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Modern Application of ***Time-Reversal*** to ***Seismic Source*** Characterization

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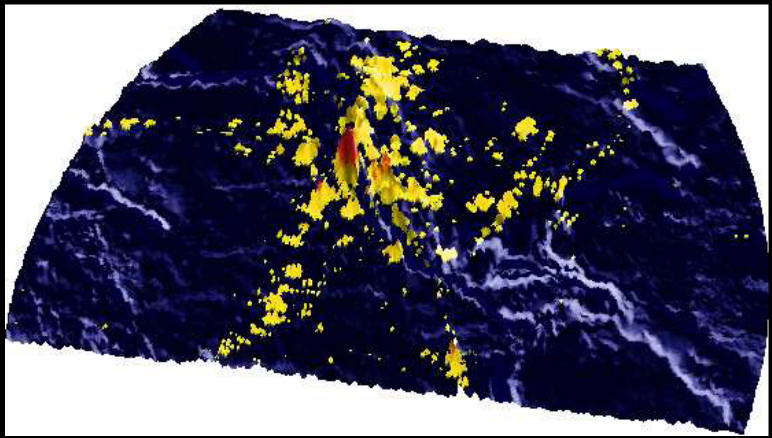
J. Tromp (Caltech/Princeton)
J. Gomberg (USGS)

J. Brown (Stanford University)

L. Rolland (IPGP/LANL)
P. Lognonné (IPGP)



Outline

1- Motivation

Seismic source study

2-Introduction to Time Reversal

Definition

Applications in laboratory

Parallel beginning in seismology and acoustics

3- Classical earthquakes study

Characterization in addition to location

4- Beyond classical earthquakes

Rupture imaging

Low SNR signals: glacial earthquakes

Emergent signals: triggered tremor in California

5-Conclusions

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Outline

1- Motivation

Seismic source study

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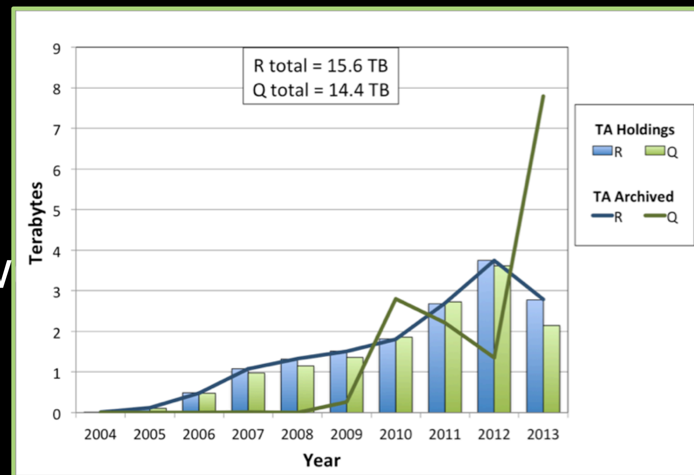
Seismic Source Study

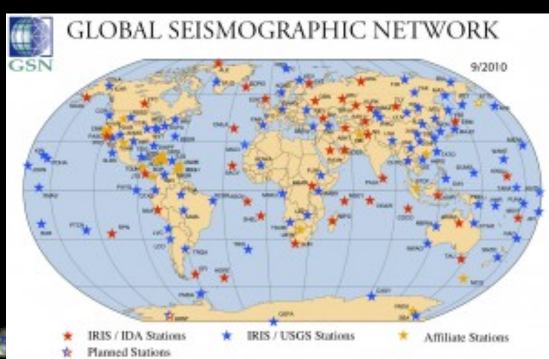
Shift from event-based temporary observation to permanent, dense observation

Factors:

- -dense seismic networks
- -drastic increase of computing pow
- -several large earthquakes



US array data holding for Raw and Quality data. http://www.iris.edu



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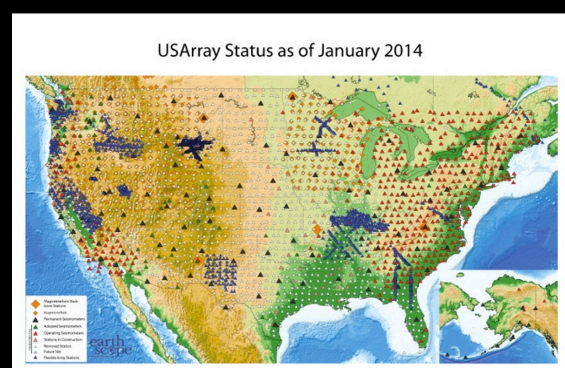

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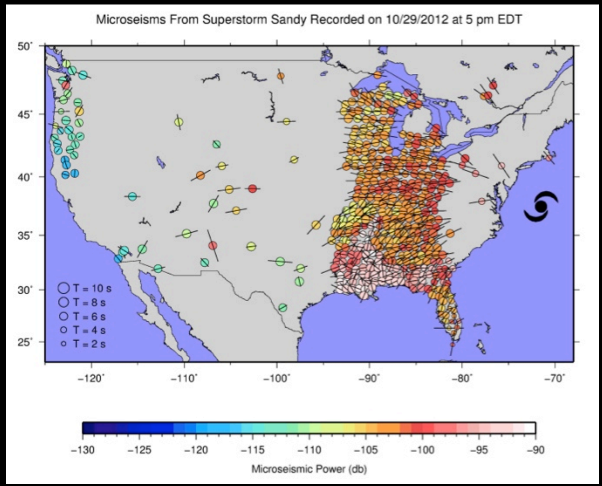
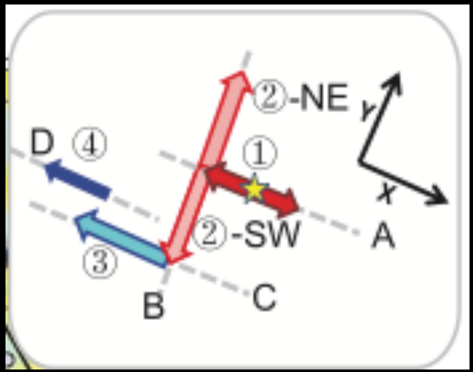
New Discoveries – New Need

-variety of processes generating seismic energy: landslides, oceans, glacial earthquakes, tremor
-complexity of fault motion: complex rupture history in the large earthquakes, slow earthquakes, branching, triggering,…

Need for versatile and efficient imaging methods



Microseismicity triggered by Sandy. http://unews.utah.edu



Fault planes and rupture direction of the 2012 Sumatra earthquake (Meng et al., 2012)

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Outline

2-Introduction to Time Reversal

Definition

Applications in laboratory

Parallel beginning in seismology and acoustics

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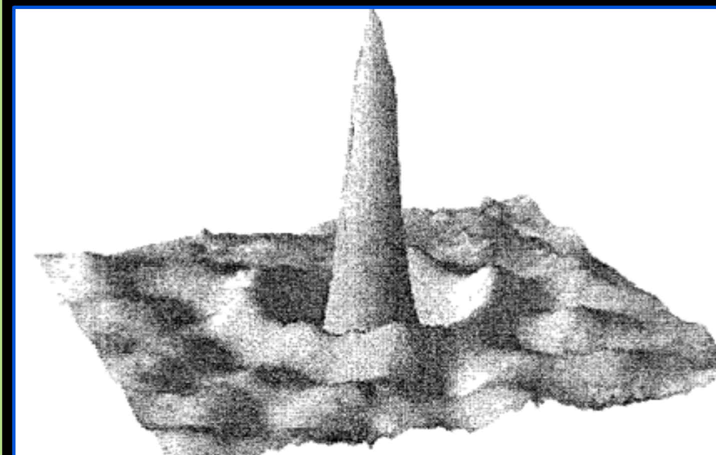
Definition

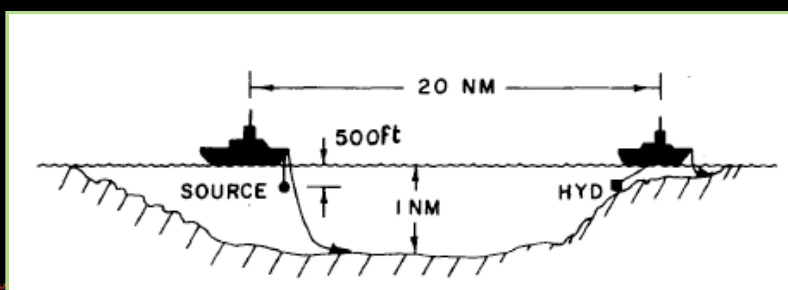
TR refers to a collection of techniques that aim to focus wave energy onto a specific point in space and time, implicitly using the source-receiver reciprocity and the invariance of the wave propagation equation (without loss) to the inversion of time.

Time Reversal thrives with complexity

Reviews: Fink et al., 2000; Fink, 2006; Anderson et al., 2008; Larmat et al., 2010a and 2010b.



From Draeger&Fink, 1997



TR used to allow communication between 2 ships in shallow water environment (highly reverberating environment). Experiment performed in 1962 in the oceanic trench (Tongue of Ocean). From Parvelescu& Clay (1965)

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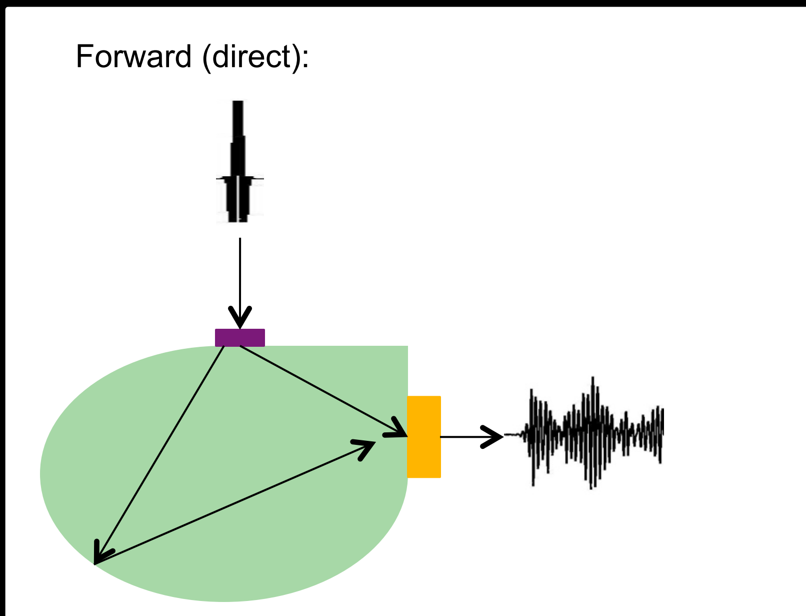
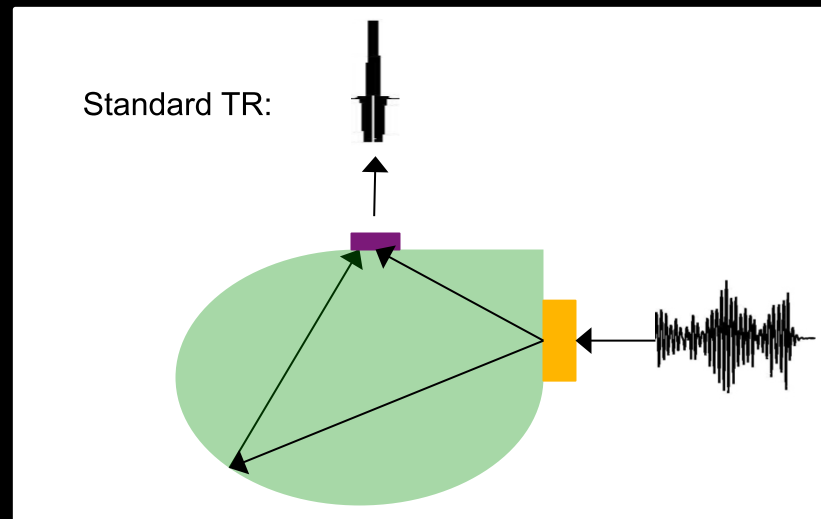
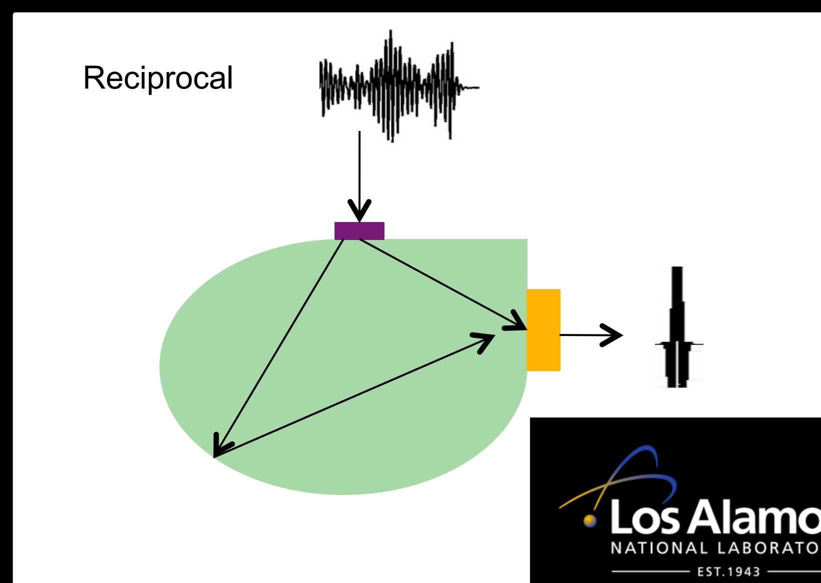
Time-Reversal in practice







Next: TR and NEWS

1. Standard TR
2. Reciprocal TR
3. Reciprocal + Standard TR

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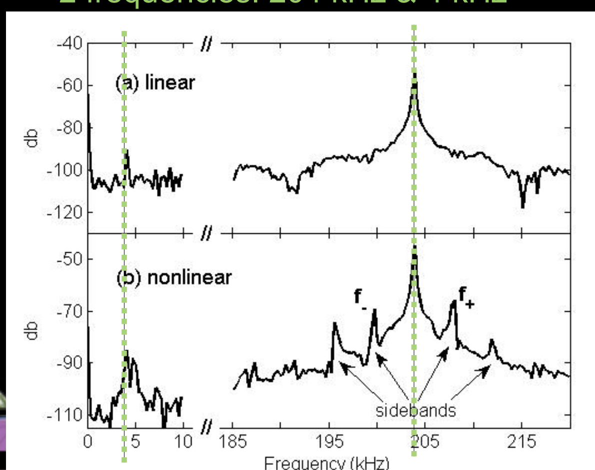
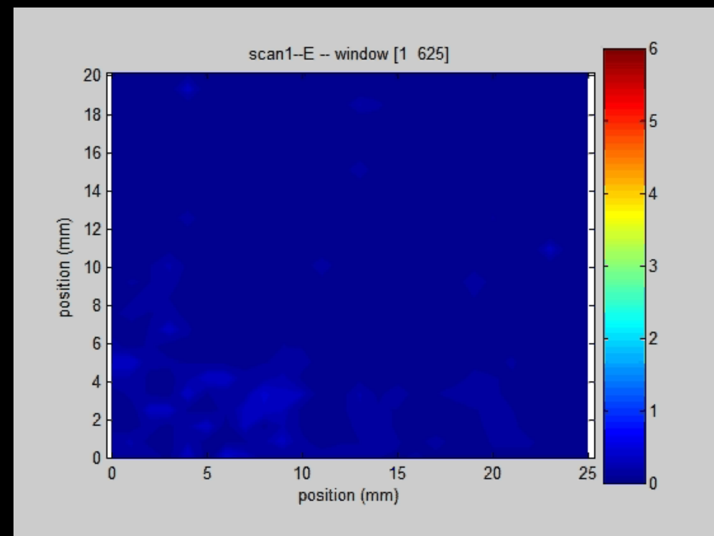
TR NEWS: standard TR

2 frequencies: 204 kHz & 4 kHz



Movie of the energy at 200kHz



Ulrich, T. J., P. A. Johnson, and R. A. Guyer (2007) ***Phys. Rev. Lett.***, ***98***(10), 104301, doi:10.1103/PhysRevLett. 98.104301

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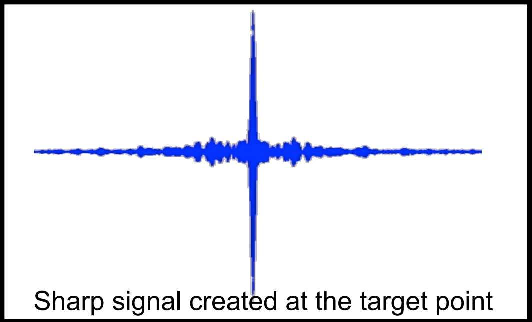
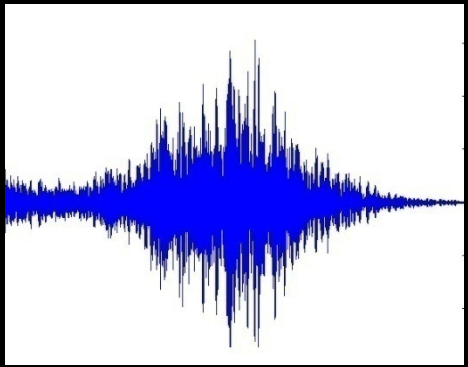
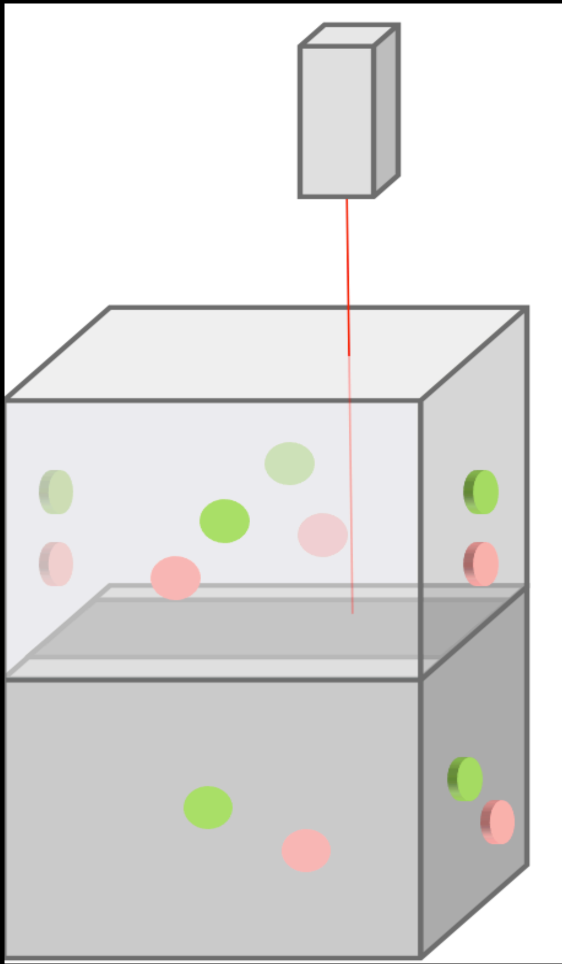
Buried NL feature: Reciprocal + Standard TR

Reciprocal to create a virtual source at the interface, green array

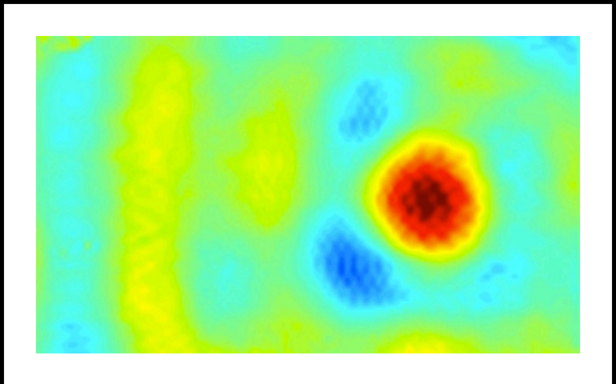


Locate the NL source, red array

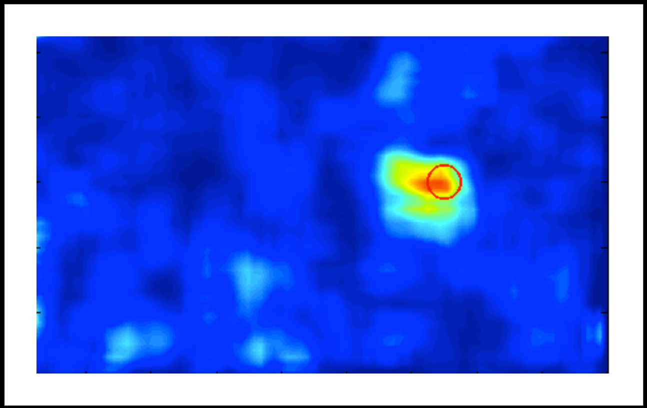




Energy flux at focus green array at 150kHz



Energy flux at focus red array at f > 1.5 x 150kHz



Le Bas, P.-Y., et al. (2011a),, *J. Acoust. Soc. Am.*, *130*(4), EL258, doi: 10.1121/1.3638926

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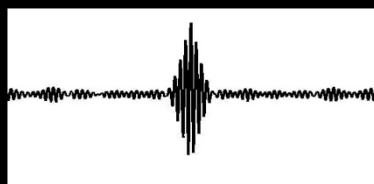
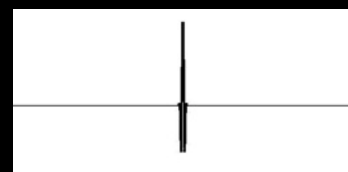
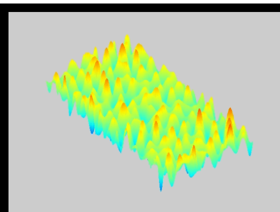
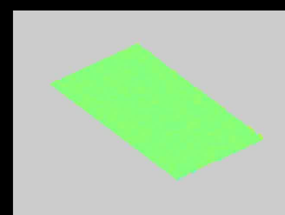
Cleaning up the focus

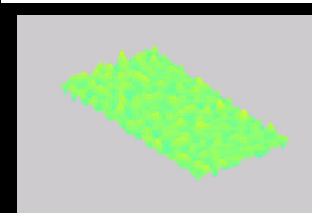
Time Reversal | Original Source | Deconvolution

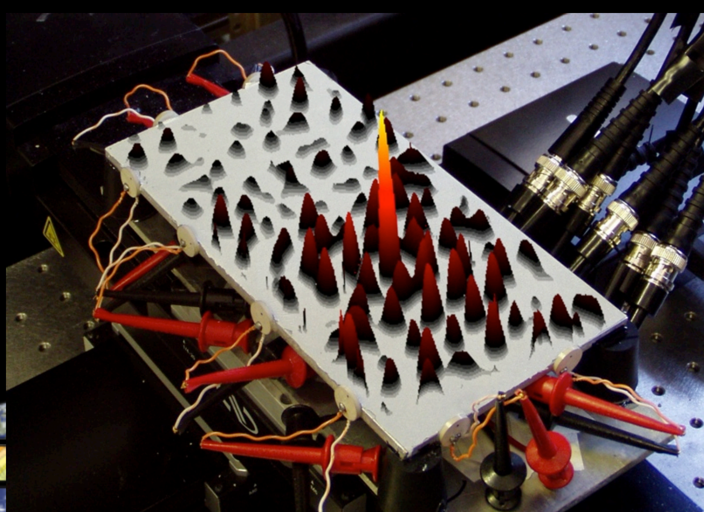


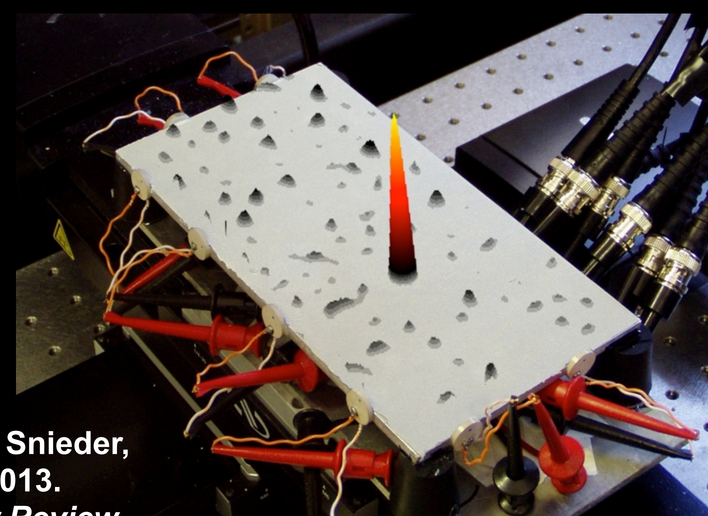








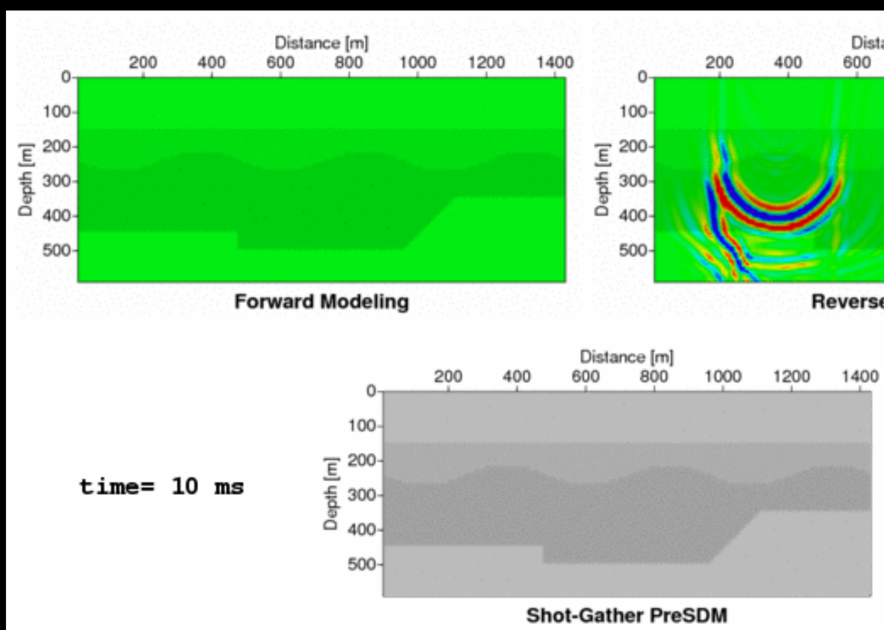




Ulrich, T., Douma, J., Snieder, R., & Anderson, B., 2013. Wave Motion, *Under Review*.

Reverse time migration

In the 70s, seismologists were developing migration algorithms which allow to image buried structures by moving (i.e. migrate) the wave energy recorded at surface receivers within the ground. In the beginning of the 80s, McMechan (82), Baysal et al. (83) found the concept of migrating in time instead of in depth : Time reverse (a.k.a. Reverse Time) migration was born.



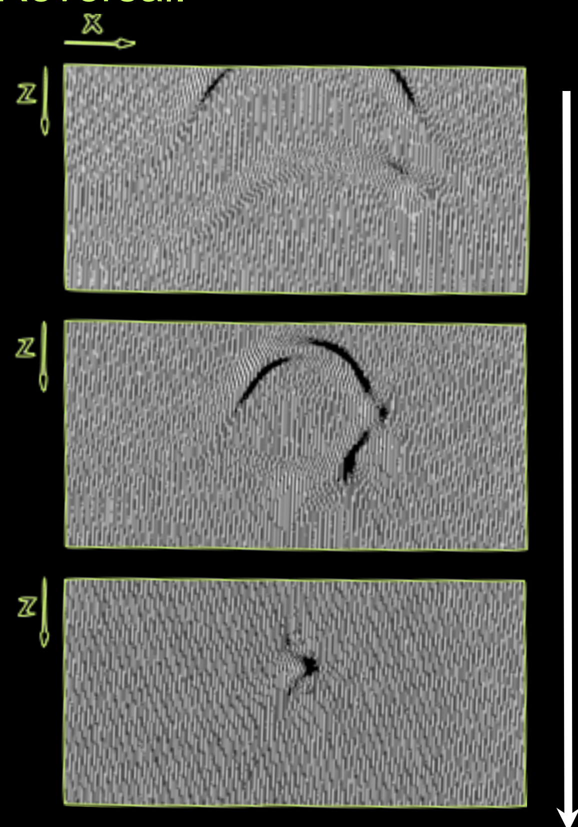
Reverse Time migration Image of the subsurface obtained by correlation of the forward and time reverse wavefield.

from www.geophysics.zmaw.de

Discovery of Time Reversal in seismology

Very quickly McMechan realized that the time reverse wavefield can be used to image seismic sources instead of the structure. Time Reversal was "rediscovered" without seismologists being obviously aware of the existing research in acoustics about Time Reversal.

source reconstructed by TR from the surface of the model with one receiver on each grid point. The propagation volume contains one reflector which improves the source location compared to a homogeneous case.



Time Reversal (McMechan, 1982).

Applying TR to an earthquake

At the beginning of TR in seismology, it was thought that the key for its success will be “dense” seismic arrays. McMechan (1982) advocates the use of one station per wavelength with the help of interpolation schemes if needed. The idea of necessity for dense networks is relayed by Kennett in his 1983 Nature paper where he expressed his enthusiasm for the new method.

> Another question of practical interest concerns the spatial data density required for wavefield imaging. Any wave contribution should be sampled over an aperture large enough that an element of wavefront can be defined (i.e. at least one wavelength). The most important restriction related to finite differences is the requirement of using a minimum of 10 grid points per wavelength to reduce grid dispersion. Wavefield processing is not generally this restrictive, requiring only that the data not be significantly spatially aliased at the frequencies of interest. Thus, for the dominant frequencies shown in the seismograms of Figs 5, 7 and 9, it would be possible to obtain unaliased traces at a spatial density about half that plotted and then to interpolate (*cf.* Larner, Gibson & Rothman 1981) to construct a profile with the higher density required for the finite difference computations. Interpolation can concurrently produce a new data wavefield with a constant spatial increment corresponding to the fixed grid from unequally spaced recordings.

McMechan, 1982

> A radical departure from the conventional approach has been suggested by McMechan (*Geophys. Jl R. astr. Soc.* **71**, 613; 1982), who has adapted methods used in geophysical prospecting to the estimation of seismic source parameters. The reversibility of the wave equation is used to take the surface recordings at a dense network of receivers and extrapolate them back in time and space until a focus occurs at the source location.

Kennett, 1983

But we found that we didn’t have to wait for the deployment of regular and extremely dense networks. TR works with current receiver arrays.

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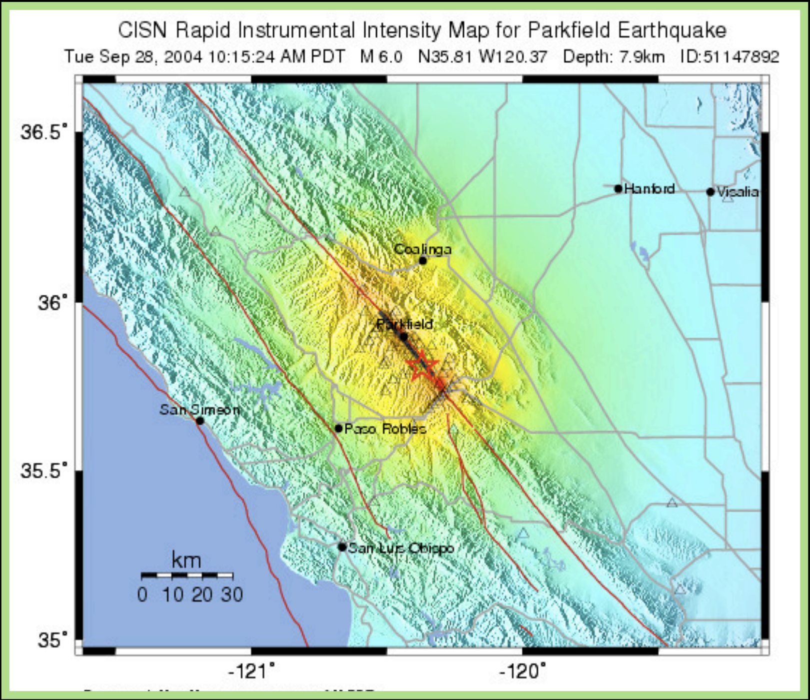
Outline

3- Classical earthquakes study

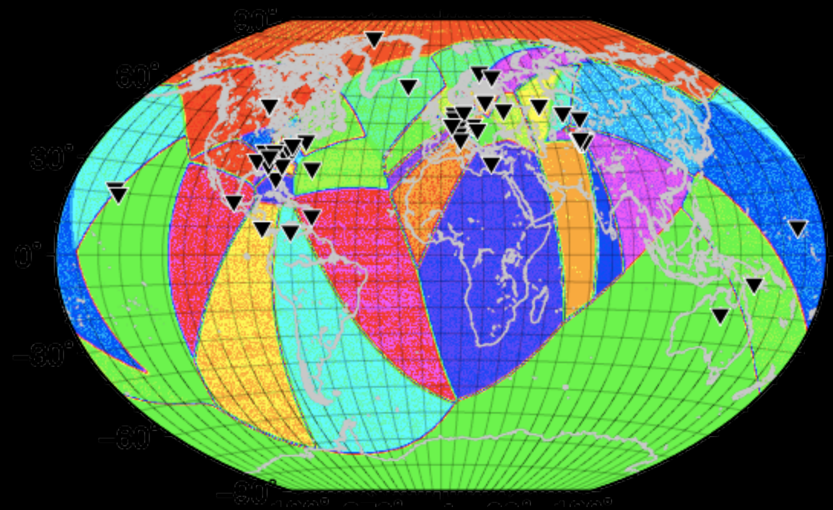
Characterization in addition to location

Example of the 2004 Parkfield earthquake



Tuesday, September 28, 2004 at 17:15:24 UTC
35.815°N, 120.374°W, 7.9km depth
Mw 6.0

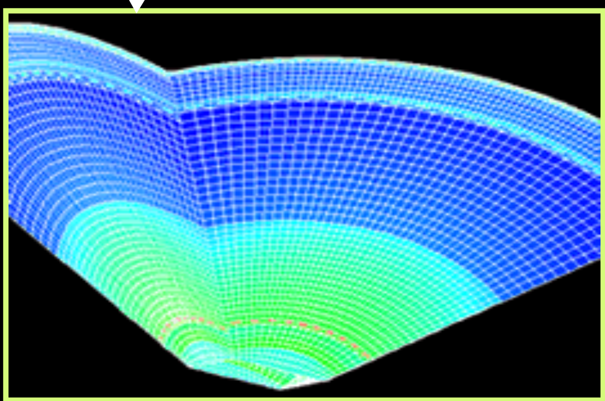
TR is performed numerically.
We use the records of 55 "best" stations (high correlation between data and synthetic). Signal corresponds to the first surface wave train filtered between 45 and 120s.

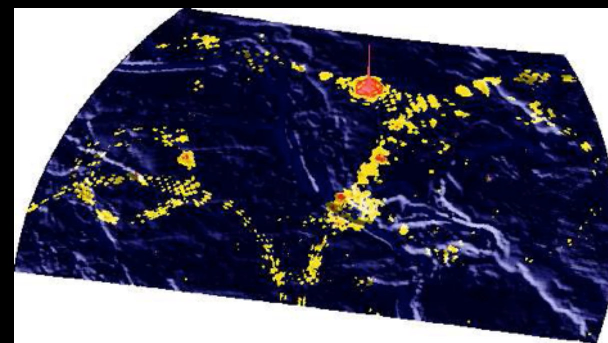


Distribution of 55 stations that was used. Notice the small number of stations in the South Hemisphere.

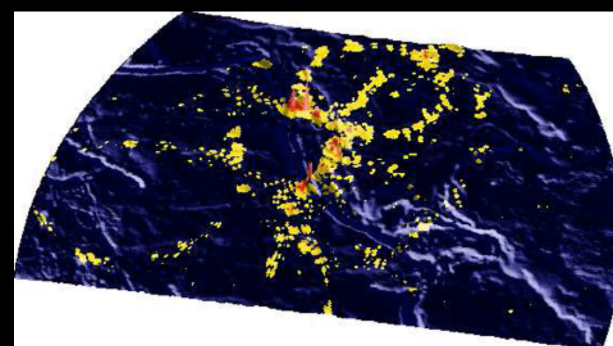
TR is performed numerically

"Best" model of the elastic properties

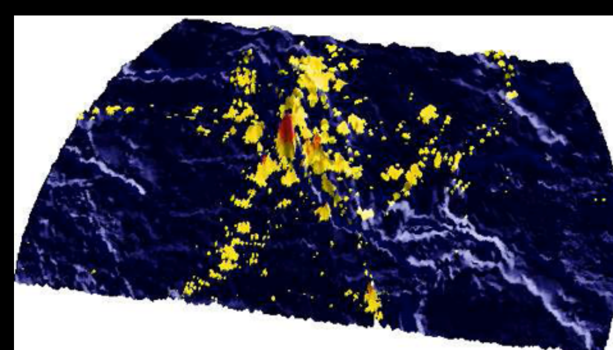




624s



312s



0s

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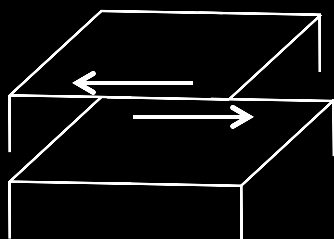
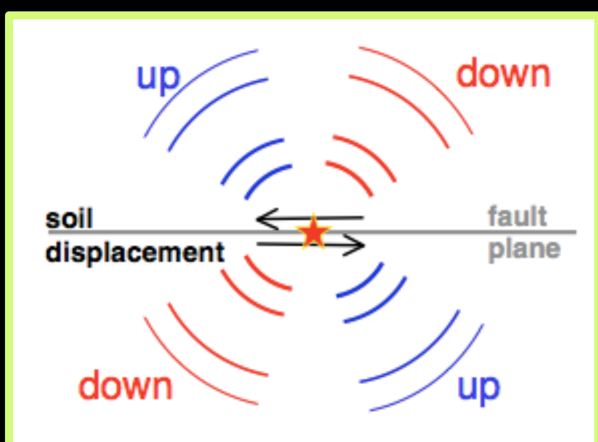
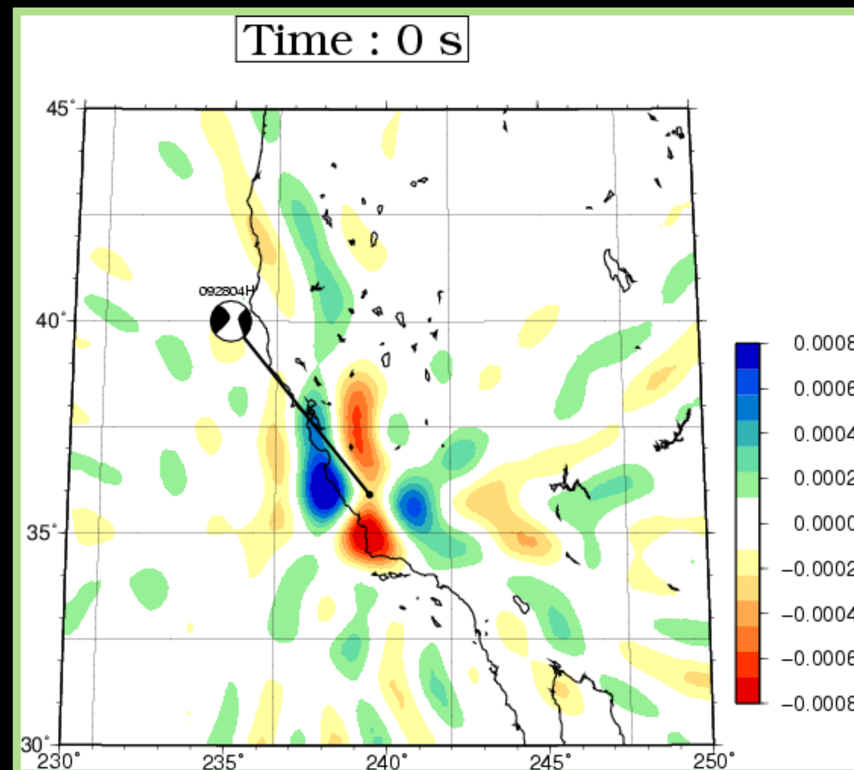
Result: reconstruction of the radiation pattern

```
Date: 2004/ 9/28   Centroid Time: 17:15:31.2 GMT
Lat=  35.92  Lon=-120.54
Depth= 12.0   Half duration= 2.4
Centroid time minus hypocenter time:  7.0
Moment Tensor: Expo=25  -0.111 -0.994 1.110 0.260 0.225 0.220
Mw = 6.0    mb = 5.4    Ms = 5.8   Scalar Moment = 1.13e+25
Fault plane:  strike=321    dip=72   slip=-178
Fault plane:  strike=230    dip=88   slip=-18
```







TR focus obtained when rebroadcasting the whole time series that is dominated by surface waves.

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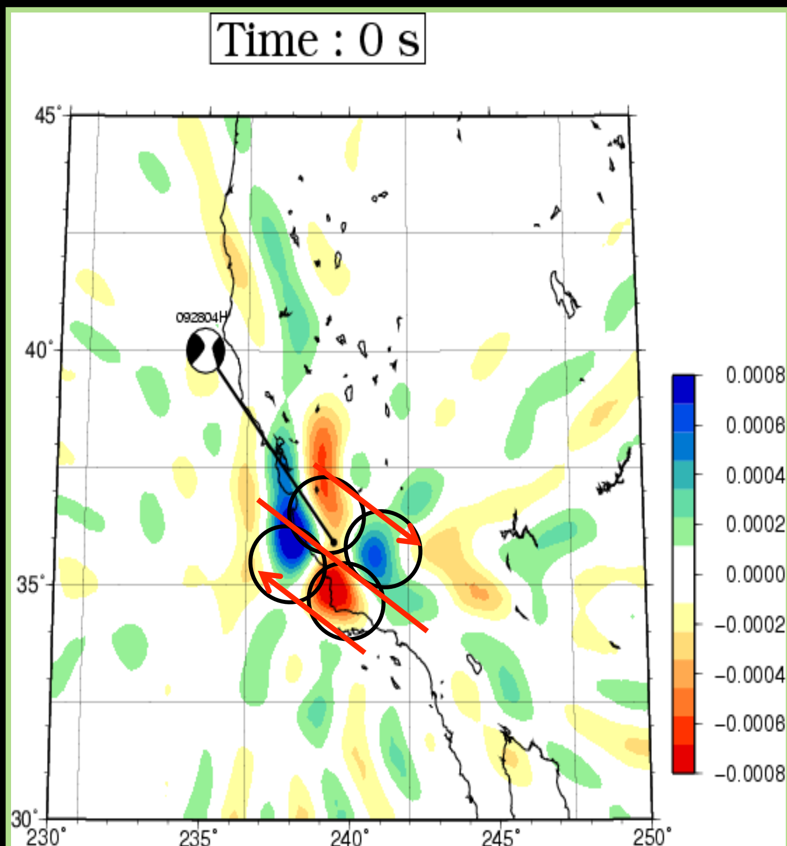
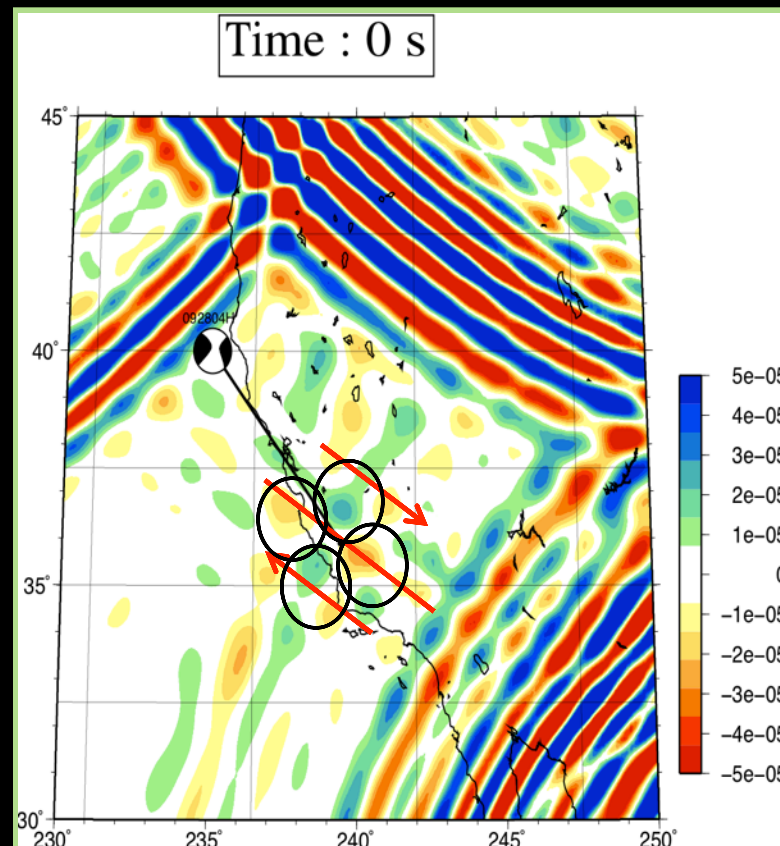
Rayleigh/Shear Wave radiation pattern





TR result with signal dominated by Rayleigh waves.

TR result with signal dominated by S-wave. Rebroadcast limited to the body-wave time window and filtered between 23 to 60s. Still 55s stations.

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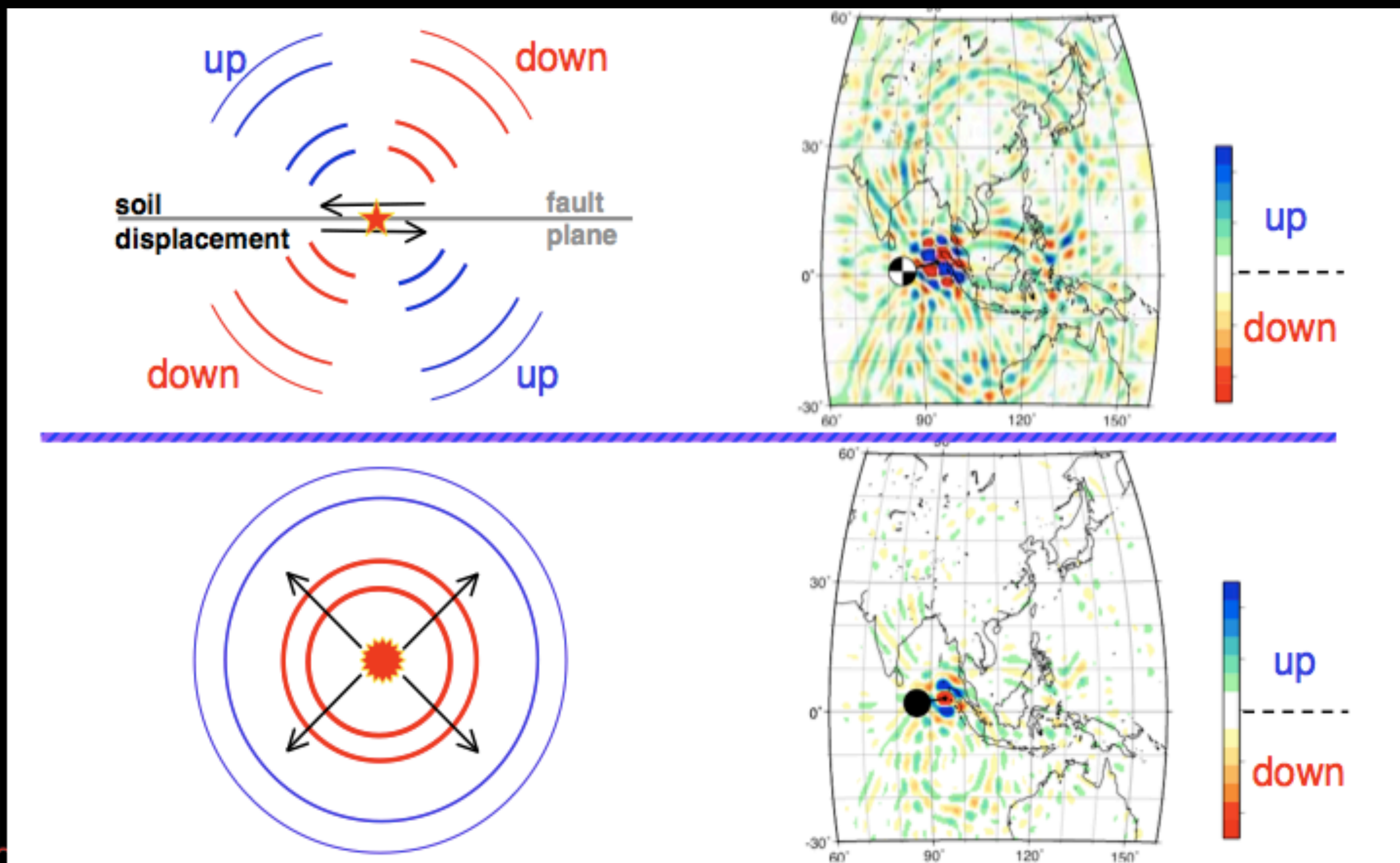
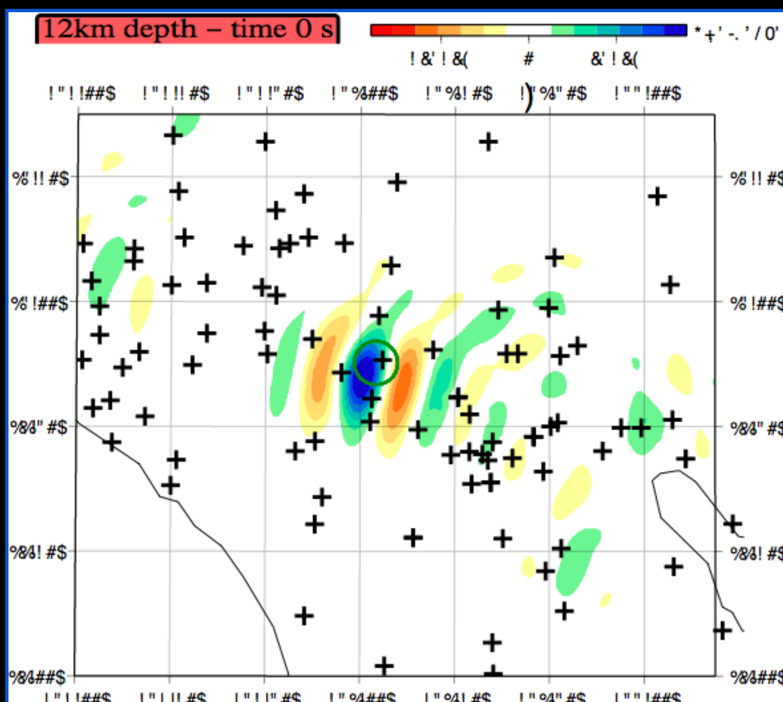
TR as a mean to distinguish between an earthquake and an explosion

Distinguish between an earthquake and an explosion: proof of concept.

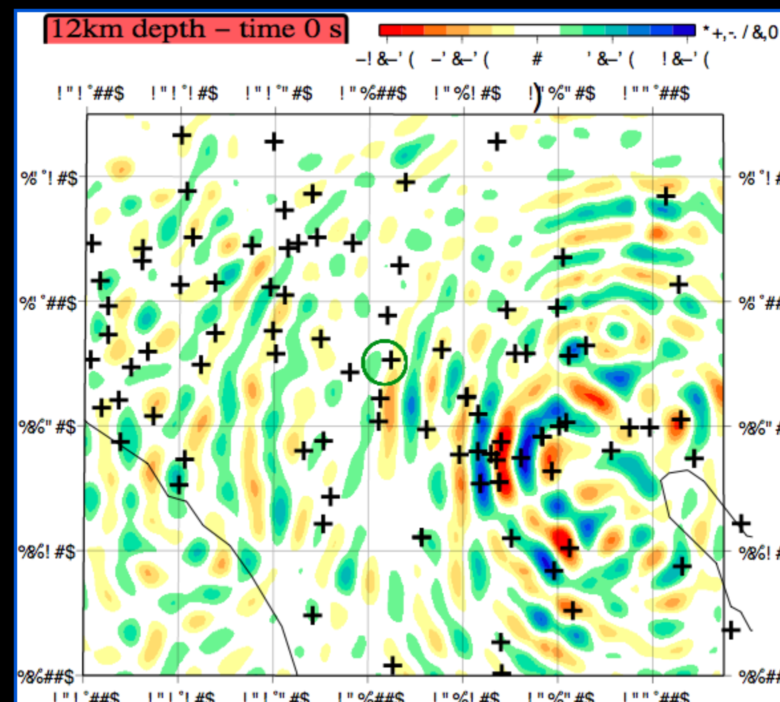


Further characterization: using imaging conditions

Proof-of-concept with synthetics: Target source is isotropic (and 12km deep)



Divergence of the Time Reversed wavefield.



Vertical component of the curl of the Time Reversed wavefield.

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Larmat, C., R. A. Guyer, and P. A. Johnson (2009), *Geophys. Res. Lett.*, *36*(22), L22304, doi:10.1029/2009GL040099.

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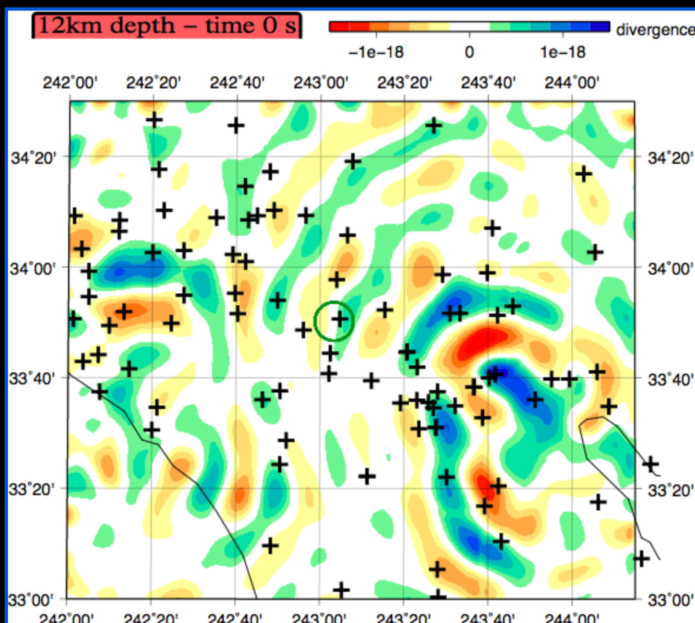
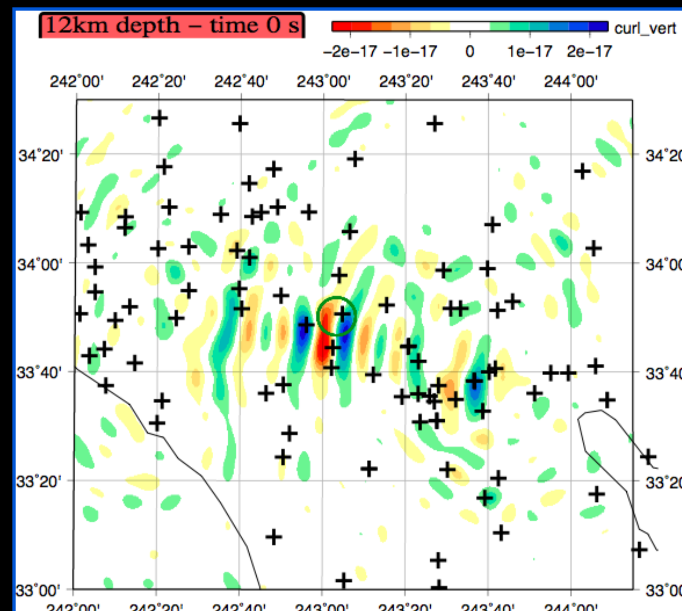
Further characterization: using imaging conditions

Proof-of-concept with synthetics: Target source is a strike-slip event (and 12km deep)



Divergence of the Time Reversed wavefield.



Vertical component of the curl of the Time Reversed wavefield.

Larmat, C., R. A. Guyer, and P. A. Johnson (2009), *Geophys. Res. Lett.*, *36*(22).

→ Elaborate and adapted interrogation of the reconstructed wavefield

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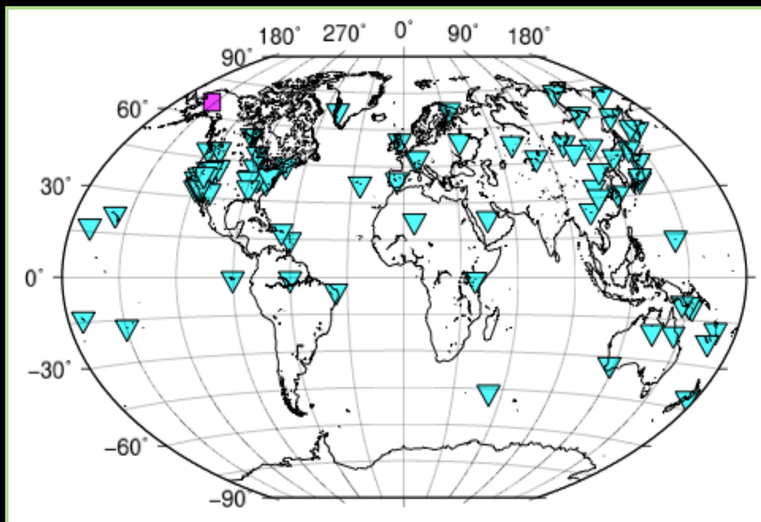
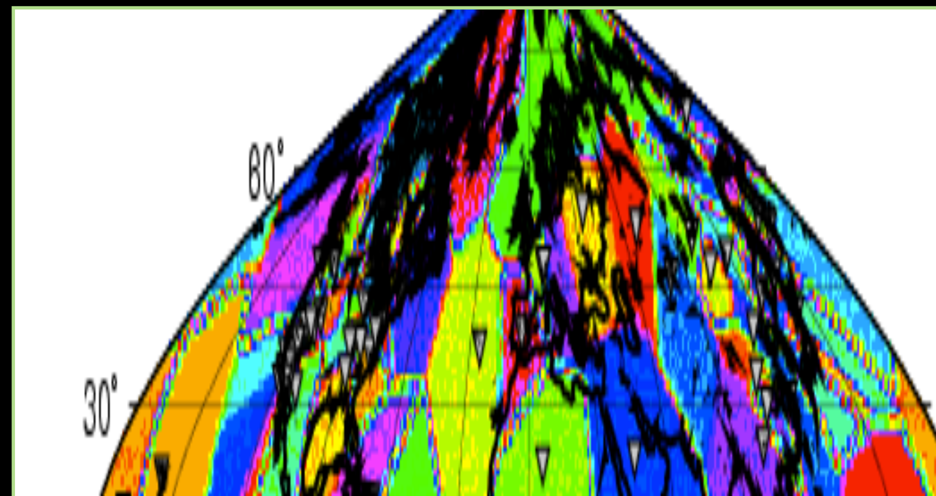
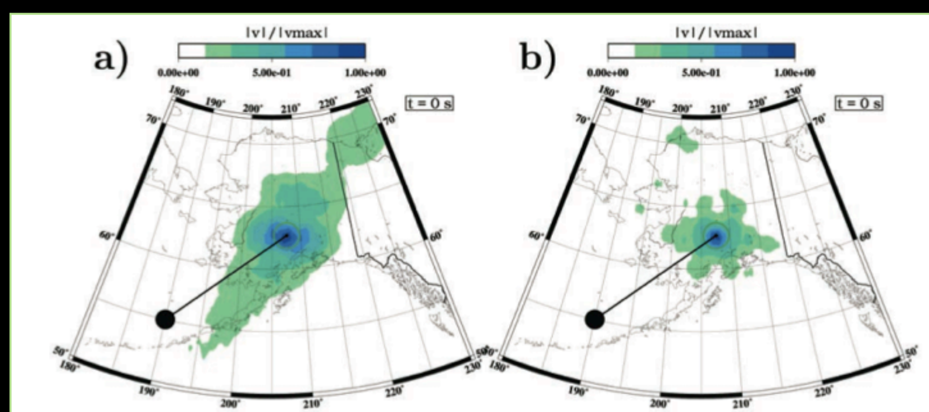
Correction for uneven station distribution





Voronoi Cell tesselation of Earth surface
⇒signal weighted according to the degree of "isolation" of the recording station



C. Larmat et al., 2008, J. Geophys. Res., "Time reversal location of glacial earthquakes".

Outline

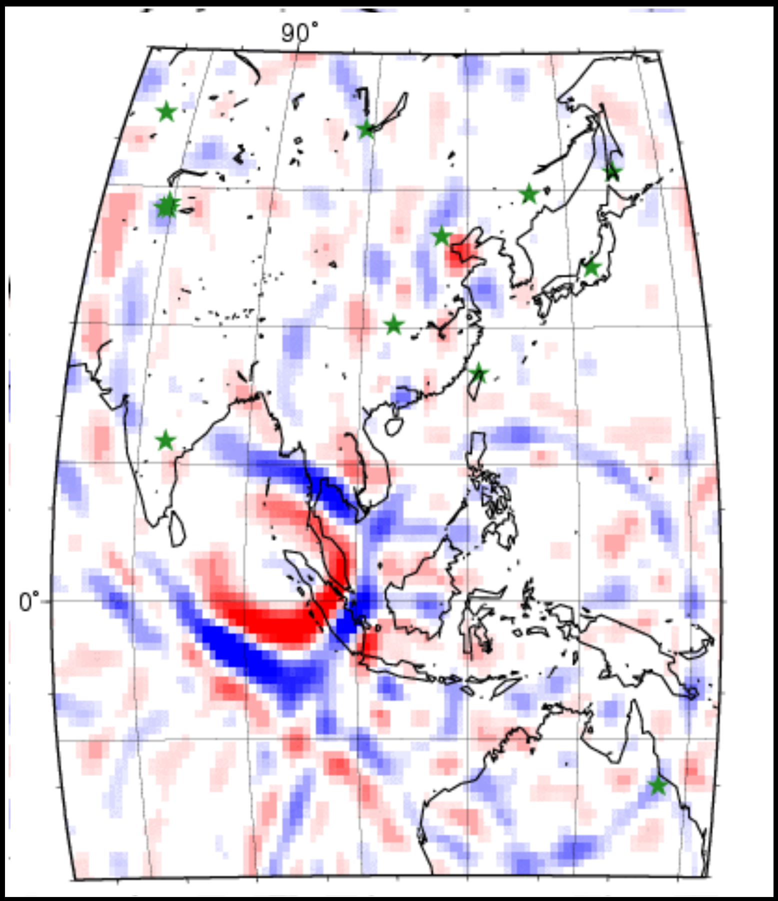
4- Beyond classical earthquakes

Rupture imaging

Low SNR signals: glacial earthquakes

Emergent signals: triggered tremor in California

Rupture Reconstruction



-200s

2004 Sumatra-Andaman Earthquake: “ribbon-like” earthquake
165 stations selected, over 100s period.

C. Larmat, et al., “Time-reversal imaging of seismic sources and application to the great Sumatra earthquake”, Geophys. Res. Lett., 33, p L19312, 2006

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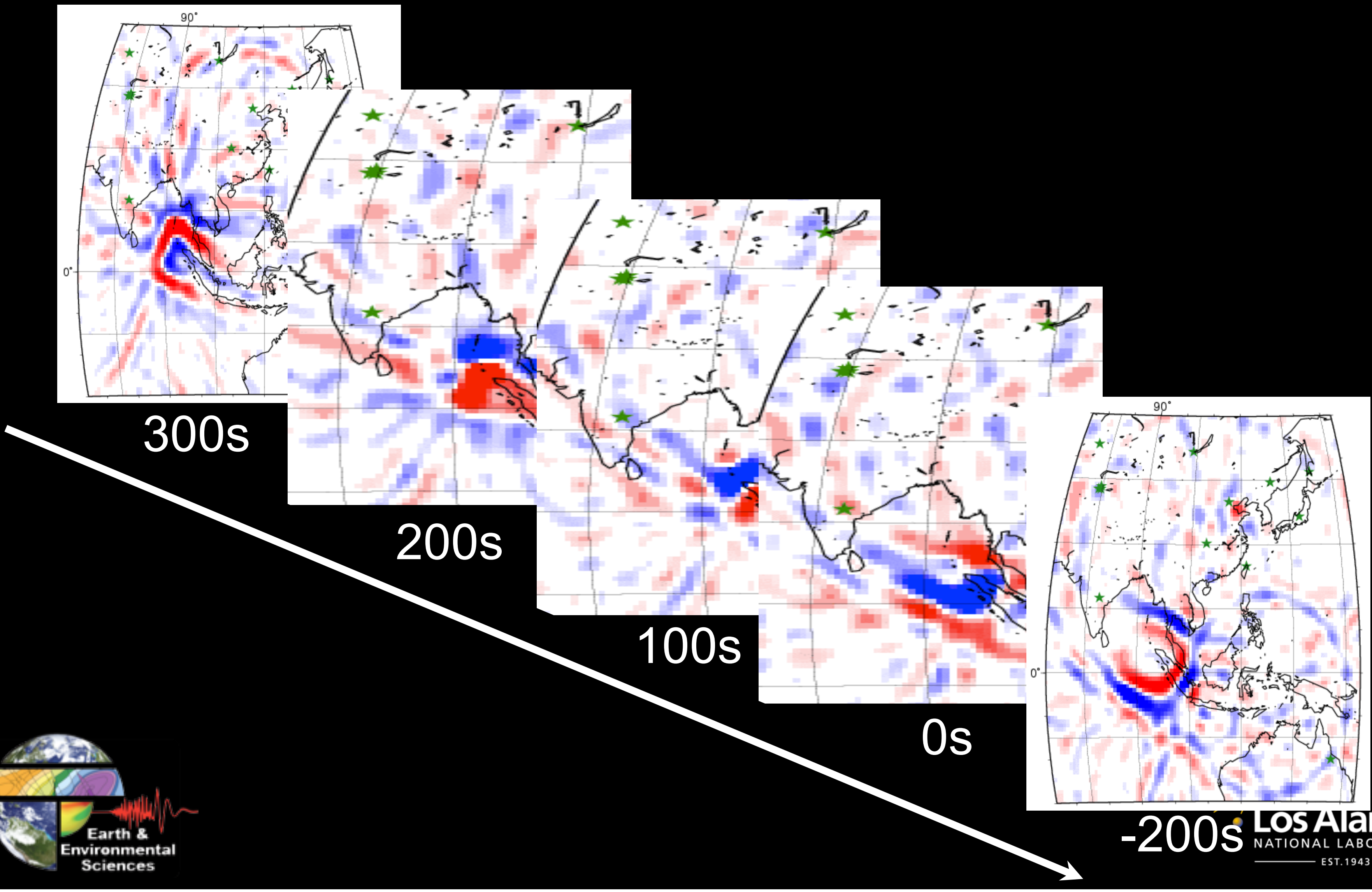
Rupture Reconstruction



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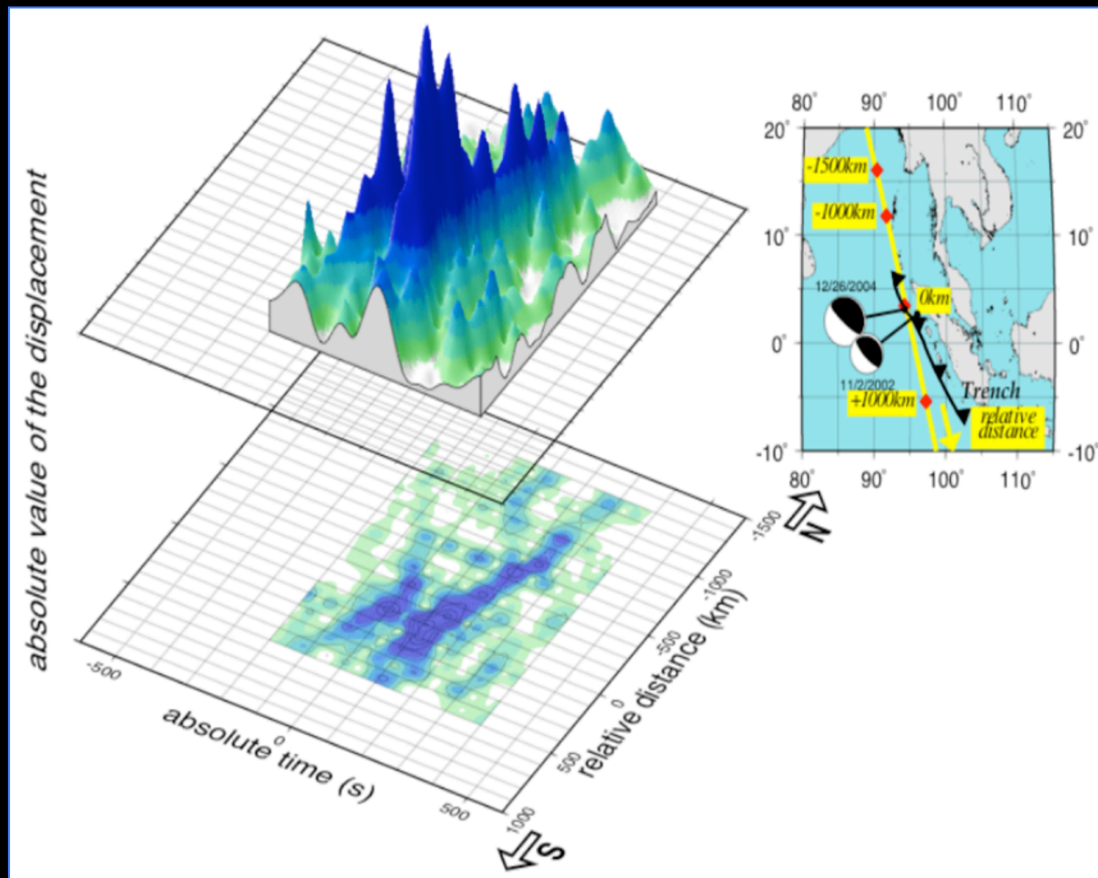
"Differential" Time Reversal



Reconstructed space-time rupture history of the rupture of the 2004 Giant Sumatra-Andaman earthquake with **deconvolution** of the Nov. 2, 2002 M7.6 earthquake

C. Larmat, et al., "Time-reversal imaging of seismic sources and application to the great Sumatra earthquake", Geophys. Res. Lett., 33, p L19312, 2006C

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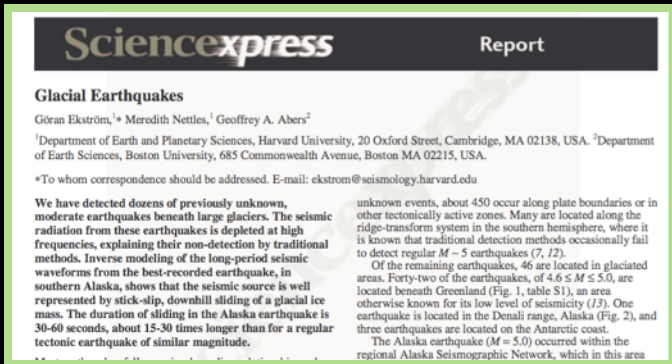
TR location of glacial earthquakes



Sciencexpress Report

Glacial Earthquakes

Göran Ekström,[1]* Meredith Nettles,[1] Geoffrey A. Abers[2]

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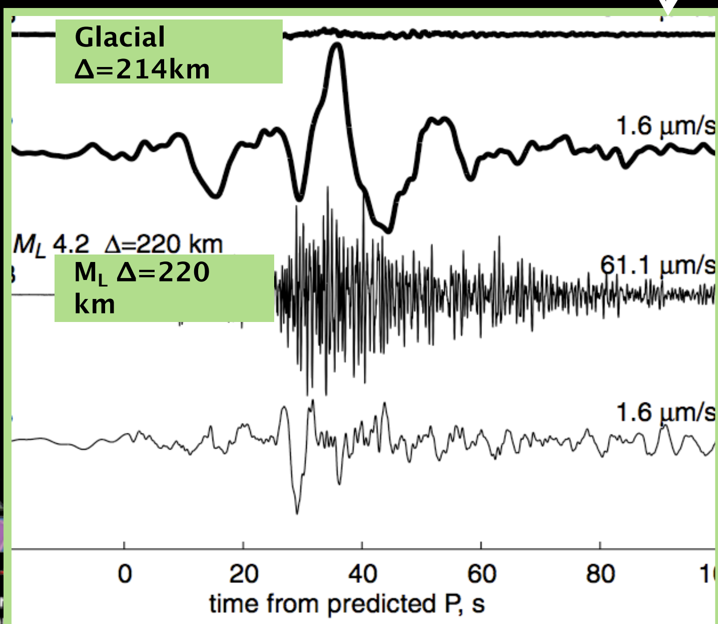
We have detected dozens of previously unknown, moderate earthquakes beneath large glaciers. The seismic radiation from these earthquakes is depleted at high frequencies, explaining their non-detection by traditional methods. Inverse modeling of the long-period seismic waveforms from the best-recorded earthquake, in southern Alaska, shows that the seismic source is well represented by stick-slip, downhill sliding of a glacial ice mass. The duration of sliding in the Alaska earthquake is 30-60 seconds, about 15-30 times longer than for a regular tectonic earthquake of similar magnitude.

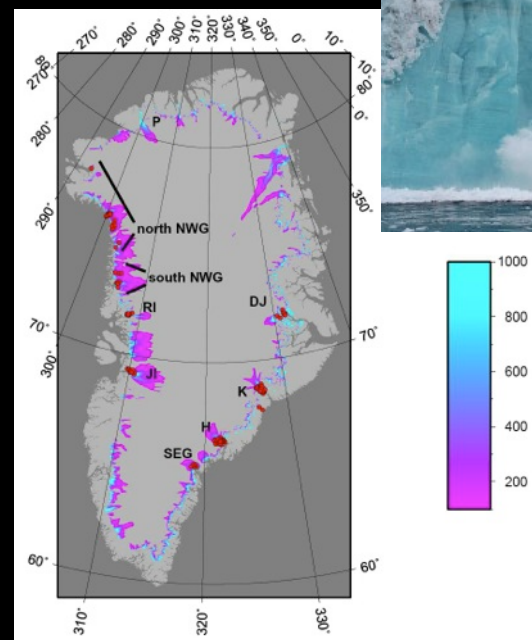
unknown events, about 450 occur along plate boundaries or in other tectonically active zones. Many are located along the ridge-transform system in the southern hemisphere, where it is known that traditional detection methods occasionally fail to detect regular $M \sim 5$ earthquakes (7, 12).

Of the remaining earthquakes, 46 are located in glaciated areas. Forty-two of the earthquakes, of $4.6 \le M \le 5.0$, are located beneath Greenland (Fig. 1, table S1), an area otherwise known for its low level of seismicity (13). One earthquake is located in the Denali range, Alaska (Fig. 2), and three earthquakes are located on the Antarctic coast.

The Alaska earthquake ($M = 5.0$) occurred within the regional Alaska Seismographic Network, which in this area

Discovered in 2003 by Ekström et al. (2003) as a weak long period signal in records of quiet days. Sources located in Alaska and Greenland.





Locations of the Greenland glacial earthquakes that occurred between 1993 and 2005.
http://www.gps.caltech.edu

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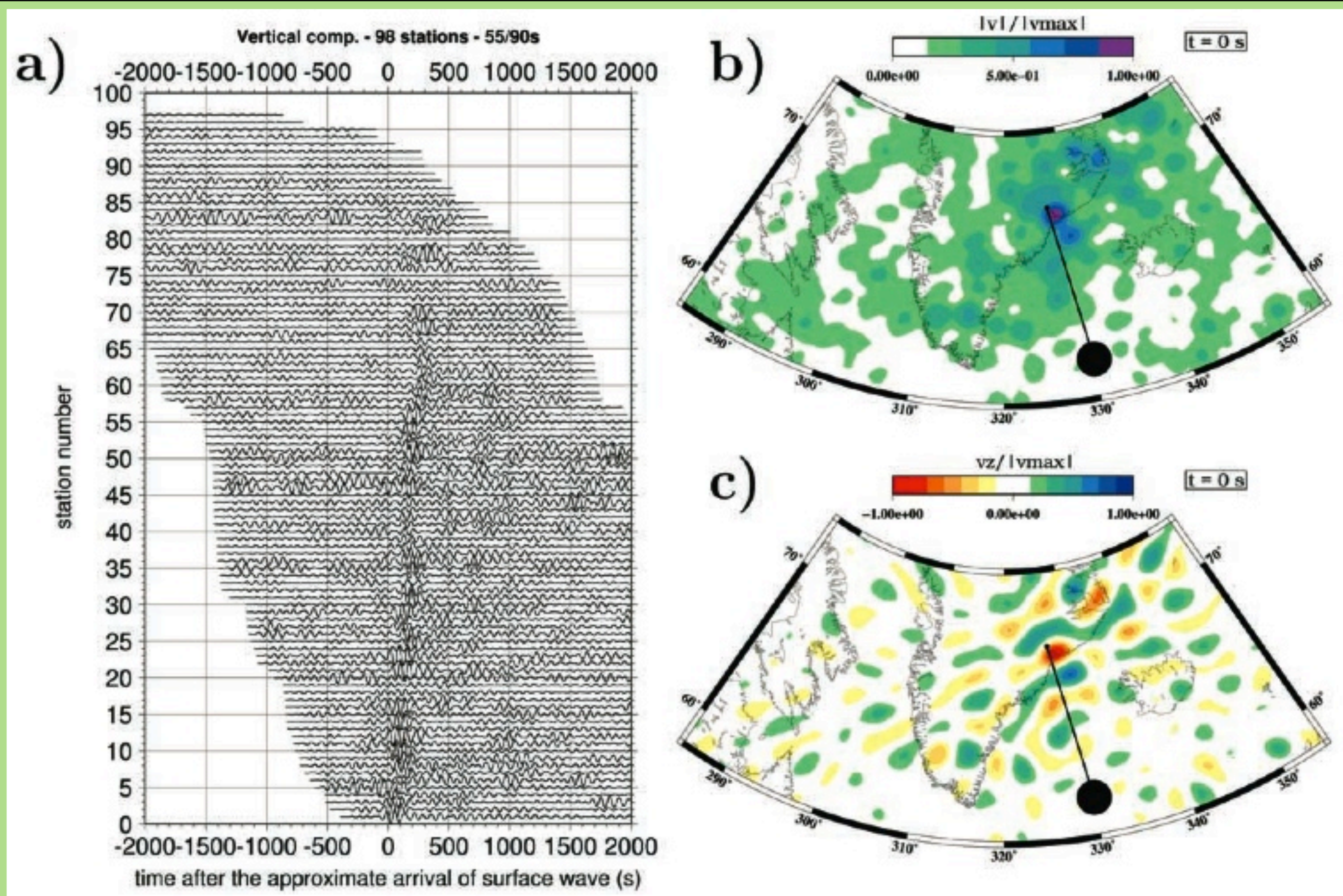
The 28 Dec. 2001, Greenland, M5.0 glacial earthquake



98 stations worlwide.
Vertical component filtered between 55s and 90s.

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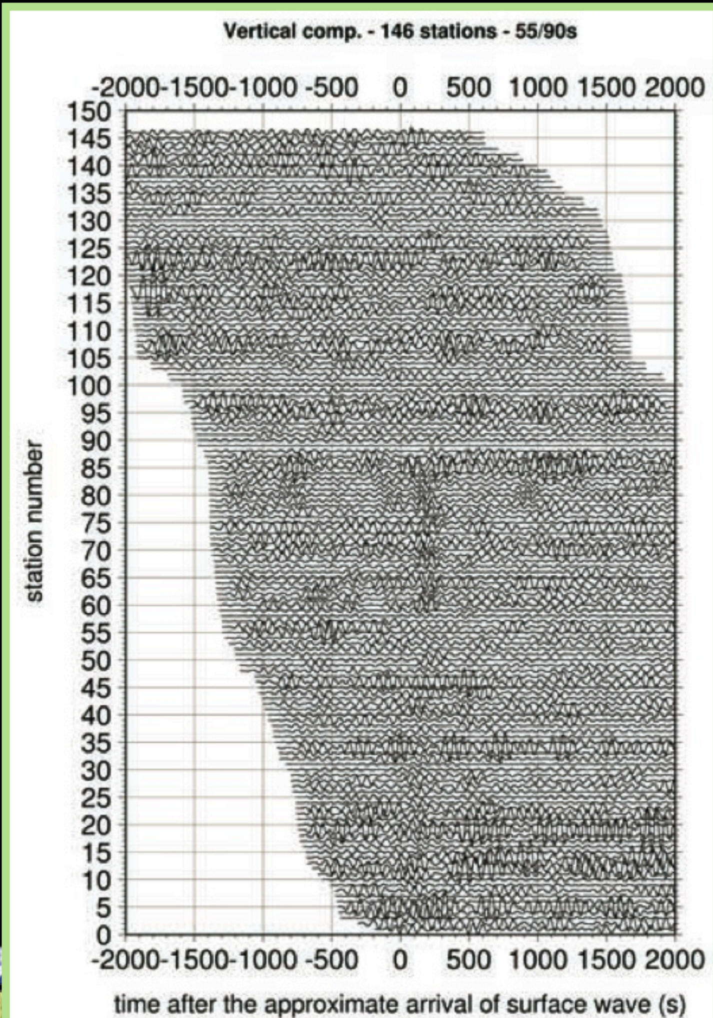
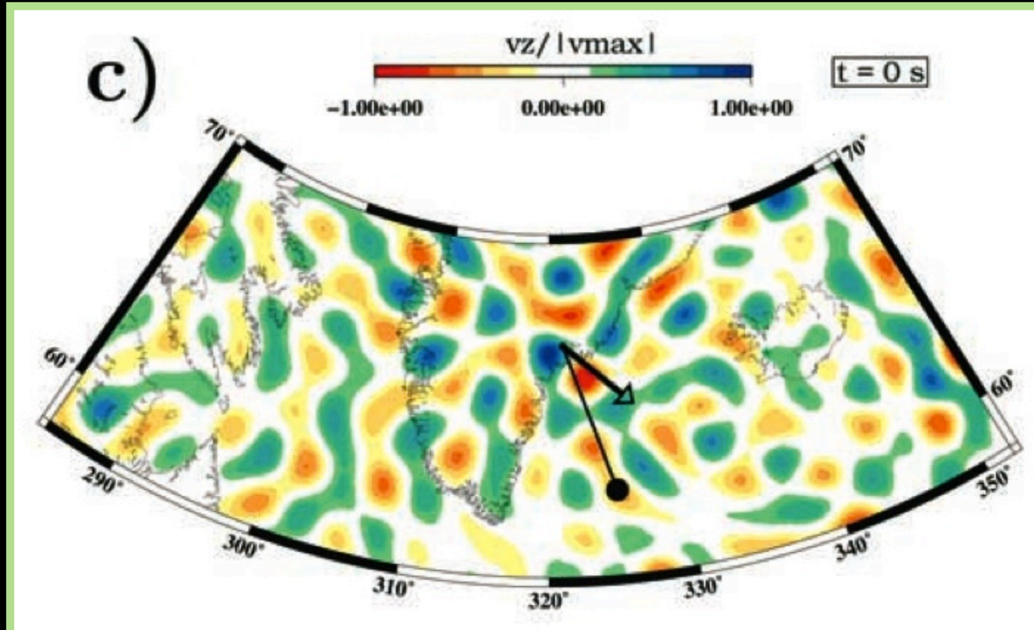
The 26 Dec. 2001, Greenland, M5.0 glacial earthquake





148 stations worlwide. Vertical component filtered between 55s and 90s.

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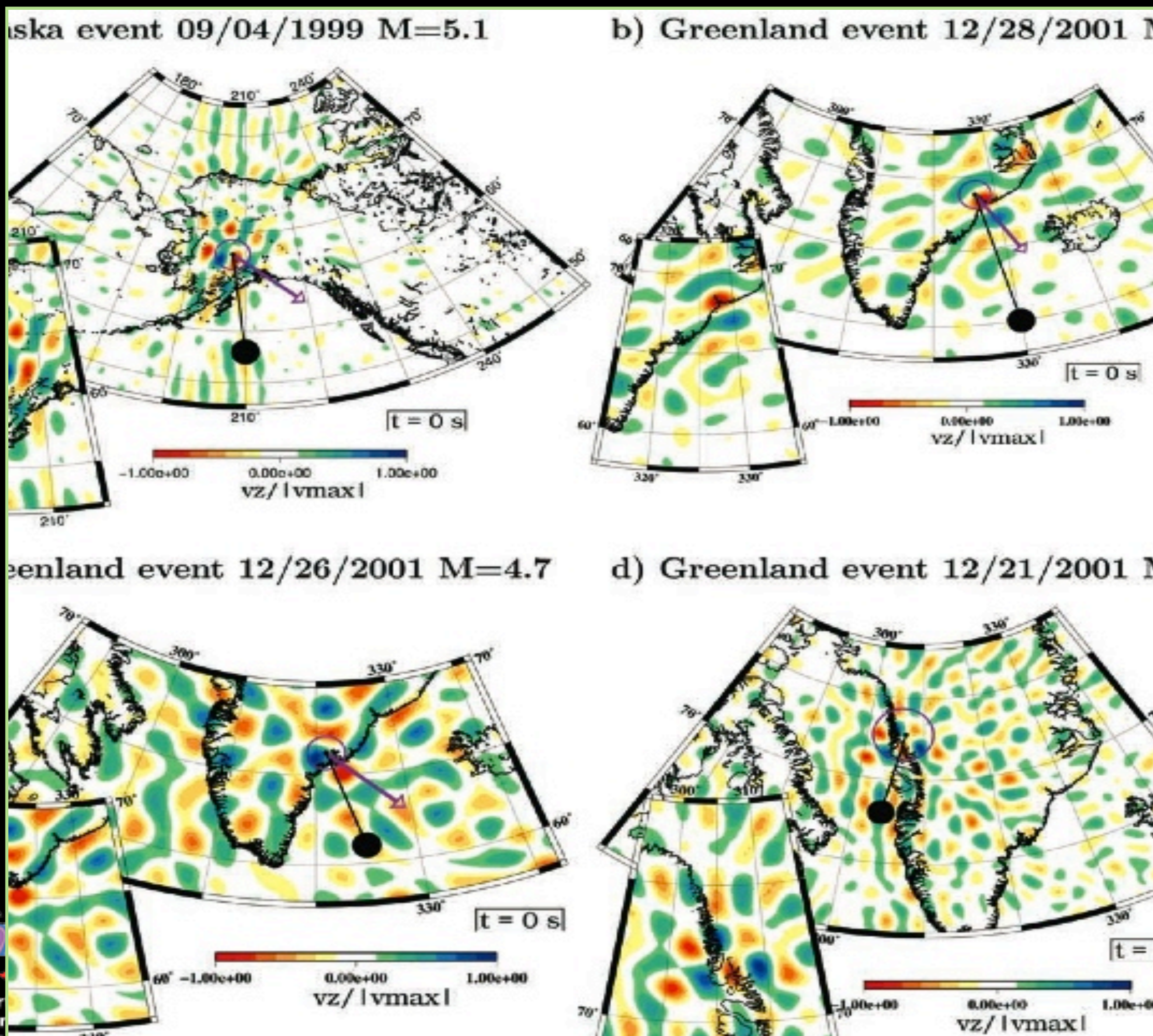
Direction of glacier motion



C. Larmat *et al*., 2008, J. Geophys. Res., "Time reversal location of glacial earthquakes".

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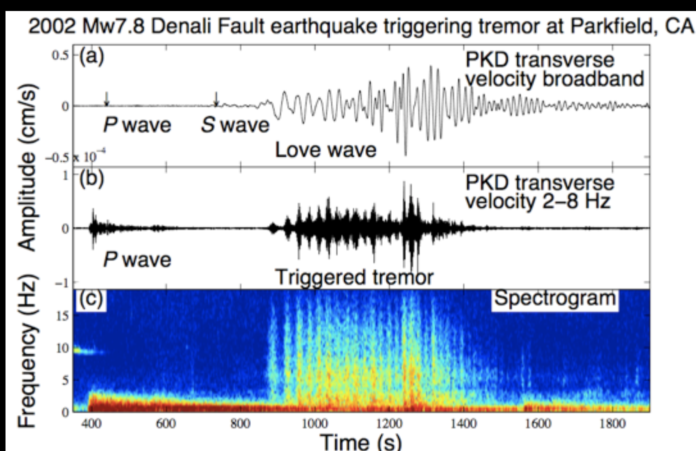
Applying Time-Reversal to tremor

- Tremor signal was first discovered in 2002 in Japan. It is a faint signal very emergent (i.e. no clear beginning, nor end, nor identifiable phases).

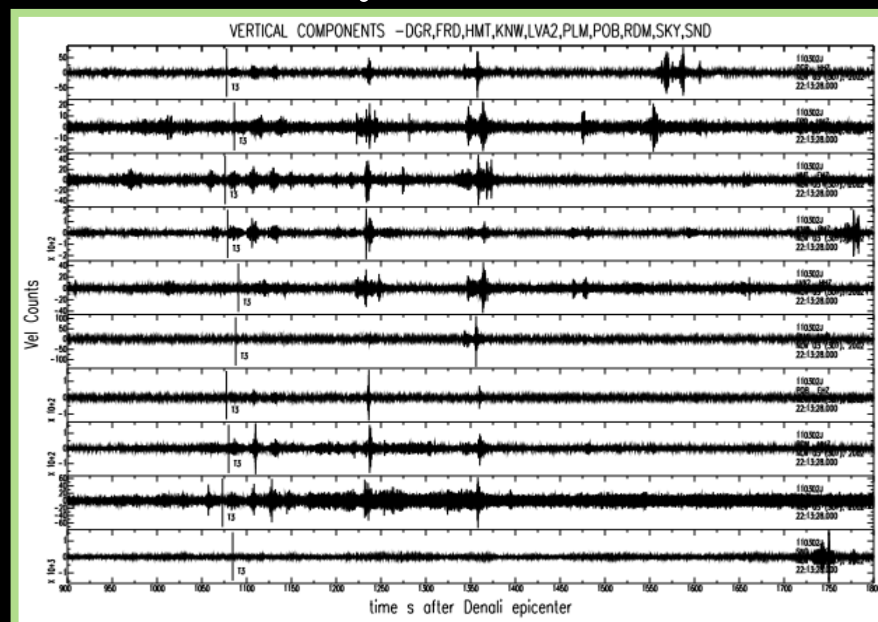
Denali earthquake

Triggers non-volcanic tremor in California

Gomberg et al., 2008



Parkfield



Hemet

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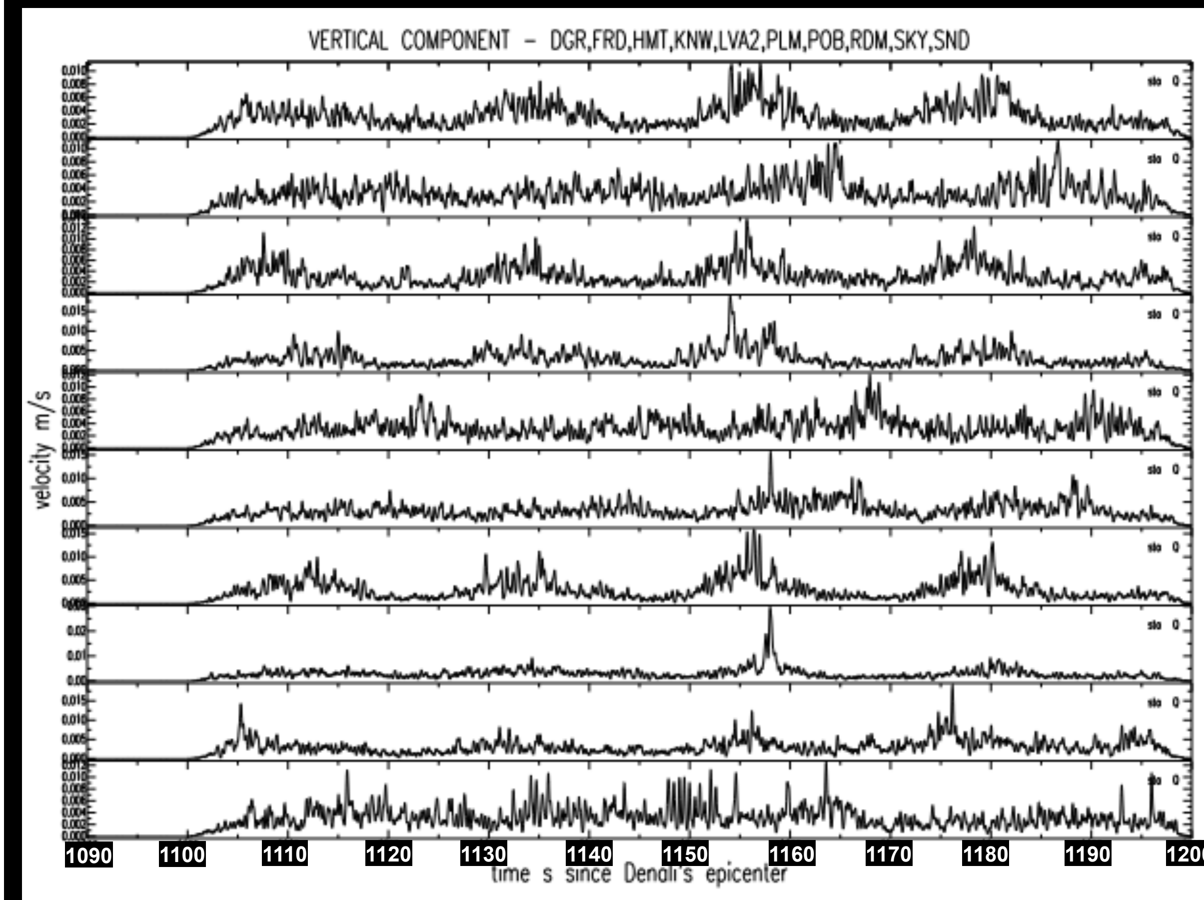
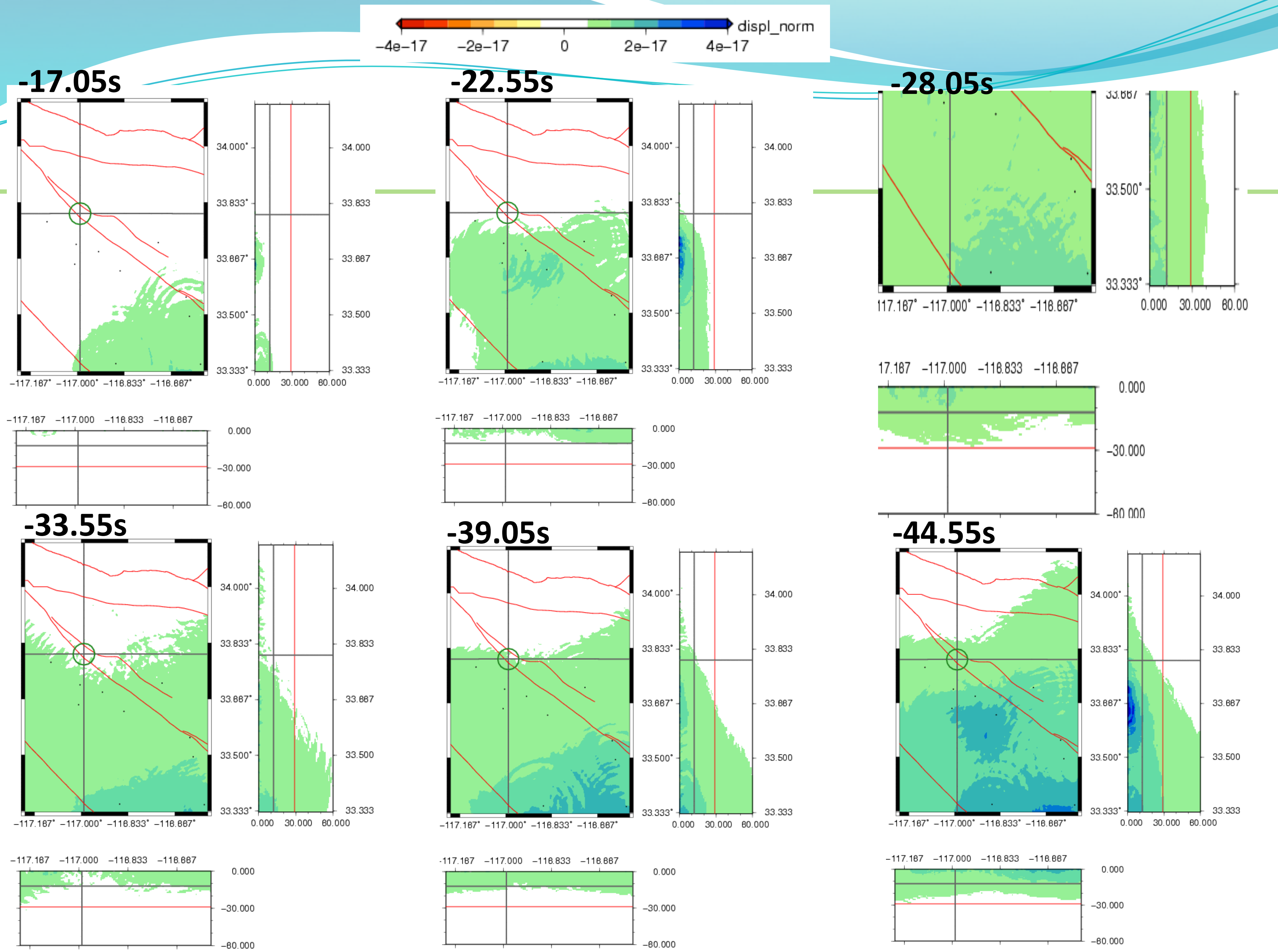
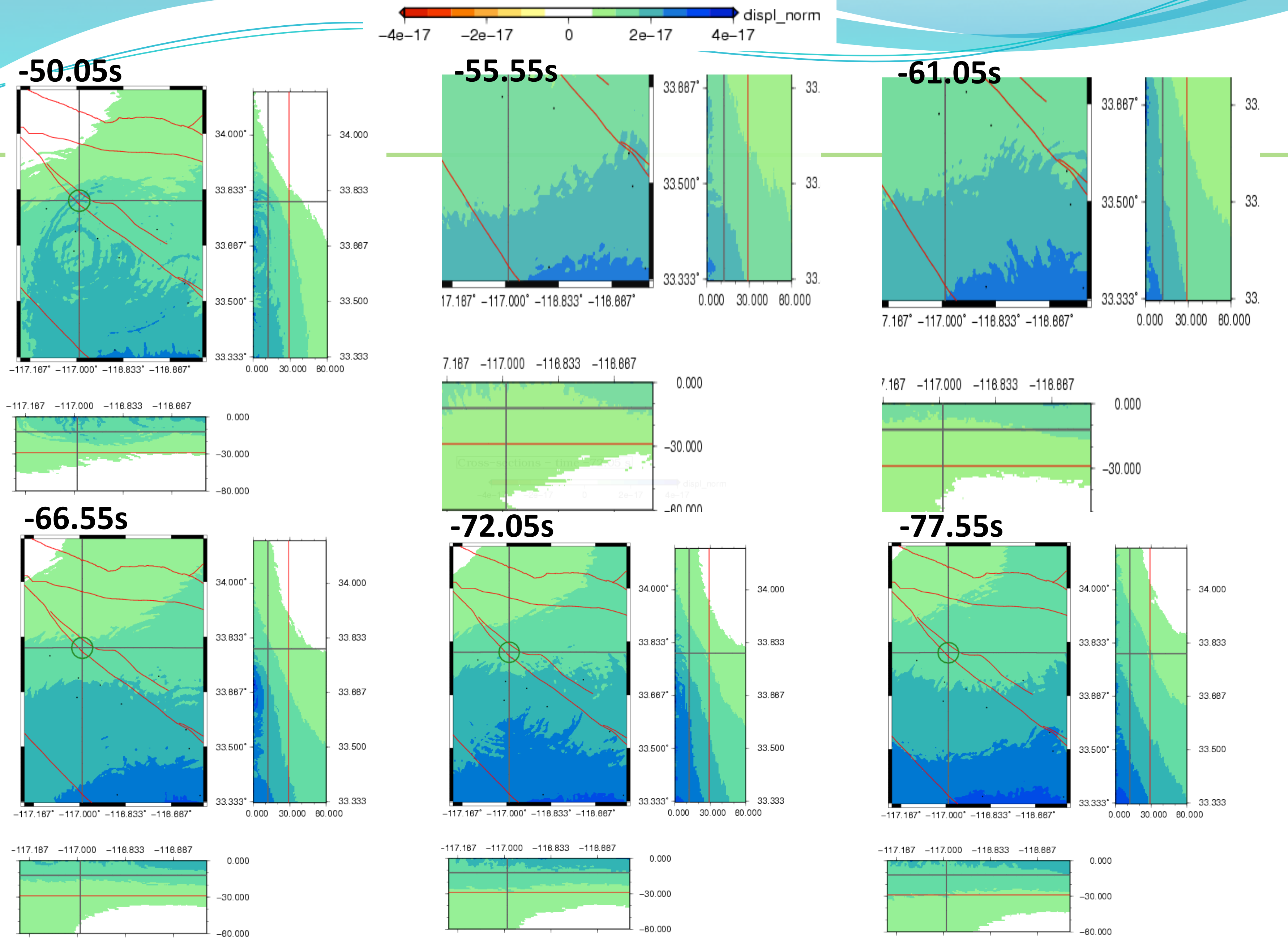
Trial 1



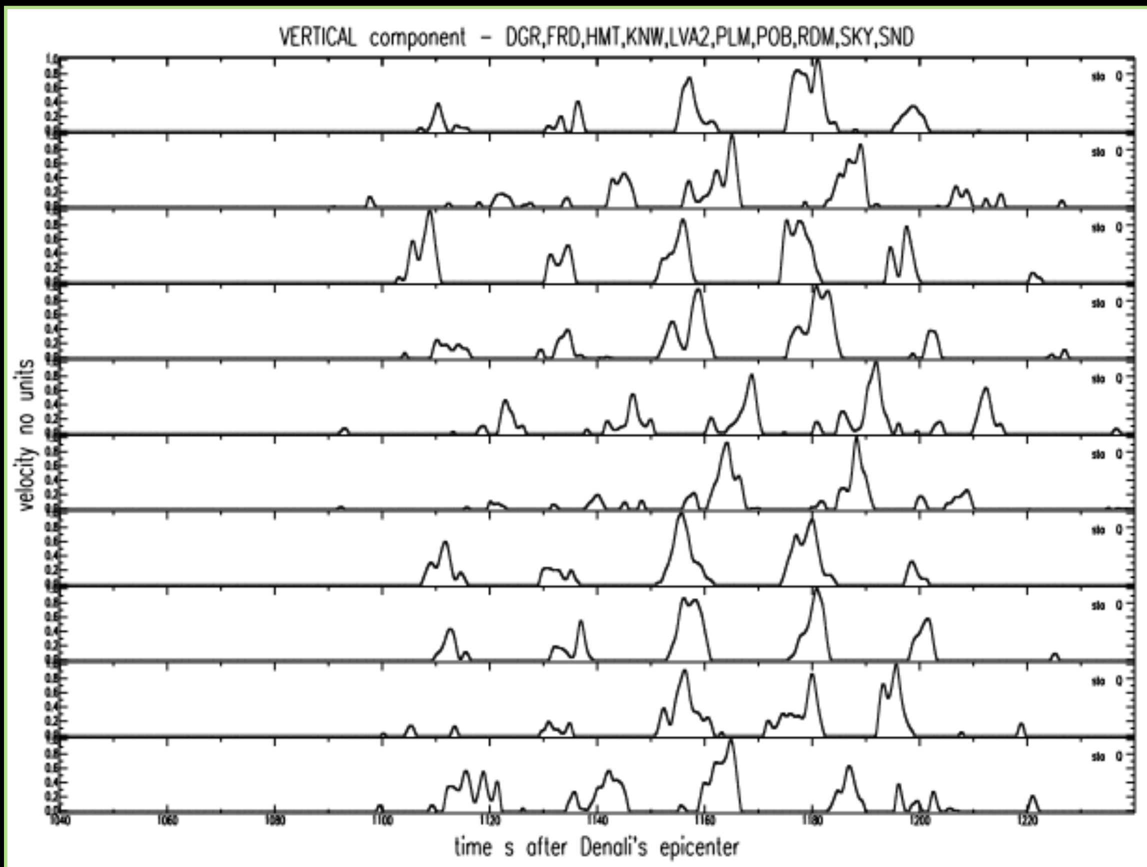
- Raw time-series, gain corrected, band-pass 5-15Hz, **envelope, low-pass 3.35Hz**
- 10 stations,
- 100s of signal (1100-1200)
- 3 components


displ_norm
−4e−17
−2e−17
0
2e−17
4e−17
-17.05s
-22.55s
-28.05s
-33.55s
-39.05s
-44.55s



-4e-17
-2e-17
0
2e-17
4e-17
displ_norm
-50.05s
-55.55s
-61.05s
-66.55s
-72.05s
-77.55s
34.000°
33.833°
33.667°
33.500°
33.333°
-117.167° -117.000° -116.833° -116.667°
0.000 30.000 60.000
0.000
-30.000
-60.000

Trial 2: Very low frequency envelop



- Raw time-series, gain corrected, **band-pass 5-15Hz, envelope, low-pass 0.33Hz, clipped, normalized to 1**
- 10 stations,
- 150s of signal (1090-1240)
- 3 components

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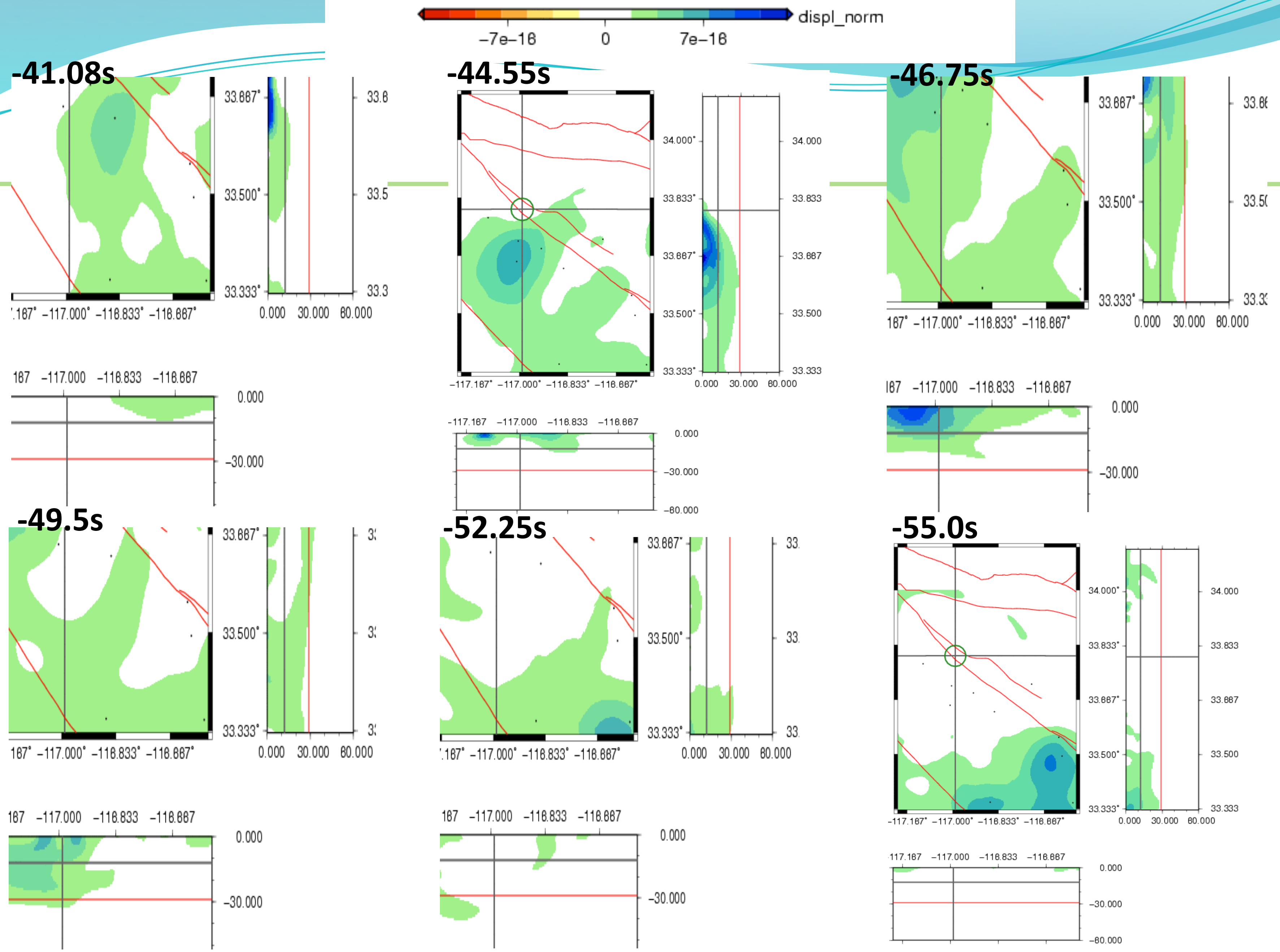
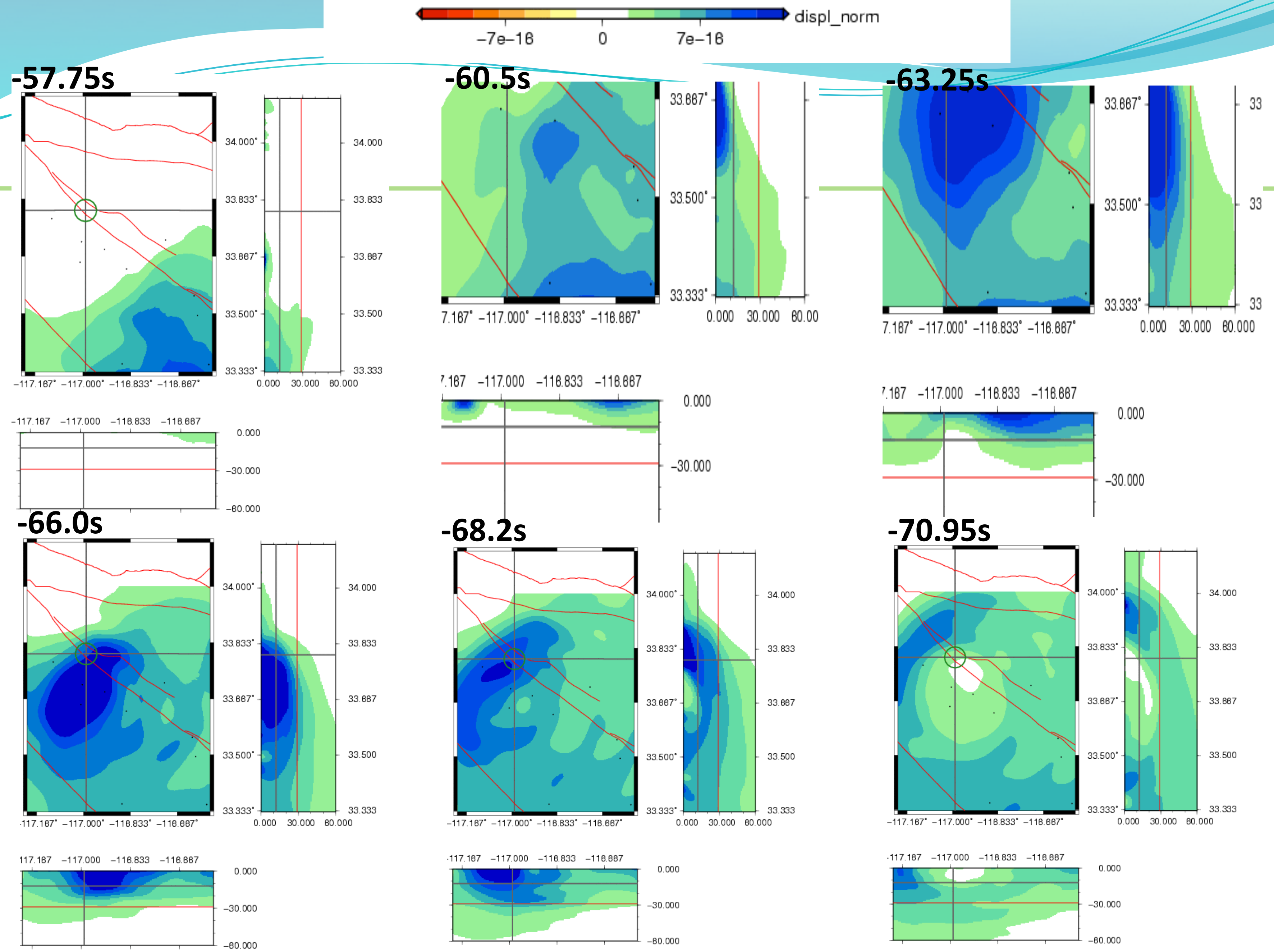
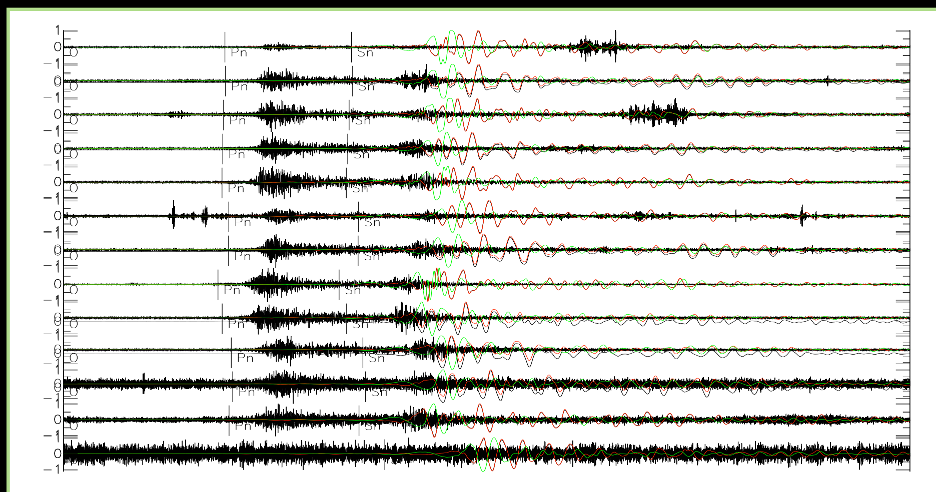
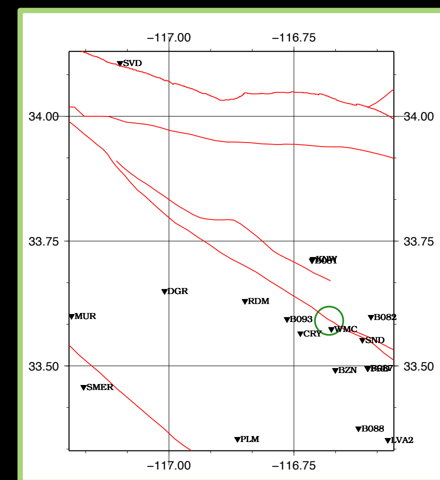


displ_norm
−7e−16
0
7e−16
-41.08s
-44.55s
-46.75s
-49.5s
-52.25s
-55.0s
33.667°
33.500°
33.333°
34.000°
33.833°
−117.167°
−117.000°
−116.833°
−116.667°
0.000
30.000
60.000
−30.000
−60.000

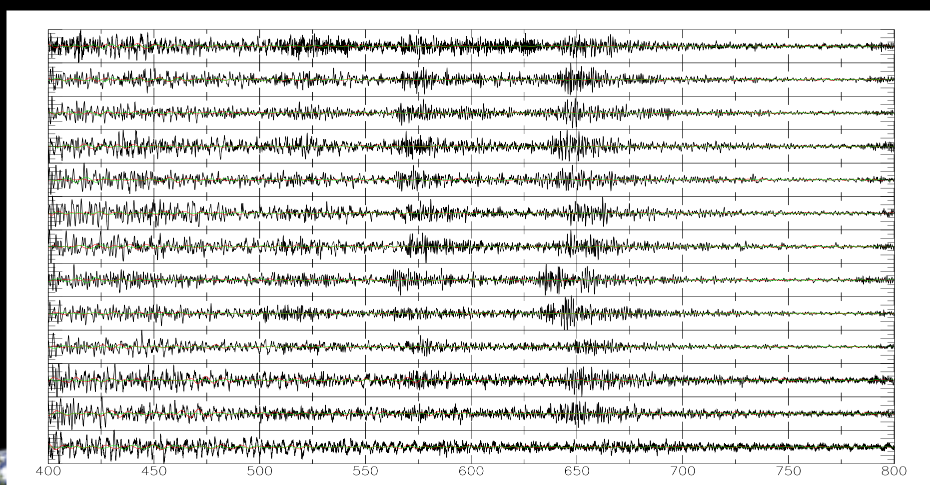

displ_norm
-7e-16
0
7e-16
-57.75s
-60.5s
-63.25s
-66.0s
-68.2s
-70.95s
-117.167° -117.000° -116.833° -116.667°
34.000° 33.833° 33.667° 33.500° 33.333°
0.000 30.000 60.000
0.000 -30.000 -60.000

Tremor triggered by the 2009 Mexicali earthquake





- Raw time-series, gain corrected, **band-pass 1-3Hz**,
- 17 stations,
- 150s of signal (550-700)
- 3 components



Triggers non-volcanic tremor in California

Mexicali earthquake

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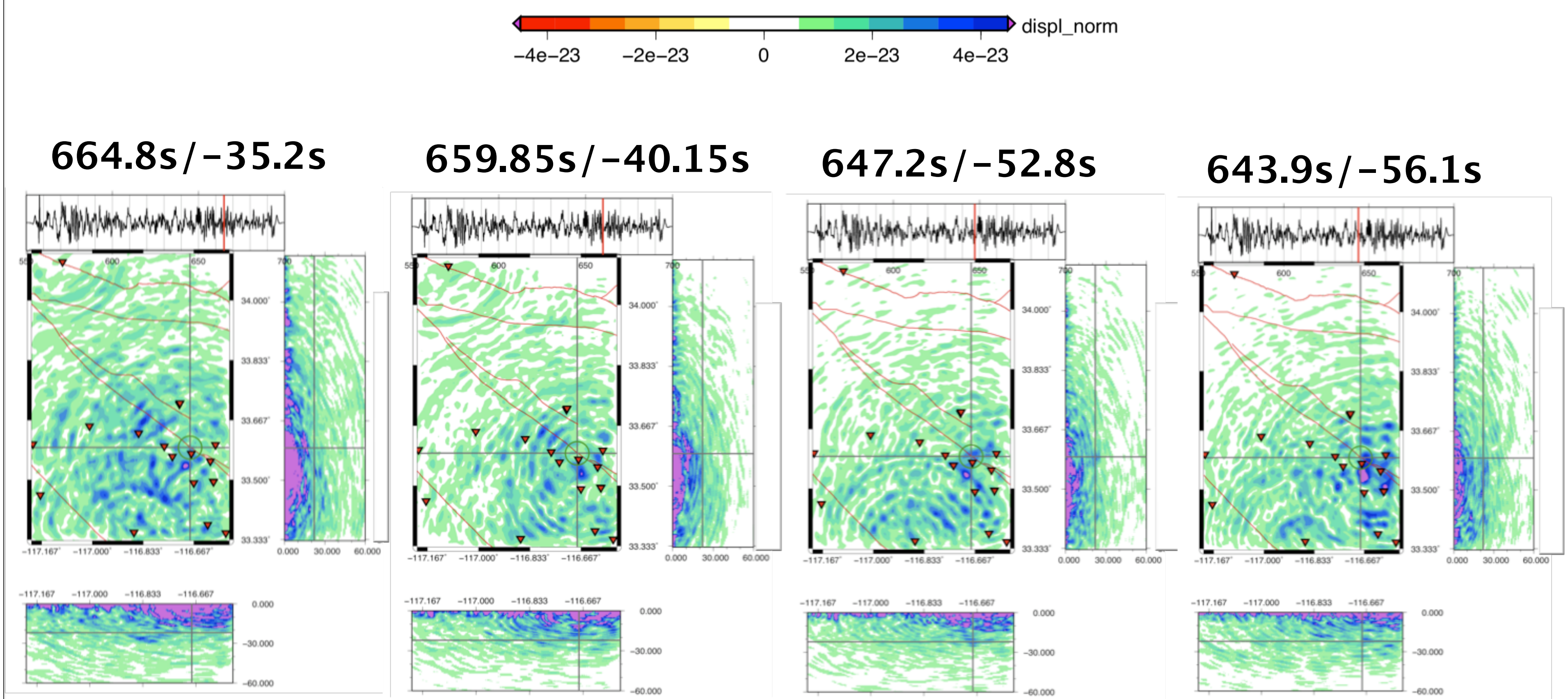
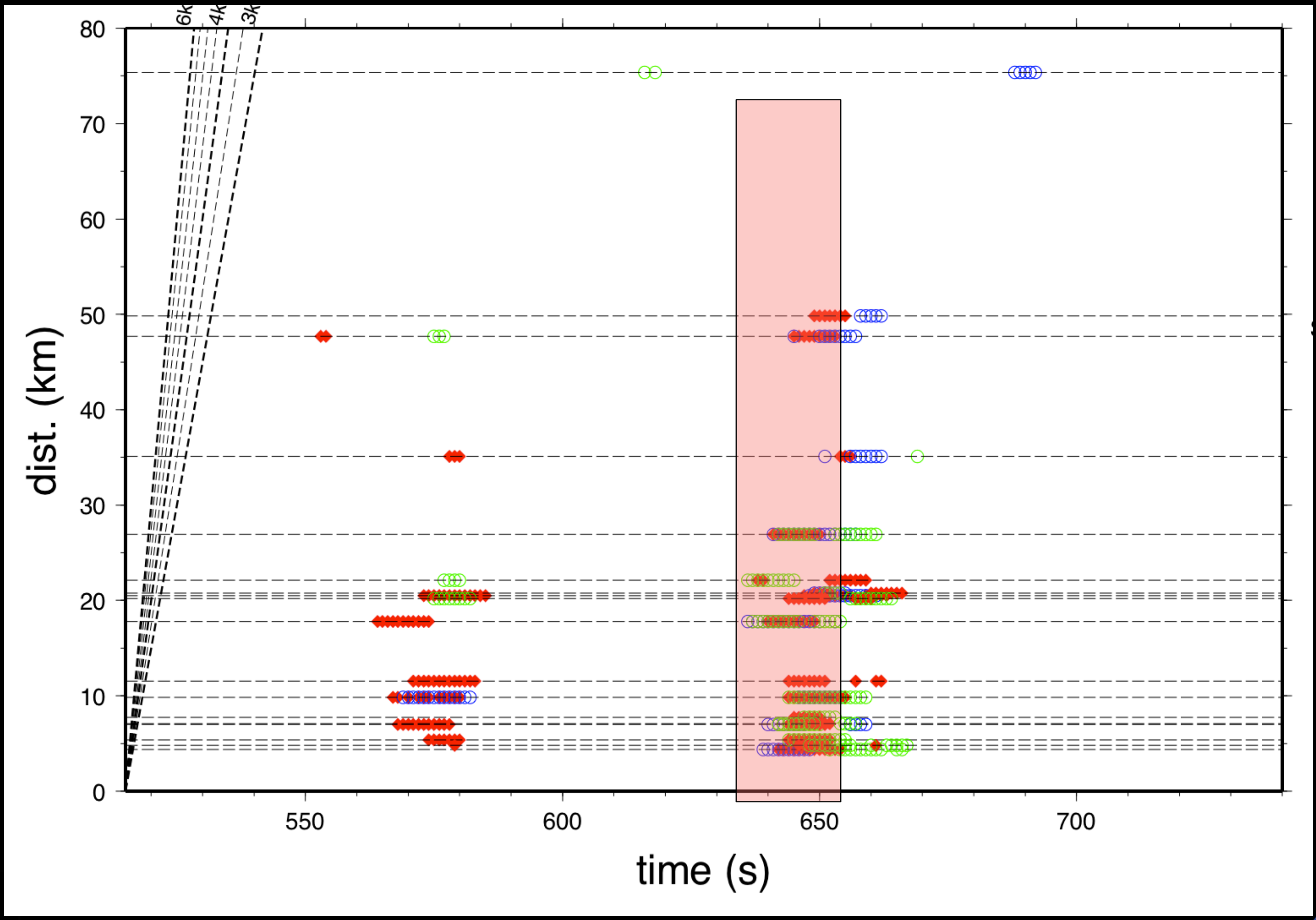
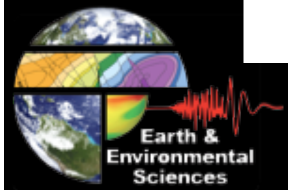
Location

- Raw time-series, gain corrected, band-pass 1-3Hz,
- 17 stations,
- 150s of signal (550-700)
- 3 components



STA/SLA analysis





Outline

5-Conclusions

Conclusions

Pleasant Tenets of Time-Reversal:

-Data handling reduced to a minimum – favor automatization

-Versatility, not bound to a particular numerical scheme.

-Time Reversal thrives with complexity

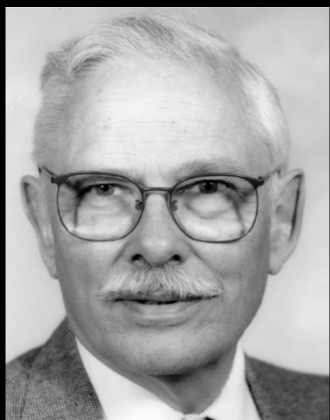
-Whole waveform inversion compared to SSA or back-projection method which are limited to a specific phase

The data are used, instead of any assumption about the source mechanism.

Time reversal converses characteristics of the original source, radiation pattern, compression and shear character.

➤source characterization

Thank you!



In memory of Clarence S. Clay (1923-2011)

References:

- C. Larmat, J.-P. Montagner, M. Fink, Y. Capdeville, A. Tourin, E. Clévédé, "Time-Reversal imaging of seismic sources and application to the great Sumatra earthquake", *Geophys. Res. Lett.*, 33, p. L19132, 2006.
- B. Anderson, M. Griffa, C. Larmat, T.J. Ulrich, P.A. Johnson , "Time Reversal", *Acoust. Today*, 4(1), p. 5-16, 2008**.**
- C. Larmat, J. Tromp, Q. Liu, J.-P. Montagner , "Time-Reversal location of glacial earthquakes", *J. Geophys. Res.*, 113(B9), B09314, 2008.
- C. Larmat, R.A. Guyer, P.A. Johnson, "Tremor location using time-reversal: selecting the appropriate imaging field", *Geophys. Res. Lett.*, 36, L22304, 2009.
- C. Larmat, R.A. Guyer, P.A. Johnson, "Time reversal in geophysics", featured article in *Physics Today*, 63, p. 31-35, 2010.
- C. Larmat, P.A. Johnson, R.A. Guyer, "Using time-reversal to locate non-volcanic tremor and to fulfill the monitoring objectives of the nuclear-test ban treaty", POMA 10(1),(2010).
- C. Larmat, C.S. Clay, "Time reversal methods" for the Encyclopedia of Solid Earth Geophysics (ESEG), Springer 2011
- In Press, J.-P. Montagner, M. Fink, Y. Capdeville**,** C. Larmat, B. Romanowicz, H. Nguyen, "Time Reversal Method and Cross-correlation techniques by normal mode theory: a 3-point problem".

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Work funded by institutional support at the Los Alamos National Laboratory

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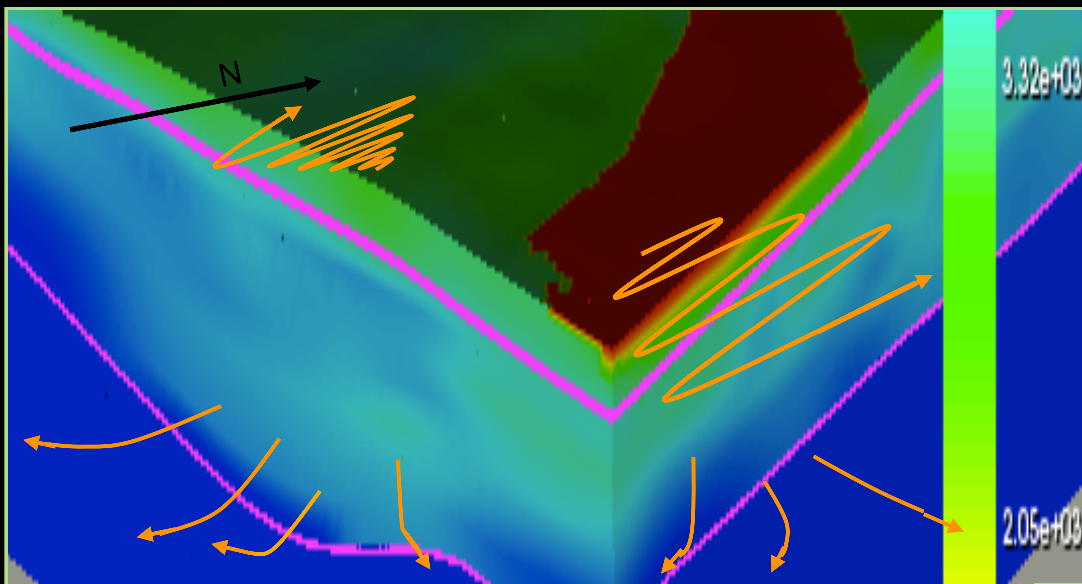
Challenges



BOX	NEX_XI	NER	NSPEC_AB	NPROC	dt		resolution			CPUU-hr/1000se tpsjhf	Execution time
					hor	vert.	hor.	vert.	abs/		
BOX1	192	47	4,672	36	0.009				2s	8	Nstep=100,100 **22h**
-	192	47	-	-						2.7	Nstep=100,100 **7h45**
-	384	47									
-	384	94	28,416	-					1s	47	Nstep=200,100 **263h=11days**
-	576	141	85,824	-						42	Nstep=300,100 **346h=14.5days**
BOX2	80	47	29,200	1	.009	.007	0.8Hz	0.9Hz	0.56Hz		
BOX2 4-1	192	141	9,536	36							
BOX2 4-2	192	214	9,920	36	0.003	0.002	2Hz	3Hz	1.41Hz	5.172	Nstep=300,100 **43h=1.75days**
BOX2	512	215	56,320	64	0.0015	0.0015	5Hz	4.7Hz	3.35Hz		
BOX2	512		43,264	64							
BOX2	528	236	24,436	121	0.0014	0.002	5.6Hz	5Hz	3.35Hz		Nstep=692,400

- Data coverage
- Velocity model
- Loss of information
- Computational limit
  - Max frequency 3.35Hz

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