Improving the measurement side of the double-difference equation: double whammy high-resolution earthquake locations

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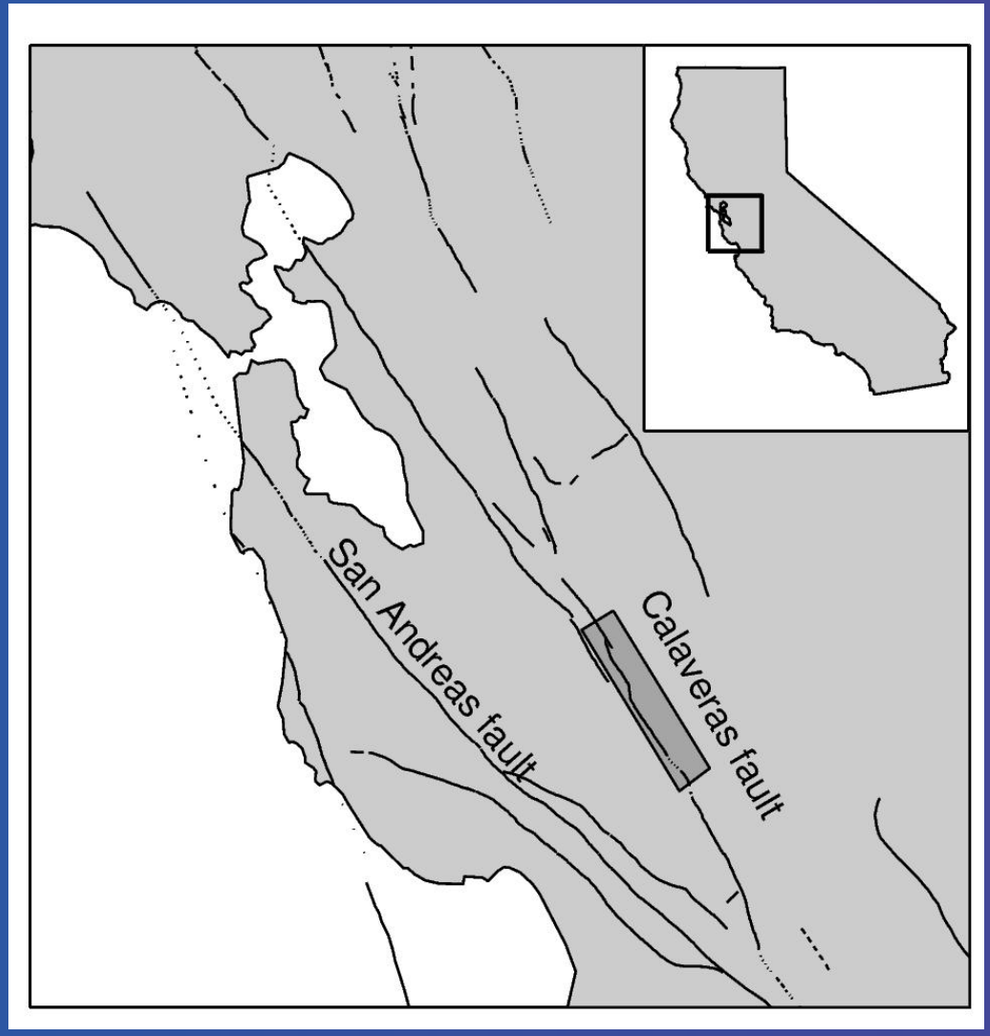
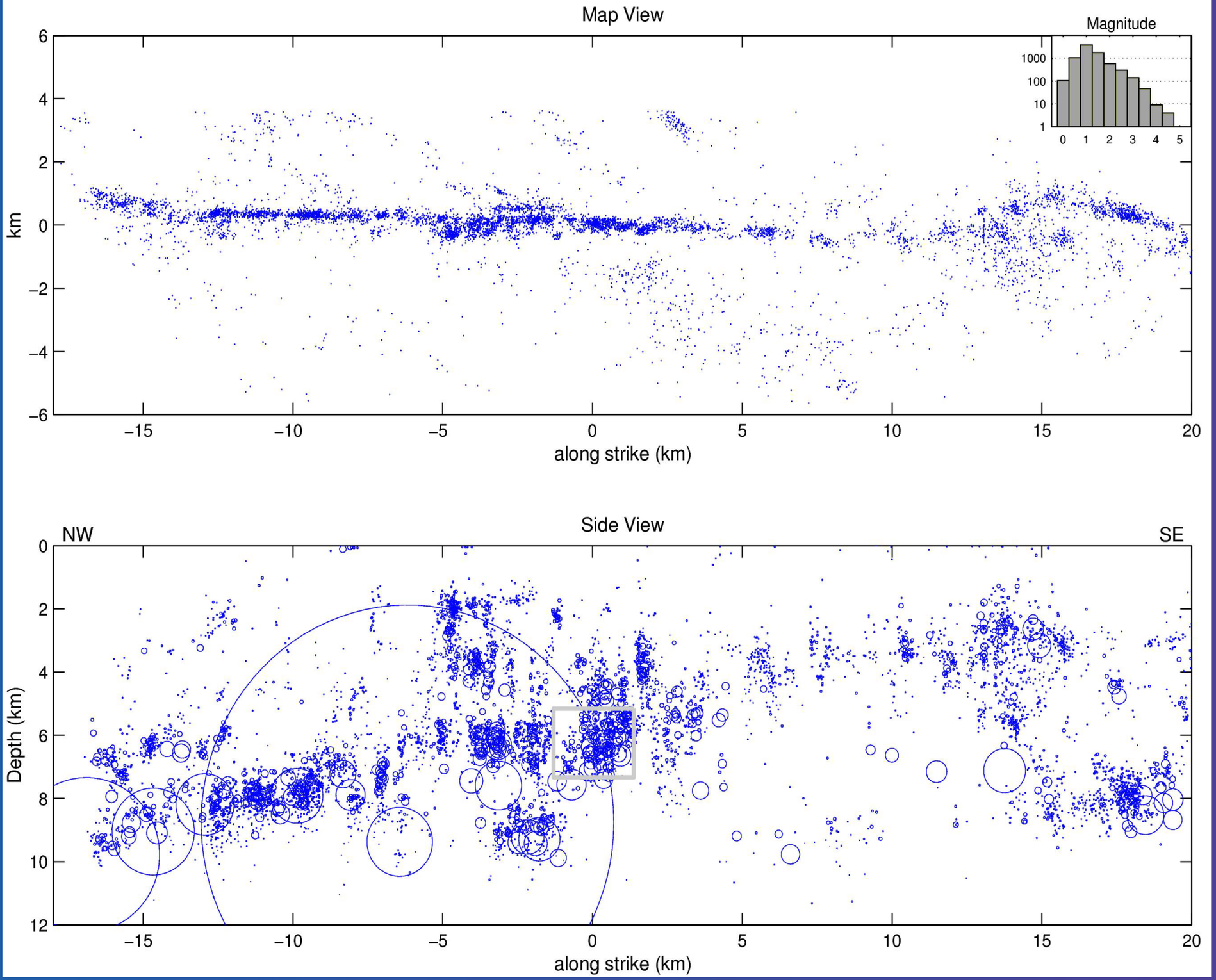
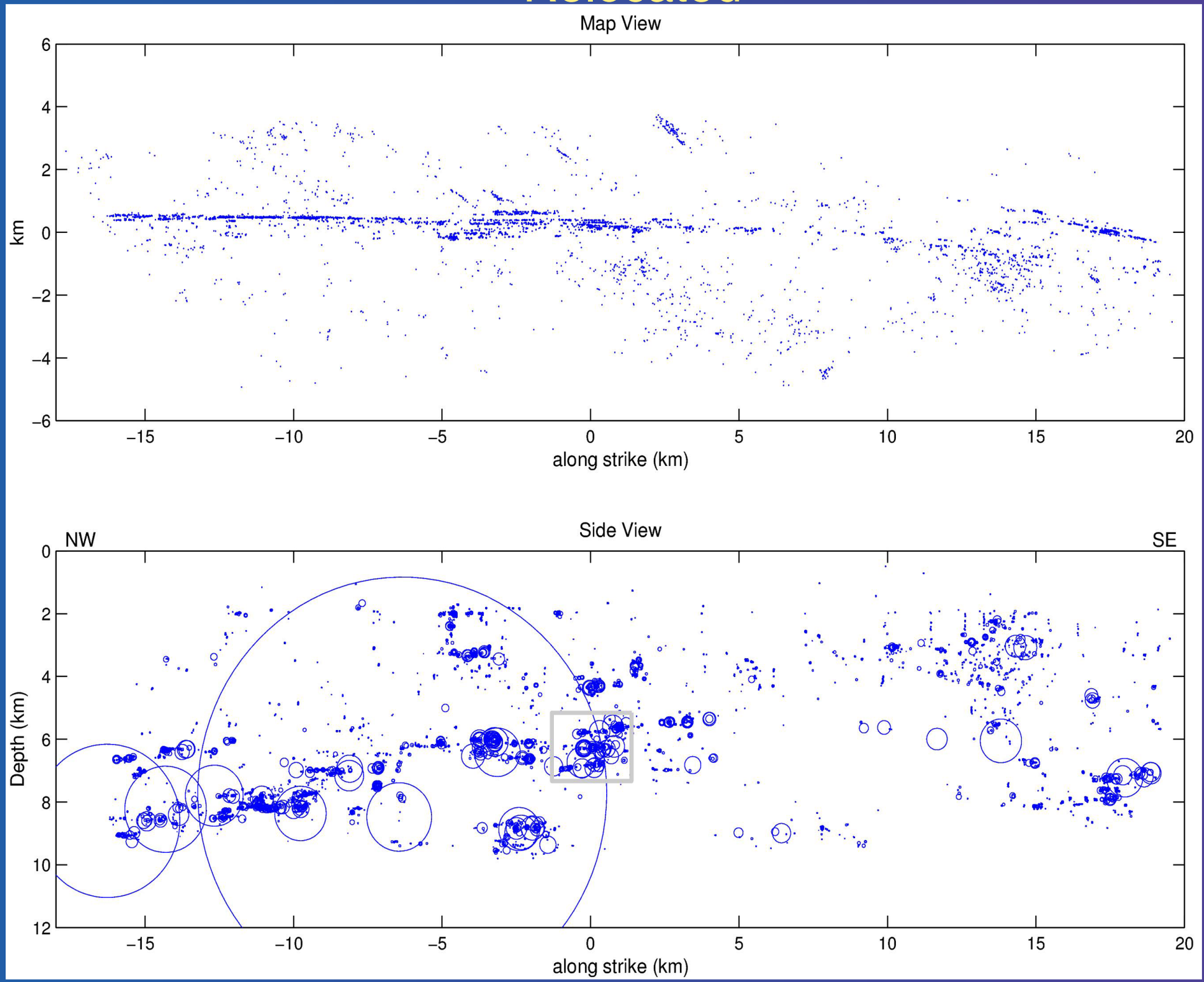
Study Area for Relocation



Catalog


Map View
Magnitude
1000
100
10
1
0 1 2 3 4 5
km
6
4
2
0
−2
−4
−6
−15 −10 −5 0 5 10 15 20
along strike (km)
Side View
NW
SE
Depth (km)
0
2
4
6
8
10
12
−15 −10 −5 0 5 10 15 20
along strike (km)

Relocated


Map View
km
along strike (km)
Side View
NW
SE
Depth (km)
along strike (km)

Overview

Motivation
- For Calaveras fault one to two orders of magnitude improvement

Theory
- 2 independent sources of error:
  - velocity model error (double difference)
  - pick measurement error (cross correlation)

Technique
- waveform cross correlation
- quantifying the quality

Application
- local
- regional
- teleseismic

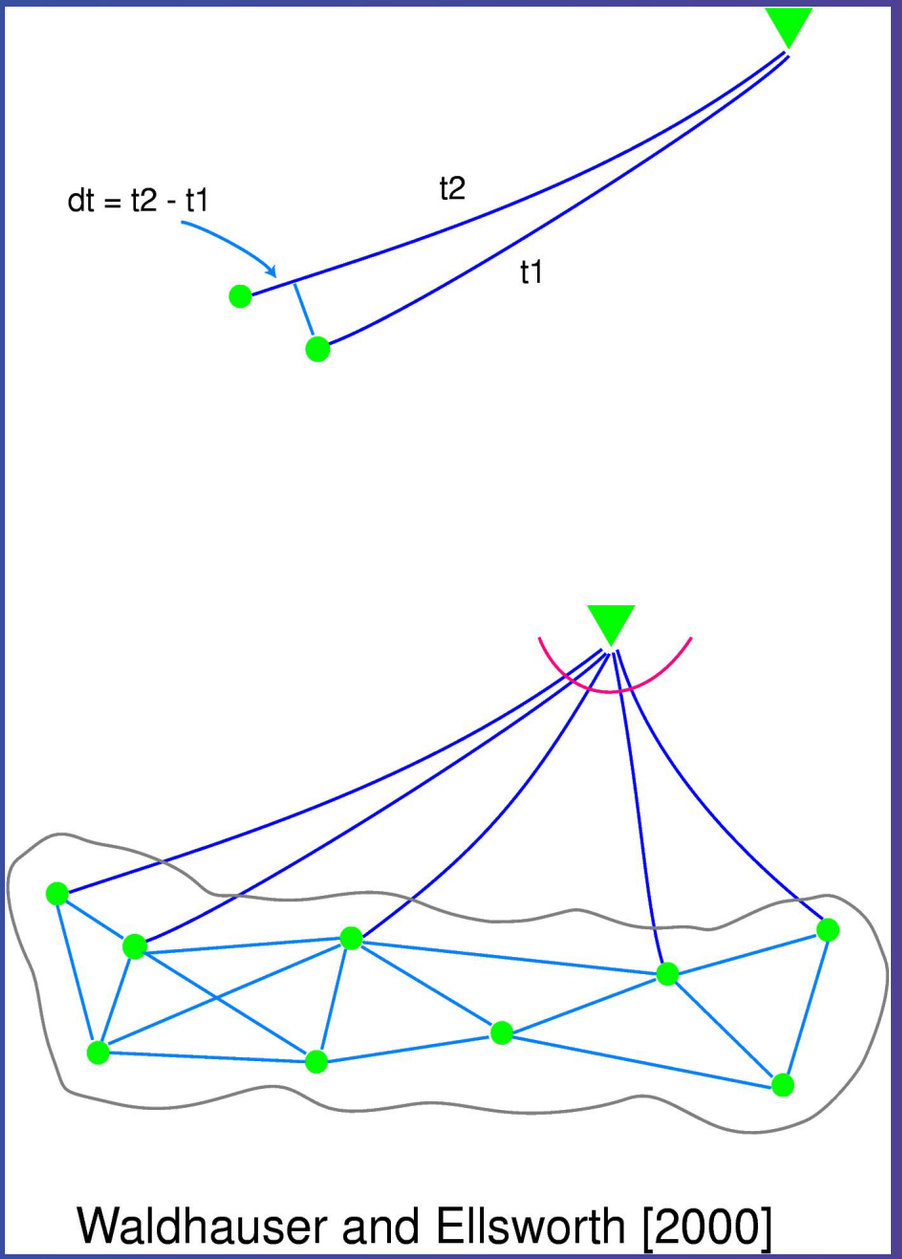
Velocity Model Error

station corrections
3D tomography
difference out (double difference)

$t_1 = t_{1c} + t_m$
$t_2 = t_{1c} + t_m + dt$

$dt = t_2 - t_1$

$\underline{d} = \underline{\underline{G}}\ \underline{m}$

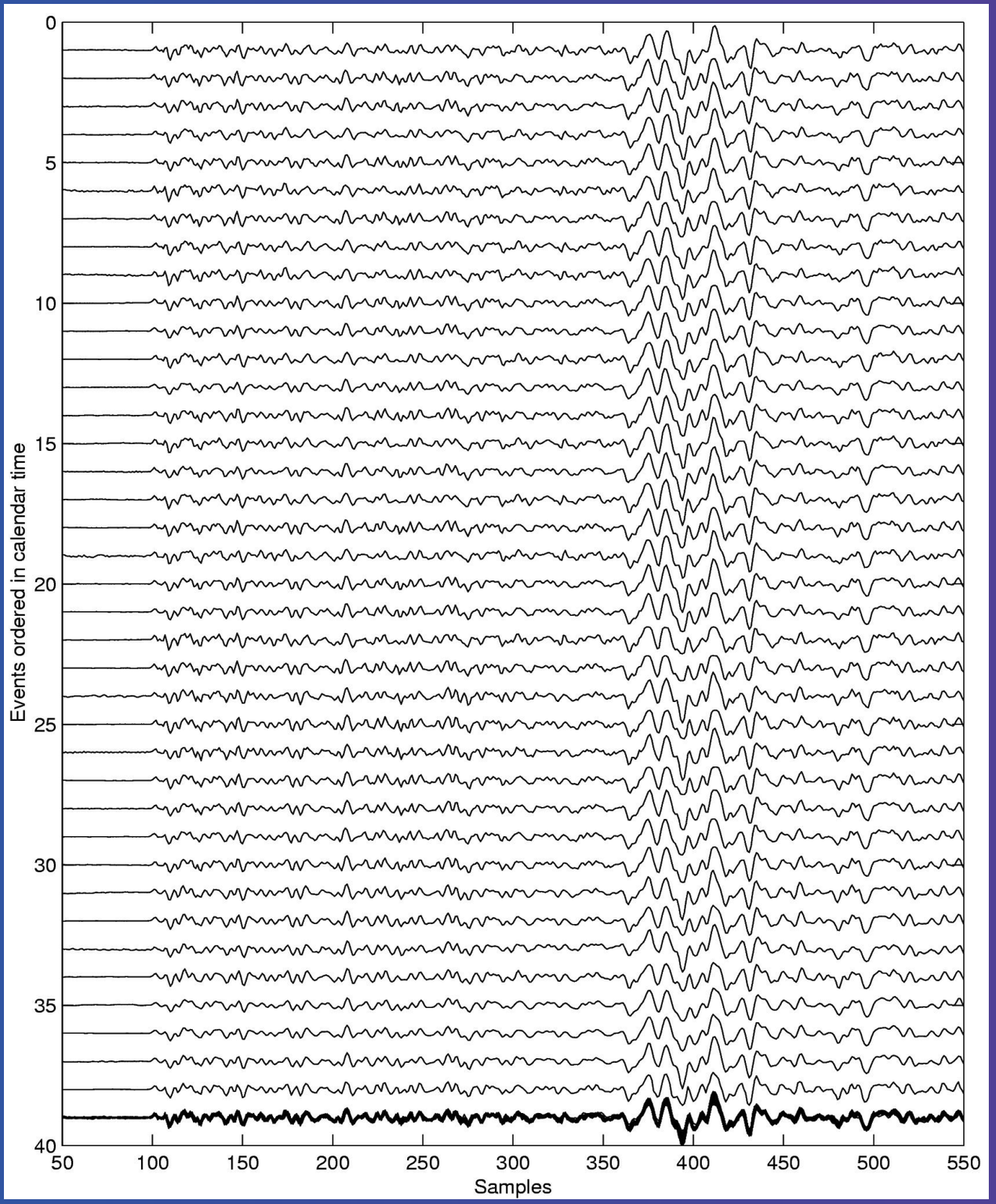


Waldhauser and Ellsworth [2000]

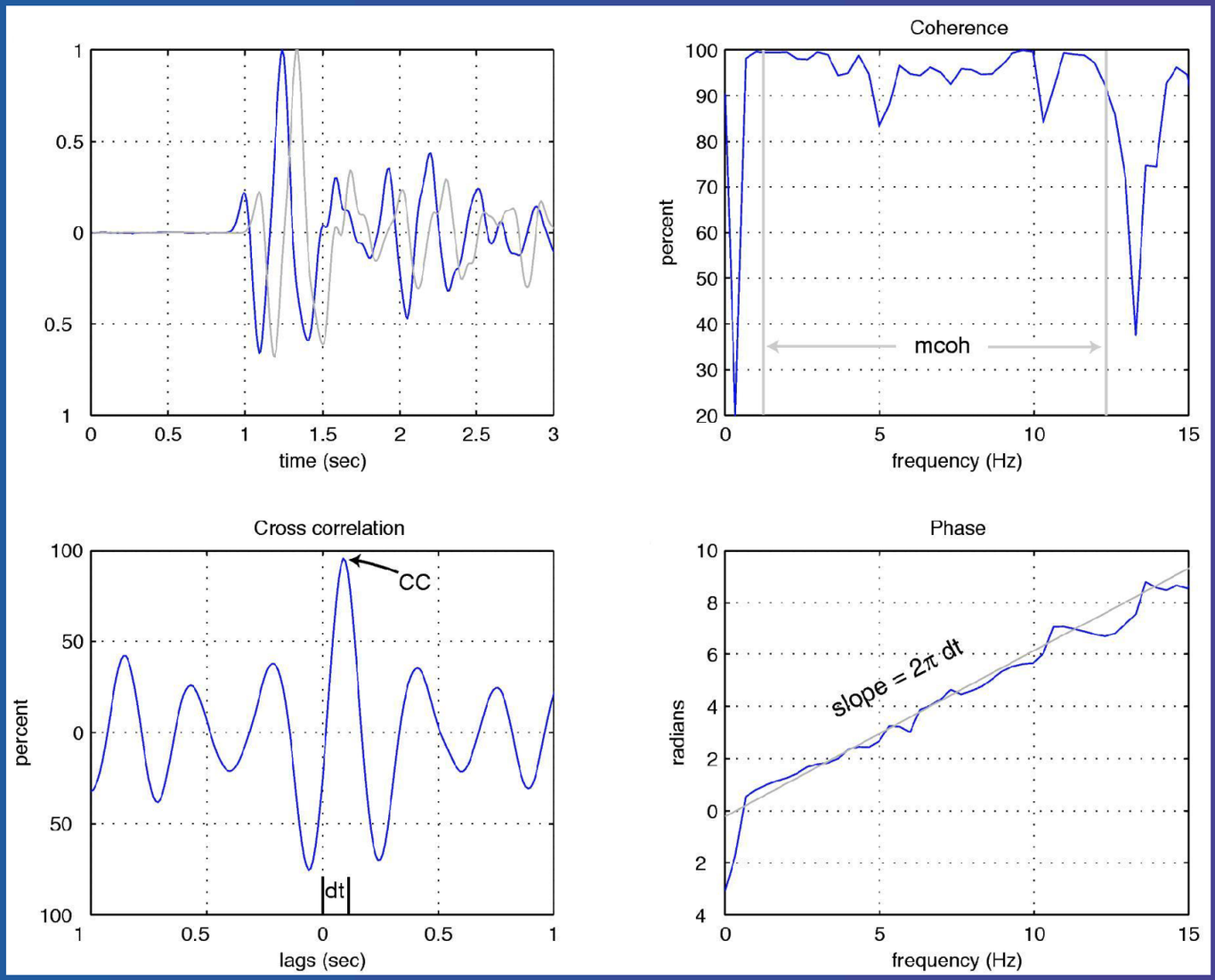
Measurement Error

38 different events

events superposed



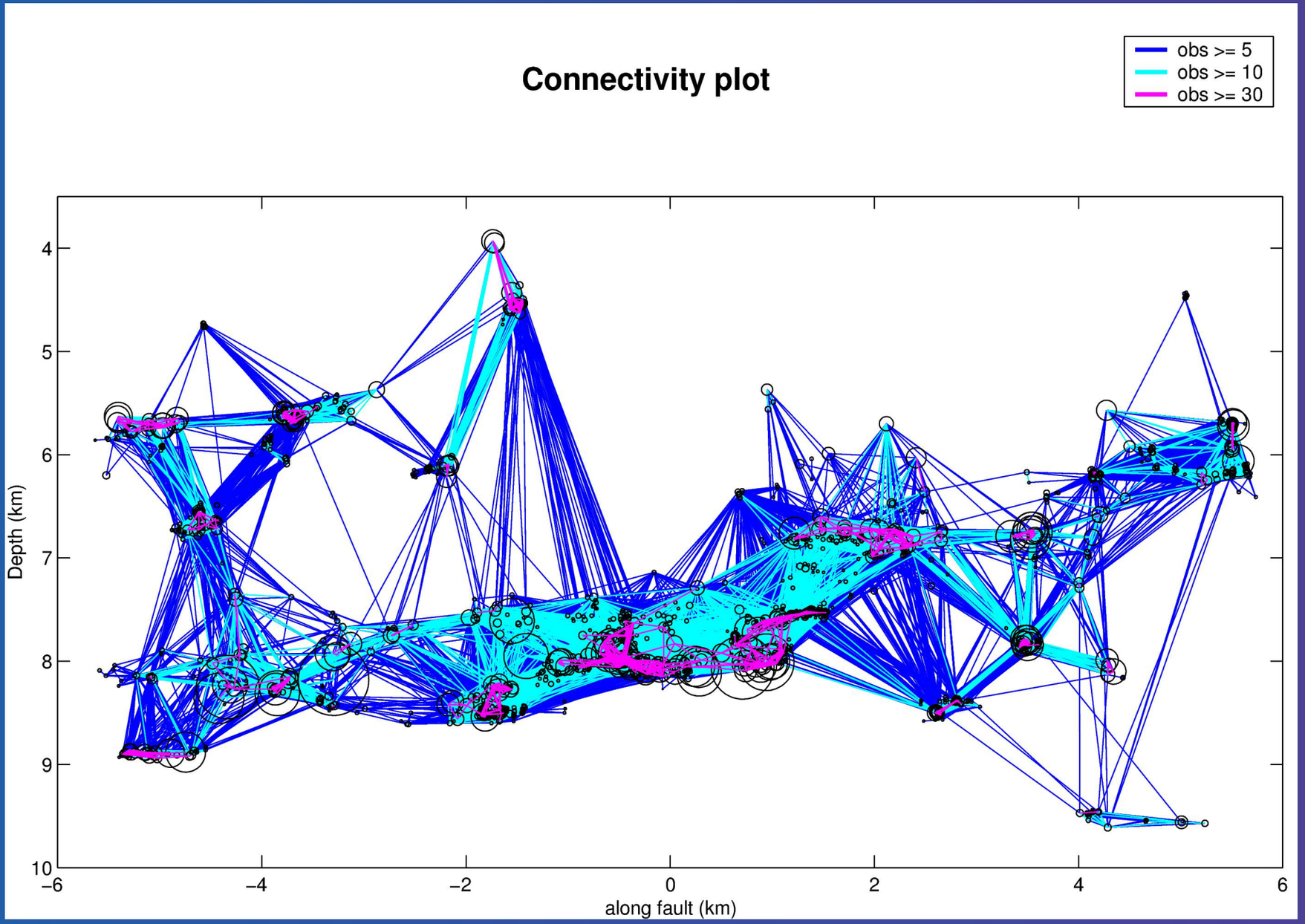
Correlation Measurement Techniques



time domain

frequency domain

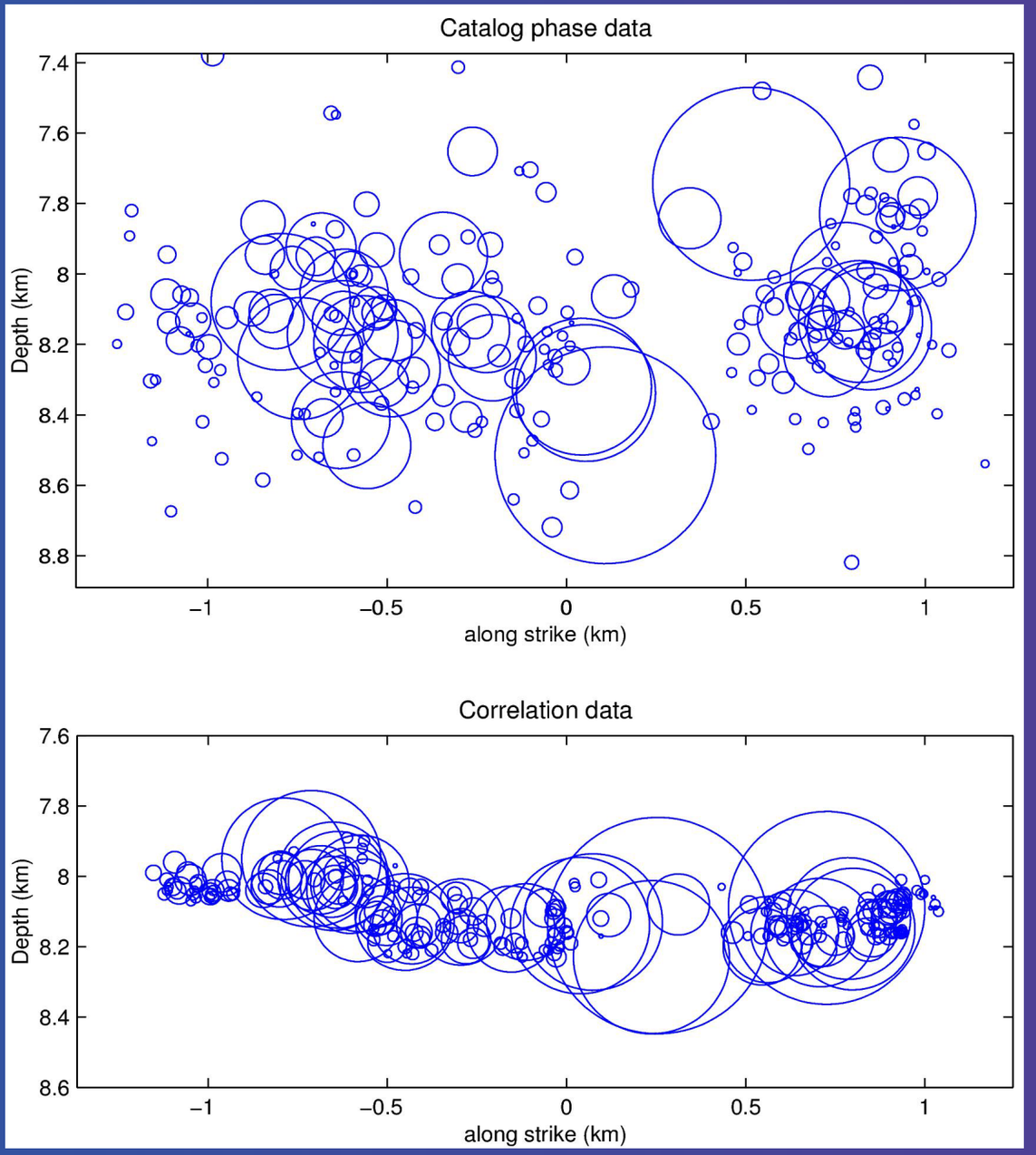
Correlation Data Quality?

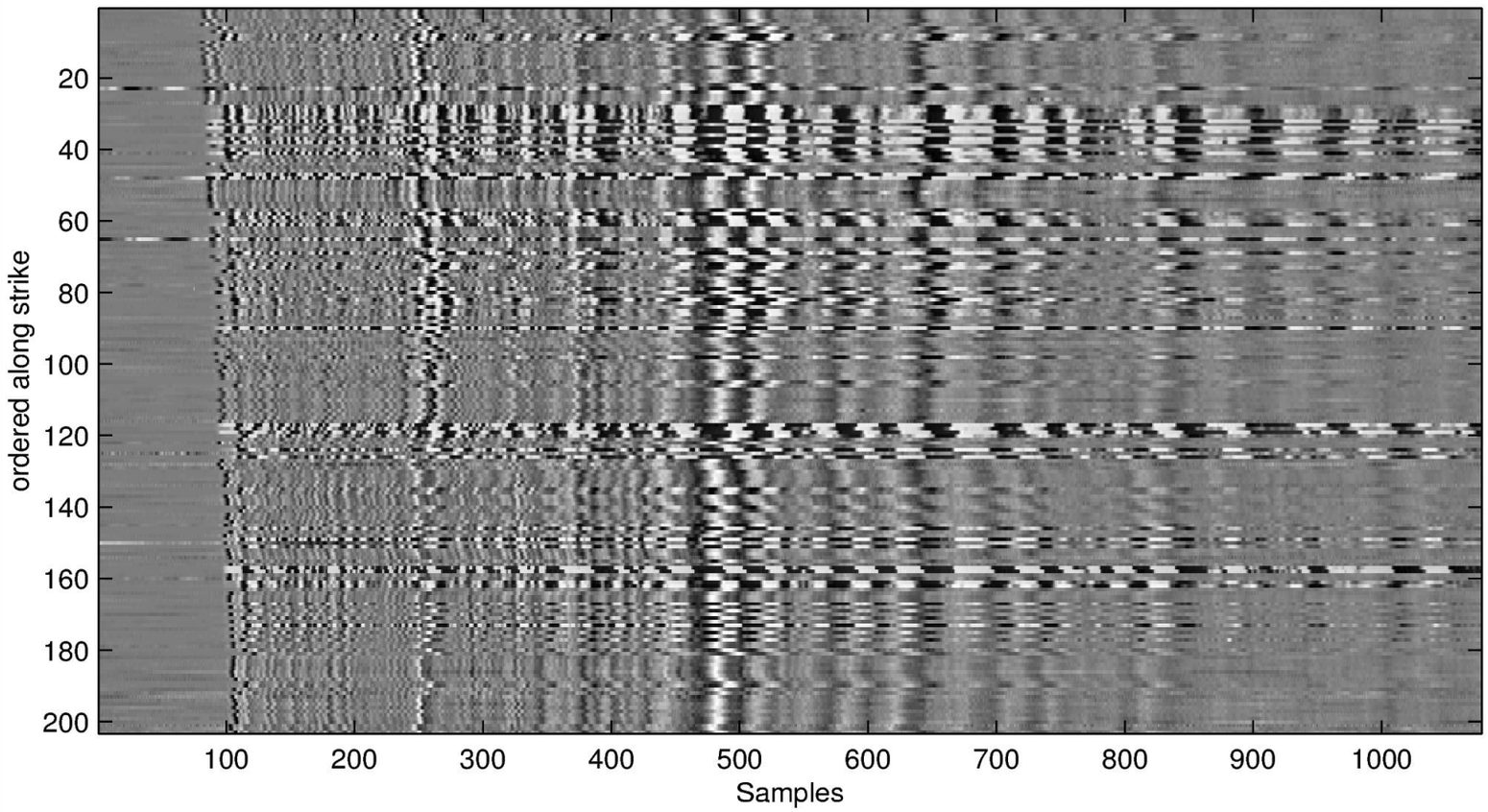


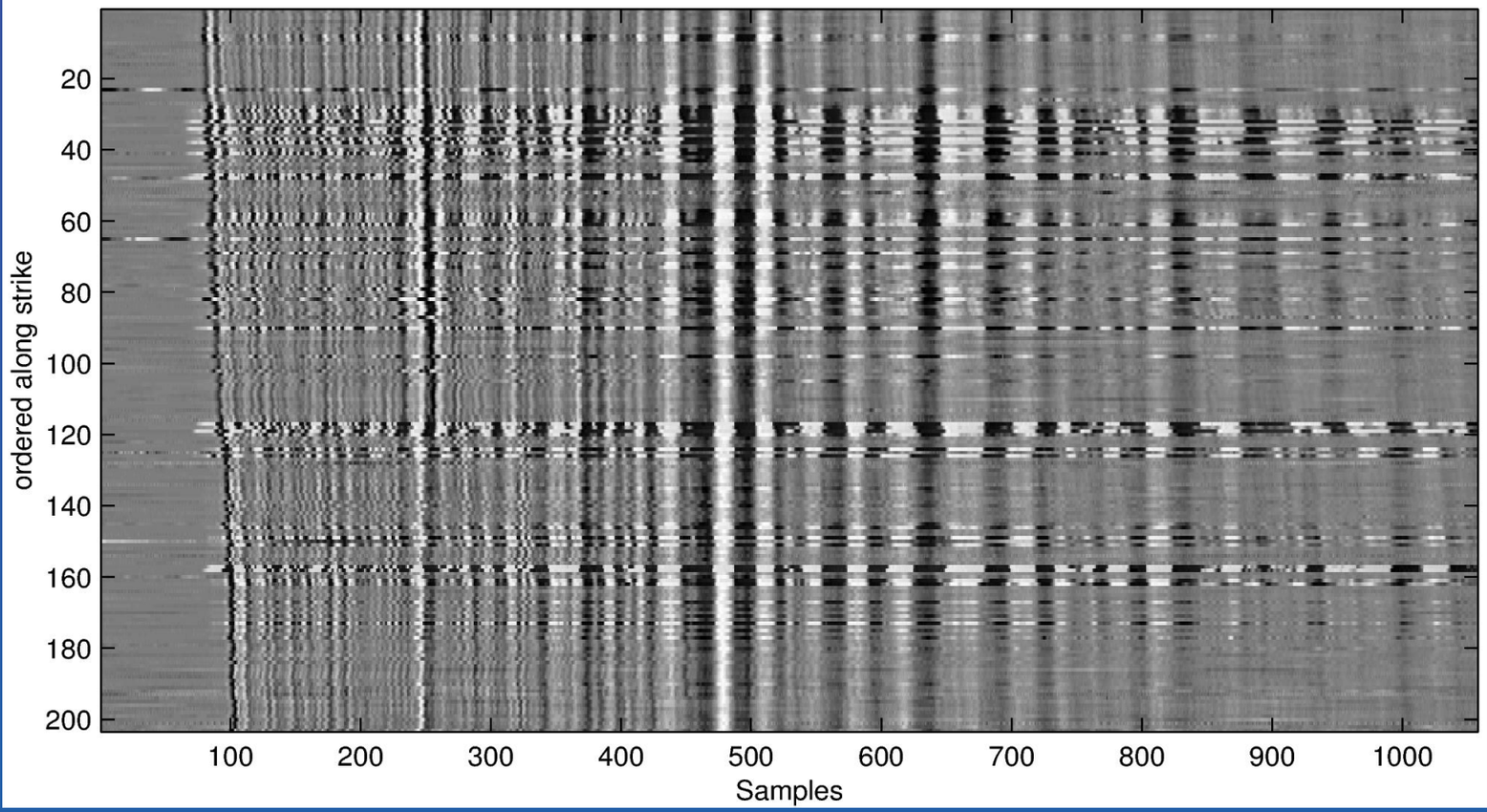
Comparison of Measurement Error

Two runs
1) catalog only
2) correlation only

299,642 identical observations (model error fixed)




ordered along strike
20
40
60
80
100
120
140
160
180
200
100
200
300
400
500
600
700
800
900
1000
Samples


ordered along strike
20
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200
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400
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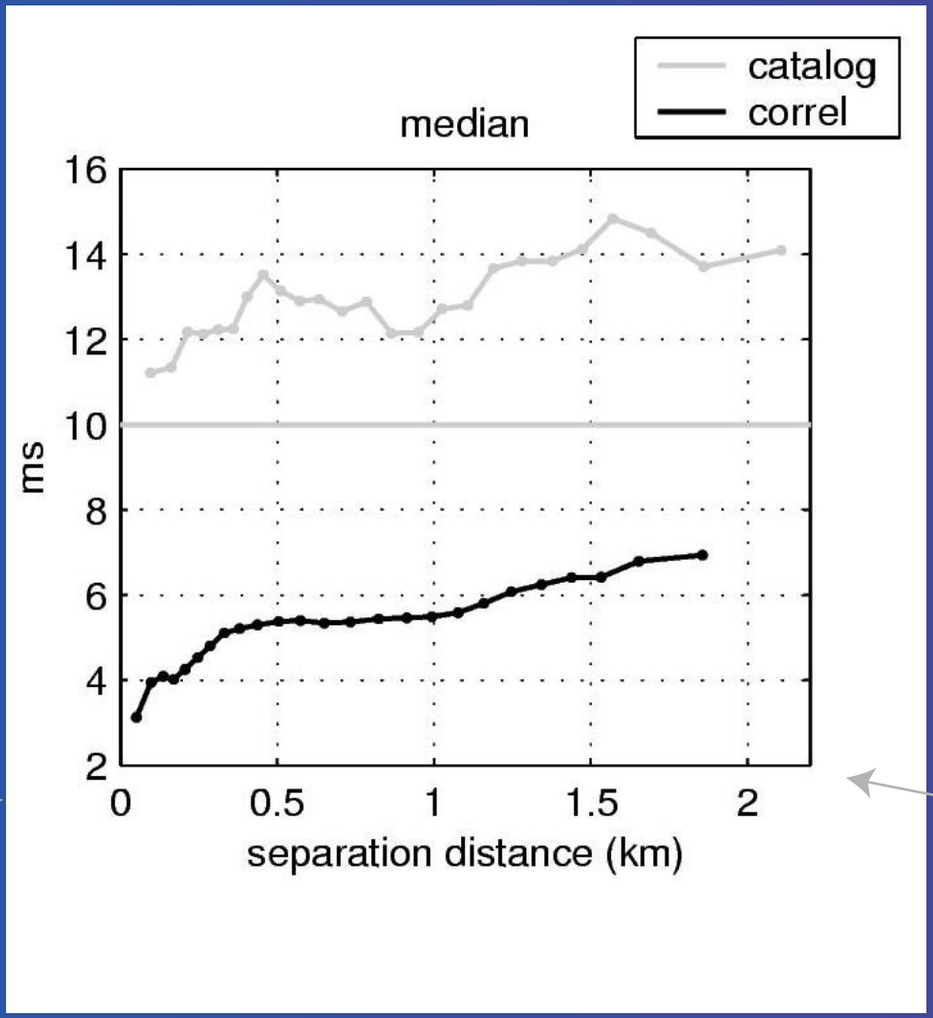
600
700
800
900
1000
Samples

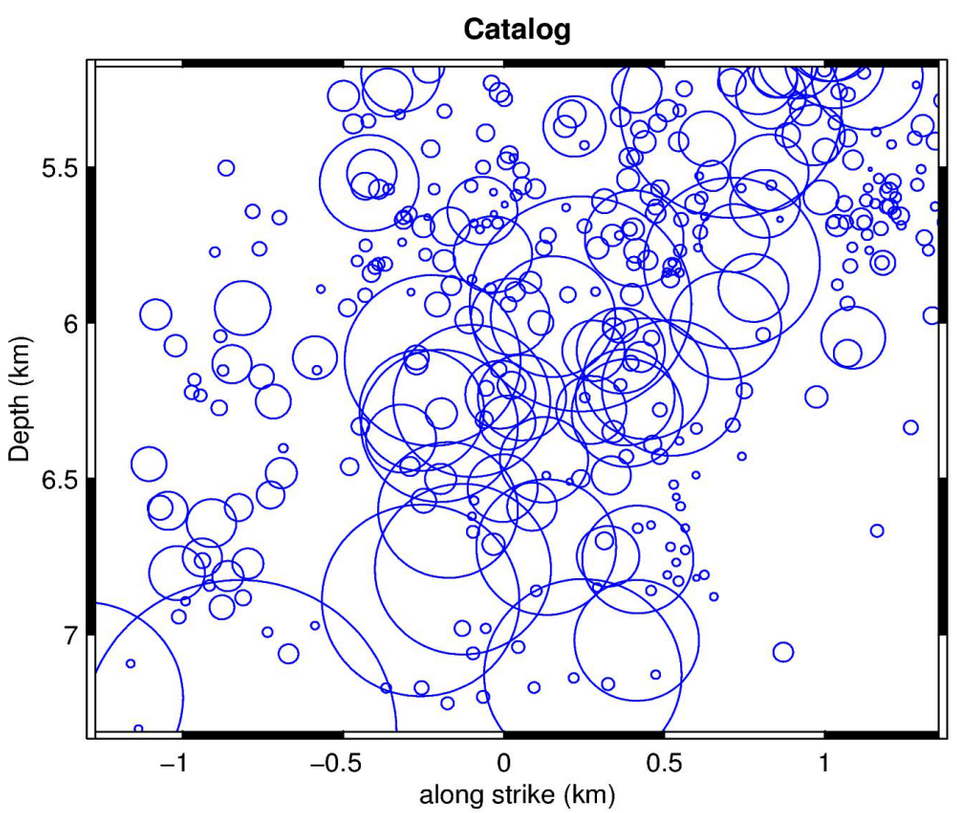
Inter-event distance dependence

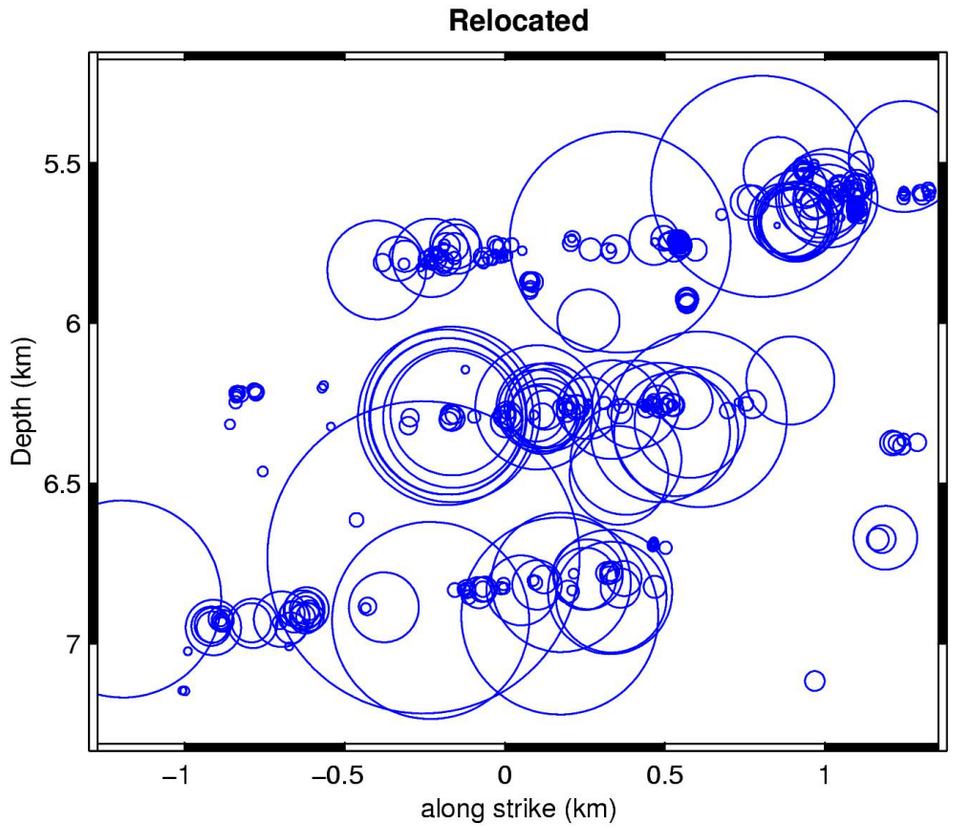


at zero distance
measurement error

increasing distance
catalog: model error
correlation: measurement + model error

Fine-scale structure



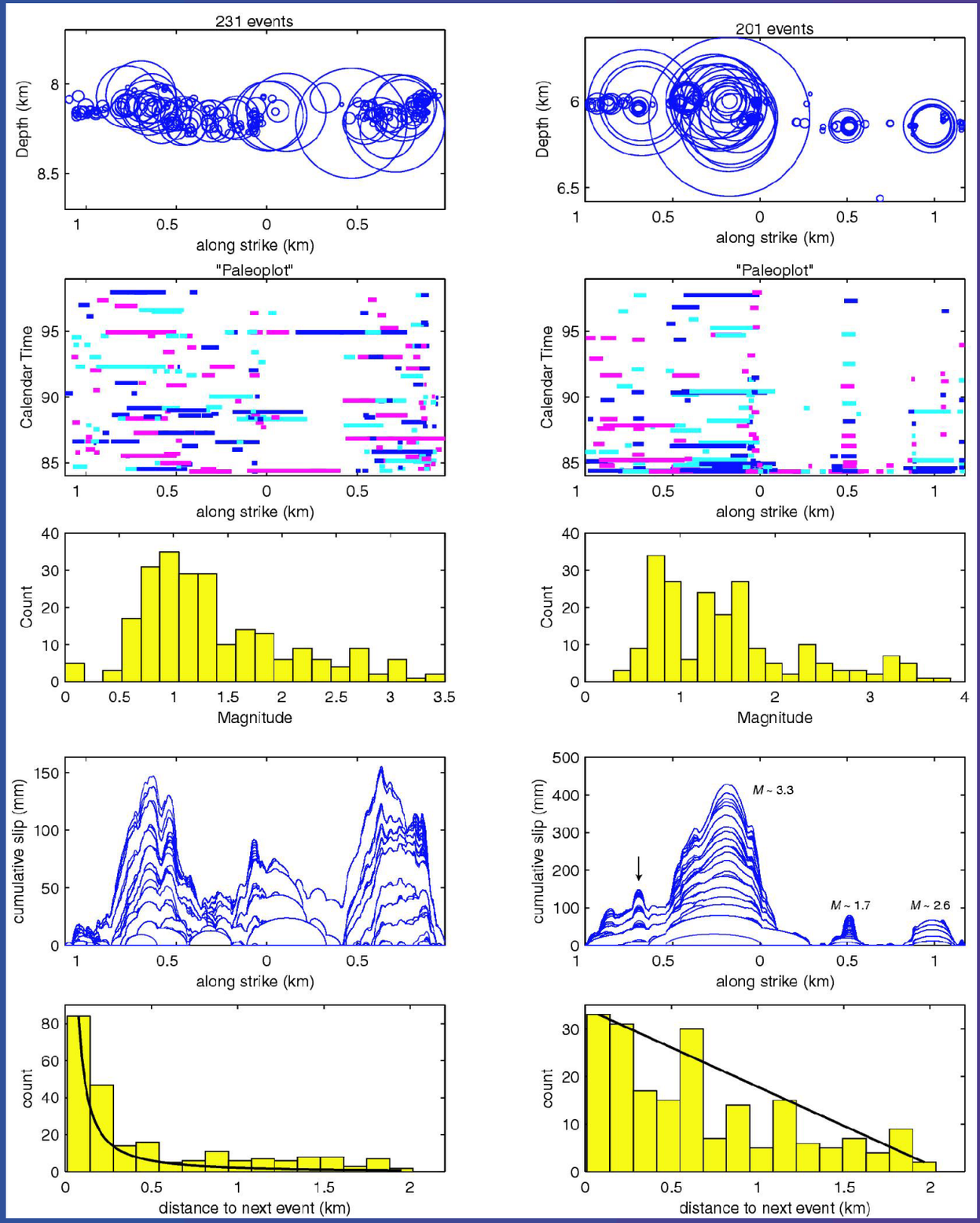


Comparison of two streaks

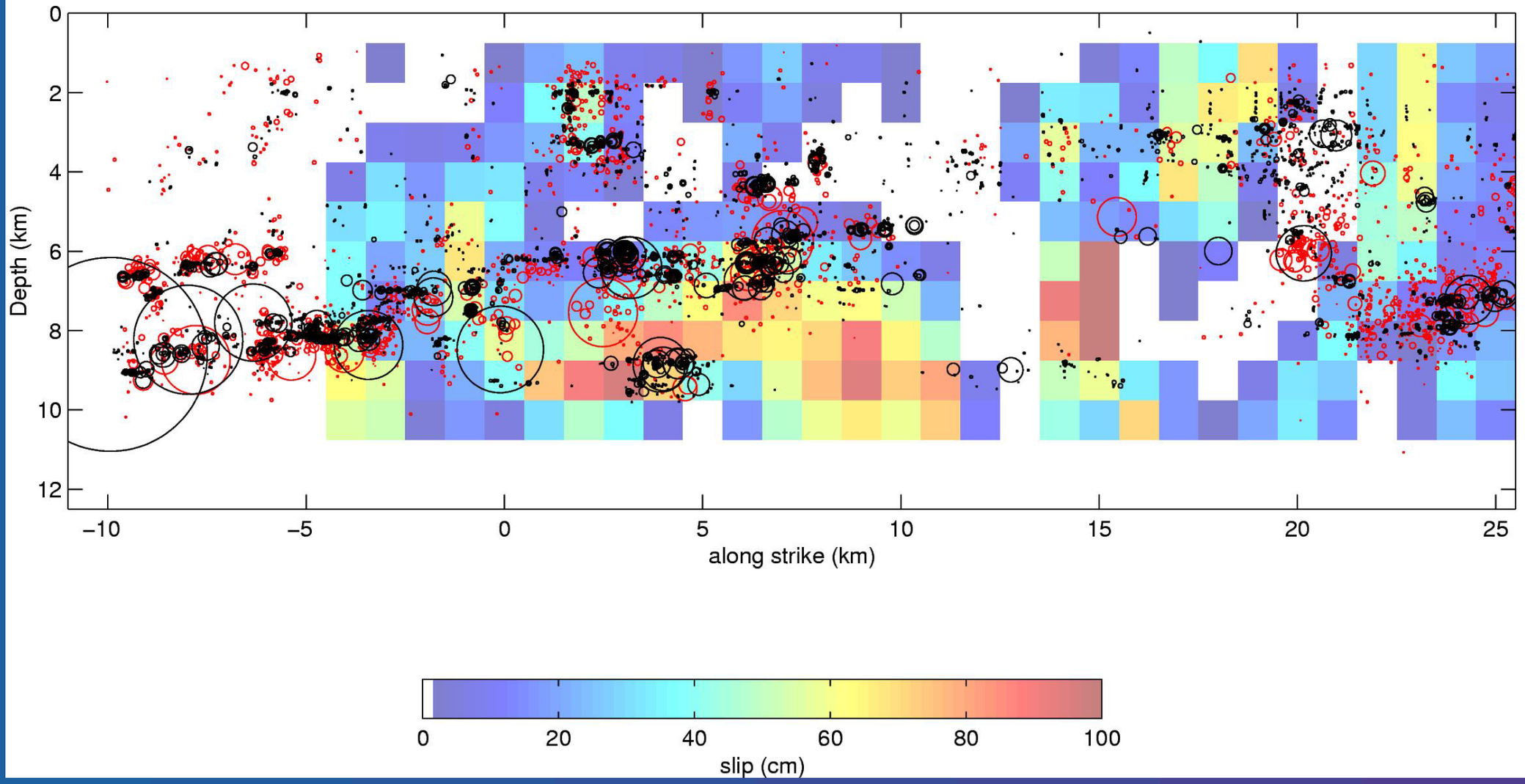
Characteristic vs. random

Seismic vs. aseismic slip

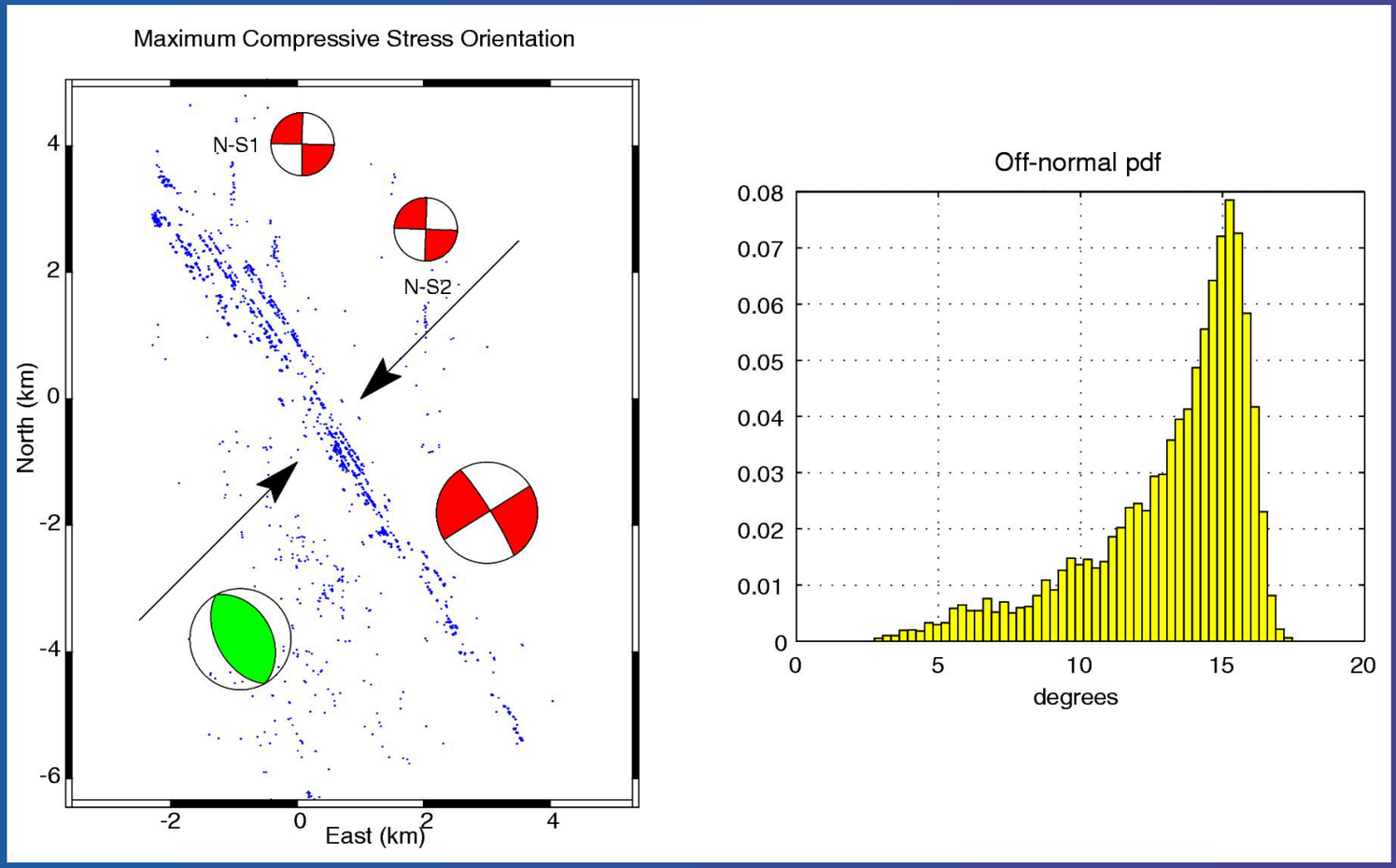
Triggering vs. minimal earthquake interaction



Complementarity with Morgan Hill Slip Model



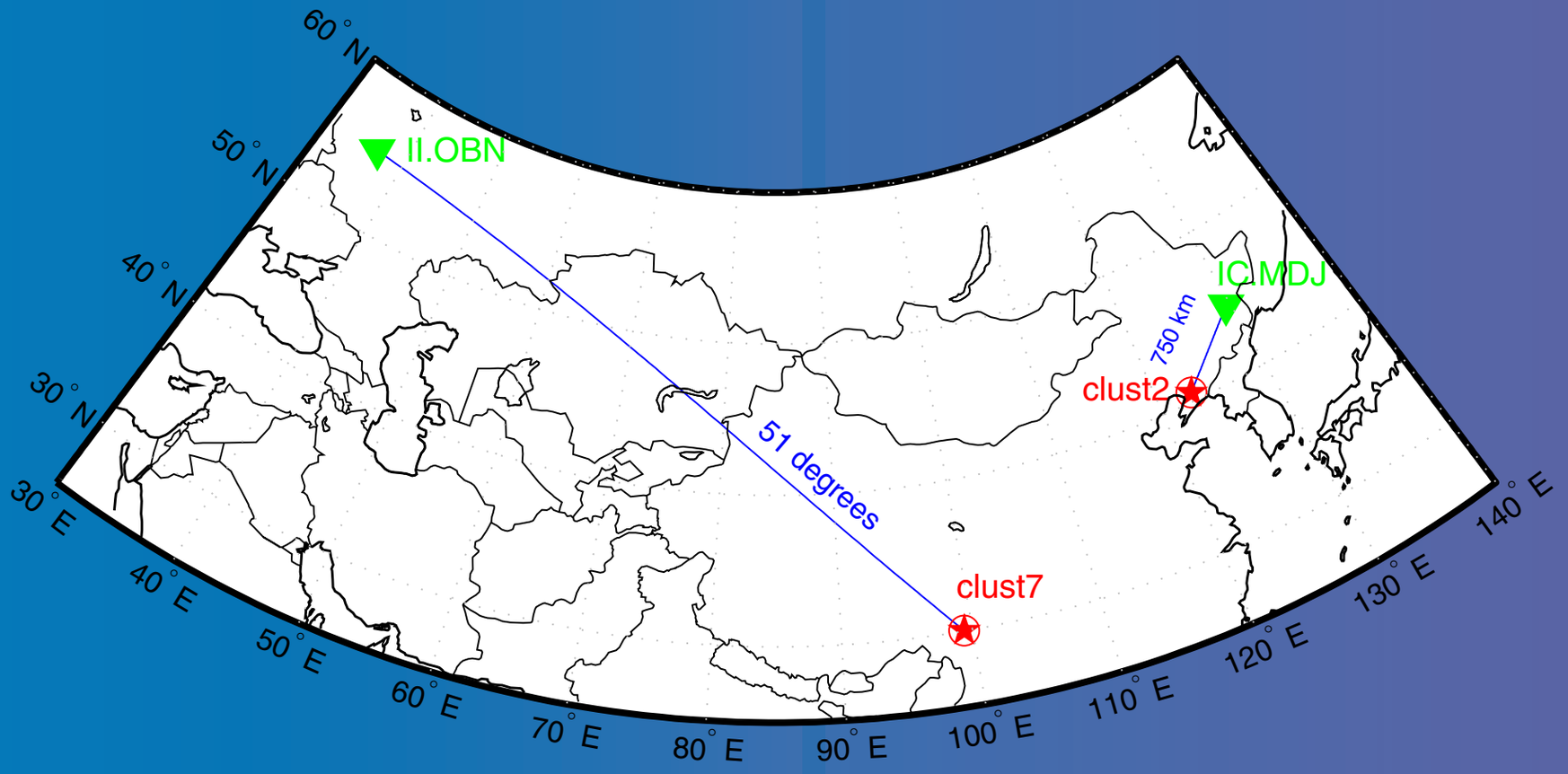
Stress Inversion



Slip directions and fault planes known.

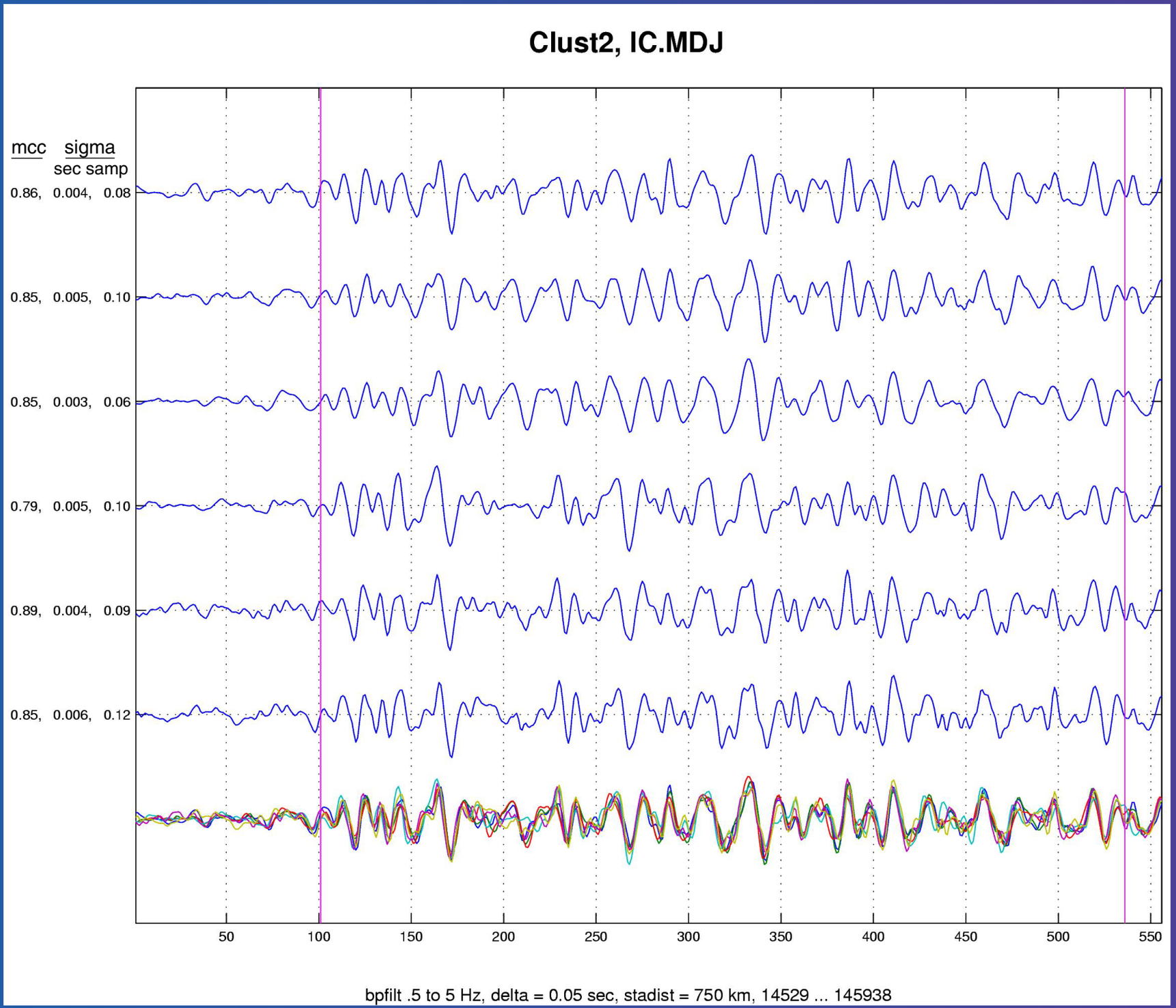
Maximum compressive stress is at a high angle to the fault implying that it is weak.

Two Clusters in China



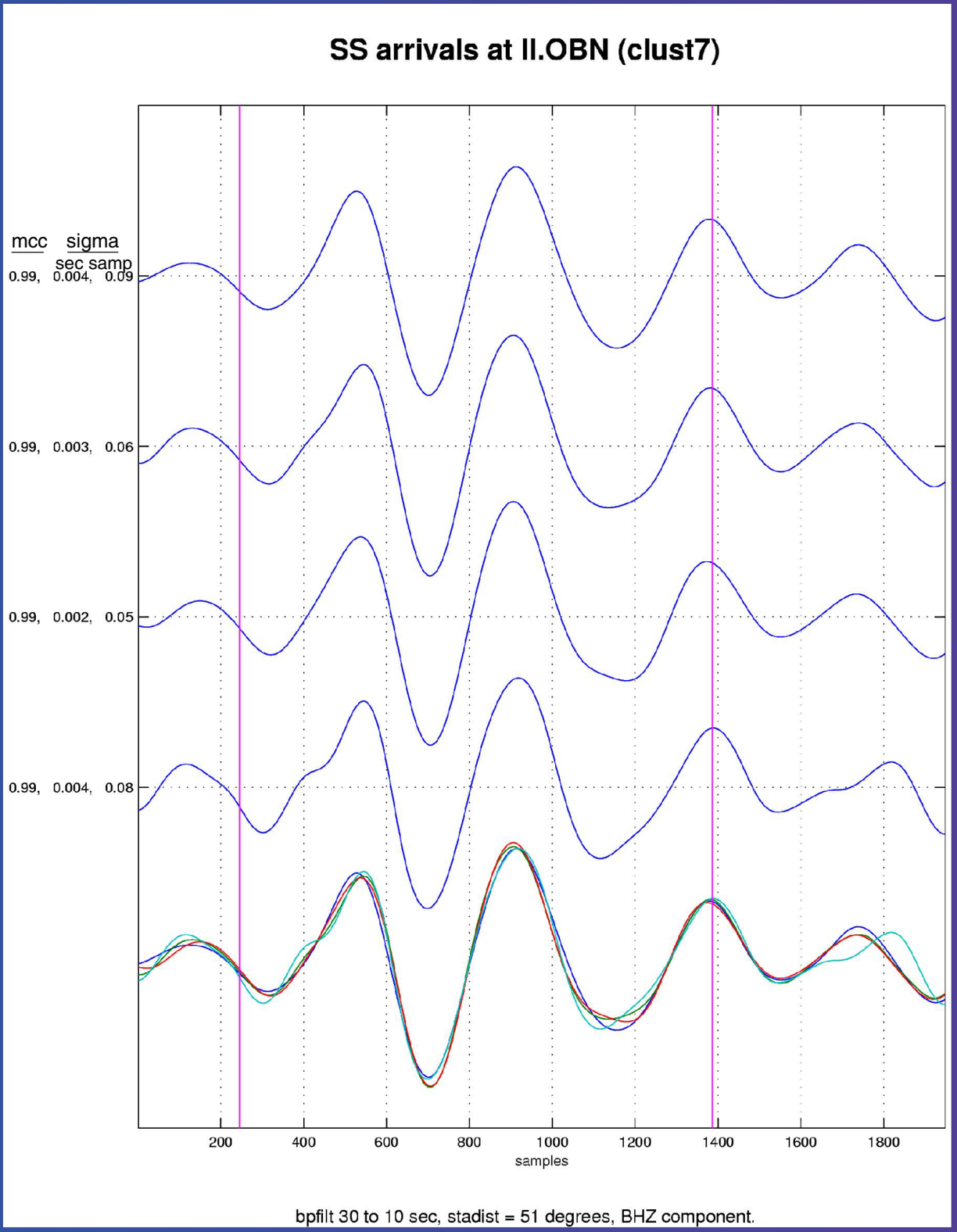
Regional and Teleseismic

Regional Lg waves 750 km away

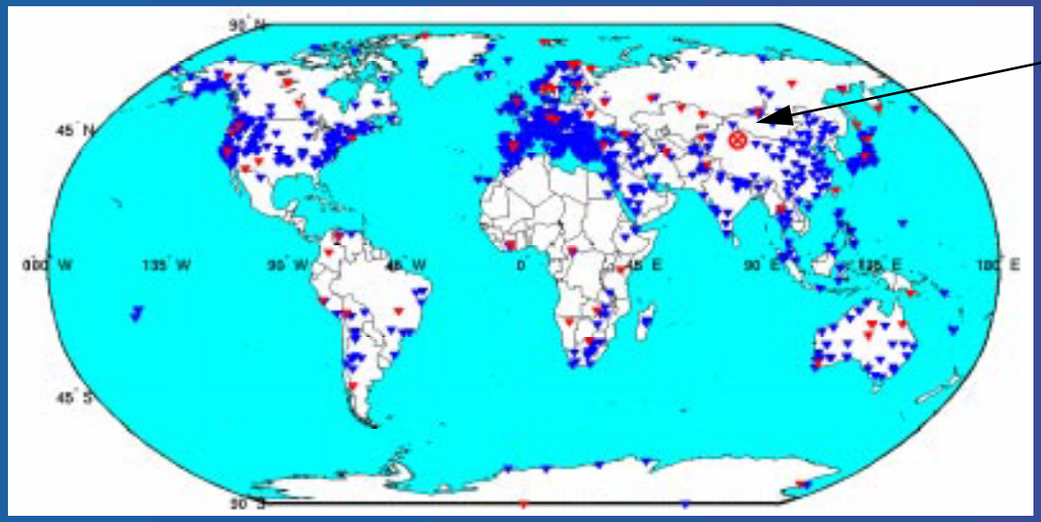


Teleseismic example in China

SS phases at 51 degrees



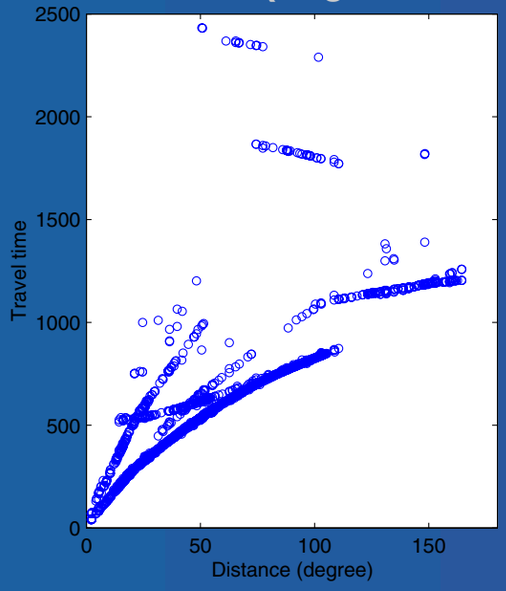
Relocation of Underground Nuclear Explostions



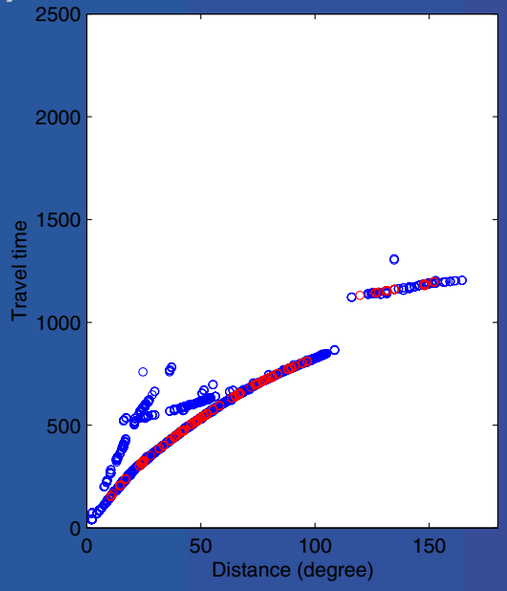
Lop Nor Test Site

▼ Phase picks @ ISC/ABCE stations
▼ X-corr @ IRIS/array stations

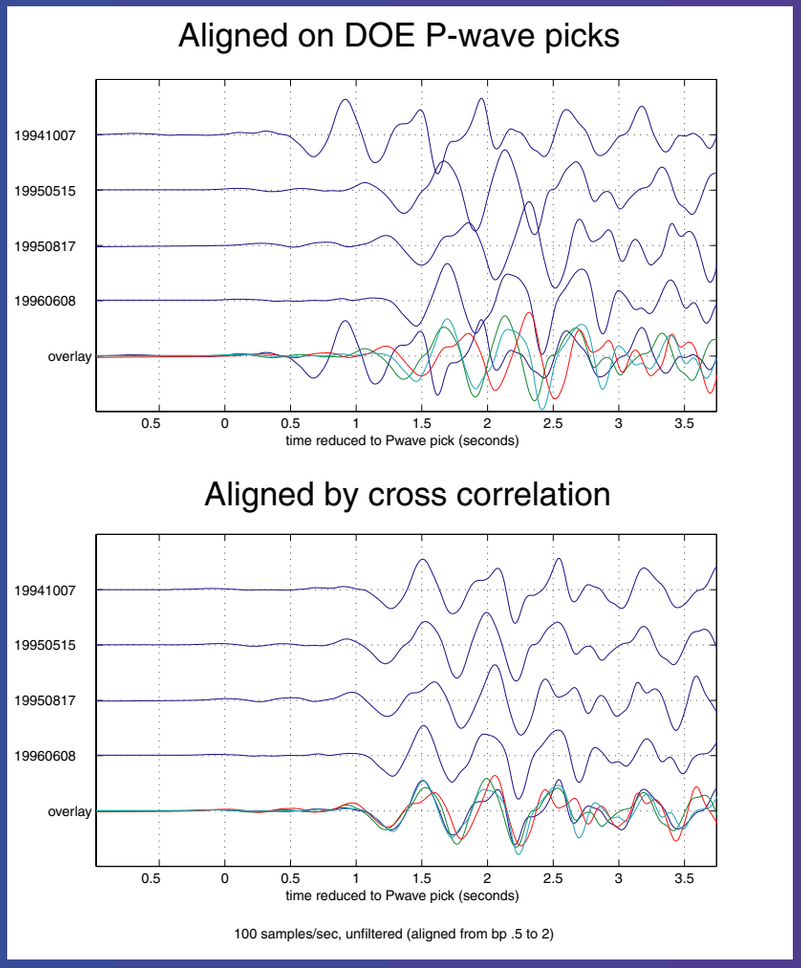
Phase Picks (Engdahl/ABCE)



Selected Phase Pairs



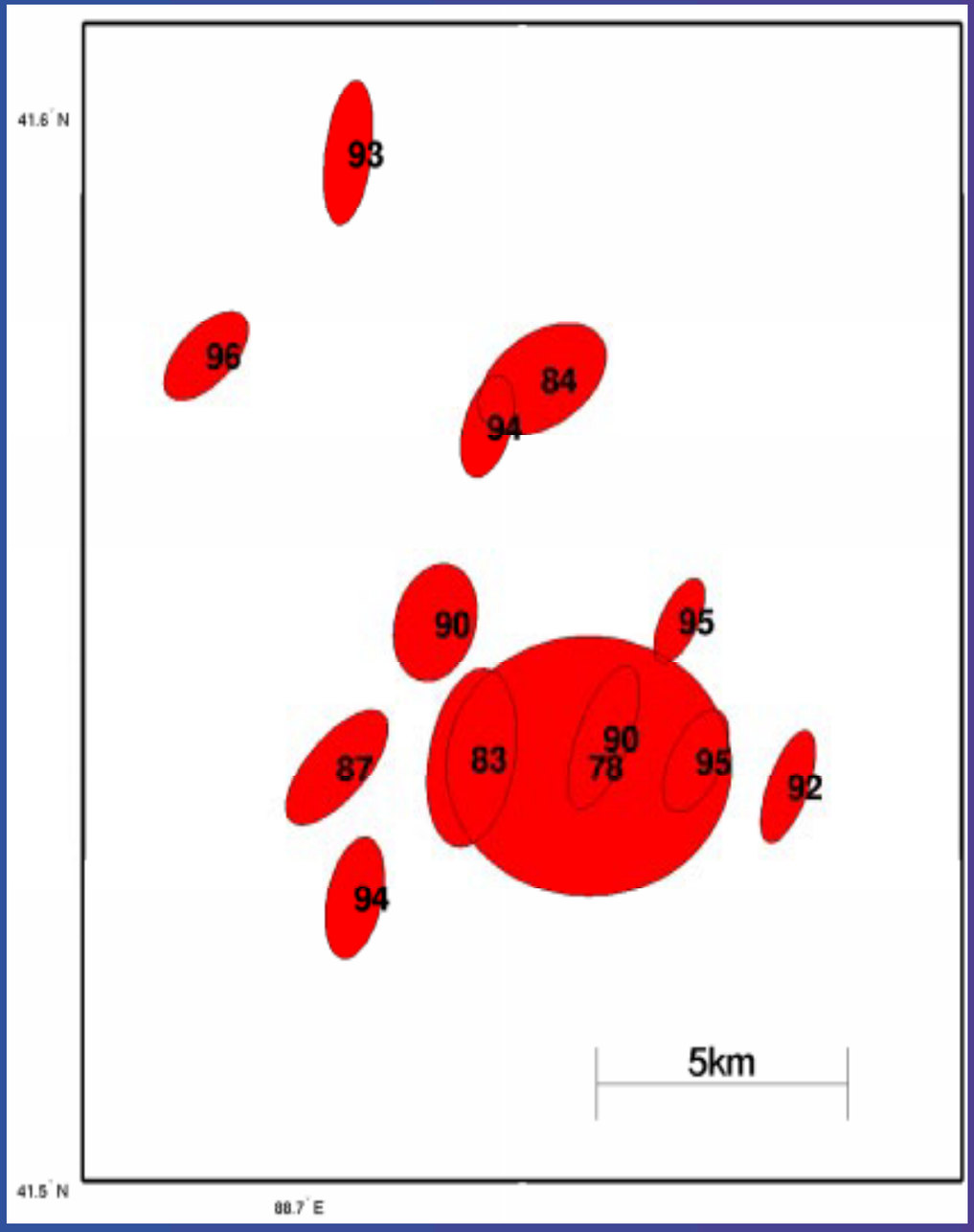
X-correlation at ULHL.HHZ



Double-difference Locations of Lop Nor Shaft Explosions

Most events are GT1

Absolute locations identified from satellite imagery.



Conclusions

Examples with order of magnitude improvement in measurement error

local -- interevent distances up to 2 km, 1 to 10 Hz band

regional -- interevent distances 5 to 10 km, 0.5 to 5 Hz band

teleseismic -- interevent distances 20 to 30 km, 30 to 10 sec band

1/4 wavelength rule more or less holds

Double whammy is when both model and measurement error can be reduced resulting in up to two orders of magnitude improvement in earthquake locations.

The new degree of resolution obtained enables more detailed studies.

Calaveras Fault

Lop Nor explosions

Double-difference approach is preferred for correlation data because it directly inverts the measured differential travel times.

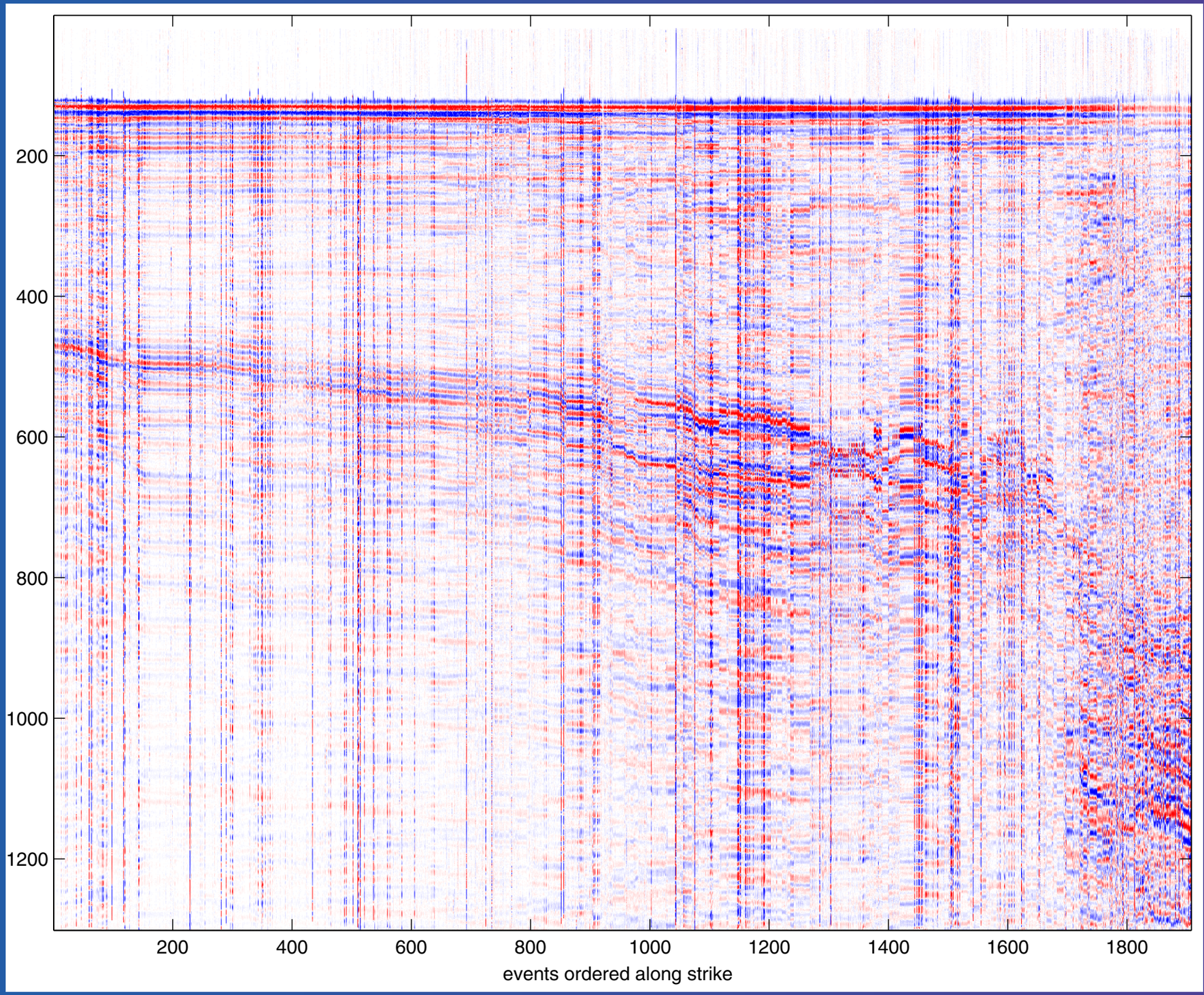
Future Directions

Differential Tomography
- model error
- measurement error

Record sections for Calaveras Fault
- converting relative travel times to absolute

Northern California correlation database
- 250,000 events
- 2.5 billion correlation measurements
- 10 million correlations per hour

35 km Record Section



Northern CA correlation database

250,000 events

2.5 billion measurements