Integrating GPS and Teleseismic Data for Fast Finite Source Inversion and Tsunami Early Warning

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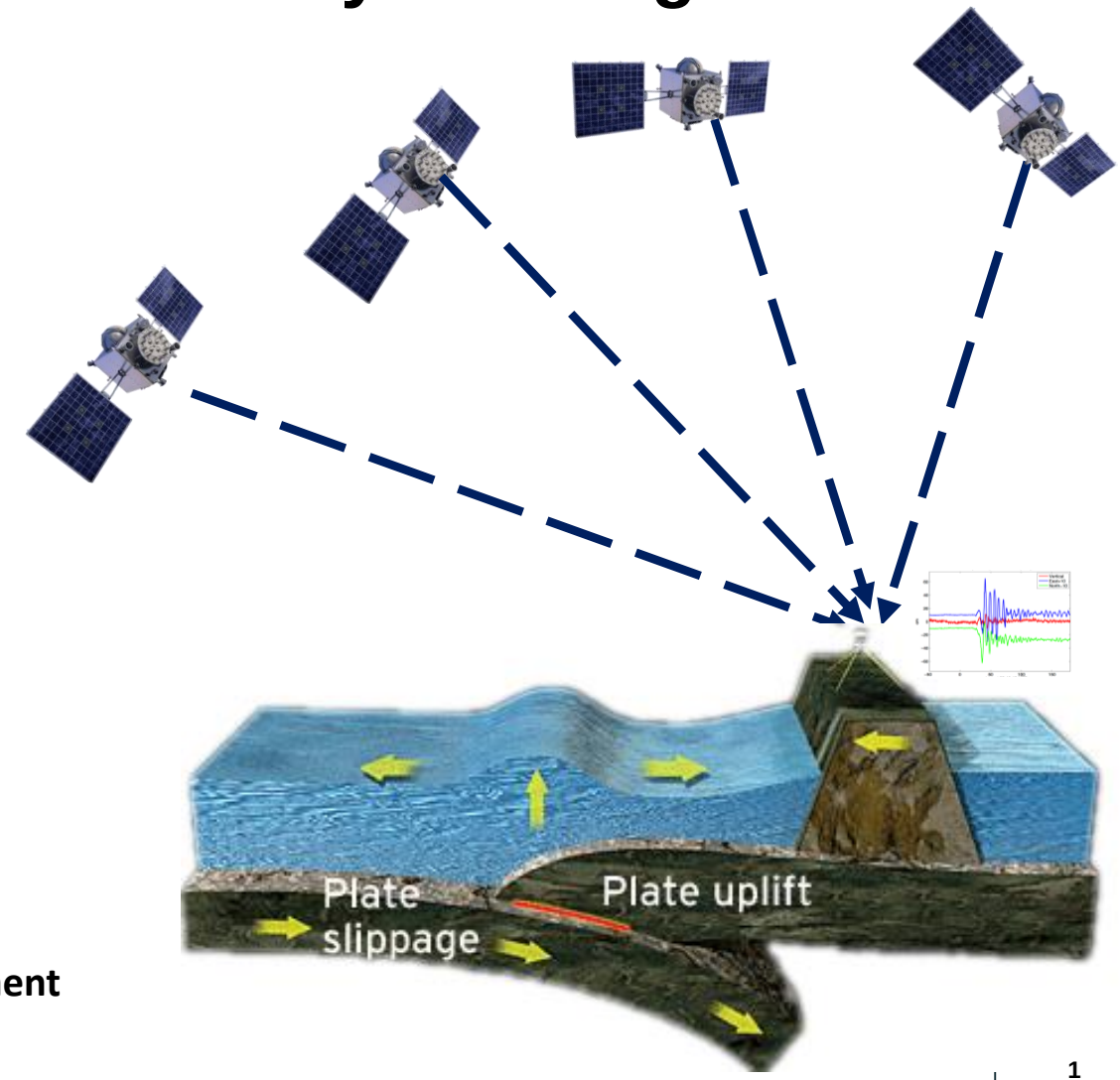

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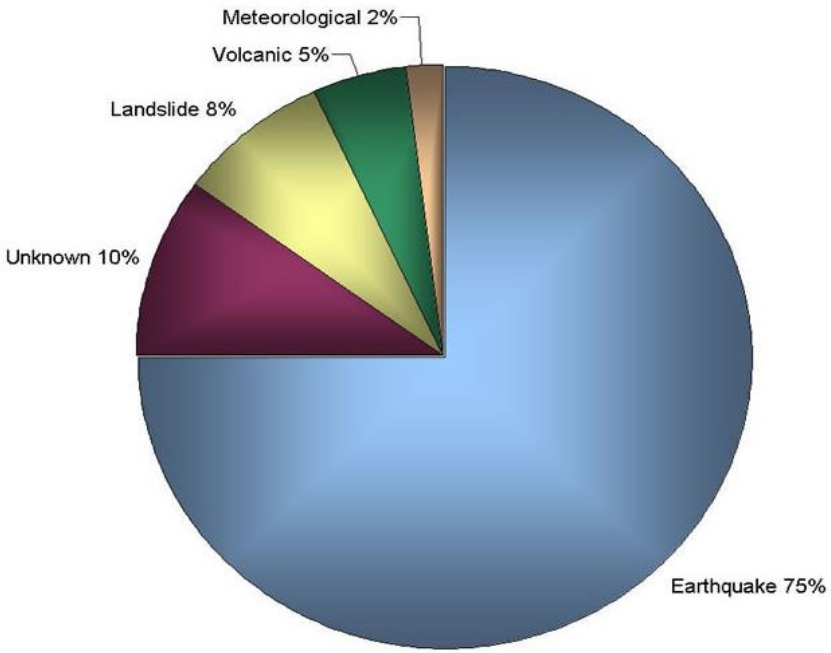
Tsunami: Rare but Devastating

Disaster film: San Andreas (2015) (from Youtube)

Causes of Tsunami

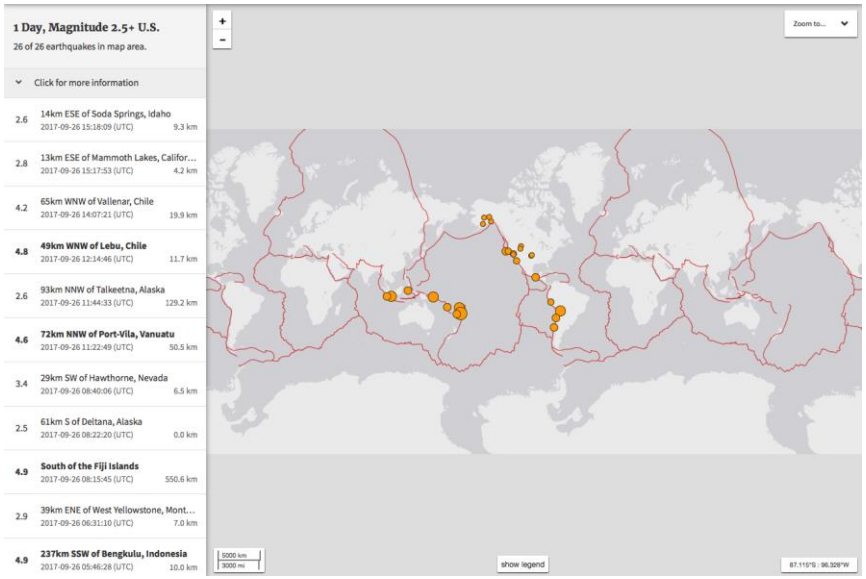


Courtesy: Geoscience Australia

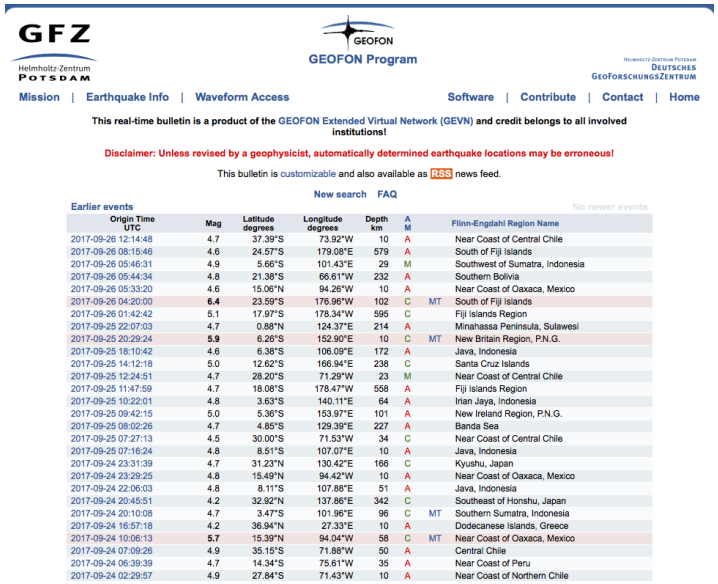
For tsunami early warning, identification of earthquake source in real-time is the most important thing!

Three basic questions must be answered in minutes for tsunami early warning (TEW):

Question 1: where is the earthquake? Longitude, latitude, depth (precisely determined within minutes)



Earthquake catalogs provided by USGS

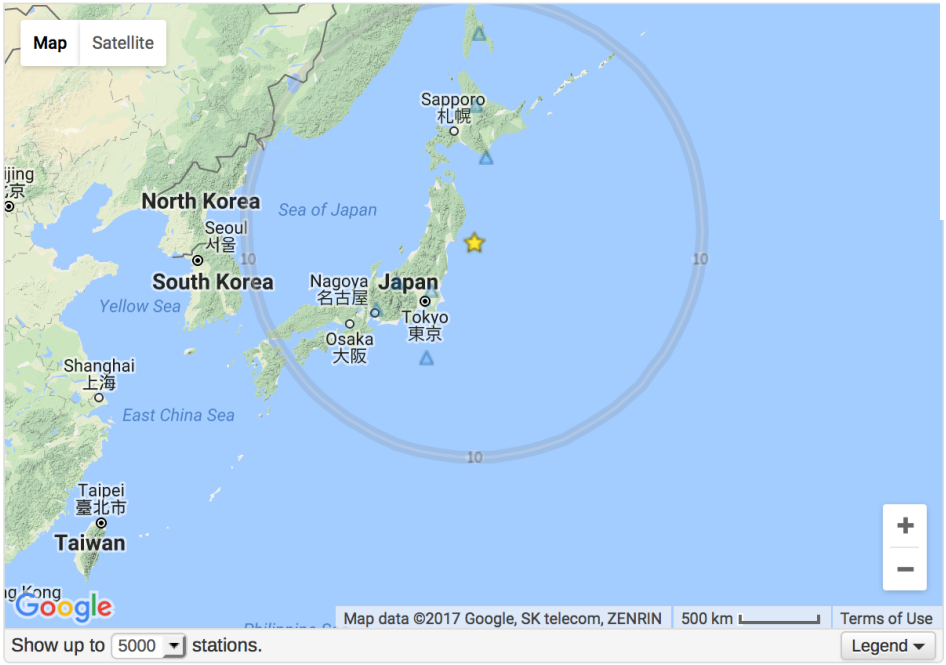


Origin Time UTC	Mag	Latitude degrees	Longitude degrees	Depth km	A	M	Flinn-Engdahl Region Name
2017-09-26 12:14:48	4.7	37.39°S	73.92°W	10	A		Near Coast of Central Chile
2017-09-26 08:15:46	4.6	24.57°S	179.08°E	579	A		South of Fiji Islands
2017-09-26 05:46:31	4.9	5.66°S	101.43°E	29	M		Southwest of Sumatra, Indonesia
2017-09-26 05:44:34	4.8	21.38°S	66.61°W	232	A		Southern Bolivia
2017-09-26 05:33:20	4.6	15.06°N	94.26°W	10	A		Near Coast of Oaxaca, Mexico
2017-09-26 04:20:00	6.4	23.59°S	176.96°W	102	C	MT	South of Fiji Islands
2017-09-26 01:42:42	5.1	17.97°S	178.34°W	595	C		Fiji Islands Region
2017-09-25 22:07:03	4.7	0.88°N	124.37°E	214	A		Minahassa Peninsula, Sulawesi
2017-09-25 20:29:24	5.9	6.26°S	152.90°E	10	C	MT	New Britain Region, P.N.G.
2017-09-25 18:10:42	4.6	6.38°S	106.09°E	172	A		Java, Indonesia
2017-09-25 14:12:18	5.0	12.62°S	166.94°E	238	C		Santa Cruz Islands
2017-09-25 12:24:51	4.7	28.20°S	71.29°W	23	M		Near Coast of Central Chile
2017-09-25 11:47:59	4.7	18.08°S	178.47°W	558	A		Fiji Islands Region
2017-09-25 10:22:01	4.8	3.63°S	140.11°E	64	A		Irian Jaya, Indonesia
2017-09-25 09:42:15	5.0	5.36°S	153.97°E	101	A		New Ireland Region, P.N.G.
2017-09-25 08:02:26	4.7	4.85°S	129.39°E	227	A		Banda Sea
2017-09-25 07:27:13	4.5	30.00°S	71.53°W	34	C		Near Coast of Central Chile
2017-09-25 07:16:24	4.8	8.51°S	107.07°E	10	A		Java, Indonesia
2017-09-24 23:31:39	4.7	31.23°N	130.42°E	166	C		Kyushu, Japan
2017-09-24 23:29:25	4.8	15.49°N	94.42°W	10	A		Near Coast of Oaxaca, Mexico
2017-09-24 22:06:03	4.8	8.11°S	107.88°E	51	A		Java, Indonesia
2017-09-24 20:45:51	4.2	32.92°N	137.86°E	342	C		Southeast of Honshu, Japan
2017-09-24 20:10:08	4.7	3.47°S	101.96°E	96	C	MT	Southern Sumatra, Indonesia
2017-09-24 16:57:18	4.2	36.94°N	27.33°E	10	A		Dodecanese Islands, Greece
2017-09-24 10:06:13	5.7	15.39°N	94.04°W	58	C	MT	Near Coast of Oaxaca, Mexico
2017-09-24 07:09:26	4.9	35.15°S	71.88°W	50	A		Central Chile
2017-09-24 06:39:39	4.7	14.34°S	75.61°W	35	A		Near Coast of Peru
2017-09-24 02:29:57	4.9	27.84°S	71.43°W	10	A		Near Coast of Northern Chile

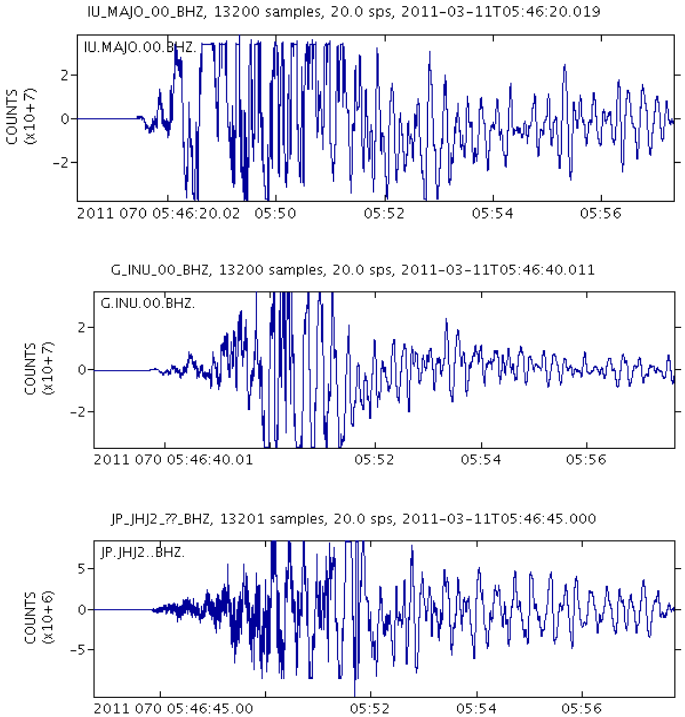
Earthquake catalogs provided by GFZ

Three basic questions must be answered in minutes for tsunami early warning (TEW):

Question 2: how large is the earthquake? (problematic for huge earthquakes)



Seismic stations within 1000 km to epicenter of 2011 Mw 9.1 Tohoku earthquake (from IRIS)



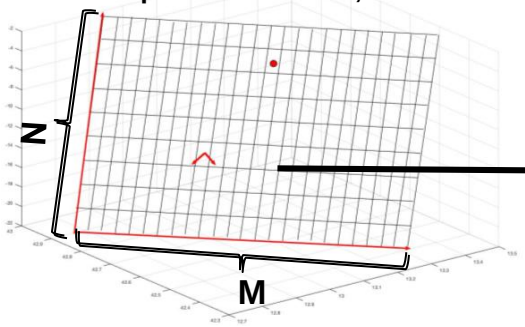
Saturation of seismographs

Three basic questions must be answered in minutes for tsunami early warning (TEW):

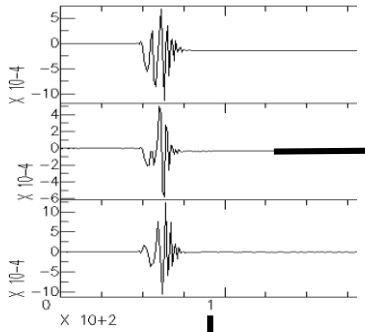
Question 3: what is the slip feature of the earthquake? Finite source inversion (quite challenging in real time)

What is finite source inversion?

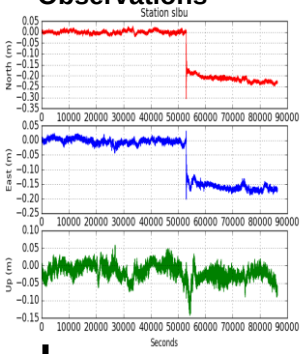
Fault plane orientation, discretization

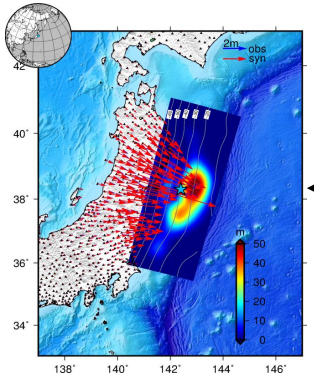


Synthetic waveforms



Observations





Finite slip distribution

$$\begin{bmatrix} G_{1E} & G_{2E} & G_{3E} & * & * & * & * & * \\ G_{1N} & G_{2N} & G_{3N} & * & * & * & * & * \\ G_{1U} & G_{2U} & G_{3U} & * & * & * & * & * \\ * & & & & & & & \\ * & & & & & & & \\ * & & & & & & & \\ * & & & & & & & \\ * & & & & & & & \end{bmatrix} \times \begin{bmatrix} S_{11} \\ S_{12} \\ S_{21} \\ S_{22} \\ S_{31} \\ S_{32} \\ * \\ * \end{bmatrix} = \begin{bmatrix} D_{1E} \\ D_{1N} \\ D_{1U} \\ D_{2E} \\ D_{2N} \\ D_{2U} \\ * \\ * \end{bmatrix}$$

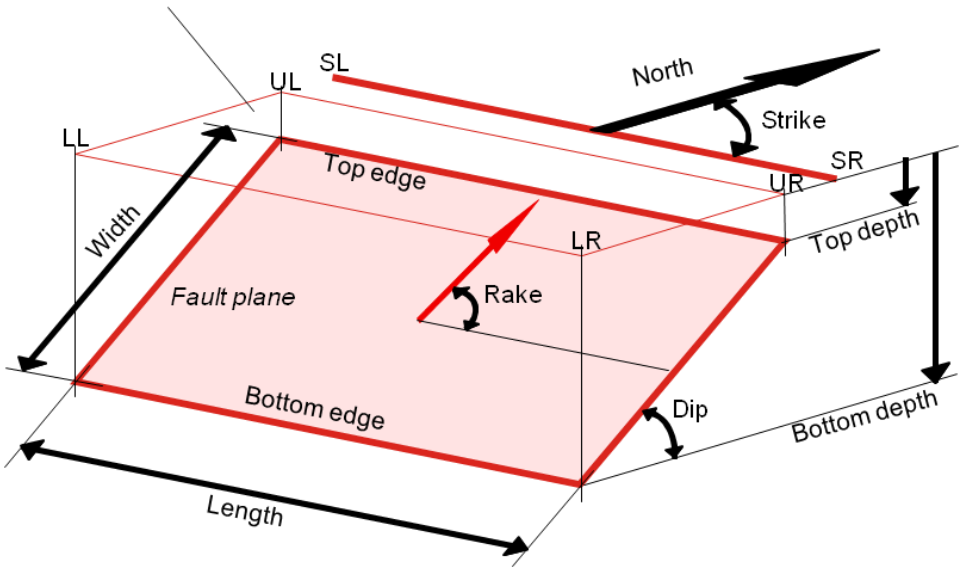
Equations

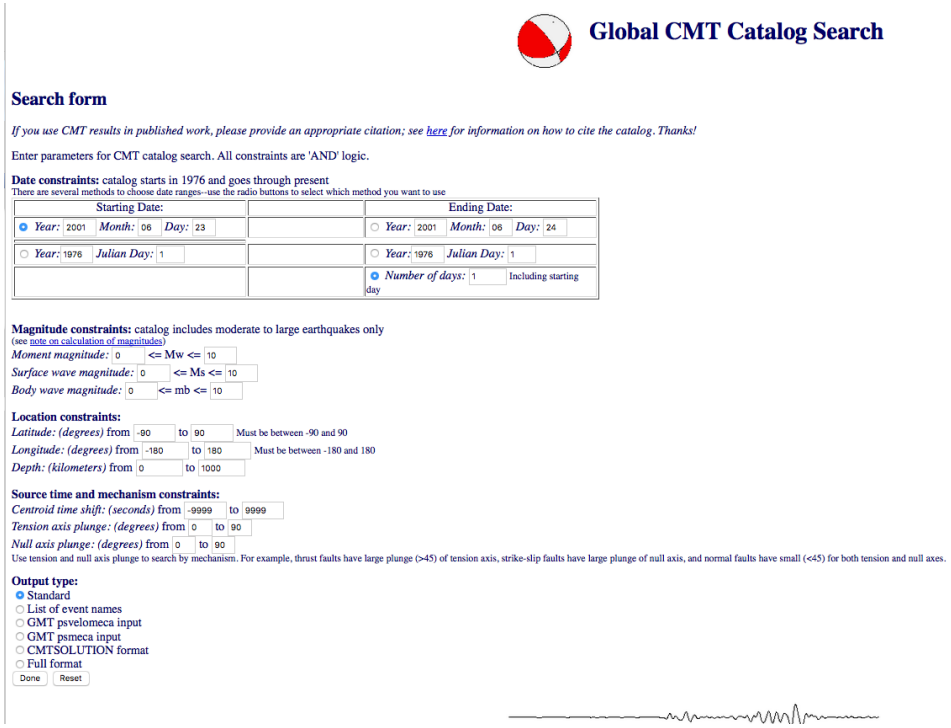
Why fast finite source inversion difficult?

Reason 1: unknown fault planes

Strike=? Dip=? Rake=?

Fault projection to ground surface





Global CMT Catalog Search

Search form

If you use CMT results in published work, please provide an appropriate citation; see here for information on how to cite the catalog. Thanks!

Enter parameters for CMT catalog search. All constraints are 'AND' logic.

Date constraints: catalog starts in 1976 and goes through present
There are several methods to choose date ranges--use the radio buttons to select which method you want to use

Starting Date:		Ending Date:
Year: 2001 *Month:* 06 *Day:* 23		*Year:* 2001 *Month:* 06 *Day:* 24
Year: 1976 *Julian Day:* 1		*Year:* 1976 *Julian Day:* 1
		Number of days: 1 Including starting day

Magnitude constraints: catalog includes moderate to large earthquakes only
(see note on calculation of magnitudes)
Moment magnitude: 0 <= Mw <= 10
Surface wave magnitude: 0 <= Ms <= 10
Body wave magnitude: 0 <= mb <= 10

Location constraints:
Latitude: (degrees) from -90 to 90 Must be between -90 and 90
Longitude: (degrees) from -180 to 180 Must be between -180 and 180
Depth: (kilometers) from 0 to 1000

Source time and mechanism constraints:
Centroid time shift: (seconds) from -9999 to 9999
Tension axis plunge: (degrees) from 0 to 90
Null axis plunge: (degrees) from 0 to 90
Use tension and null axis plunge to search by mechanism. For example, thrust faults have large plunge (>45) of tension axis, strike-slip faults have large plunge of null axis, and normal faults have small (<45) for both tension and null axes.

Output type:
- Standard
- List of event names
- GMT psvelomeca input
- GMT psmeca input
- CMTSOLUTION format
- Full format

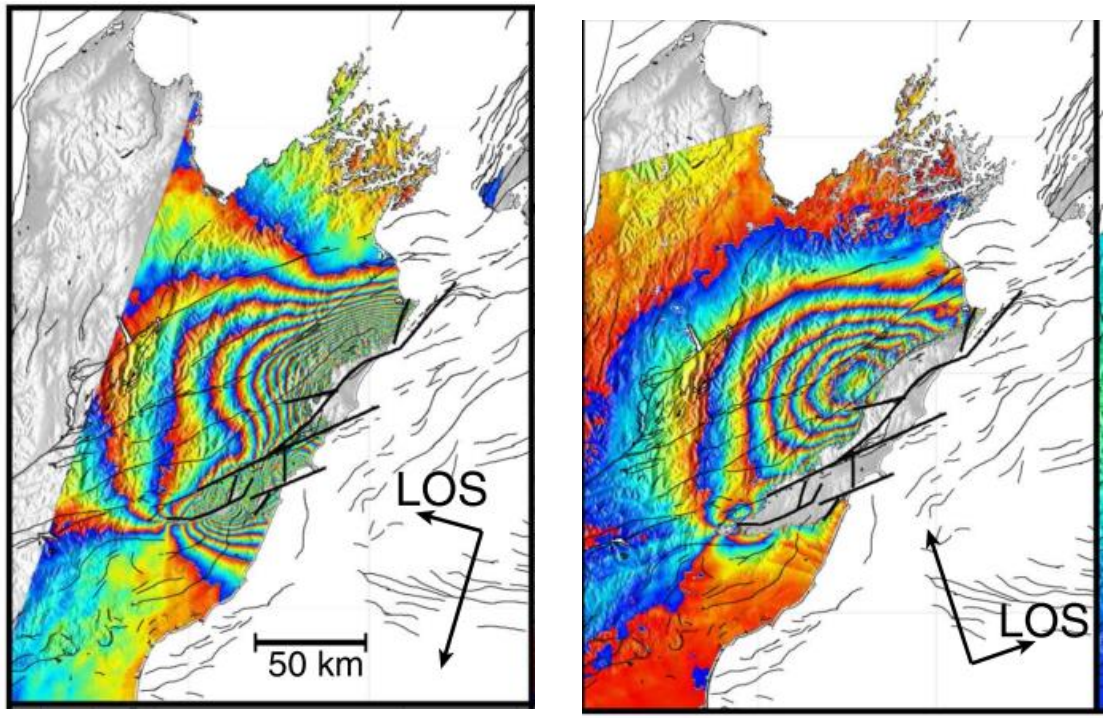
Done Reset

Hours later, Global Centroid Moment Tensor (GCMT)

Why fast finite source inversion difficult?

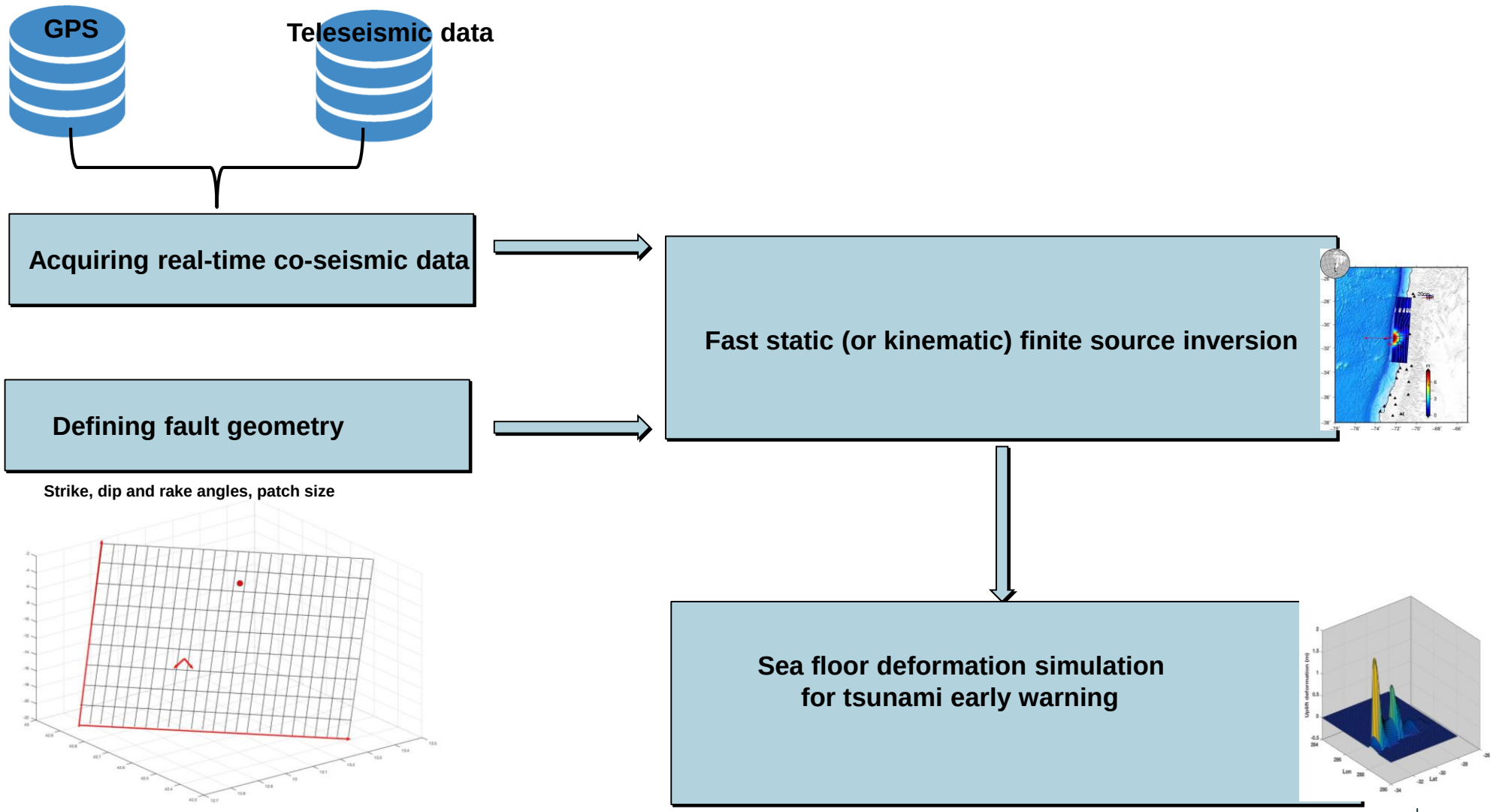
Reason 2: limited available datasets

InSAR observations for 2016 Mw 7.8 Kaikoura earthquake , weeks later

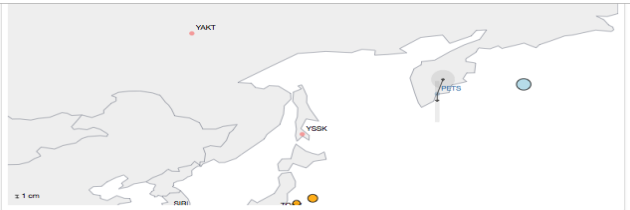


Hamling et al. (2017)

Our aims: fast (less than 15 min) finite source inversion for TEW

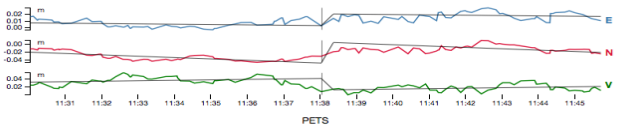


The Global Differential GPS System run by JPL monitors earthquakes and aids tsunami early warning

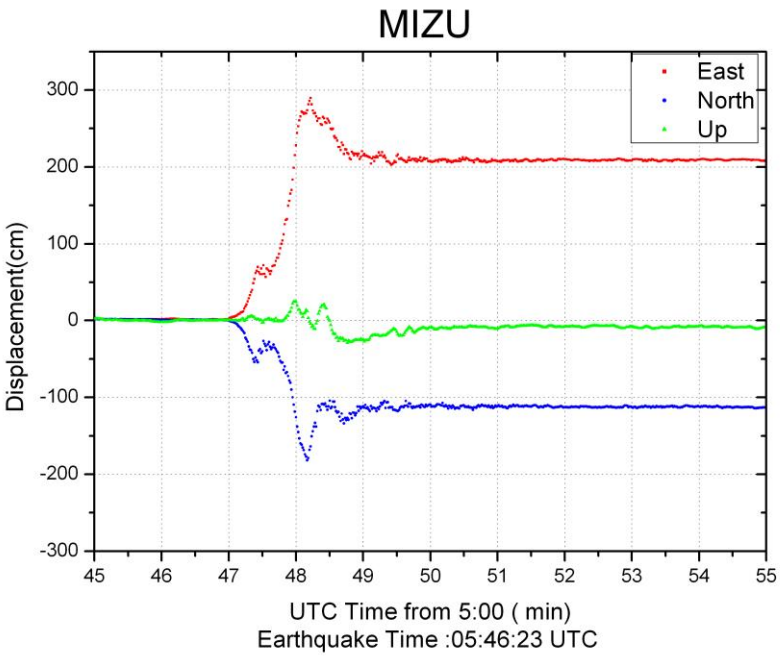


Magnitude	Place	Time	ID
5.1	75km NW of Gyamotang, China	Thu, 12 Oct 2017 07:52:28 GMT	us1000aqmb
5	108km ESE of Iwaki, Japan	Thu, 12 Oct 2017 06:12:39 GMT	us1000aqls
5.3	152km ENE of Visokoi Island, South Georgia and the South Sandwich Islands	Thu, 12 Oct 2017 03:12:27 GMT	us1000aqkz
5.1	31km E of Patitirion, Greece	Wed, 11 Oct 2017 22:49:44 GMT	us1000aqij
5.2	57km SE of Madang, Papua New Guinea	Wed, 11 Oct 2017 21:56:55 GMT	us1000aqhq
6.3	36km SSW of Putre, Chile	Tue, 10 Oct 2017 06:32:20 GMT	us2000b3dm
6.3	Balleny Islands region	Sun, 08 Oct 2017 20:48:58 GMT	us2000b2v1
6	255km ESE of Ishinomaki, Japan	Fri, 06 Oct 2017 07:59:33 GMT	us2000b1v8
7.7	**202km ESE of Nikol'skoye, Russia**	**Mon, 17 Jul 2017 23:34:13 GMT**	**us20009x42**
7.9	35km WNW of Panguna, Papua New Guinea	Sun, 22 Jan 2017 04:30:22 GMT	us10007uph
7.6	41km SW of Puerto Quellon, Chile	Sun, 25 Dec 2016 14:22:27 GMT	us10007mn3
7.9	54km E of Taron, Papua New Guinea	Sat, 17 Dec 2016 10:51:10 GMT	us200081v8
7.8	69km WSW of Kirakira, Solomon Islands	Thu, 08 Dec 2016 17:38:46 GMT	us20007z80
7.8	54km NNE of Amberley, New Zealand	Sun, 13 Nov 2016 11:02:56 GMT	us1000778i

Station	Distance (km)	E (cm)	N (cm)	V (cm)	Significance
PETS	689	1.70 ± 3.33	5.35 ± 3.60	−2.83 ± 7.45	94% (EN); 59% (V)



Advantage of GPS: Never Clip

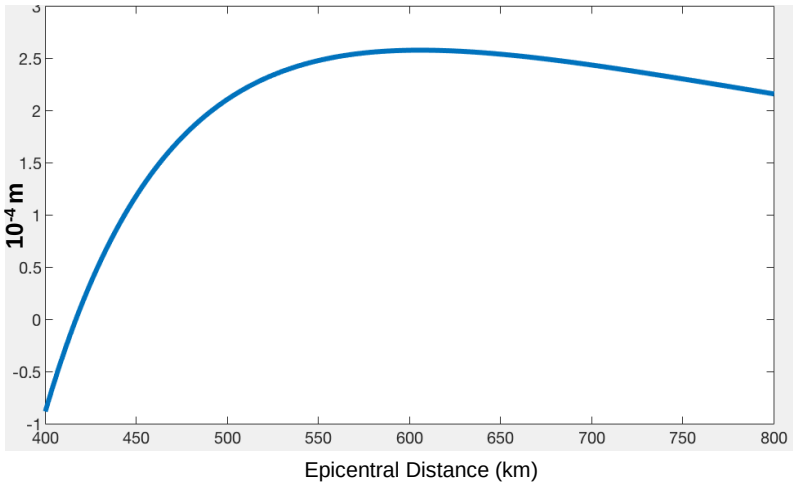


Displacement waveform at station MIZU (200 km to the epicenter) during 2011 Tohoku earthquake (up to 3 m)

Limitations of GPS

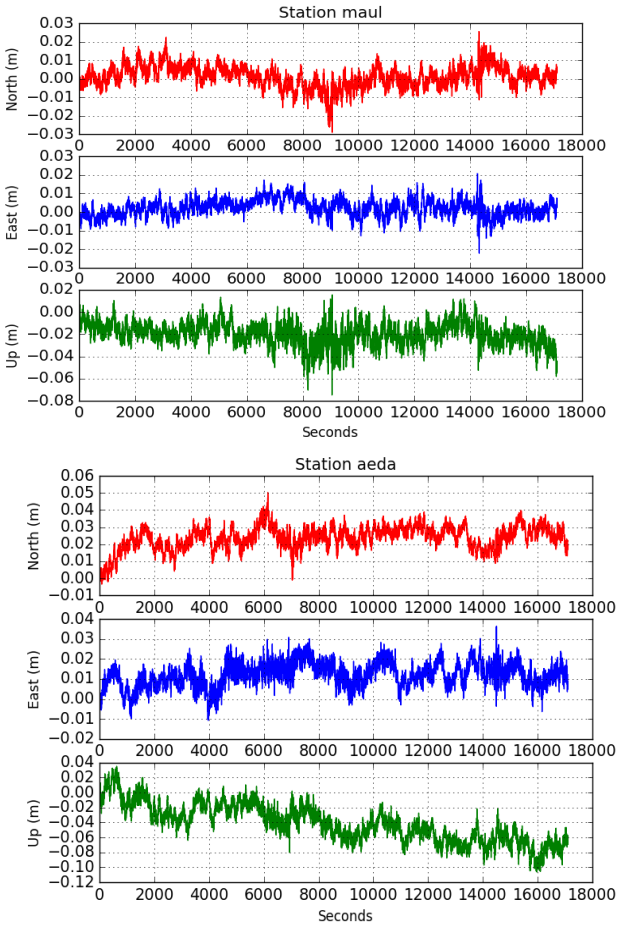
Accuracy is limited to cm

Seismic signal decays very fast in the near field



Simulated vertical deformation for an Mw 8.0 event with 30 km epicenter depth

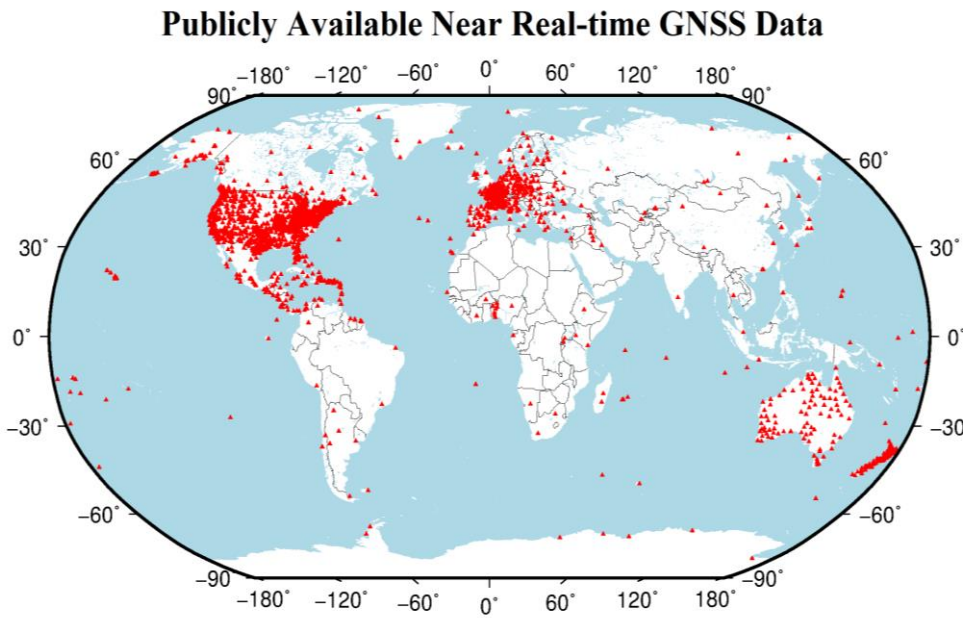
Cannot detect earthquake offsets



Displacement waveforms at two GPS stations(> 500 km to the epicenter) recorded during 2015 Mw 8.3 Illapel earthquake, can you tell where are the earthquake signals?

Limitations of GPS

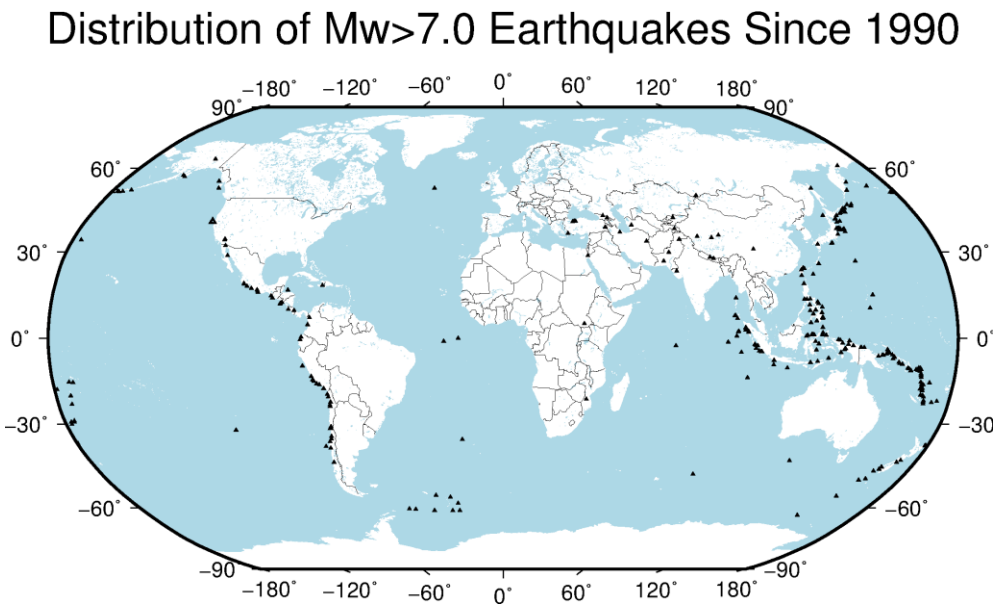
Network is sparse



Dense network exists in US, New Zealand and Europe

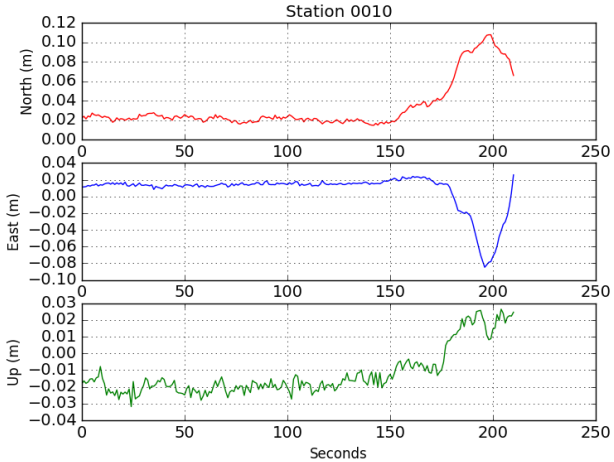
Chen et al. (2016)

Fail to cover many seismic active regions

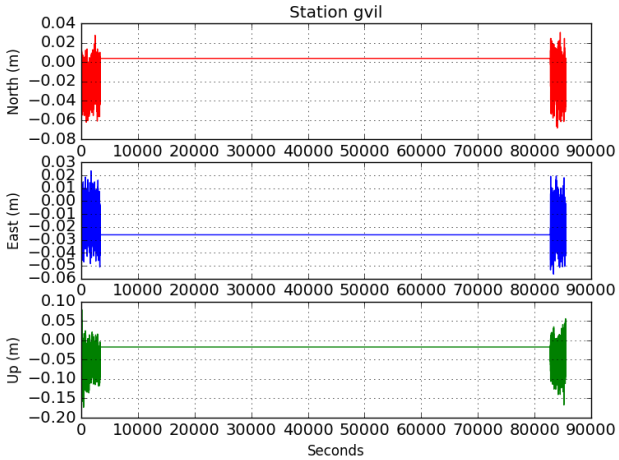


Limitations of GPS

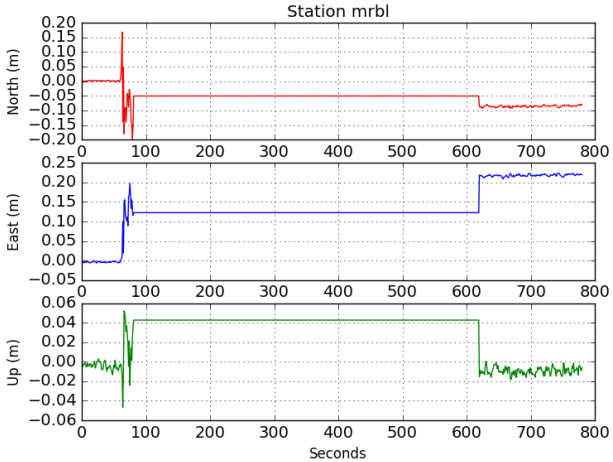
Data loss during strong shaking for near field stations



2011 Tohoku earthquake

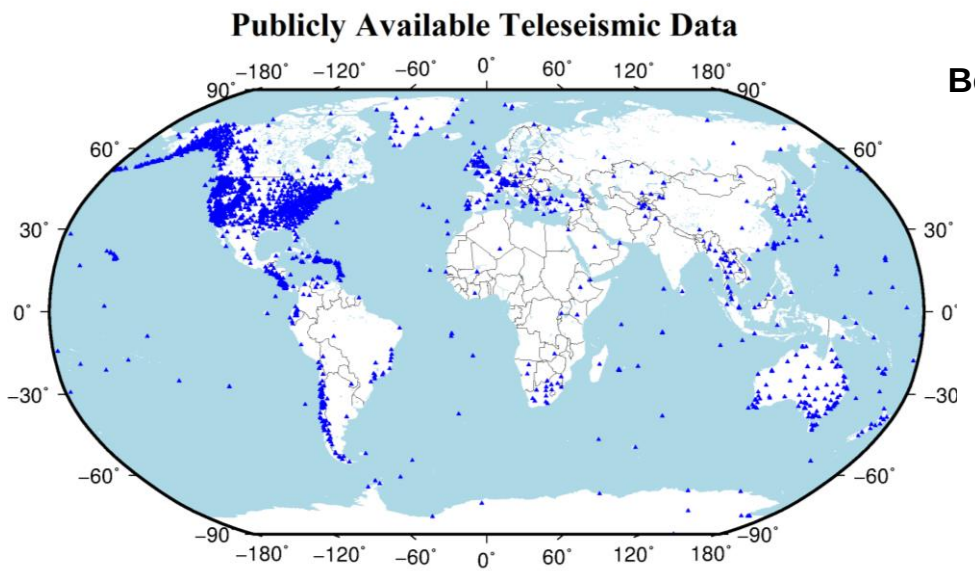


2015 Illapel earthquake



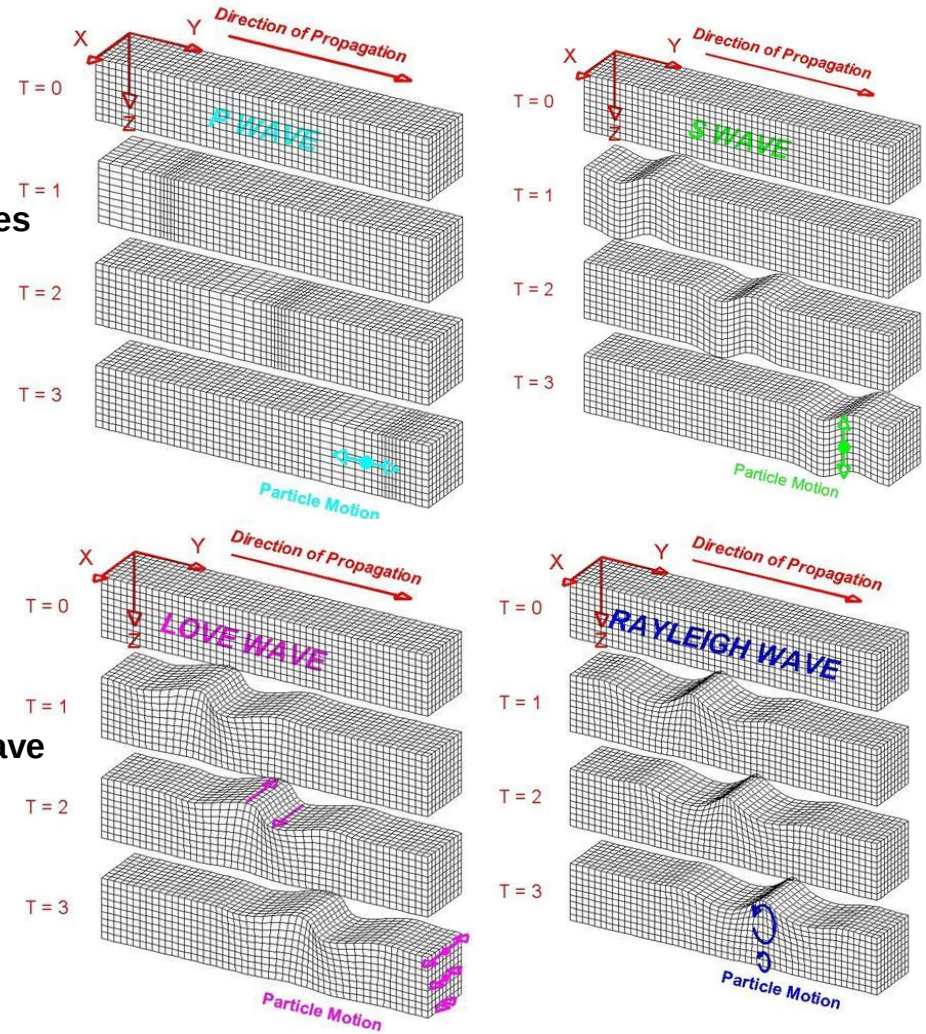
2016 Kaikoura earthquake

Global Seismographic Network (GSN)



Body waves

Surface wave



Seismic waves (from UPSeis)

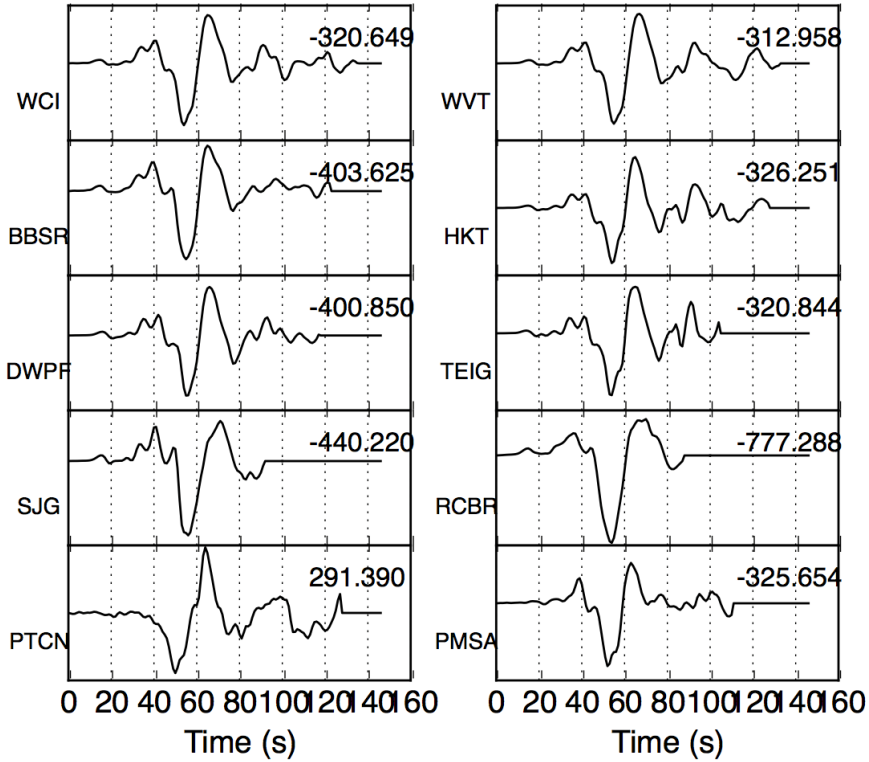
Seismographs are more accurate than GPS

For a Mw 8.2 event, stations at global distance can record it clearly

2014 Mw 8.2 Iquique earthquake

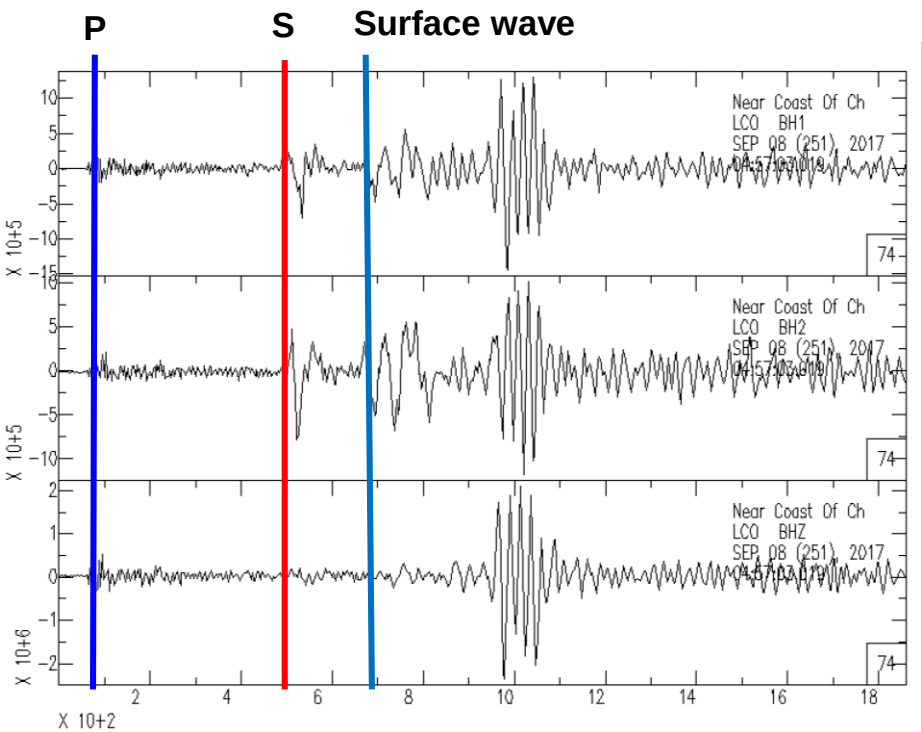
Precision up to 10^{-5} m

P wave displacment waveforms (1e-6 m,sorted by latitude)



Using teleseismic P wave for finite source inversion

Why teleseismic P wave?

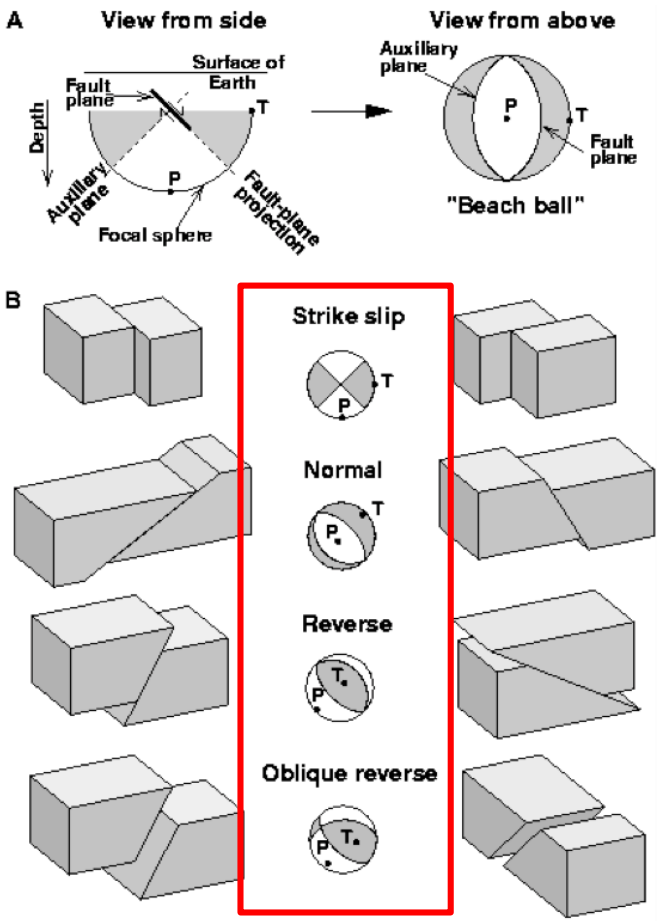


An exemplary seismograph record during 2017 Mw 8.2 Mexico earthquake

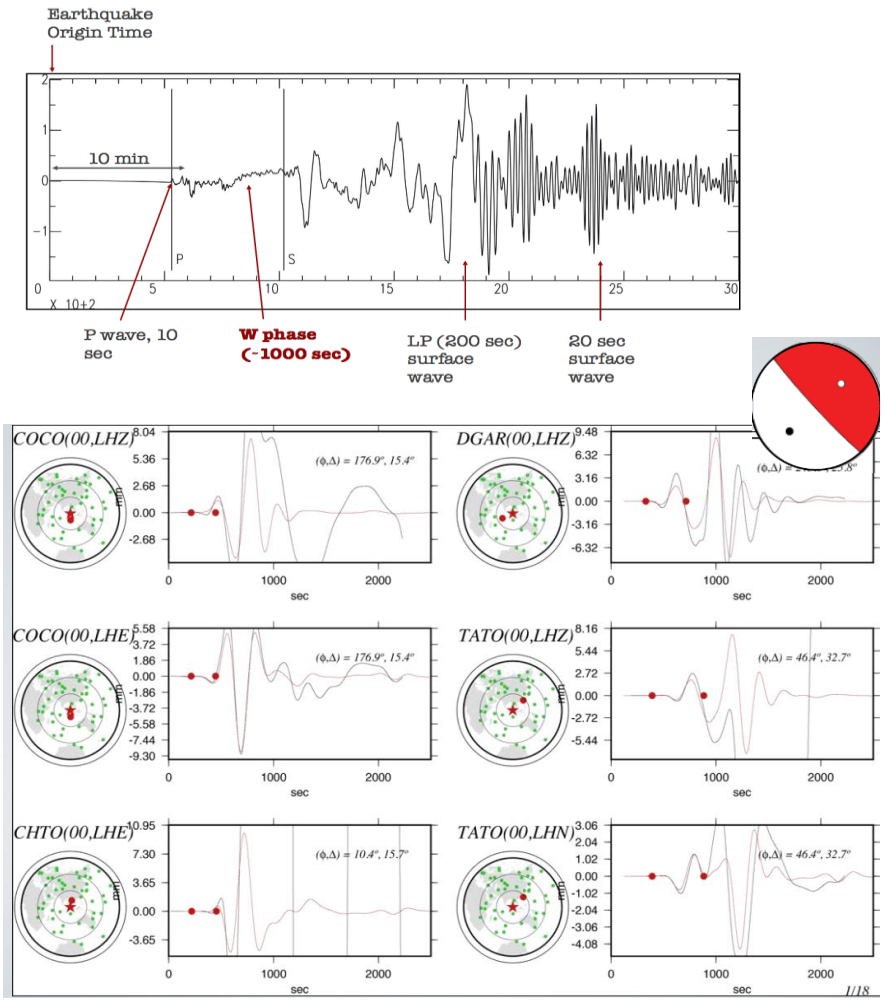
Disadvantage: it takes a longer time (around 8 min) to get P waves at teleseismic stations

How to decide the fault plane?

Traditionally, from moment tensor inversion by long period seismic waves



From Berkeley Seismology Lab

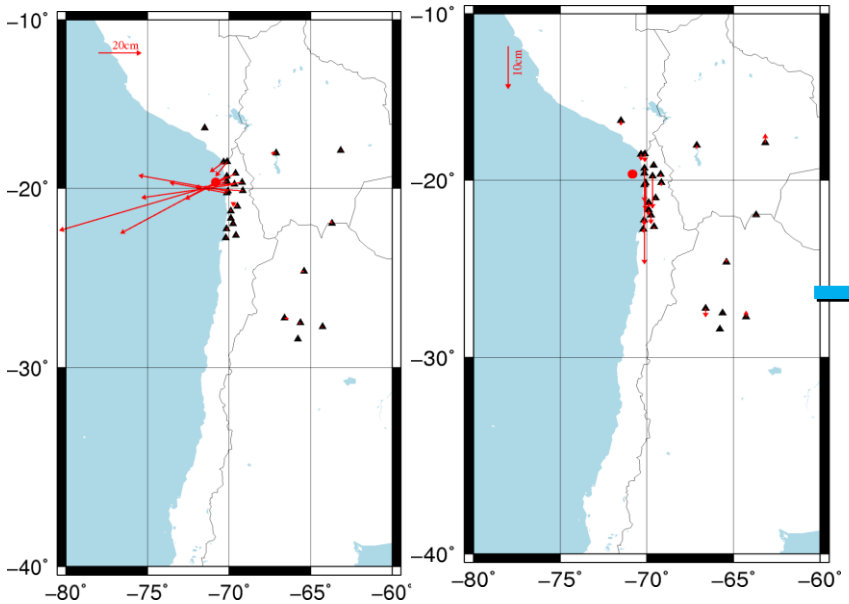


CMT using W phase, (Kanamori and Rivera,2008), about 30 min

Can we get CMT in minutes?

FastCMT using GPS offsets

GPS static offsets can be treated as the longest period waves



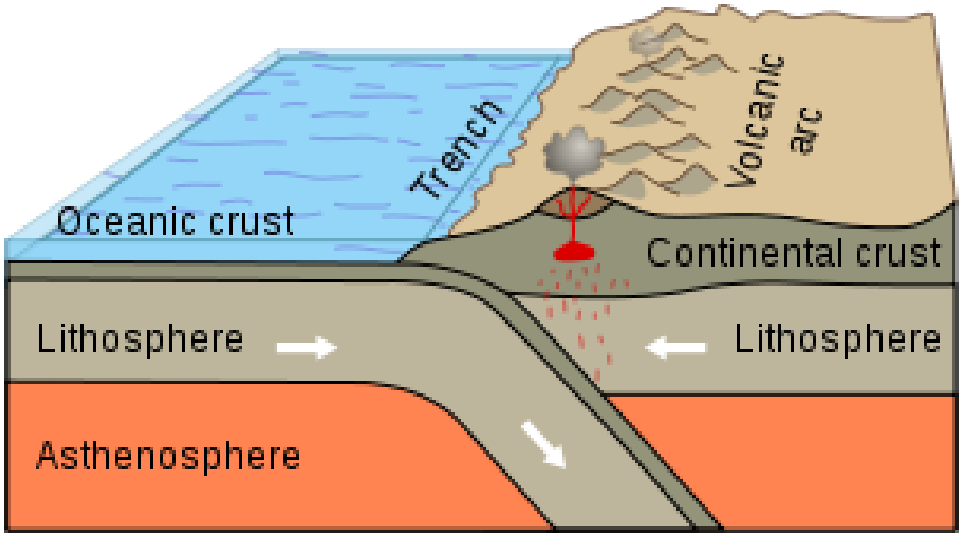
Fast CMT			
Lon= -70.81	Lat= -19.90	Depth=34.9	
Mw=8.2			
NP1	Strike	Dip	Rake
	17	45	126
NP2	Strike	Dip	Rake
	151	55	59

Global CMT			
Lon= -70.81	Lat= -19.70	Depth=21.6	
Mw=8.1			
NP1	Strike	Dip	Rake
	355	15	106
NP2	Strike	Dip	Rake
	159	76	86

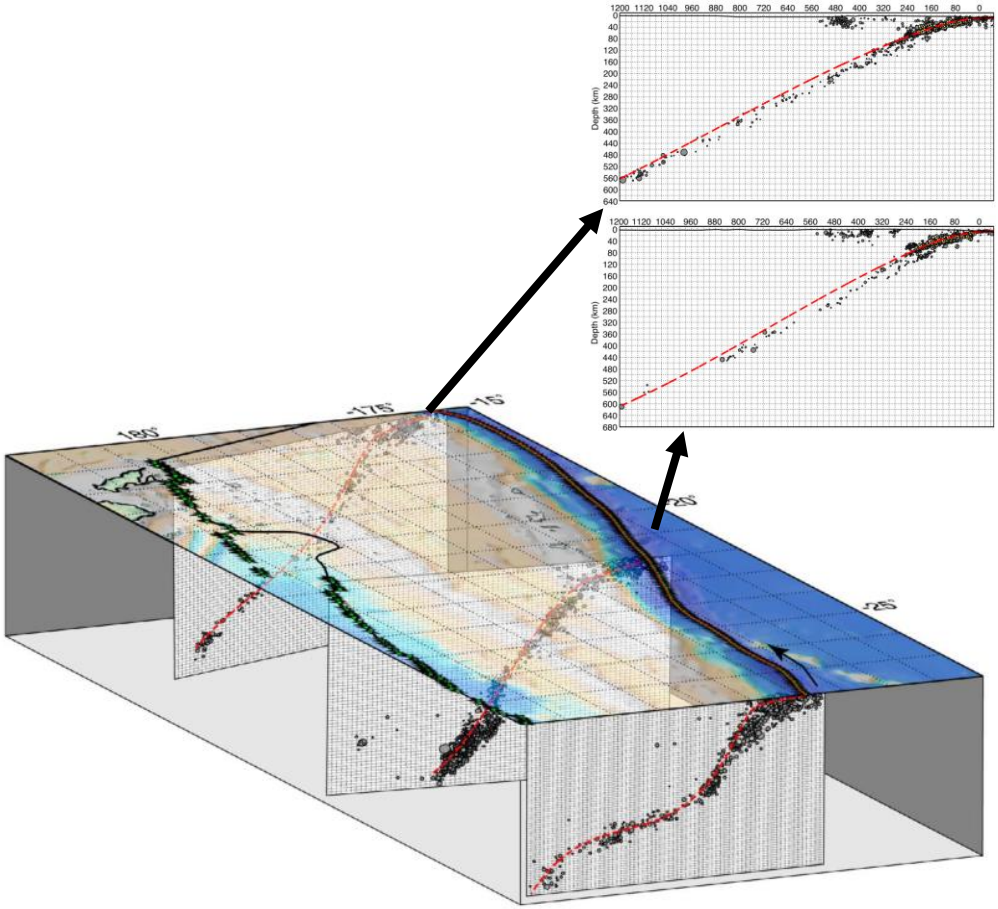
Horizontal and vertical GPS co-seismic displacements

What to do if no GPS data available?

From SLAB 1.0



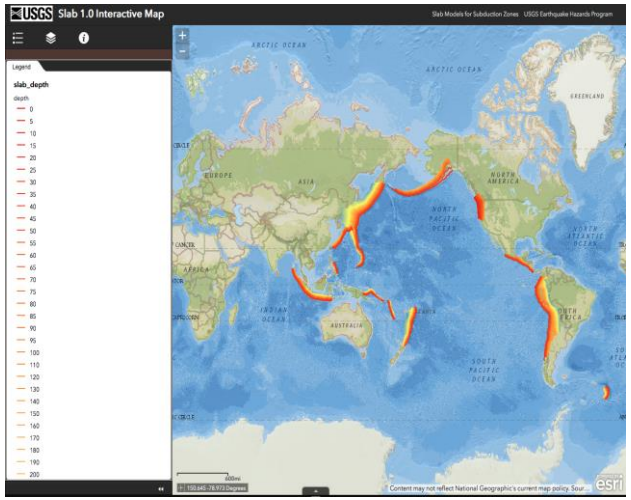
Coastal area where an ocean plate is subducting beneath a continental plate. USGS



Schematic describing the construction of the slab three-dimensional geometry model from a collection of two-dimensional profiles, Hayes et al. (2012)

What to do if no GPS data available?

From SLAB 1.0



SLAB 1.0 subduction model

Data bank

Current Folder

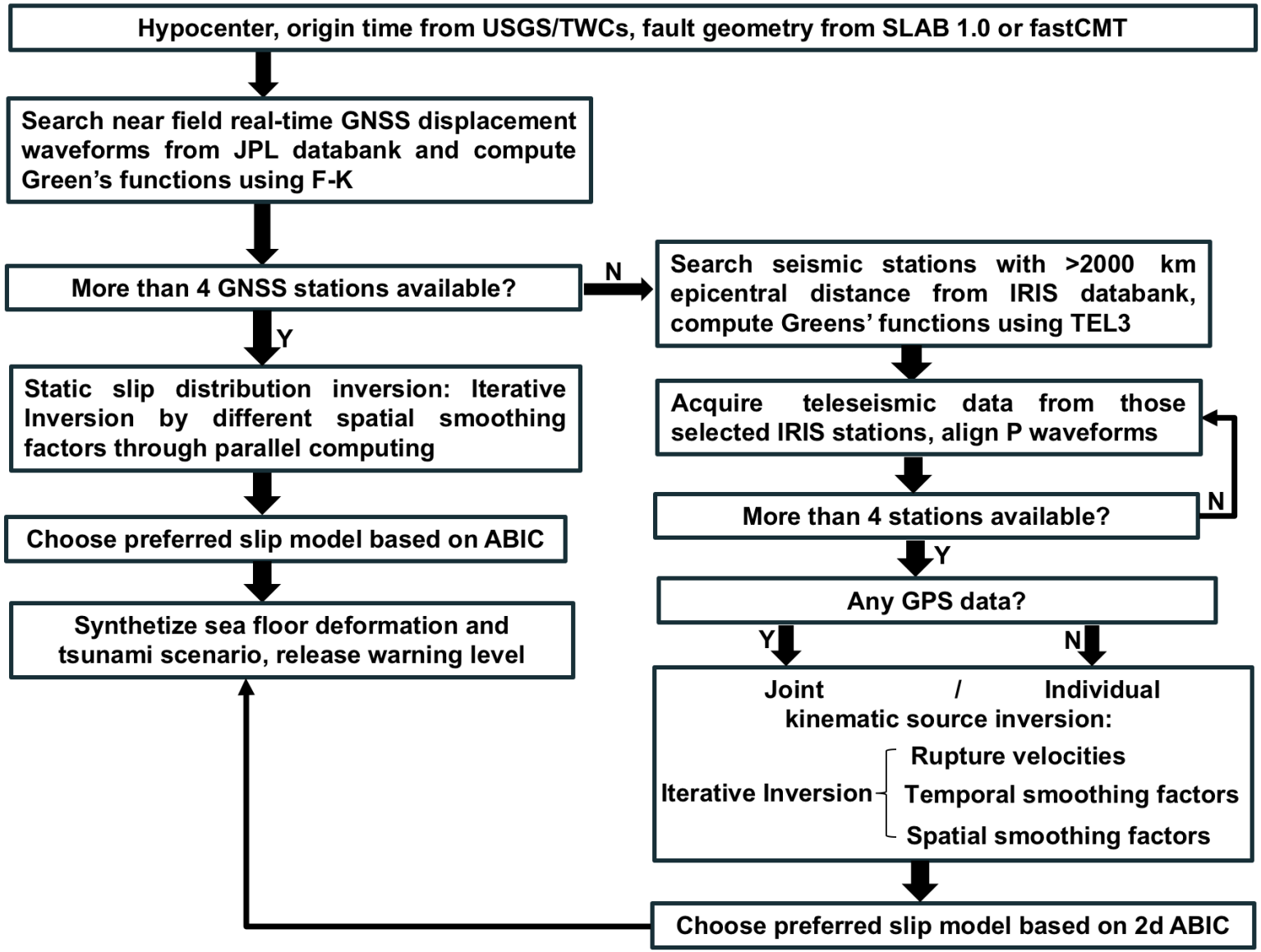
Name ▲

- alu
- cas
- izu
- ker
- kur
- mex
- phi
- ryu
- sam
- sco
- sol
- sum
- van

```
1 Event(s) in Catalog:
2014-04-01T23:46:47.380000Z | -19.619,  -70.788 | 8.1 MW
Origin
        resource_id: ResourceIdentifier(id="smi:service.iris.edu/fdsnws/event/1/query?originid=2239030
               time: UTCDateTime(2014, 4, 1, 23, 46, 47, 380000)
          longitude: -70.7877
           latitude: -19.6193
              depth: 17100.0
```

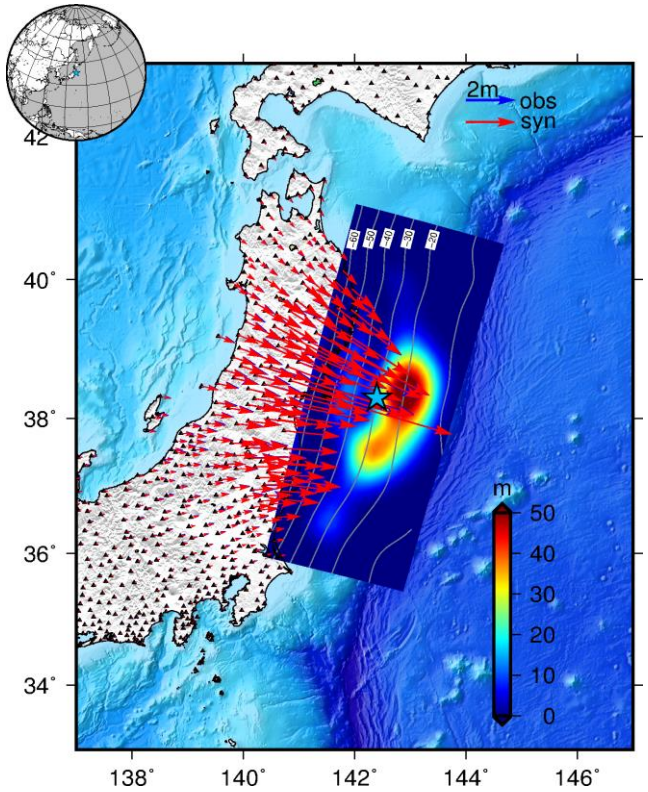
Earthquake happens in South America Region

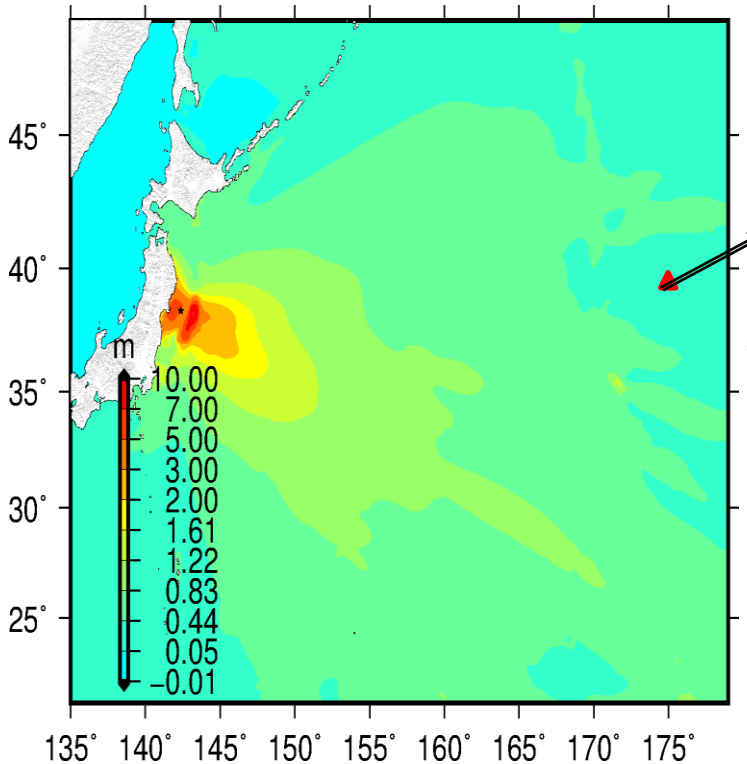
strike= 347.35 dip= 16.3973 dep= -26.3231

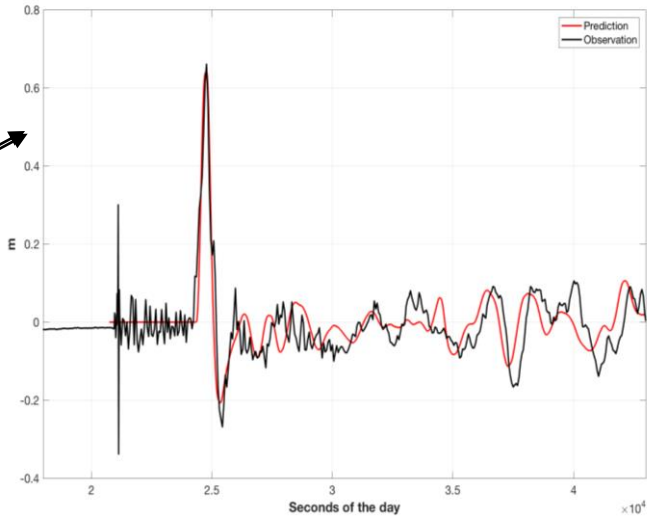

Hypocenter, origin time from USGS/TWCs, fault geometry from SLAB 1.0 or fastCMT
Search near field real-time GNSS displacement waveforms from JPL databank and compute Green's functions using F-K
More than 4 GNSS stations available?
N
Y
Static slip distribution inversion: Iterative Inversion by different spatial smoothing factors through parallel computing
Choose preferred slip model based on ABIC
Synthetize sea floor deformation and tsunami scenario, release warning level
Search seismic stations with >2000 km epicentral distance from IRIS databank, compute Greens' functions using TEL3
Acquire teleseismic data from those selected IRIS stations, align P waveforms
More than 4 stations available?
N
Y
Any GPS data?
Y
N
Joint / Individual kinematic source inversion:
Iterative Inversion
Rupture velocities
Temporal smoothing factors
Spatial smoothing factors
Choose preferred slip model based on 2d ABIC

GPS-only for tsunami early warning:

Fault geometry is from SLAB 1.0

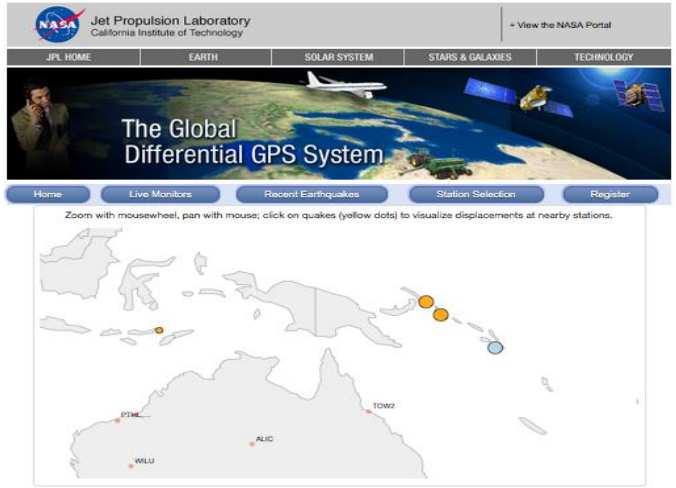






2011 Mw 9.0 Tohoku earthquake slip distribution, about 8 min after the origin time, and can be faster with less GPS stations Chen et al., 2017)

Teleseismic-only tsunami early warning

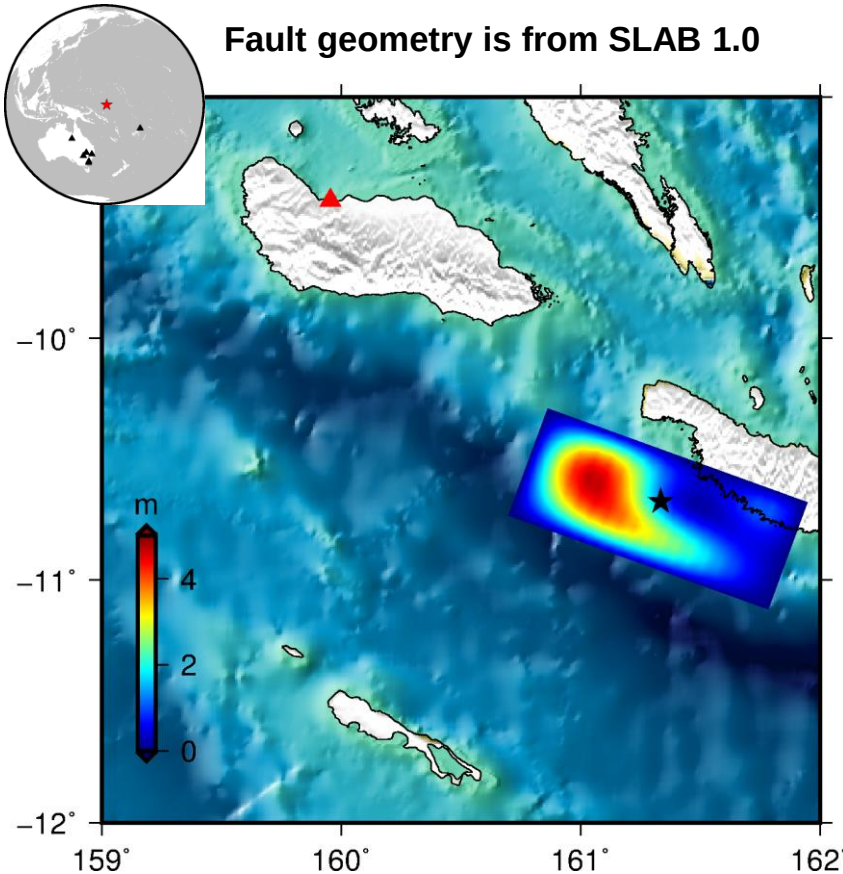


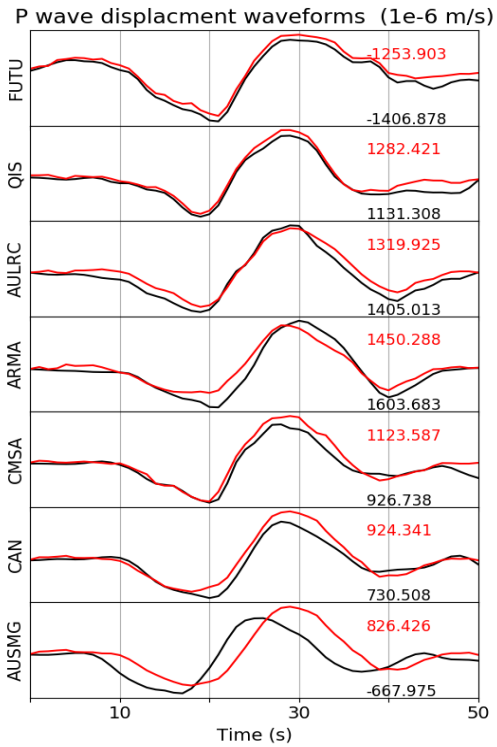
Magnitude	Place	Time	ID
6.7	Bouvet Island region	Tue, 10 Oct 2017 18:53:28 GMT	us1000spql
5	Central East Pacific Rise	Tue, 10 Oct 2017 14:36:02 GMT	us2000b3ii
6.3	36km SSW of Putre, Chile	Tue, 10 Oct 2017 06:32:20 GMT	us2000b3dm
5	77km ENE of Duang, Indonesia	Mon, 09 Oct 2017 22:23:47 GMT	us2000b39g
6.3	Balleny Islands region	Sun, 08 Oct 2017 20:48:58 GMT	us2000b2v1
6	255km ESE of Ishinomaki, Japan	Fri, 06 Oct 2017 07:59:33 GMT	us2000b1v8
7.7	202km ESE of Nikol'skoye, Russia	Mon, 17 Jul 2017 23:34:13 GMT	us20009x42
7.9	35km WNW of Panguna, Papua New Guinea	Sun, 22 Jan 2017 04:30:22 GMT	us10007uph
7.6	41km SW of Puerto Quellon, Chile	Sun, 25 Dec 2016 14:22:27 GMT	us10007mn3
7.9	54km E of Taron, Papua New Guinea	Sat, 17 Dec 2016 10:51:10 GMT	us200081v8
7.8	**69km WSW of Kirakira, Solomon Islands**	**Thu, 08 Dec 2016 17:38:46 GMT**	us20007z80
7.8	54km NNE of Amberley, New Zealand	Sun, 13 Nov 2016 11:02:56 GMT	us1000778i

No stations within 1000 km of 69km WSW of Kirakira, Solomon Islands.

2016-12-08 Solomon Islands Mw 7.8 Event

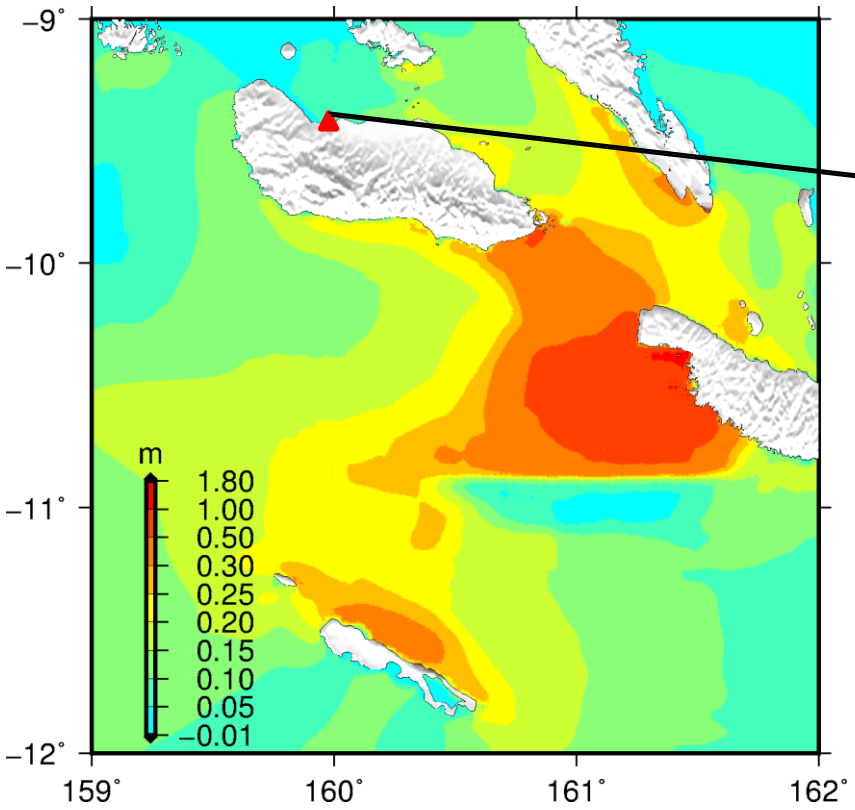
Fault geometry is from SLAB 1.0



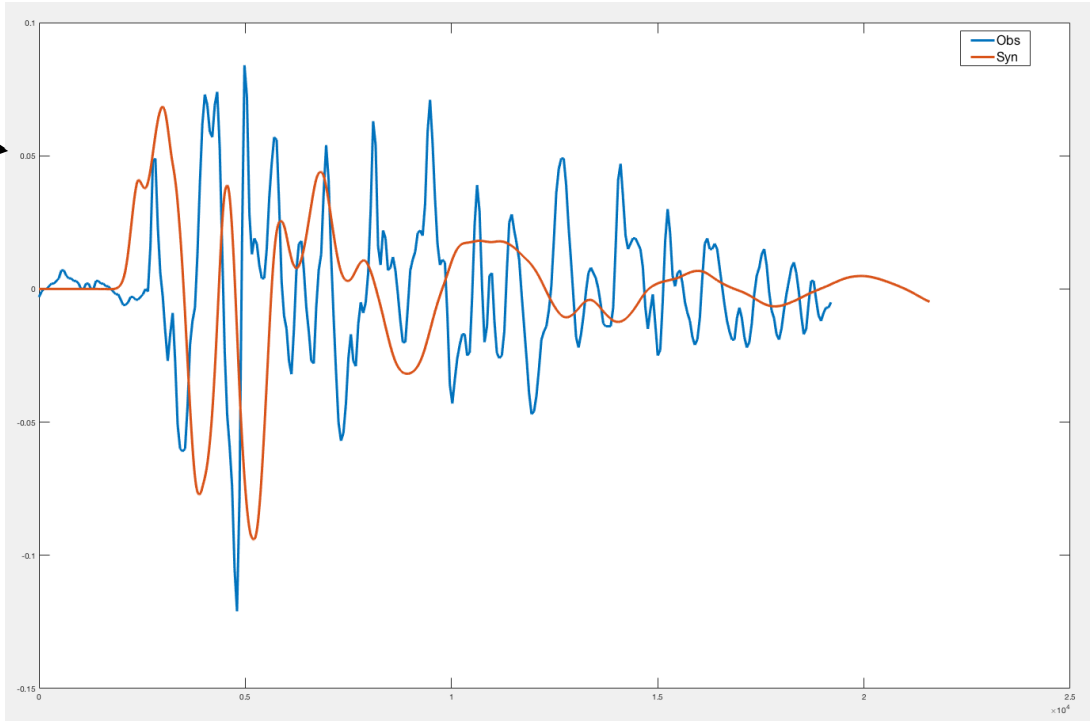


Slip model for 2016-12-08 Mw 7.8 Solomon earthquake (in about 11 minutes)

Teleseismic-only tsunami early warning



Maximum tsunami height prediction

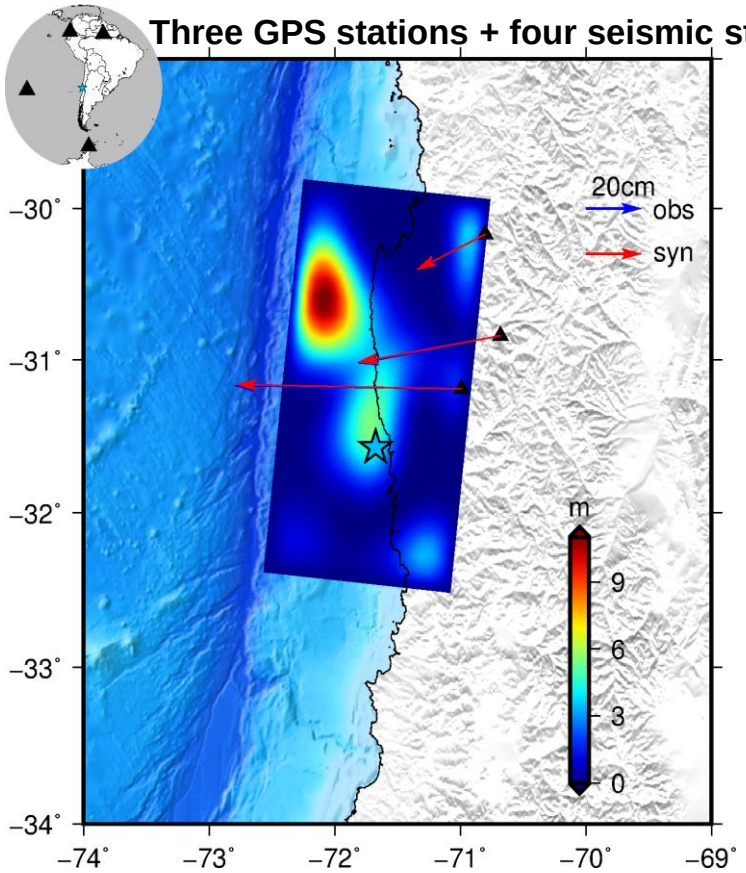


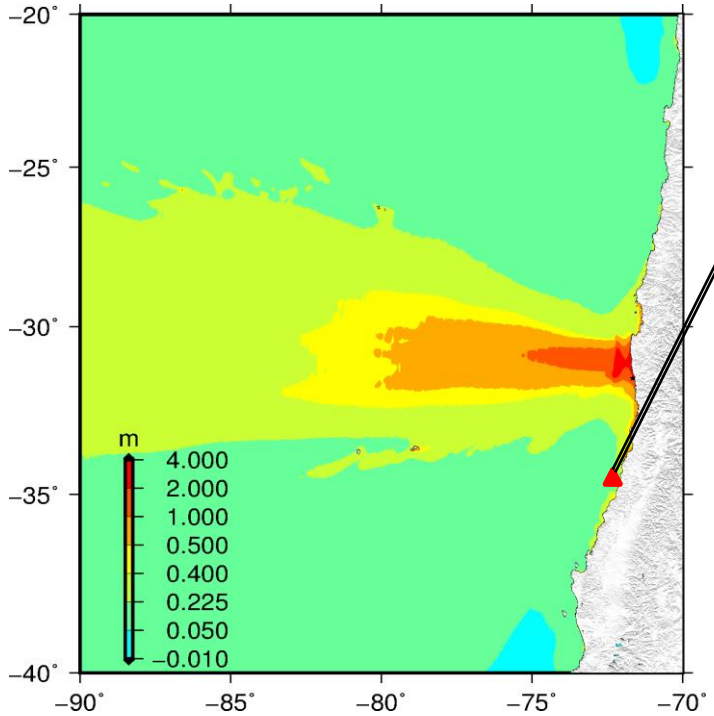
At the nearest tide gauges Solo

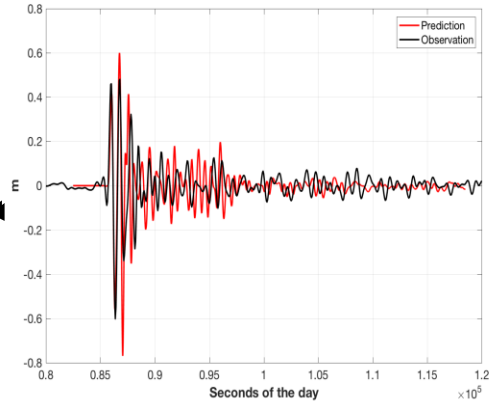
GPS+Teleseismic data for tsunami early warning:

Fault geometry is from SLAB 1.0

Three GPS stations + four seismic stations





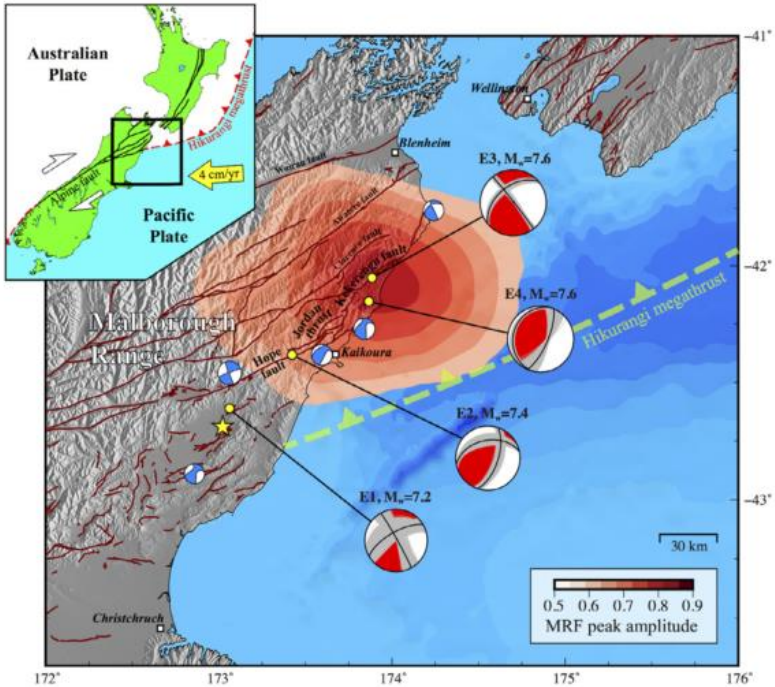


Slip distribution for 2015 Mw 8.2 Illapel earthquake (in about 10 min)

2016 Mw 7.8 Kaikoura earthquake:

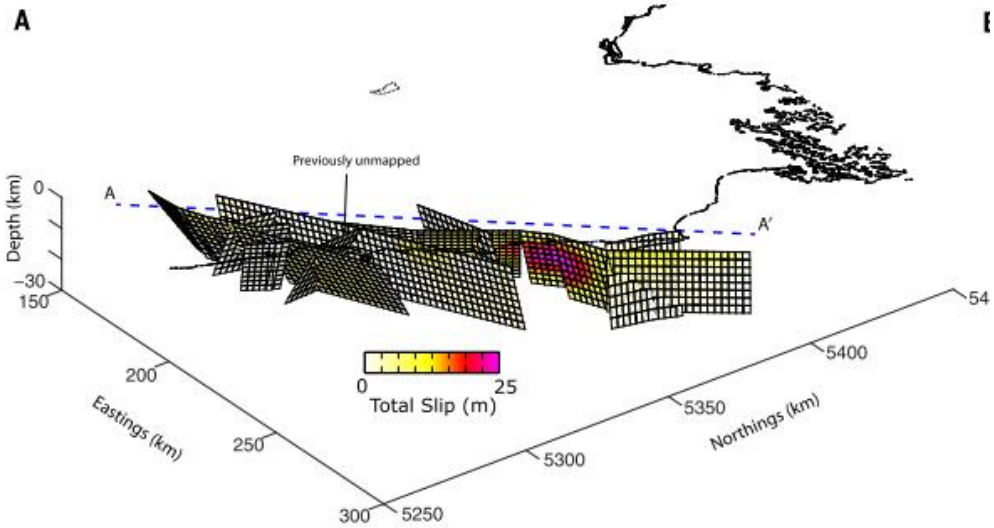
One of the MOST COMPLEX earthquakes ever recorded

The 2016 Kaikoura earthquake sequence from CMT



Duputel and Rivera (2017)

Complex multifault rupture during the 2016 Mw 7.8 Kaikōura earthquake, best fitting by 20 faults

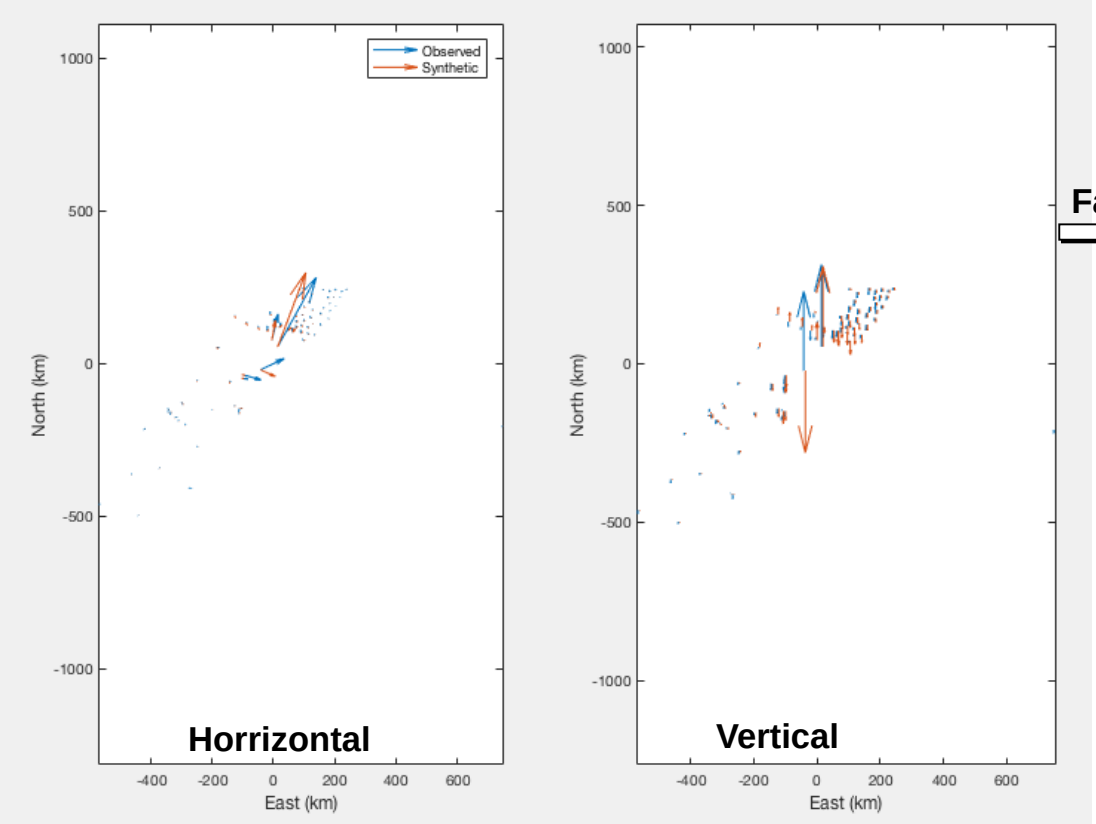


Hamling et al. (2017)

2016 Mw 7.8 Kaikoura earthquake:

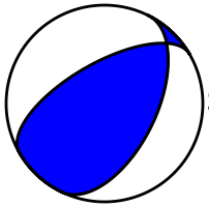
For TEW, it is very difficult to use that complex faults, we test a single fault

Out of SLAB 1.0 zone, first CMT inversion

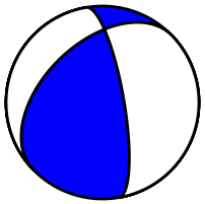


GPS data fits for fastCMT

Fast CMT



Strike:240 Dip:53 Rake:112

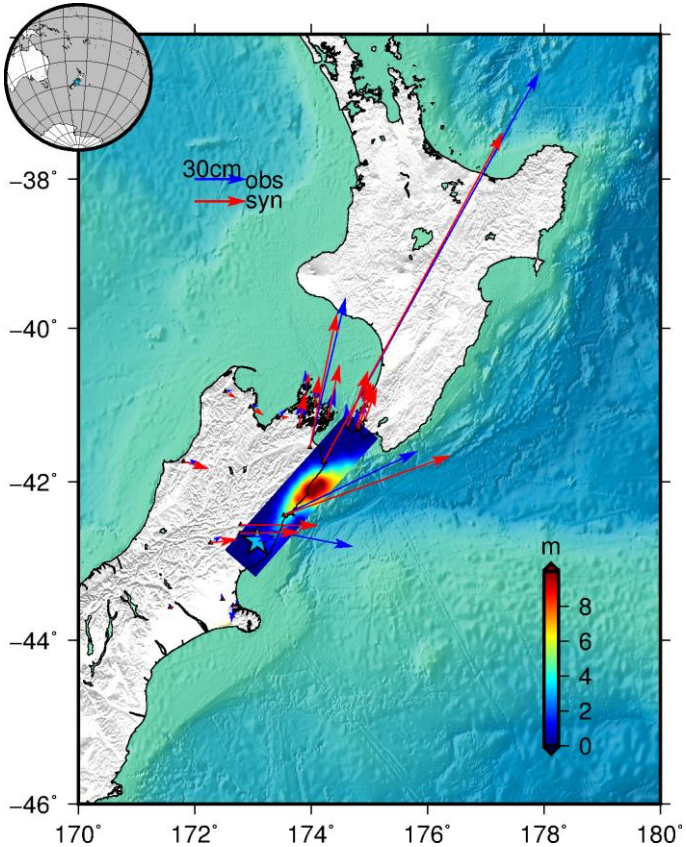


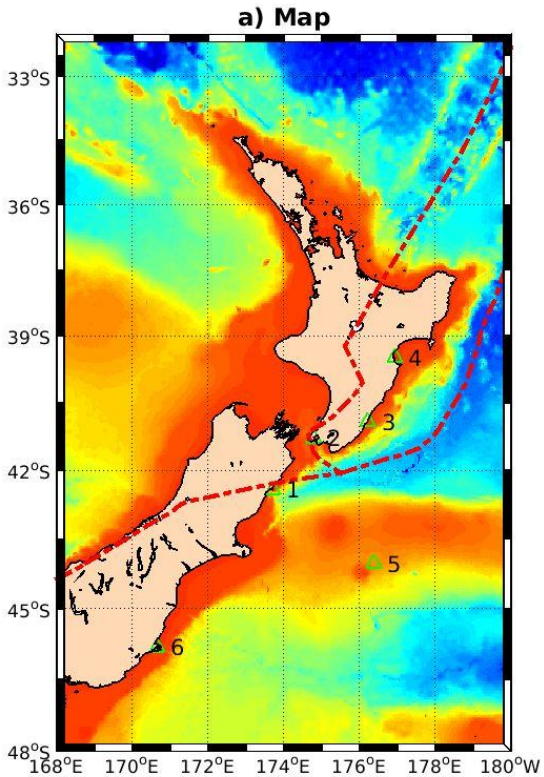
Strike:240 Dip:33 Rake:141

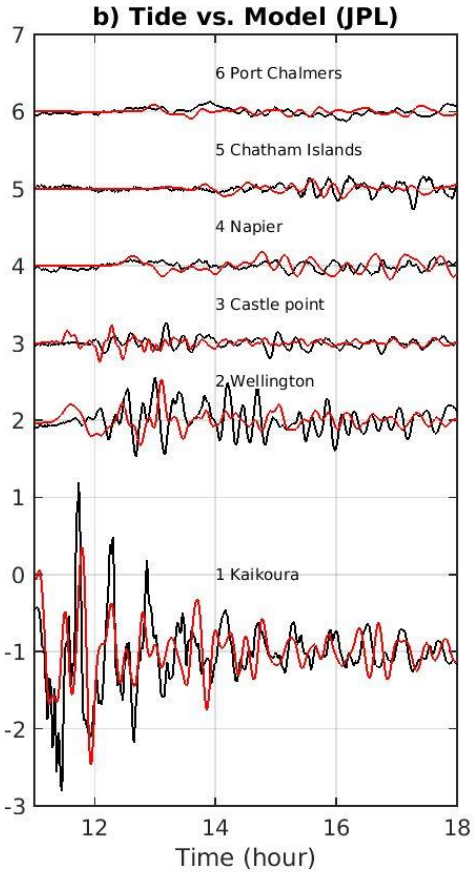
From GCMT

2016 Mw 7.8 Kaikoura earthquake:

Finite source inversion using GPS and tsunami prediction



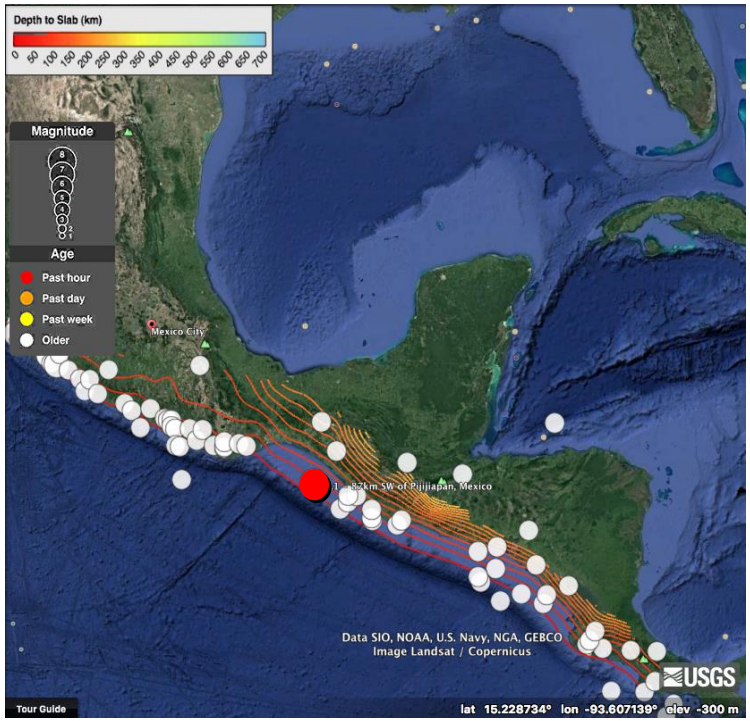


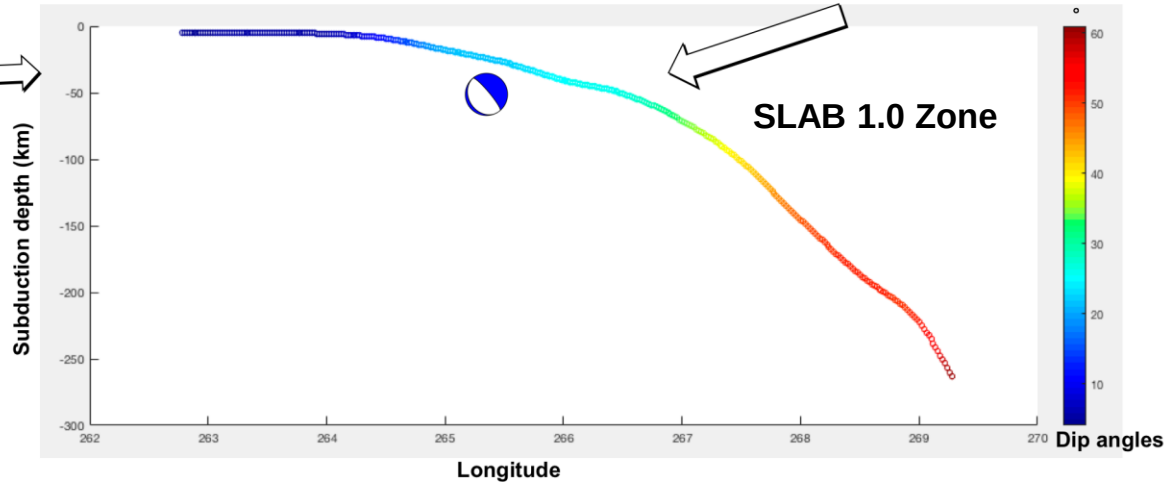


Slip model from GPS (in 10 min) (Chen et al., in prep)

2017-09-08 Mw 8.2 Mexico Chiapas Earthquake:

The largest normal earthquake in a subduction zone, very rare and challenges the reliability of TEW



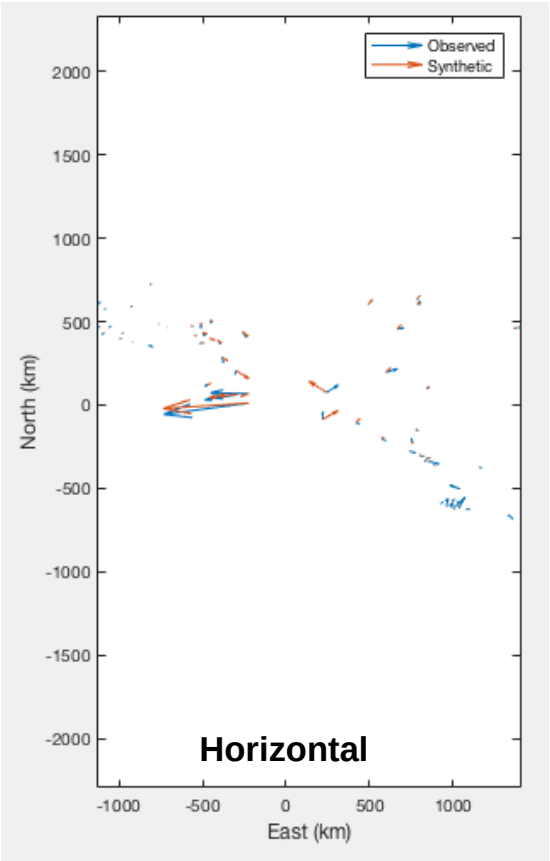


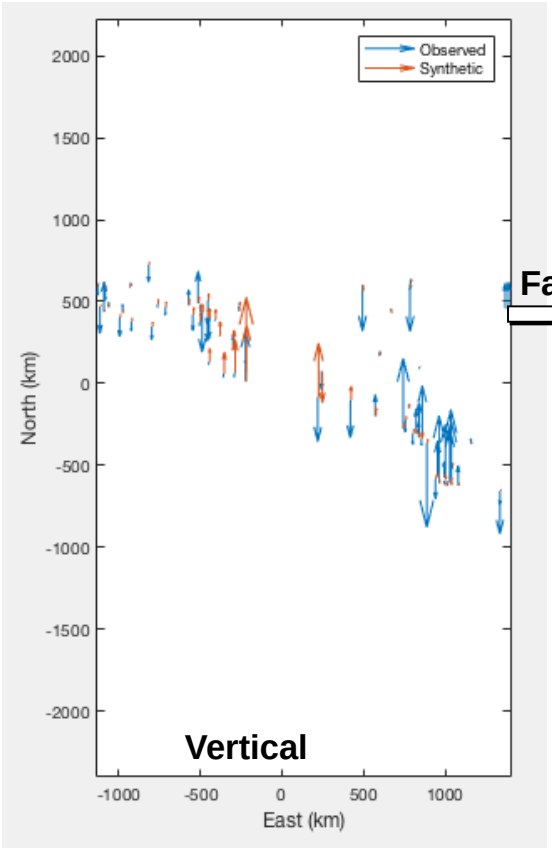
We cannot SLAB 1.0 fault geometry

Most of the historical earthquakes in this region are thrust ones, but this one is a normal faulting

2017-09-08 Mw 8.2 Mexico Chiapas Earthquake:

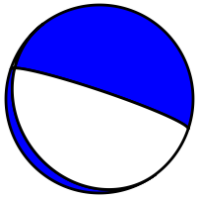
Perform CMT inversion first



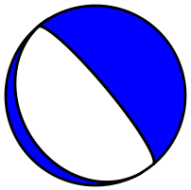


GPS data fits for fastCMT

Fast CMT



Strike: 288 dip: 81 rake: -95

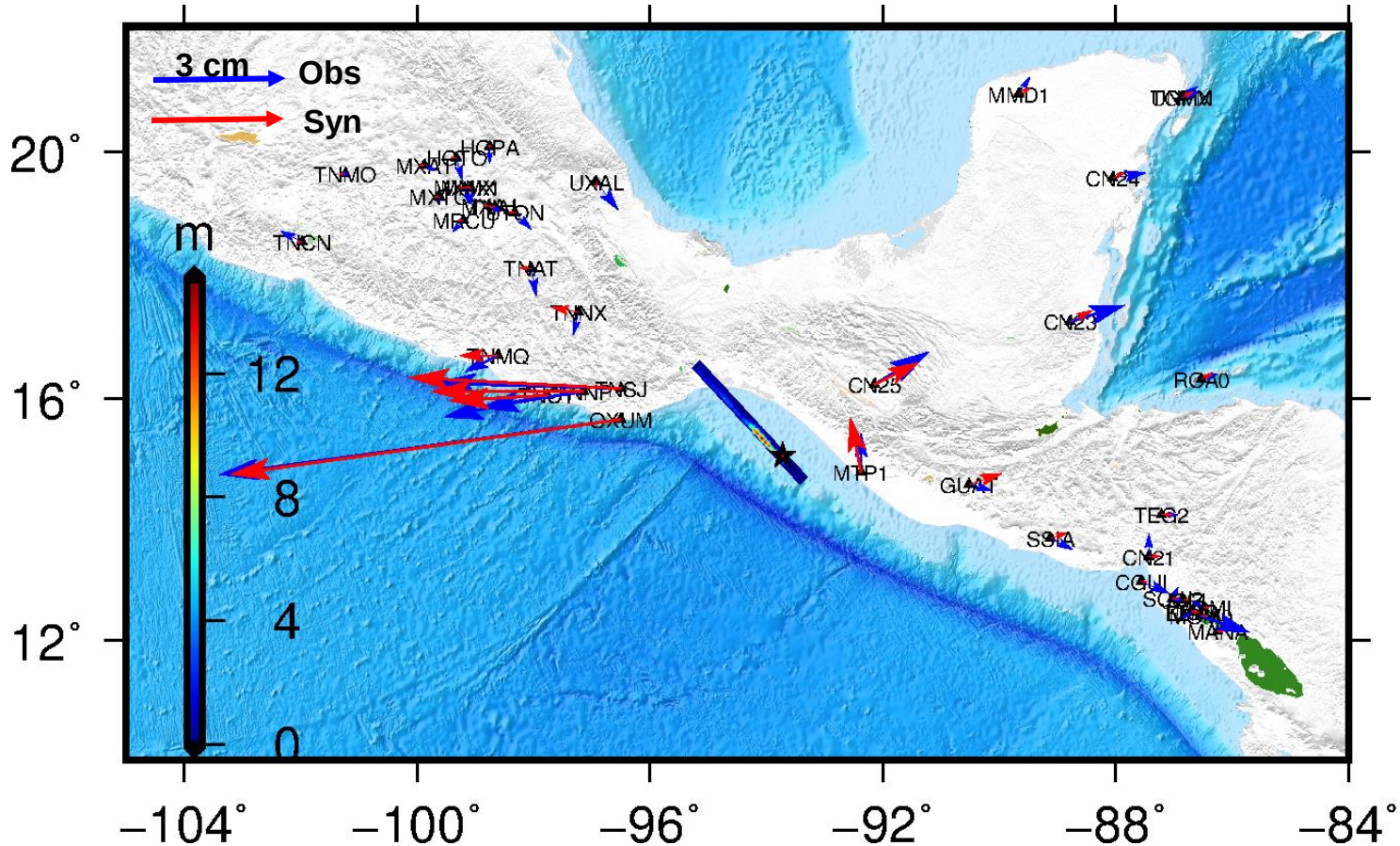


Strike: 320 dip: 77 rake: -92

From GCMT

2017-09-08 Mw 8.2 Mexico Chiapas Earthquake:

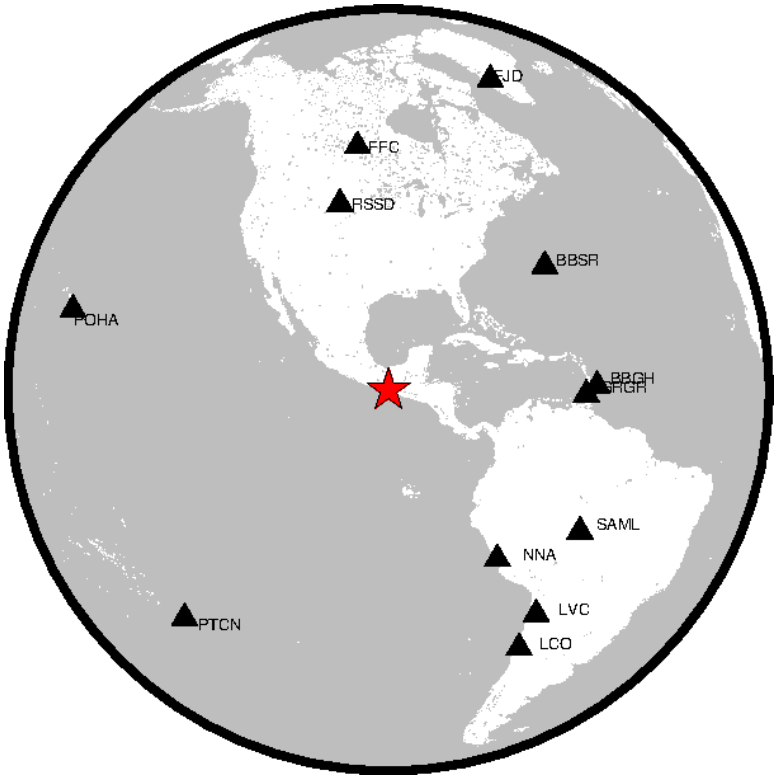
Finite source inversion using GPS and teleseismic waves



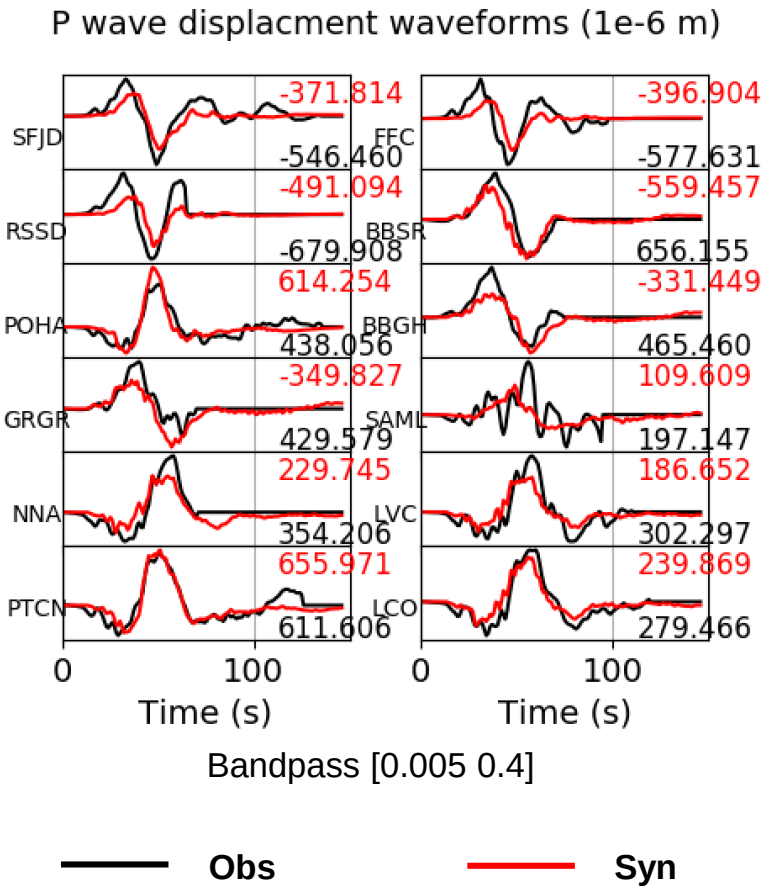
GPS data fits and slip model (in about 12 min and can be faster if we do not use seismic data) (Chen et al., in prep)

2017-09-08 Mw 8.2 Mexico Chiapas Earthquake:

Teleseismic data fits

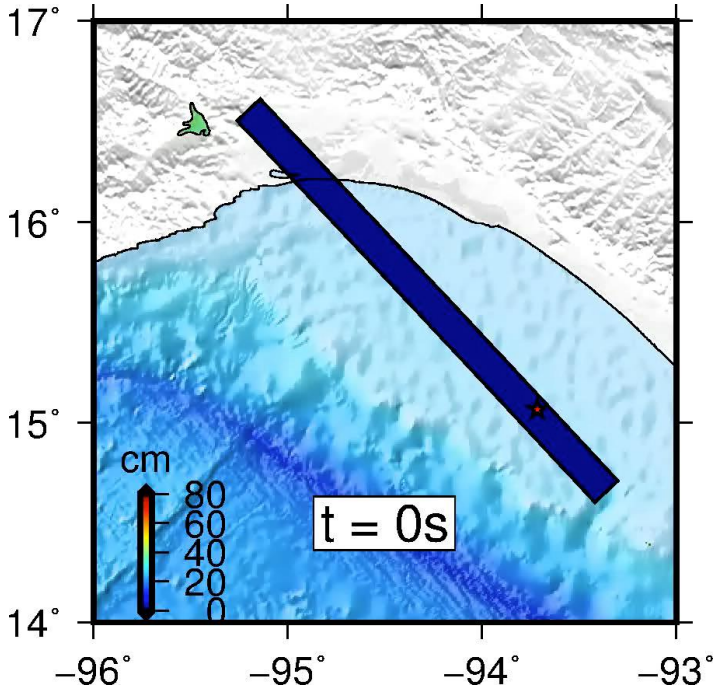


Distribution of teleseismic data



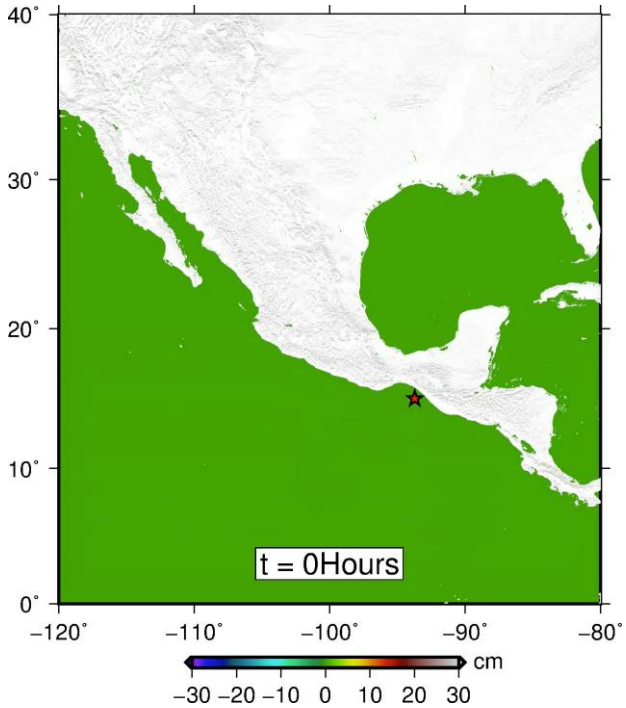
2017-09-08 Mw 8.2 Mexico Chiapas Earthquake:

Rupture evolution and tsunami prediction



Earthquake Rupture propagation

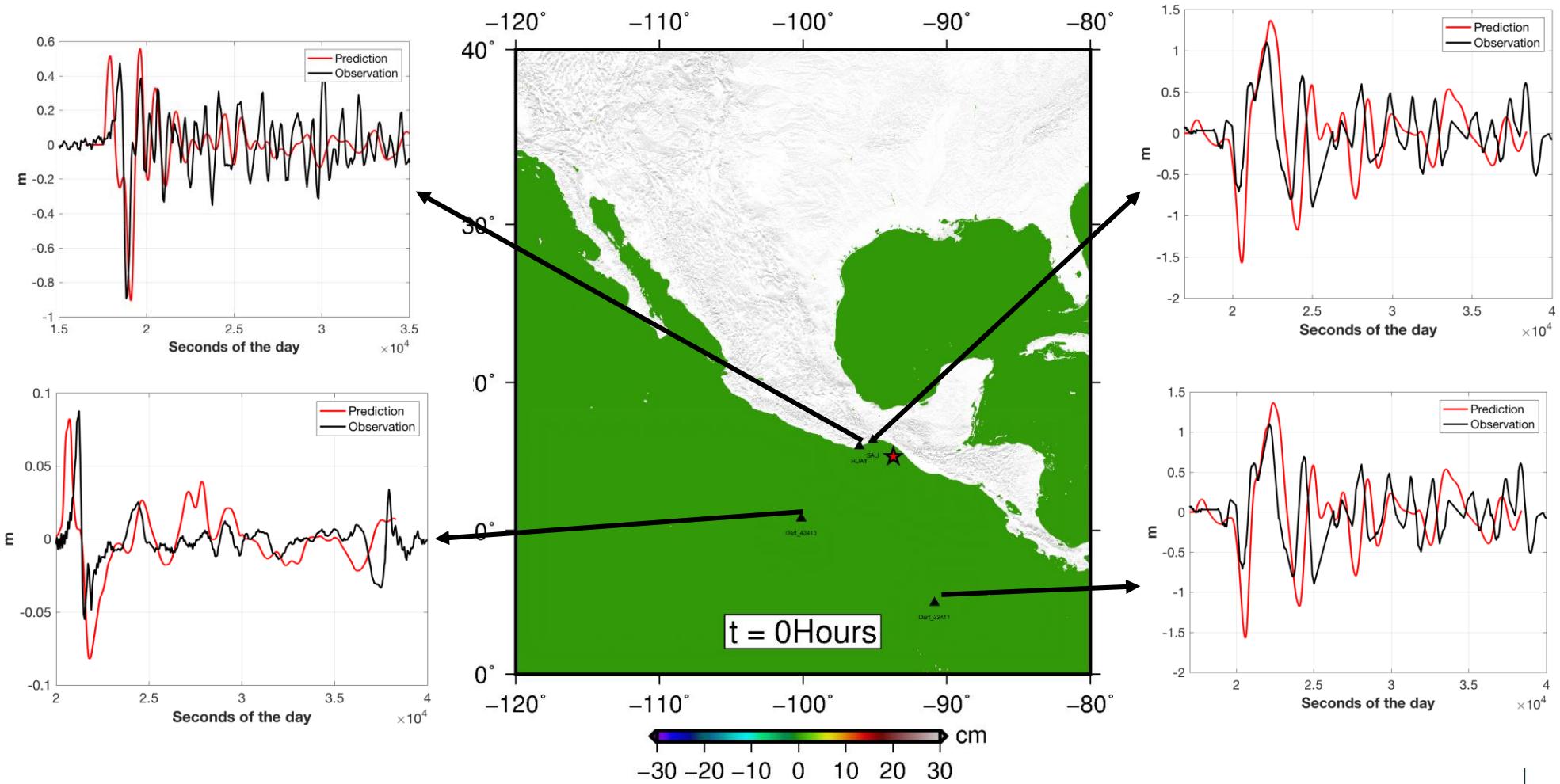
(Chen et al., in prep)



Tsunami prediction

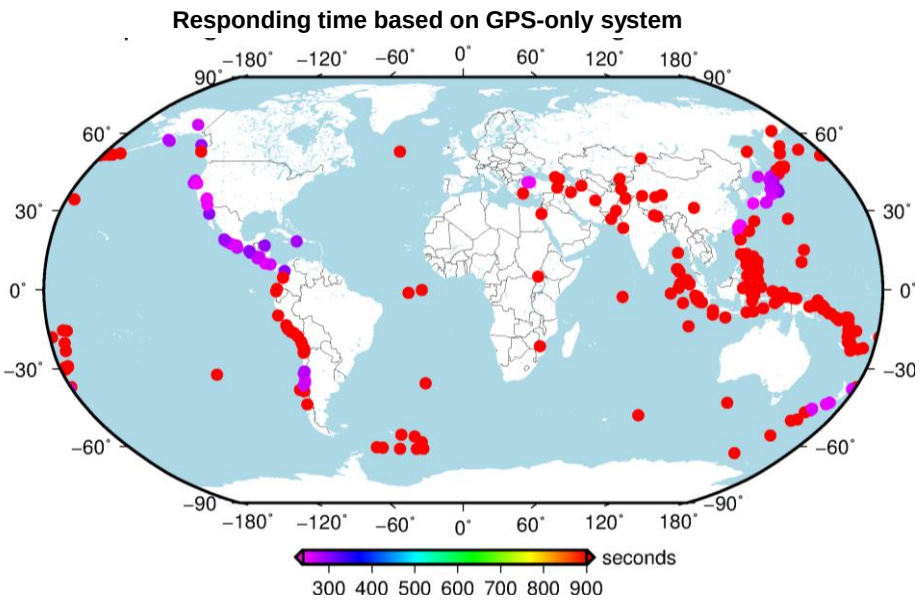
2017-09-08 Mw 8.2 Mexico Chiapas Earthquake:

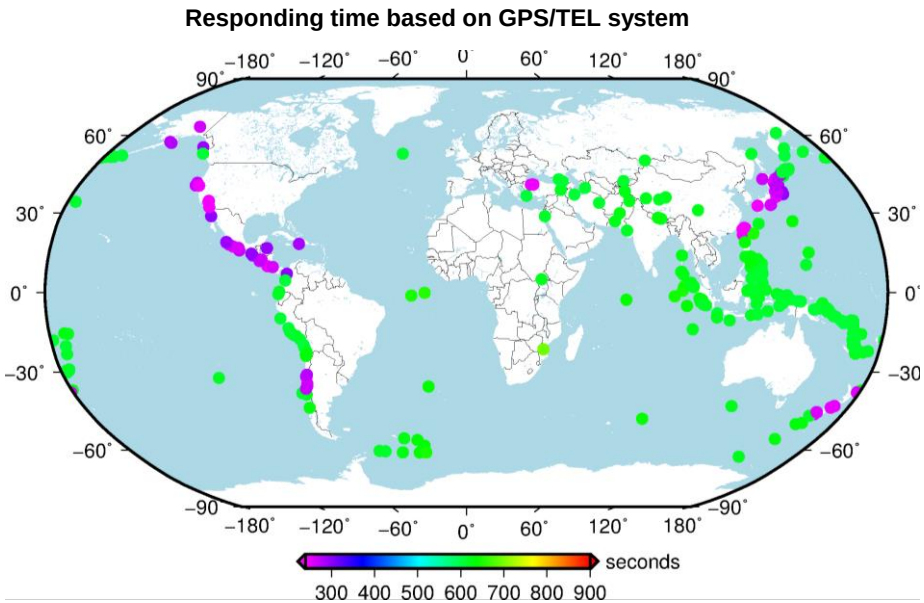
Tide gauges validation



Conclusions:

Integration of GPS and P wave makes TEW always available

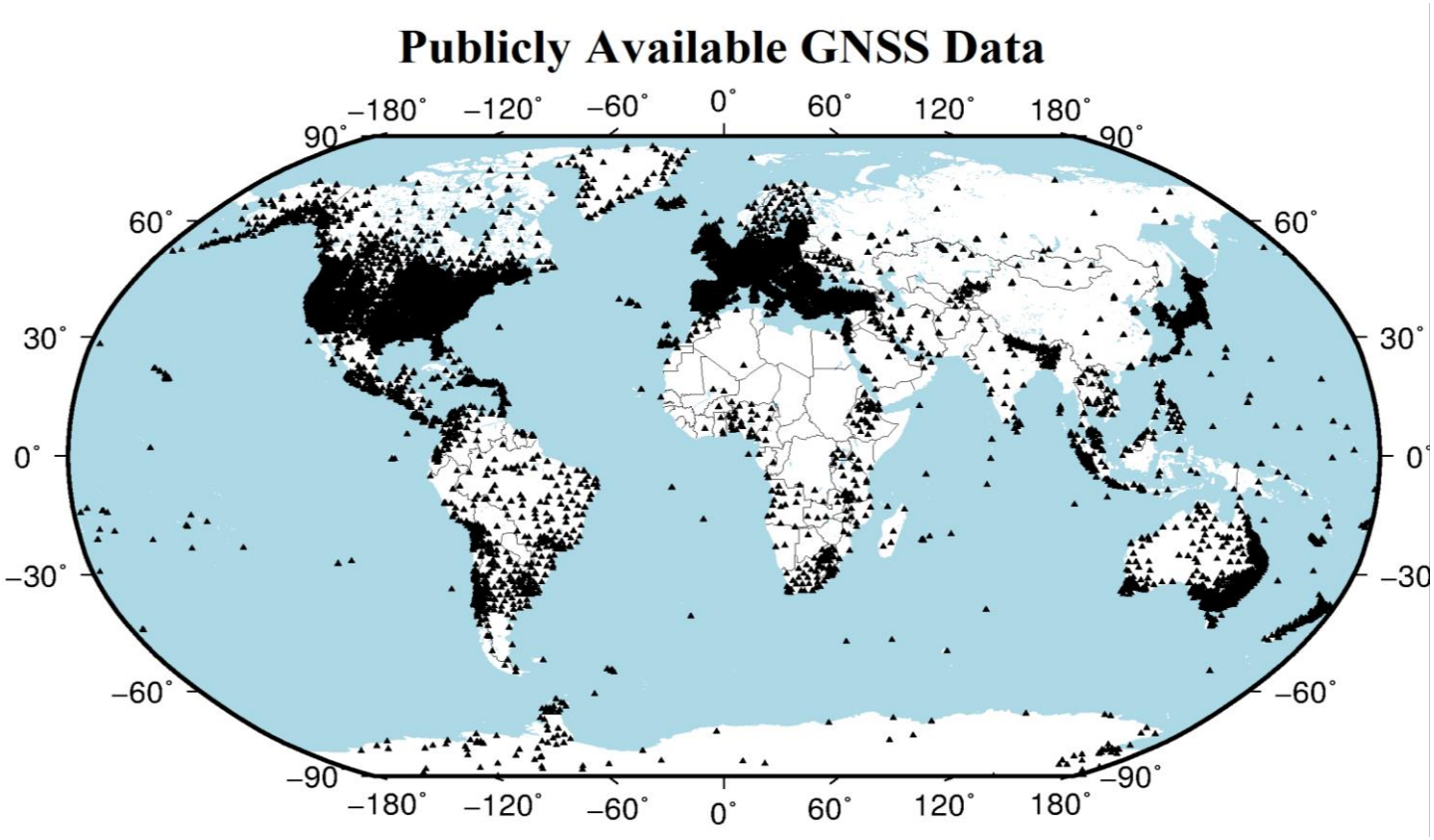




Time needed for earthquake source inversion: (right) using GPS data only, and (right) using GPS and seismic data, for all Mw>7.0 earthquakes (color dots on the map) since 1990. **(Chen et al., in prep)**

Future work:

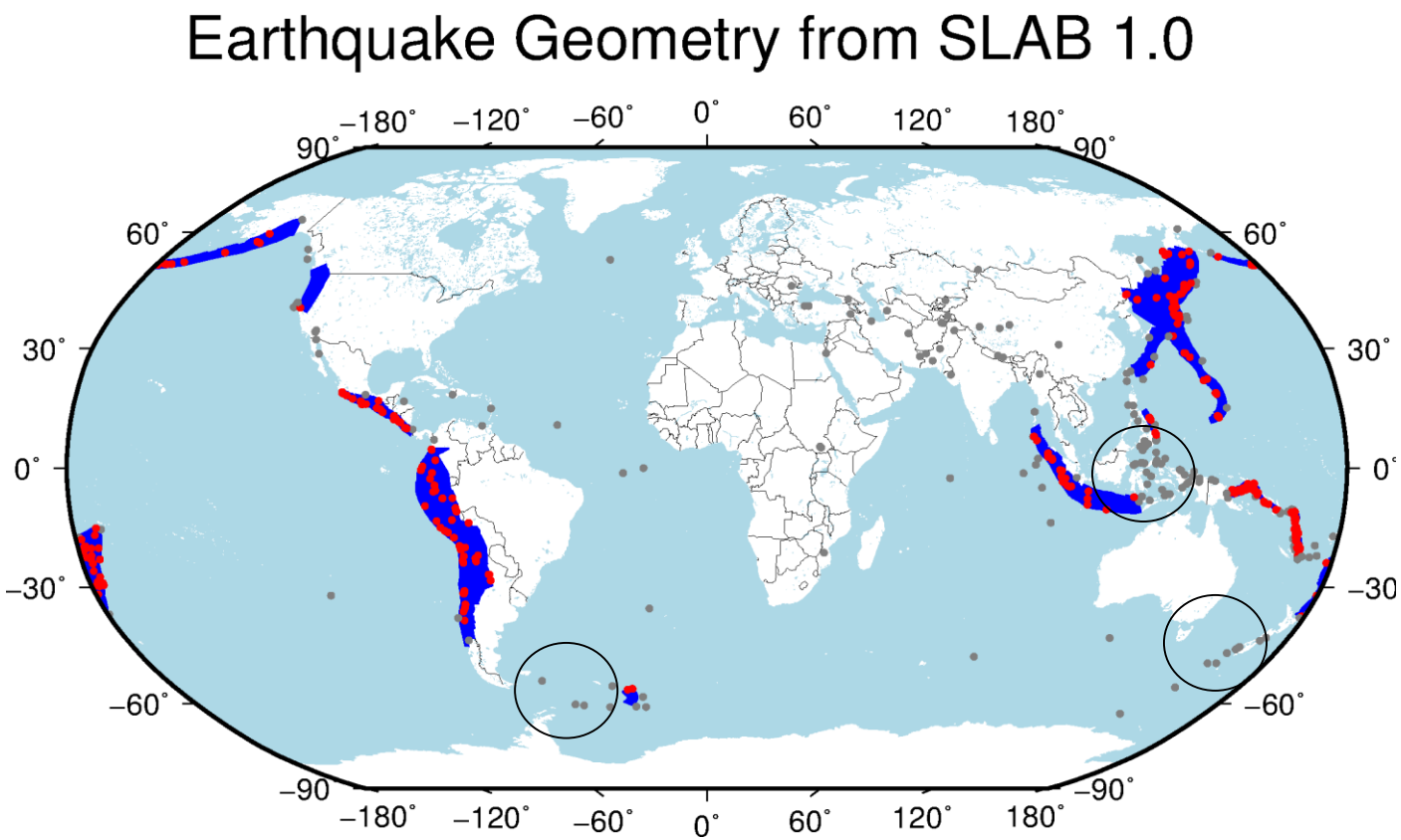
Have more GPS data stream in



GPS is very crucial in fault geometry determination

Future work:

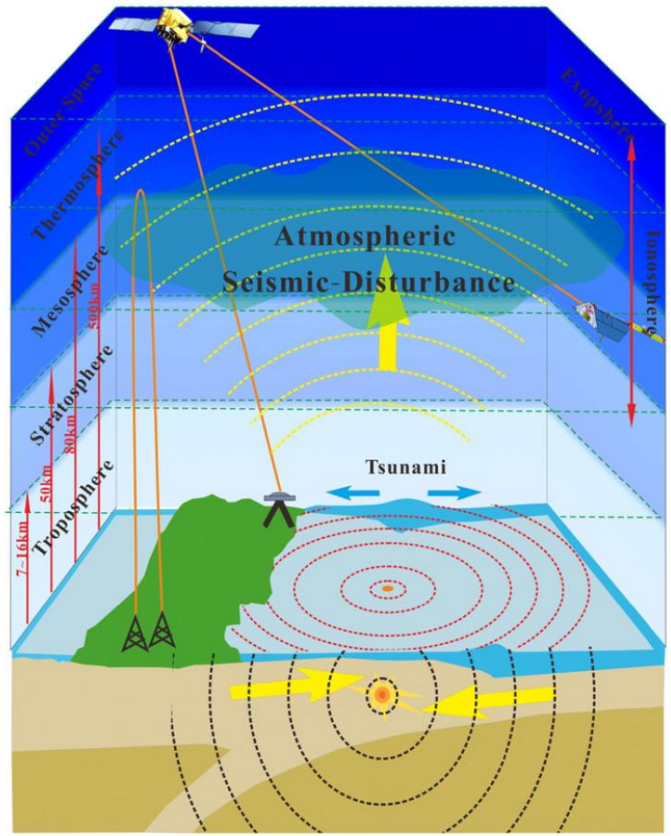
Fault geometry determination using seismic data



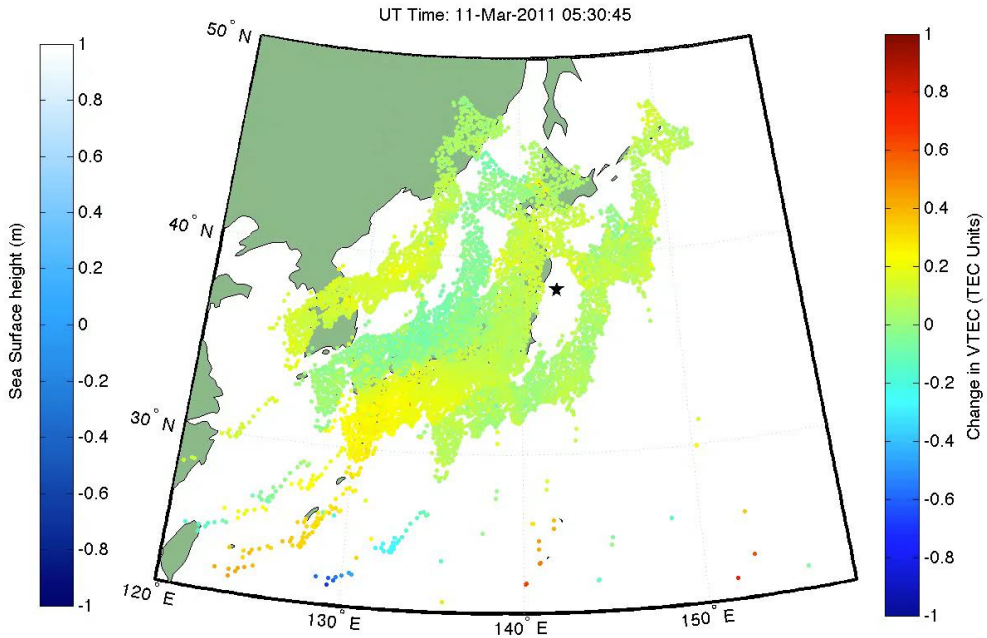
Red dots: earthquakes within the SLAB 1.0 zone
Grey dots: earthquakes outside of SLAB 1.0 zone

Future work:

Coupling between lithosphere and ionosphere



Seismic–ionospheric disturbances from GNSS observations, Jin et al. (2015)



2011 Japan earthquake and tsunami disturbed Earth‘s upper atmosphere, as measured by GPS. Komjathy et al. (2015)

Future work:

Coupling between lithosphere and ionosphere

Travelling ionosphere disturbances from both ground and spaceborn observations

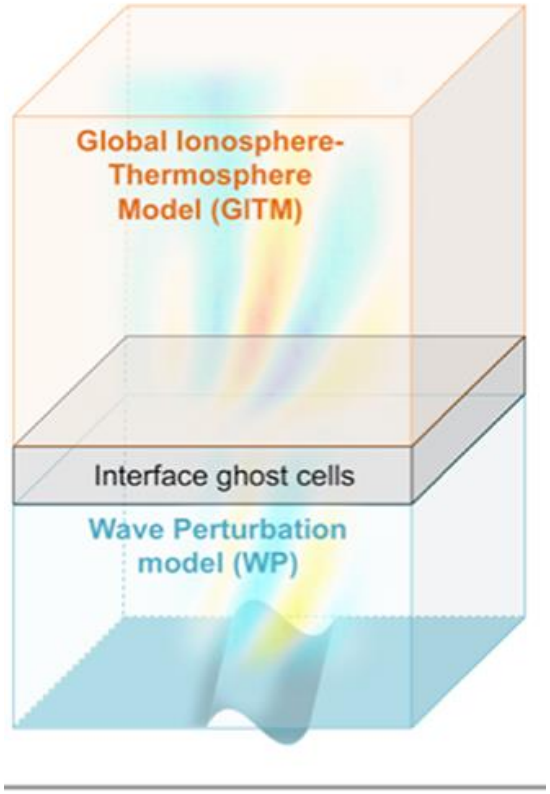
Solar wind conditions, solar irradiance, auroral precipitation

Synthetic tsunami scenario (etc., wave height, period, wavelength, propagation direction)

Fast earthquake source inversion

Retrieving co-seismic GNSS displacement

Wave Perturbation -Global Ionosphere Thermosphere Model (WP-GITM)
Meng et al. (2015)



Ionospheric - thermospheric state between 100 to 600 km altitudes

Cross validation to confirm the seismic source and the predicted tsunami scenarios

Thank you very much for your attention