What Physics Underlies Seismogram Correlation?

Exploring Correlation Methods to Identify Explosions

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Signal Analysis Review

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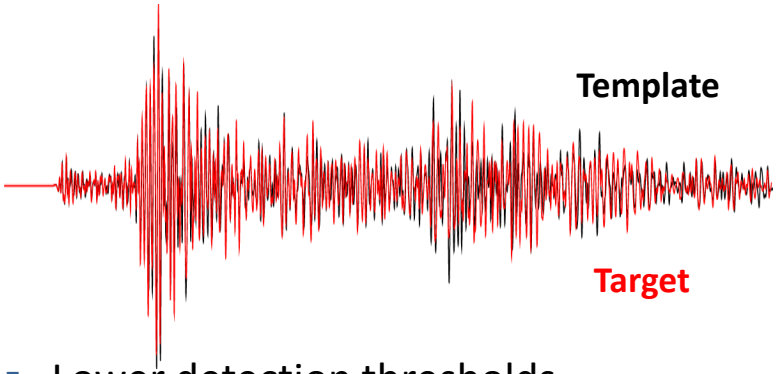
How unique is any given seismogram?

If nonunique then correlation is a powerful tool

- We can find matches



- Lower detection thresholds
  - (e.g., multichannel correlation; Gibbons and Ringdal, 2006, 2012)
- Precise relative locations
  - (e.g., Schaff and Richards, 2004; Wen and Long, 2010)
- Event identification
  - (e.g., Schaff and Richards, 2004)
- Relative magnitude/yield
  - (e.g., Zhao et al., 2012)

Similar waveforms allows correlation processing to work but what is the physical relationship between events?

- How close in epicenter?
  - (e.g. Menke, 1999 used CC to locate)
- How close in depth?
- How close in mechanism?
  - (e.g. Kagan and Jackson, 2014 focal mechanism rotation angle)
- How close in size?
  - Magnitude or Yield
- Can we confidently use correlation to discriminate between event types and identify explosions?

Similar seismograms in point force elastic theory

$$M^1_{pq} * G^1_{pq,n} \sim M^2_{pq} * G^2_{pq,n}$$

If two events are very closely located (similar Green functions) then sources must also be very similar for seismograms to match

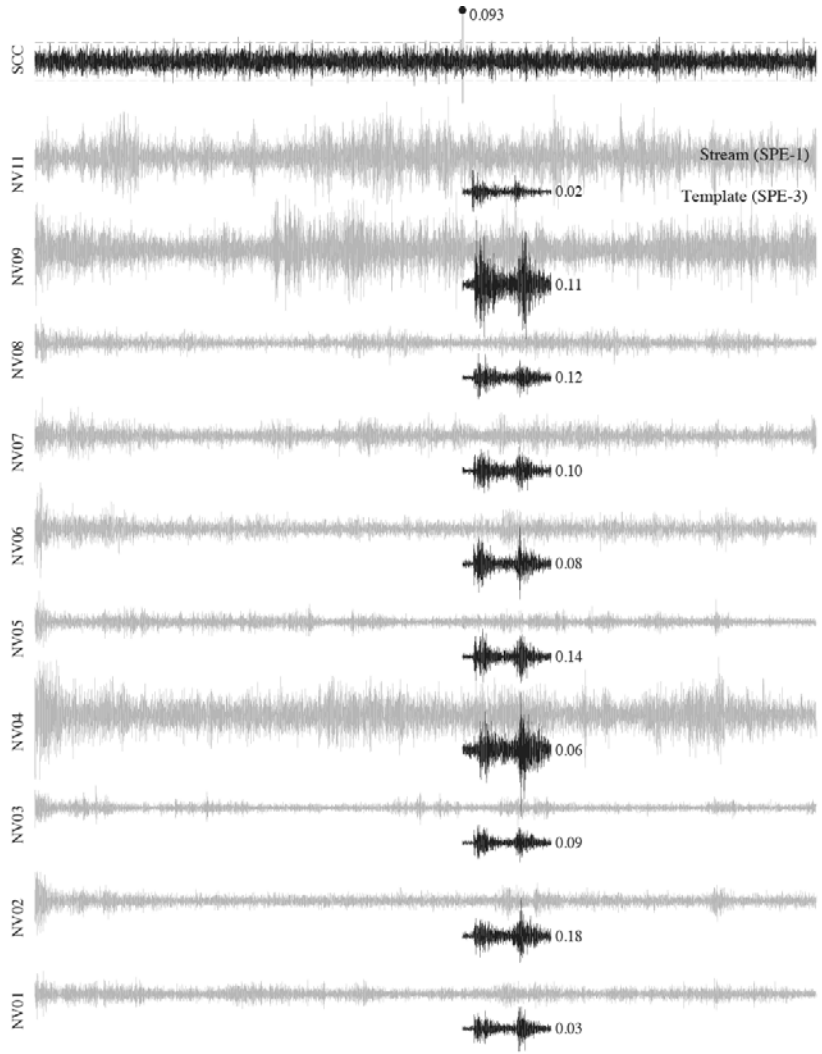
If events have different source and/or Green functions it might be possible for for tradeoffs to cause a seismogram match at some level

For narrow bands how unique are source and Green functions?

1) At what rate will we get misleading correlations for events of different types and/or large separations? (False Alarms)

2) How often will closely located explosions not correlate well? (Missed Violations)

Example: we can detect a 100 kg explosion 220 km away using a 1 ton template at the NVAR array



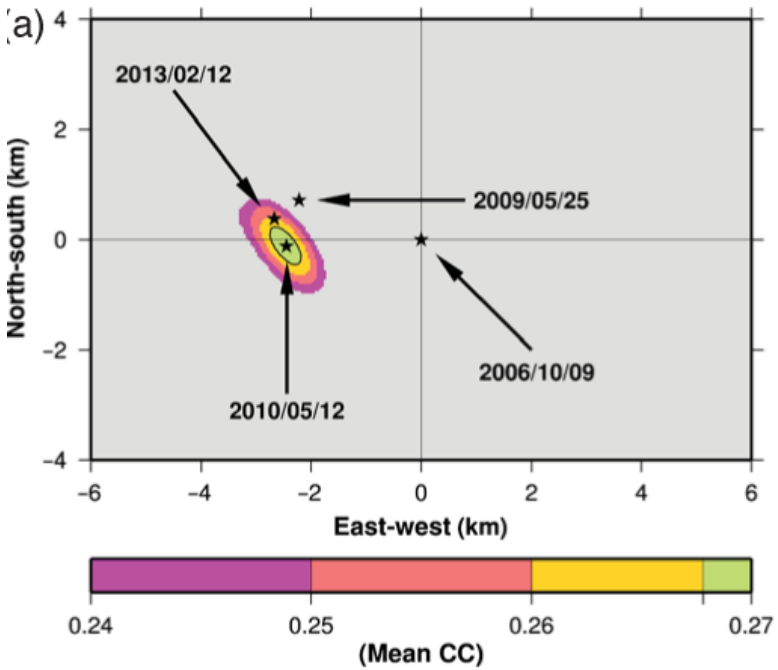
A 60 second template of the 1 ton SPE-3 run over a 10 minute data stream containing the 0.1 ton SPE-1 detects it very nicely

1-6 Hz

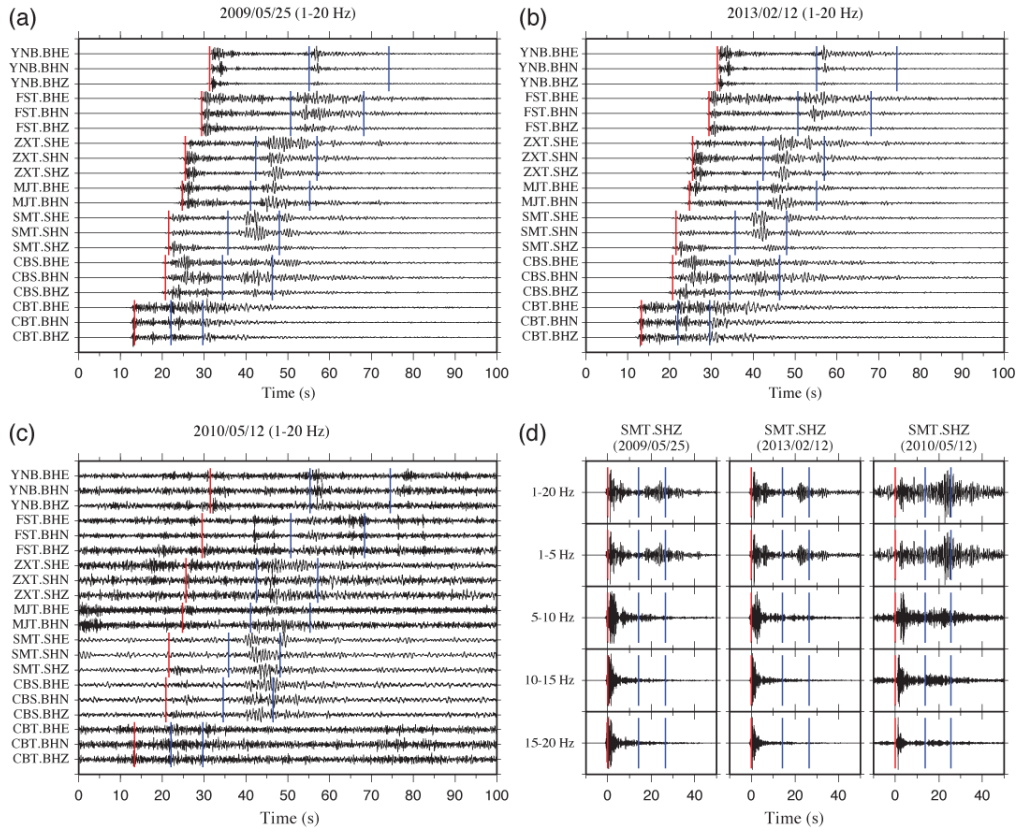
Ford and Walter, July/August 2015 SRL

In an February 2015 SRL publication Zhang and Wen claim to observe a seismic signal from an unannounced DPRK nuclear test in May 2010

Location from Zhang and Wen, 2015)



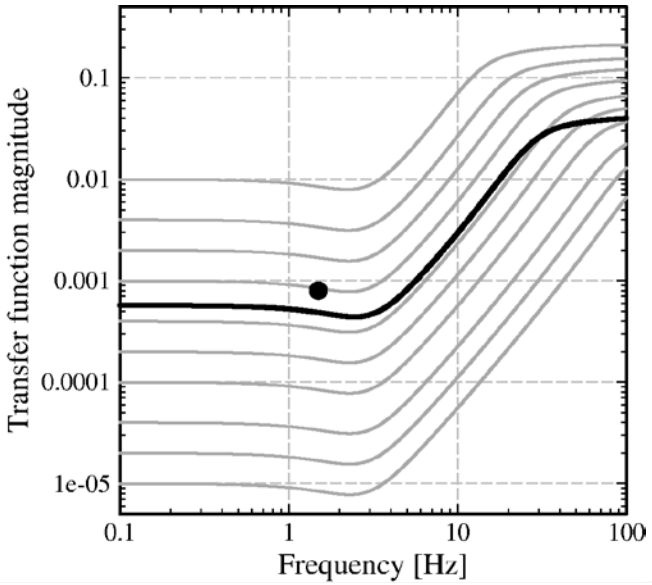
China network seismograms from Zhang and Wen, 2015)

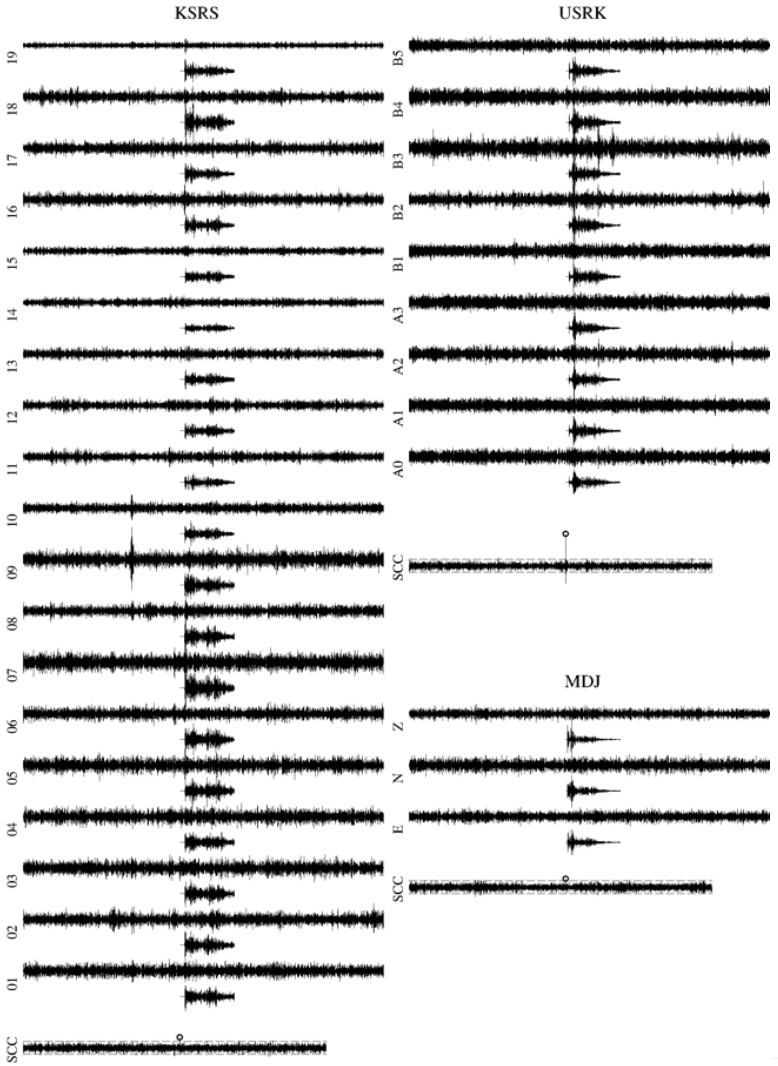


Example 2: We should be able to see the 12 May 2010 event if the Zhang and Wen 2015 source parameters for DPRK 2009 and 2010 are correct

DPRK2013 correlated with DPRK2009 X 2.9t@230m/7kt@610m (proposed yield and depth of the Zhang and Wen (2015) event and Zhang and Wen (2013) estimate of DPRK 2009).

We scaled the amplitude ratio:



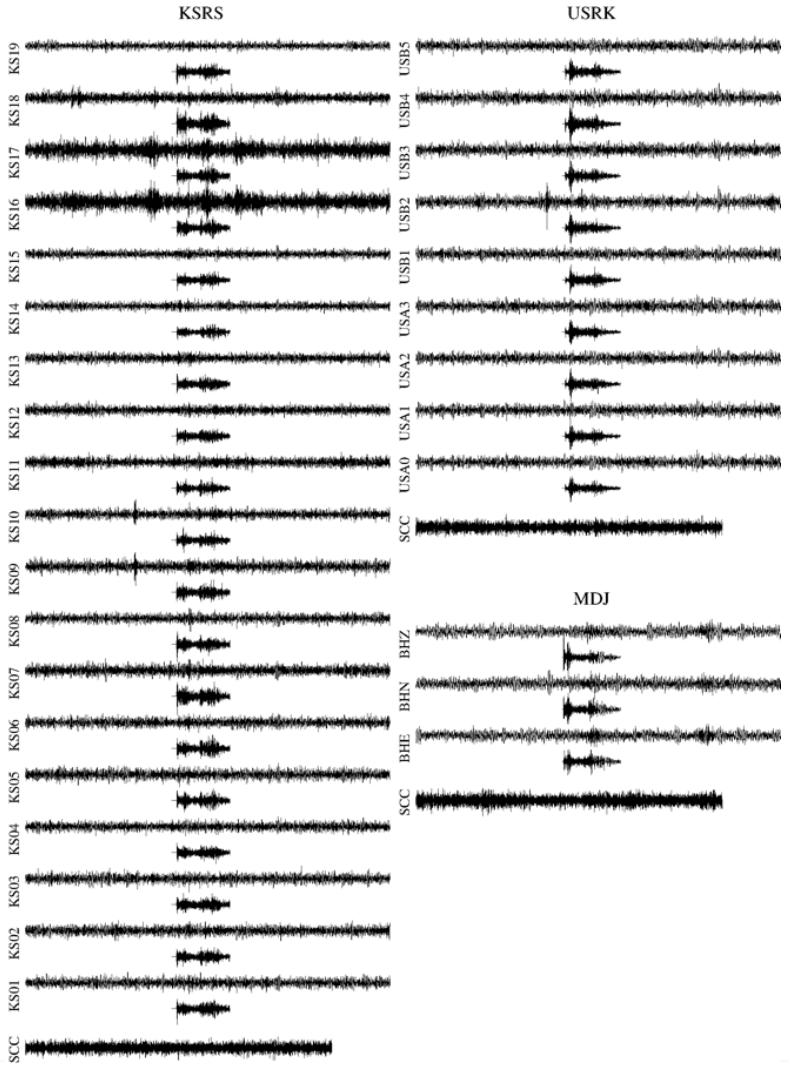


When we look for the 12 May 2010 event at USRK, KSRS and MDJ using the 2013 DPRK test as a template - we do not find anything

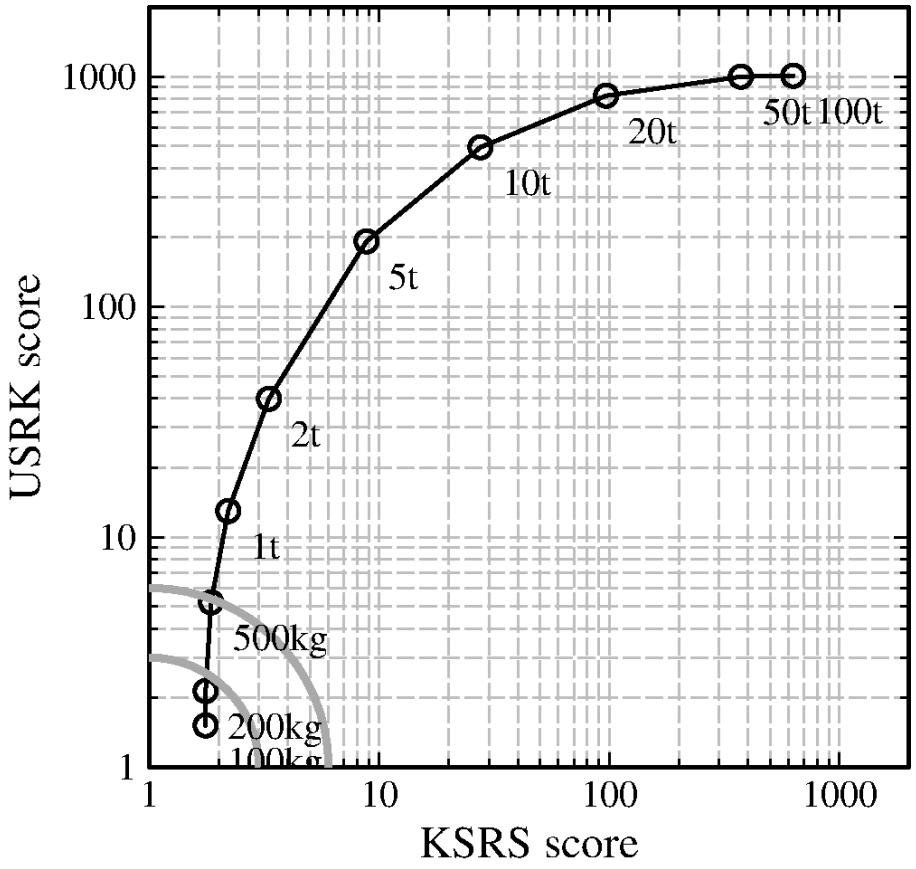
The 12 February 2013 explosion at Punggye-Ri at 2-8 Hz correlated with the stream during the predicted arrival of the event reported in Zhang and Wen (2015). The stacked correlation coefficient (SCC) is shown for each array and the three-component station MDJ.

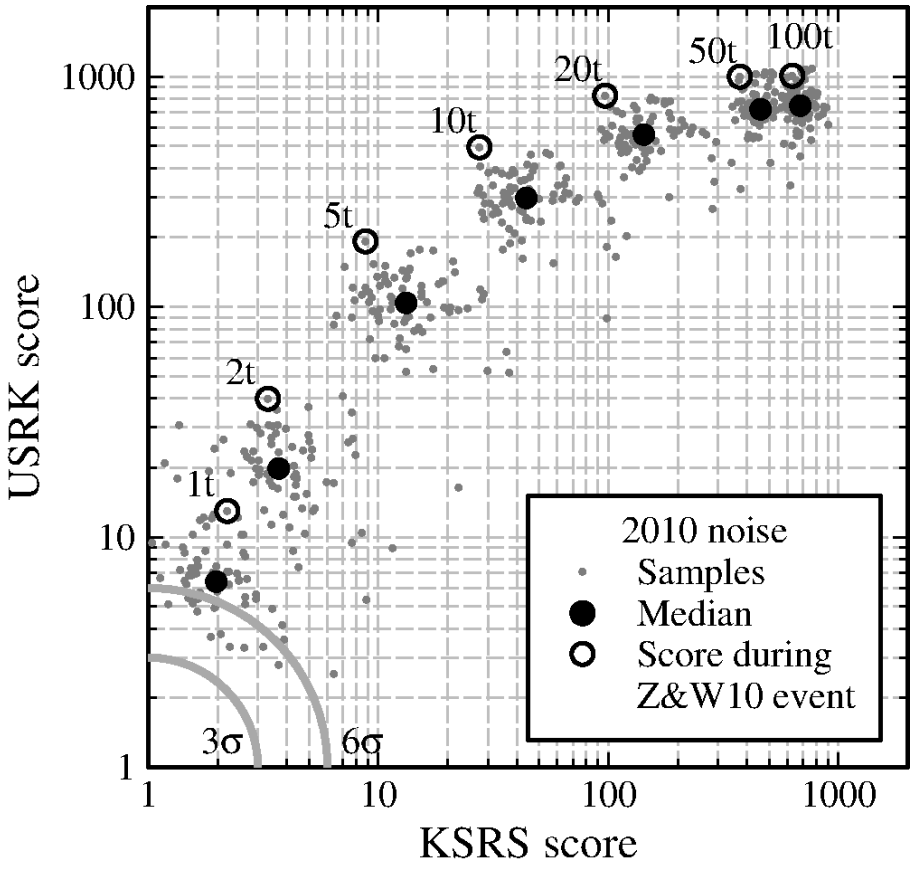
No signal is detected.

Similar results are found using the 2009 explosion as a template.



Joint USRK and KSRS detection thresholds for 120s at 2-8 Hz at time of 12 May 2010 event and 75 different times over a 1-year time period





For 12 May 2010 something well under 1 ton should be detectable and more generally 1-2 tons similarly sited should always be detectable.

Possible reasons for a correlation non-detection of the May 2010 seismic event with explosion templates

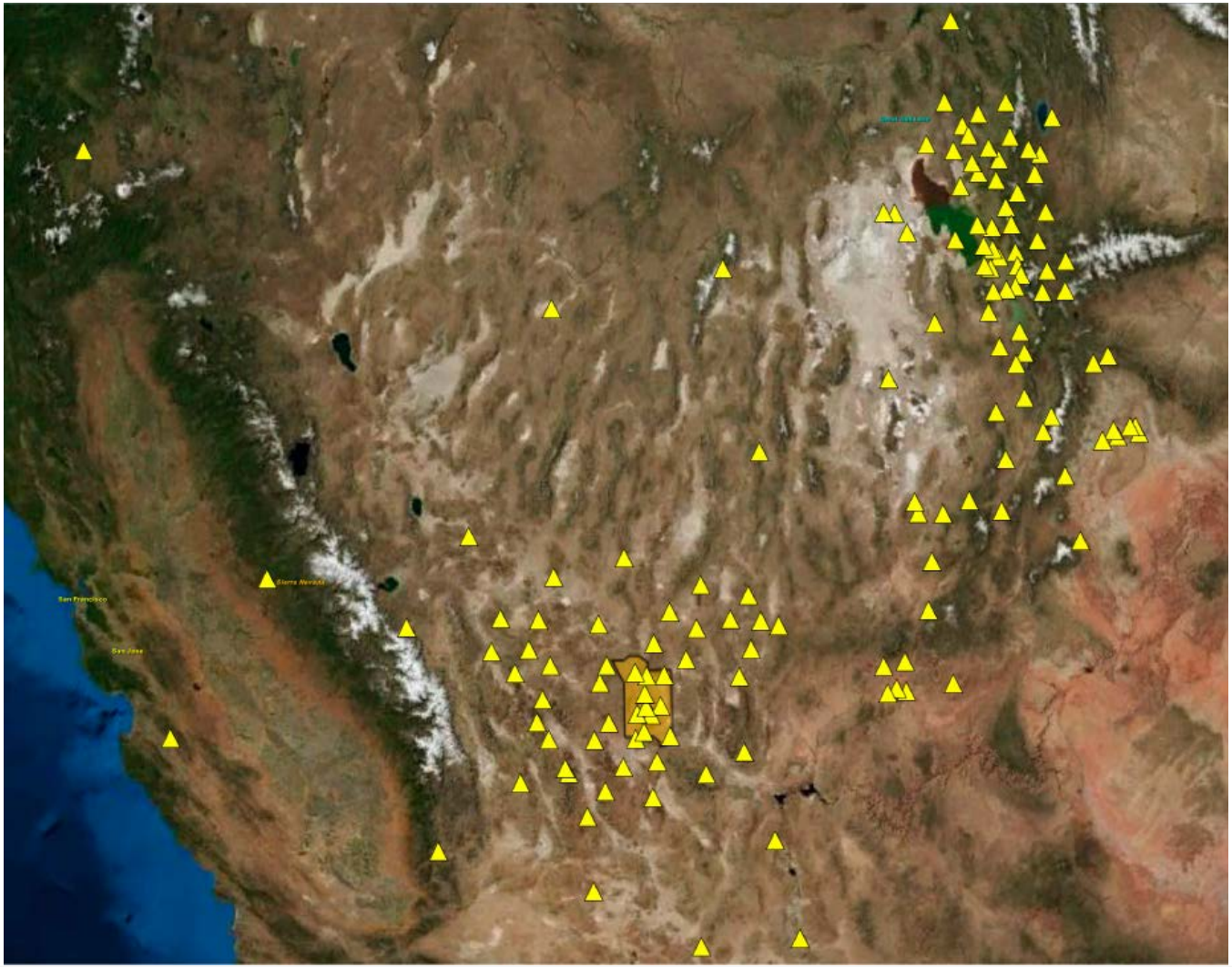
- Seismic event is smaller than claimed (well under 1 ton instead of 2.9 t)
- Seismic event is farther away from template events than claimed
- Seismic event is a different source type than a nuclear test
- Other factors – scaled depth, material properties, tectonic release, etc., that we do not currently understand are degrading the correlation

We need to better understand the physics underlying seismic event correlation

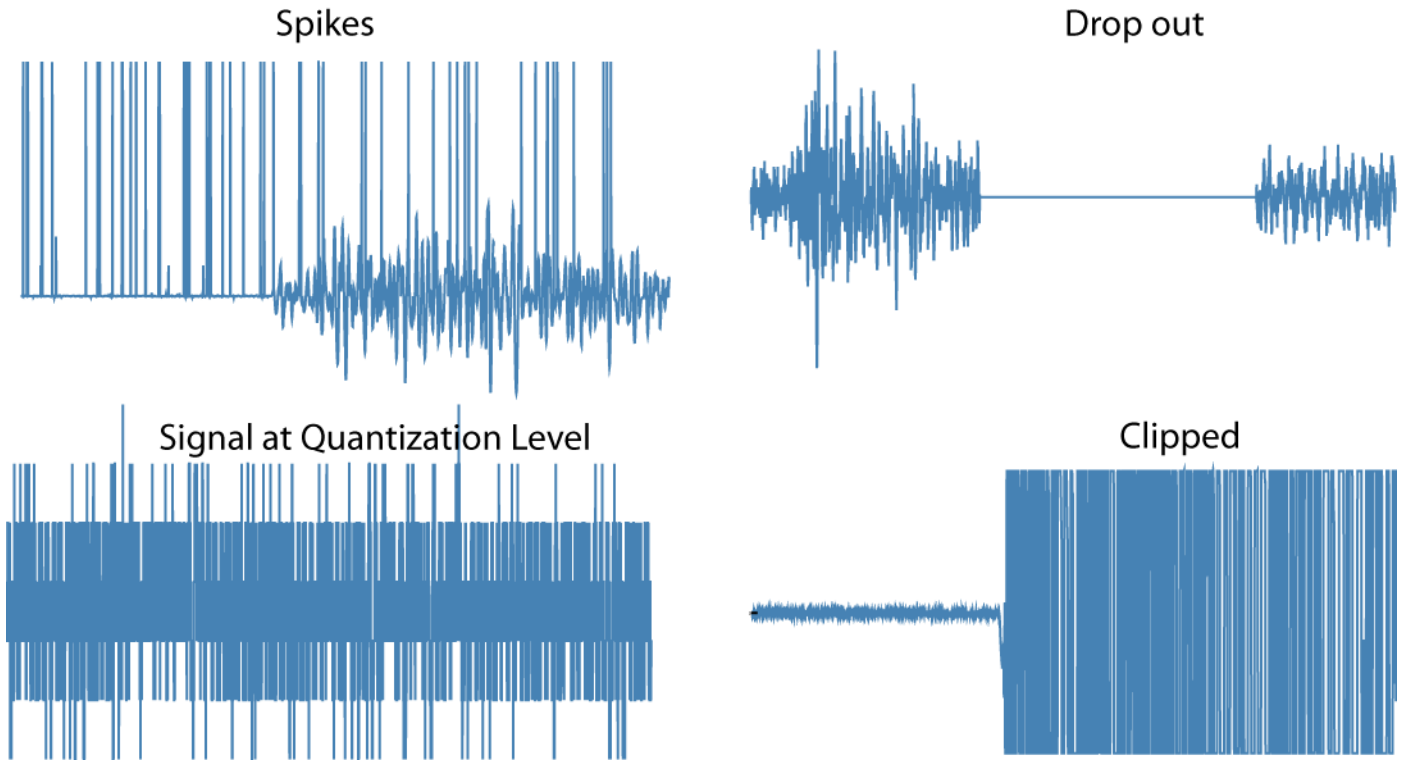
To better understand correlation behavior we are studying the historic nuclear tests in southern Nevada

- Started with
  - 452 nuclear explosions from 1966 to 1992
  - 250 earthquakes, 692 probable earthquakes and 16 chemical explosions
  - 61,845 waveforms at 242 stations
  - 885 distinct STA-CHAN pairs
  - > 1 billion STA-CHAN-PHASE-EVID1-EVID2 combinations processed
- Data processed on a 3-node cluster for ~5 days
  - Same methodology as Dodge and Walter (2015)
  - 15 frequency bands and 8 phase windows
  - Min wavelength criteria, SNR>0, distance < 90^{o} and QC processing
- In this first cut we finished with
  - 354 nuclear explosions, 16 chemical explosions and 546 likely quakes at 157 stations
  - 34,807 waveforms with 445 STA-CHAN pairs
  - 45.5 million correlations (no CC threshold)

Regional and local stations studied



Historic data has too many problems to fix by hand – we use a supervised machine learning QC process

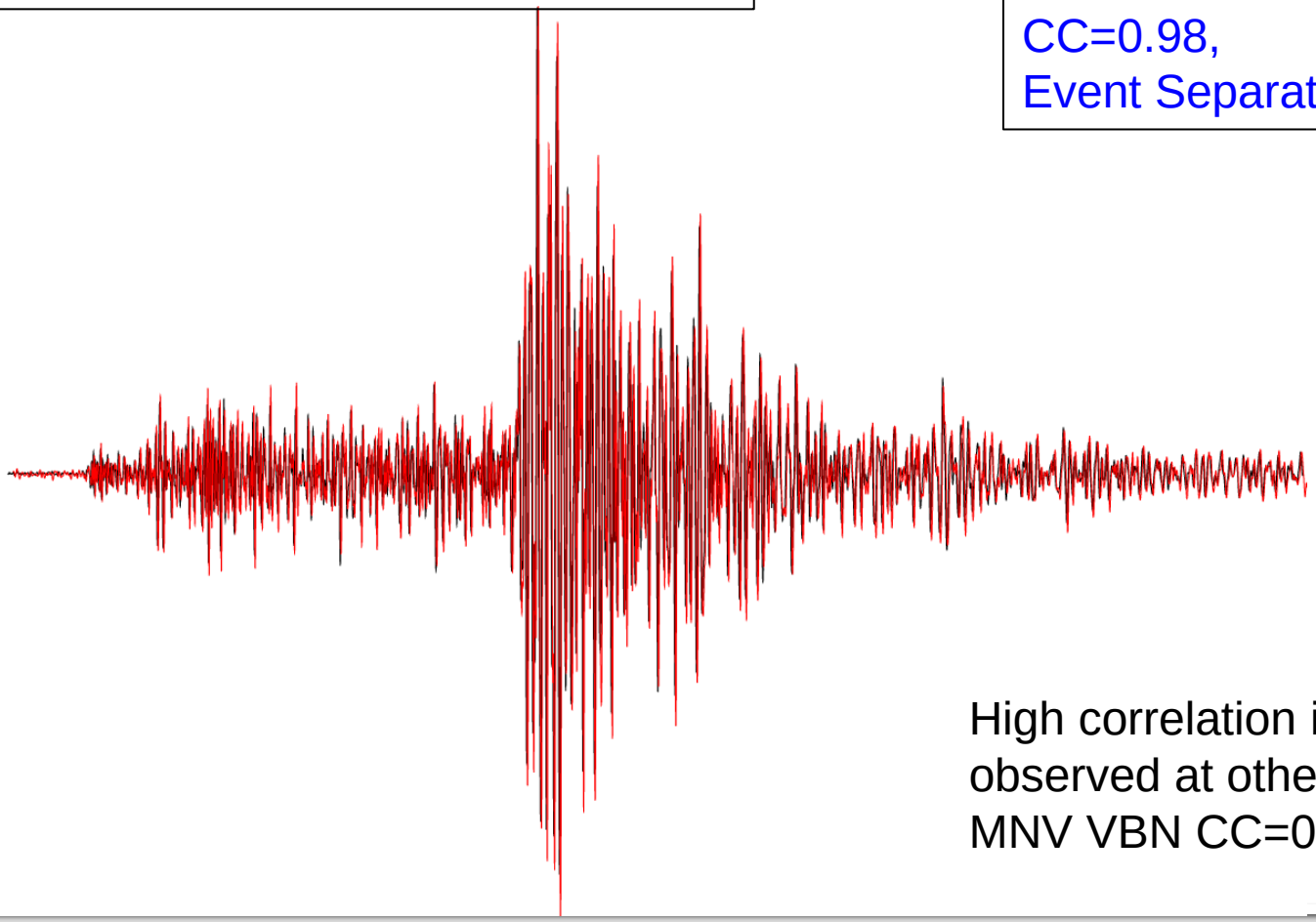


- Training data consisted of 8005 hand labeled samples: 5184 good / 2821 bad
- Used Weka tool suite (Hall et al., 2009) to classify
- 10-fold cross validation: 97% of true & 99% of artifacts are correctly classified

As expected there are some very highly correlated earthquakes in the results

November 6, 1992 ML 3.4 earthquake
September 10, 1992 ML 3.2 earthquake

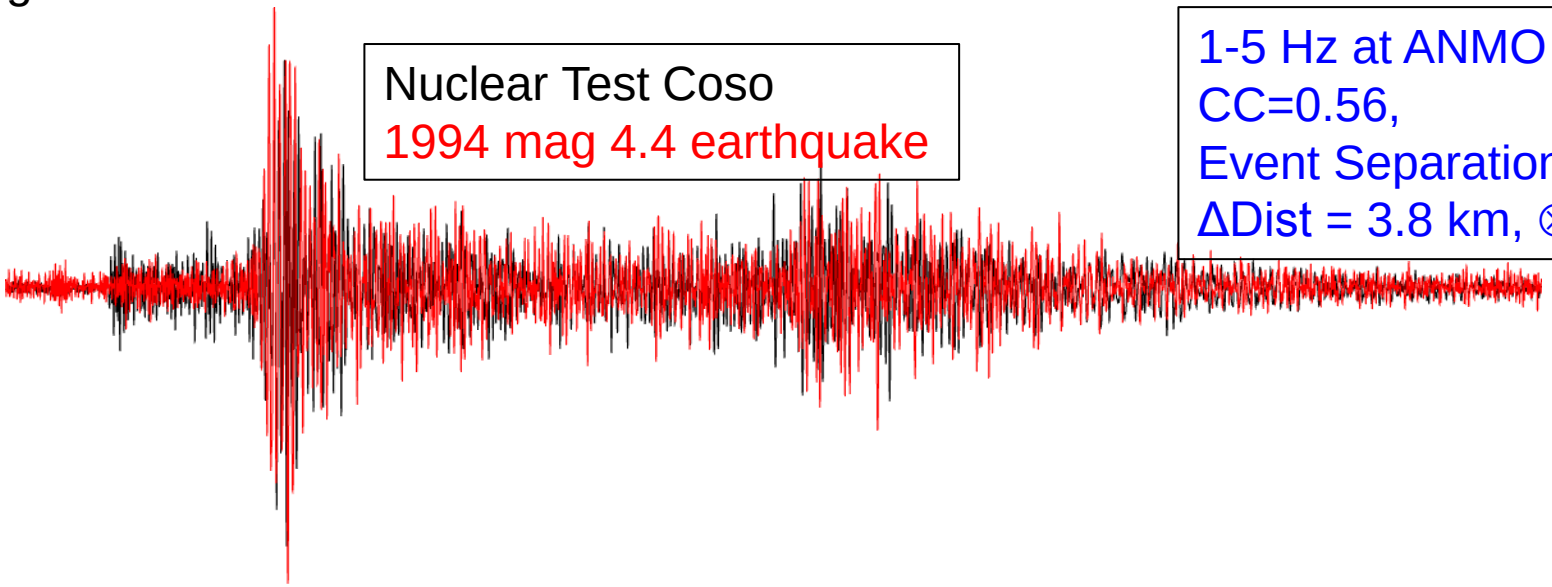
1-5 Hz at KNB VBN
CC=0.98,
Event Separation 0.5 km



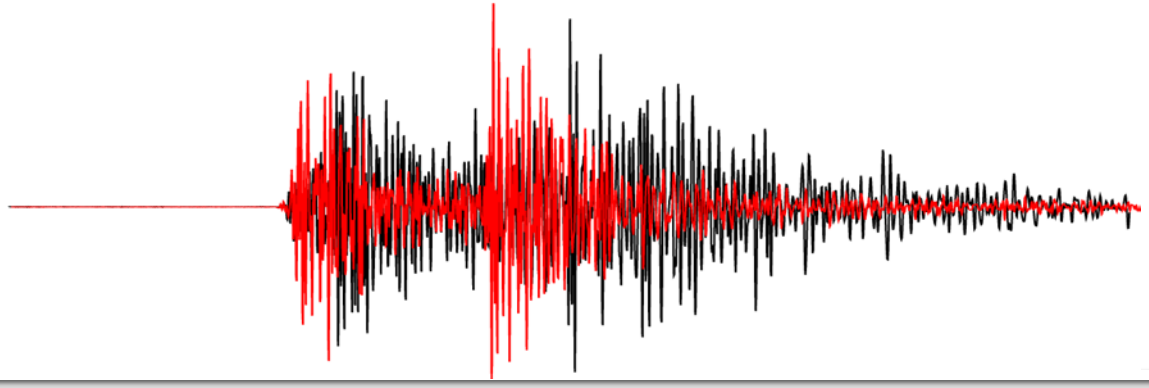
High correlation is also observed at other stations:
MNV VBN CC=0.96

Also as expected the nuclear tests do not correlate very highly with the earthquakes

Highest correlation for broad bands is a CC of about 0.5

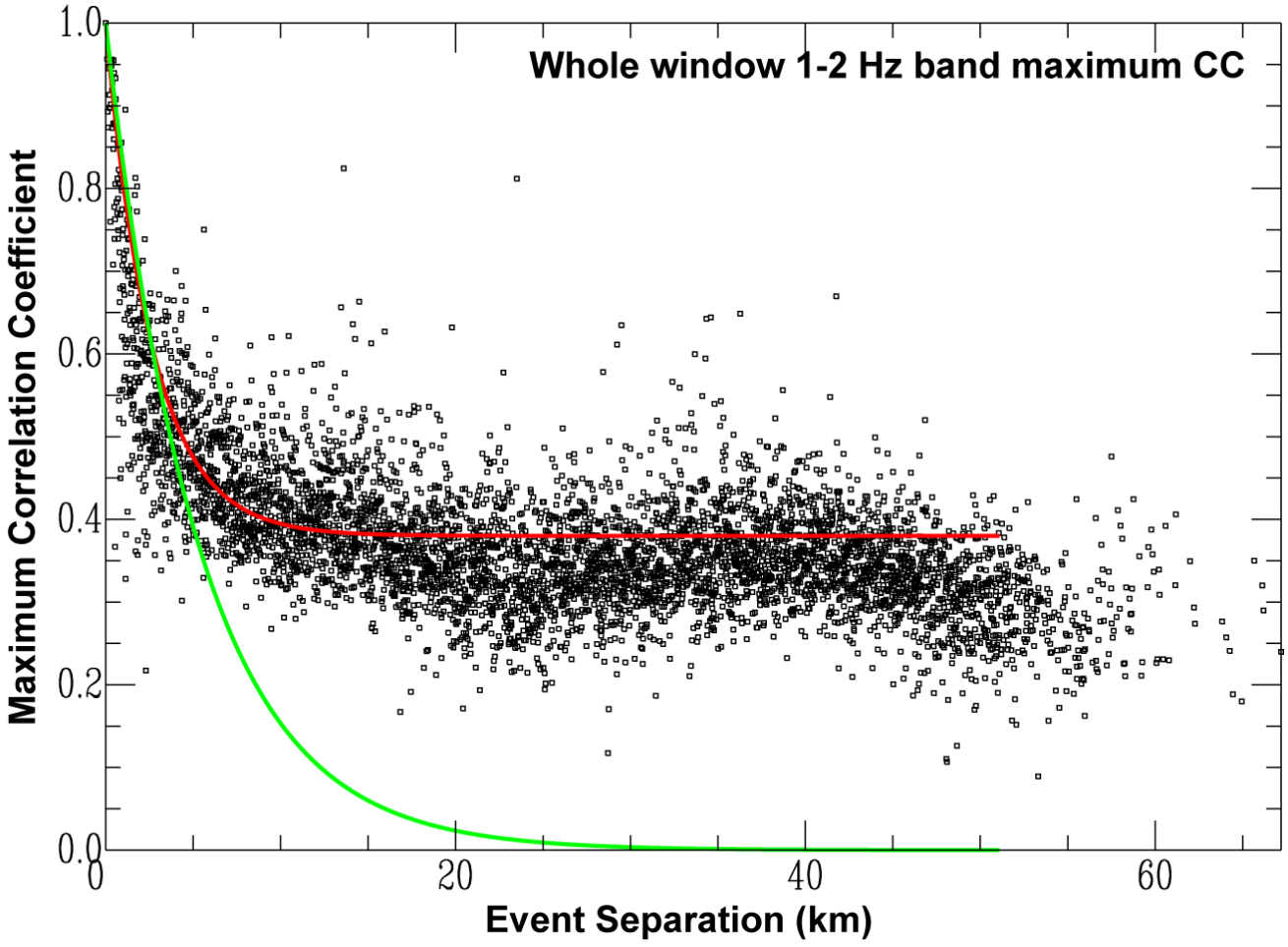


However at other stations the same events correlation is much lower:



So what about explosions?

For the maximum correlation the nuclear tests show the expected decrease in correlation as event separation increases…



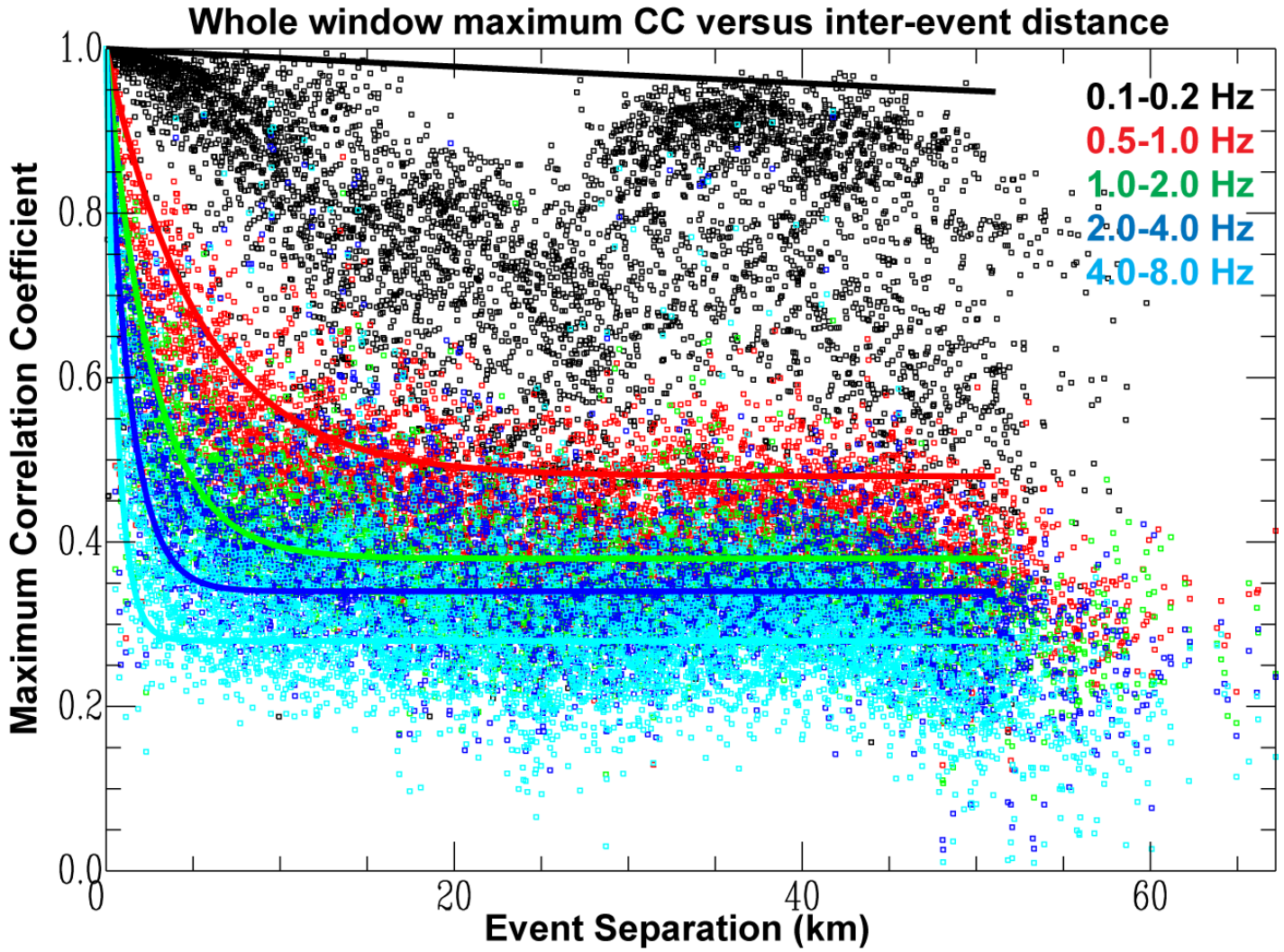
Good SNR events

Menke (1999)
CC = exp(-Δ/s)
Where *Δ* is event separation and *s* is related to wavelength

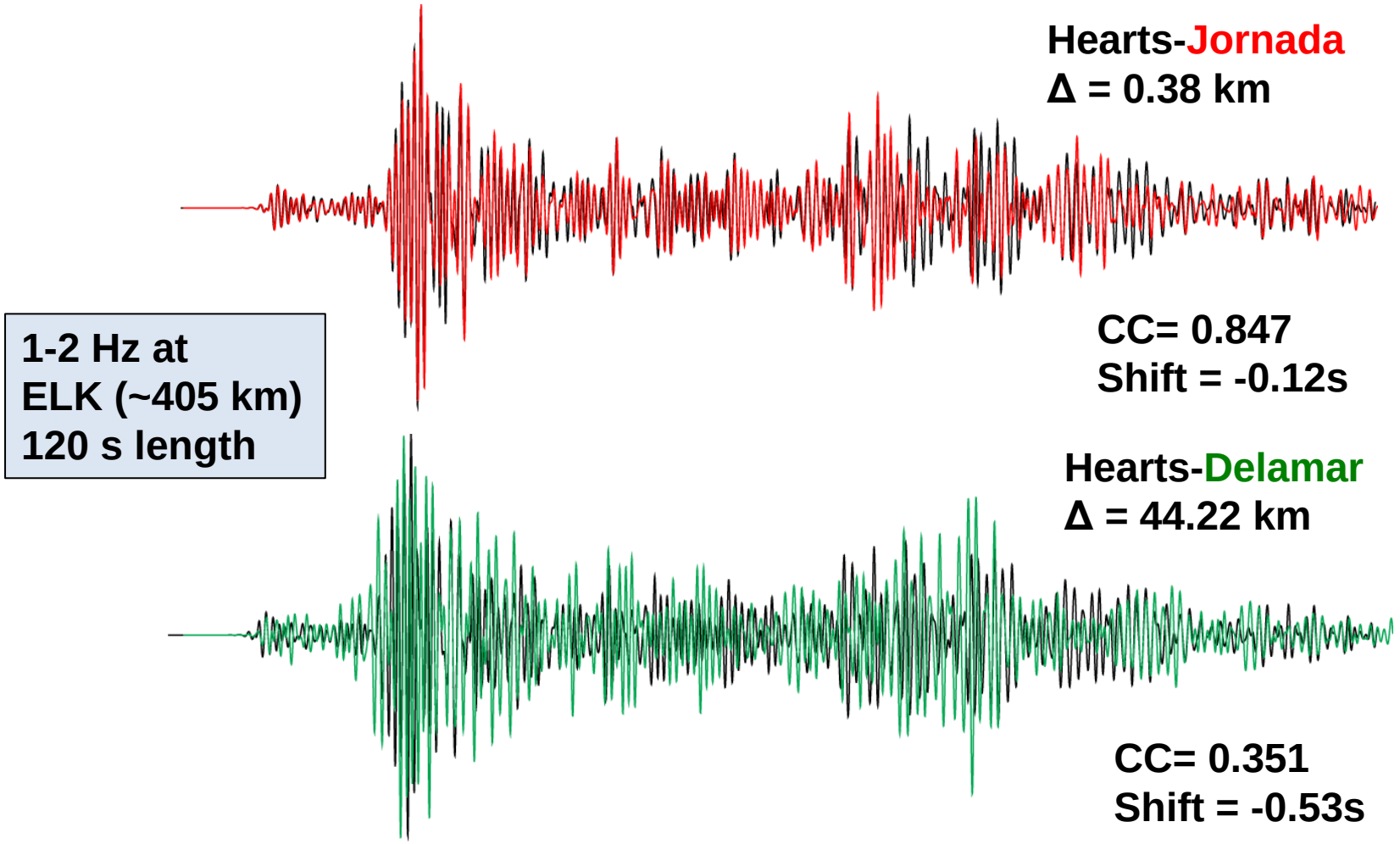
Here f = 1.5 Hz and s ~ 2λ or ~5 km

A better fit is found using a CC floor for large event separation when events have good SNR

To first order the wavelength model works for short separations and each frequency has a different floor

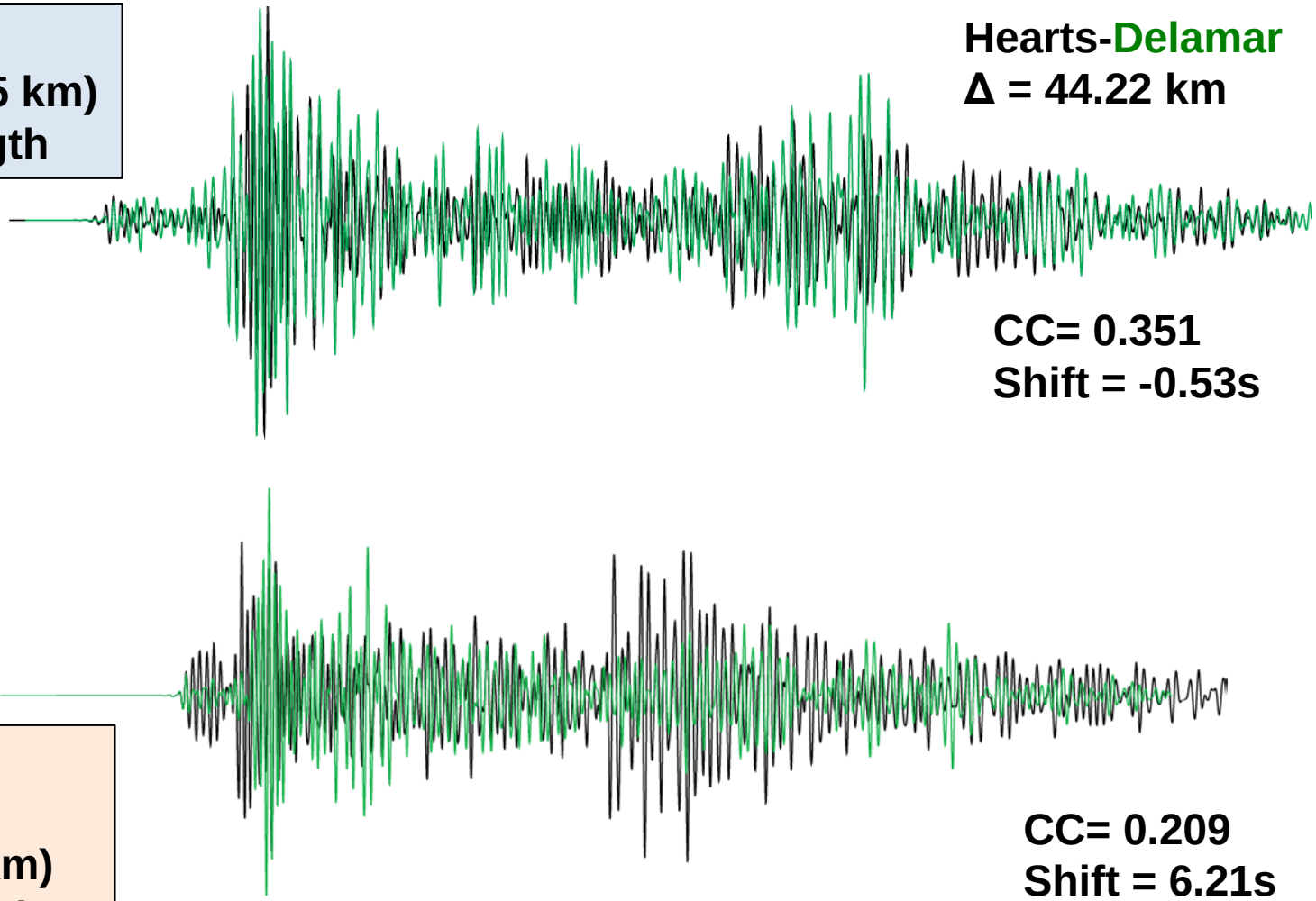


At large separations for events with good SNR there is a lower CC floor above zero that is azimuthally dependent

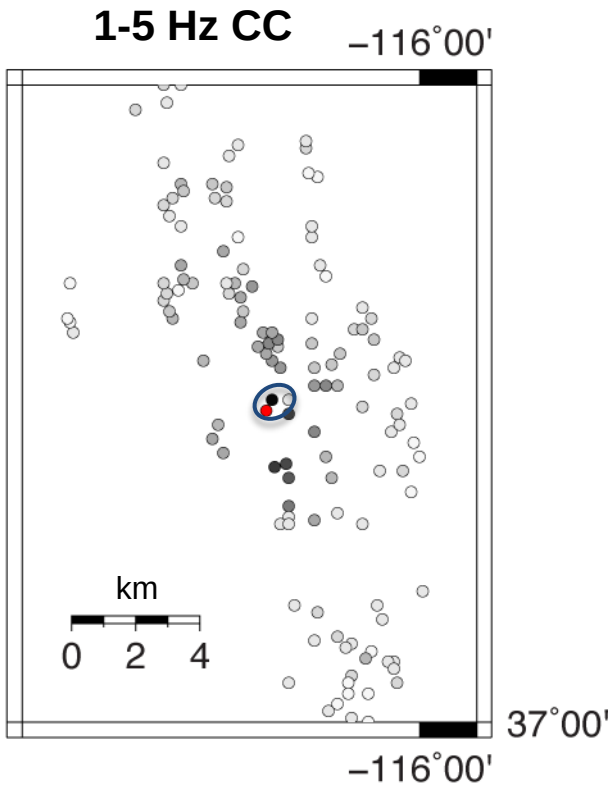


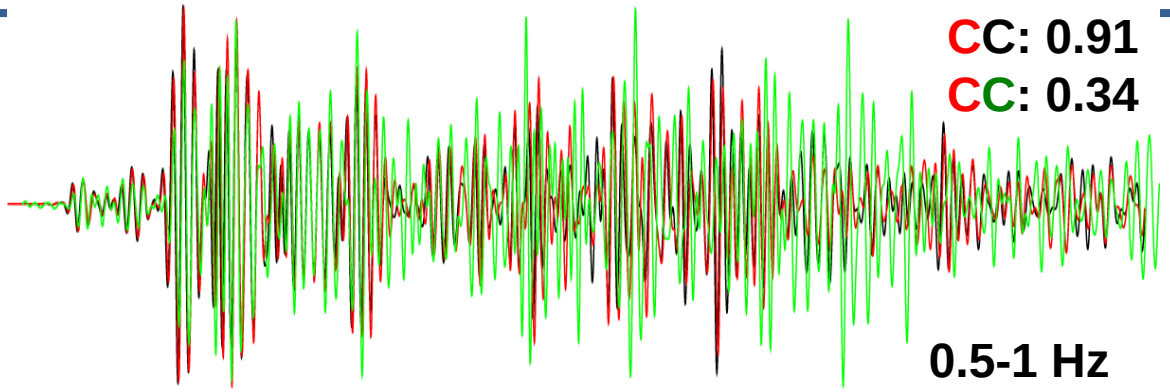
Events with at the same distance to the recording station are causing the floor

This issue can be addressed by using more information e.g. more bandwidth and/or multiple stations with azimuthal separation

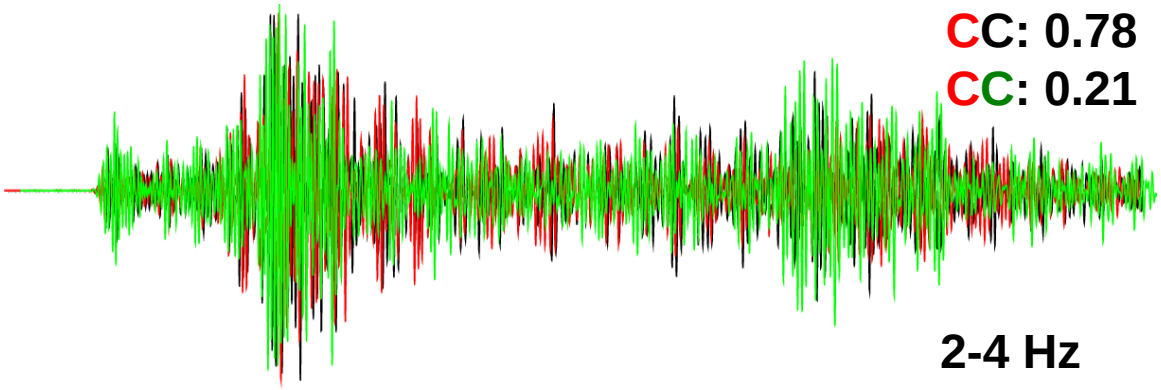


However some close explosions correlate poorly: Hearts, Jornada and Borrego at ELK





Hearts - Jornada separation is 380 m
Hearts - Borrego separation is 790m



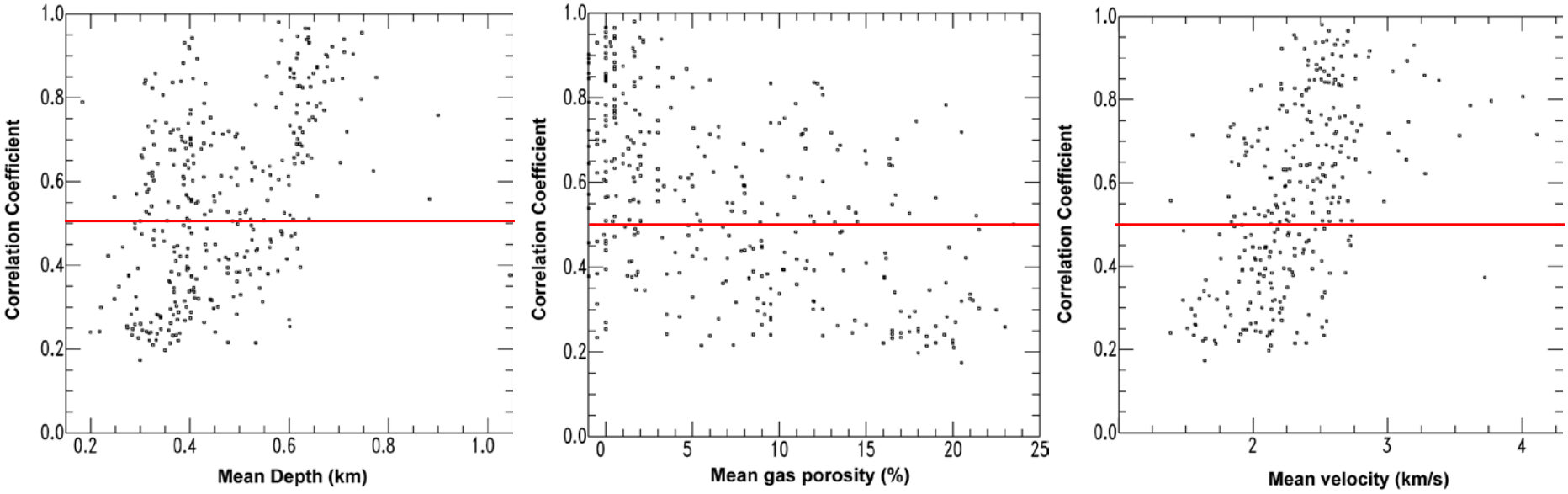
Hearts – DOB:640m mb:6.0
Jornada – DOB:639m mb:5.9
Borrego – DOB:563m mb:4.1

Same event type, located very close by does not guarantee a high CC!

Hearts-Baseball separation is 720 m, 0.5-1 Hz CC is 0.83, 2-4 Hz CC is 0.50

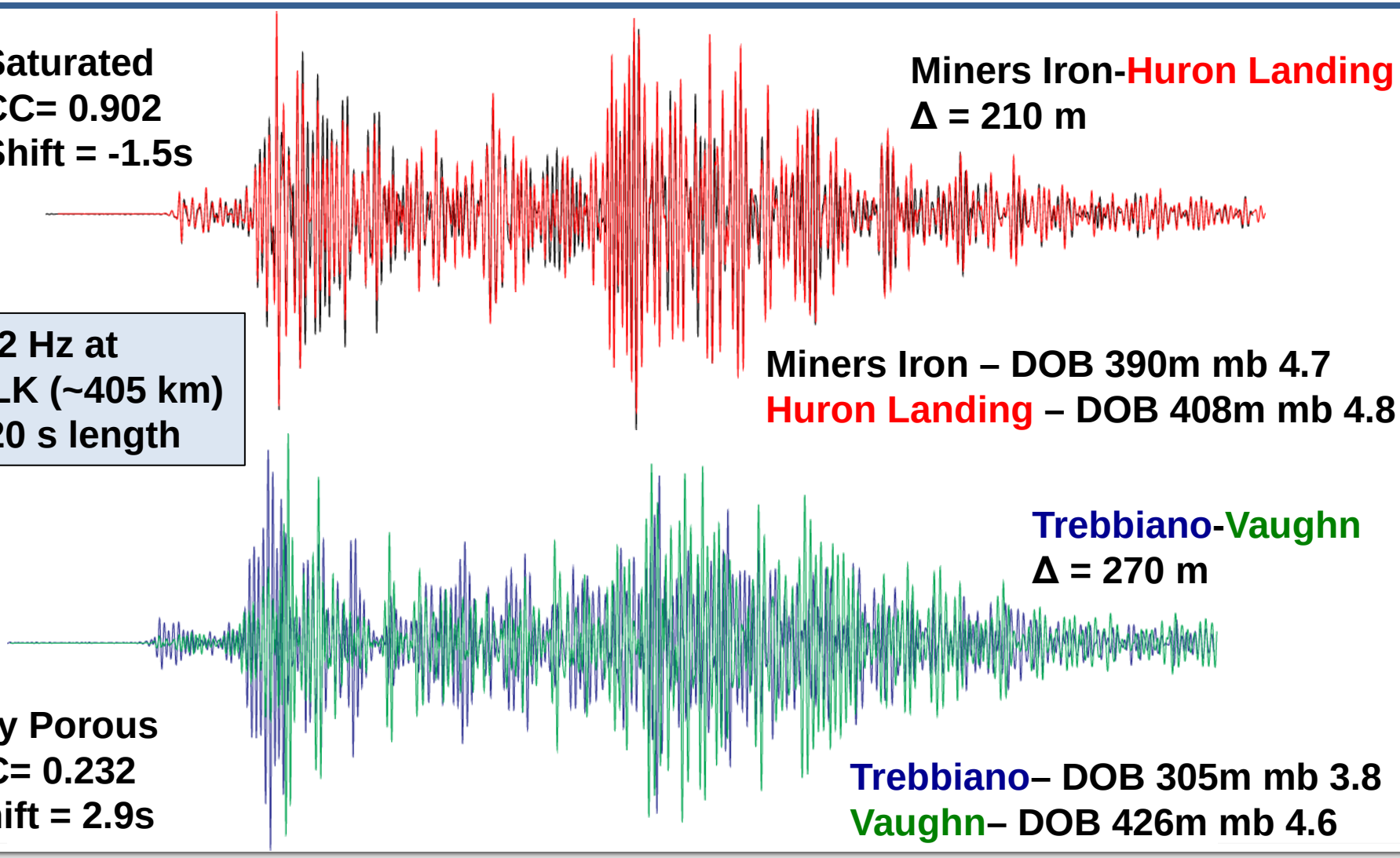
Focusing only on explosions with 1 km of each other we note that deep ones below the water table correlate better than shallow ones

Nuclear explosions within 1 km of each other recorded at ELK on the vertical component Whole window, 1-2 Hz



Note there are many explosions within 1 km of each other with a CC < 0.5!
These tend to be shallow, with high gas porosity and low velocity

Example pairs – one in the perched water table of Rainier Mesa and one above the water table at Yucca Flat



Summary

- If the right template exists correlation may be able to dramatically drive down event detection thresholds and provide high precision location, identification and yield estimation – What is the right template?
- As expected some earthquakes correlate very highly within sequences
- Also as expected the Nevada nuclear tests do not correlate well with any earthquakes in the region
- Explosions in saturated material generally correlate well when closely located (< 1-2 wavelengths)
- Shallow, dry, porous, low-velocity material explosions correlate poorly even when closely located
- The SPE program is providing insight into the effects of material and SDOB on seismograms
- Correlation is not a silver bullet – for the first event in a new region no empirical template exists and correlation will not work – so must use other processing
- This is work in progress and we have much more data analysis to do

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