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Long Period Long Duration Seismic Events During Hydraulic Stimulation of a Shale Gas Reservoir*

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Abstract

We investigate two classes of unusual events of long duration and relatively low frequencies observed during hydraulic fracturing operations in a gas shale reservoir. Multiple stages of hydraulic fracturing operations in five sub-parallel wells were monitored with an array of seismometers deployed in the central horizontal well. When this well was fractured, the array was deployed in a vertical well. Some of the unusual seismic events recorded are clearly tube waves that propagate along the monitoring well from the heel toward the toe with a velocity along the borehole of ~1.5km/s. The tube waves propagate down the well from surface, but origin of the tube waves is not known. The other unusual events are similar in appearance to non-volcanic seismic tremor sequences. They are of 10-50 seconds in duration and are observed in the frequency band of 10-40 Hz, which is much lower than the characteristic frequency band of microearthquakes (100-300 Hz). Complex but coherent wave trains are observed in both the horizontal and vertical arrays. These wave trains have very slight moveouts corresponding to apparent velocities ranging from 25 km/s to 9 km/s. The moveout recorded on the vertical array indicates that they are not caused by a surface noise source; rather they result from a source in the reservoir. Although it is difficult to resolve any clear P- and S-wave arrivals, one possible source of these low frequency, long duration events is sub-seismic slow slip on pre-existing faults. The first of these unusual events were observed in the later part of the very first hydrofrac stage of the first experiment and then in almost all the following stages in the five wells. One interesting observation is that they occur before the pumping starts in some stages and even after the pumping stops in other stages. In our ongoing work we will be trying to locate these events using waveform cross-correlation and double-difference tomography.

References

Nadeau, R. M. and A. Guilhem, 2009, Nonvolcanic Tremor Evolution and the San Simeon and Parkfield, California Earthquakes: Science, v. 325/5937, p. 191-193. doi:10.1126/science.1174155

Obara, K., 2002, Nonvolcanic Deep Tremor Associated with Subduction in Southwest Japan: Science, v. 296/5573, p. 1679-1681. doi:10.1126/science.1070378

Peng, Z. and J. Gomberg, 2010, An integrated perspective of the continuum between earthquakes and slow-slip phenomena: Nature Geoscience, v. 3, p. 599-607. doi:10.1038/ngeo940

Shelly, D.R., G.C. Beroza, S. Ide, and S. Nakamuta, 2006, Low –Frequency earthquakes in Shikoku, Japan, and their relationship to episodic tremor and slip: Nature, v. 442, p. 188-191. doi.10.1038/nature04931.

Vermylen, J.P. and M.D. Zoback, 2011, Hydraulic Fracturing, Microseismic Magnitudes, and Stress Evolution in the Barnett Shale, Texas, USA: SPE, 140507-MS, 15 p. doi:10.2118/140507-MS

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Long Period Long Duration Seismic Events during Hydraulic Stimulation of a Shale Gas Reservoir.

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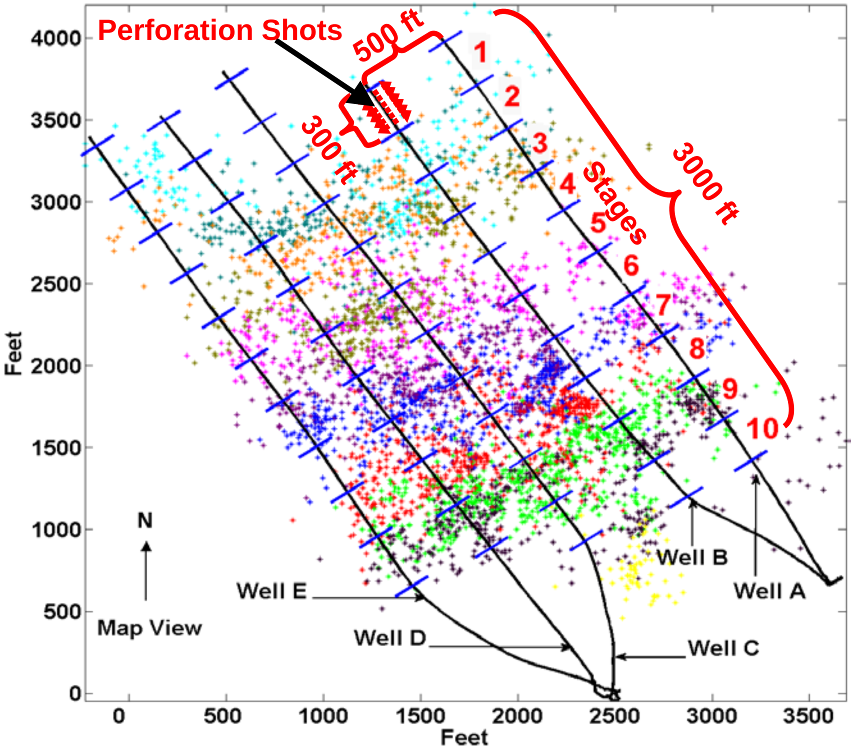
Motivation: How exactly does stimulation by hydraulic fracturing occur ?

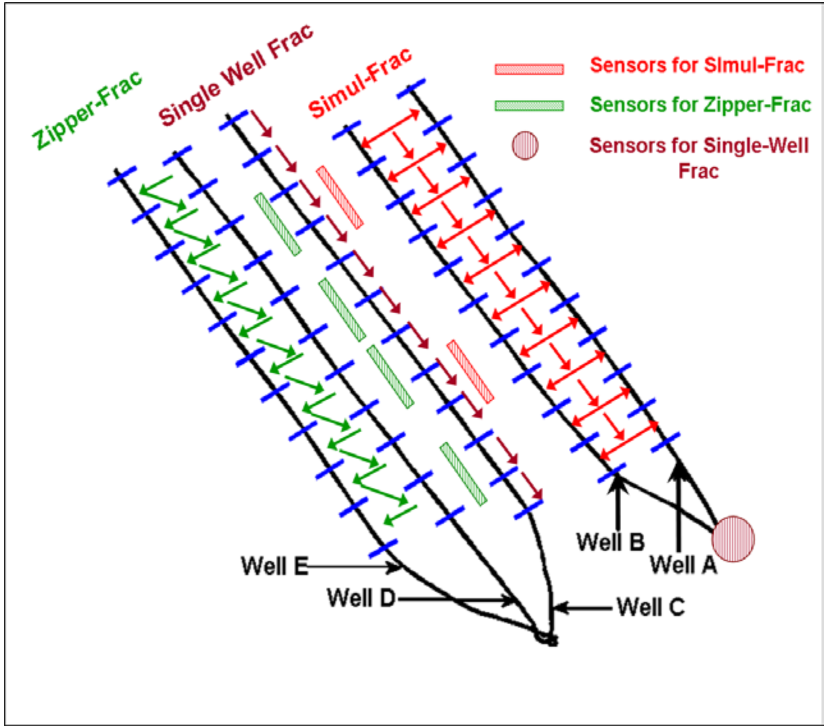
- Typical induced micro-earthquakes during hydraulic stimulation of a shale gas reservoir are of magnitudes ~ -2 to -4 and correspond to maximum patch size of ~0.6 m and a displacement of < 0.1 mm.
- Do these micro-earthquakes change the reservoir permeability sufficiently to give the observed recovery rates or are there other modes of deformation responsible for the stimulation ?
- Can these processes be observed in the seismograms used for microseismic monitoring and analysis ?

Hydraulic Fracturing and Micro-seismic Monitoring Program

5 Wells, total 40 stages, ~4500 located micro-earthquakes, ~100 per stage,
3 different fracturing programs

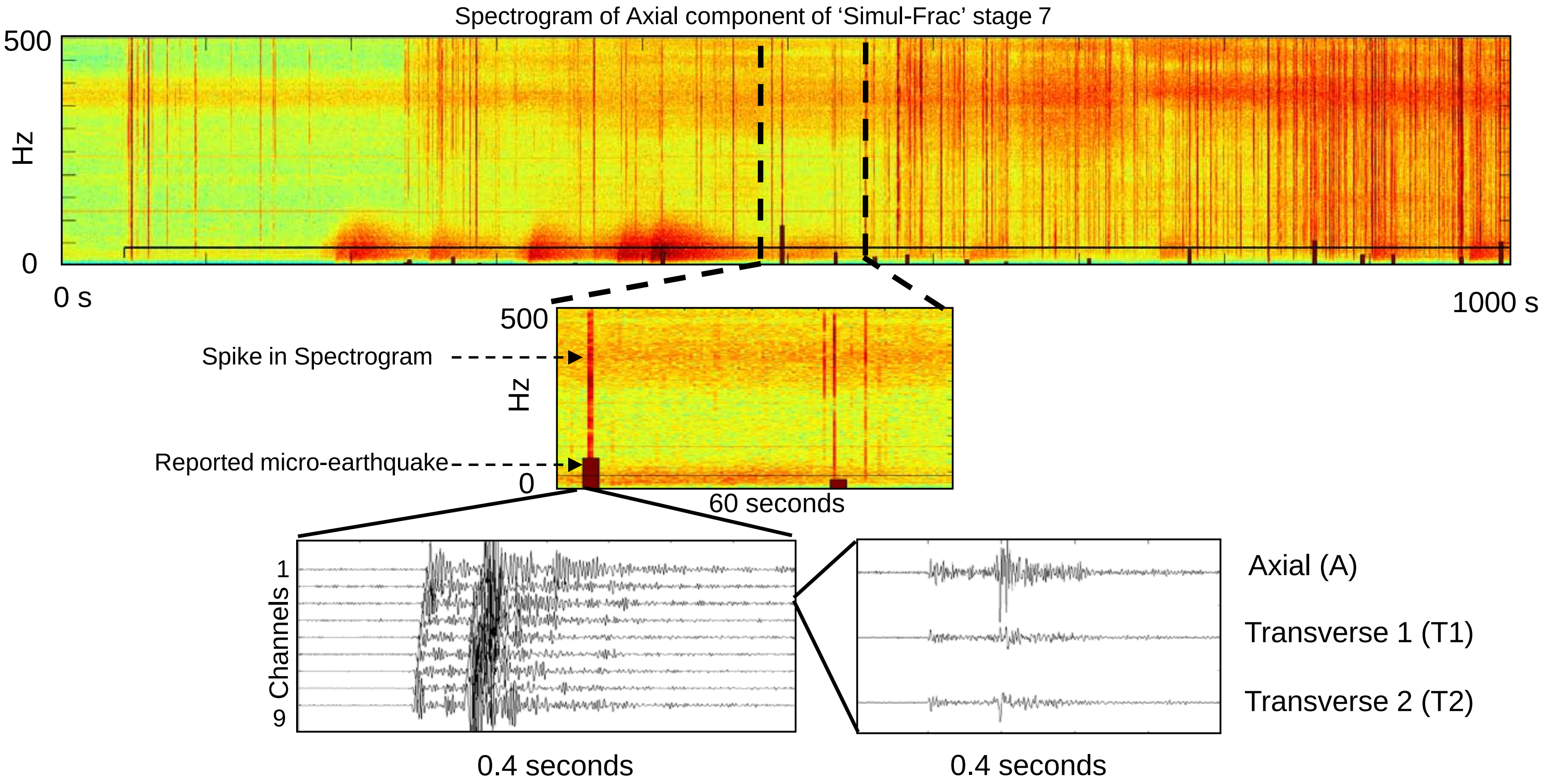
- "Simul-Frac" or Simultaneous Fracturing of A & B.
- "Zipper-Frac" or Alternate Sequential Fracturing of D & E.
- Conventional Single Well Fracturing in C.





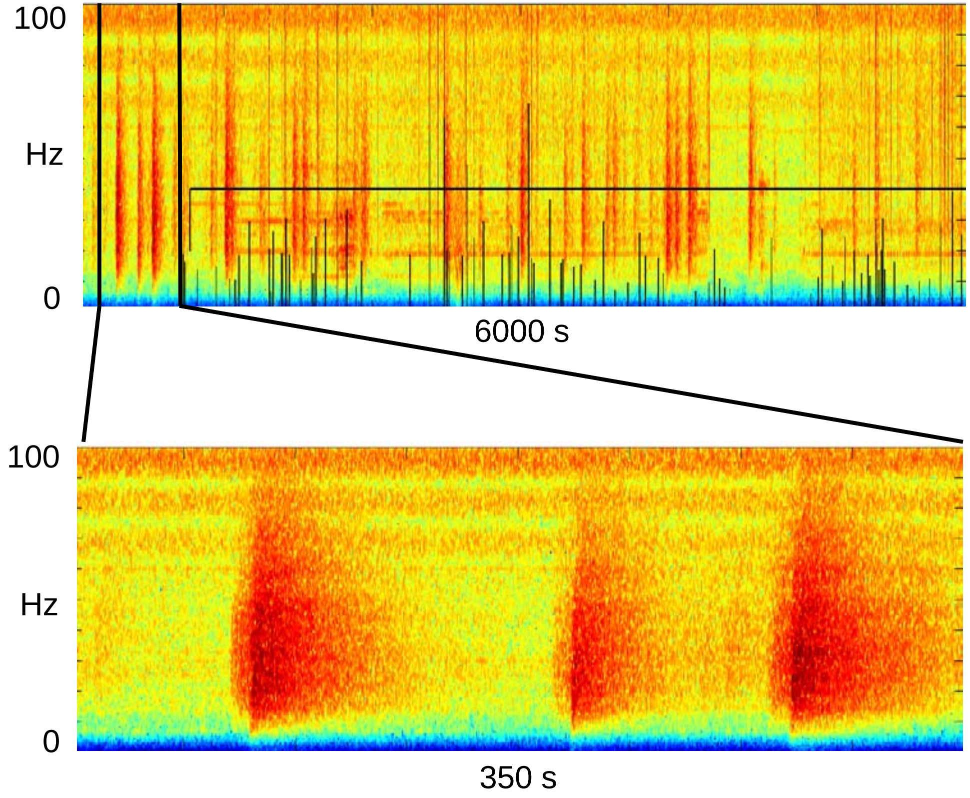
Analyzing spectrograms as a good way of detecting coherent signals.

High Frequency energy spikes on spectrograms matches exactly with reported micro-earthquakes.

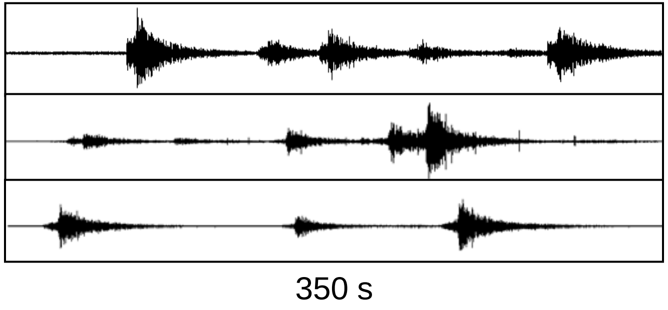


Long Period Long Duration (LPLD) events in the same spectrograms

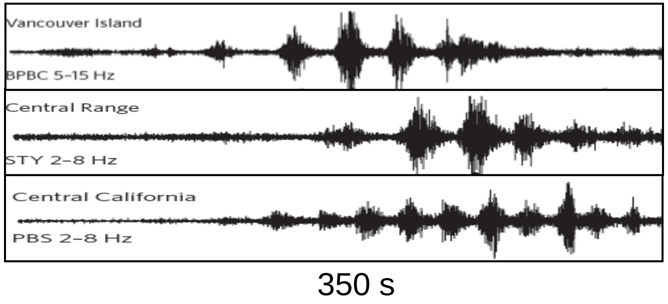
Long period (below 80 Hz) long duration (10-100 s) events detected in the spectrograms



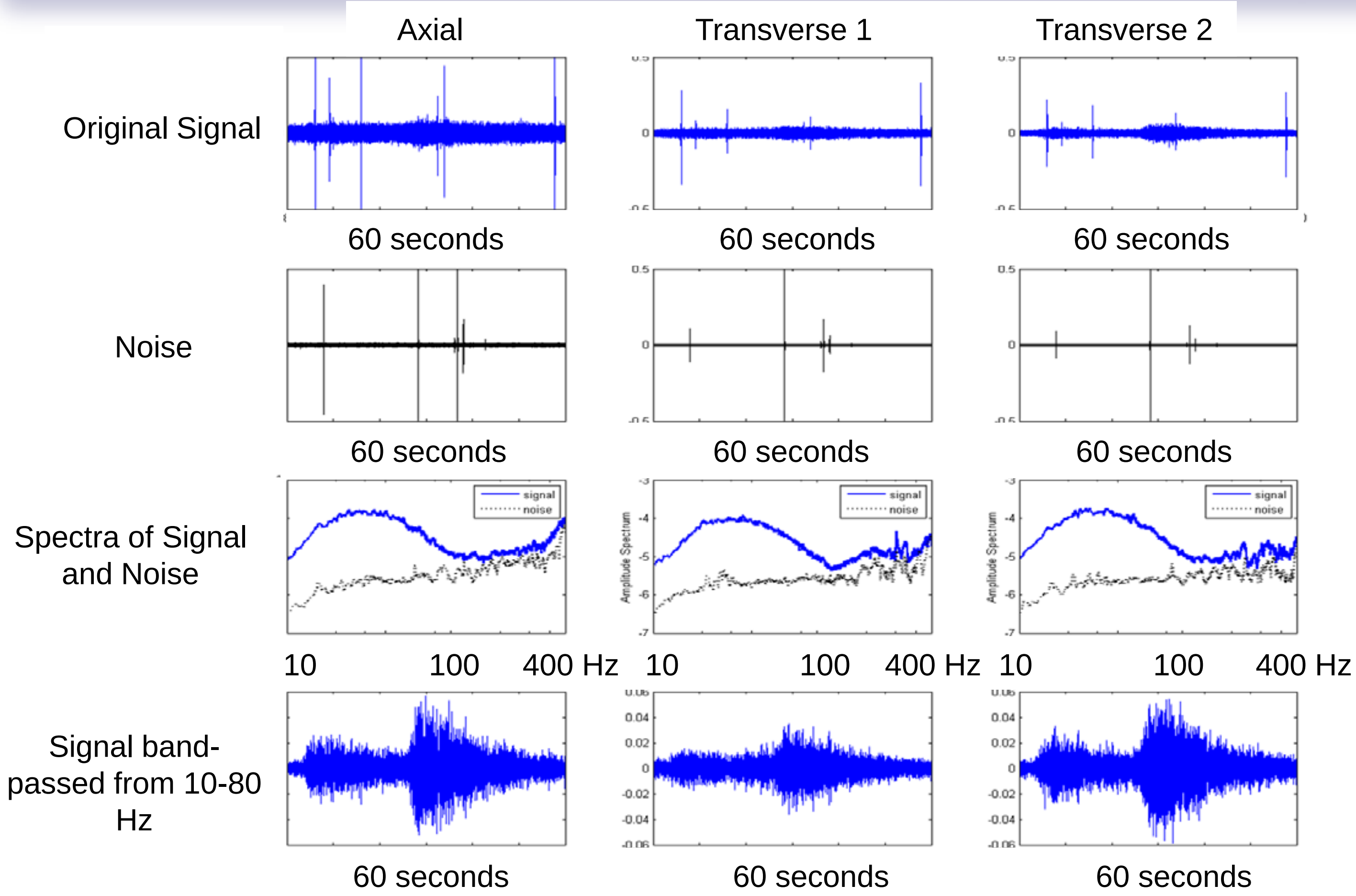
LPLD waveforms after band-pass filtering from 10-80 Hz



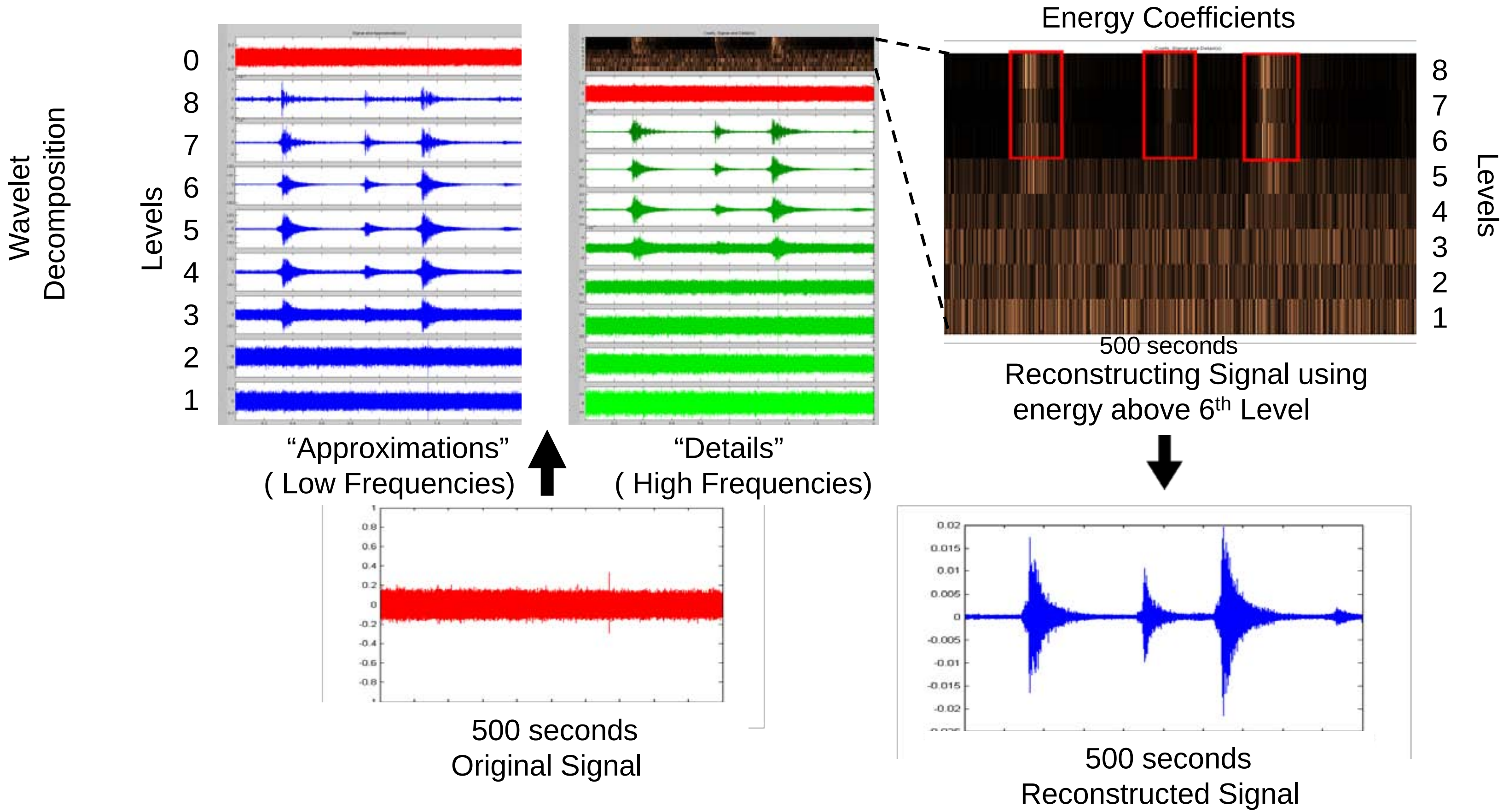
Tectonic tremor waveforms from Vancouver Island, Central Range in Taiwan and the SAF (Peng and Gomberg, 2010)



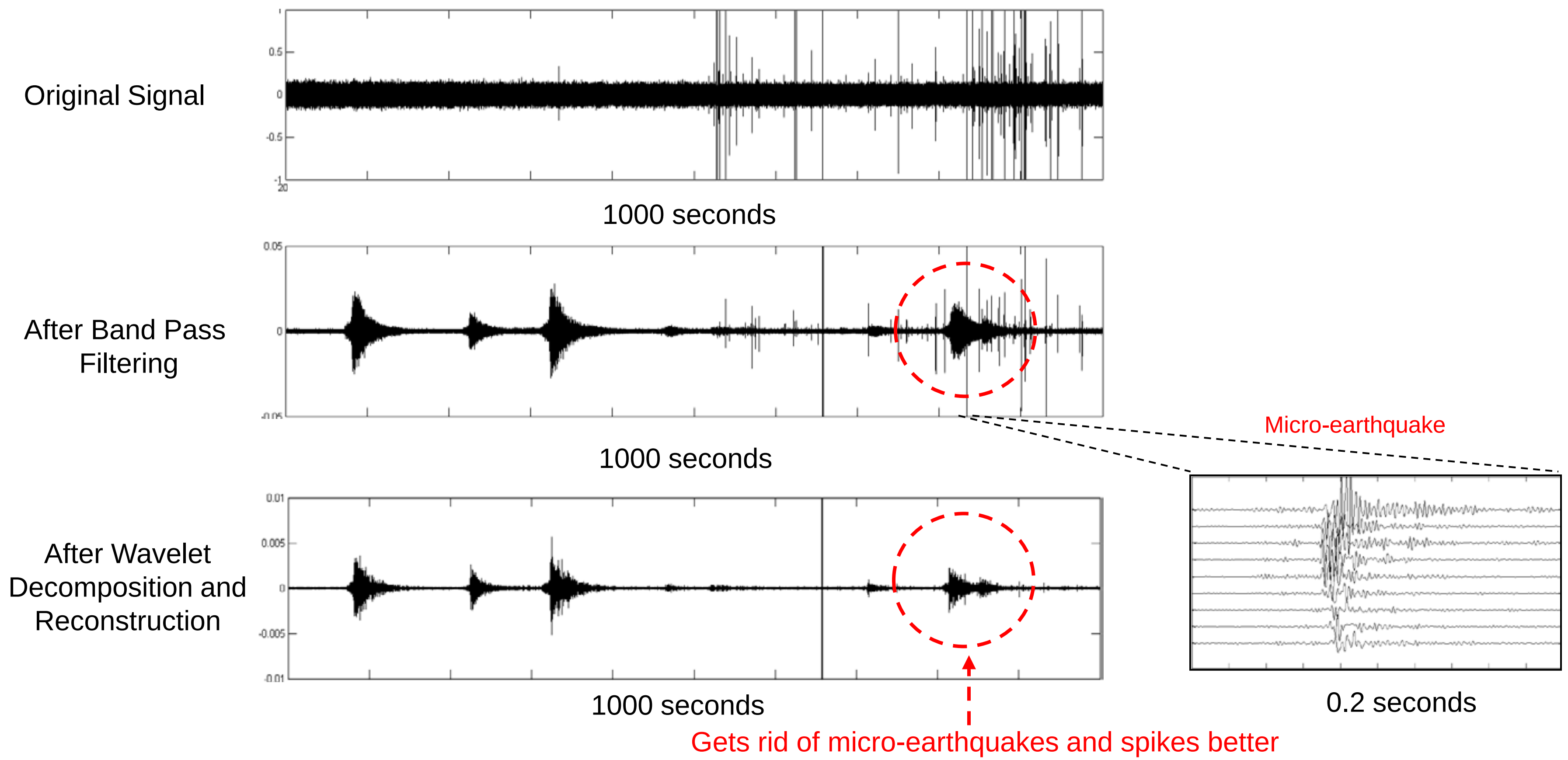
Identifying LPLD events: 1) Band-pass filtering method



Identifying LPLD events: 2) Wavelet Decomposition & Reconstruction Method

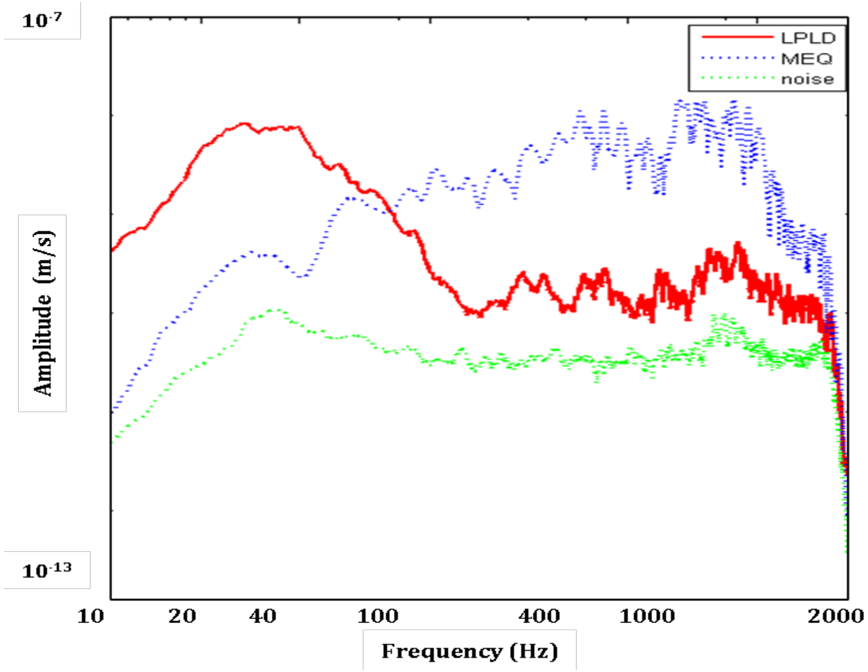


Wavelet Decomposition Method slightly better than Band-Pass Filtering



LPLD events in the frequency domain

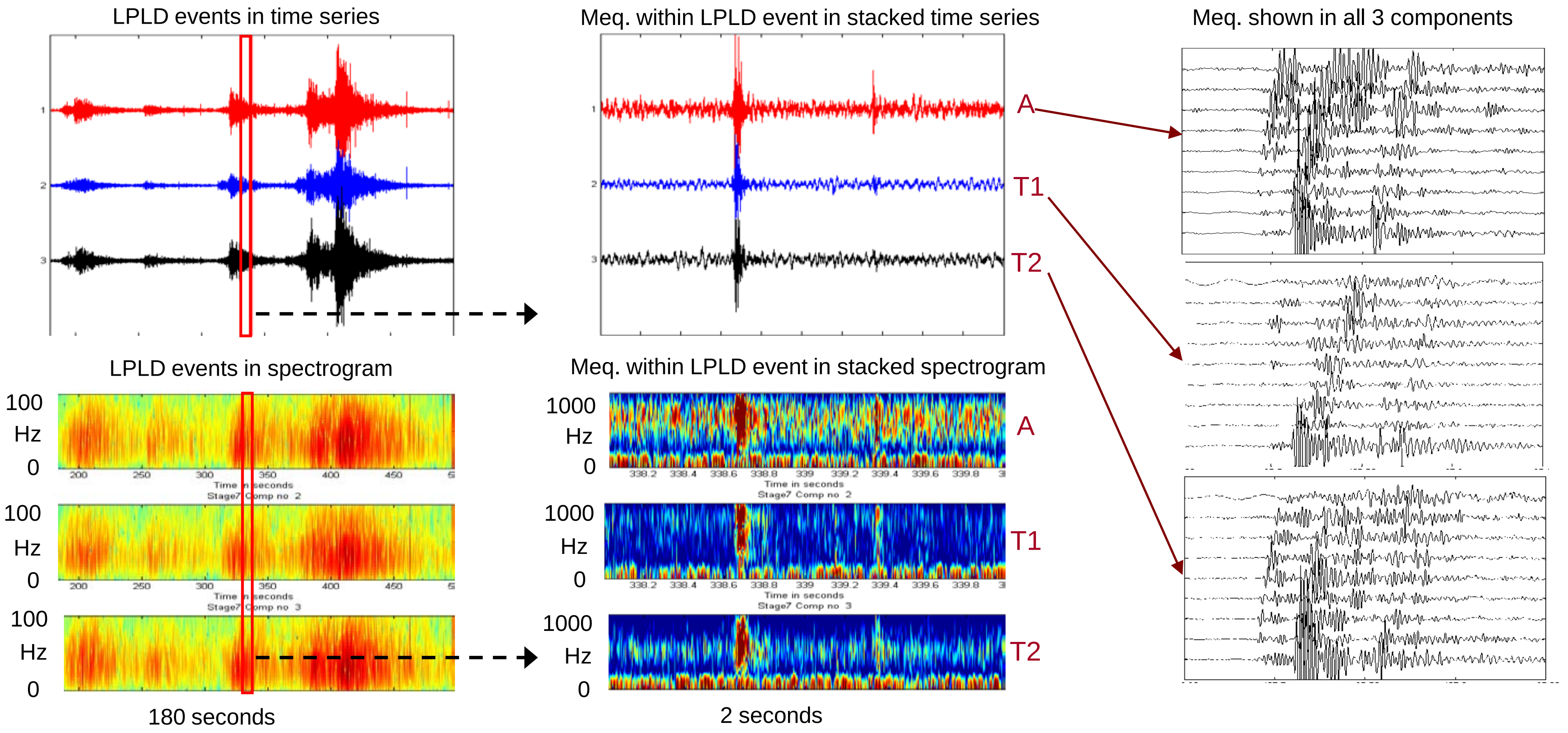
Frequency Amplitude Spectrum of LPLD events, Micro-earthquake and Noise.



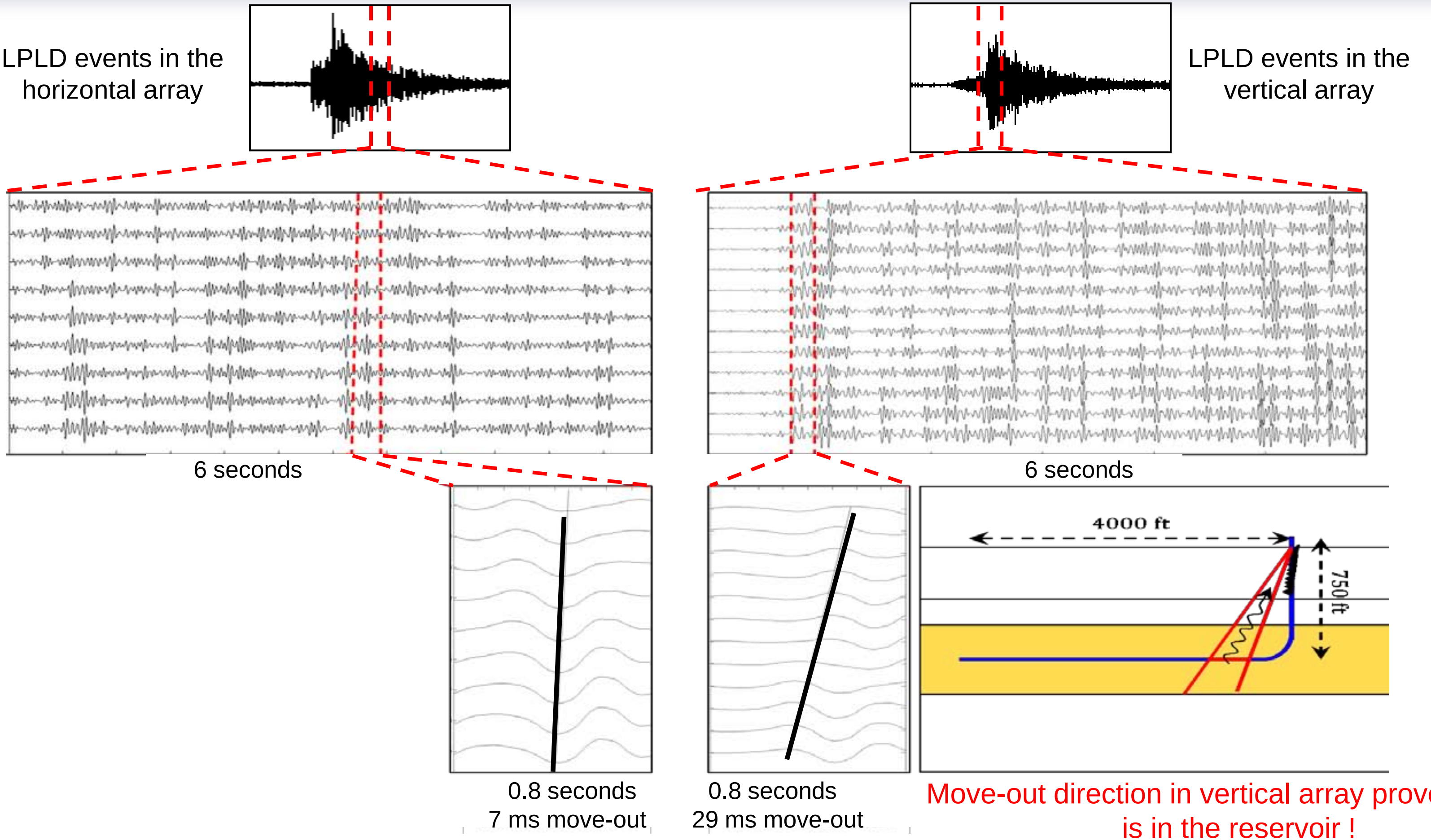
LPLD events are deficient in high frequency energy relative to micro-earthquakes and enriched in low frequency energy.

LPLD events in the time domain.

Microearthquakes detected within some LPLD events. Coincidental or Causal ?



Impulsive arrivals with finite move-outs but no clear P or S phases

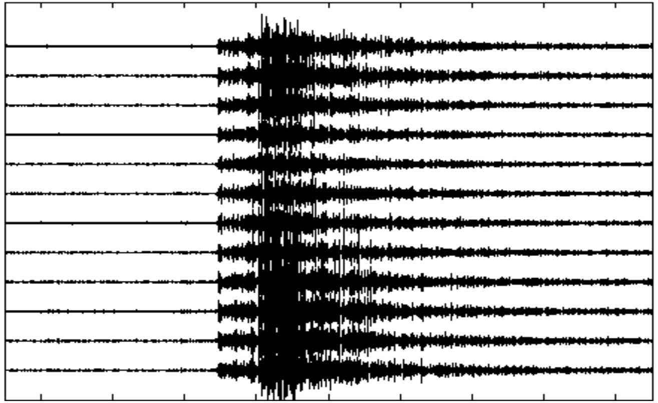


Move-out direction in vertical array proves source is in the reservoir !

Exact Move-outs obtained from waveform cross-correlation

Move-out across the array is obtained by cross-correlating the LPLD signal envelope in the first channel with the rest of the channels

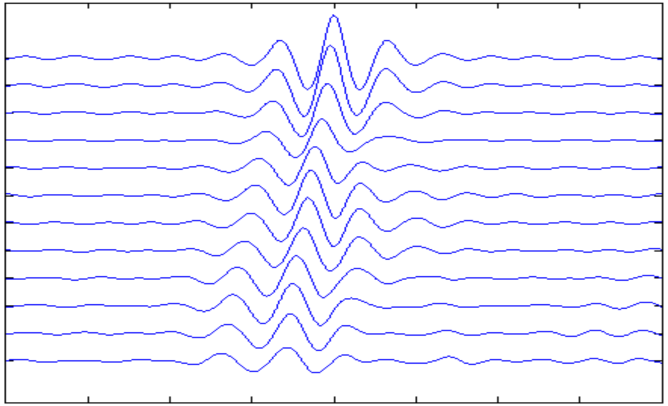
LPLD Signal



90 Seconds

Cross-correlating 1st channel with the rest of the channels

Cross- Correlogram



-0.2 s 0s 0.2 s

Lag time

From the move-out we can get the apparent velocity across the array.
From apparent velocity we can get the approximate angle of arrival.

Density and Orientation of Natural Fractures in the Reservoir

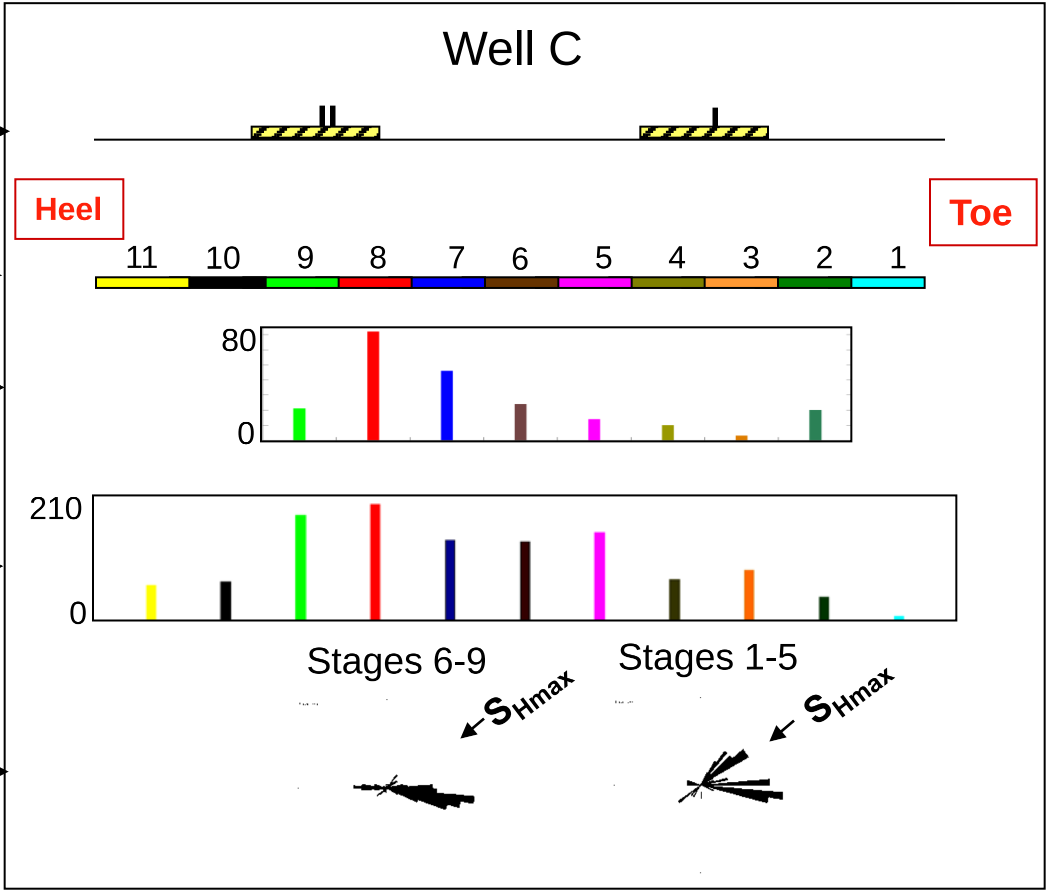
Position of Sensors in well C during “Simul-Frac”

All stages in well C colored differently.

Number of natural fractures per stage in well C

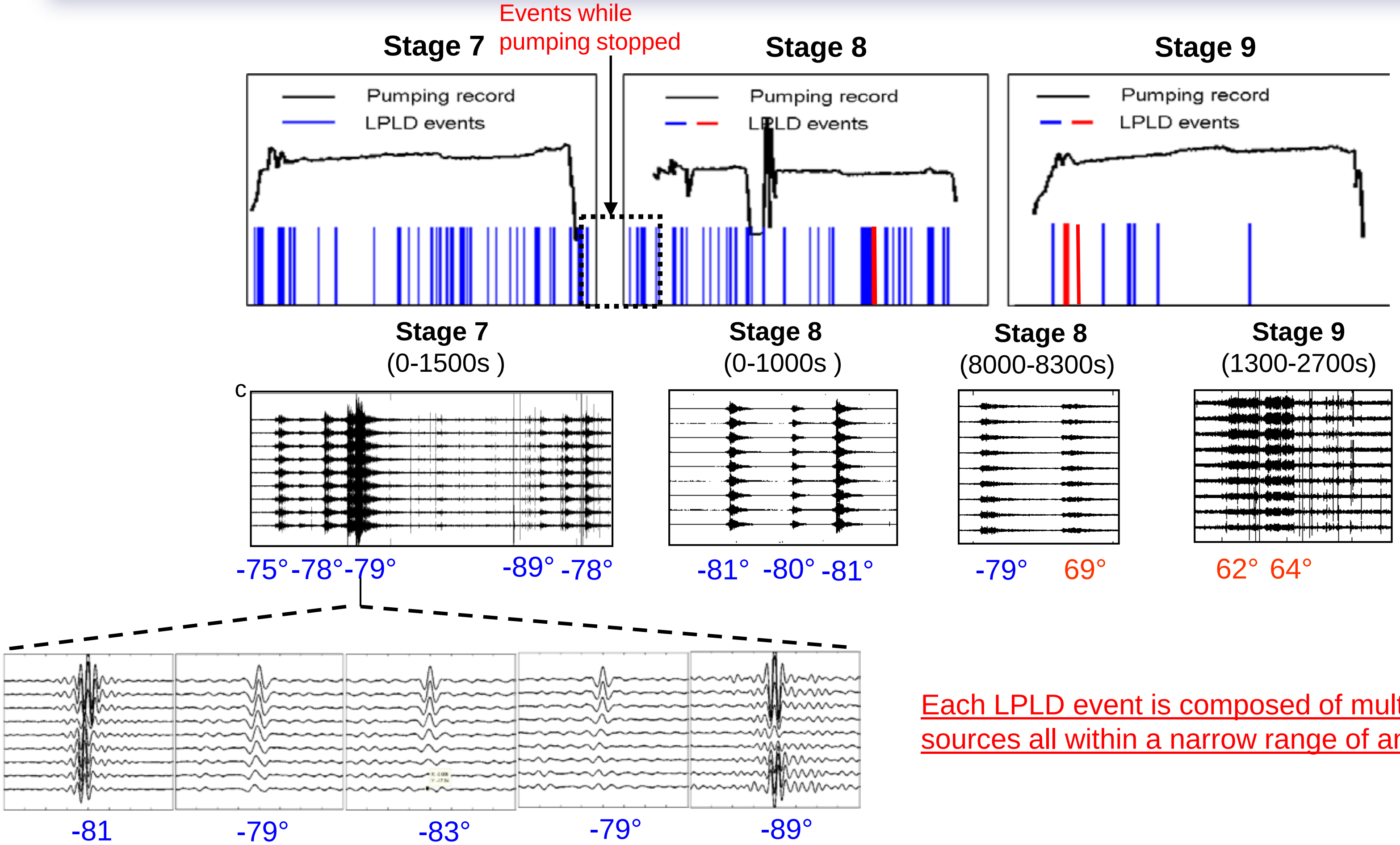
Number of Microearthquakes per stage

Rose Diagram showing fracture orientations



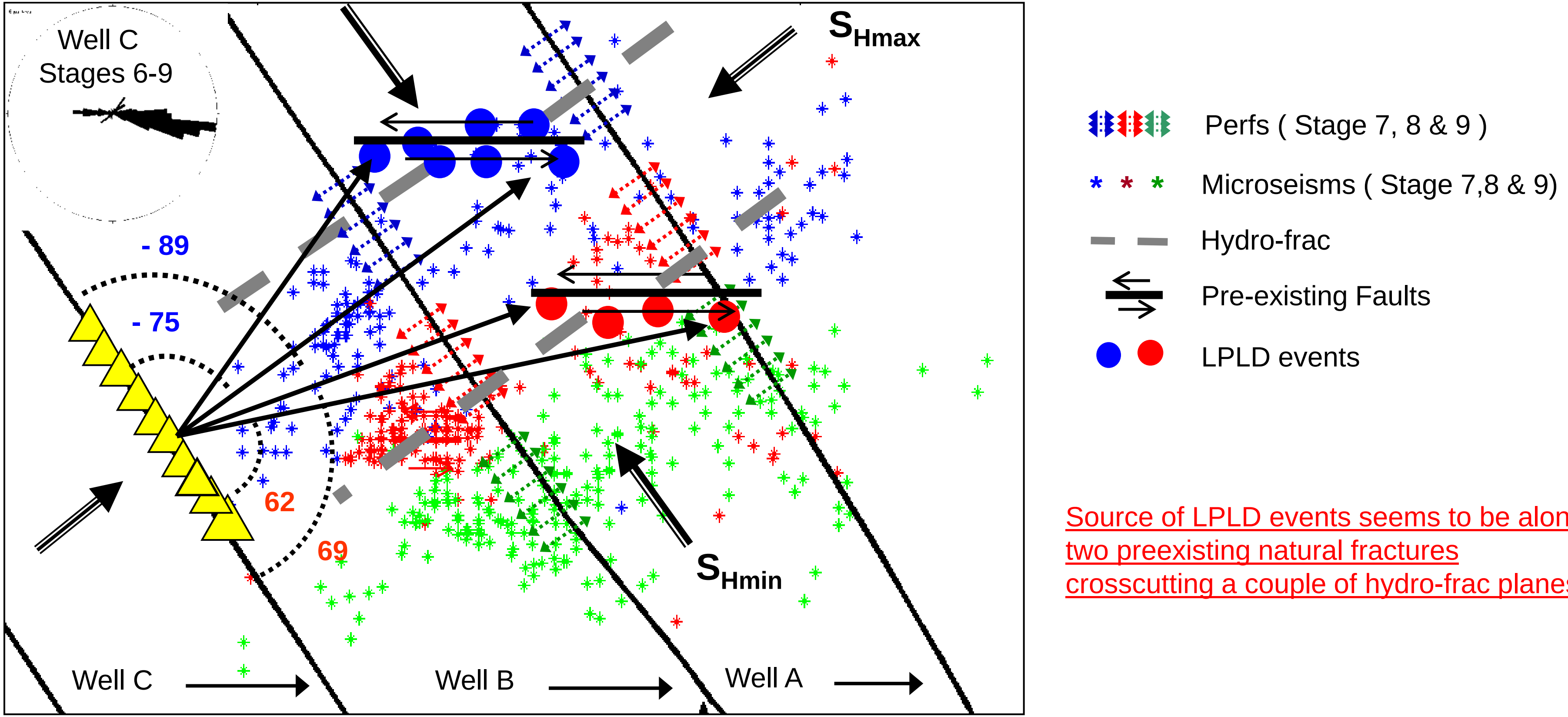
Fracture density and orientations from well C has been extrapolated to well A, B, C & D for subsequent analysis

Where do the LPLD events occur ?



Each LPLD event is composed of multiple adjacent sources all within a narrow range of angles.

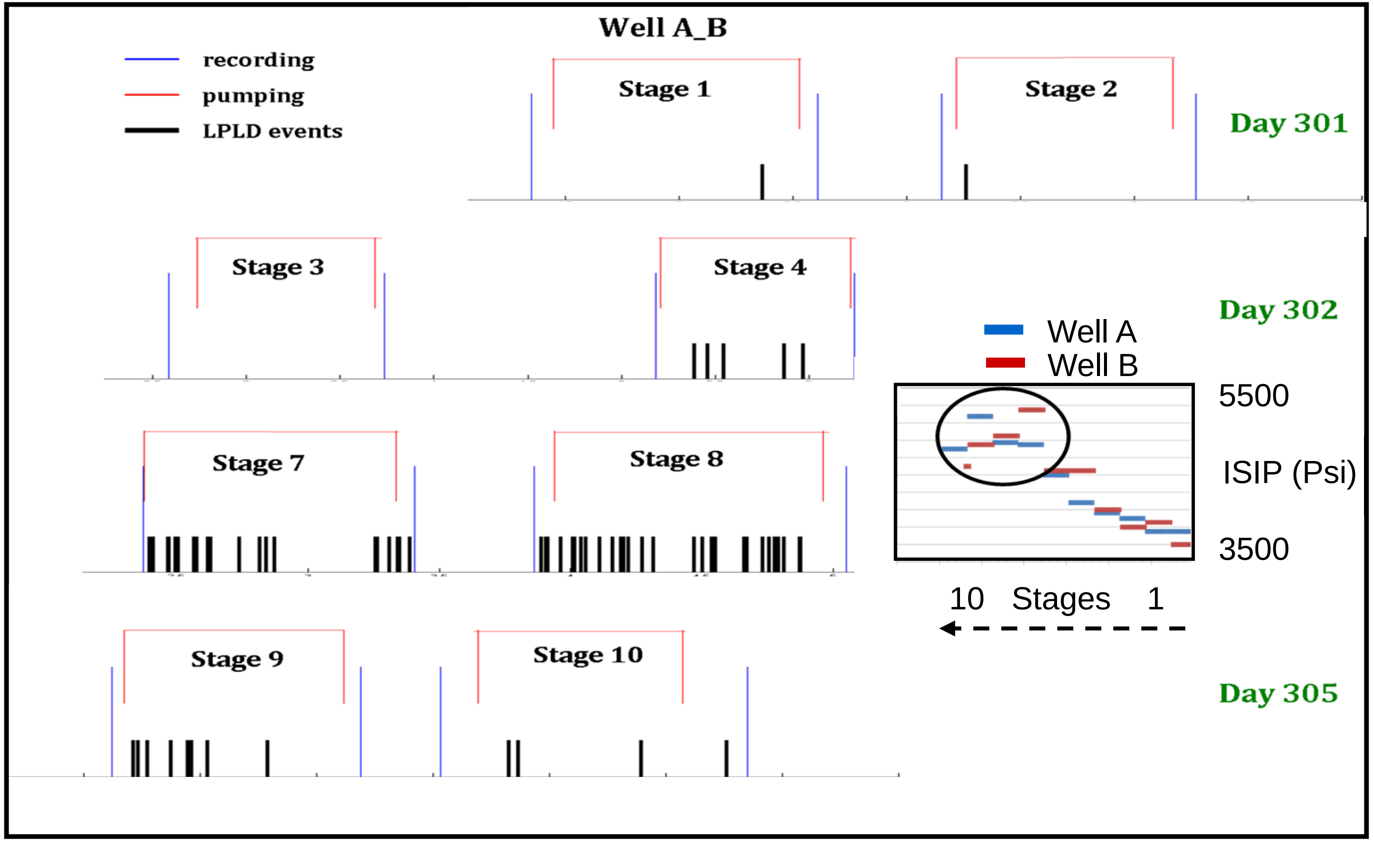
Where do the LPLD events occur ? (conceptual model)



Source of LPLD events seems to be along two preexisting natural fractures crosscutting a couple of hydro-frac planes.

When do the LPLD events occur ?

Stages with maximum number of LPLD events (stage 7 & 8) are also the stages with the highest pumping pressure and highest natural fracture density.



Conclusions

- Long period long duration seismic events , similar in appearance to tectonic tremor observed in subduction zones and strike slip margins, was identified during hydraulic stimulation of shale gas reservoir.

- These LPLD events lack clear P and S phases but have coherent arrivals with finite move-outs. Some of the LPLD episodes have micro-earthquakes within them although it is not yet known whether they are coincidental or causal?

- From the moveout direction of all the events in the vertical array it was confirmed that they are coming from the reservoir.

- Analysis of stage 7,8 and 9 of well A-B suggests that all LPLD events maybe coming from two faults crosscutting a couple of hydrofrac planes.

- Maximum number of LPLD events were detected in the stages with the highest pressure during pumping and the highest natural fracture density.

- All observations suggests that the long duration signals are generated by slow shear slip on a few preexisting natural fractures due to the high fluid pressure in the reservoir. We believe this process might be contributing significantly to the stimulation.