Supershear Rupture Velocity in Earthquakes

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Acknowledgement

Most of the material in this talk is from:

Direct Observation of Earthquake Rupture Propagation in the 2004 Parkfield, California, Earthquake

Jon B. Fletcher, Paul Spudich, and Lawrence M. Baker

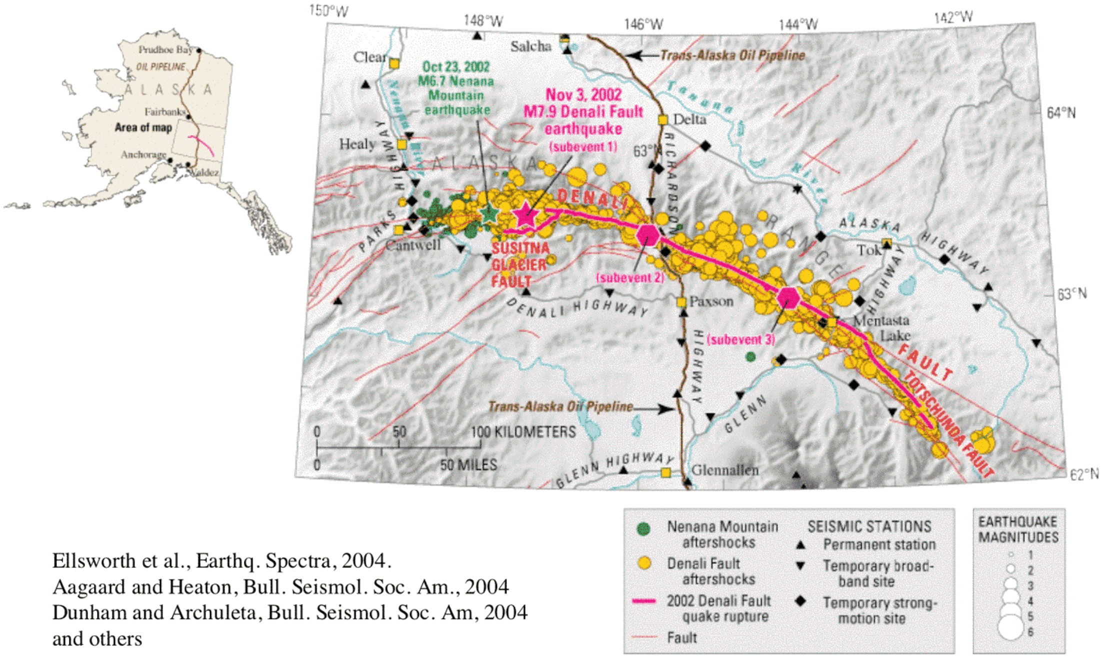
submitted, Science

Apologies

In some figures the rupture travels to the right and in others to the left. Sorry.

Several recent large to very large earthquakes have evidence of supershear rupture velocity

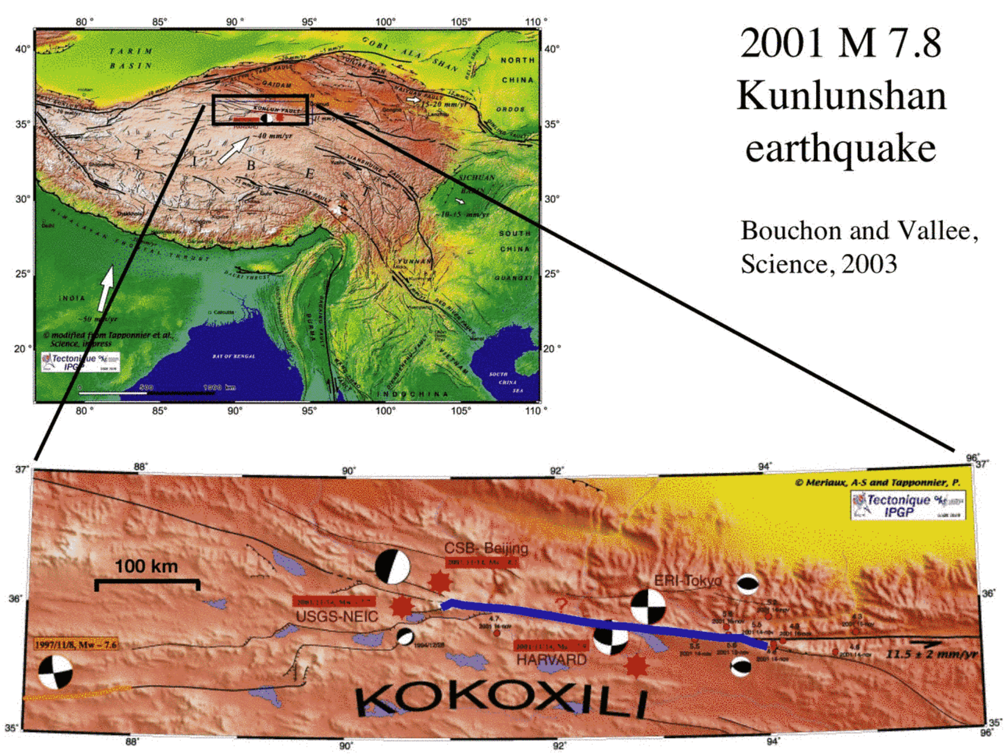
2002 M 7.8 Denali earthquake



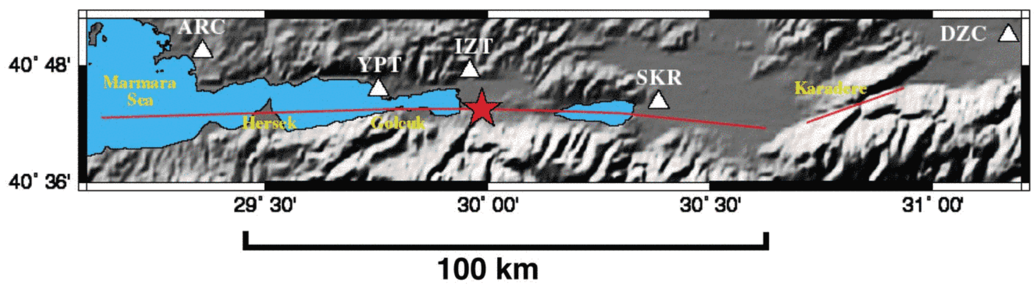
Ellsworth et al., Earthq. Spectra, 2004.
Aagaard and Heaton, Bull. Seismol. Soc. Am., 2004
Dunham and Archuleta, Bull. Seismol. Soc. Am, 2004
and others
.

2001 M 7.8 Kunlunshan earthquake

Bouchon and Vallee, Science, 2003

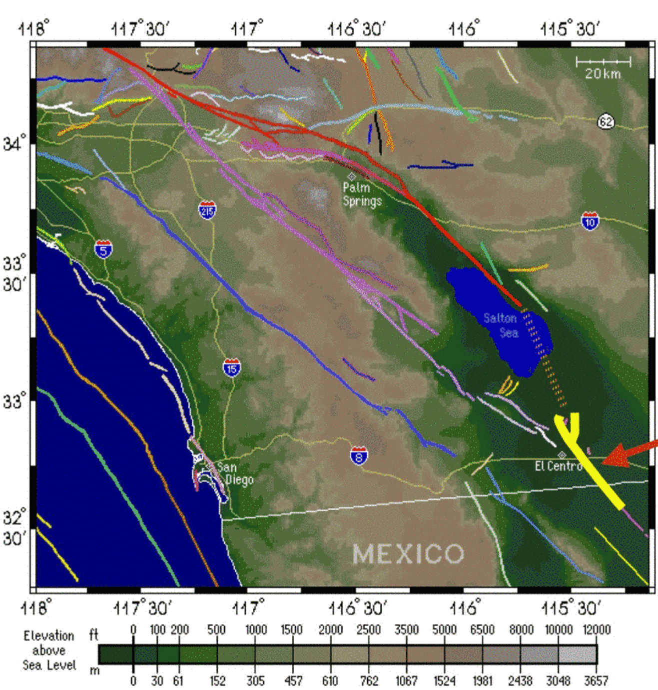


1999 Kocaeli (Izmit), Turkey, earthquake M7.4



Bouchon et al., Geophys. Res. Lets., 2001,
Bouchon et al. Bull. Seismol. Soc. Am., 2002
Sekiguchi et al. Bull. Seismol. Soc. Am., 2002,
disputed: DeLouis et al. Bull. Seismol. Soc. Am, 2002.

1979 M6.5 Imperial Valley earthquake



Archuleta, Bull. Seismol. Soc. Am, 1984

Spudich and Cranswick, BSSA, 1984

Some evidence for supershear rupture velocity in

1992 M 7.2 Landers, California, earthquake
Peyrat, Olsen, and Madariaga, J. Geophys. Res, 2001

1999 M 7.2 Duzce, Turkey earthquake
Bouchon et al., Geophys. Res. Lets., 2001
Bilgoren et al., Geophys. Res. Lets., 2004

Several recent large strike-slip earthquakes show evidence of supershear rupture velocity.

There is independent evidence that large (M>7.3) earthquakes have unexpectedly small high-frequency ground motions (still being debated).

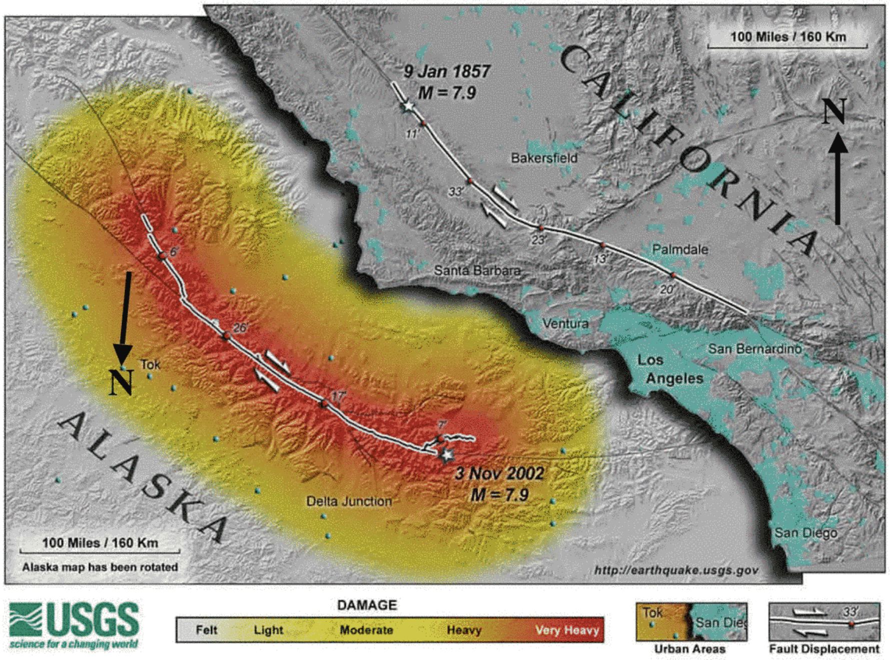
Questions

Could supershear rupture velocity be associated with reduced high-frequency ground motions?

Is supershear rupture velocity the *general rule* in large strike-slip earthquakes?

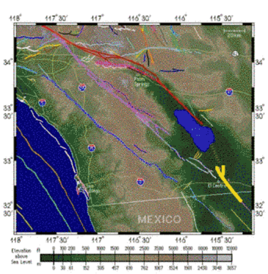
Is supershear rupture velocity *limited* to *large* strike-slip earthquakes?

Comparison of 2002 Denali (rotated) and 1857 Ft. Tejon rupture lengths

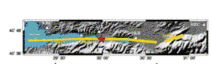


All quakes on same scale

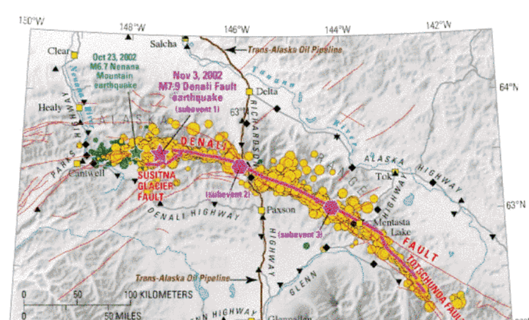
Imperial Valley M6.5

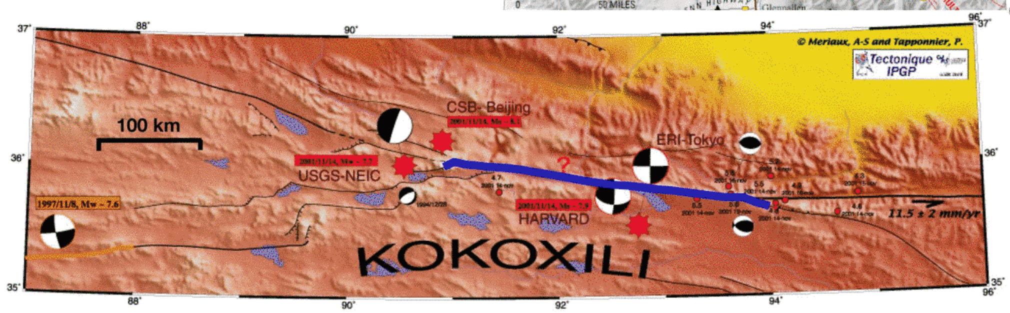


Kocaeli/Izmit M7.4

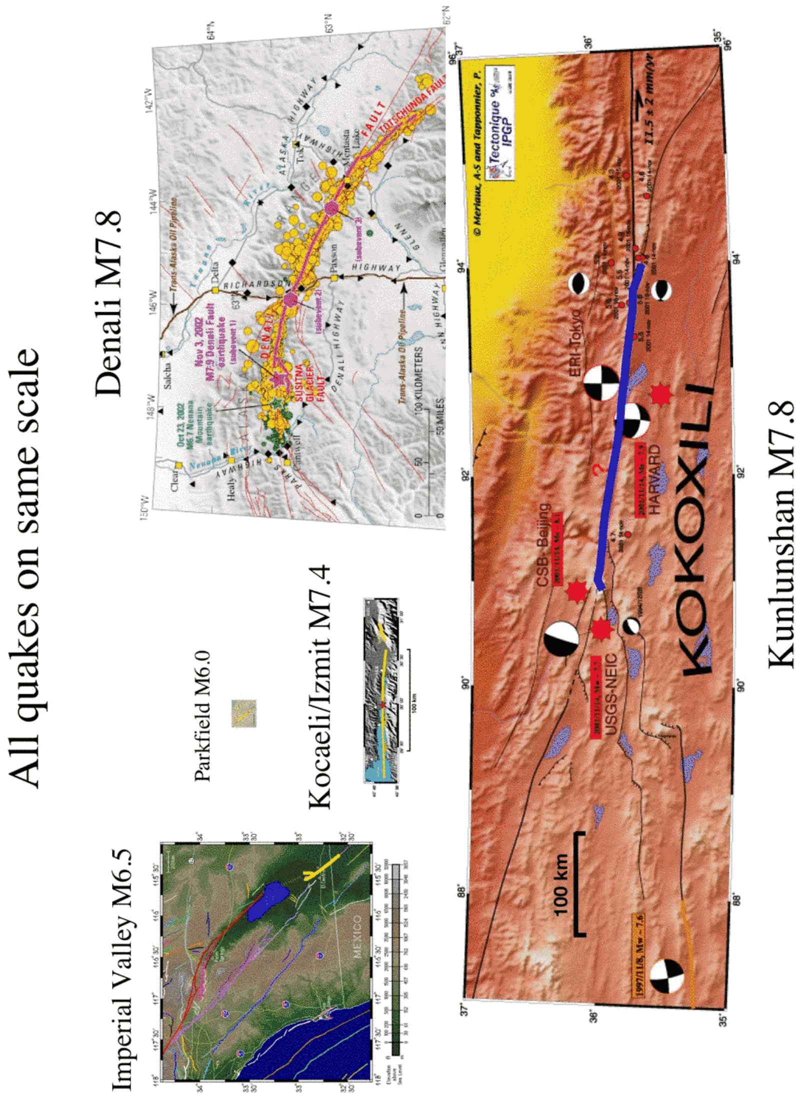


Denali M7.8





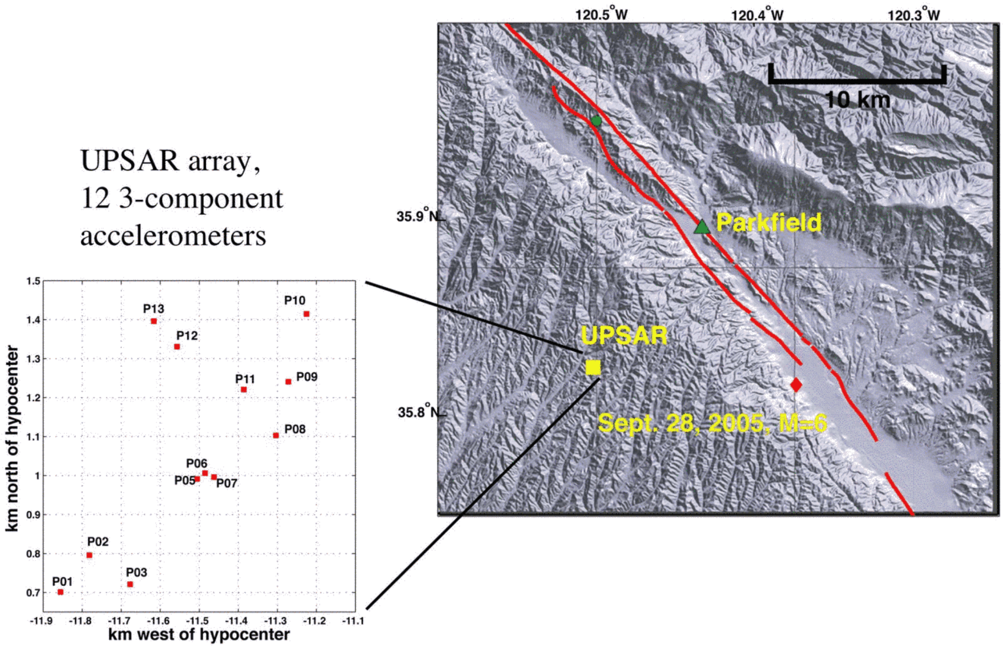
Kunlunshan M7.8


All quakes on same scale
Denali M7.8
Parkfield M6.0
Kocaeli/Izmit M7.4
Imperial Valley M6.5
Kunlunshan M7.8
KOKOXILI
100 km
CSB-Beijing
ERI-Tokyo
HARVARD
USGS-NEIC

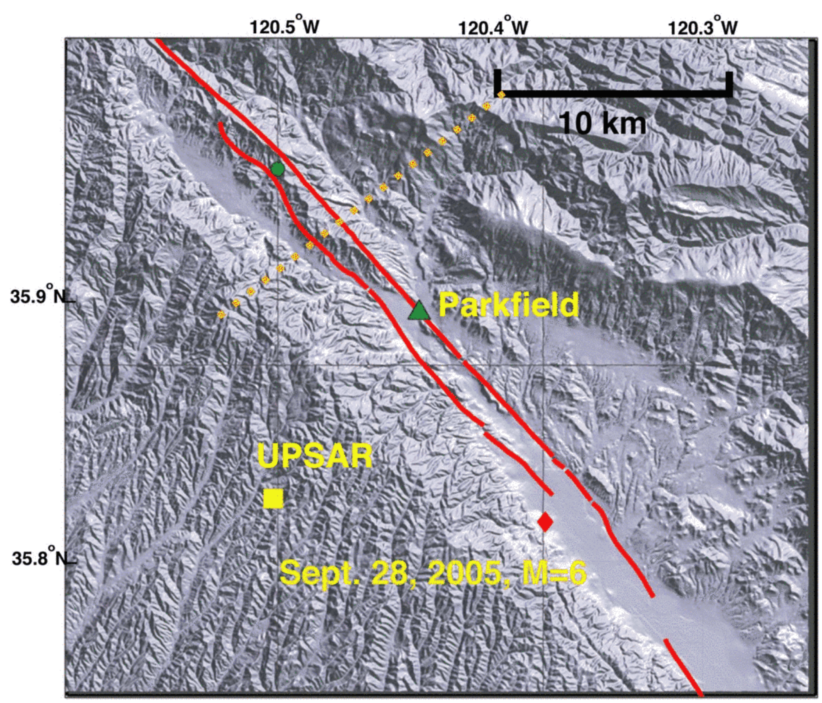

NEVADA
CALIFORNIA
PARKFIELD
Pacific Ocean
Los Angeles
San Diego
Bakersfield
Fresno
Sacramento
San Francisco
Sutter Buttes

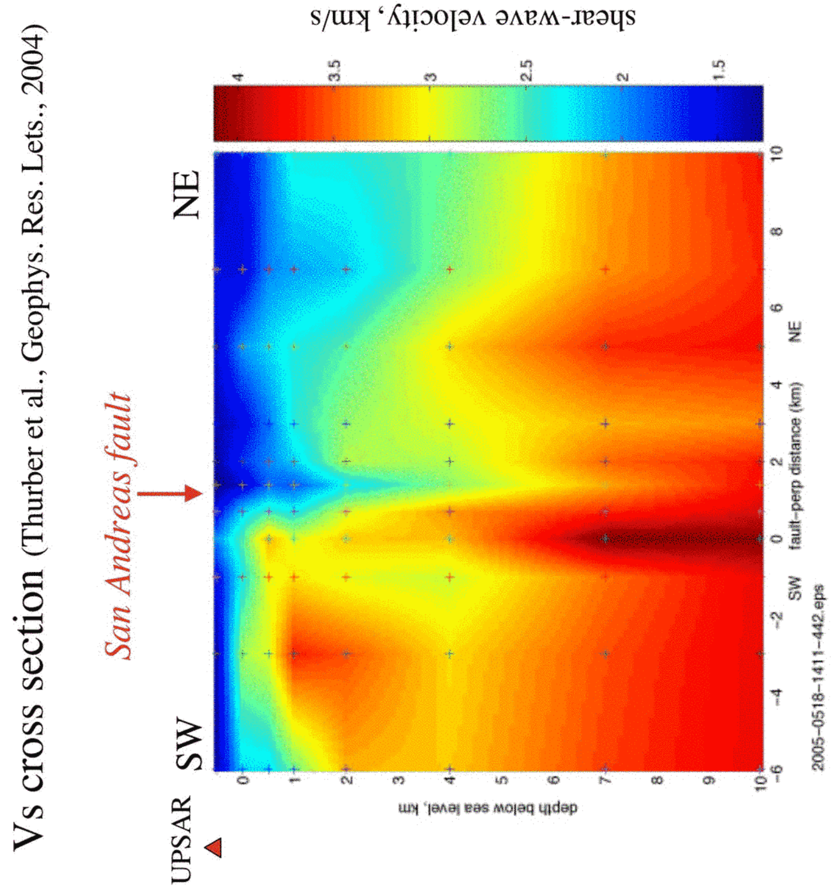
Location of the UPSAR short-baseline array

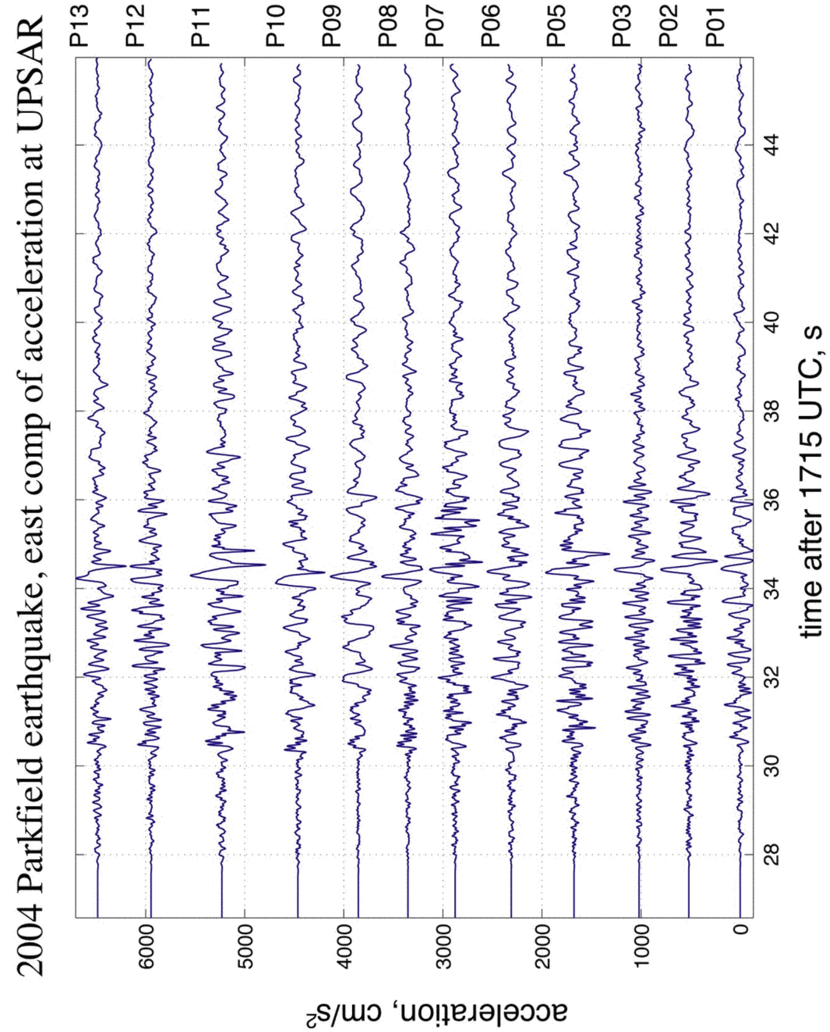
UPSAR array,
12 3-component
accelerometers



Location of Vs cross section




Vs cross section (Thurber et al., Geophys. Res. Lets., 2004)
San Andreas fault
SW
NE
UPSAR
shear-wave velocity, km/s
depth below sea level, km
fault-perp distance (km)
2005-0518-1411-442.eps


2004 Parkfield earthquake, east comp of acceleration at UPSAR
P13
P12
P11
P10
P09
P08
P07
P06
P05
P03
P02
P01
acceleration, cm/s²
time after 1715 UTC, s

For a particular time window of the data, find the propagation direction (vector slowness) of the best fitting plane wave

This vector slowness is assumed to be that which maximizes the average cross-correlation of all station pairs

Plane wave: $u(t - \vec{s} \bullet \vec{x}),\ \vec{s} = (s_E\ s_N\ s_z)$

$$s_z^2 = \left(1/v_s\right)^2 - s_E^2 - s_N^2,\ v_s = \text{shear wave speed}$$

a_j = accelerogram time series, station j at location $\vec{x}_j$

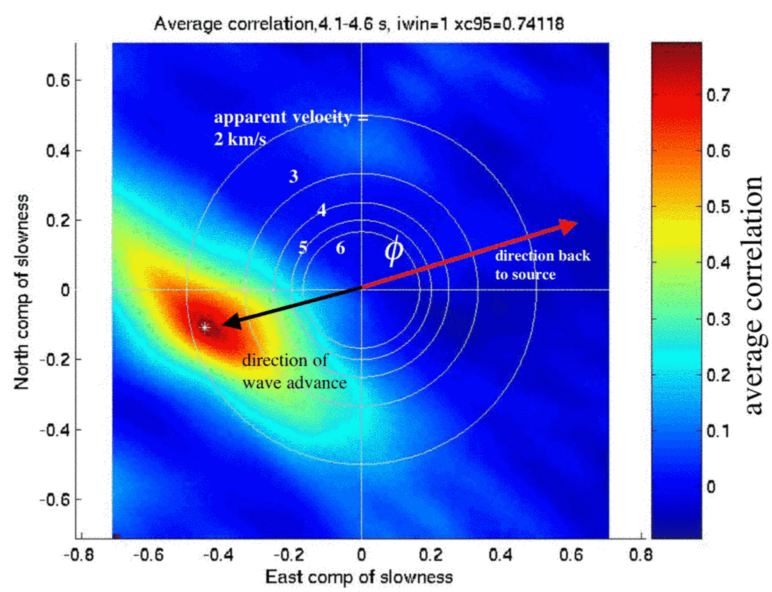
$$\text{Cross correlation } C_{ij}(\vec{s}) = \left[\frac{\left(a_i(t-\vec{s}\bullet\vec{x}_i),a_j(t-\vec{s}\bullet\vec{x}_j)\right)^2}{\left(a_i(t-\vec{s}\bullet\vec{x}_i),a_i(t-\vec{s}\bullet\vec{x}_i)\right)^2+\left(a_j(t-\vec{s}\bullet\vec{x}_j),a_j(t-\vec{s}\bullet\vec{x}_j)\right)^2}\right]^{\frac{1}{2}}$$

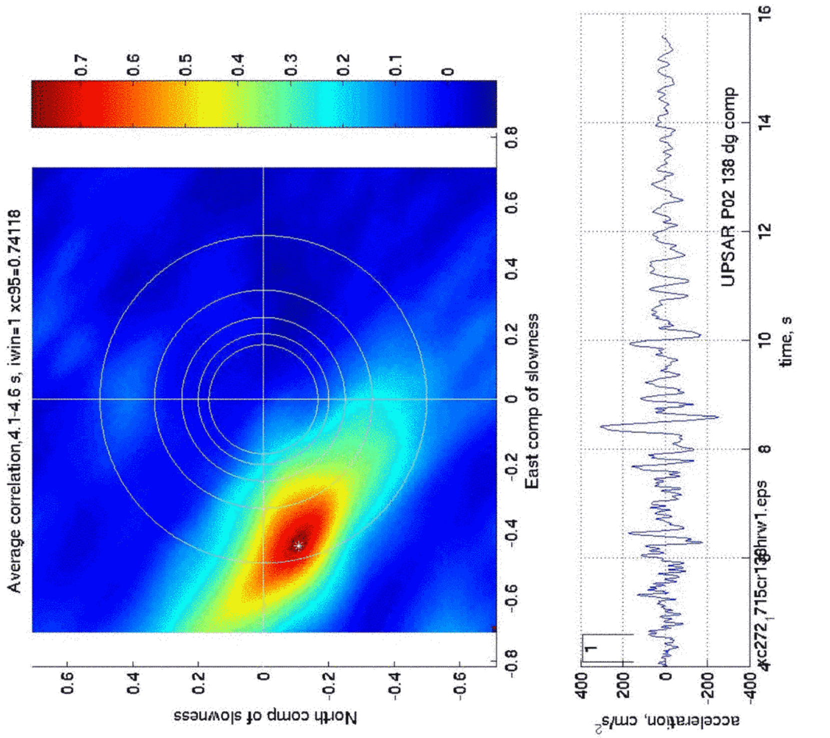
$$\text{Average cross correlation } C(\vec{s}) = \frac{1}{N}\sum_i\sum_j C_{ij}(\vec{s})$$

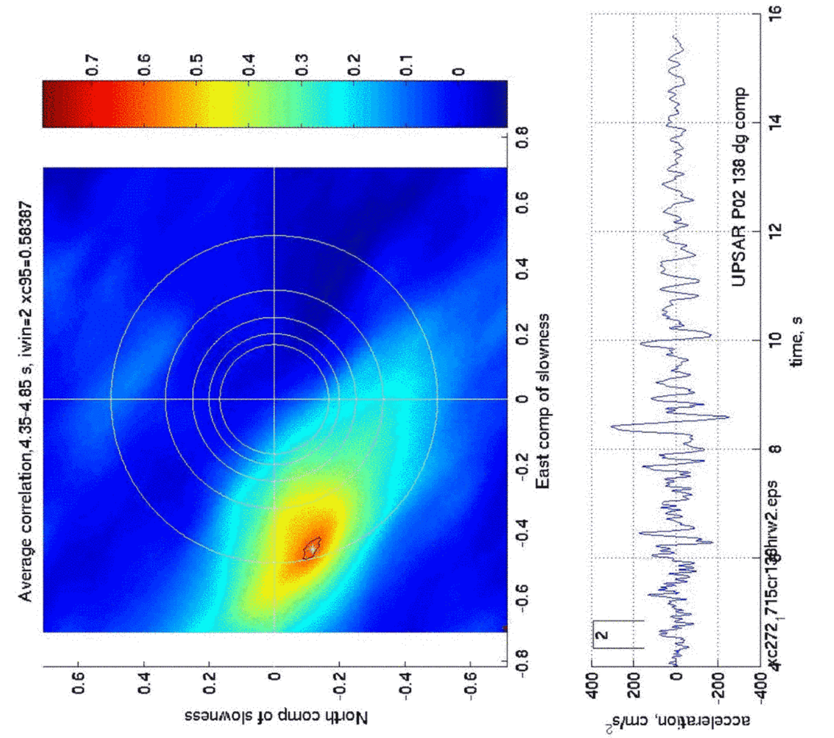
Example: 0.5 s window around hypocentral S wave

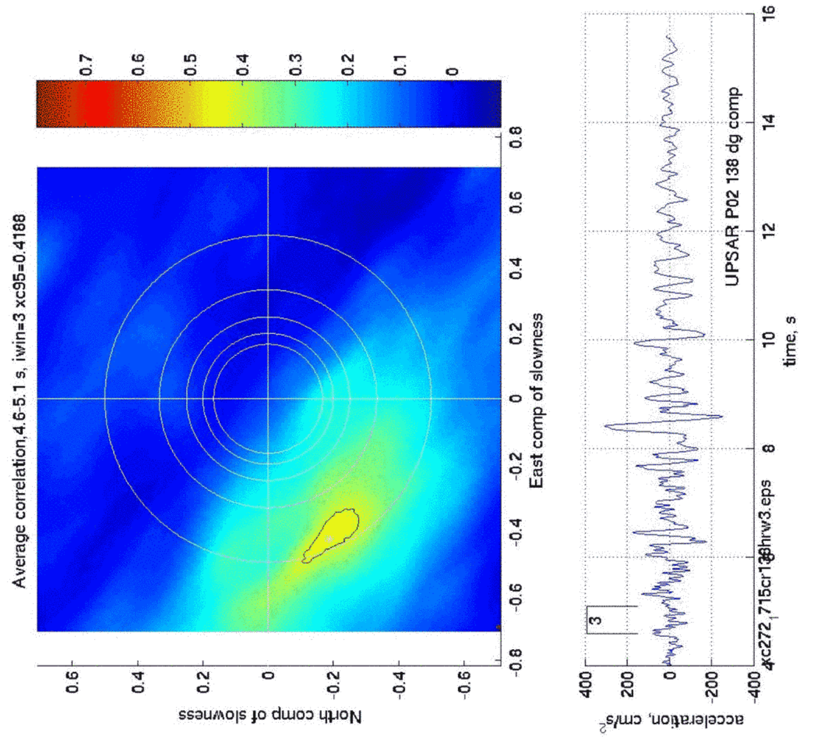
ϕ = azimuth back to source = $\tan^{-1}\left(s_E / s_N\right)$

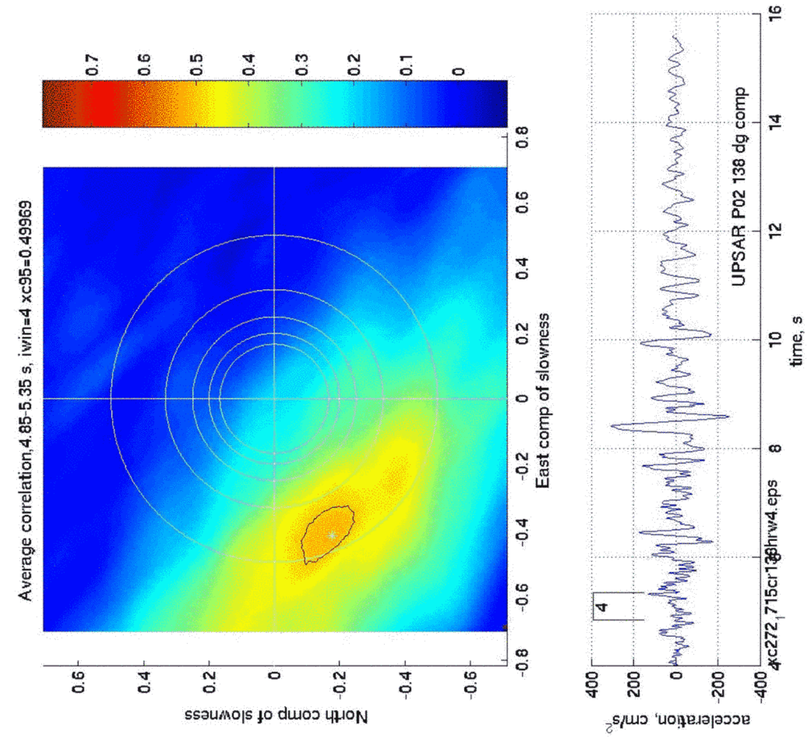
Apparent velocity = horizontal phase velocity = $\left(s_E^2 + s_N^2\right)^{-1}$

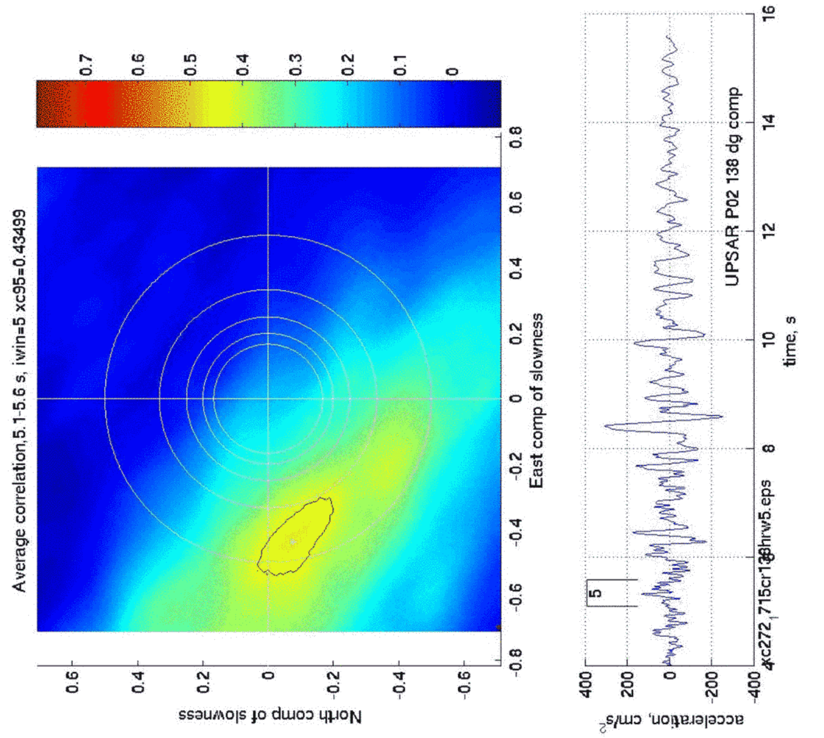


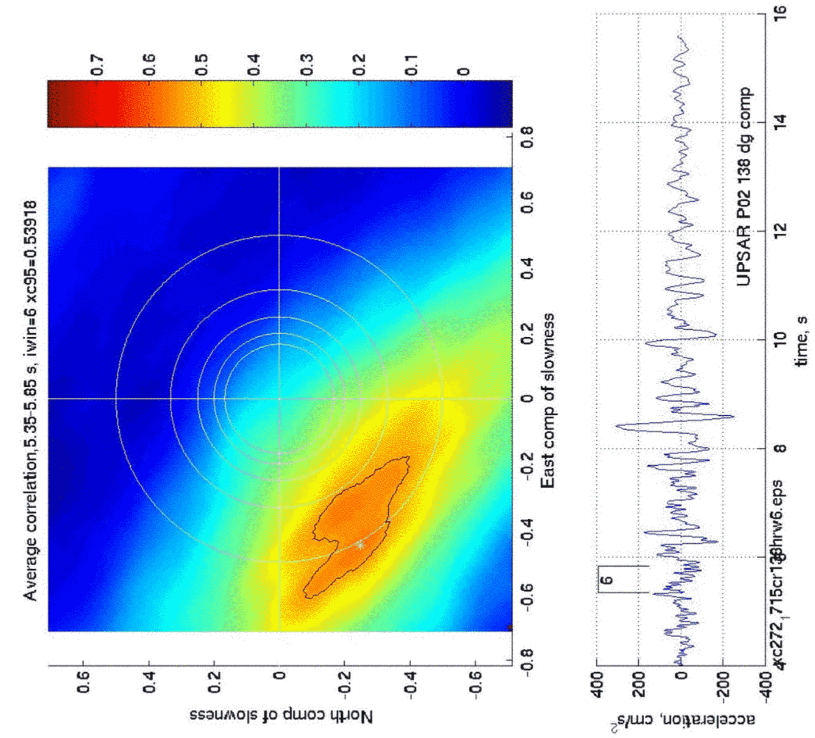

Average correlation,4.1-4.6 s, iwin=1 xc95=0.74118
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
time, s
acceleration, cm/s^2
xc272_715cr138hrw1.eps

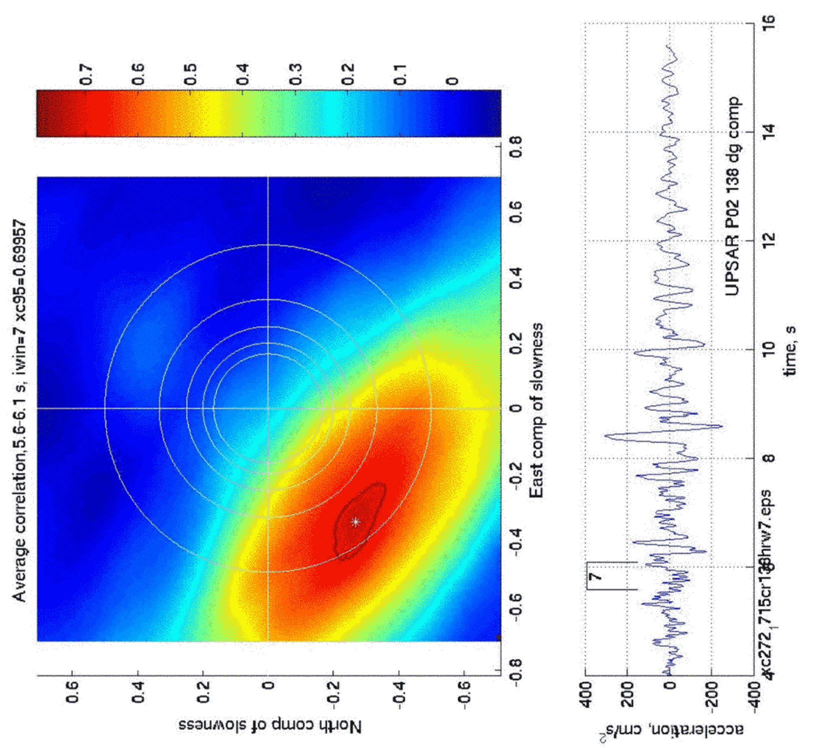

Average correlation,4.35-4.85 s, iwin=2 xc95=0.58387
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
time, s
acceleration, cm/s^2
xc272_715cr138hrw2.eps

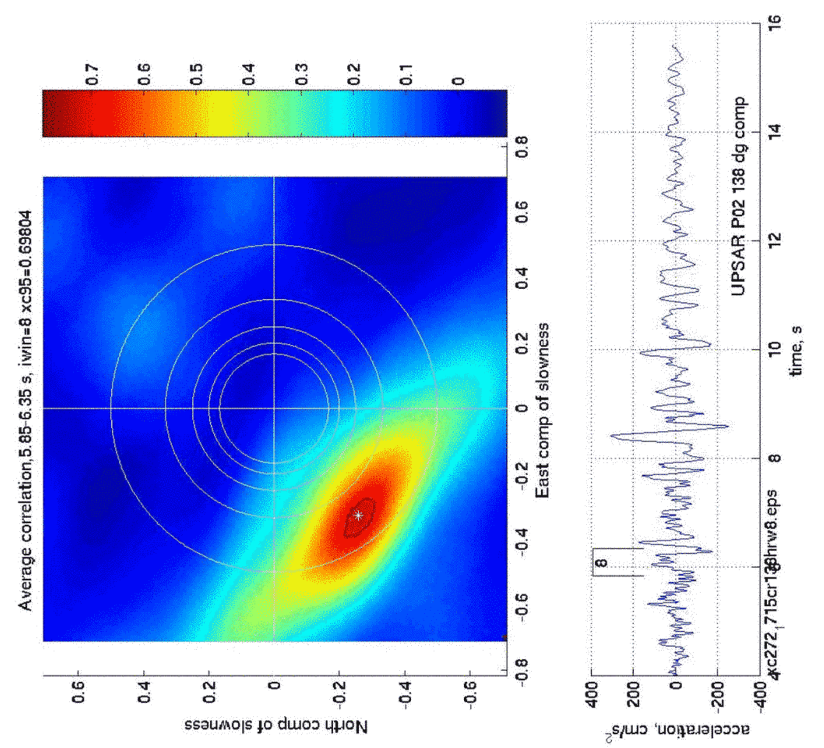

Average correlation,4.6-5.1 s, iwin=3 xc95=0.4188
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
acceleration, cm/s^2
time, s
xc272_715cr138hrw3.eps
3

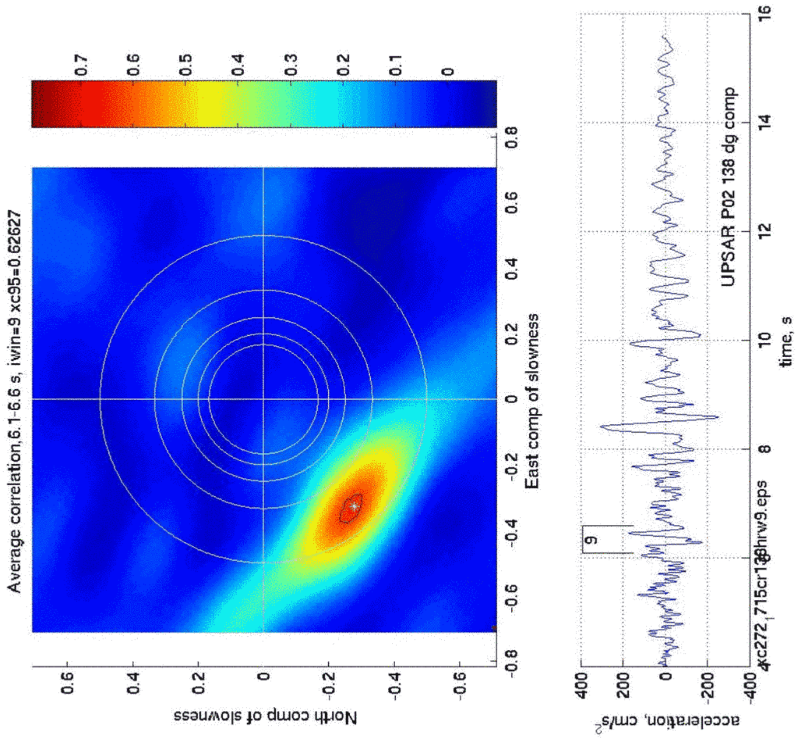

Average correlation,4.85-5.35 s, iwin=4 xc95=0.49969
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
acceleration, cm/s^2
time, s
xc272_715cr138hrw4.eps
4

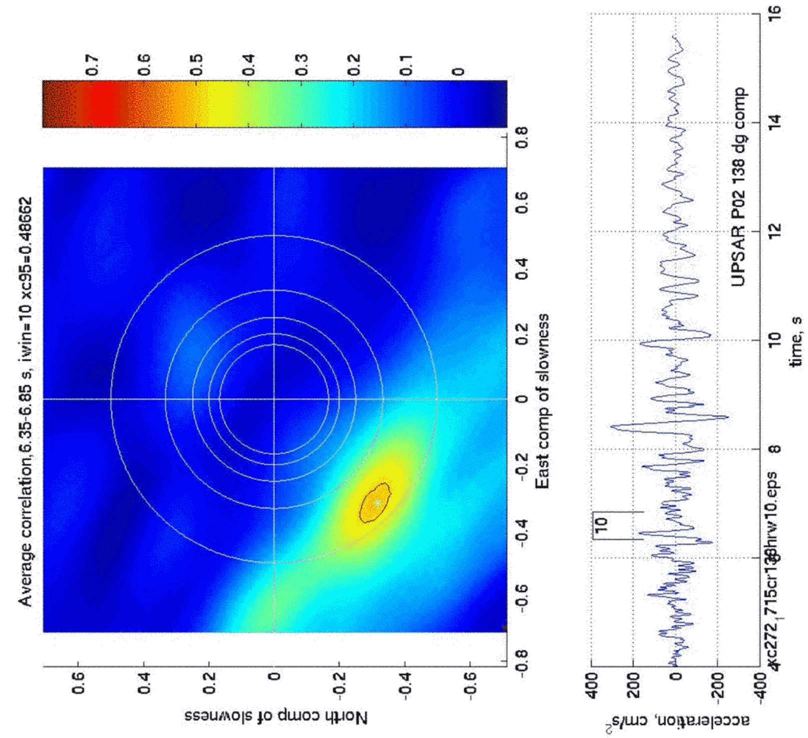

Average correlation,5.1-5.6 s, iwin=5 xc95=0.43499
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
time, s
acceleration, cm/s^2
xc272_715cr138hrw5.eps
5

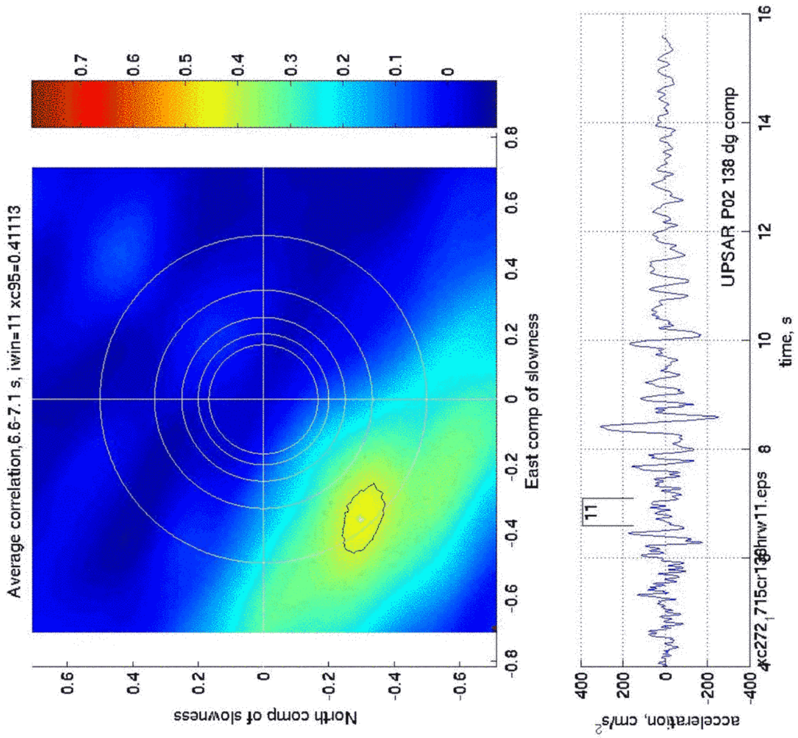

Average correlation,5.35-5.85 s, iwin=6 xc95=0.53918
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
time, s
acceleration, cm/s^2
xc272_715cr138hrw6.eps
6

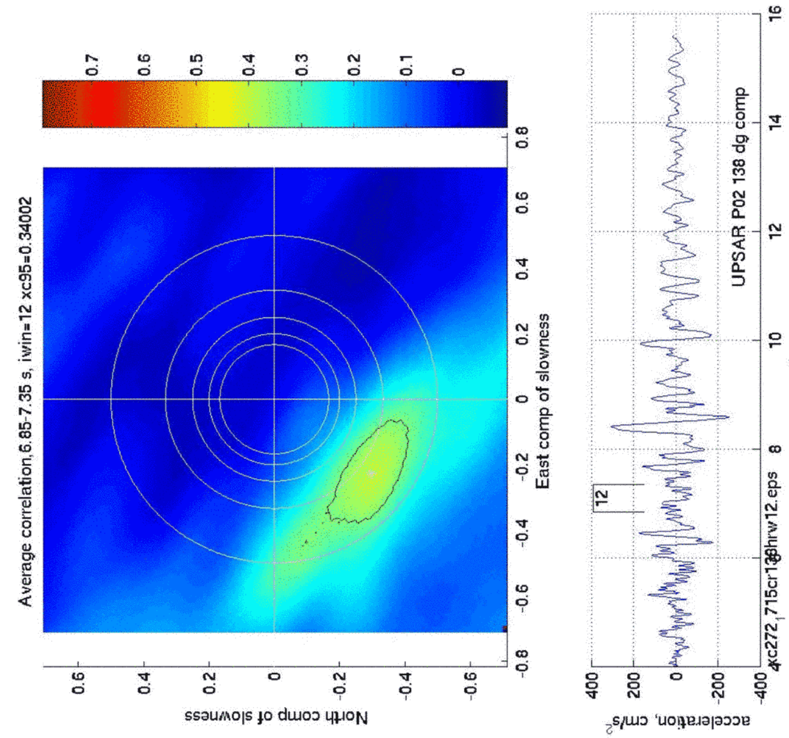

Average correlation,5.6-6.1 s, iwin=7 xc95=0.69957
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
acceleration, cm/s2
time, s
xc272_715cr138hrw7.eps

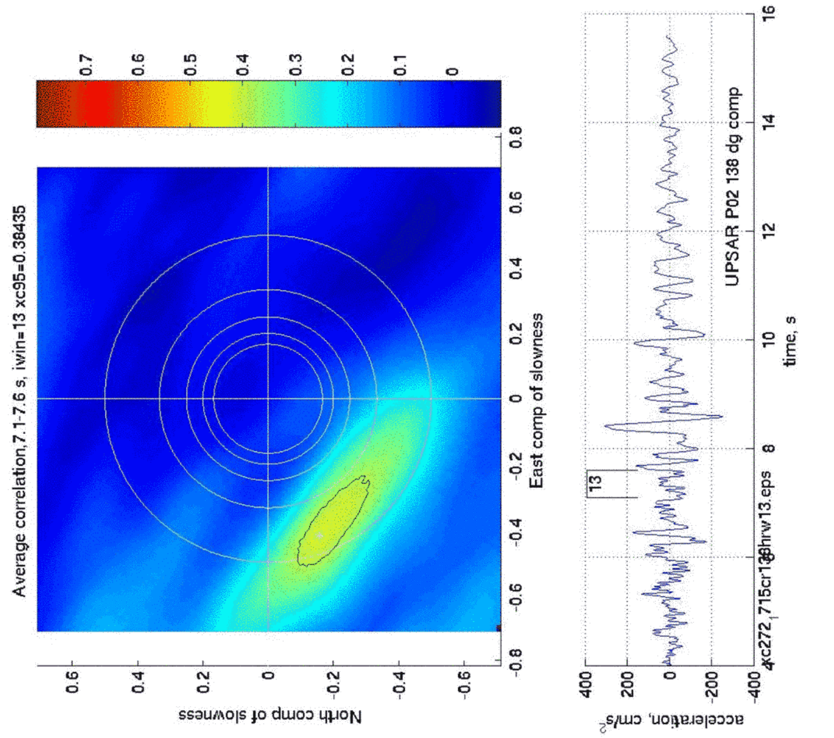

Average correlation,5.85-6.35 s, iwin=8 xc95=0.69804
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
acceleration, cm/s2
time, s
xc272_715cr138hrw8.eps

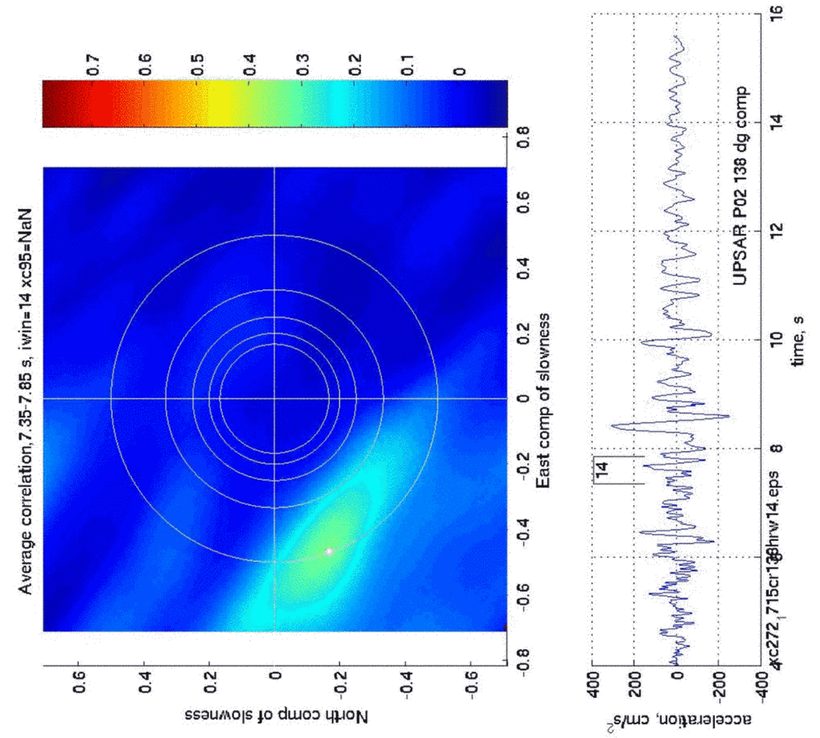

Average correlation,6.1-6.6 s, iwin=9 xc95=0.62627
East comp of slowness
North comp of slowness
UPSAR P02 138 dg comp
time, s
acceleration, cm/s^2
xc272_715cr138hrw9.eps
9

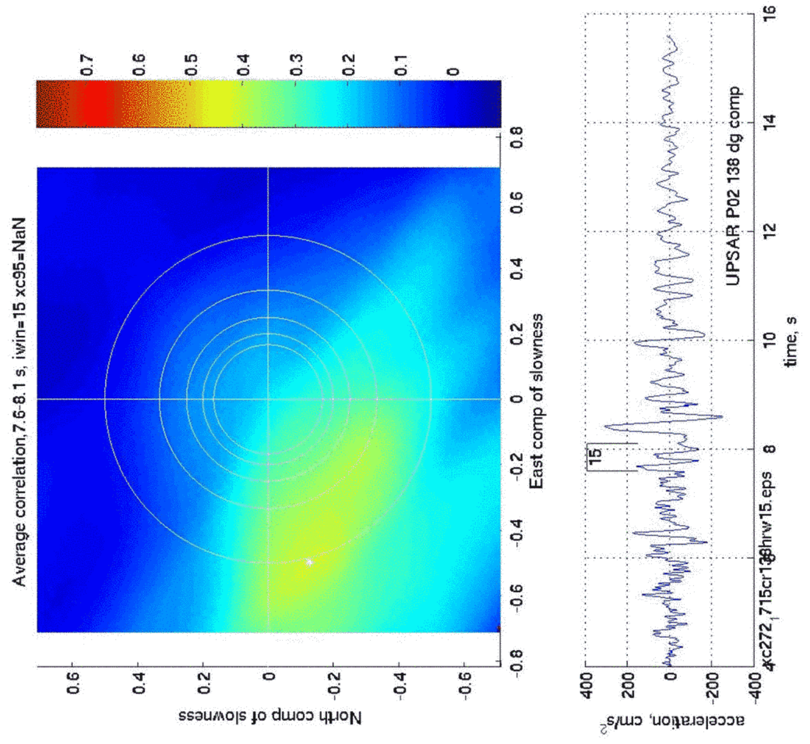

Average correlation,6.35-6.85 s, iwin=10 xc95=0.48662
East comp of slowness
North comp of slowness
UPSAR P02 138 dg comp
time, s
acceleration, cm/s^2
xc272_715cr138hrw10.eps
10

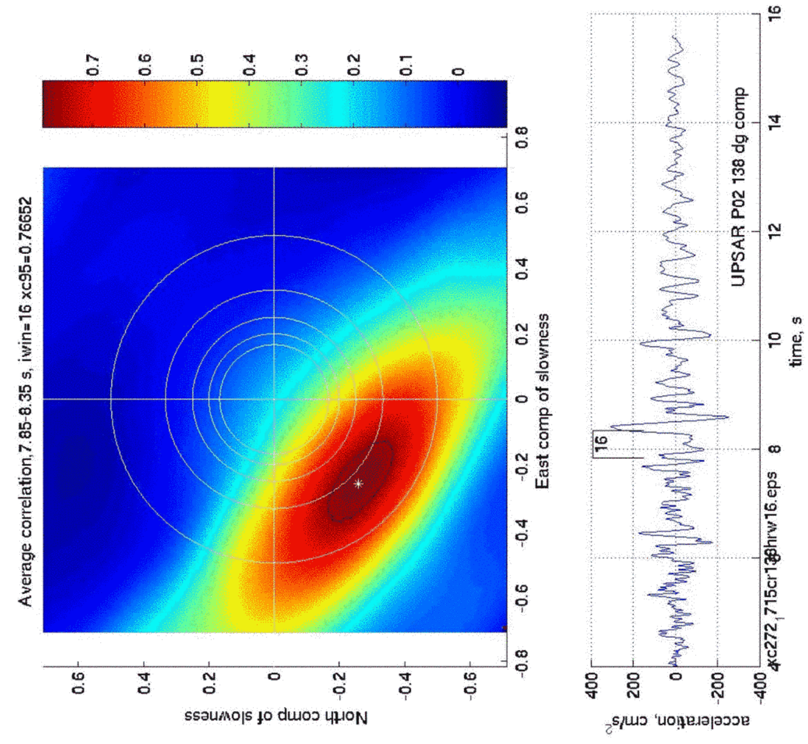

Average correlation,6.6-7.1 s, iwin=11 xc95=0.41113
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
acceleration, cm/s2
time, s
11
xc272_715cr138hrw11.eps

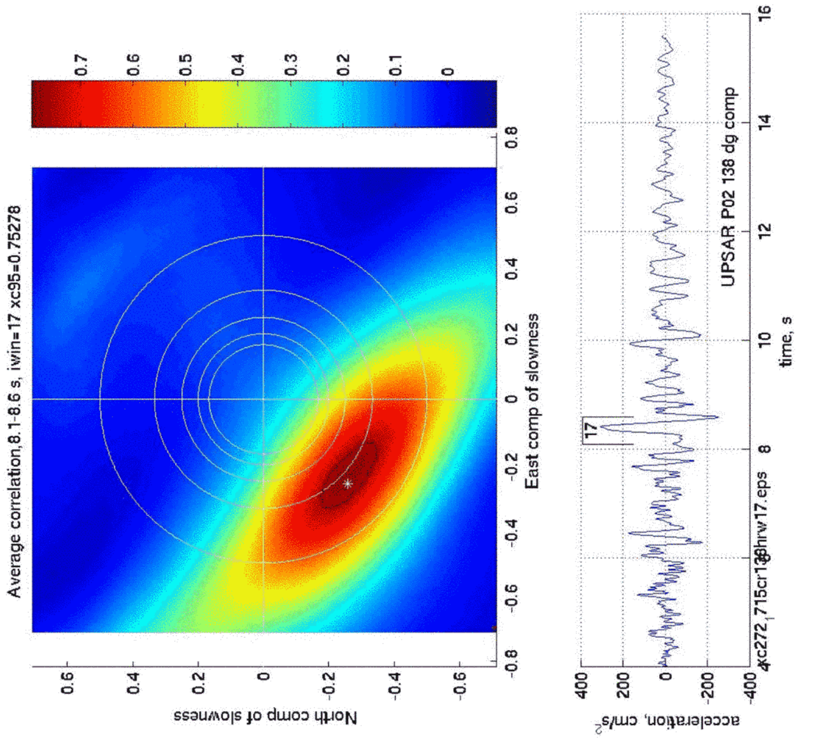

Average correlation,6.85-7.35 s, iwin=12 xc95=0.34002
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
acceleration, cm/s2
time, s
12
xc272_715cr138hrw12.eps


Average correlation,7.1-7.6 s, iwin=13 xc95=0.38435
North comp of slowness
East comp of slowness
13
UPSAR P02 138 dg comp
acceleration, cm/s^2
time, s
xc272_715cr138hrw13.eps

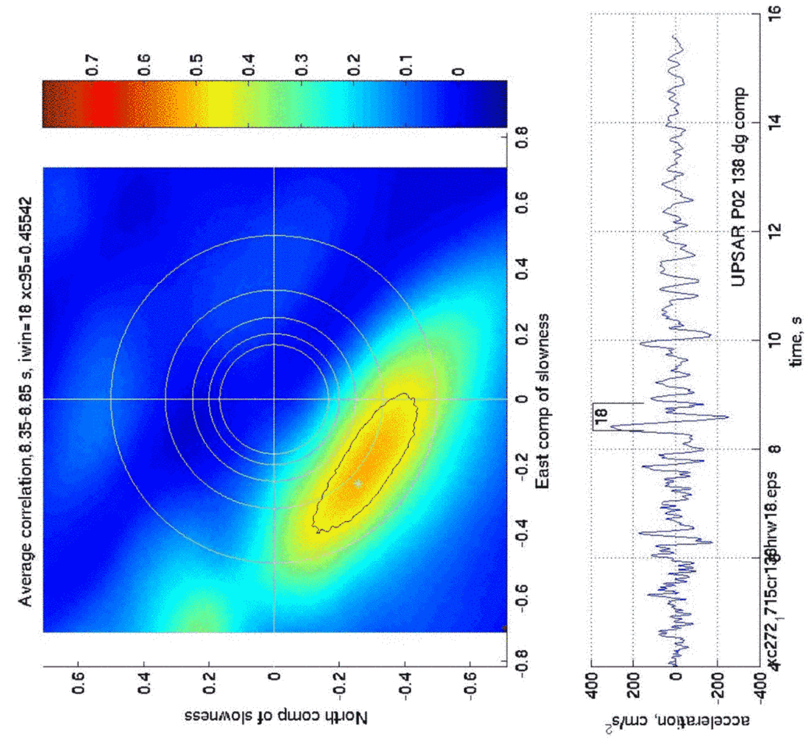

Average correlation,7.35-7.85 s, iwin=14 xc95=NaN
North comp of slowness
East comp of slowness
14
UPSAR P02 138 dg comp
acceleration, cm/s^2
time, s
xc272_715cr138hrw14.eps


Average correlation,7.6-8.1 s, iwin=15 xc95=NaN
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
time, s
acceleration, cm/s2
15
xc272_715cr138hrw15.eps

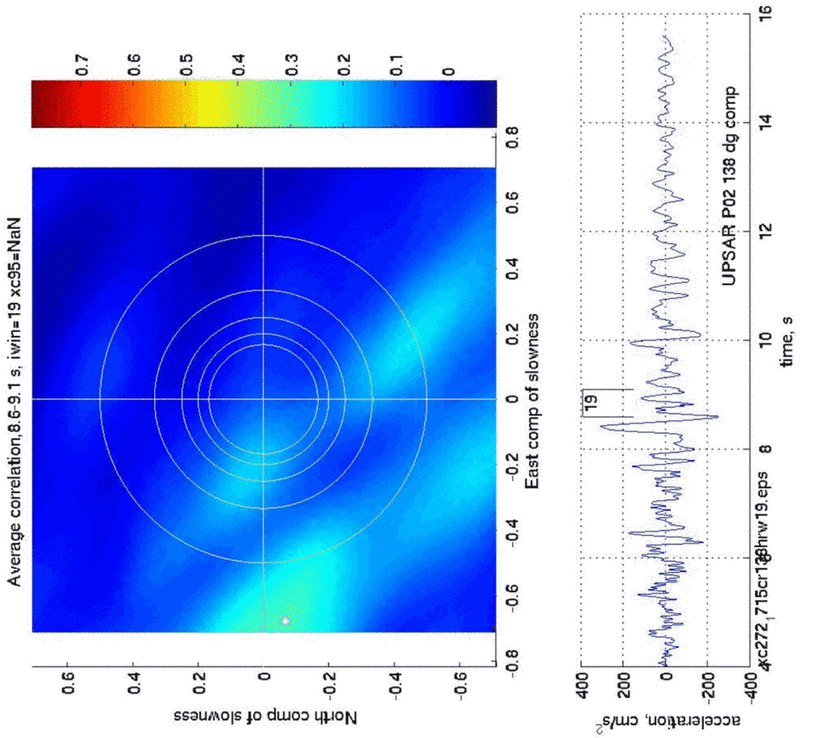

Average correlation,7.85-8.35 s, iwin=16 xc95=0.76652
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
time, s
acceleration, cm/s2
16
xc272_715cr138hrw16.eps

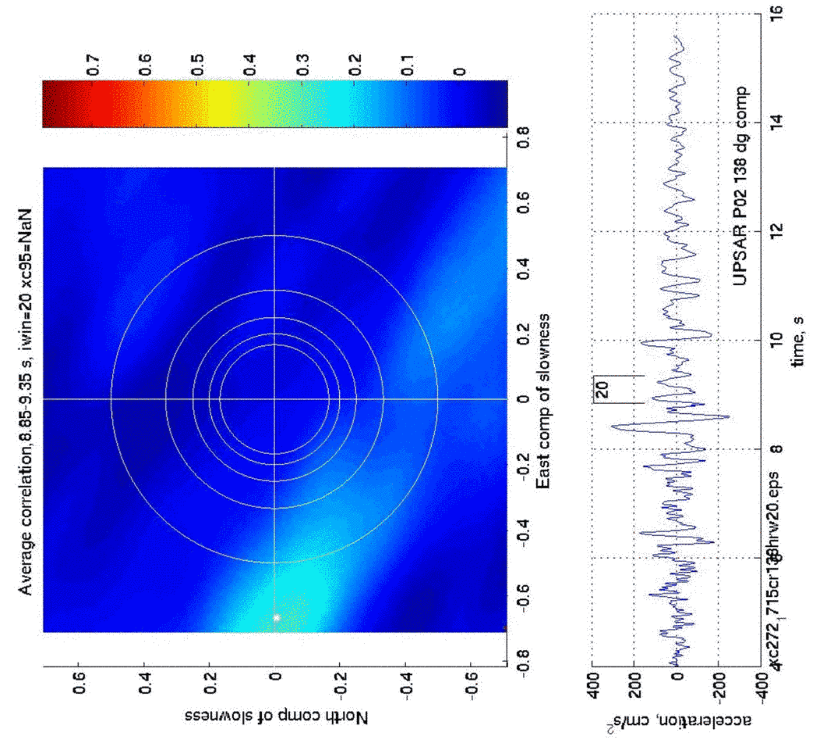


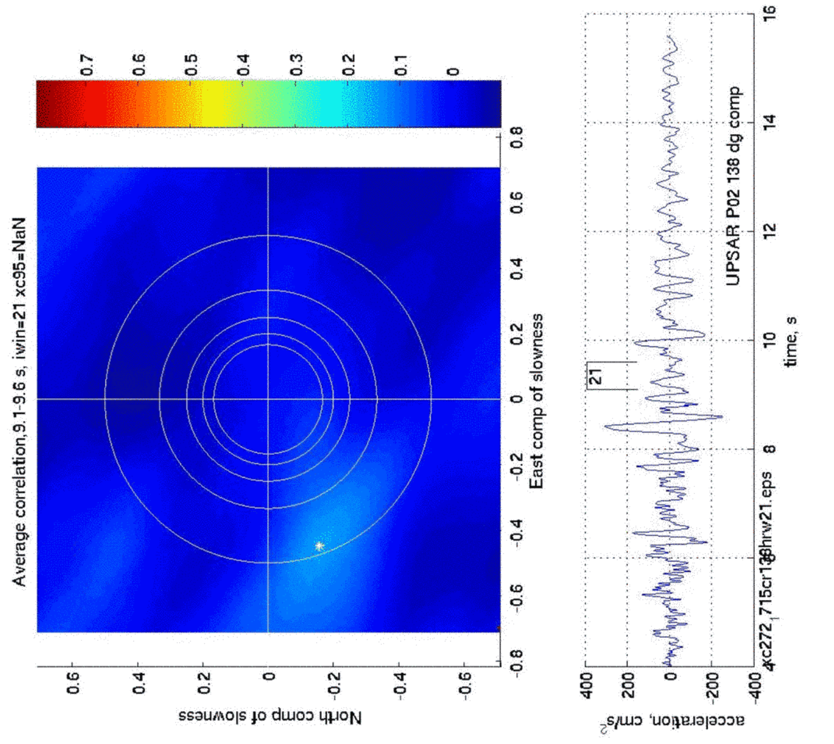
Average correlation,8.1-8.6 s, iwin=17 xc95=0.75278
East comp of slowness
North comp of slowness
17
UPSAR P02 138 dg comp
time, s
acceleration, cm/s^2
xc272_715cr138hrw17.eps

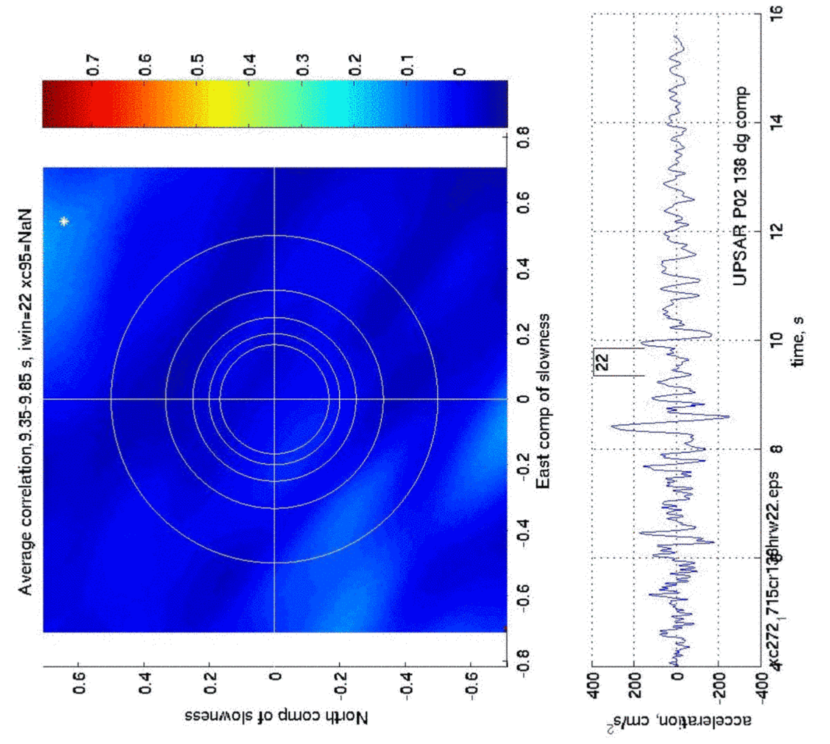


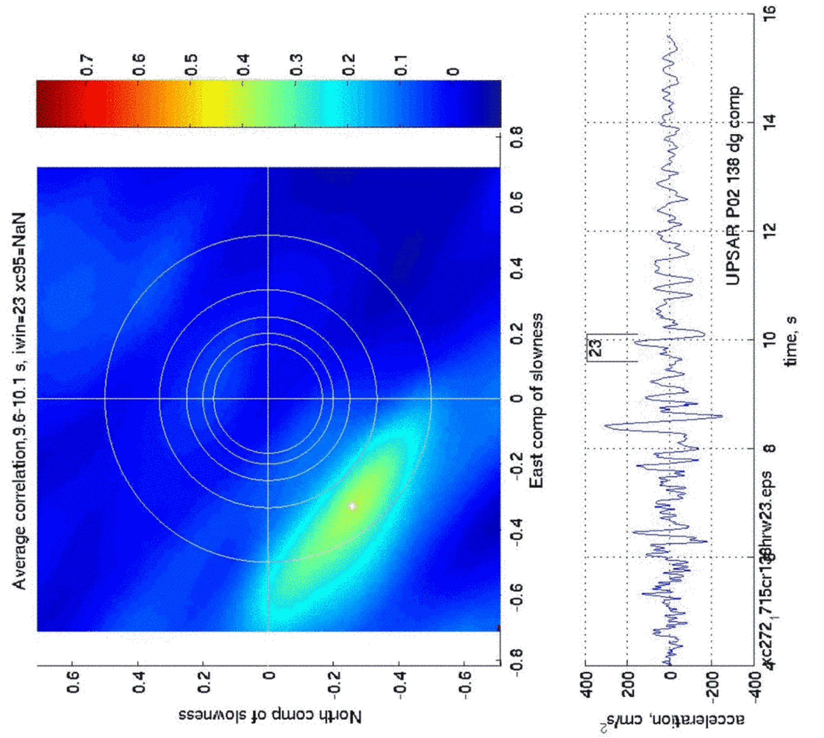
Average correlation,8.35-8.85 s, iwin=18 xc95=0.45542
East comp of slowness
North comp of slowness
18
UPSAR P02 138 dg comp
time, s
acceleration, cm/s^2
xc272_715cr138hrw18.eps

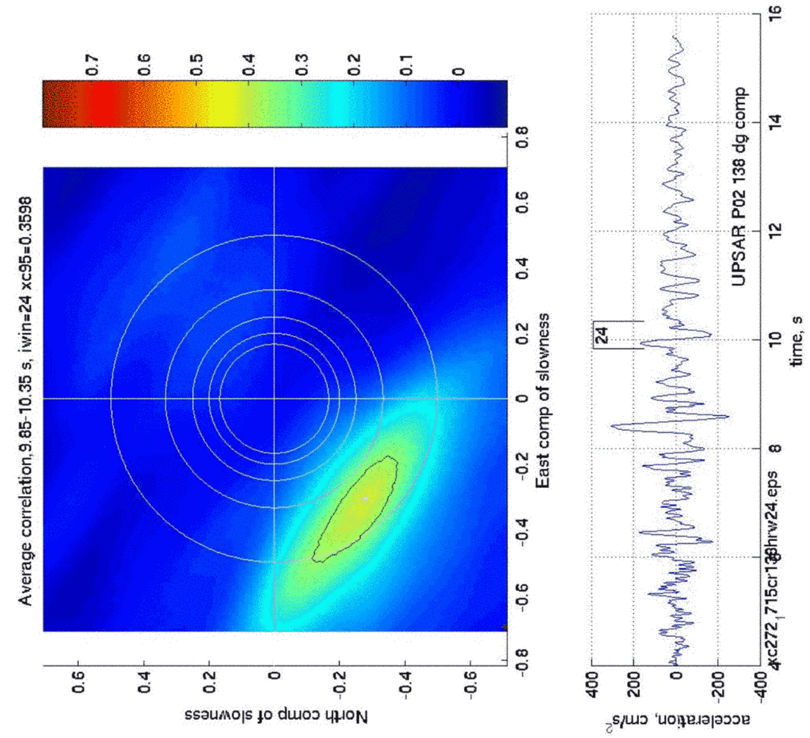

Average correlation,8.6-9.1 s, iwin=19 xc95=NaN
East comp of slowness
North comp of slowness
UPSAR P02 138 dg comp
time, s
acceleration, cm/s2
xc272_715cr138hrw19.eps
19

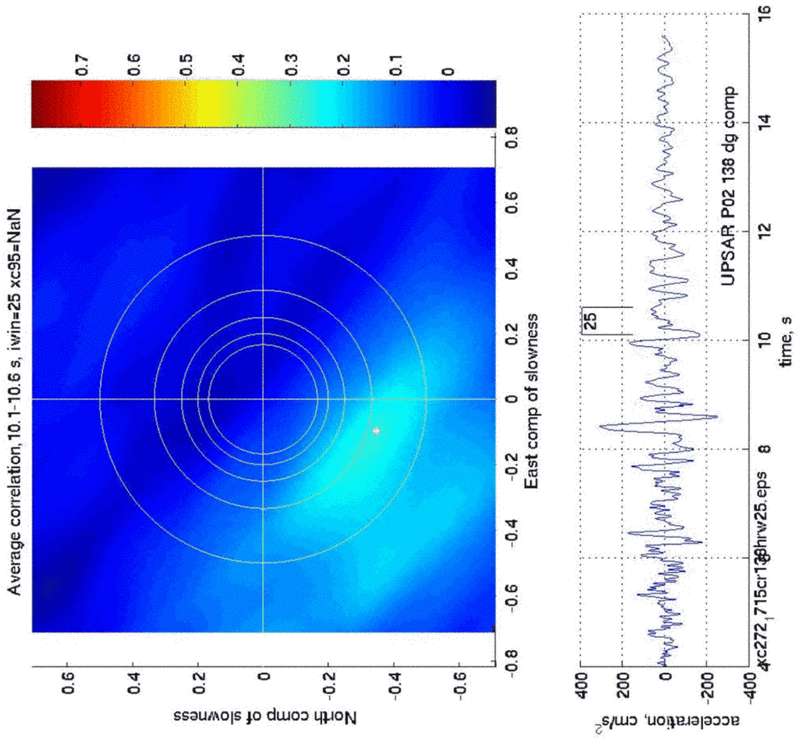

Average correlation,8.85-9.35 s, iwin=20 xc95=NaN
East comp of slowness
North comp of slowness
UPSAR P02 138 dg comp
time, s
acceleration, cm/s2
xc272_715cr138hrw20.eps
20

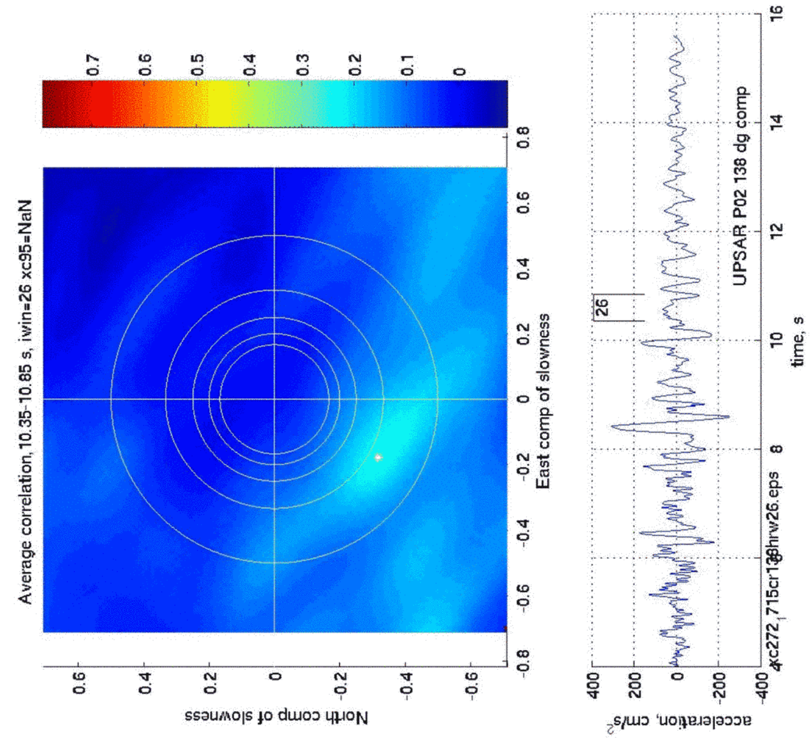

Average correlation,9.1-9.6 s, iwin=21 xc95=NaN
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
acceleration, cm/s^2
time, s
21
xc272_715cr138hrw21.eps

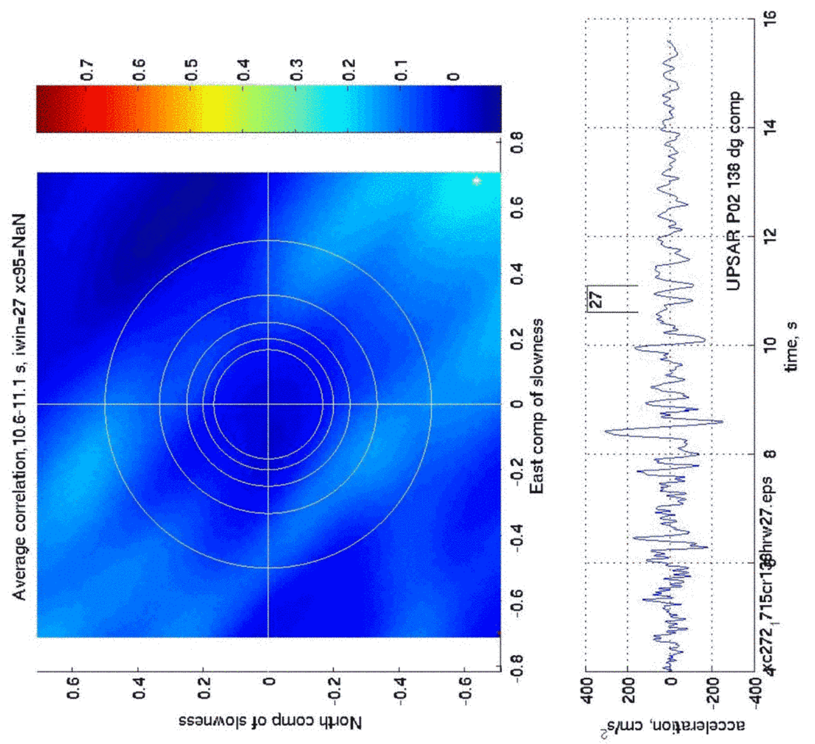

Average correlation,9.35-9.85 s, iwin=22 xc95=NaN
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
acceleration, cm/s^2
time, s
22
xc272_715cr138hrw22.eps


Average correlation,9.6-10.1 s, iwin=23 xc95=NaN
North comp of slowness
East comp of slowness
acceleration, cm/s2
time, s
UPSAR P02 138 dg comp
xc272_715cr138hrw23.eps
23


Average correlation,9.85-10.35 s, iwin=24 xc95=0.3598
North comp of slowness
East comp of slowness
acceleration, cm/s2
time, s
UPSAR P02 138 dg comp
xc272_715cr138hrw24.eps
24


Average correlation,10.1-10.6 s, iwin=25 xc95=NaN
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
25
time, s
acceleration, cm/s^2
xc272_715cr138hrw25.eps


Average correlation,10.35-10.85 s, iwin=26 xc95=NaN
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
26
time, s
acceleration, cm/s^2
xc272_715cr138hrw26.eps


Average correlation,10.6-11.1 s, iwin=27 xc95=NaN
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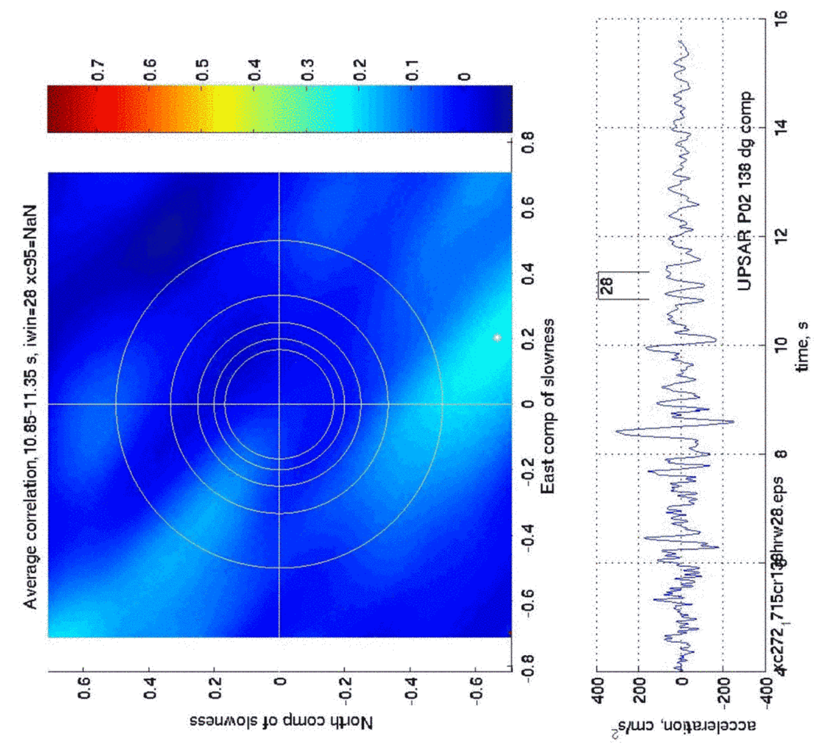
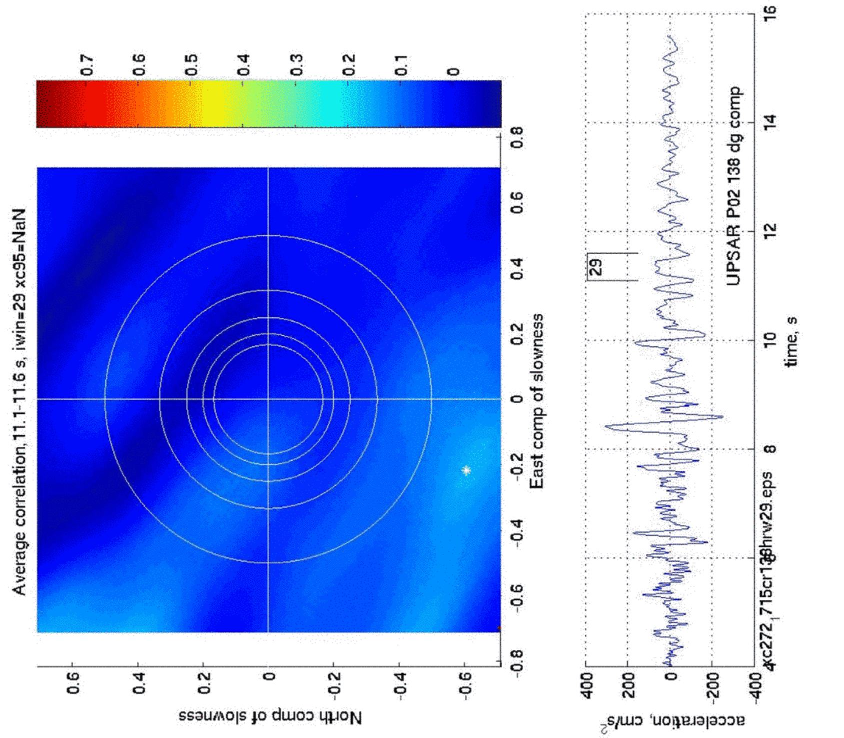
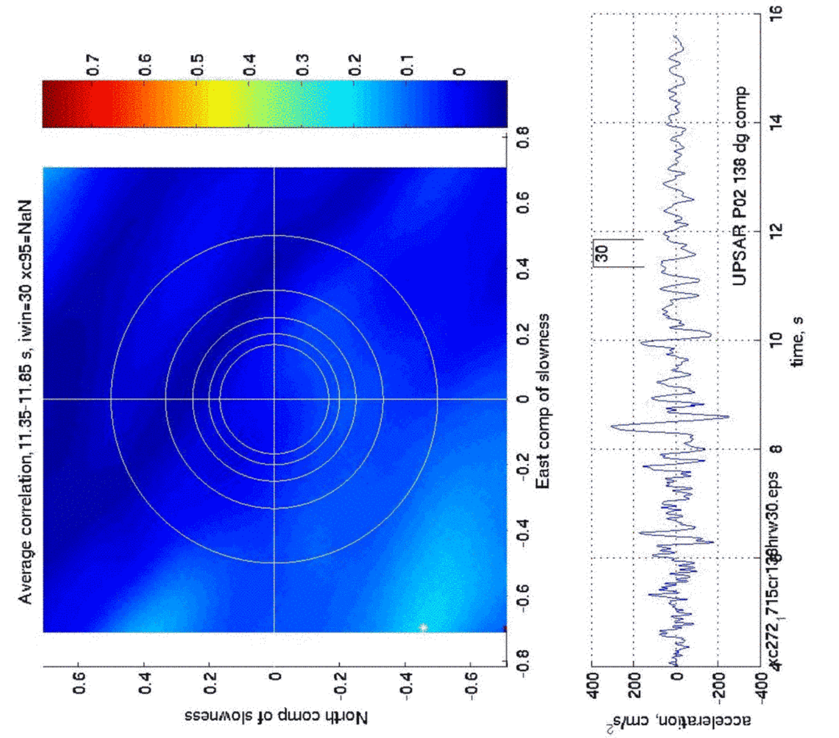
East comp of slowness
27
UPSAR P02 138 dg comp
acceleration, cm/s^2
time, s
xc272_715cr138hrw27.eps


Average correlation,10.85-11.35 s, iwin=28 xc95=NaN
North comp of slowness
East comp of slowness
28
UPSAR P02 138 dg comp
acceleration, cm/s^2
time, s
xc272_715cr138hrw28.eps

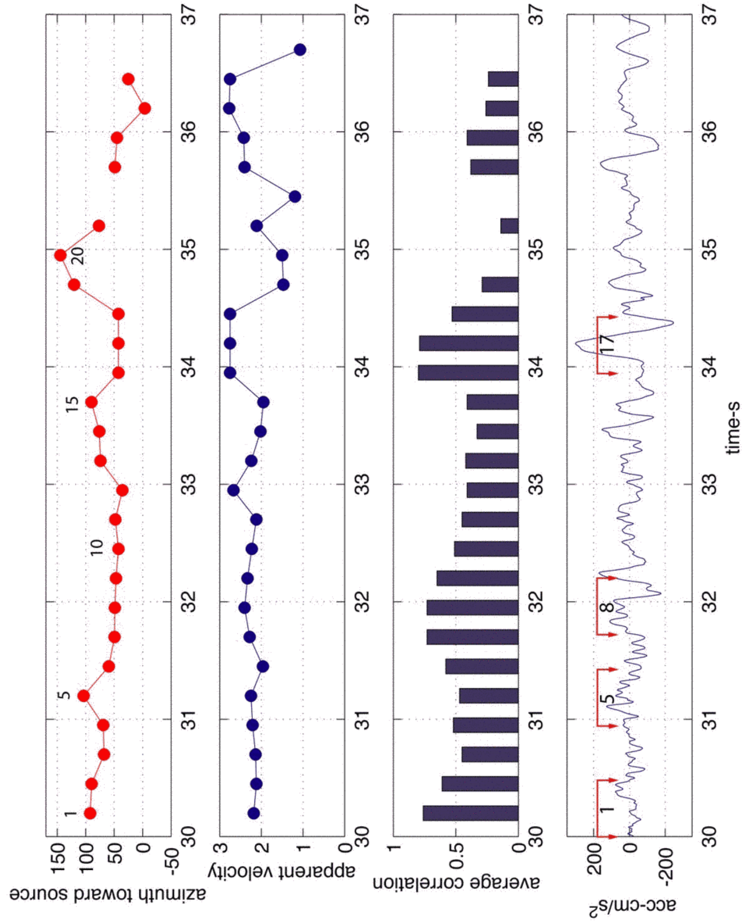


Average correlation,11.1-11.6 s, iwin=29 xc95=NaN
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
acceleration, cm/s^2
time, s
29
xc272_715cr138hrw29.eps

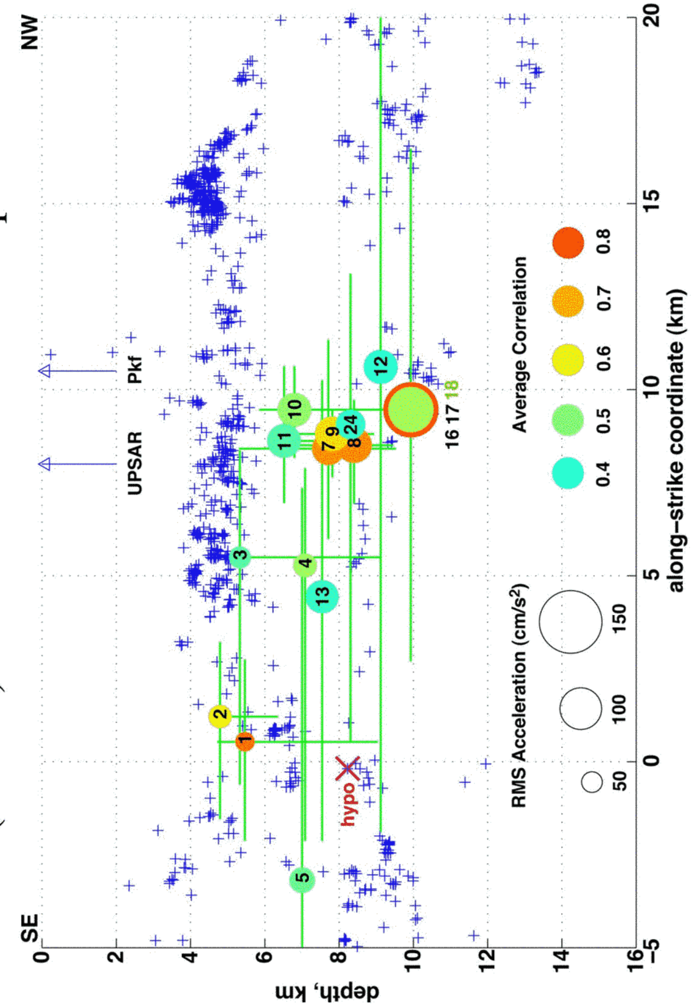


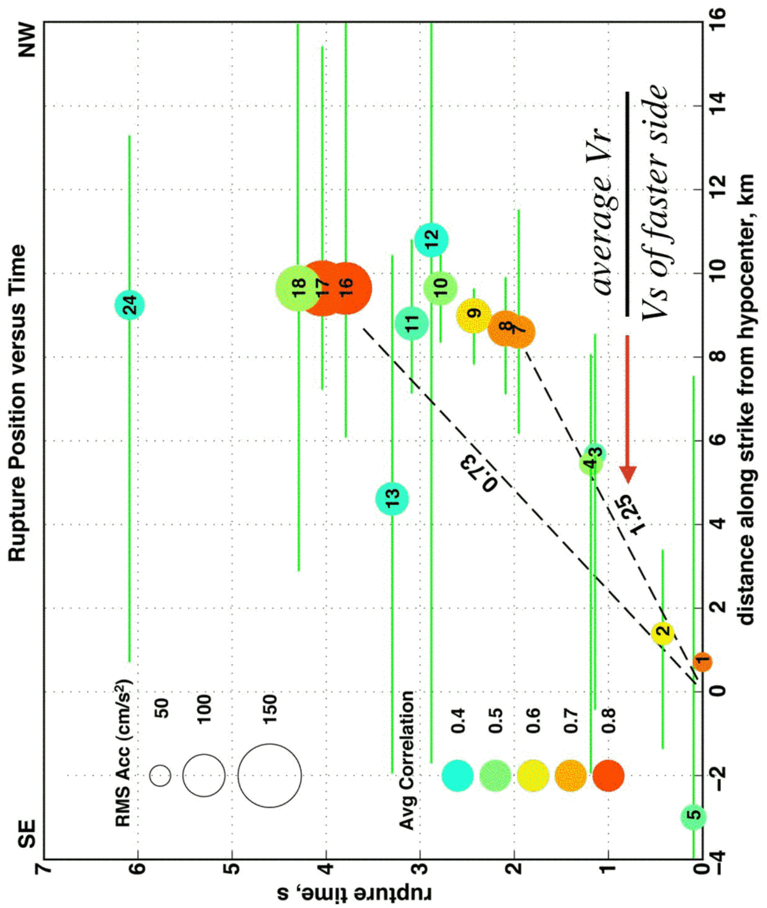
Average correlation,11.35-11.85 s, iwin=30 xc95=NaN
North comp of slowness
East comp of slowness
UPSAR P02 138 dg comp
acceleration, cm/s^2
time, s
30
xc272_715cr138hrw30.eps

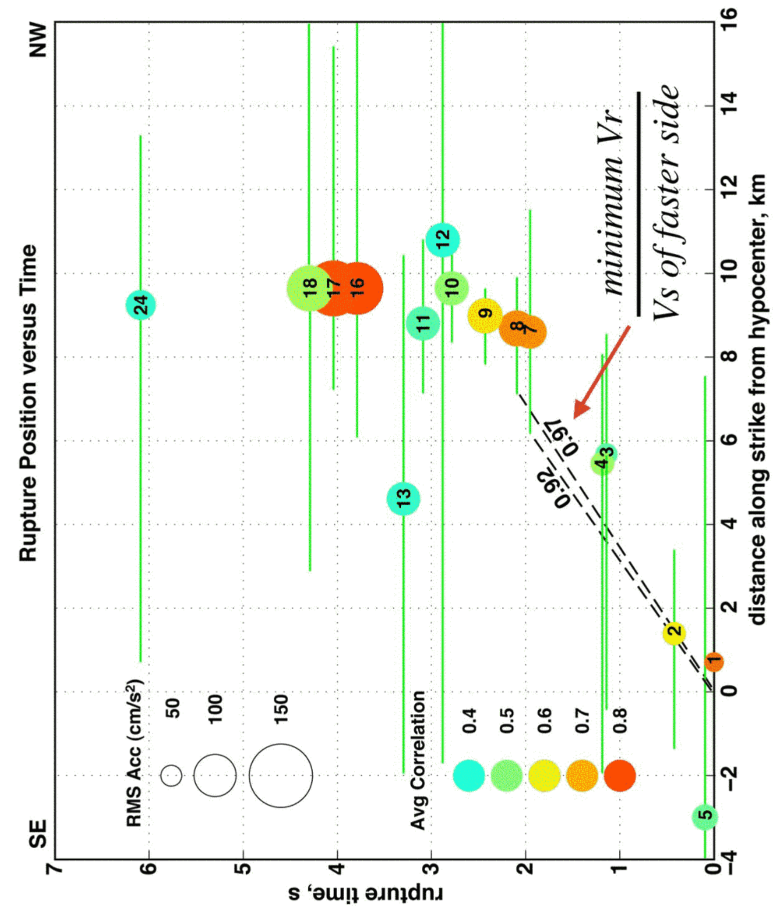
Summary of results for all time windows



Map of source locations (circles) and aftershocks (crosses) on the San Andreas fault plane



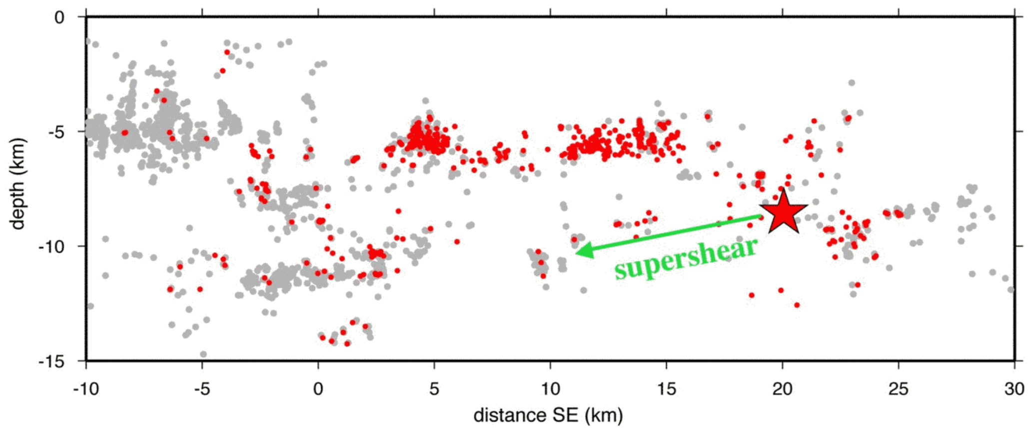

Rupture Position versus Time
NW
SE
rupture time, s
distance along strike from hypocenter, km
RMS Acc (cm/s²)
50
100
150
Avg Correlation
0.4
0.5
0.6
0.7
0.8
0.73
1.25
average Vr
Vs of faster side


Rupture Position versus Time
NW
SE
rupture time, s
distance along strike from hypocenter, km
RMS Acc (cm/s²)
50
100
150
Avg Correlation
0.4
0.5
0.6
0.7
0.8
0.97
0.92
minimum Vr
Vs of faster side

Comparison of aftershocks (red) to pre-earthquake seismicity (gray) on the San Andreas fault surface (from J. Hardebeck, USGS)

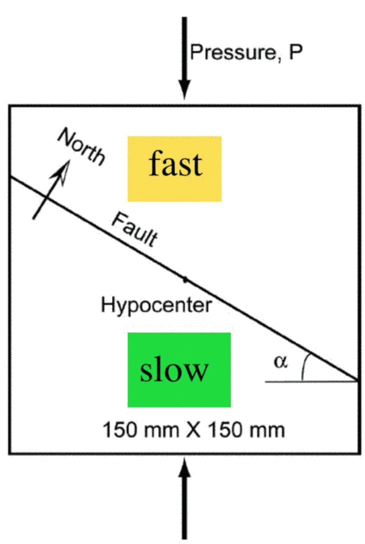
Aftershocks and pre-earthquake seismicity are in the same locations, despite presumed stress changes of main shock

Strongly suggests that the position of microearthquakes is controlled by material properties of faults, not stress distribution

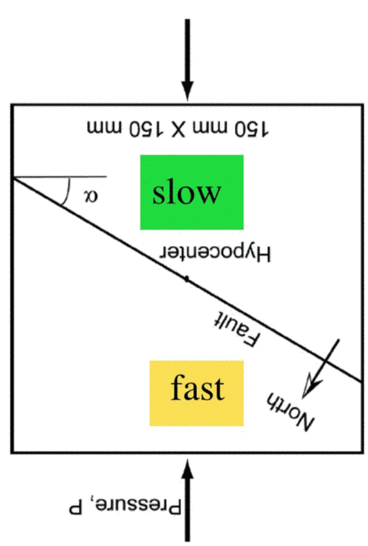


Comparison with lab experiments of rupture on a bimaterial interface, by Xia, Rosakis, Kanamori, and Rice (2005)

Xia et al. geometry



Parkfield geometry



Xia et al. (2005) lab results show supershear in same direction as 2004 Parkfield earthquake

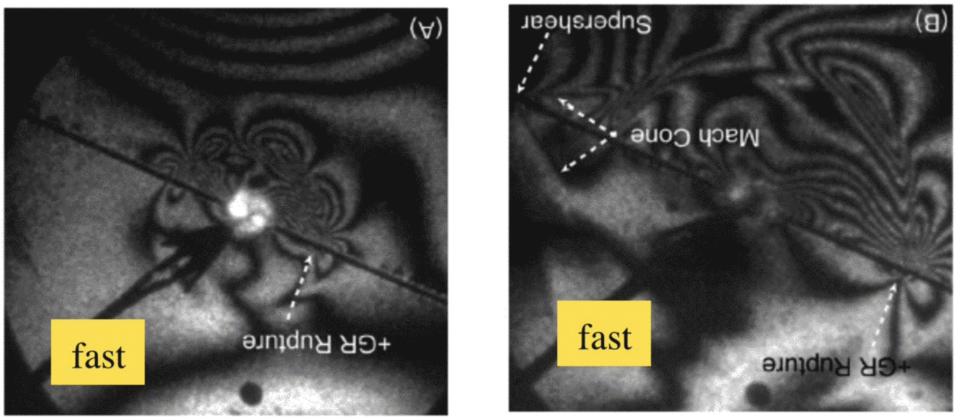


Figure 4. Rupture case-3. Experimental results for $\alpha = 25°$ and $P = 13$ MPa showing transition of the eastward moving rupture to supershear. The westward rupture retains a constant velocity $V^W \approx +C_{GR}$.

Conclusions - 1

- 2004 Parkfield quake is smallest for which supershear rupture velocity observed
- Rupture travels at 1.18-1.25 Vs of the faster side of the fault
- Super-shear velocity to NW (in direction of slip on the faster side of the fault) is consistent with numerical predictions (Harris & Day, 1997) and lab observations (Xia et al, 2005)
- Supershear velocity is observed to occur for a 7% Vs contrast across fault (excluding 4 km wide wedge), smaller than in numerical and lab results
- Sub- to supershear transition distance < 10 km here, like the Izmit, Turkey, quake, but smaller than the 25-50 km postulated for the Kunlunshan, China, quake based on lab scaling

Conclusions - 2

- Strong acceleration pulses are well correlated, suggesting a compact source area, probably caused by acceleration or deceleration of rupture front at some barrier on the fault
- Similarity of pre-shock and aftershock distributions on the fault suggests that material or frictional property variations control the locations of microearthquakes
- Coincidental locations of the source of the supershear acceleration pulse and a cluster of aftershocks suggest that a material/frictional property variation on the fault caused the rupture to decelerate from supershear speed

THE END