DAS and DTS at Brady Hot Springs: Observations about Coupling and Coupled Interpretations

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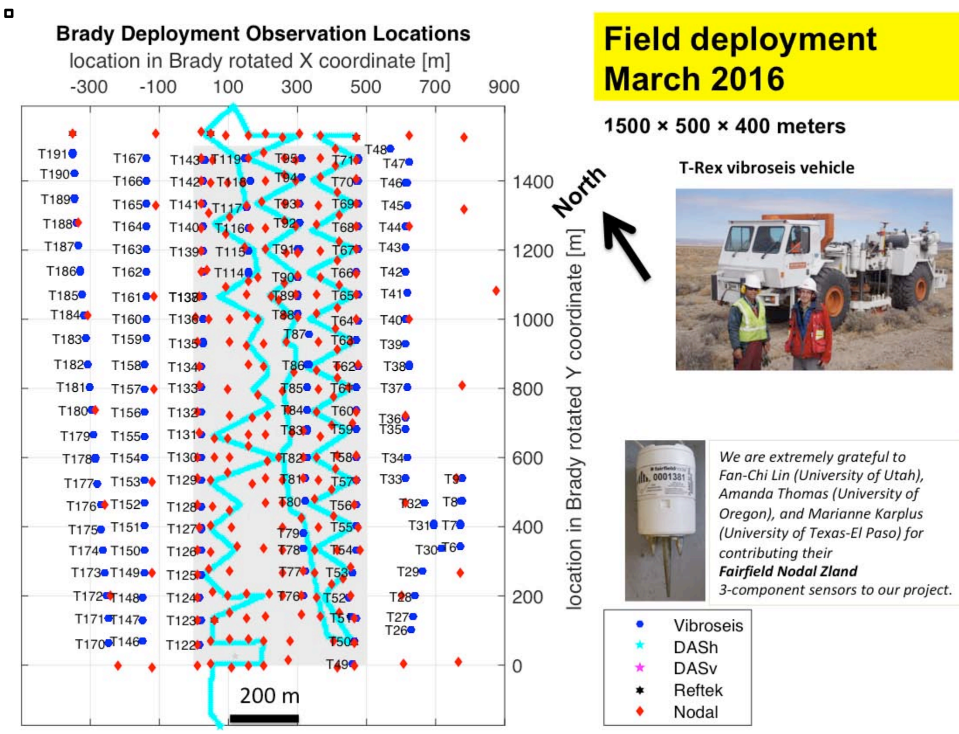
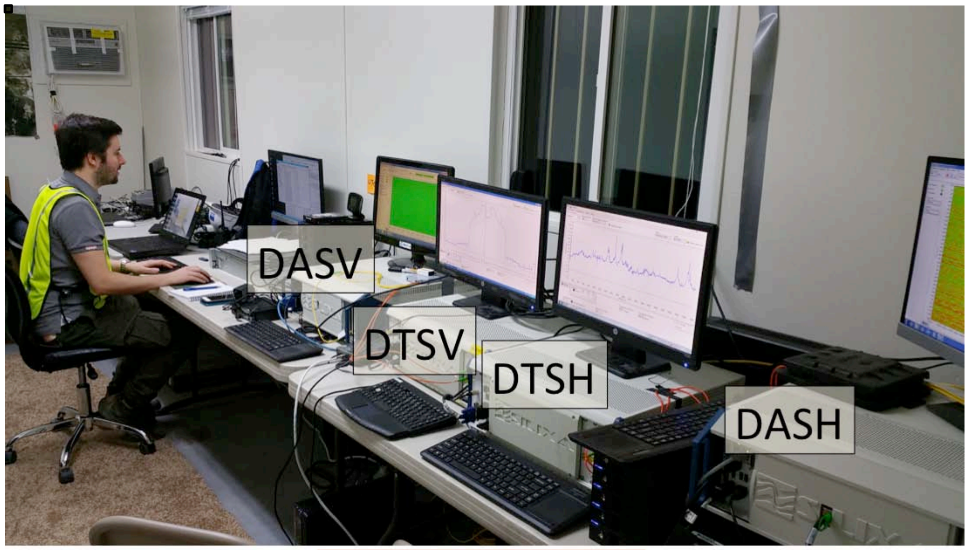
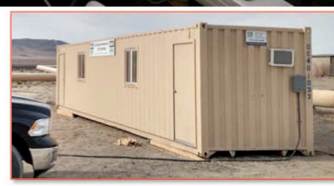
http://geoscience.wisc.edu/feigl/porotomo/

There have already been several talks about the PoroTomo survey at Brady Hot Springs. This is one more.



This slide (from Kurt Feigl's overview) shows the layout of the survey.
Eastbound I-80 runs northeast at Brady and is approximately aligned with the vertical axis in this coordinate system





Here’s a view of the four interrogators inside the shed.
Each unit is labeled by function (DTS or DAS) and by the installation (vertical or horizontal
The DASH unit sits on a rack of RAID drives. More than 44 Terabytes of data were recorded continuously during the 14 day survey -
About 100 GB/hour

DAS and DTS Measurement

- Laser Pulses are sent into the fiber; Reflected light is captured and processed to give:
  - Fiber temperature (DTS) sampled with dz = 126 mm and dt = 60 sec;
  - Fiber strain rate (DAS) sampled dz = 1 m and dt = 1 msec

DTS and DAS are based on optical time domain reflectometry (OTDR) measurement techniques in which an ***incident pulse of light*** *is coupled into an optical fiber and* ***backscattered light is sampled****. As the incident pulse travels along the fiber, at each sampling interval of fiber, a small amount of light is scattered and recaptured by the fiber waveguide in the return direction.* ***Local variations of the backscatter waveform provide information on the state of the fiber at successive sampling intervals determined by the roundtrip transit time from launching end to point of interest****. Through continuous analyses of the backscattered signal from successive incident pulses, dynamic profiles of both temperature and acoustics (dynamic strain) are realized as a continuous 2D function of recording time and distance along the fiber. The principles of DAS and DTS are discussed in the published literature (e.g. Parker et al. 2014, Daley et al. 2015, and Dakin et al. 1985). The DTS data delivered to the PoroTomo project were collected using an ULTIMA-S™ DTS with a double-ended configuration that utilizes a loop of optical fiber and had spatial sampling intervals of 0.126 m. Silixa's iDAS™ was utilized for DAS acquisition with channel spacing of 1.021 m and a gauge length of 10 m.*

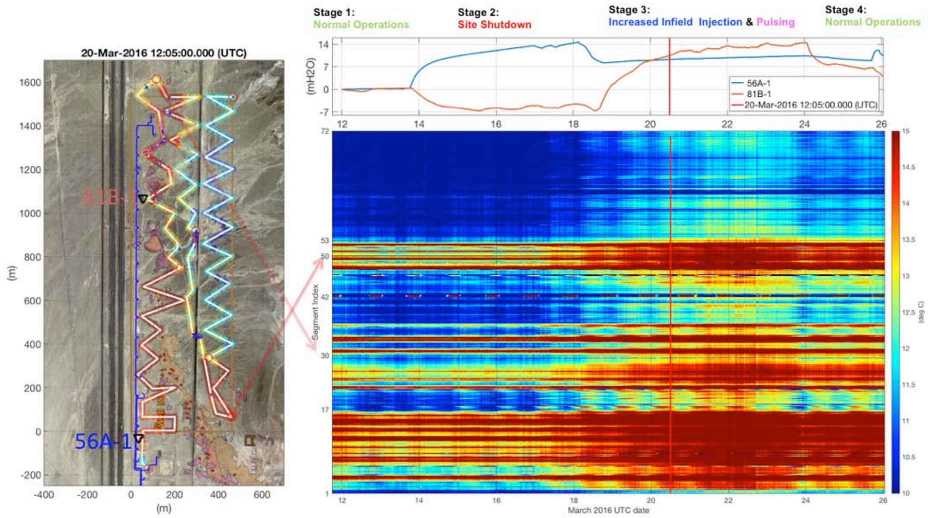
I won't make you listen to this. The math is in the paper & references.

DTS is precise in distance and represents 1 minute averages in time.
DAS is precise in time and represents 10 meter averages in distance

DAS can be averaged in time to evaluate narrowband fiber strainrate as microstrain per minute with a samplerate matched to the DTS.
I'll call that NDAS in my slides

In the remainder of the talk I will show you results of the various data sets
I'll start with DTS and NDAS in the trenched cable.

DTSH with Narrowband DASH (NDASH) overlay

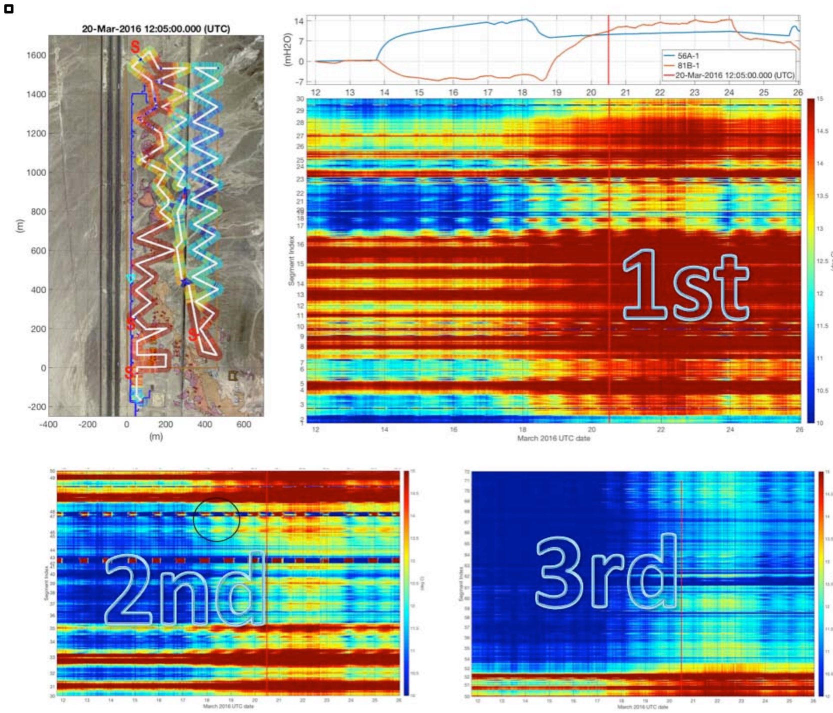


The Left panel is a plan view of the survey area.
Underlain is a Google Earth image with PoroTomo's prejob annotations for fumaroles, warm ground and silicate gravel.
Overlain along the trajectory of the trench are timeslices with DTSH in a wide track and NDASH in a narrower track.

The Lower Right panel shows all the DTSH for the entire survey;
Time indexed by UTC date runs horizontally;
Distance indexed by segment number runs vertically.
The red circles on the left indicate the segment starts labeled on the right;
Segments 1 through 29 are the outbound from the recording shed; 30 through 49 are inbound and 50 through 71 are outbound.

The upper right panel shows the reference pressure measurements in the two monitor wells.

The red vertical lines on the right mark the time of the slice on the left;
Note that noon UTC was local 6 am so this slice is at local 6 am; just before sunrise.

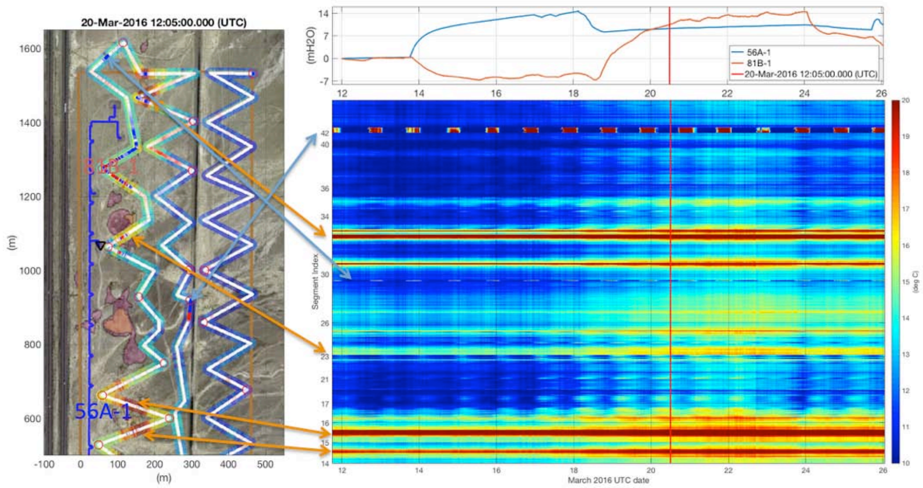


This slide splits the full DTS panel to separate panels for each section.

The 2nd section, shown at bottom left, has been flipped so that all three displays run outbound from bottom to top.
Note that the 1st section is warmest. The 3rd section is coolest.

Note that all areas warm up in response to increased pumping during stage 3;
Diurnal cycles are also evident; Exposed sections directly responding to air temp;
Elsewhere, in general there is a latency of about 12 hours so the highest daily temperatures occur at night.
I've circled one spot adjacent to segment 47 where this is particularly clear
I suppose we could fit a model of thermal properties of the ground covering the cable to match the response

DTSH with Narrowband DASH (NDASH) overlay



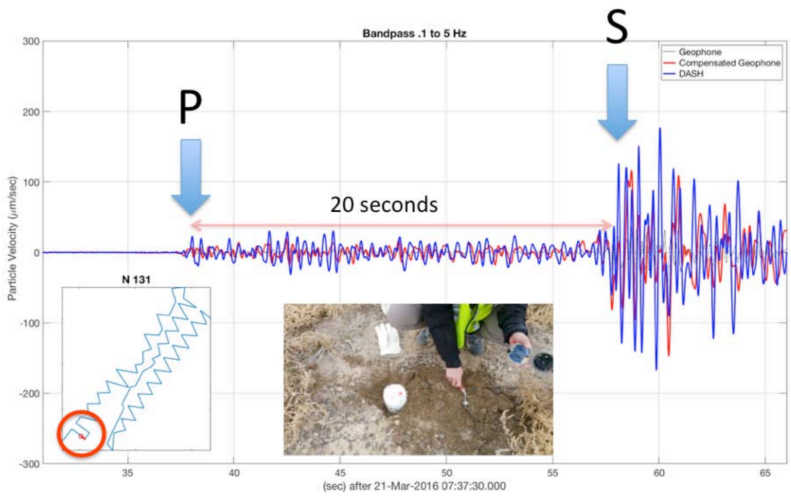
Segments 14 through 43

Here’s the outer end near the injectors 10 to 20 degree color scale that shows a bit more detail in warm zones.

The blue arrows identify the exposed segment 42 and a splicebox in segment 29. The brown arrows identify some hotspots.
Note that some of the hotspots are quite localized in space.

In the following slides I will show you broadband DASH responding to a regional mag 4.3 earthquake that occurred near Hawthorne NV (about 100 km south of Brady.

21-Mar-2016 07:37:37.5 Hawthorne Earthquake



By way of introduction, here's an overlay of waveforms representing horizontal ground motion at two adjacent locations in segment 3. Details are in the paper.

The blue waveform was extracted from the DASH after converting from fiber strain to fiber particle velocity.

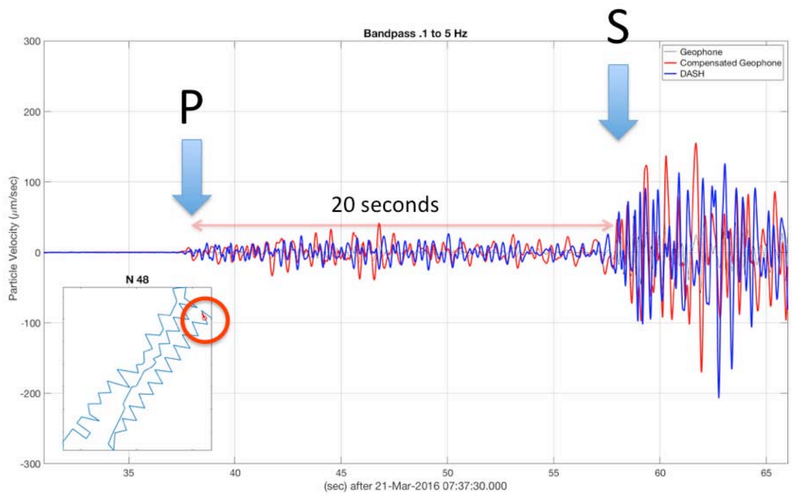
The red waveform was extracted from the two horizontal components of one of nodal geophone sensors by reorienting to match the cable direction rand compensating for the instrument response.

The inset photo shows a 3C nodal unit being placed.

It is important to note that no match-filtering or adaptive scaling was applied. The manufacturers' values for the geophone and DAS sensitivity were used without adjustment.

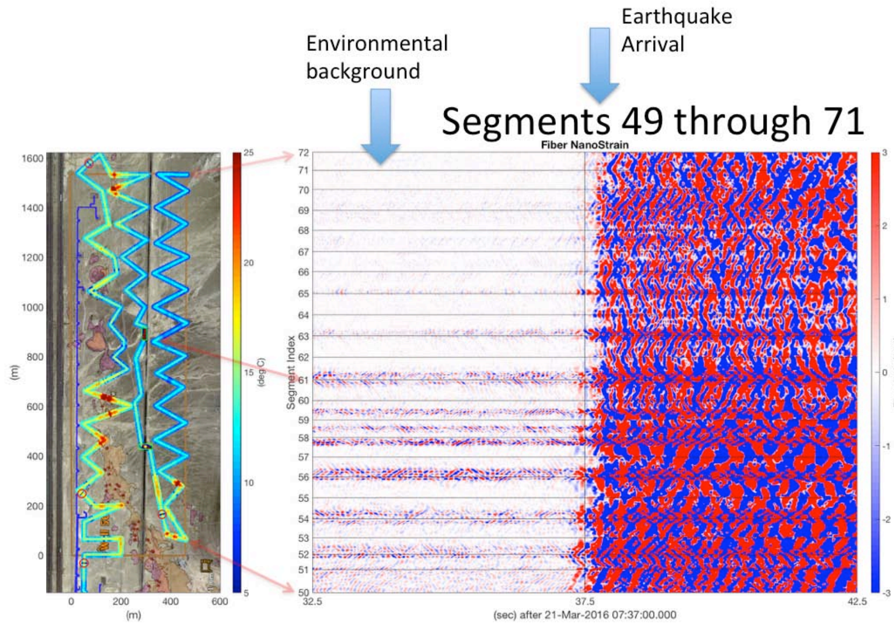
Both waveforms were bandpassed to the .1 to 5 Hz temporal band.

21-Mar-2016 07:37:37.5 Hawthorne Earthquake



Here's another using Node 48 in segment 70.
Now let's look at lots of channels together.

21-Mar Hawthorne EQ: Compressional @ 07:37:37.5

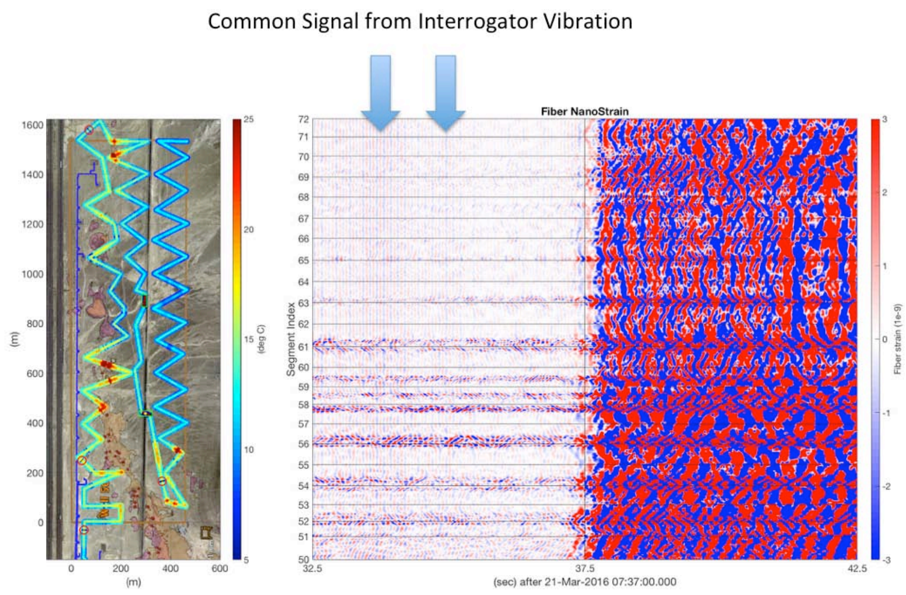


Here is the broadband DASH strain response for
the 3rd section of the DASH channels (that is segments 50 through 71)

windowed in time 10 seconds containing the Primary earthquake arrival and displayed with a high gain sufficient to show background environmental signal.

Here and in the following the planview panel on the left shows min and max temperature at each DTSH location.

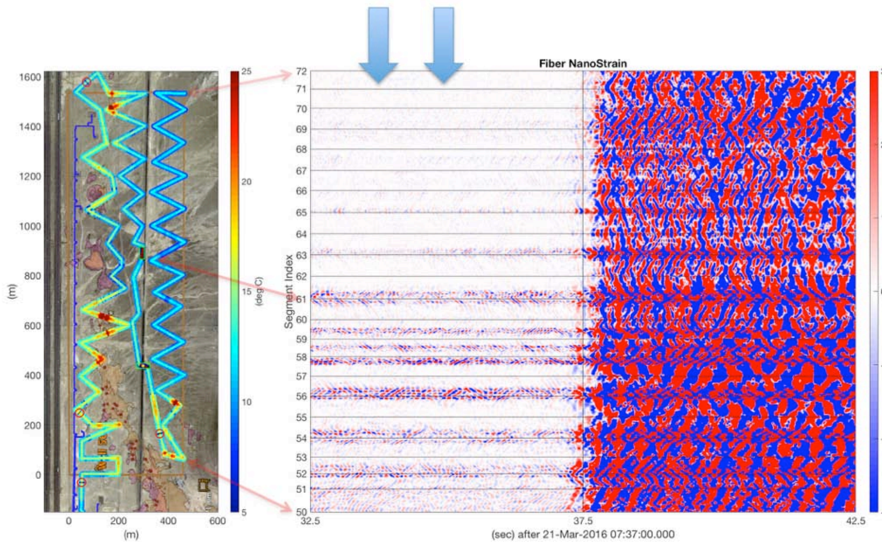
21-Mar Hawthorne EQ: Compressional @ 07:37:37.5



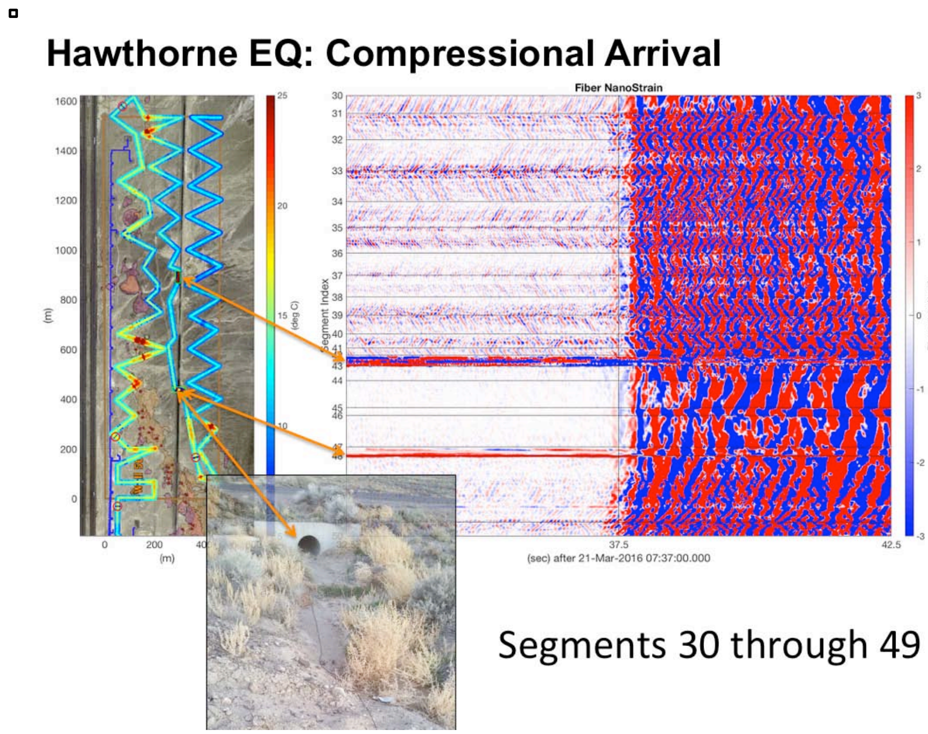
There is a small sensitivity to vibration of the interrogator.
The result is a common signal that is aligned on all channels and is easy to estimate & remove.

21-Mar Hawthorne EQ: Compressional @ 07:37:37.5

Common Signal Removed



It gone



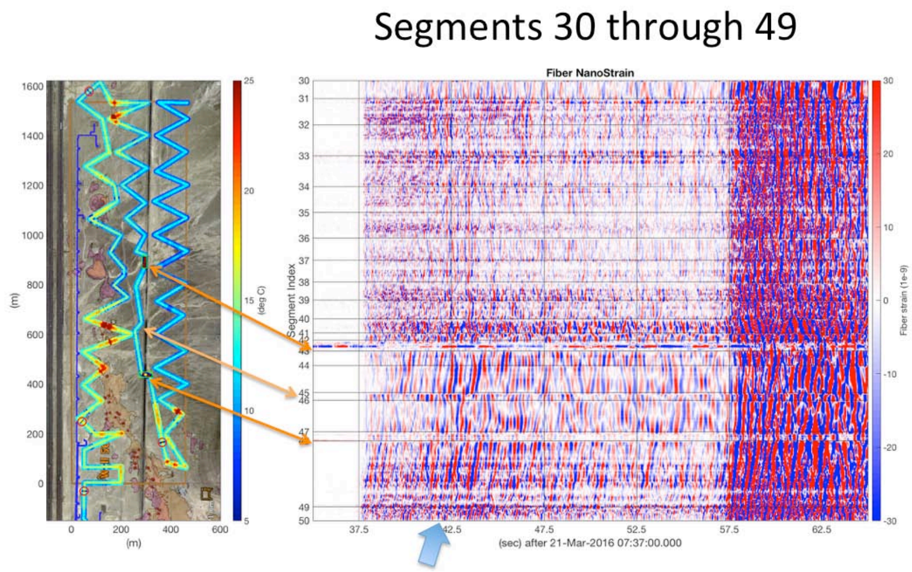
Here’s a similar view of the middle section in outbound order.

The inset photo shows the cable passing through a culvert under the service road. That’s segment 47.

Note the clear change in signal and noise that occurs at the exposed section 42.

The next two slides show the DAS strain and particle velocity responses for the 30 second interval that contains the main EQ arrivals

Hawthorne EQ: 30 Sec DASH strain response



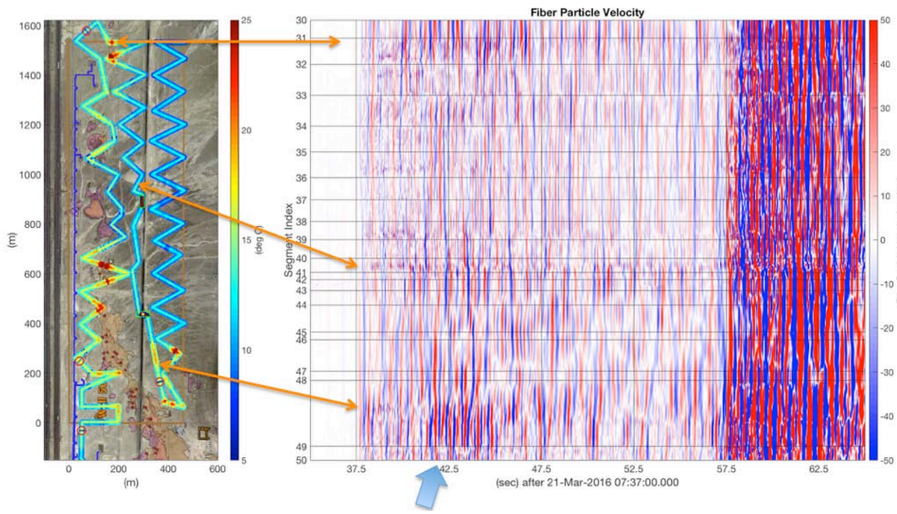
30 seconds

Here the gain is set to show the main compressional signal so the shear arrival is saturated in the display and the environmental noise is invisible except at exposed channels.

These are the same middle segments shown in my previous slide.
The section with segments 43 to 50 is evidently rich in locally converted shear signal (e.g. at 43.5 sec)

Hawthorne EQ: 30 Sec DASH velocity response

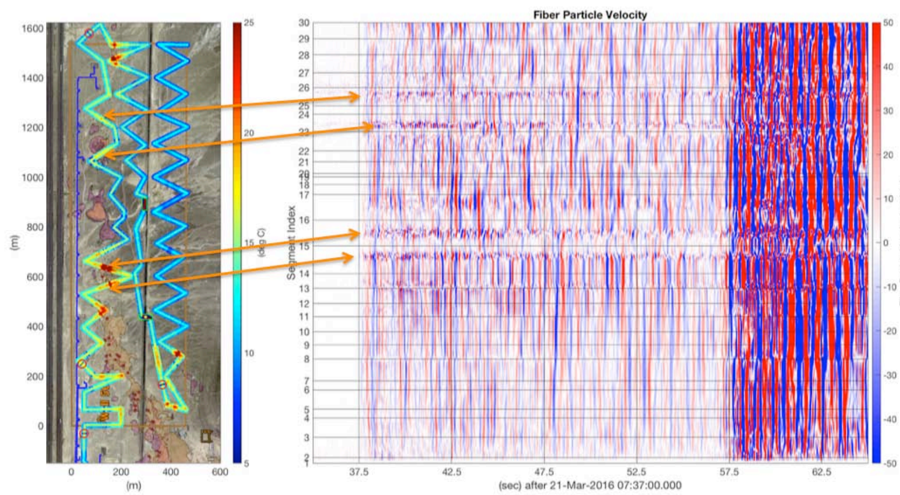
Segments 30 through 49



Here are the same traces after conversion to fiber particle velocity

Hawthorne EQ: 30 Sec DASH velocity response

Segments 1 through 29

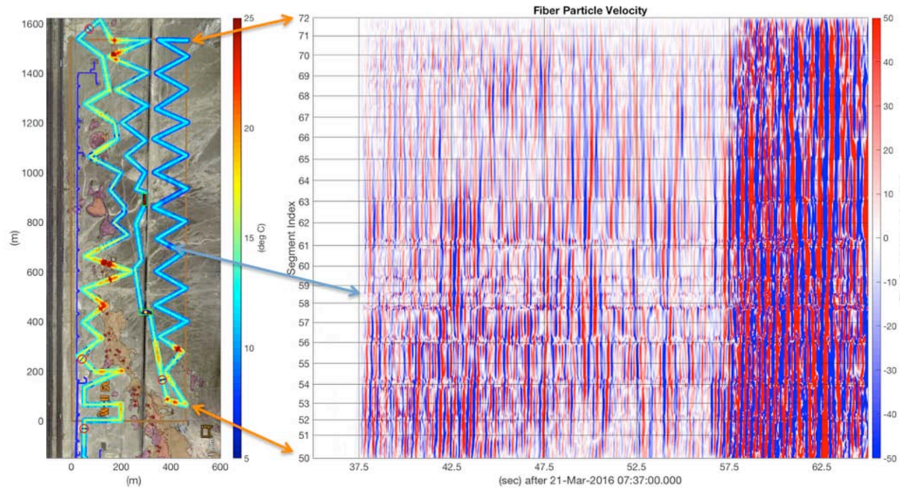


Here is the velocity response from 1st section

Note the evident change at the locations of the hot spots.

Hawthorne EQ: 30 Sec DASH velocity response

Segments 50 through 71



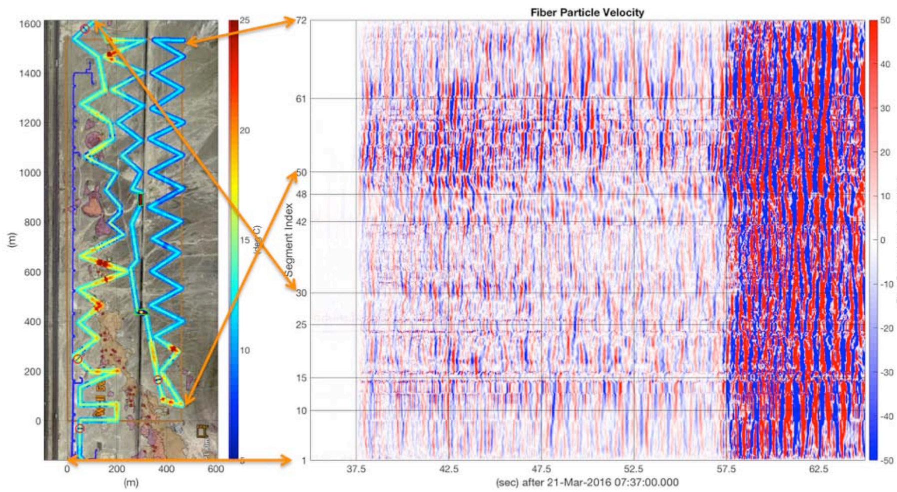
Final outbound section
The anomaly in segment 58 matches a cold spot that may be due to a change in material at an outwash strip

The next two slides show DASH velocity and strain responses for all segments

▫

21-Mar Hawthorne EQ: DASH velocity response

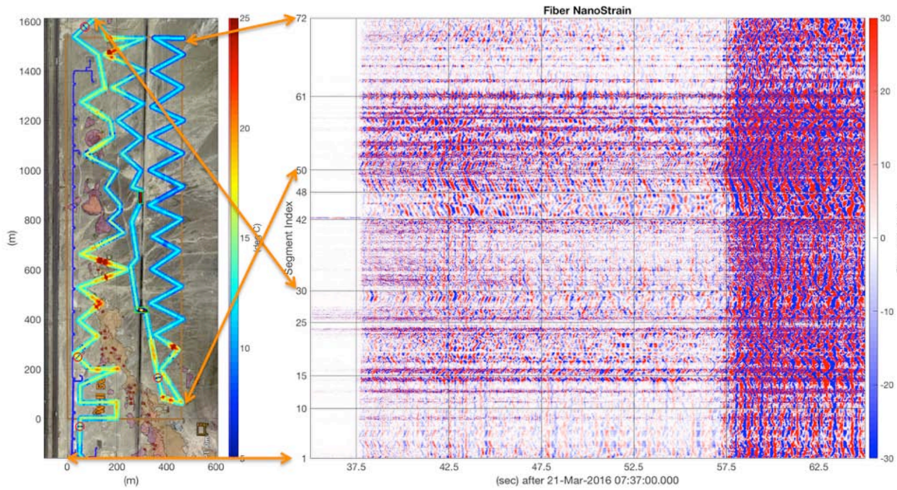
Segments 1 through 71



Fiber particle velocity

21-Mar Hawthorne EQ: DASH strain response

Segments 1 through 71

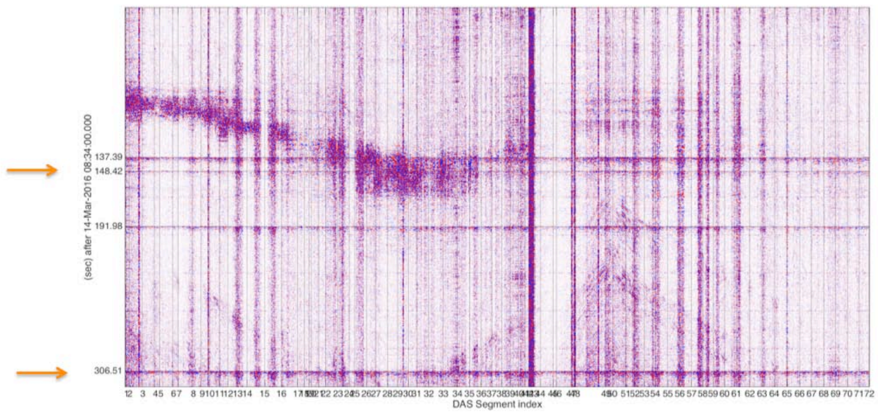


Fiber strain

The next two slides show DASH strain response to small local events that are thought to be triggered by the shutdown of production during stage 2.
Details are in the paper.

14-Mar Local Events: DASH strain response

Y-ticks at Picked times



Date	Time	Lat	Lon	Depth	Mag	Magt	Nst	Gap	Clo	RMS	SRC	Event ID
2016/03/14	06:47:46.45	39.79377	-119.01800	-0.106	-0.17	ML	0	0	0	0.04	LBL	2201048
2016/03/14	08:36:26.61	39.79442	-119.02161	-0.426	-0.48	ML	0	0	0	0.06	LBL	2201049
2016/03/14	08:39:05.23	39.79350	-119.01717	-0.106	0.07	ML	0	0	0	0.06	LBL	2201050
2016/03/14	12:11:34.92	39.79328	-119.01897	-0.119	0.05	ML	0	0	0	0.06	LBL	2201051
2016/03/16	22:03:10.24	39.79222	-119.01427	-0.424	-0.29	ML	0	0	0	0.06	LBL	2201052

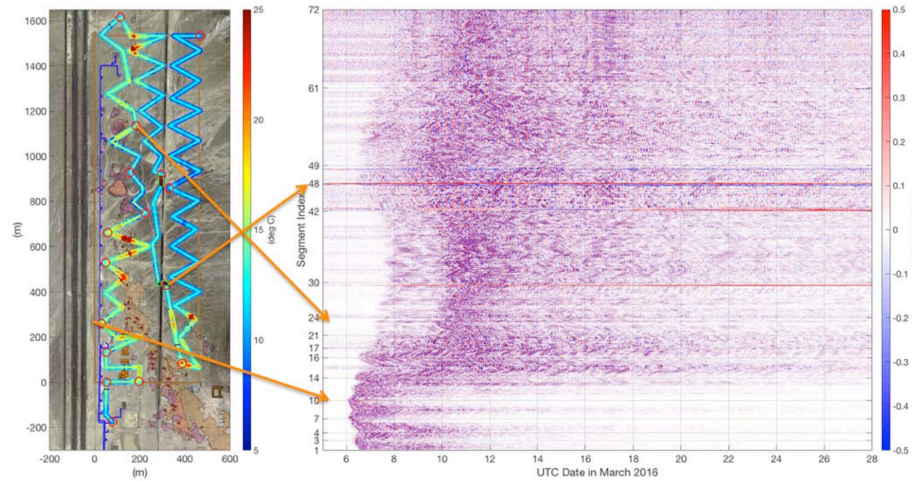
http://www.ncedc.org/cgi-bin/catalog-search2.pl

The seismic network operated at Brady by Lawrence Berkeley Laboratory detected fiver small local earthquakes during the period of the PoroTomo survey. The list is shown at bottom of slide.

All were detectible on the DASH array
The upper panel shows a 5-minute interval containing the two that are highlighted with arrows plus two more not in the catalog.

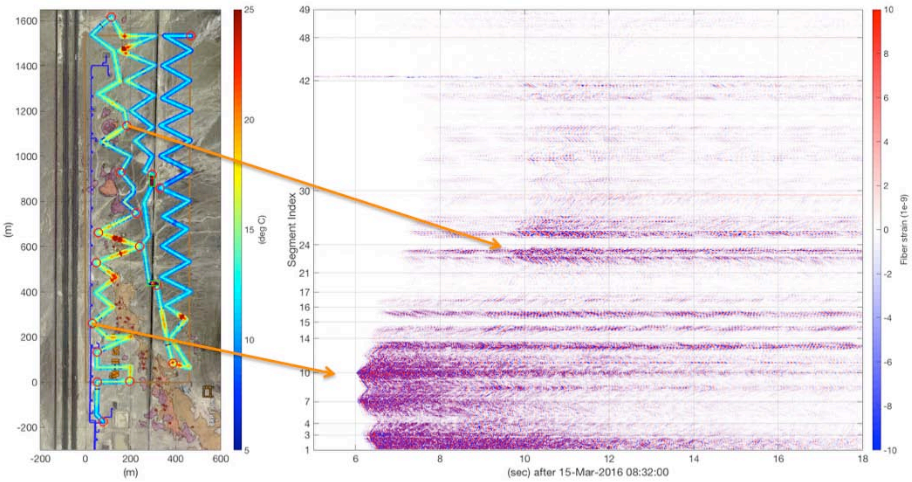
There are more details in the paper.

Mystery event at 08:32:06 (UTC) on March 15



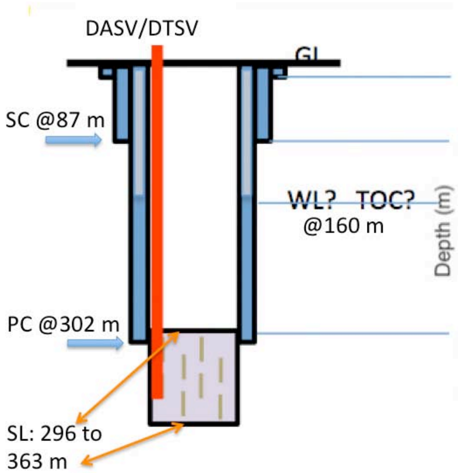
Here's a very intriguing event from March 15 that was not in the LBL catalog
Here in trace normalization

Mystery event at 08:32:06 (UTC) on March 15



Here un-normalized fiber strain

DASV/DTSV Well 56-1 completion geometry



- 56-1 was drilled to 725 m in 1991
- FIMT optical cable was deployed to 369 m
- Records show a fully cemented annulus but DTSV+DASV suggest otherwise

My next slides are about the Vertical Installation, the DTSV and the DASV
Mike Cardiff and Whitney Trainor-Guitton discussed some of this earlier so I'll try to focus on points where combined interpretation of DTSV & DASV give essential insight about coupling and the borehole l environment

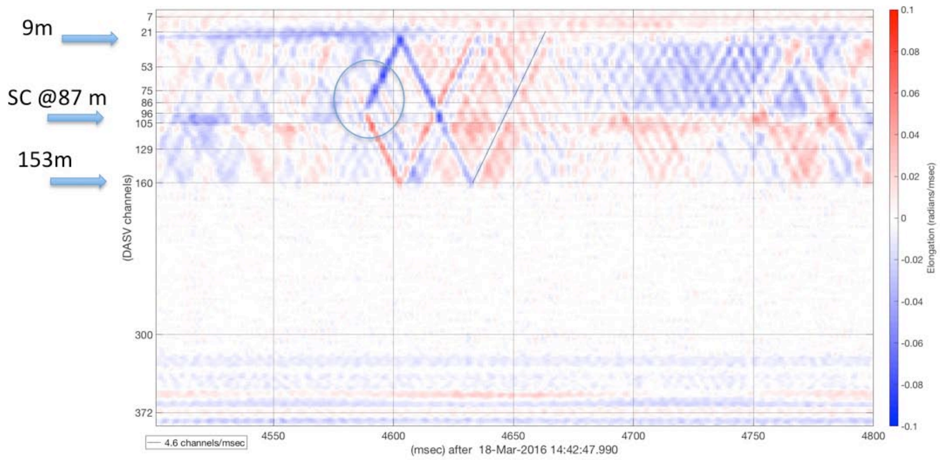
Records show that the well has problems with lost circulation at about 300 m when it was drilled in 1991.

The well schematic shows the three principal tubulars that were installed at that time. The depths indicated on the left all show up as significant boundaries in our surveys but there is another important feature at 160 m that does not directly match a recorded installation depth

Records show a fully cemented annulus but DTSV+DASV suggest to me that the feature at 160 m is a symptom of missing cement.

First let's look at the broadband DASV

It Rings



Here's some typical raw DASV data

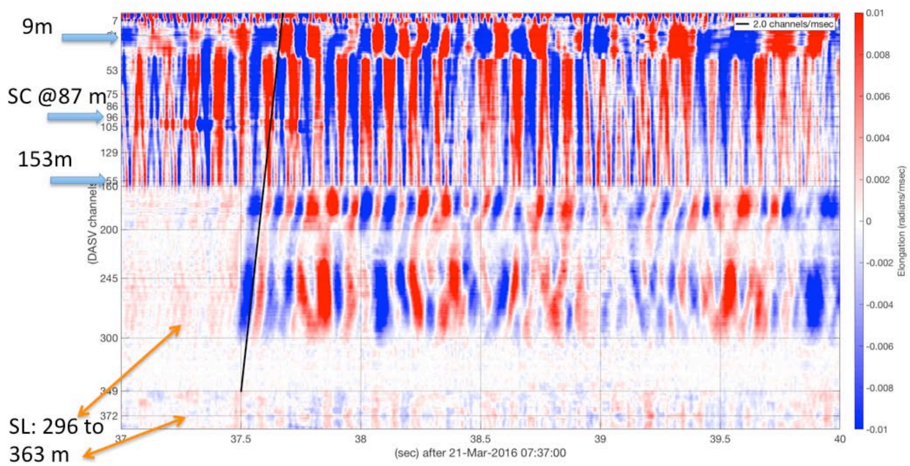
Note that its vertical axis is denominated in channels.
There is a U-splice at channel 372 which is at 369 m

The section between channels 21 and 160 always rings.

Always with propagation speed 4600 m/sec.
That's a typical speed for extensional propagation in steel.
This type of undamped ringing is typical for free casing but I've worried that it could be carried in free cable.

This event is diagnostic: It strongly suggests the that point is not a discontinuity in coupling of fiber to casing.
Ask me about it if you care to discuss.

Hawthorne EQ: DASV Strain Rate Response

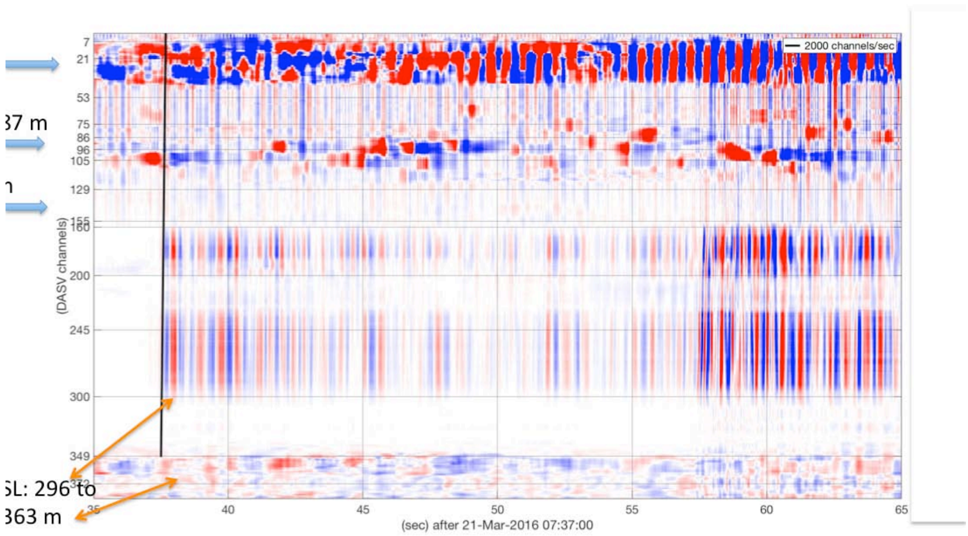


Here’s a 3-second record of the Primary arrival from the Hawthorne earthquake

The data is raw strainrate in radians per millisecond. Gain is10x higher than in previous

The earthquake arrival is clear from channel 300 at the top of the slotted line to channel 160 at 153 m
Below 300 is quiet
Above 160 is a lot of reverberation
The eq arrival is at about 2 km/sec

Hawthorne EQ: DASV Strain Response

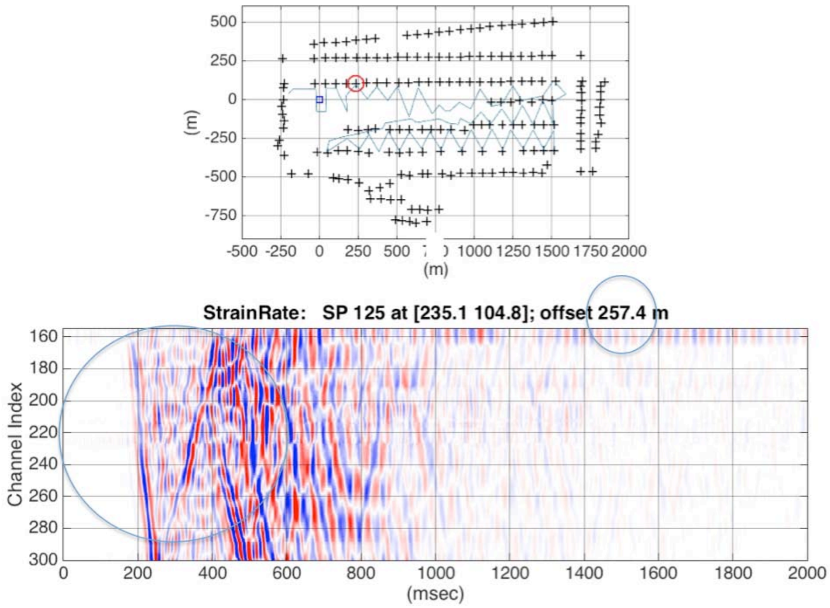


Here’s the 30-secon view. I think this has been time-integrated to show fiber strain

The next slides show examples of processed active source data restricted to the good-data zone

▫

Processed DASV Strain Response



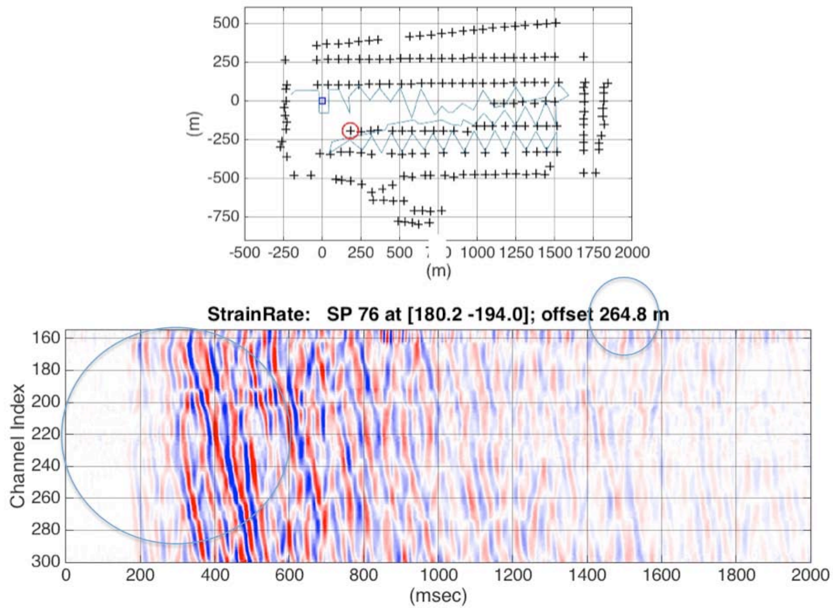
I'll show you data from 5 shotpoints at similar offset of about 260 m from the well
Whitney showed some of these slides in her talk.

Note that the planview at to has been rotated 90 degrees clockwise from previous displays
The welli location is the blue circle at the origin and the shotpoint is circled in red

The circle calls your attention to downgoing Compressional and Shear. The upgoing arrival here is a P to S reflection

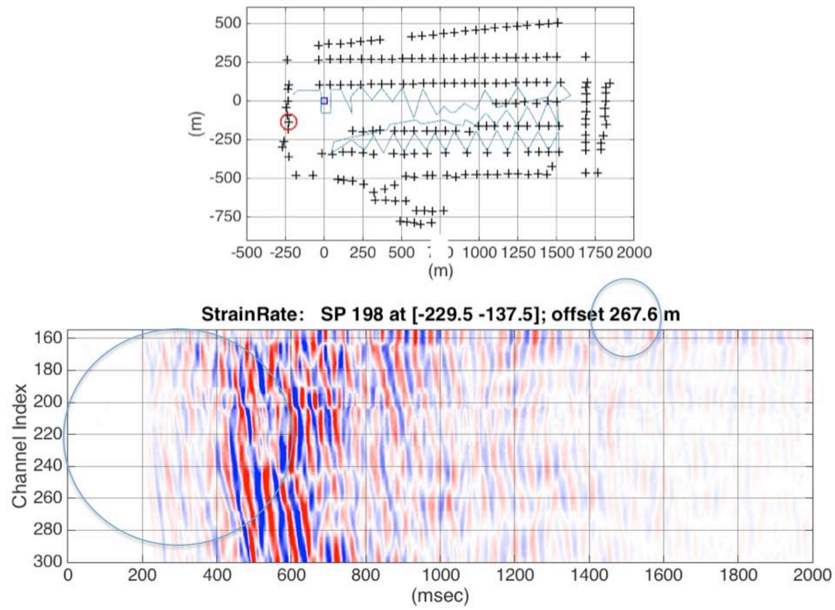
I'll go clockwise from SP 125

Processed DASV Strain Response



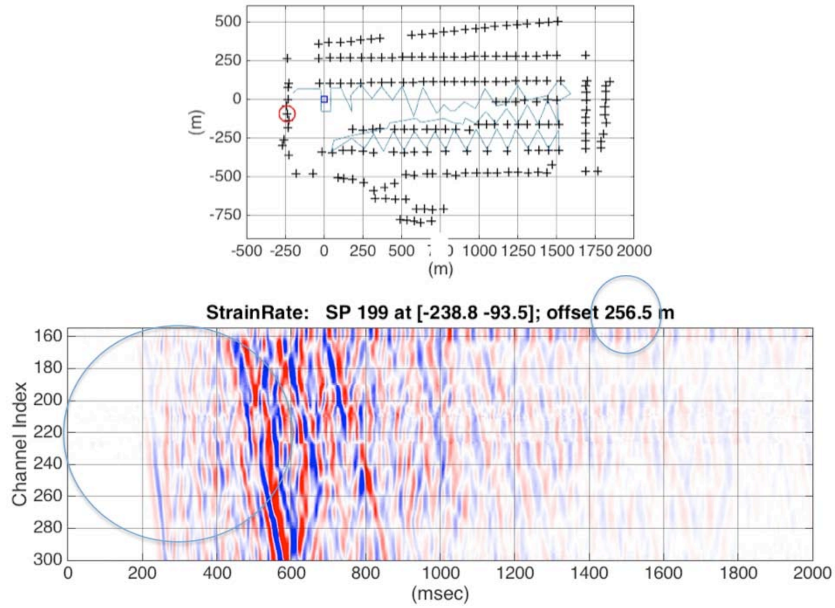
SP 76
Faster weaker P
Dramatic change in S
The Vibe is close to segment 47 in the culvert

Processed DASV Strain Response



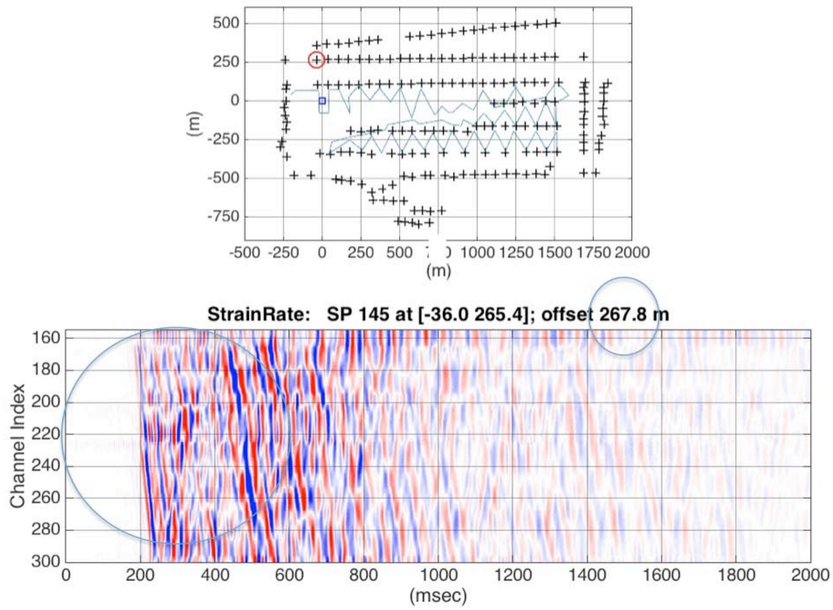
There is a rather dramatic change in shear from SP 198 to adjacent SP 199

Processed DASV Strain Response



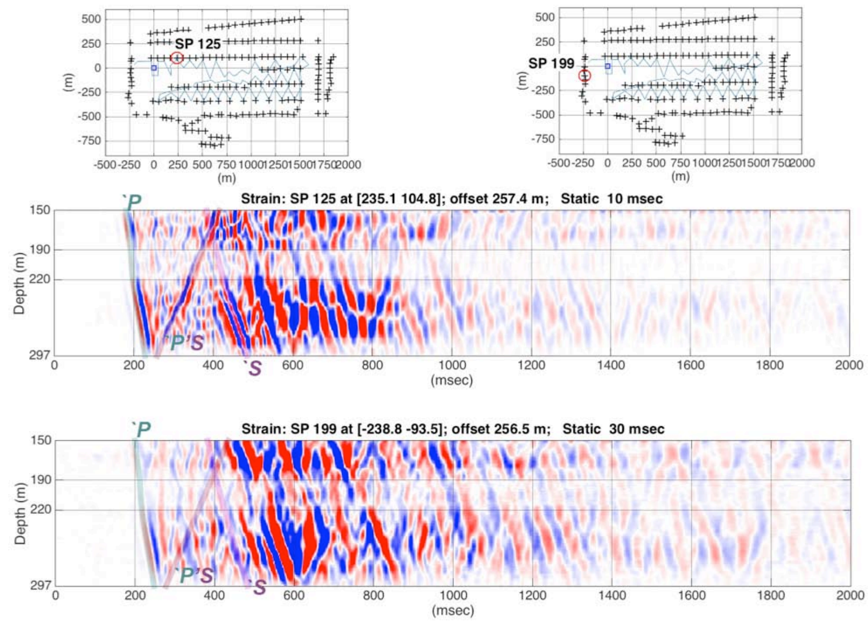
There is a rather dramatic change in shear from SP 198 to adjacent SP 199

Processed DASV Strain Response



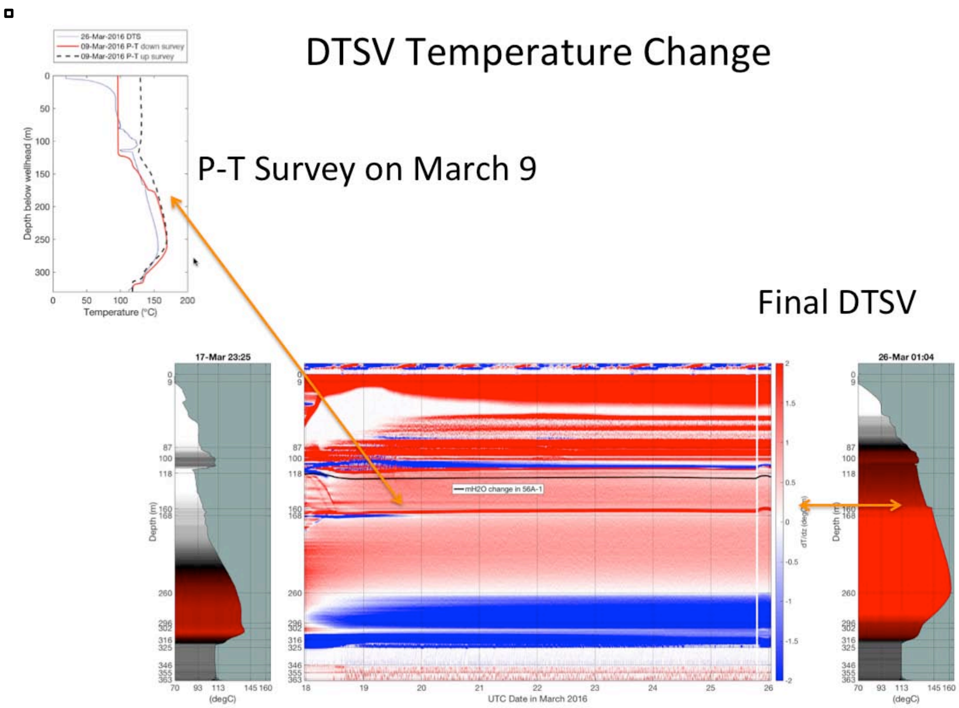
SP145

Processed DASV Strain Response



Here are two with annotations from a model derived from the DASV. Details are in the paper.
The simple model was plotted by Kurt and Whitney. It is strictly constrained by data within the interval 150 to 300m but unconstrained above and below that interval.

The next slides compare DASV observations with DTSV.



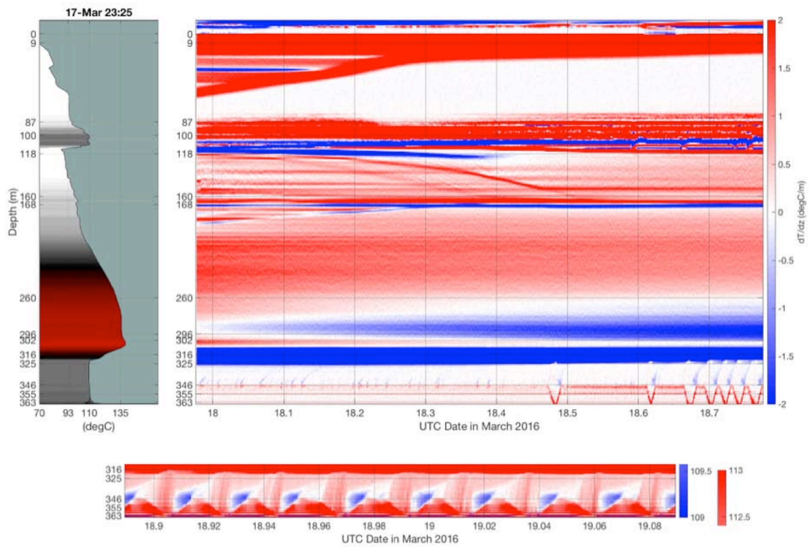
At upper left is a figure taken from Patterson (2017) that was shown in Mike Cardiff's talk.
It shows a P-T log run before the optical cable was placed in the well. It shows a discontinuity near 160m

This colored temperature profiles at bottom are the first and last DTSV recordings, The center panel shows the vertical temperature gradient in °C/m for the entire eight day recording period.

It clearly shows that the bottom of our reverberant zone matches a discontinuity in the DSLV profile that shifts with shifting reservoir pressure.

I think it might be a fluid level in the annulus

DTSV Early Temperature Change



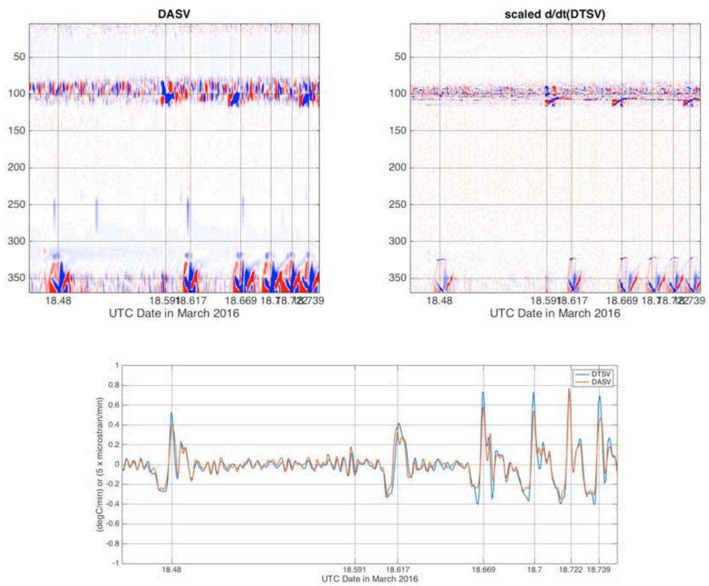
semi-hourly process at slotted liner

DTSV data are rich in observable phenomena and a discussion is included in my paper as well as in Mike Cardiff's.

The panel at top shows the first day of DTSV recording & is dominated by features related to recovery from the cold bath that accompanied installation of the vertical cable.

At the level of the slotted liner you see the first six examples of a process that continues regularly throughout the survey. A temperature strip with 10 repeat events in 5 hours is shown at bottom. The temperature scale is from 109 C to 109.5 C.

NDASV and DTSV Responses Match



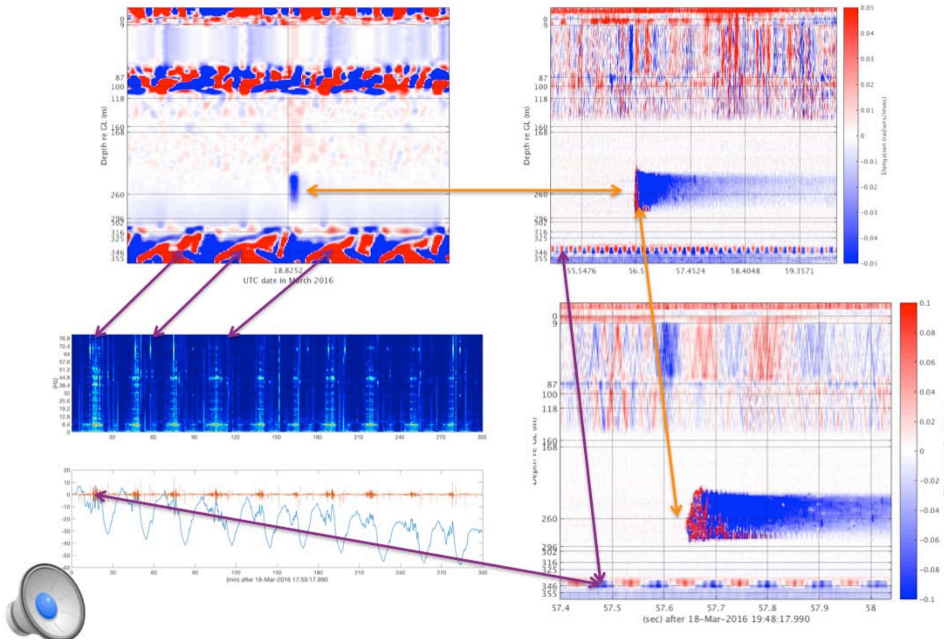
The Narrowband DASV shows a remarkable match to the thermal change measured by the DTSV. This slide shows a side-by-side comparison of a 9.5 hour interval on March 18. The lower panel shows an overlay comparison using the channels at 367 m. The same quality of match is seen throughout the 8-day borehole-recording period.

The DTS has sharper depth resolution and the match improves if the DTS data are smoothed by a 20 m running average in depth to mimic the effect of the inherent DAS gauge-length smoothing.

The paper discusses an interesting point regarding the thermal coupling coefficient making the match.

The NDAS shows some extra events. They are slips: thermally driven but sudden loss of frictional contact between cable and casing

Extra NDASV Events are Slips



Here is a typical slip event VDASV (left) and raw broadband DASV strain rate (right). Bottom right zooms in time showing that the event is a result of the loss of frictional copuling between casing and cable. It looks like a little earthquake rupture

The slip is independent of the sequence of deep events seen in the deep zone. The deep cycles are sometimes but not always accompanied by reverberant vibration at about 6 Hz as indicated by purple lines. Sped up by a factor of 60 to turn minutes to seconds it sounds interesting.

My Summary

- Distributed Optical Sensing clearly has potential to provide dramatic improvement in our ability to permanently and continuously monitor EGS resources.

- Combined DTS/DAS provides insight & constraint on interpretation beyond what either alone can give

- Engineered coupling is key to further progress

That's all that time permits. Please chat with me if you have questions or answers.

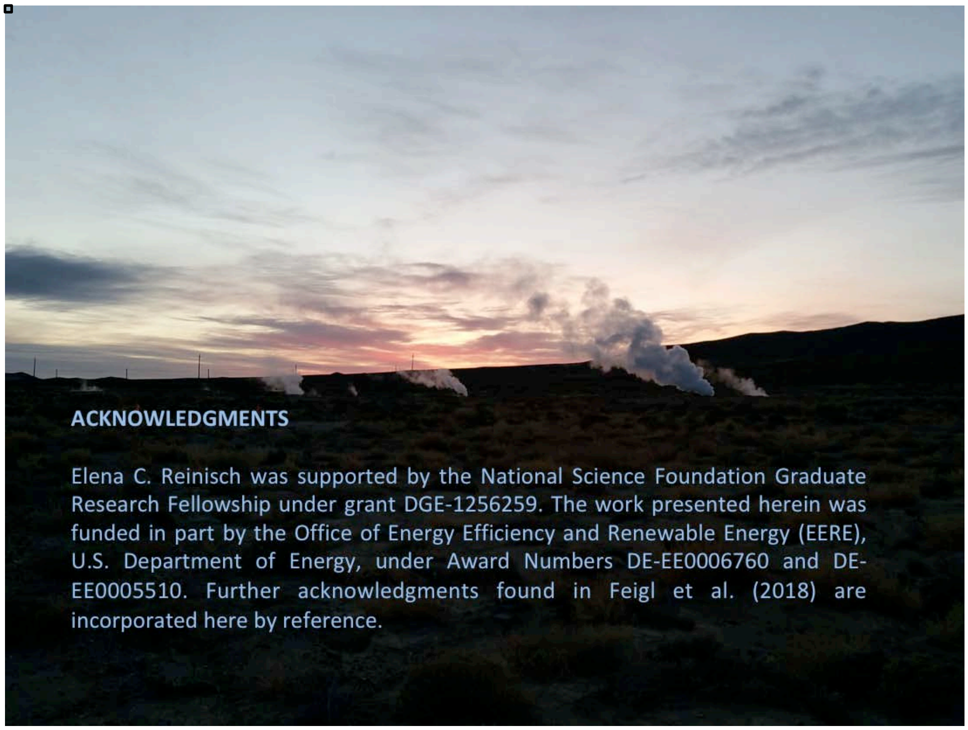
My Thanks

- to DOE for funding a real science project
- to Kurt and the PoroTomo team for collecting, archiving and organizing the analysis of this trove of science treasure
- to Thomas, Kurt, Mike, Herb, Cliff, Dante, Whitney, Jeremy, Xiangfang, Michelle and all for lots of encouraging help & discussion

CONCLUSIONS

Combined analysis of both DAS and DTS in both horizontal and vertical deployments show details, including puzzling observations, where the combined datasets help to identify and interpret anomalous coupling of the fiber measurements to environmental signal. Patterns in DTSH response as a function of both time and position document thermal response to daily temperature cycles and to changes in injection and production pressure. A magnitude 4.3 regional earthquake from a source in Hawthorne NV, 100 km south of Brady, was clearly detectable by both DASH and DASV. Comparison with Nodal geophones confirmed and cross-calibrated the instrument response of each system. Local earthquakes detectable by the DASH installation include all of those catalogued by the local LBL Brady seismic array plus several additional events of likely interest.

Slow strain measured by the DASV is highly correlated to temperature change measured by DTSV. Synchronous patterns in DASV and DTSV document repetitive cycles of thermal exchange both at the expected fluid level in the well and at the level of the slotted liner. DASV documents resonant acoustic behavior associated with the process. Events in DASV data suggest that thermal reaction to borehole rewarming periodically breaks the frictional coupling between cable and borehole wall causing slippage. Patterns in the DASV and DTSV data suggest that the upper section of casing is backed by a fluid annulus that is hydraulically connected to the main bore. Low-frequency (6.4 Hz) resonant pressure transients detected by the DASV at the slotted liner correlate to quasi-periodic (semihourly) thermal events at the same location detected by the DTSV array. Both the earthquake arrival and VSP waveforms extracted from the DASV active-source recordings show a vertical compressional propagation velocity close to 2 km/sec.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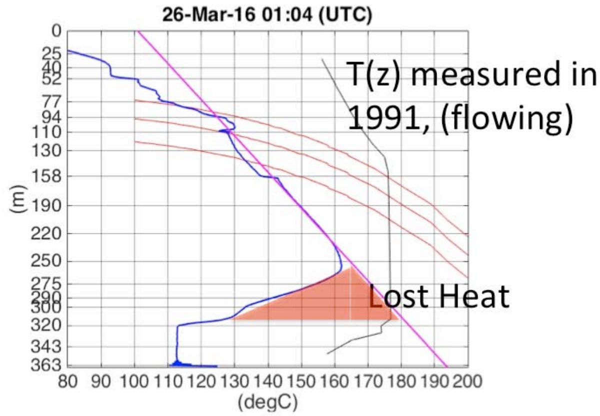

- Black curve is Temp from 56-1_PT_9-29-91.pdf (recorded as “flowing”)
- Blue curve is final DTSV
- Magenta line projects the gradient in DTSV and meets the black curve at its deepest point. So magenta line could be 1991 thermal gradient
- The shaded area is a triangle with area .5 x 50 m x 50 °C
- Supposing thermal contraction at 10e-6/°C that accounts for 5x50x50x1e-6 = .0125 m = 12.5 mm of vertical shrinkage since 1991