

Seismologist Nick Ackerley says the aftershock was a magnitude 2.6, the same magnitude as the earthquake on Sunday night that impacted the neighbourhoods.

"The typical aftershock sequence is that the largest aftershock is about a unit of magnitude smaller than the foreshock, so already we're deviating from that a little bit," explained Ackerley.

In a release issued early Tuesday morning, Halifax Regional Police said numerous reports came in around 12:42 a.m. on Tuesday from people in East Dartmouth who felt their homes shaking and heard what sounded like an explosion.

There were no injuries or damage reported.

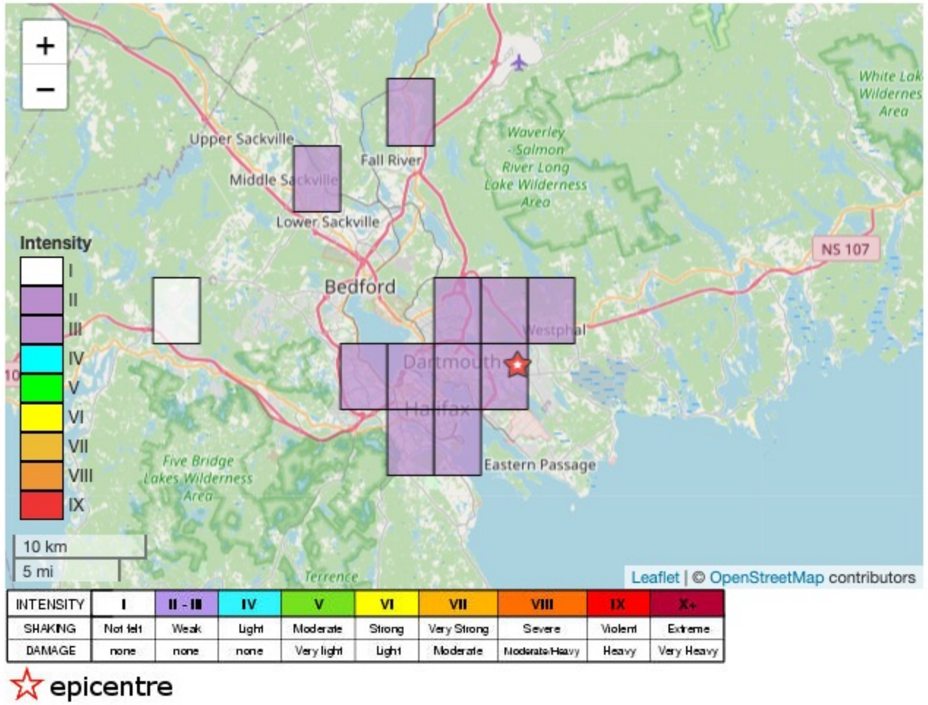
Ackerley says those loud noises people in the area heard, both on Tuesday morning and Sunday night during the first earthquake, are a result of how shallow these events were.

https://www.halifaxtoday.ca/local-news/aftershock-shakes-parts-of-dartmouth-says-earthquakes-canada-2133739

Magnitude: M_N 2.6 (Earthquakes Canada, M_L 2.1 - USGS)
Depth: 2 km (Earthquakes Canada)

Did you feel it?

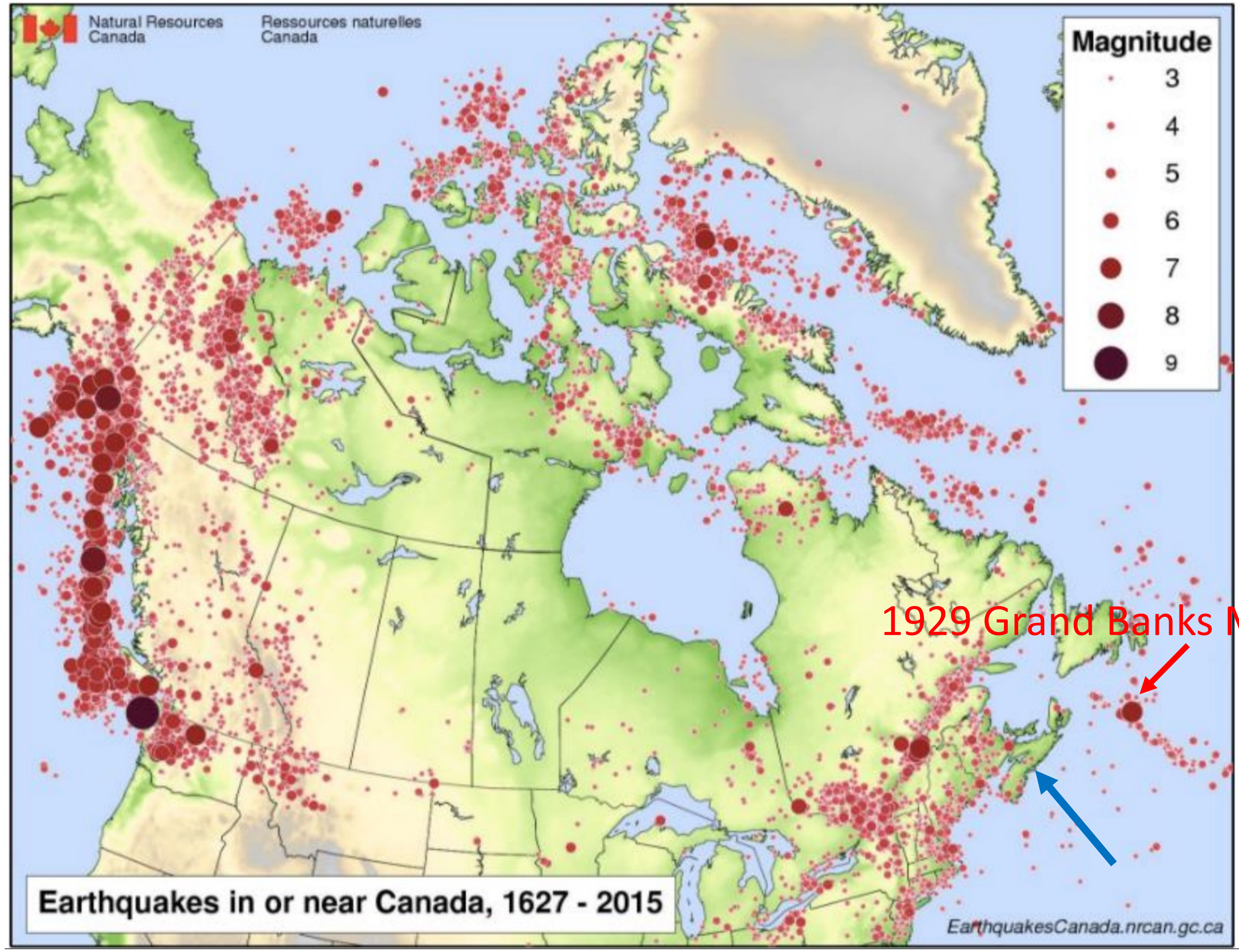
Intensity	Reports
I	8
II	206
III	82
IV	10
V	1
VI	0
VII	0
VIII	0
IX	0
Total	307



https://earthquakescanada.nrcan.gc.ca/recent/2020/20200303.0442/dyfi-en.php

- No reported damages and injuries
- But widely felt by residents with loud noise

Seismicity in or near Canada



1929 Grand Banks M7.2 earthquake

https://earthquakescanada.nrcan.gc.ca
/historic-historique/caneqmap-en.php

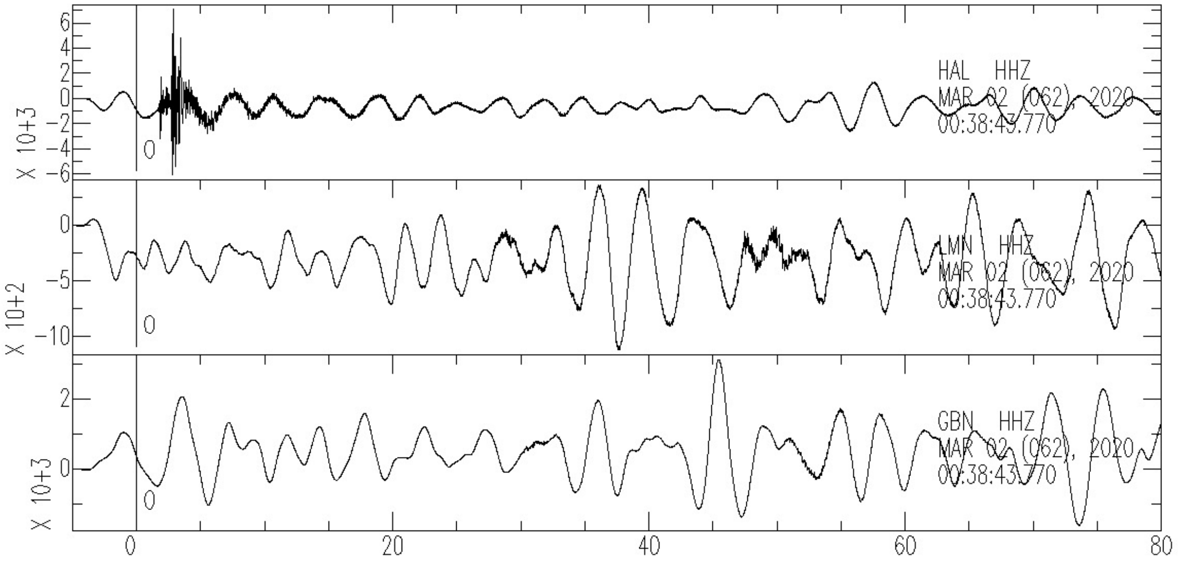
CTV live interview

Questions

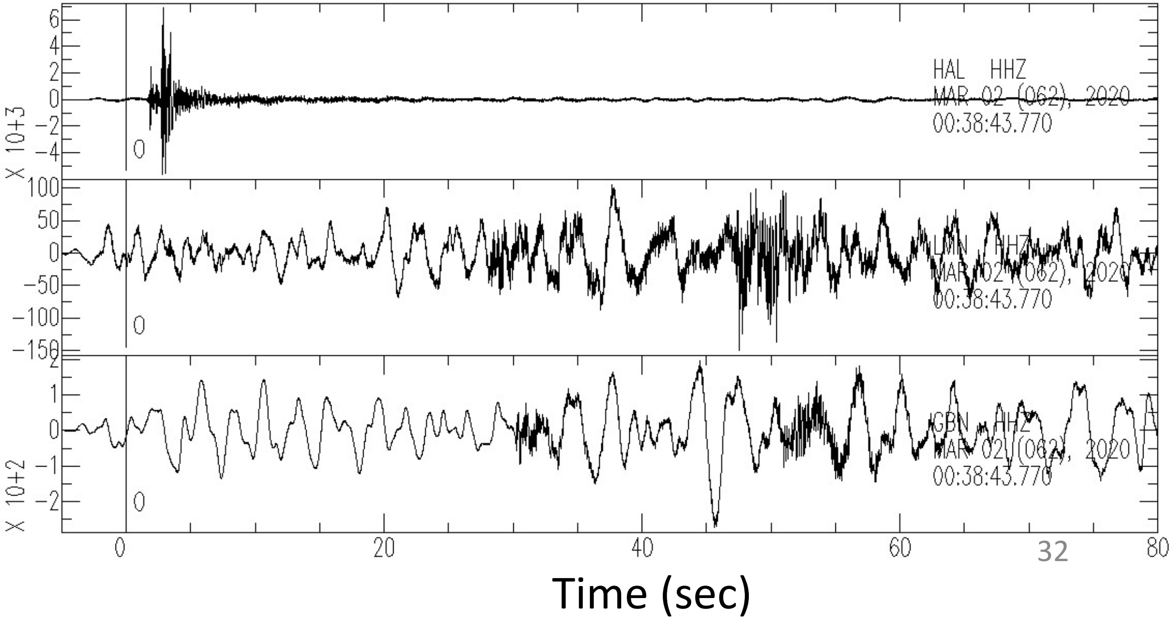
- What are their exact locations? (epicenters vs. shaking report)
- How shallow are the two earthquakes? (extreme loud sound, like explosion)
- How about the aftershocks and historical events?
- What are the potential mechanisms for the two earthquakes?

Three seismic stations (<200 km) recorded the two earthquakes

Raw data (broadband)



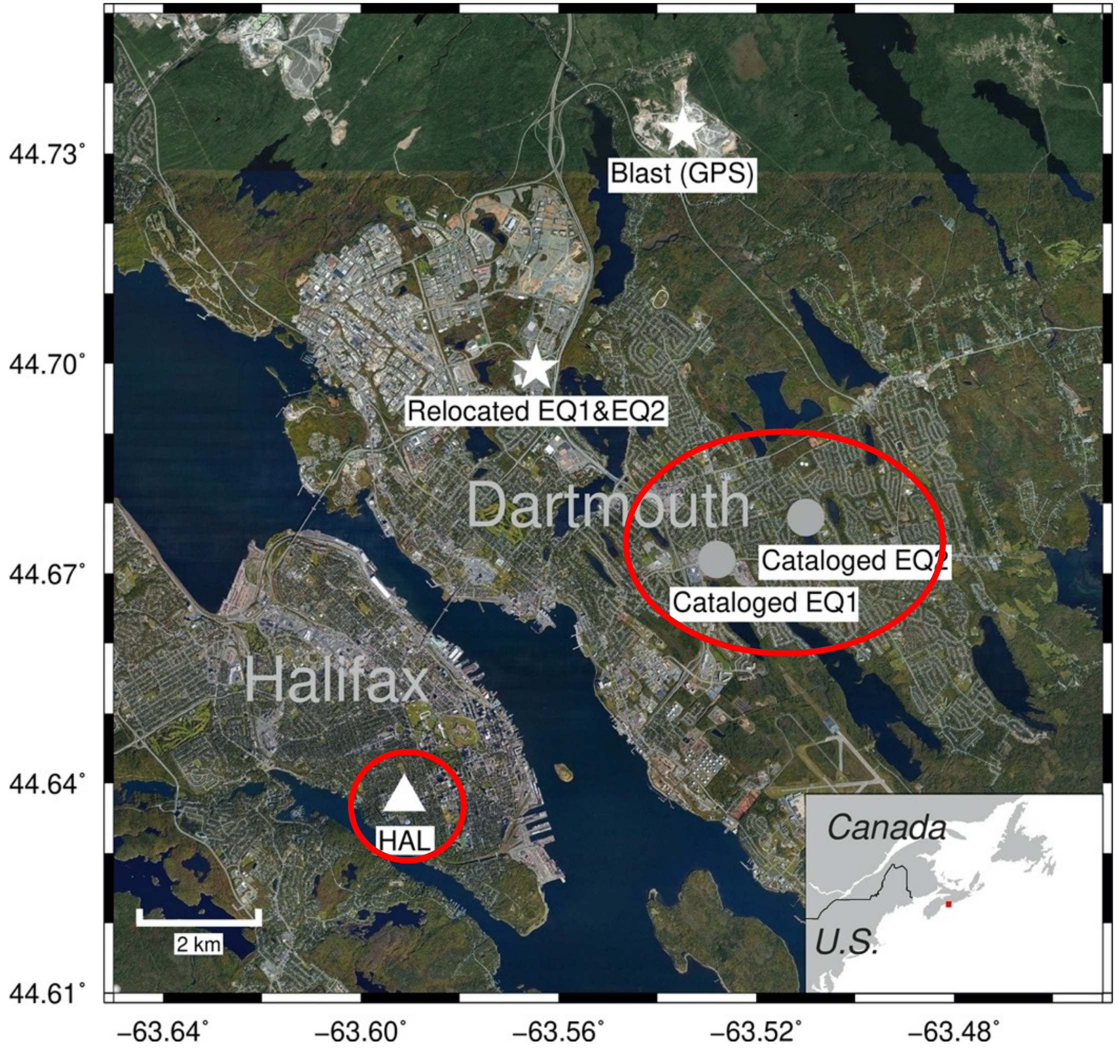
1Hz High pass filtering (hp c 1)

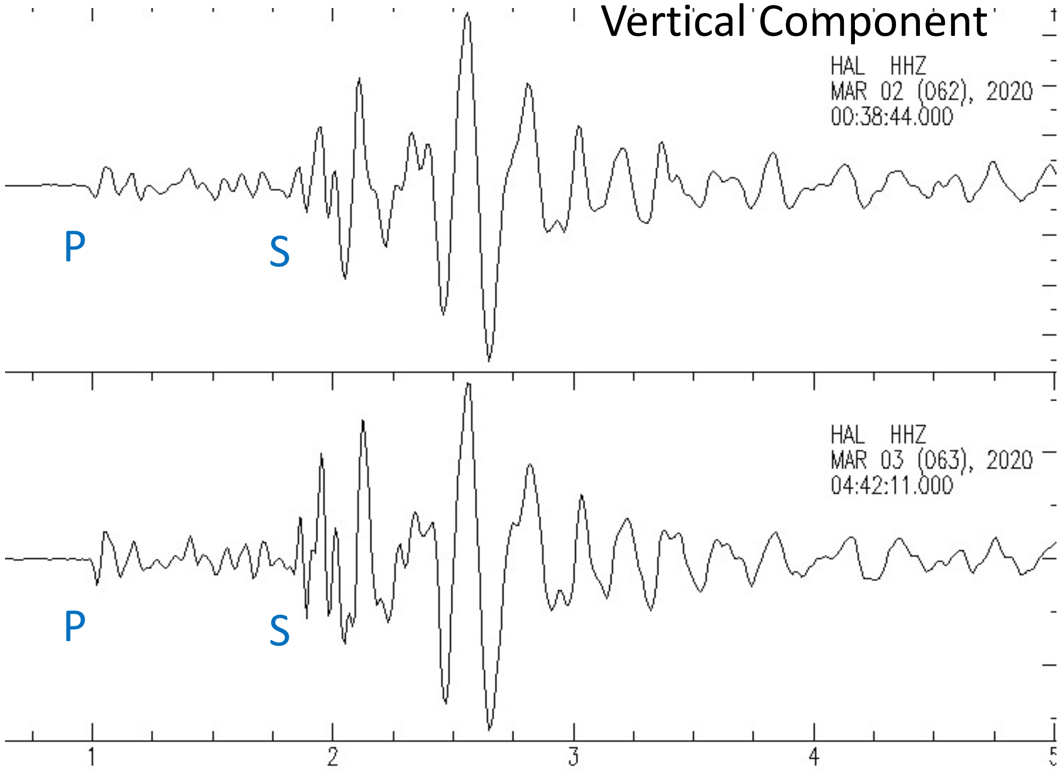


Challenges for pick-based absolute location:

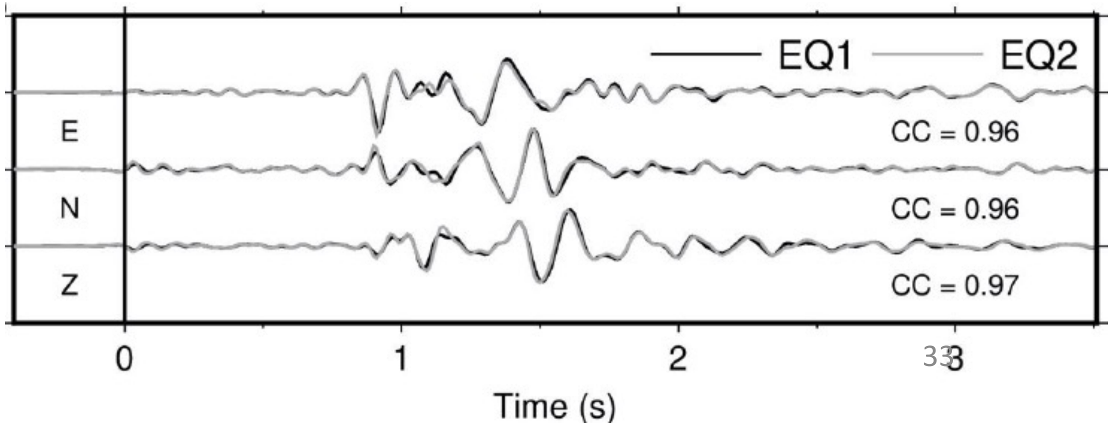
1. Only three stations are available, and low SNR at the two further stations
2. Unknown local velocity model

Waveforms at station HAL



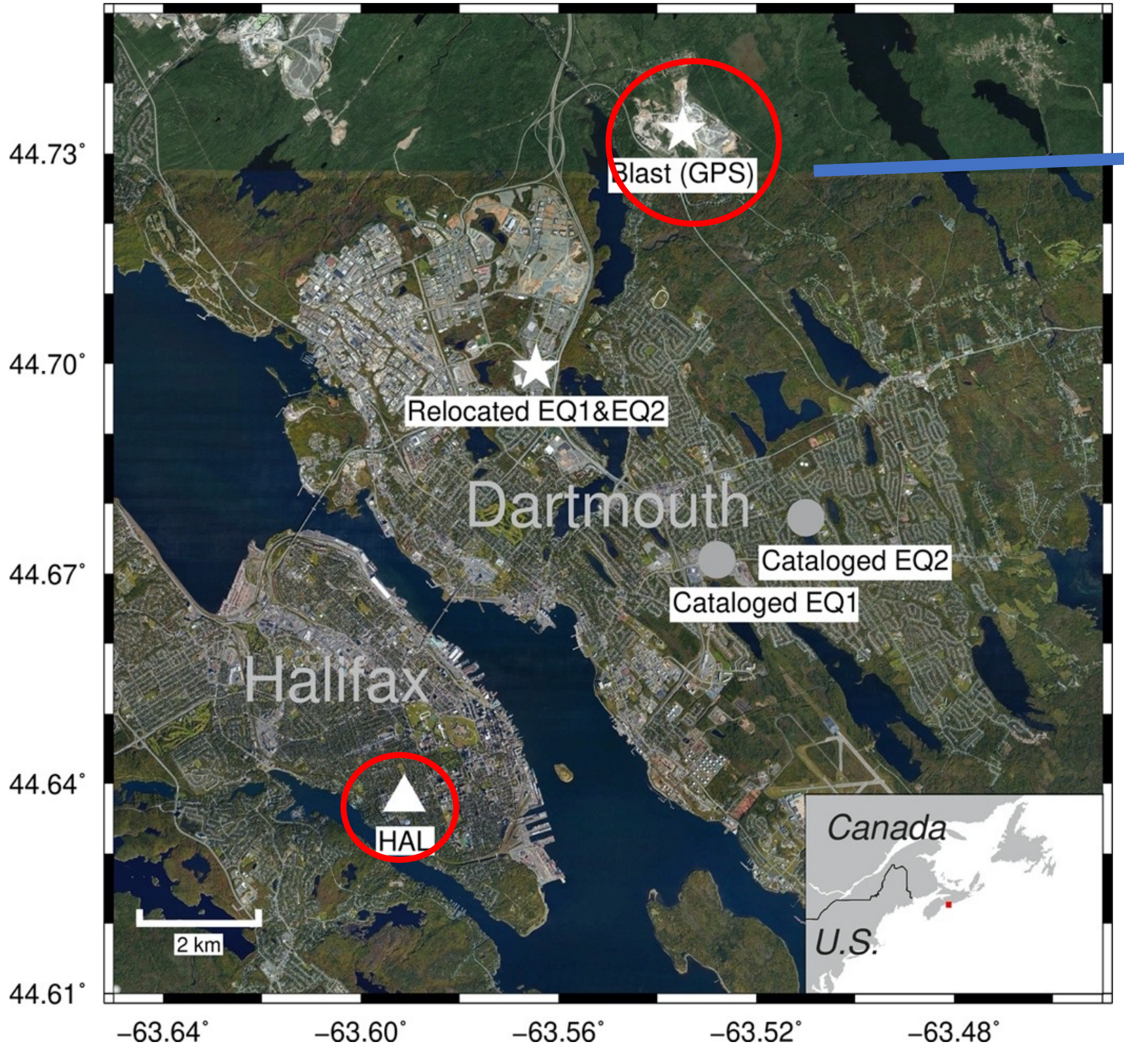


Band-pass filtering (3 – 12 Hz)

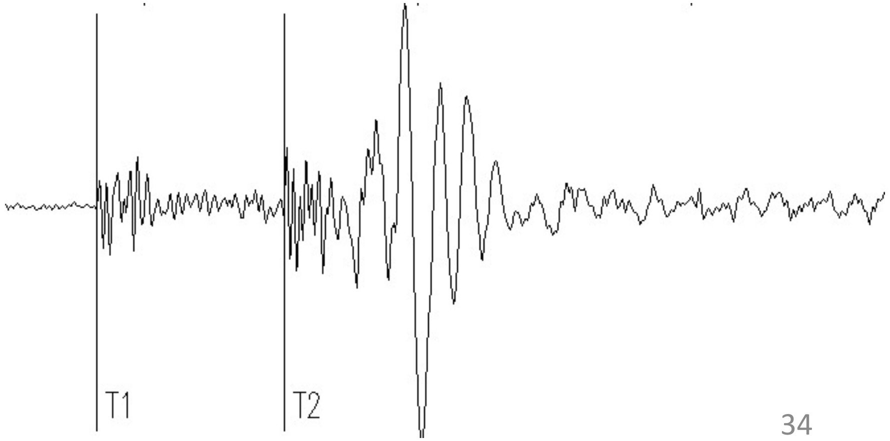


High cross-correlation: approximately co-located earthquakes

Quarry blast nearby



Quarry blast with GPS location
on March 3, 2020 (M_N 2.0)



Workflow

Velocity model building

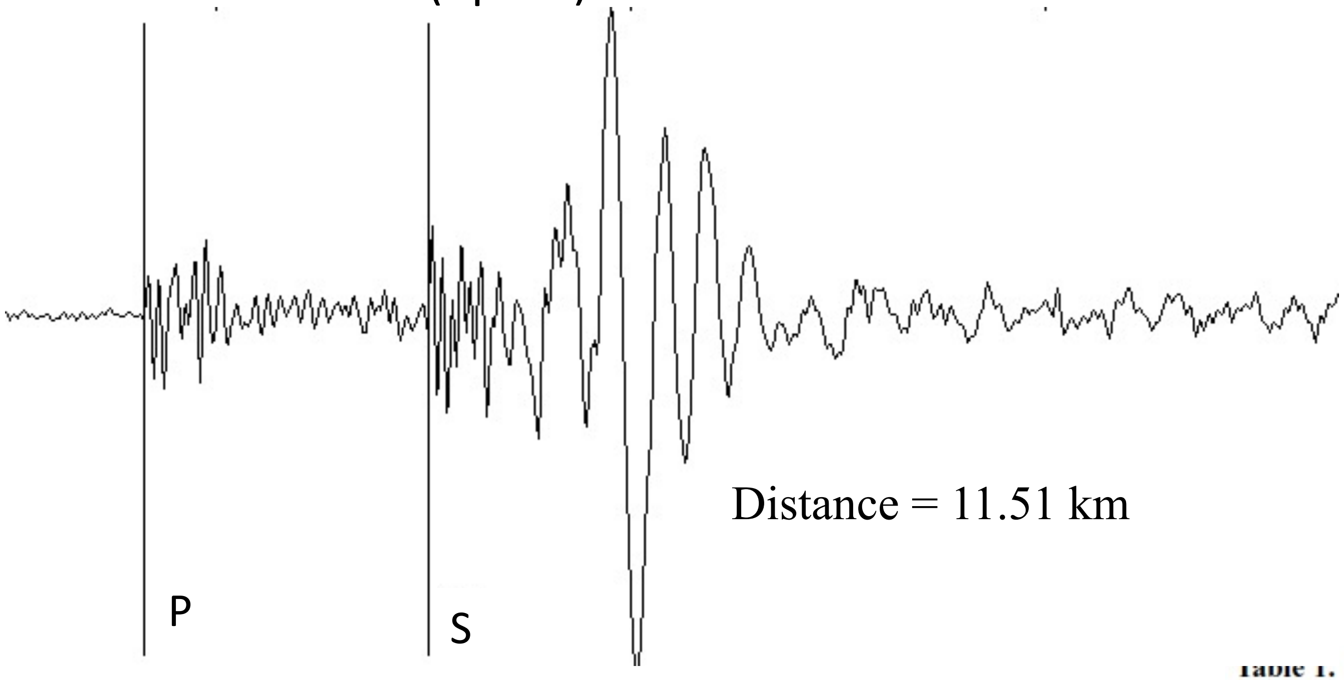
- **Half space 1-D velocity** ← **Ts – Tp of the blast**
- **Shallow low velocity layer** ← **Full waveform fitting surface waves + body waves**

Earthquake location

- **Back azimuth calculation** ← **Calibrated by the ground truth blast**
- **Source-station distance estimation** ← **Ts – Tp of the pair of earthquakes**
- **Source depth determination** ← **Full waveform fitting & Rg/S ratio**

Half-space velocity estimation

Vertical component of the Blast
(hp c 1)



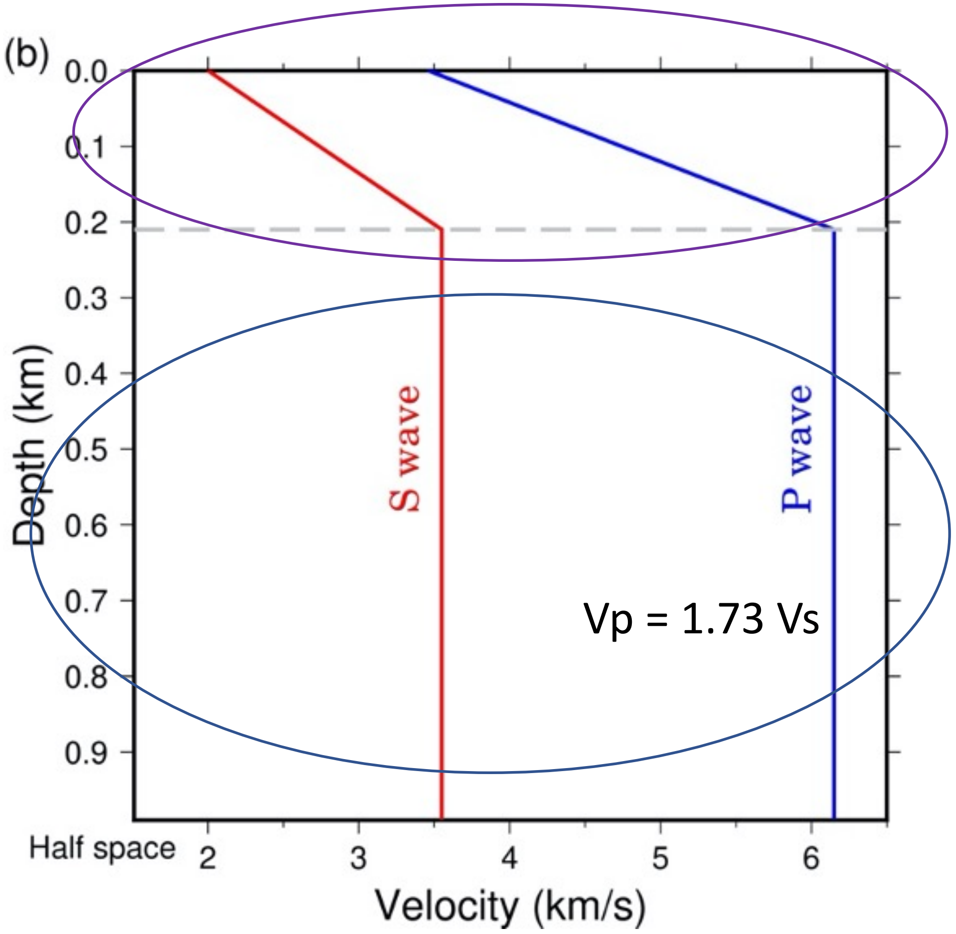
Ts-p = 1.37 sec
Vp=6.15 km/s
Vs=3.55 km/s
With Vp/Vs=1.73

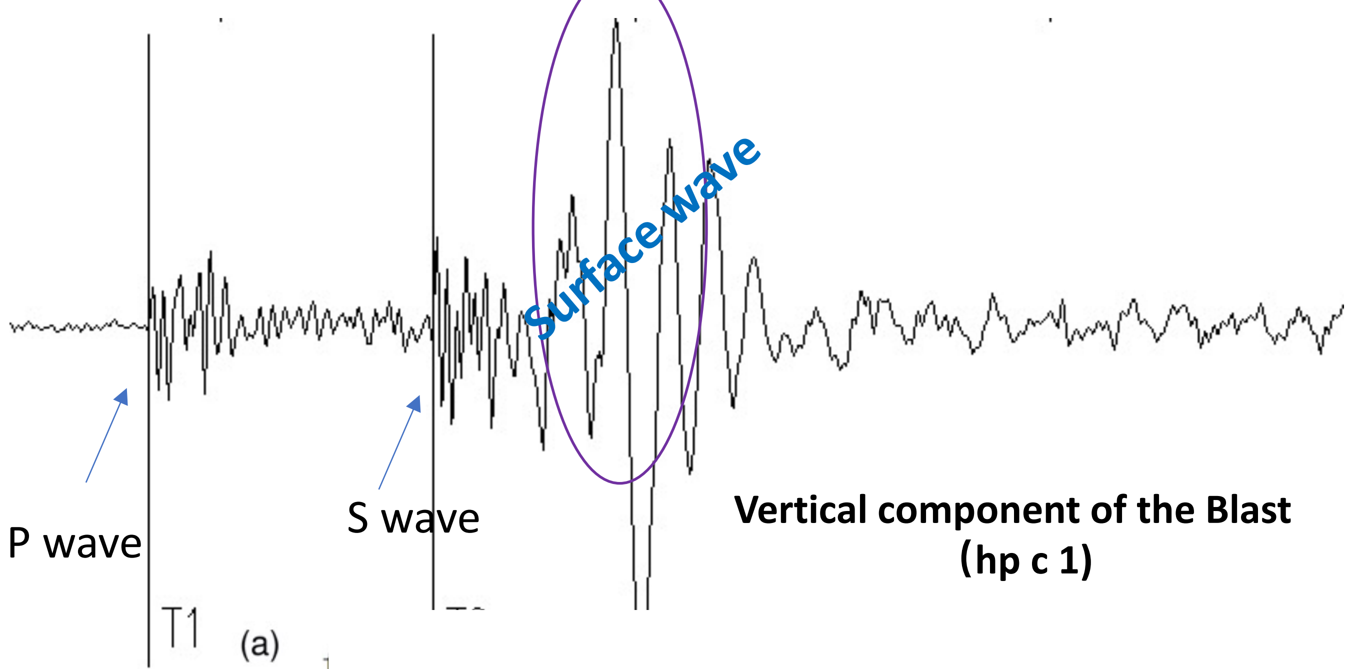
Table 1. Crustal model for eastern Canada (modified from Mereu *et al*. 1986).

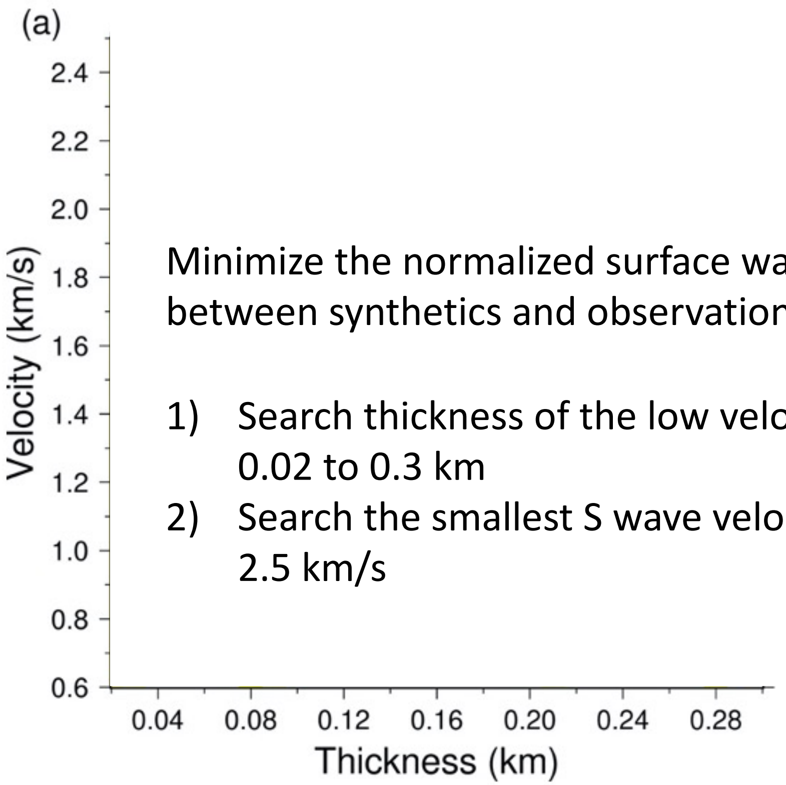
No	Thickness (km)	V_p (km s^{-1})	V_s (km s^{-1})	Density (g cm^{-3})	Q_p	Q_s
1	8	6.25	3.61	2.53	1350	600
2	9	6.50	3.75	2.63	1350	600
3	7	6.60	3.81	2.67	1350	600
4	6	6.70	3.87	2.71	1350	600
5	6	7.10	4.10	2.87	1350	600
6	Moho	8.00	4.62	3.23	1350	600

Ma and Eaton, GJI, 2011

Velocity model building







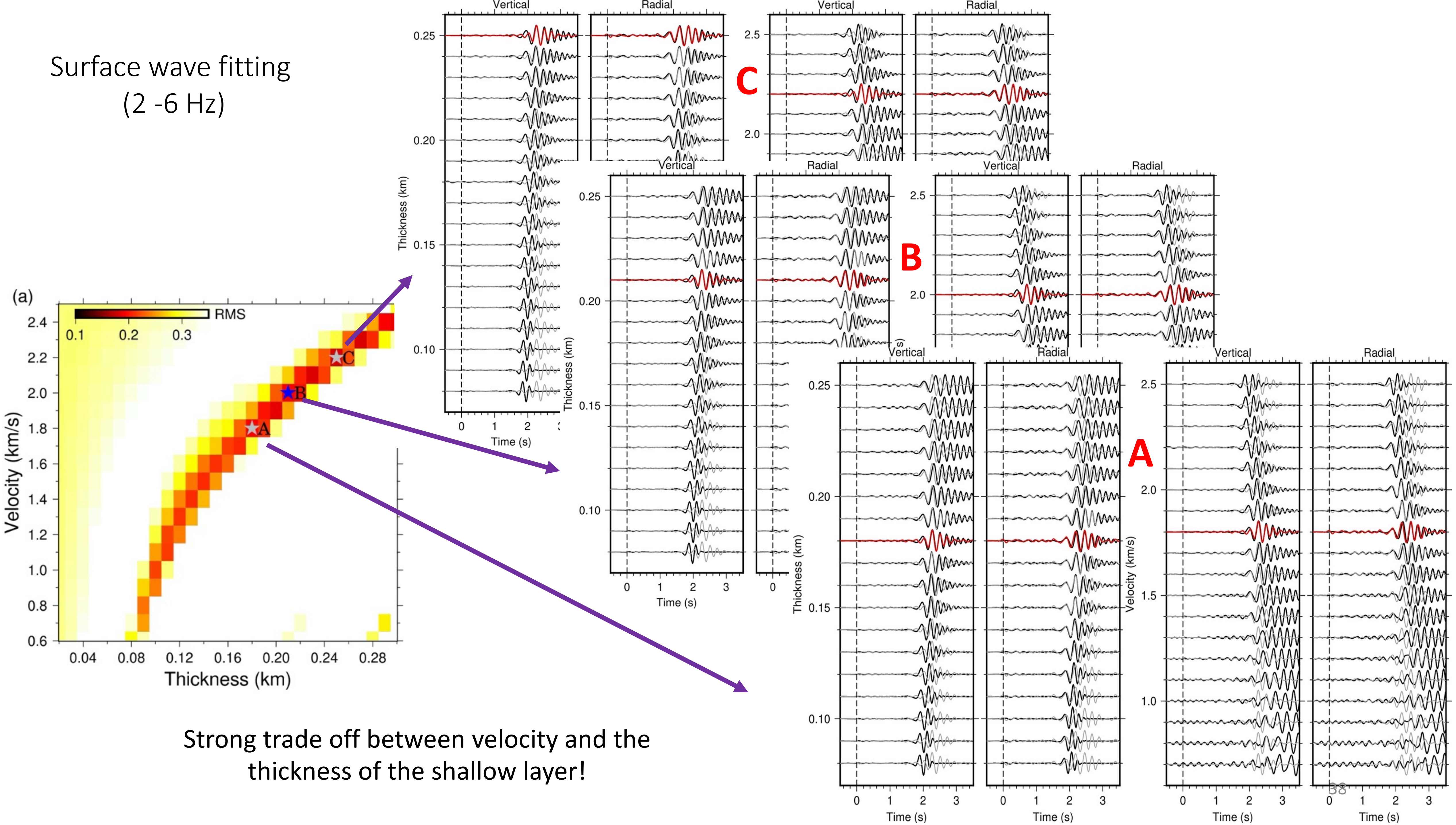
Minimize the normalized surface waveform residual between synthetics and observations of the blast:

1) Search thickness of the low velocity layer from 0.02 to 0.3 km
2) Search the smallest S wave velocity from 0.6 to 2.5 km/s

Low velocity layer:

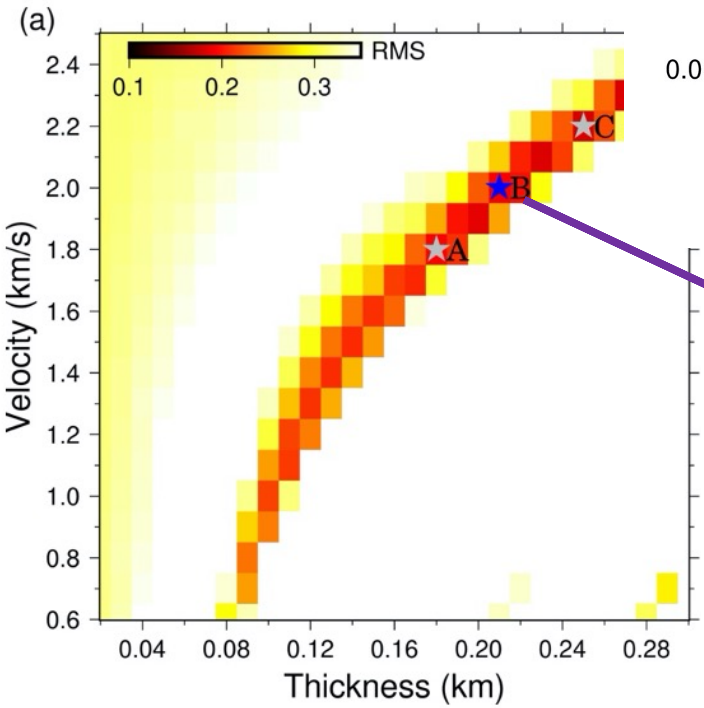
1. Assuming velocity linearly increases with depth
2. P is converted by vp/vs = 1.73
3. Qp=100; Qs=50.

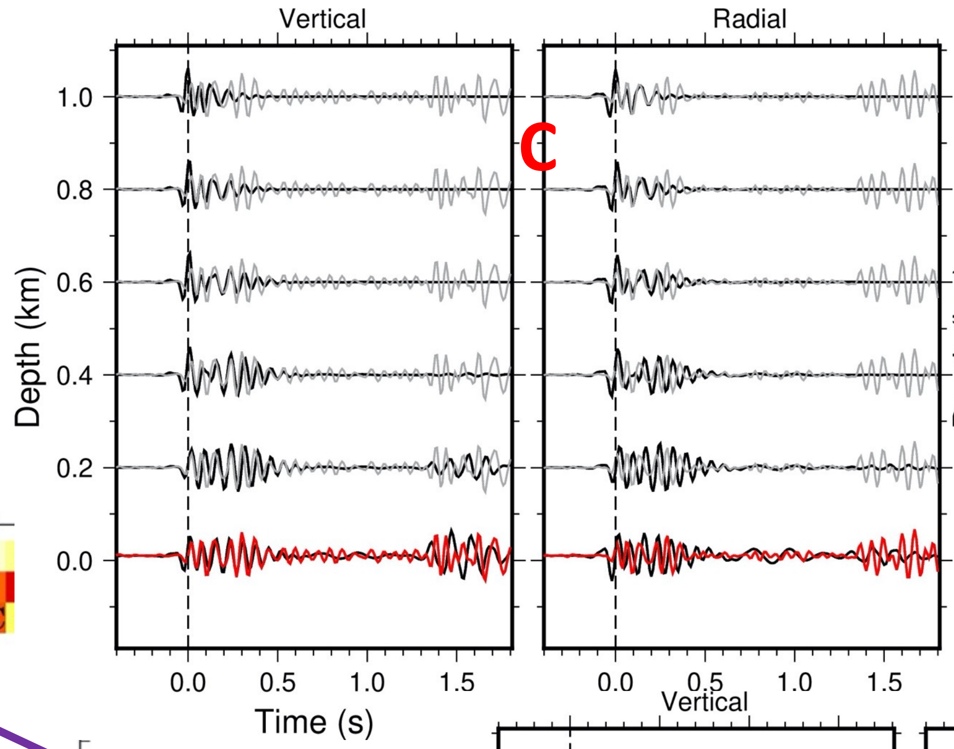
Surface wave fitting
(2 -6 Hz)

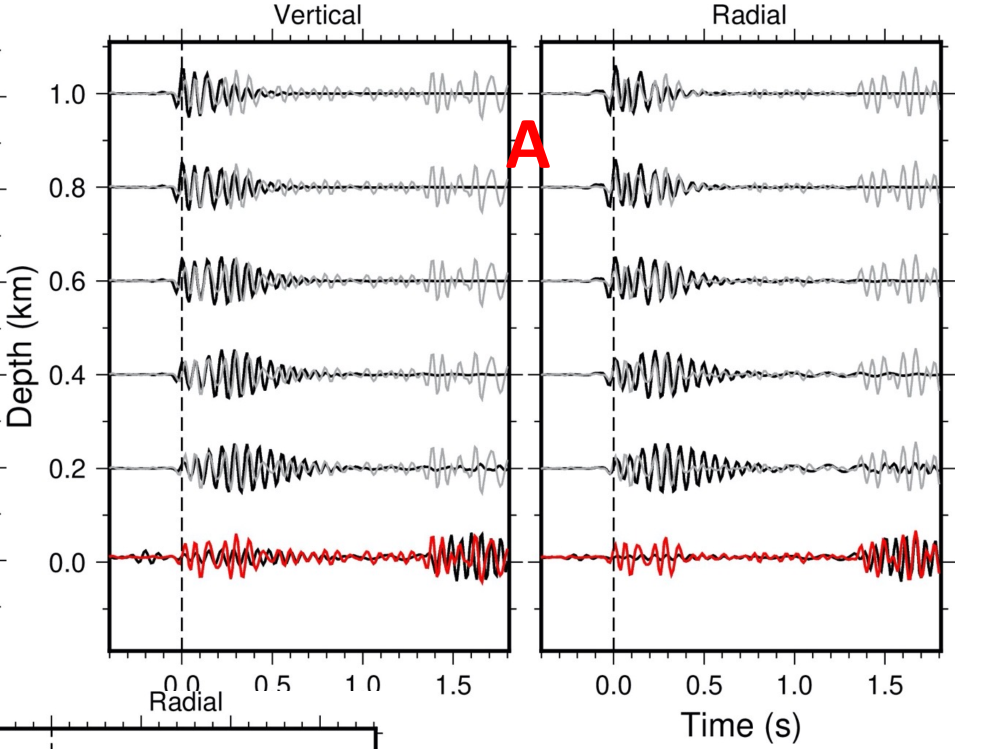


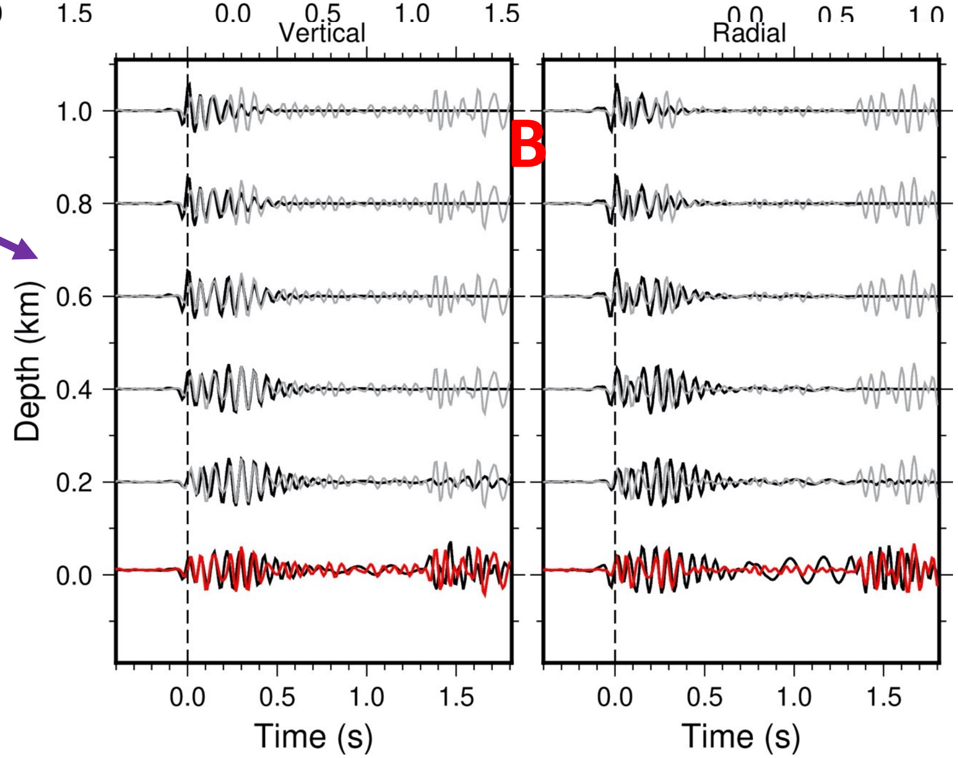
Strong trade off between velocity and the thickness of the shallow layer!

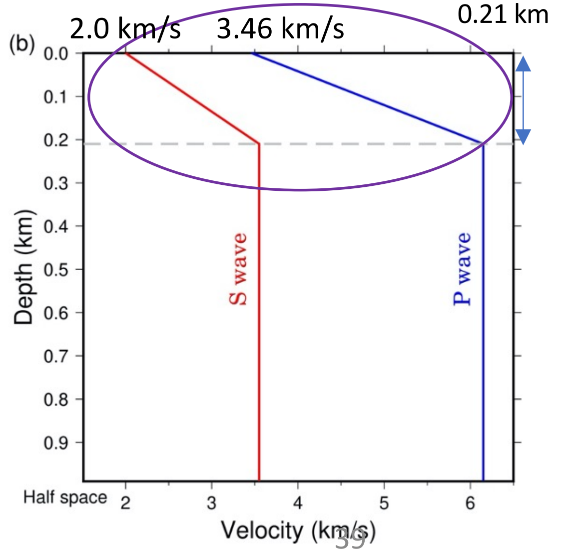
Body wave fitting
(7 - 20 Hz)











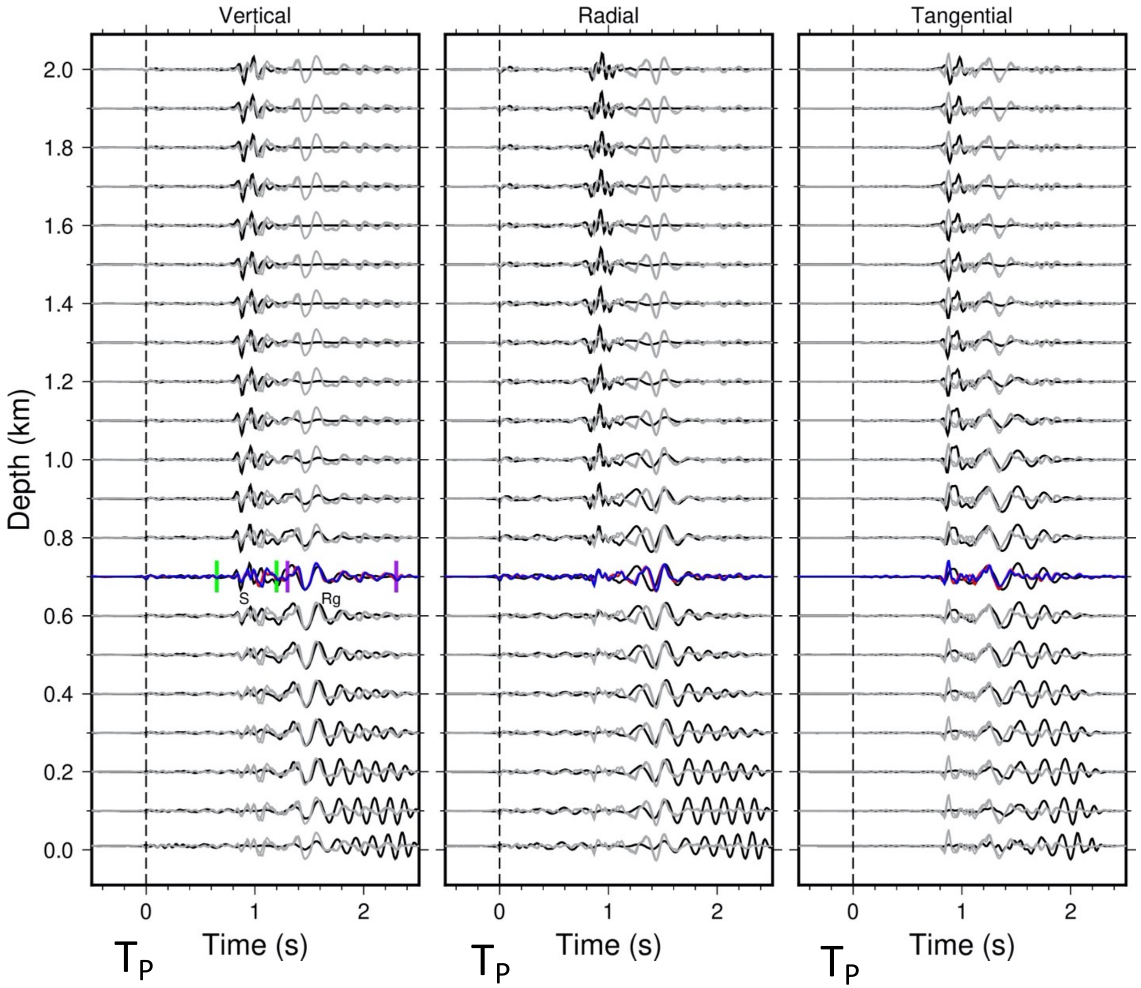
Confirm the optimal velocity model for the shallow layer

Source depth determination: I. Waveform fitting

1. Back azimuth (calibrated by the ground truth blast): 17.15° $\pm$ 2.5°.
2. Source-station distance (roughly estimated from ts-tp 0.85 sec with a source depth of 0 km): ~ 7.1 km
3. Focal mechanism (try three fundamental double couple mechanisms, i.e., vertical strike-slip, 45° dip-slip and vertical dip-slip, with an assumption of 0° strike).

The three focal mechanisms suggest a common source depth of 0.7 km.

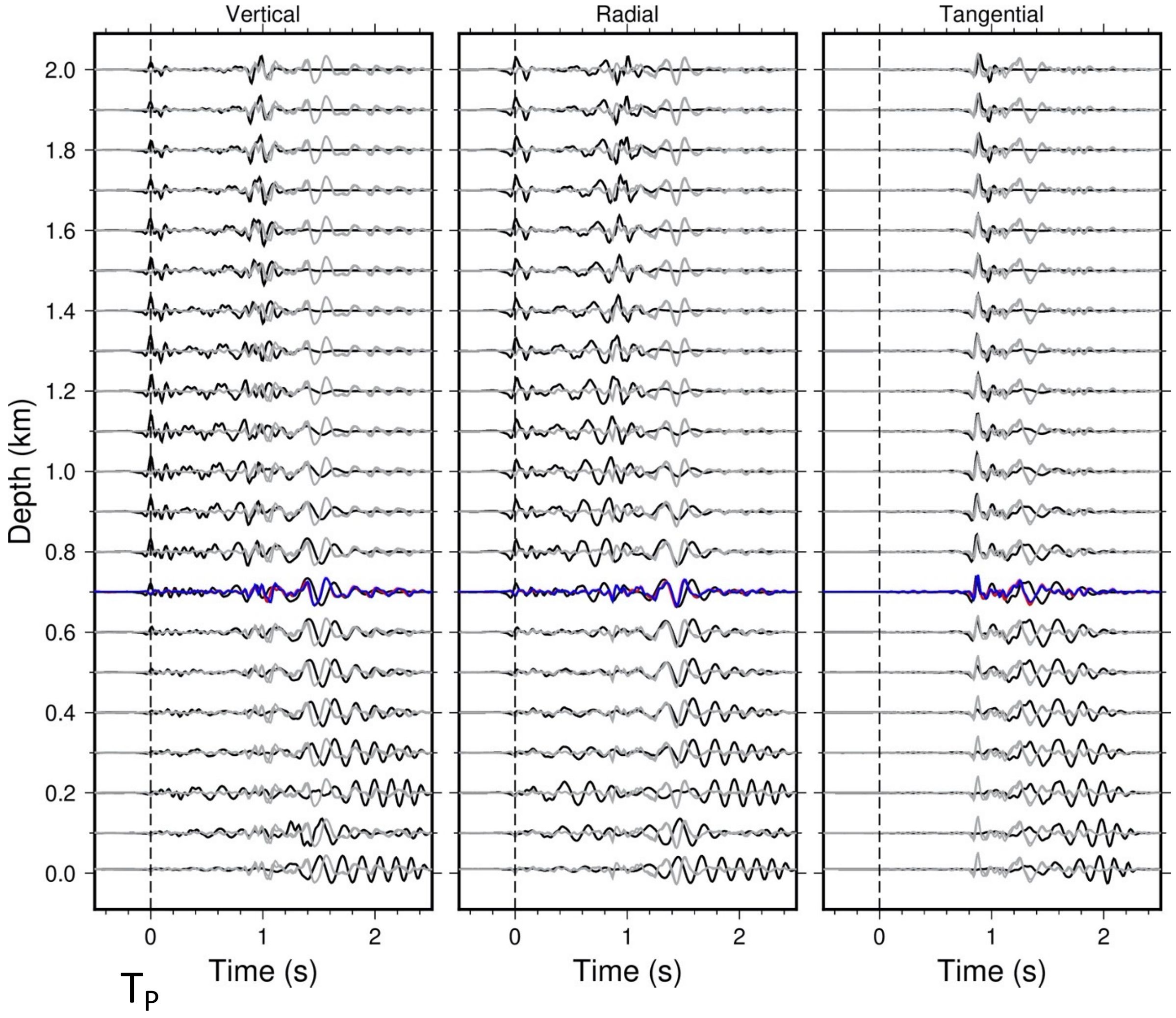
Vertical dip-slip fits best.



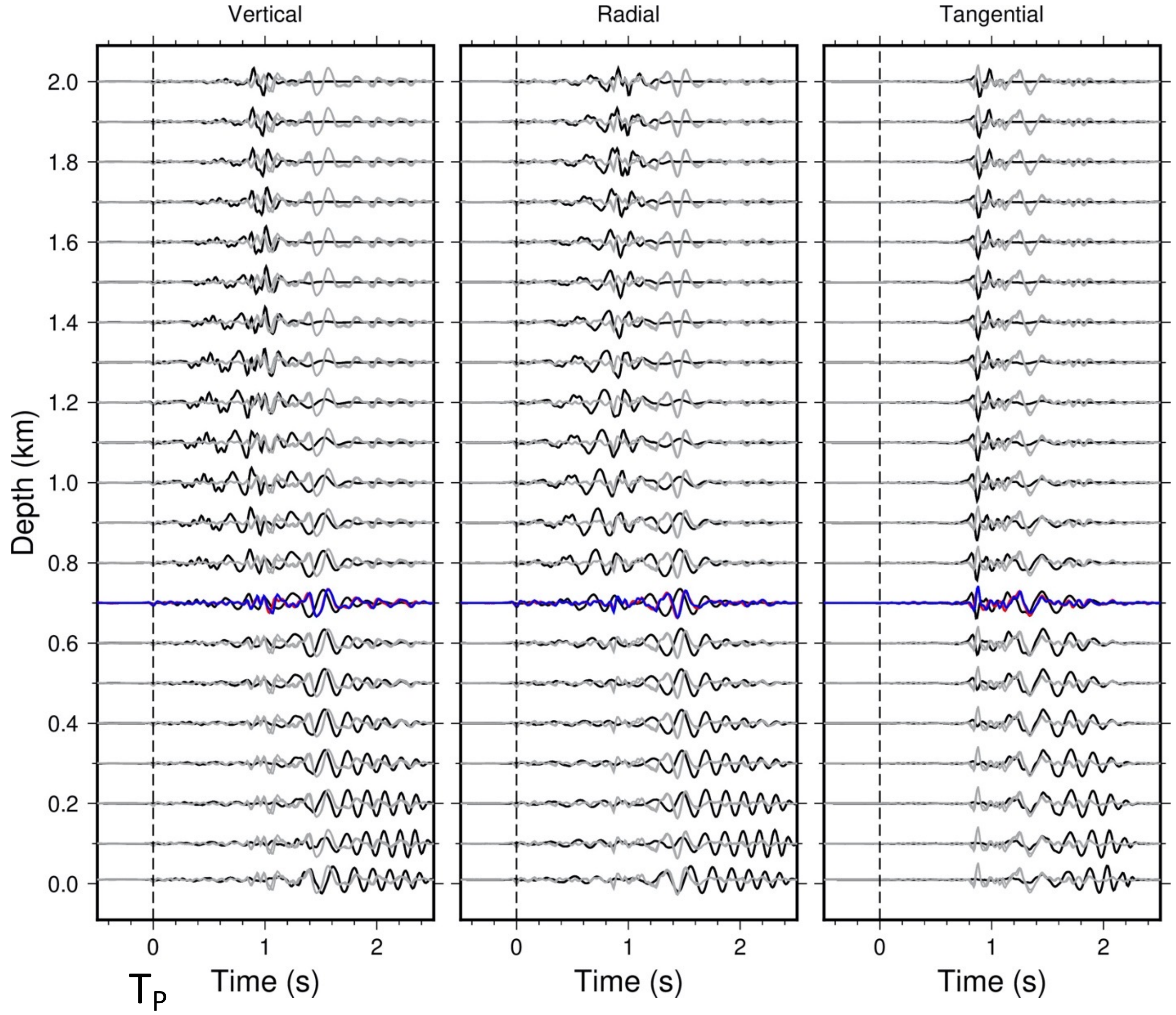
Vertical dip-slip waveform fitting (3–15 Hz)

Black traces: synthetics
Gray traces: observations
Blue&red traces: best fitting

Strike-slip waveform fitting (3–15 Hz)



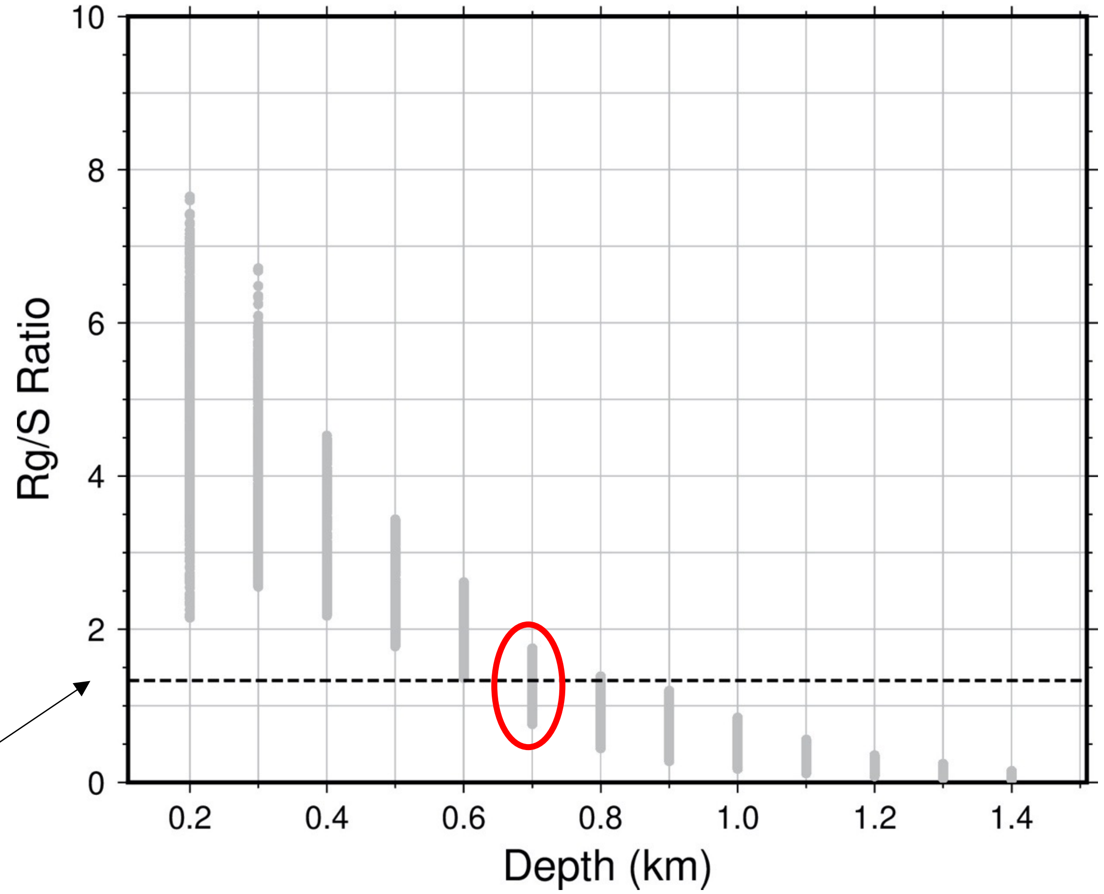
45° dip-slip waveform fitting (3–15 Hz)



Black traces: synthetics; Gray traces: observations; Blue&red traces: best fitting

Source depth determination: II. Rg/S amplitude ratio

1. Grid-search source depth, ranking from 0 to 1.5 km
2. Grid-search focal mechanism (strike: 0–360; dip:0–90; rake:-180–180)
3. Compute corresponding Rg/S amplitude ratios at vertical synthetic waveform (3 -15 Hz)
4. Compare with Rg/S amplitude ratios of the two earthquakes



Overlapped (two lines for two events)

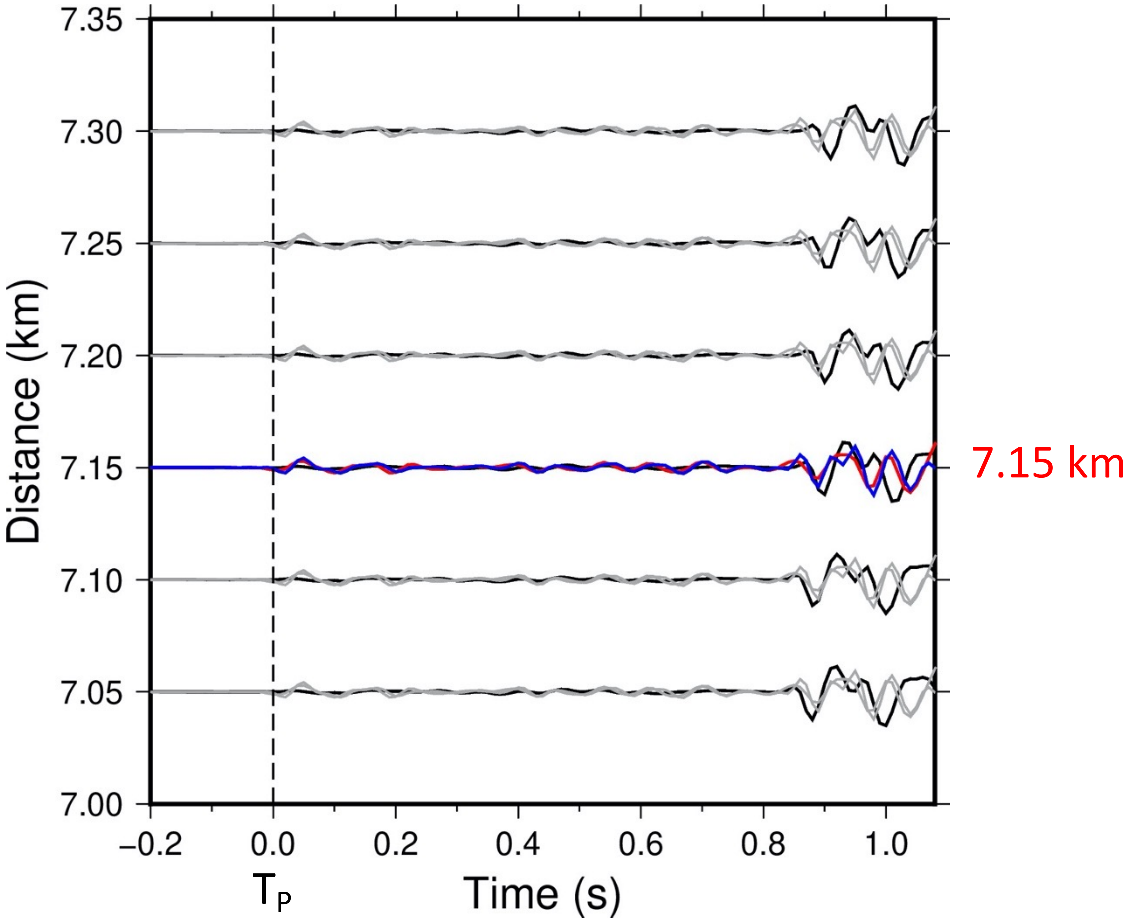
At specific source depth, each gray dot represents one focal mechanism.

The optimal source depth is determined at 0.7 km (< 0.1 km uncertainty)

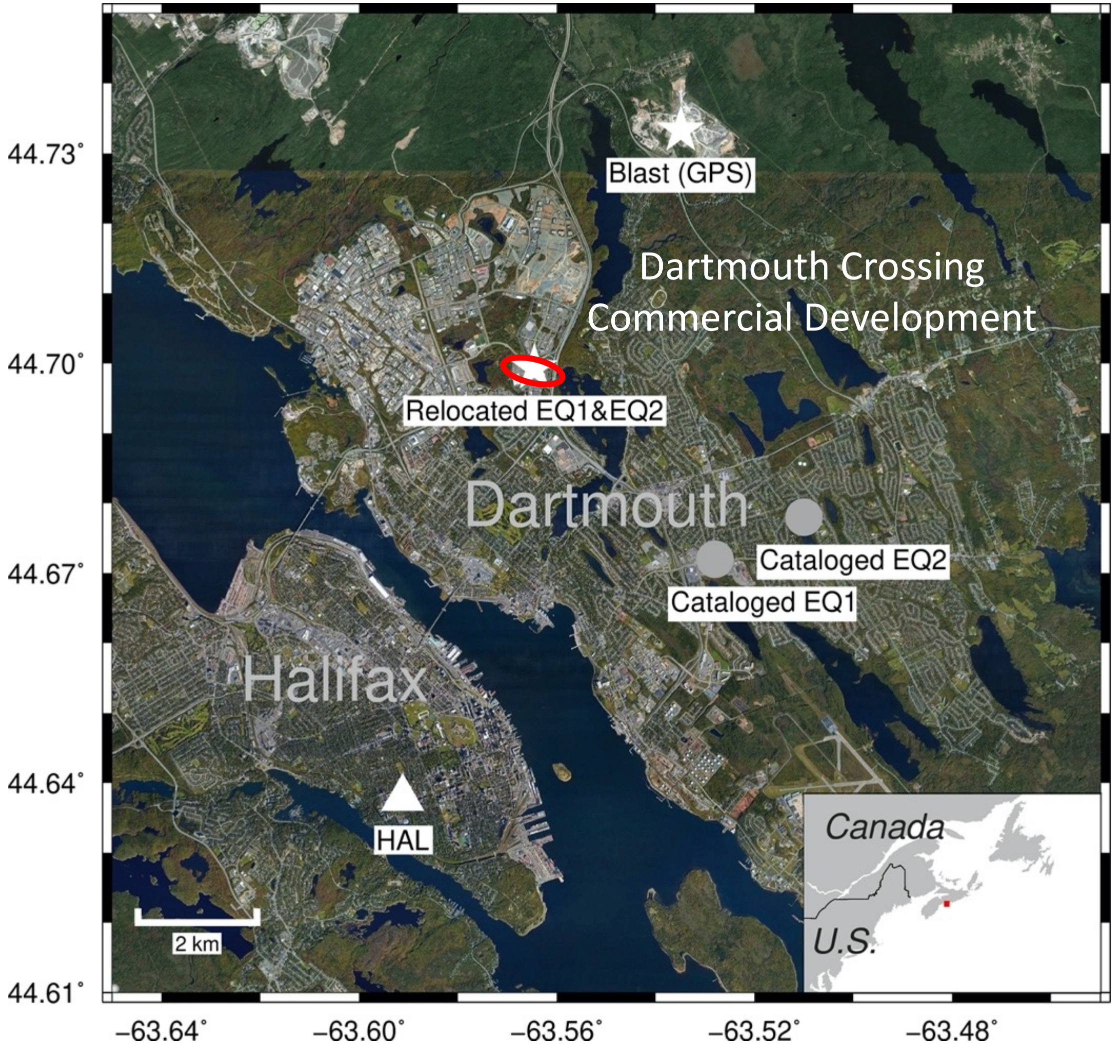
Consistent with the waveform fitting very well (i.e., 0.7 km).

Given accurate source depth 0.7 km, re-estimate the source-station distance by fitting the P and S body waves

The distance is corrected to be at 7.15 km.



Waveform fitting (5–15 Hz) at vertical component



Uncertainty: 300 m perpendicular to the source-station direction (baz) and 50 m along the source-station direction (grid size)

“Did You Feel It” maps for the Mar. 2 (left) and Mar. 3 earthquakes (right).

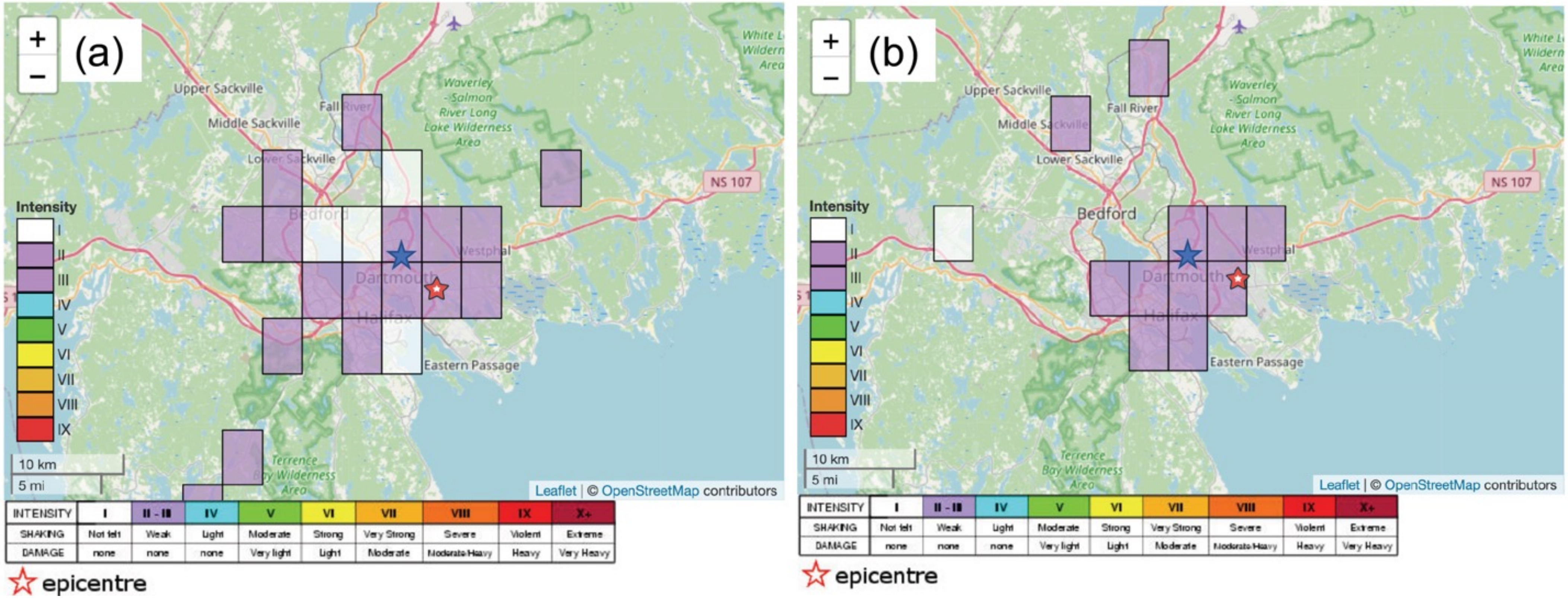
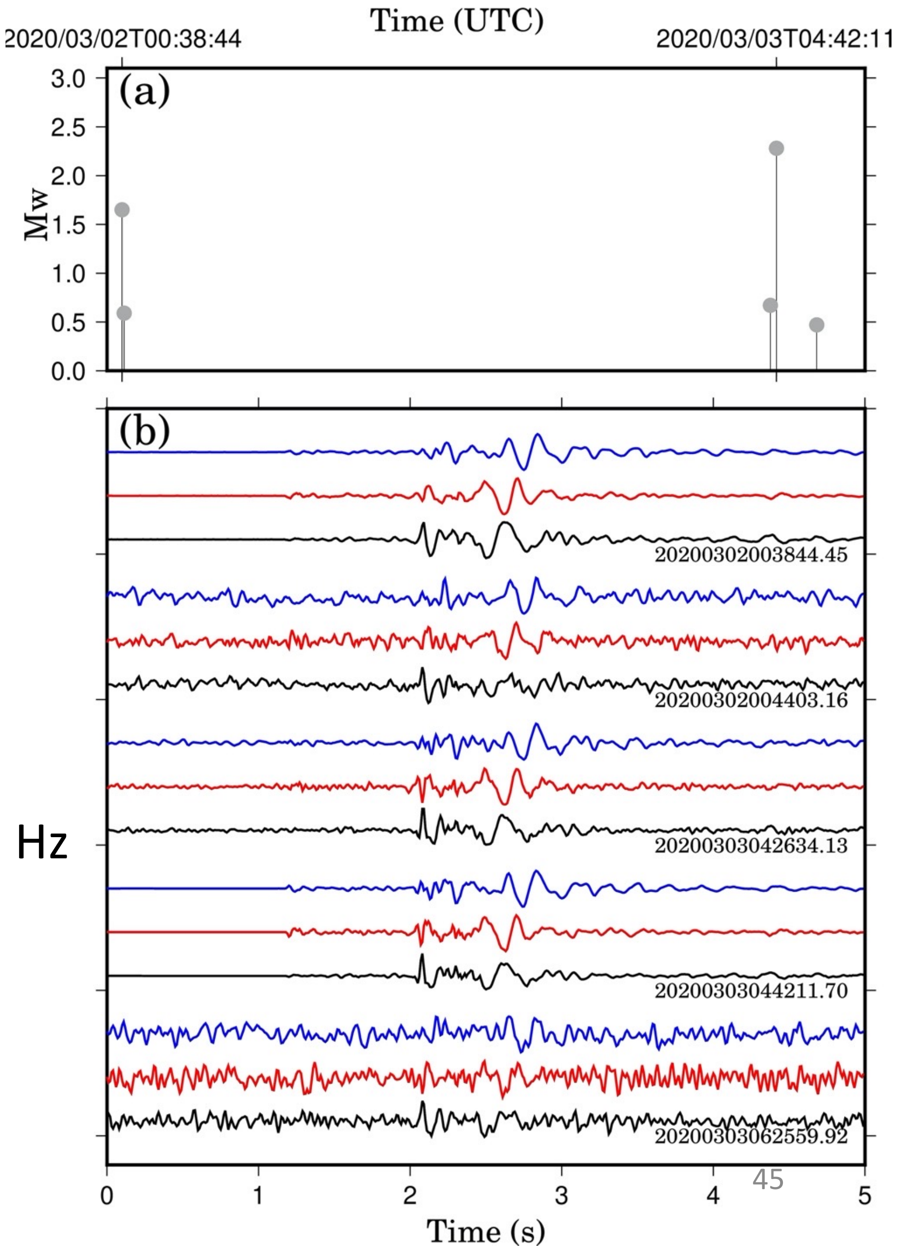


Table 1. Source parameters of the two earthquakes and the blast

	Origin time	Latitude (°)	Longitude (°)	Depth (km)	Mw
EQ1	20200302T00:38:44.45	44.6993	-63.5646	0.7	1.7
EQ2	20200303T04:42:11.70	44.6993	-63.5646	0.7	2.3
Blast	20200303T18:22:50.72	44.7333#	-63.5349#	0	1.9

#As reported by the quarry operators

Single-station template matching



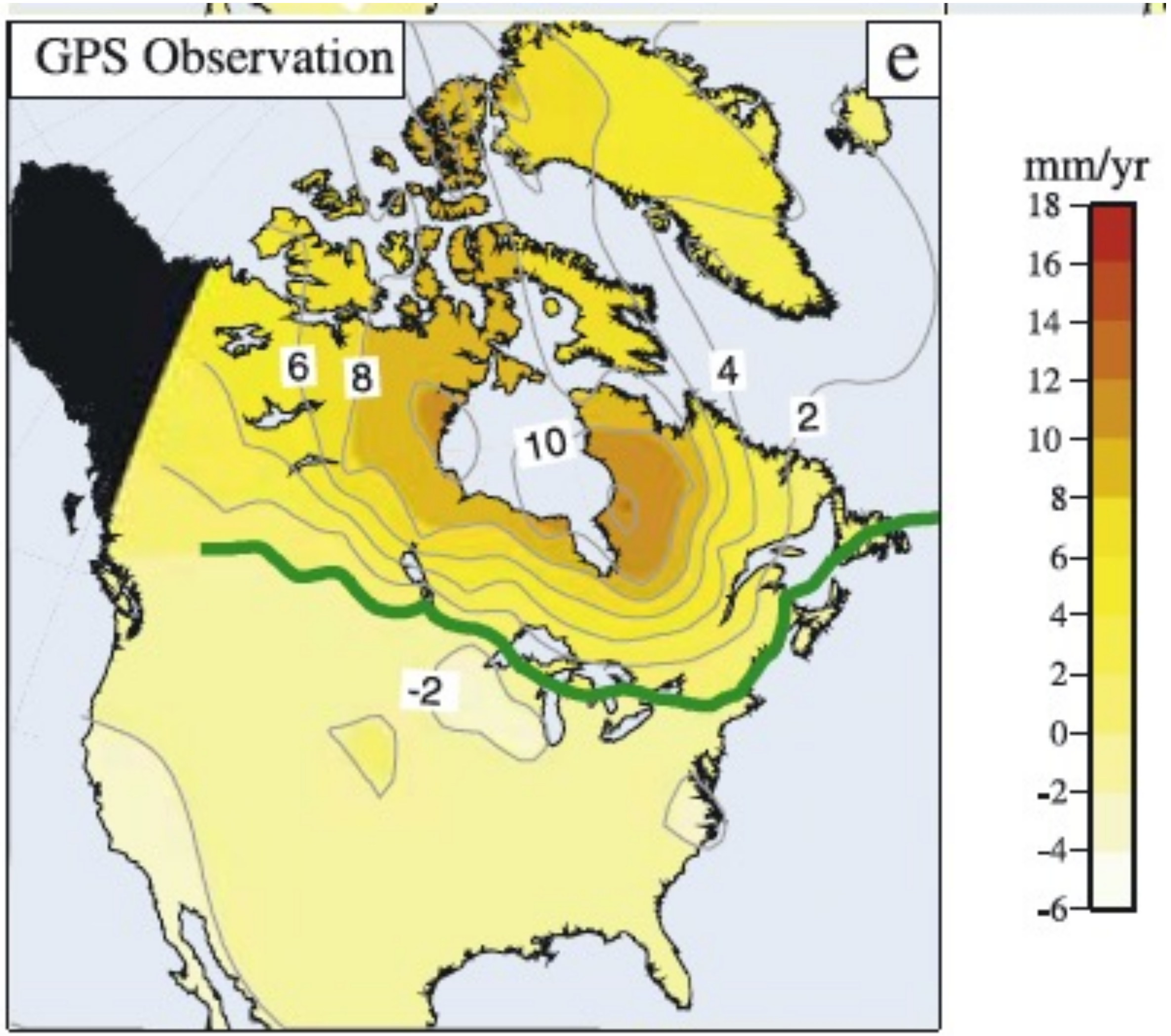
3–12 Hz

1. No historical earthquakes in the past decade (template matching)
2. Only detected three aftershocks until July 2020 (template matching)
3. No clear surface ruptures (on-site survey)
4. No mapped faults in the region (local geology)

- ➢ Few aftershocks
- ➢ Very shallow source depths

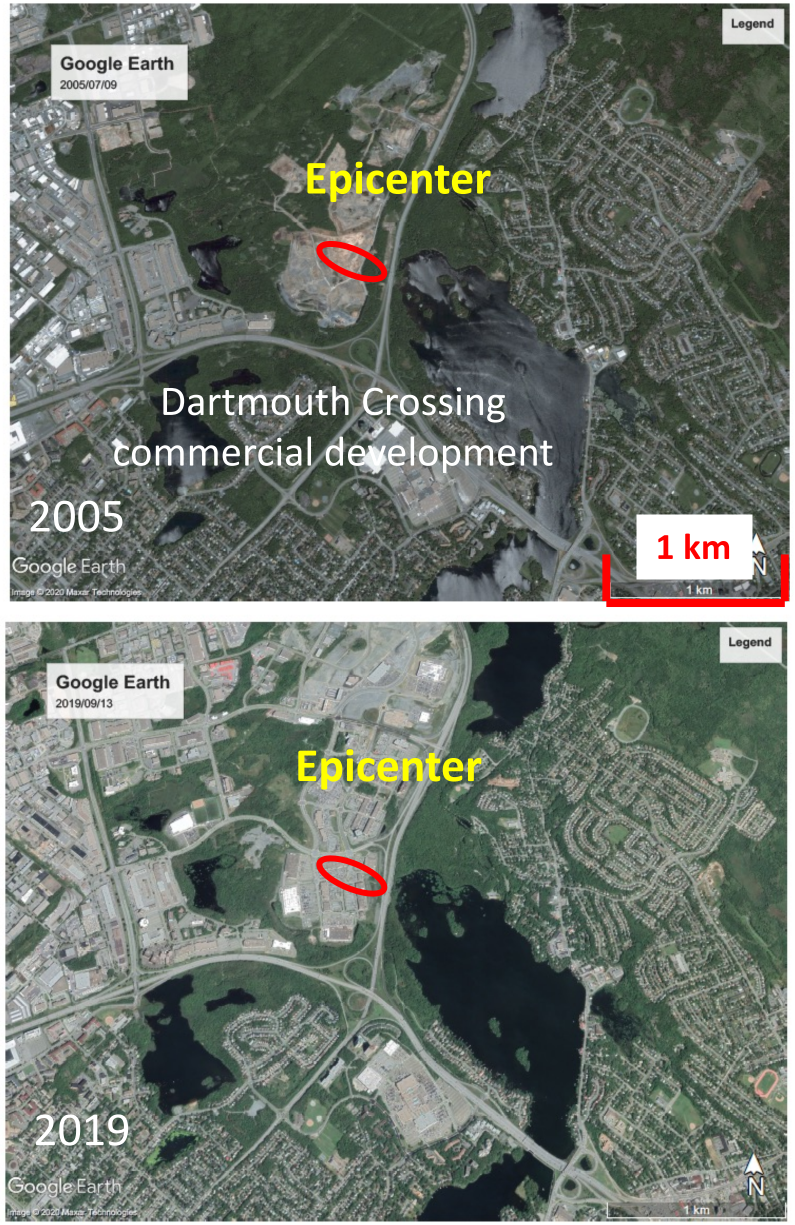
Potential mechanisms

1. Crustal stress perturbations associated with regional glacial isostatic adjustment?



Sella et al., GRL, 2007

2. Triggering by mass unloading?



4 MT of rock was moved during the 2006 construction

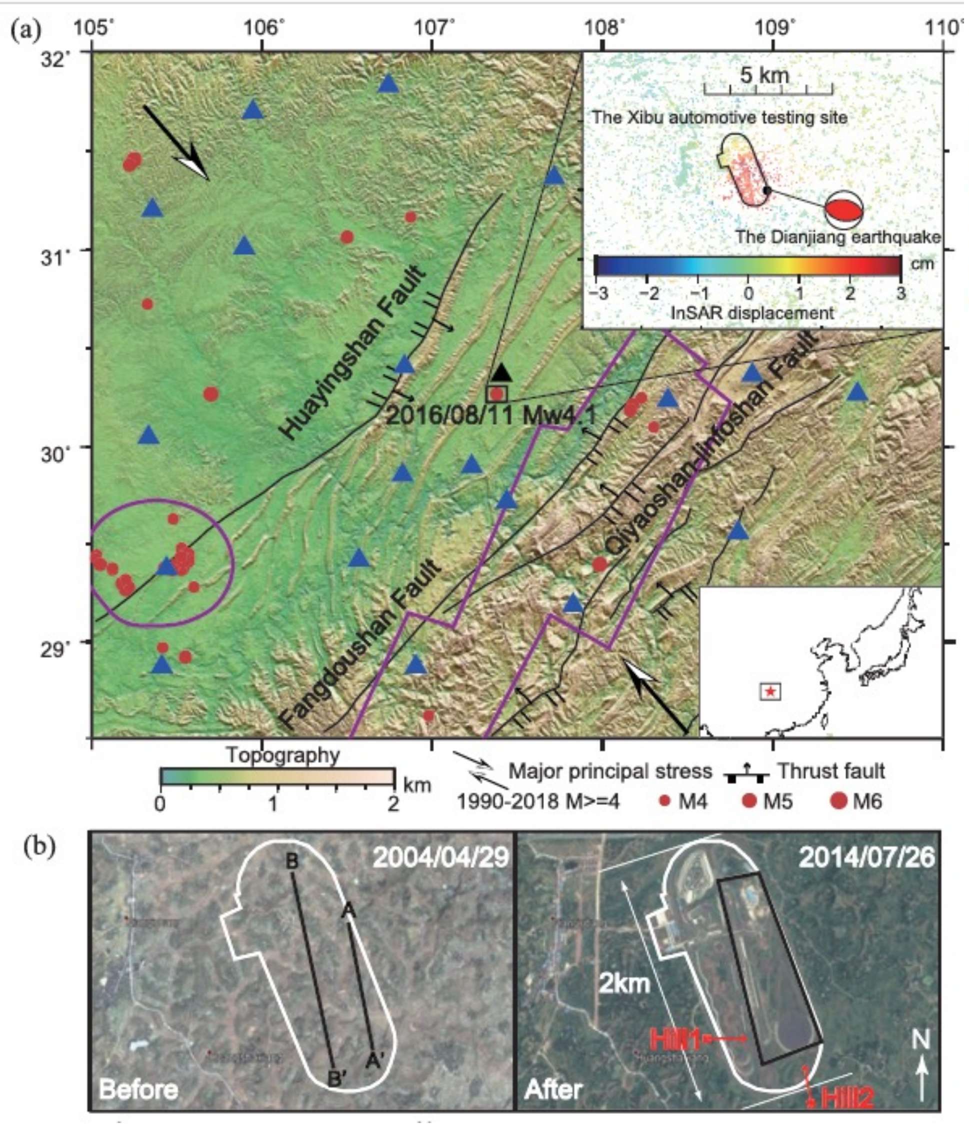
2006 Construction

2020 Dartmouth Crossing Commercial Development

4M tons of rock
Average thickness $\approx 2m$

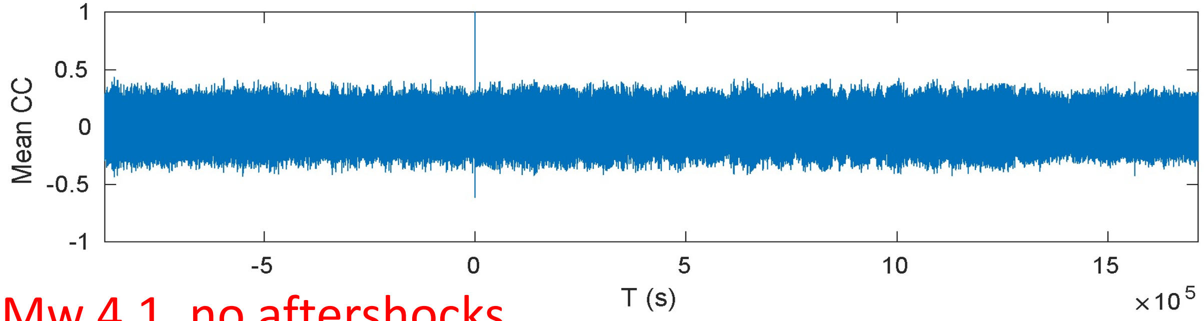
Triggered by unloading?

Another similar unloading triggered event



An Extremely Shallow M_w4.1 Thrust Earthquake in the Eastern Sichuan Basin (China) Likely Triggered by Unloading During Infrastructure Construction

Yunyi Qian[1,2], Xiaofei Chen[1], Heng Luo[3], Shengji Wei[4,5], Teng Wang[6], Zhenguo Zhang[1], and Xinyu Luo[2]



- Mw 4.1, no aftershocks
- Source depth: 1 km
- 10 m hill leveled
- Delayed triggering by unloading (2-year)

In our case:

- Mw 1.7&2.3, three aftershocks
- Source depth: 0.7 km
- 2 m rock removed
- Delayed triggering by unloading? (14-year)

Qian et al., GRL, 2019

Summary

- We build a two-layer regional velocity model (near-surface linear gradient + half-space) using a blast and waveform fitting, then accurately locate the two small earthquakes (M 1.7&2.3) using the constructed velocity model and waveform simulation.
- The epicenters of these two earthquakes are situated in a recently constructed commercial development. They are likely triggered by mass unloading (though cannot exclude deglaciation).
- Earthquake source depths are determined as 0.7 km using waveform fitting and Rg/S amplitude ratio. Such shallow source depth explains the "really loud bang" reported by local residents.
- Potential applications: station-sparse regions and other planets.

Reference

- Miao Zhang, Min Liu, Alexandre Plourde, Feng Bao, Ruijia Wang and John Gosse. Source characterization for two small earthquakes in Dartmouth, Nova Scotia, Canada: pushing the limit of single station. *Seismological Research Letters*, 2021, in press.

DALHOUSIE UNIVERSITY

Thank you for your attention!

Miao Zhang

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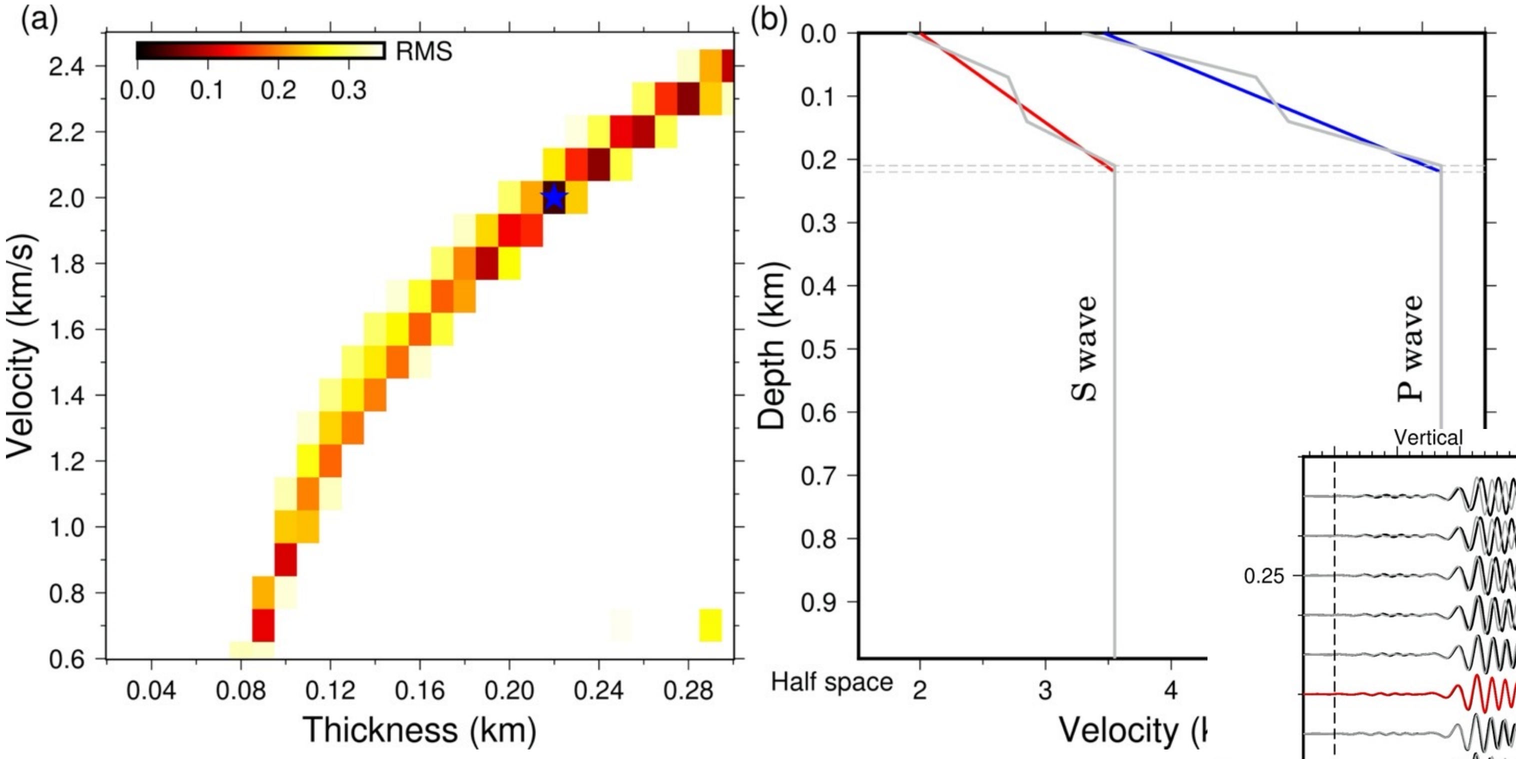
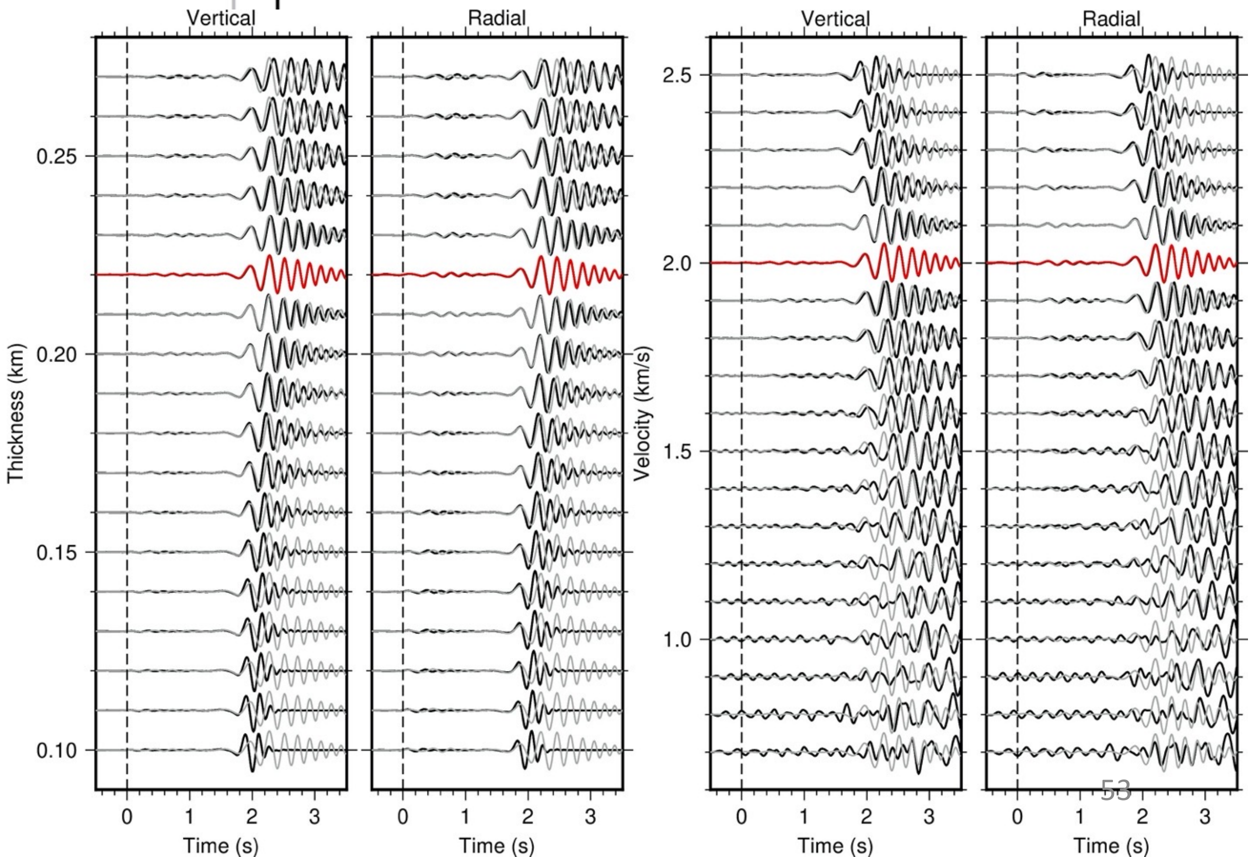
backup

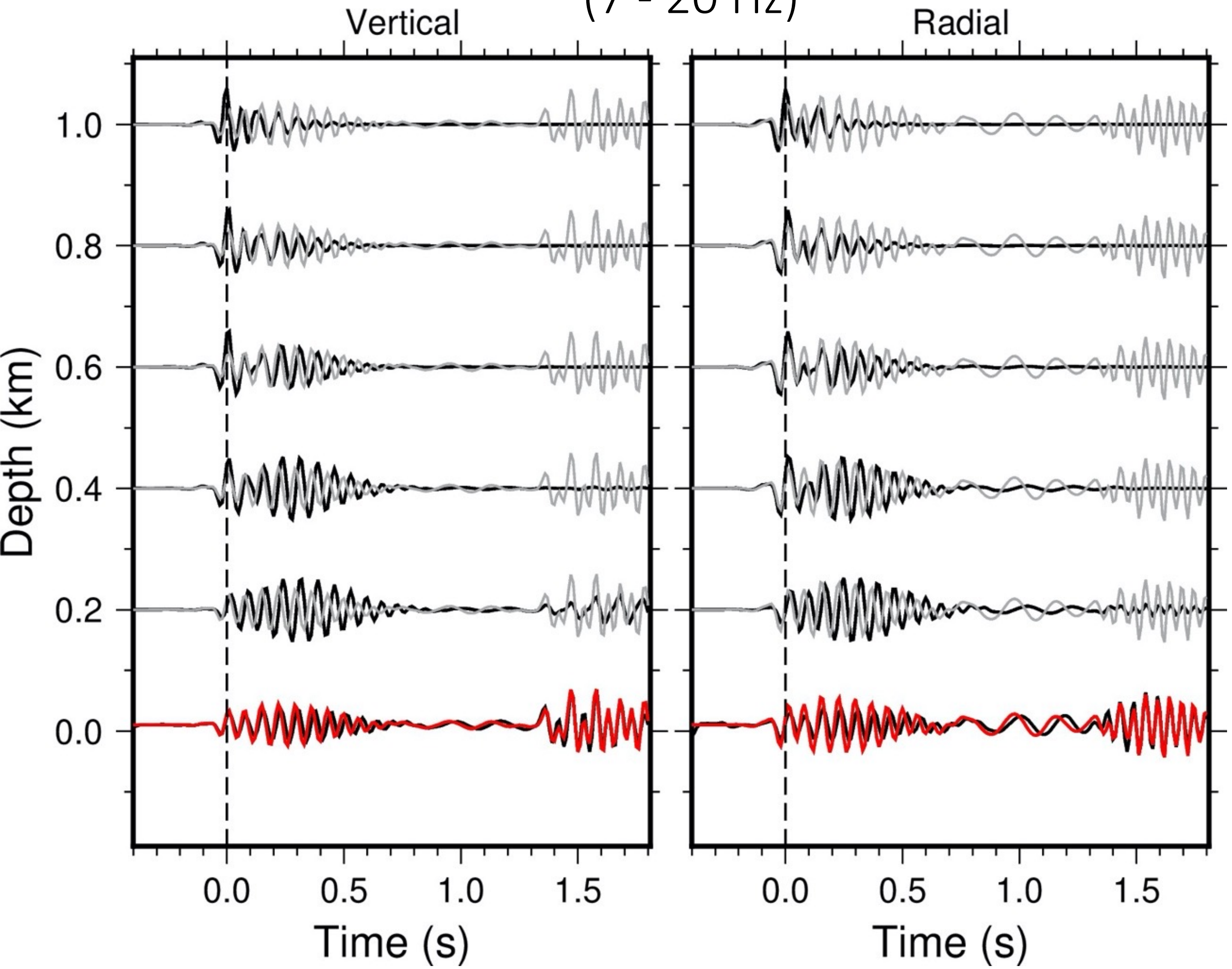
Synthetic test: construct a three-layer model with similar average velocity in the shallow layer



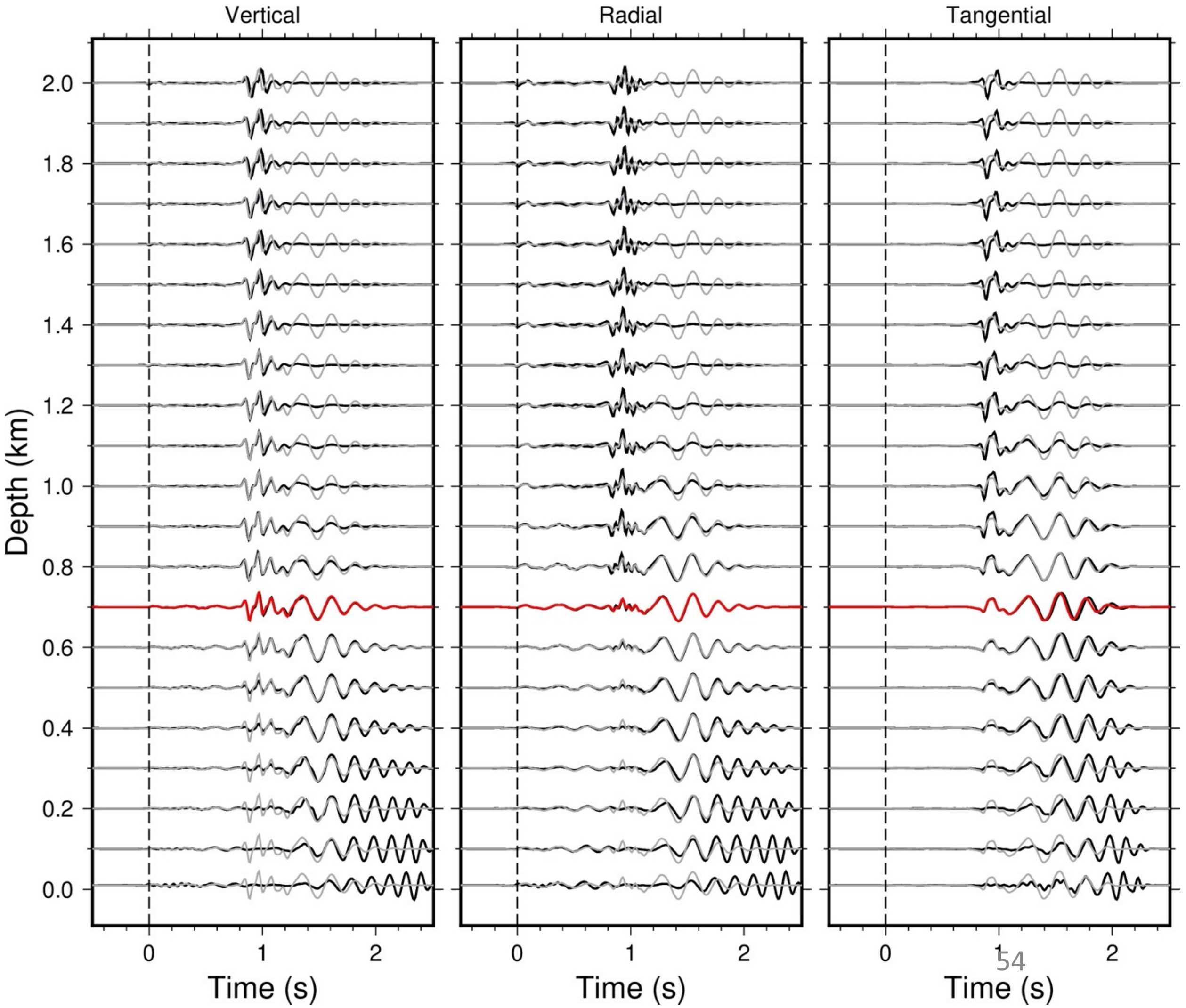
Surface wave fitting
(2 -6 Hz)



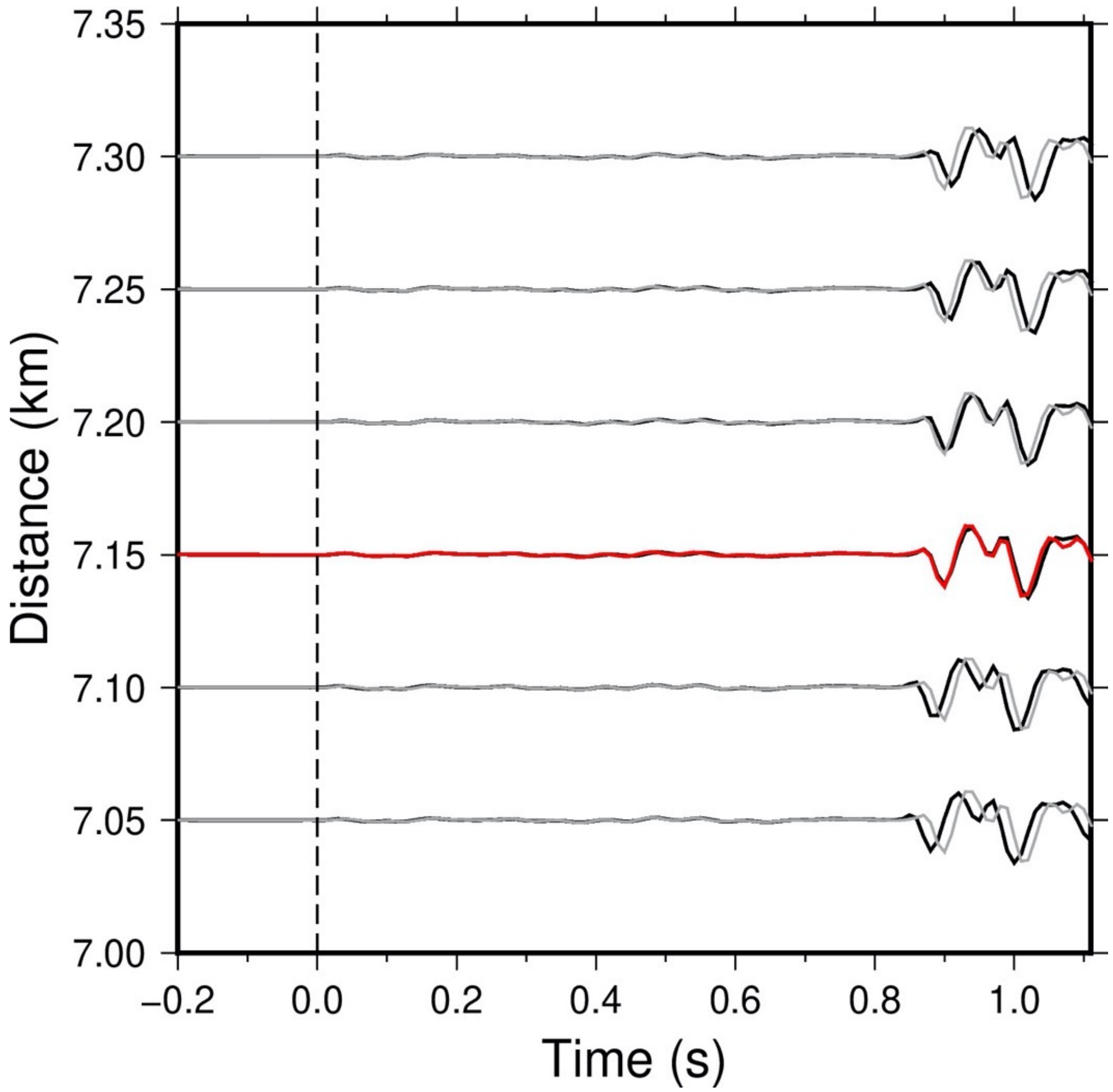
Body wave fitting
(7 - 20 Hz)



Full-waveform fitting
(3–15 Hz)

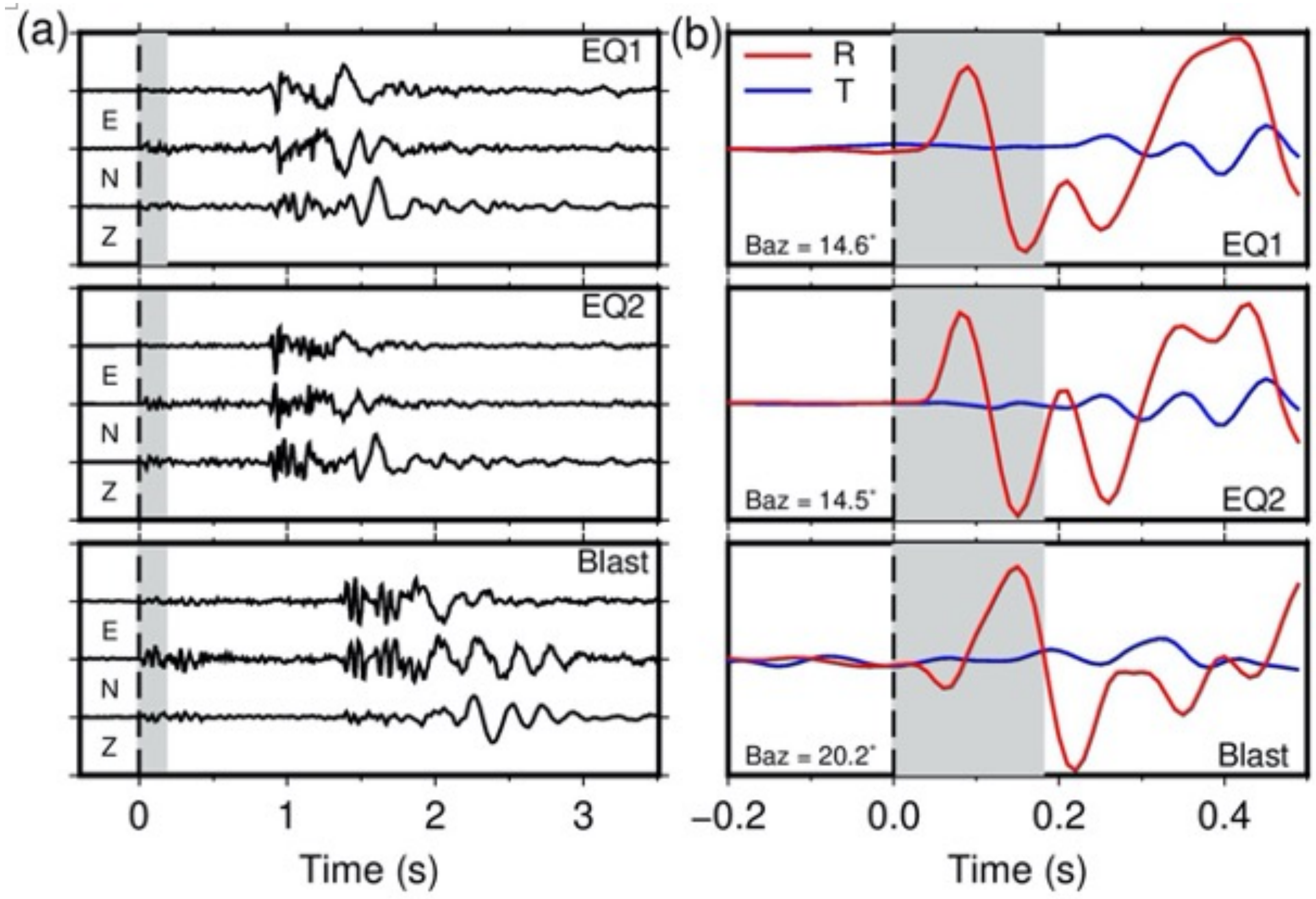


Vertical body wave fitting (5–15 Hz)



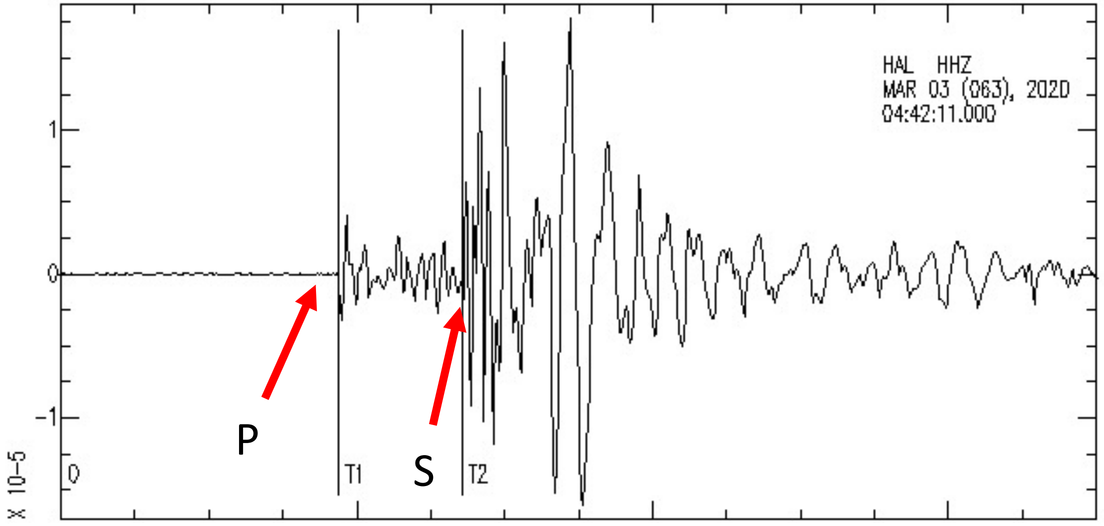
Back azimuth estimation

1 – 20 Hz　　1 – 8 Hz



Station azimuth calibration: Baz_obs – Baz_ref = 2.6°
Calibrated baz for the two events: 17.15°
Time window and frequency effects.: within 2.5°

Initial epicentral distance estimation



Source-station distance (estimated from ts-tp 0.85 sec with a source depth of 0 km): 7.1 km