Swiss Centre of Competence
for Deep Geothermal Energy
for power and heat production

Microseismic Monitoring and Risk Mitigation Plan for the First Utah FORGE Stimulations at the Toe of 16A-32

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The Authors

FORGE Utah

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- Phil Wannamaker – Resource characterisation and downhole monitoring design

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- Jim Rutledge – Microseismic Frac monitoring specialist

Geo-Energie Suisse – Swiss Competence Centre for Deep Geothermal

- Falko Bethmann – Risk mitigation/ATLS
- Ben Dyer – Network modelling and monitoring system
- Peter Meier – Hydraulic specialist. CEO of GES

Abstract

The injection well, 16A-32, drilled at the FORGE site towards the end of 2020 has a lateral section of ~4000ft that dips at around 30° and terminates at 8500ft at a temperature of ~240°C. It is planned to perform a small number of stimulation tests at the toe of 16A this autumn (2021) which will be monitored in real time by a deep microseismic network and large surface array. In this talk we present the design of the deep monitoring network, the anticipated network performance and mitigation of seismic risks.

The deep network will consist of three established high temperature geophone strings and realtime processing software to derive event hypocentres and magnitude estimates. This primary network will be supplemented by behind casing and wireline DAS in the same monitoring hole together with a three level, 3 component fibre optic sensor string to evaluate the relative seismic performance of these less established systems. The aim is to process all of the data from the deep 3C geophone and fibre optic 3C sensor strings together with a subset of the DAS data in real time in order to monitor the data quality and synchronisation of these separate sensor systems, which will be a challenge due to large data volumes, different file formats and remote acquisition locations. For mitigation of seismic risk, processed data will be fed into a 'classical' traffic light system and an advanced traffic light scheme that incorporates lessons that have been learned from geothermal stimulations in Basel, Pohang and most recently from the Bedretto underground lab.

Role of Geo-Energie Suisse (GES) at FORGE

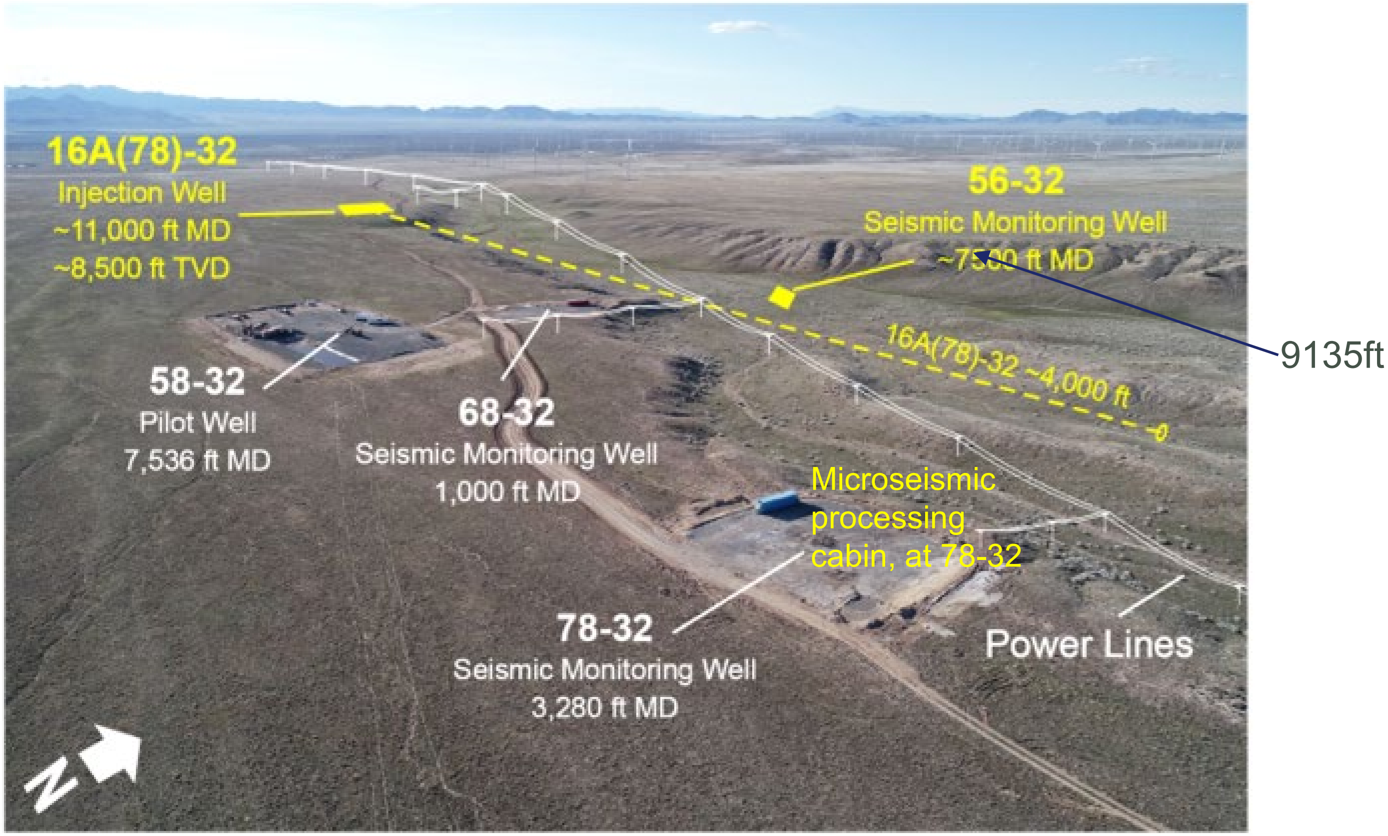
IASS - *Innovative Acquisition Systems and Software for Deep Geothermal Evaluation and Monitoring*

- The aim of IASS is to identify and validate through field trials a proven microseismic monitoring and processing system for the deep EGS project of GES at Haute-Sorne in Switzerland
- IASS is a Swiss project to test and validate innovative acquisition systems and imaging techniques that will minimise the seismic risk of deep geothermal projects
- Two principal field aspects to IASS
    - i) Tool selection and low temperature pre-qualification seismic performance testing at the Bedretto underground lab in Switzerland.
    - ii) Participation in the FORGE program is an essential part of IASS for high temperature downhole testing and validating realtime microseimic processing/risk mitigation methods.

Contributions to FORGE

- Resolution and sensitivity modelling.
- High temperature 3C strings for the stimulation this winter.
- Real time monitoring and preliminary microseismic event locations and magnitudes.
- TLS/ATLS seismic risk mitigation.

FORGE Site Overview

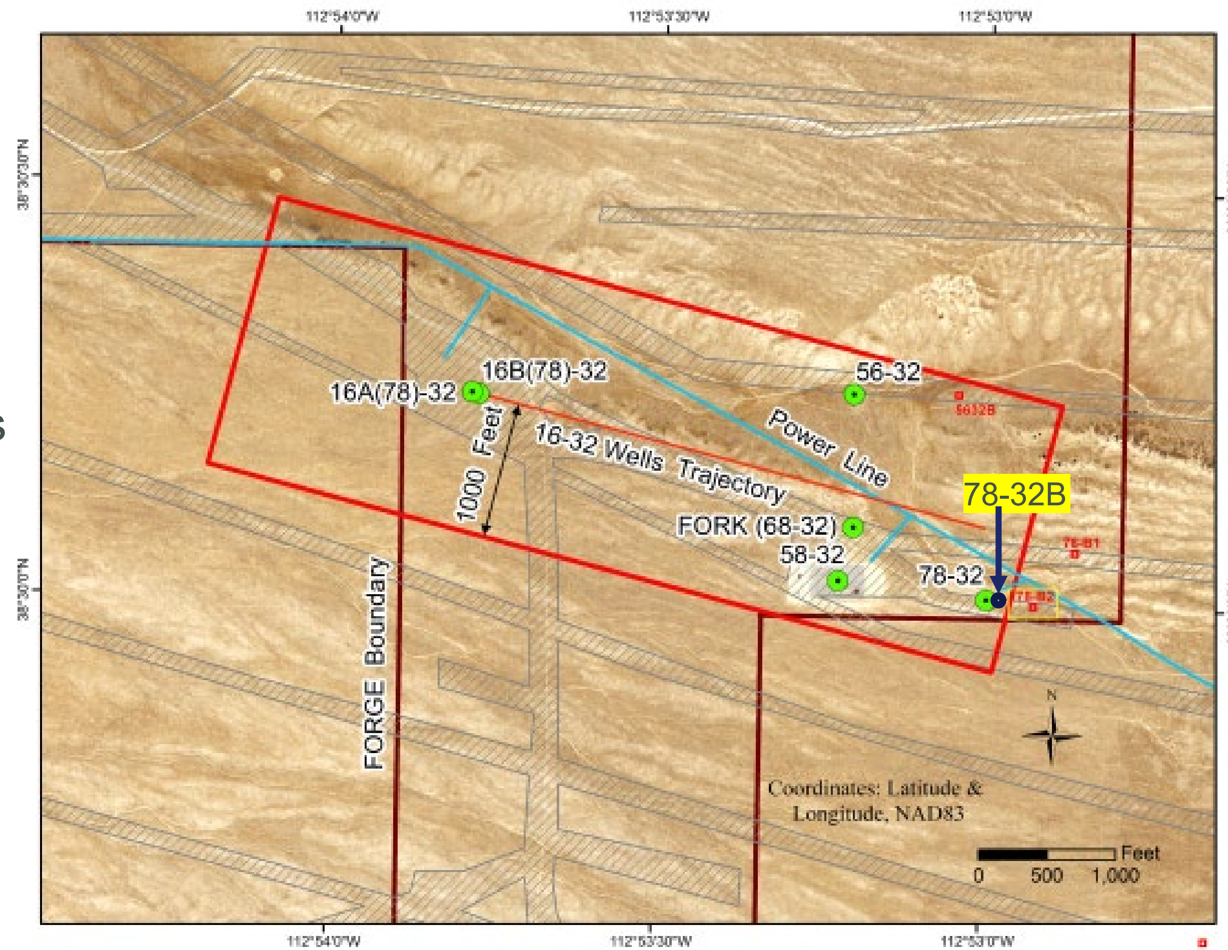


The origin of the local coordinate system used here is ground level at the 16A-32 wellhead

All distances are in feet (ft)

Modelling Aims

- Identify the optimum network for monitoring a stimulation at the toe of 16A
- Positions for the new 56-32 and 78-32B boreholes
- Number of sensors, depths and spacing within each hole
- Relative location accuracy
- Network sensitivity



Deep Microseismic Monitoring Objectives

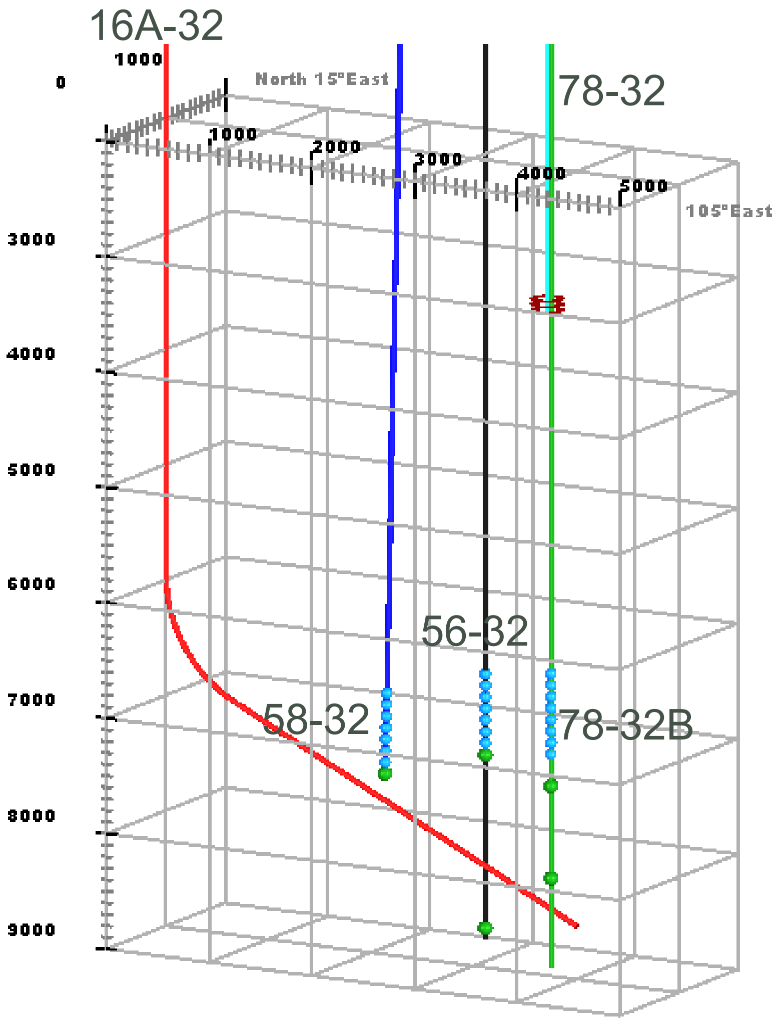
Objectives for the 16A-32 stimulation monitoring, winter 2021

- Realtime locations and magnitudes during the 16A-32 stimulations
- Realtime TLS/ATLS seismic risk mitigation
- Long term deep network installation and monitoring
- Testing innovative tools

Approach and Preparation

- Weekly technical/planning meeting for the last year or so covering
  - locations for the two new monitor holes
  - microseismic network design
  - selection of tools and wirelines
  - site services and access
  - data network
  - check shots and vibes for velocity evaluation and geophone orientation
- Weekly meeting with the wireline service provider over the last few months

3D View of Planned Sensor Strings – (April 2021)



The origin of the local coordinate system used here is ground level at the 16A-32 wellhead.
Grid is rotated 15° from North
All distances are in feet (ft)

Primary network

Blue. 8 level, 3C digital geophone chains deployed to <195°C in 56/58-32 and <215°C in 78-32B during stimulation. In fact 78-32B may be at max. 210°C the current specification limit

Long term network

Green. 2 level, 3C analogue geophone pairs deployed post stimulation to <225°C, shallow position, and <246°C deepest positions

Innovative systems

Red circles. BOSS, 3 level, 3C fibre optic string and wireline DAS

78-32 and 78-32B DAS behind casing

78-32B string at >195°C

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Primary Network Geophone Strings

Avalon ASR High Temperature, Digital, 3C Geophone String

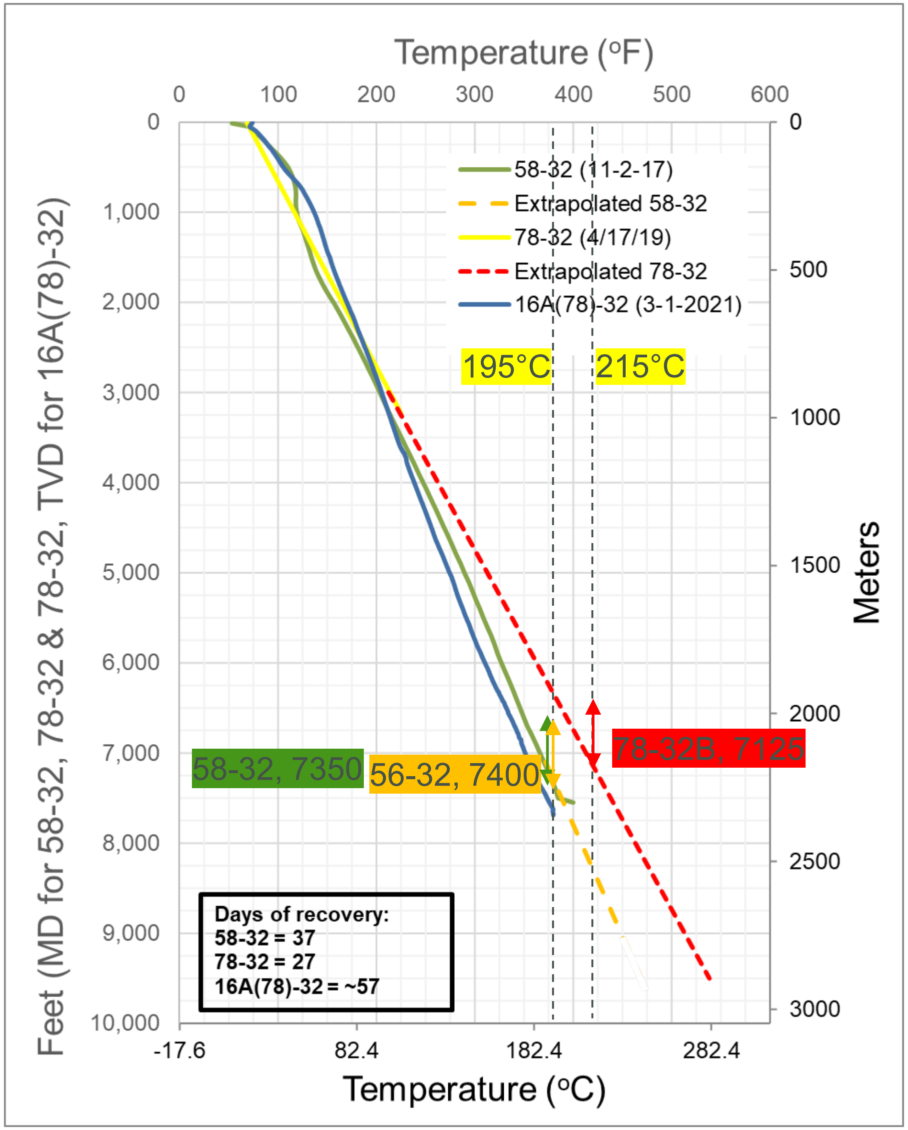
Key Features

- Proven reliability, high sensitivity and highest temperature spec
- Active cooling keeps the internal temperature <165°C
- Motorised clamping arm. Can be re-positioned according to temperature
- High side indicator (measures the relative bearing of the geophone group)

General spec

- 8 levels at 100ft intervals
- 3” OD210/215°C (current/future) temperature limit
- 3C fixed cartridges with 4 omni directional sensors / axis.198 V/m/s damped sensitivity
- 24 Bit A/D, 0.25ms sample interval, 1600Hz roll off
- Continuous (gap less) data acquisition
- High temperature, 7 conductor wireline deployment by ASL and Schlumberger

Geophone String Depths vs Temperature



78-32B

- Top tool at 6425ft to bottom tool at 7125ft 215°C (419F). 5.82” ID

58-32

- Top tool at 6650ft to bottom at 7350ft, 194°C (382F). 6.276” ID casing surface to 7364ft. TD at 7536

56-32, following the 58-32 temperature profile

- Top tool at 6700ft to bottom tool at 7400ft, 195°C (383F)

NB the 56-32 temperature was logged 29/6/21 and overlays the 58-32 profile. 4.892” casing ID. TD 9135ft

Resolution – Relative Event Location Accuracy

Primary Network Resolution

The overall, worst case, resolution is calculated for the specified data accuracies

8 level, 3C strings at 100ft intervals have been modelled in 56-32, 58-32 and 78-32B for the following depth ranges

Receiver Strings

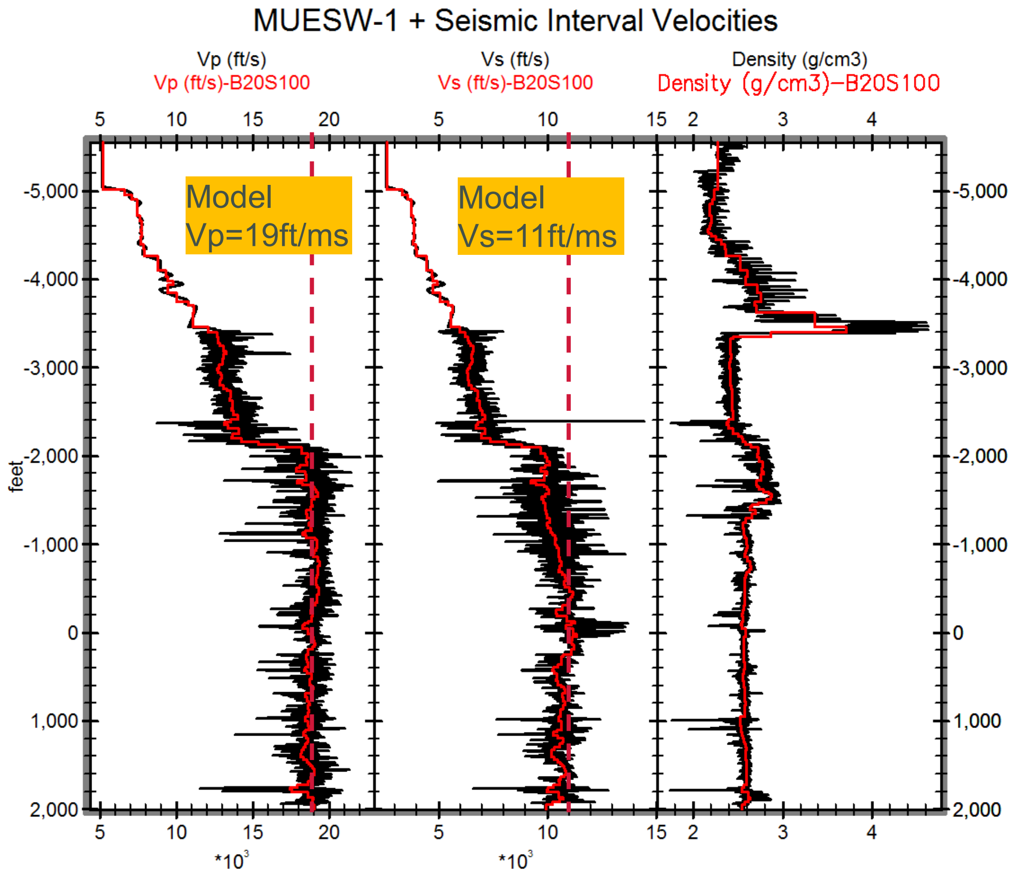
- 58-32. 6650-7350ft MD (Casing shoe at 7364ft)
- 56-32. 6700-7400ft BGL
- 78-32B. 6425-7125ft BGL

Model Data

- Vp 19ft/ms, Vs 11ft/ms. Constant
- Picking accuracies, P+-1ms, S+-2ms
- P and S picks for all groups
- Hodogram not included here

Hodogram Note - The geophone groups will be oriented using surface vibes in case it is necessary to locate with hodograms, for example in case of a string failure.

Velocity Logs, MUESW-1 (58-32)



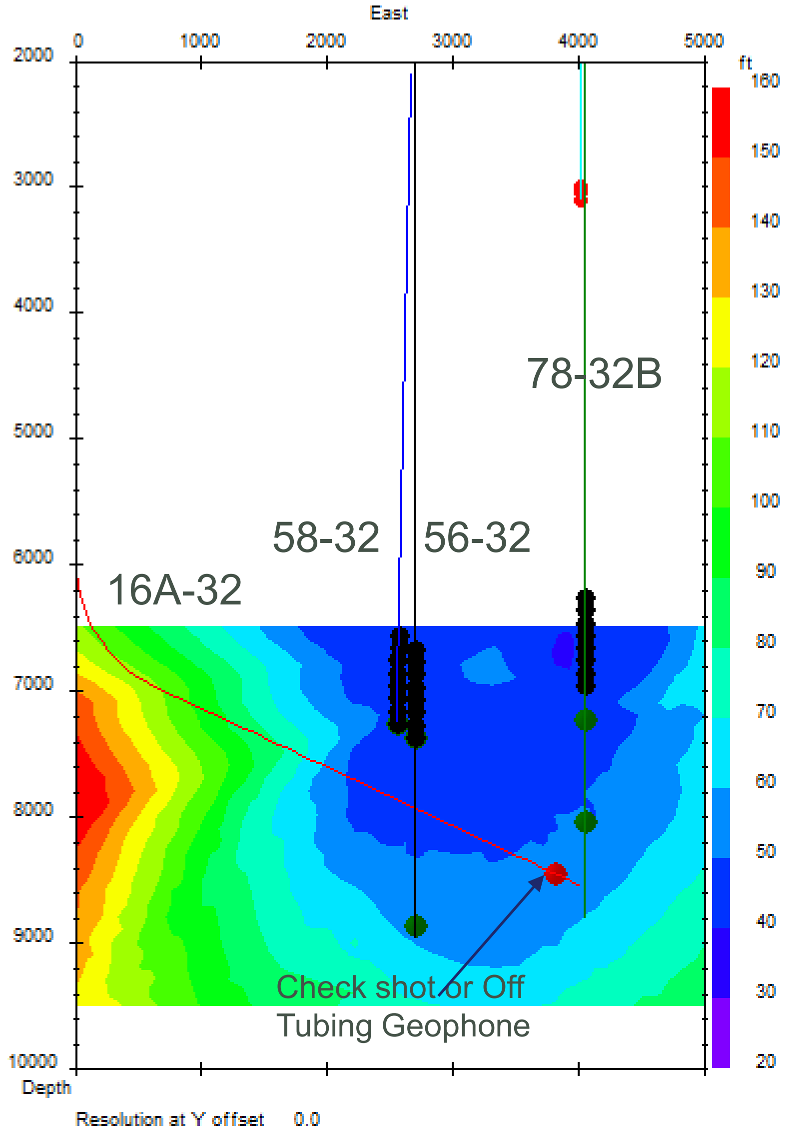
Velocity Logs from:
UtahFORGE_Phase03_FeasibilityModeling_NewMonitorWell_Position2_ForReviewMay14_2020. Jim Rutledge

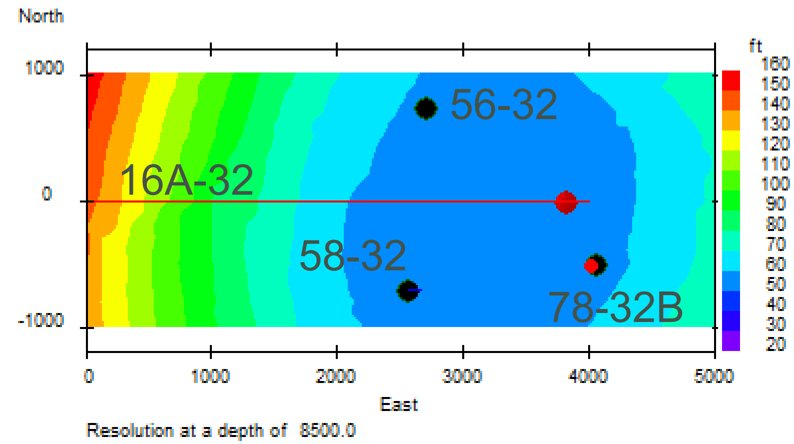
Relative Event Location Accuracy - Resolution

General

- The coordinates have been rotated -15° anti-clockwise so that 16A-32 is aligned nominally West to East
- The resolution is calculated on West-East and South-North vertical planes and the Horizontal plane
- At each grid point evaluate the
  - Horizontal resolution
  - Vertical resolution
  - Overall resolution in any direction
- The resolution is a step wise search moving out at increments of 1ft from the grid point searching for the furthest offset that fits within the data accuracies

Primary Network Relative Resolution





Good resolution for fracture mapping and correlation with the borehole logs

Relative resolution is NOT absolute.

Absolute resolution depends on the velocity model accuracy as well as the P and S picking accuracies.

Ideally use a check shot with known origin time at the toe of 16A-32 for Vp OR place a geophone close to the stimulation depth. Acts a bit like a Vp and Vs check shot

Likely best solution will be a check shot and no T zero. Vp & Vs from moveouts and relative arrival times between the arrays

Resolution Method

For the point g:

$$t_{Avg} = \sum_{i=1}^{n} \frac{(t_p^i + t_s^i)}{2n}$$

$$\Delta t_p^i = (t_p^i - t_{Avg})$$

For P (and S) times, the point test and offset r_g

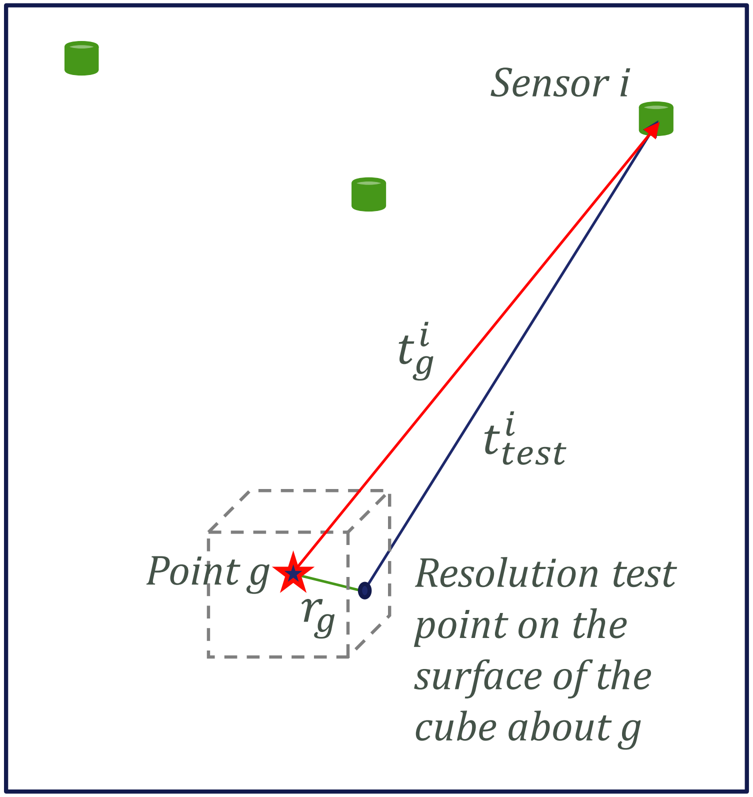
$$t_{AvgTest} = \sum_{i=1}^{n} \frac{(t_{pTest}^i + t_{sTest}^i)}{2n}$$

$$\Delta t_{pTest}^i = (t_{pTest}^i - t_{AvgTest})$$

$$\Delta t_{pErr}^i = \Delta t_p^i - \Delta t_{pTest}^i$$

Using successively larger cubes, find the maximum value of r_g where

Δt for P and S to all sensors is < the respective P or S picking accuracy



i is 1 of n sensors

g is a point where the resolution will be evaluated

$t_{p/s}^i$ *is the P or S time from g to sensor i calculated from the ray length and P or S velocity*

$t_{p/sTest}^i$ *is the P or S time from test to sensor I*

test is a point on the surface of a cube about g distance r_g *from g*

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Sensitivity Modelling

Sensitivity Method

Following Freudenreich et. al., 2012 the ***minimum detectable magnitude*** has been estimated for a representative sensor assuming an average S wave source radiation pattern over the focal sphere

Parameters derived by fitting the Mw values of the Pilot hole stimulation April-May 2019 processed by Schlumberger

- Q = 350.
- Vs = 11ft/ms (3.35m/ms)
- S corner frequency = 120Hz
- Density = 2.6g/cc

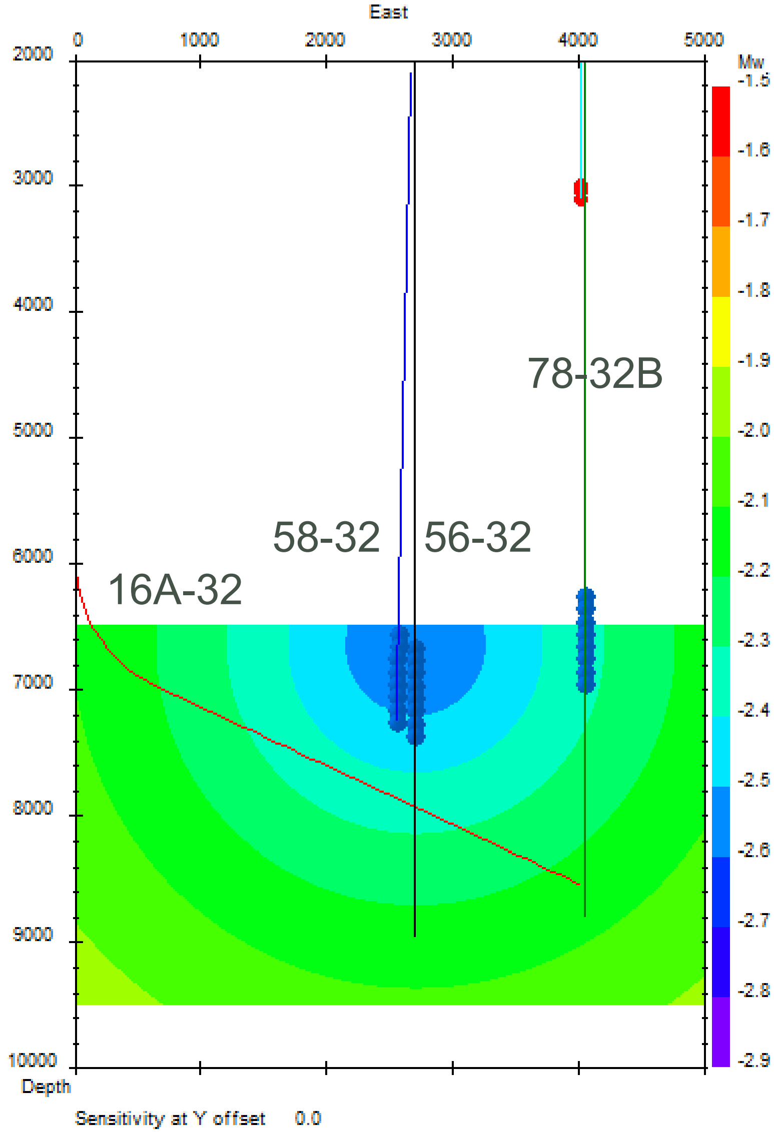
Typical parameters from other monitoring using geophones

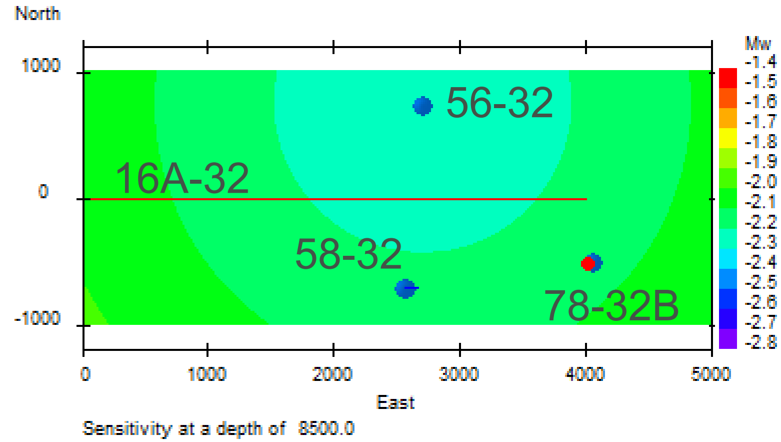
- S wave signal to noise ratio, 3 (N.B. P wave is not modelled)
- Background noise level 0.01 microns/sec (≡~0.5µV for a typical sensor)

Models

- The most distant sensor, which is the shallowest geophone group in 56-32

Network Sensitivity for the Furthest Sensor





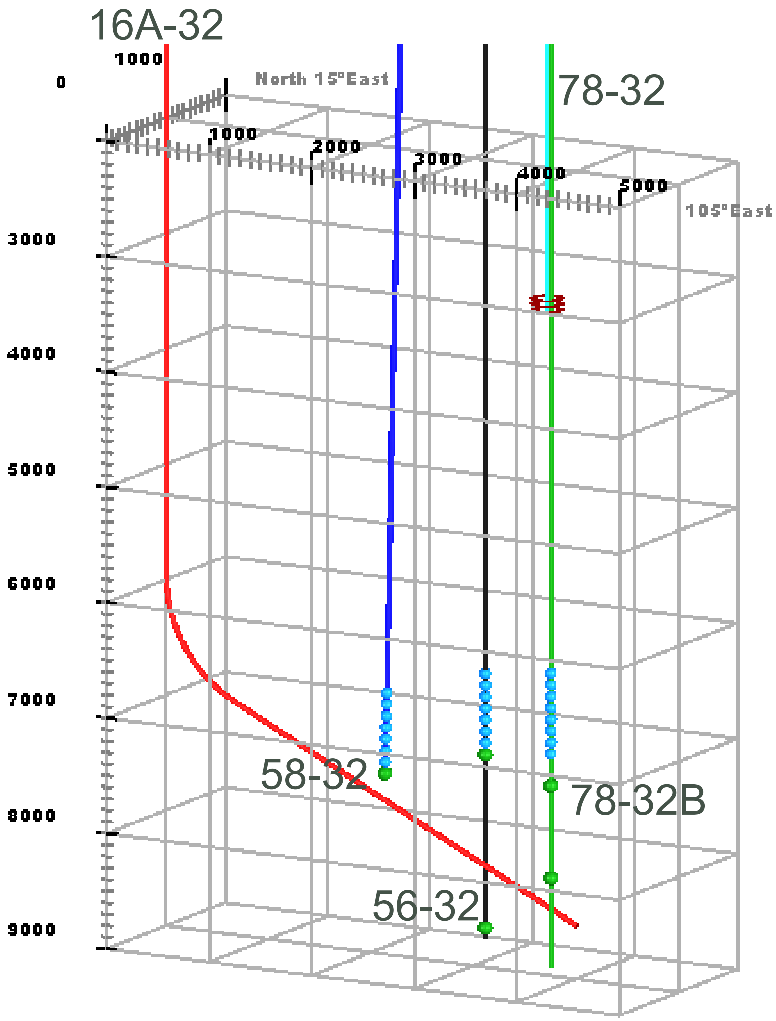
Looking for good sensitivity for ATLS

The most distant sensor of the network is at the top of the string in 56-32

From this sensor the limit of detectability is ~-2.15 at the toe of 16A

Q=350, S wave S/N=3, fc=120Hz, minimum trace level=0.01um/s

Long Term Network Configuration



The origin of the local coordinate system used here is ground level at the 16A-32 wellhead.
Grid is rotated 15° from North
All distances are in feet (ft)

Long term network

In each hole a two level, analogue 3C string will be deployed post stimulation, green spheres

Clamping by spring loaded, time release arms

Receiver Configuration

- 58-32. Lower tool at 7350ft MD (Casing shoe at 7364ft)
- 56-32. Top tool at 7400ft, lower tool at 8900ft
- 78-32B. Top tool at 7400ft, lower tool 8200ft

Shallow tools are 225°C spec

Deep tools are 260°C spec

Long Term Network Two Level Strings

Avalon PSS High Temperature, Analogue, 3C Geophone, Two Level Strings

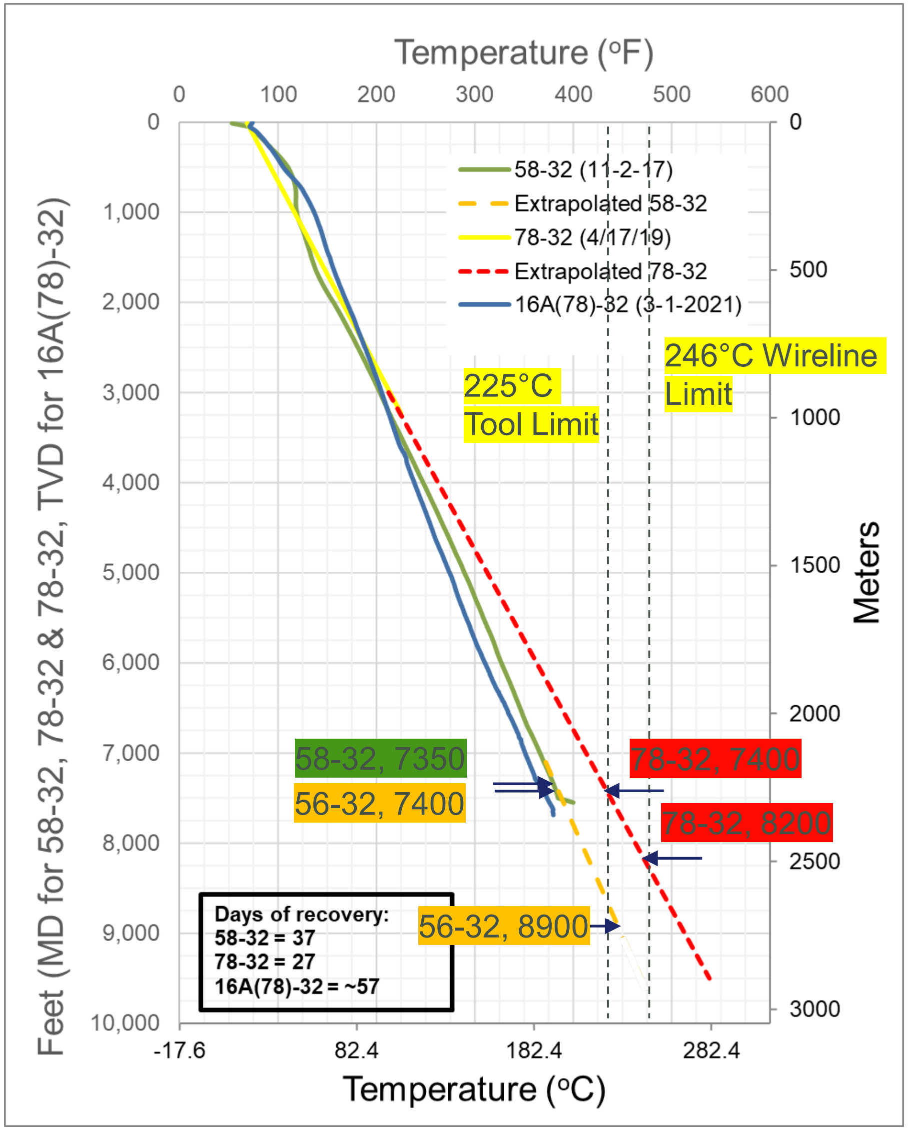
Key Features

- Single shot, time delay release, spring loaded clamping arm
- Long term deployment of 225°C or 260°C versions without active cooling
- Simple, low cost analogue tools with x500 downhole amplifier for good S/N over a 7 conductor wireline. Damped sensitivities 87,570 and 89,590 V/m/s 225°C and 260°C versions

General Spec

- Two, 3” OD levels at up to 1000ft intervals
- 3C fixed cartridges with 4 omni directional sensors / axis
- High temperature, 7 conductor wireline deployment by ASL and Schlumberger

Long Term Network Depths vs Temperature



78-32B

- Upper tool at 7400ft, 223°C,(433F)
- Lower tool at 8200ft, 245°C (473F). Casing shoe 8000ft, TD 9500ft

58-32

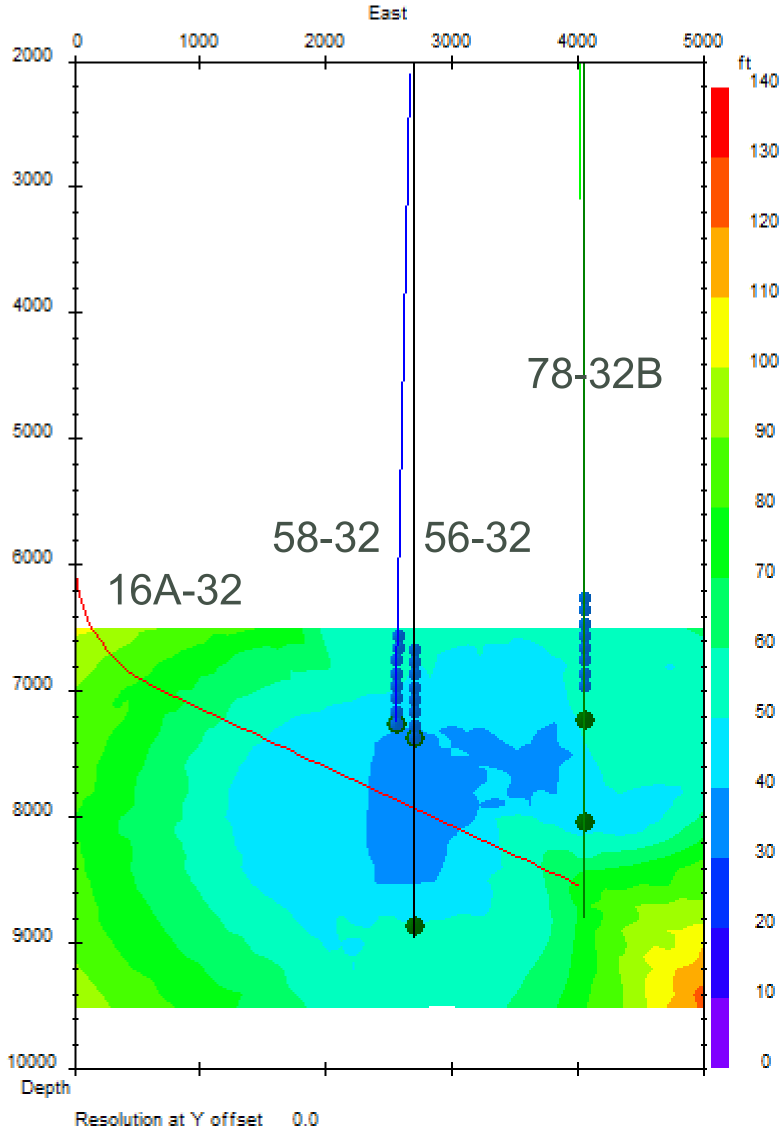
- Lower tool at 7350ft, 194°C (382F). Casing shoe at 7364ft

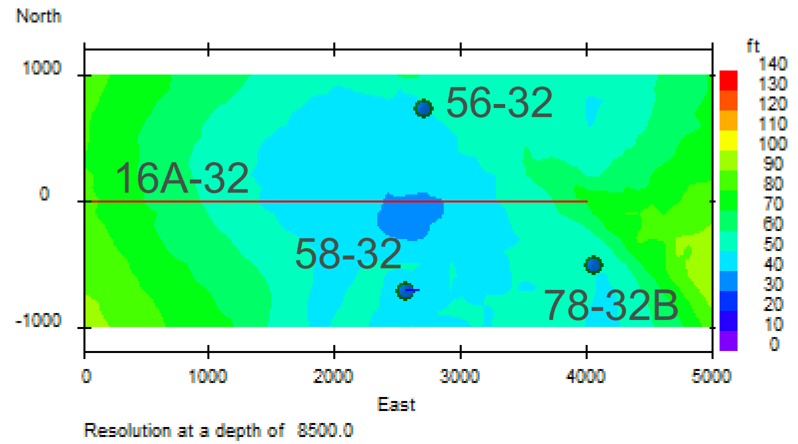
56-32 - following the 58-32 temperature profile

- Upper tool at 7400ft, 195°C (384F)
- Lower tool at 8900ft, 229°C (444F, TD 9000ft)

NB the 56-32 temperature was logged 29/6/21 and overlays the 58-32 profile

Overall Resolution of the Long Term Network



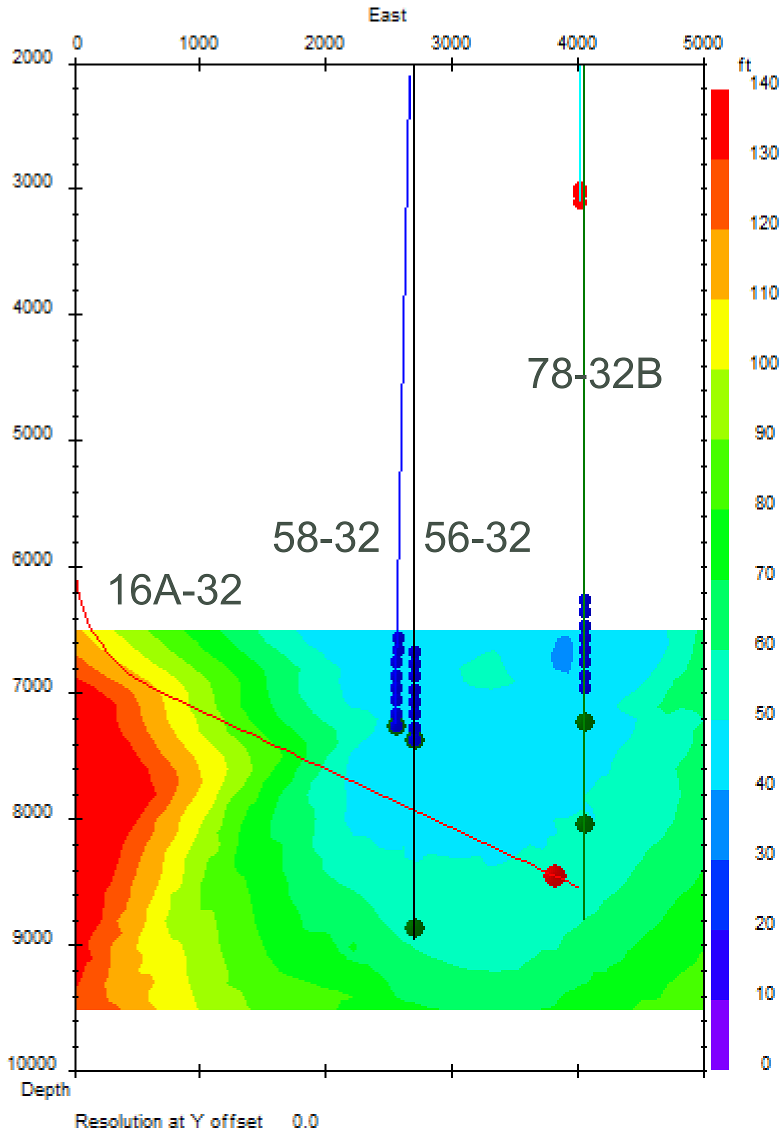


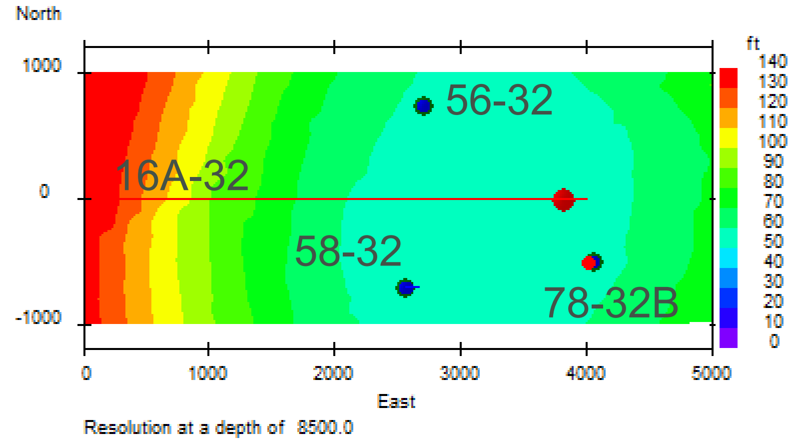
The Long Term Network sensors are indicated by the larger green disks.

The overall, worst case, resolution has been calculated for the following model parameters

- Vp 19ft/ms, Vs 11ft/ms. Constant
- Picking accuracies, P+-1ms, S+-2ms
- P and S picks for all groups

Overall Resolution of the Primary Network

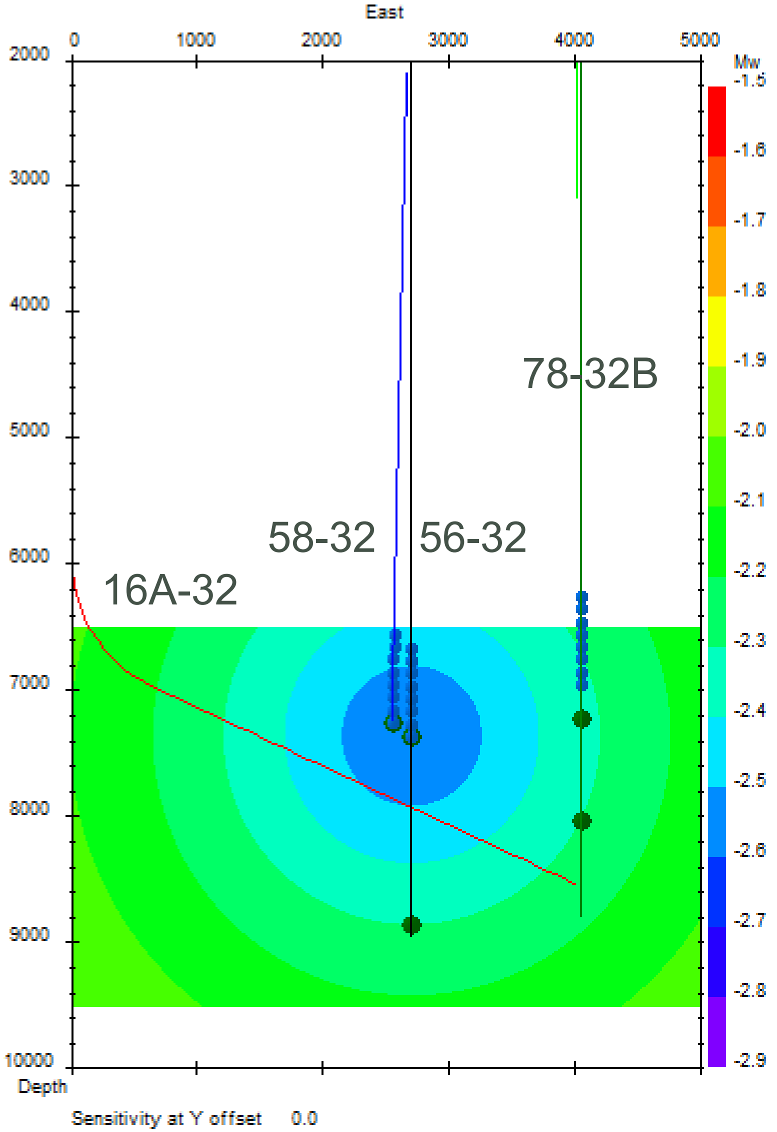


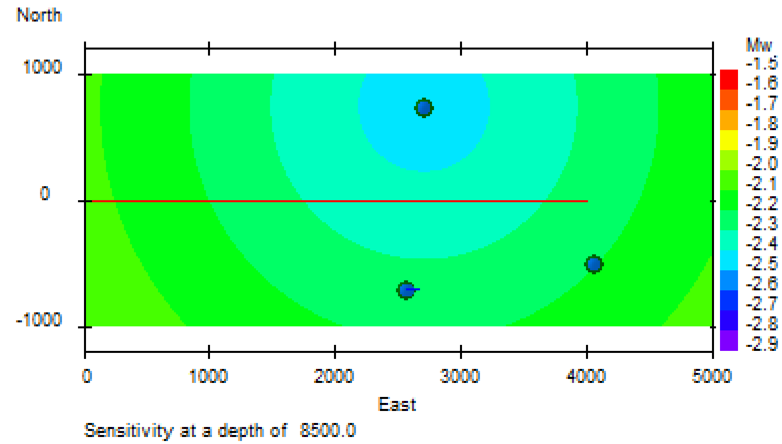


At best, the resolution of the Long Term Network is a little better than the Primary Network as the two level strings are closer to the target

The resolution is constrained by the geometry not the number of sensors

Long Term Network Sensitivity





The most distant sensor of the network is the upper group in 56-32

Assuming similar trace parameters to the digital strings, the limit of detectability is ~-2.25 at the toe of 16A-32

However, the noise floor of these analogue tools may be greater than the digital strings

Q=350, S wave S/N=3, fc=120Hz, minimum trace level=0.01um/s

Innovative Tools

Silixa – DAS behind casing in 78-32 and 78-32B

- Carina engineered fibre system
- 10m fixed gauge length, 1m trace interval

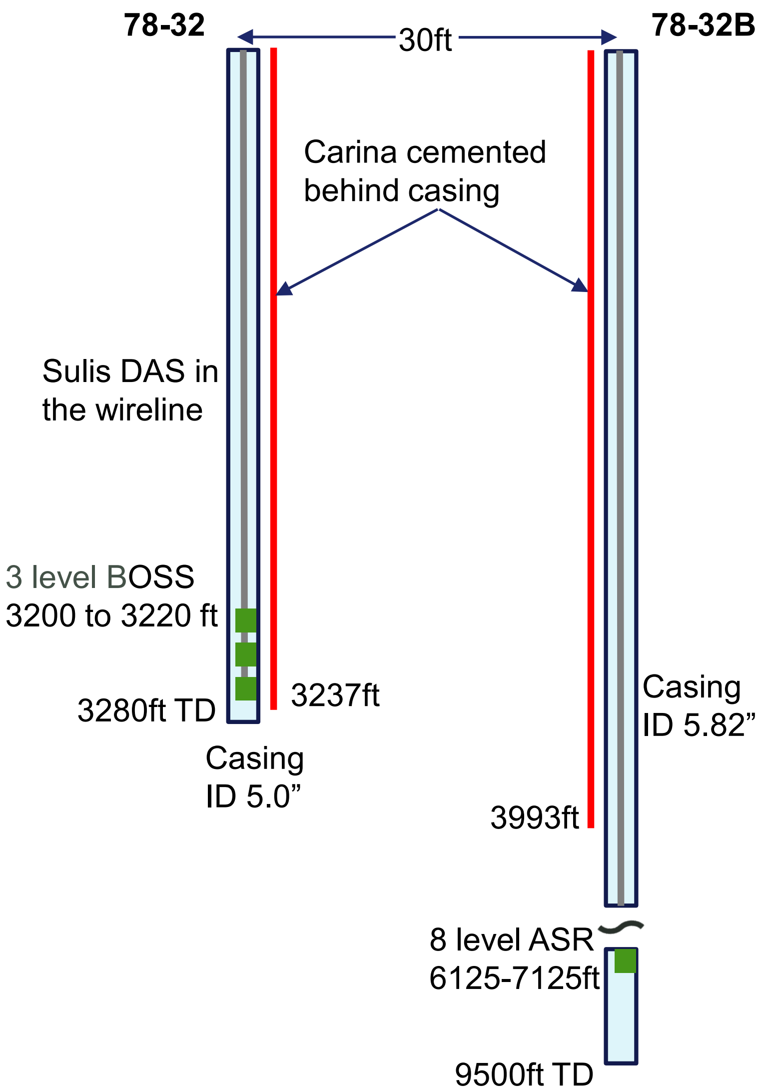
Avalon – Sulis wireline DAS

- Single mode DAS
- 5-20m selectable gauge length, 0.8m trace interval

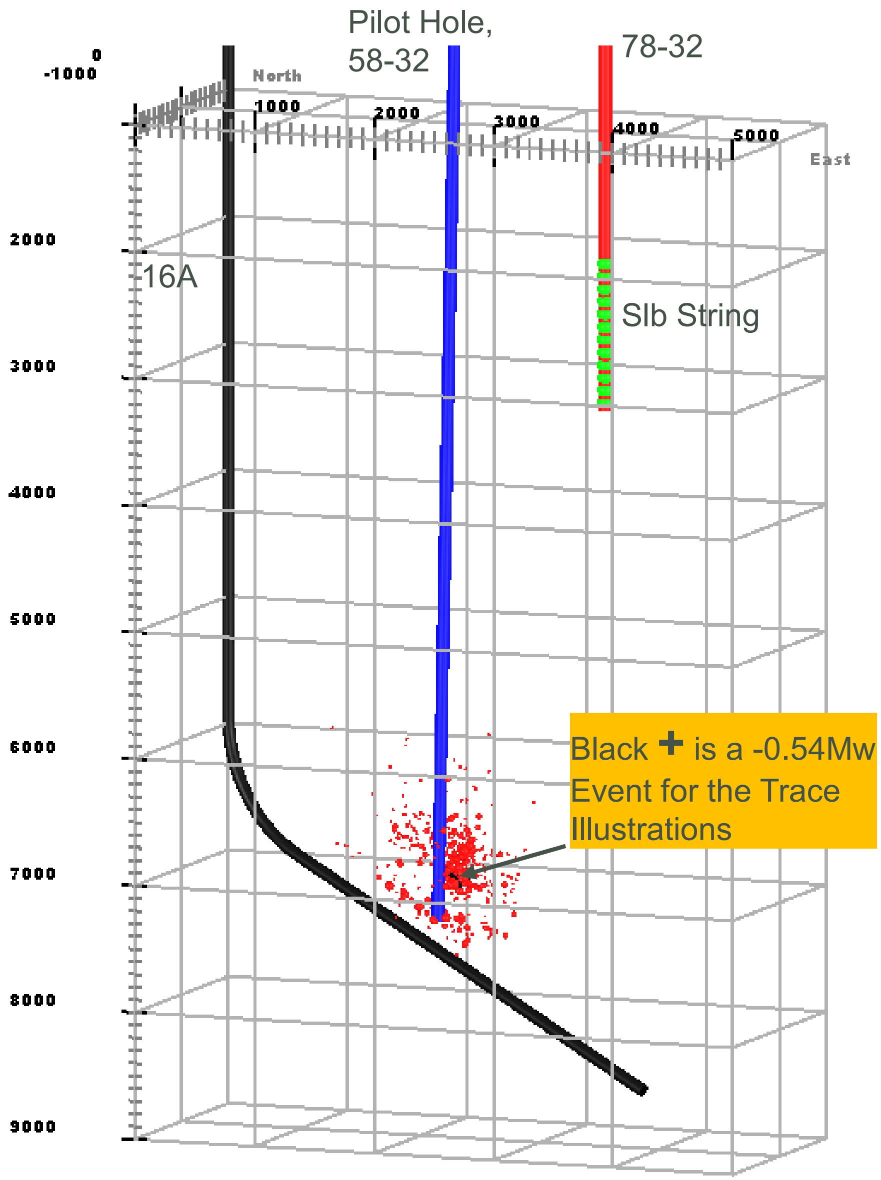
Avalon – BOSS, clamped 3C fibre optic sensor string

- 3 levels, 5m group interval

Avalon – ASR 210°C, clamped 3C 8 level digital geophone string



2019, Pilot Hole Stimulation. Raw Silixa Trace Data



The data are from the monitoring on the behind casing Carina type fibre optic DAS installation in Forge hole 78-32 (Red)

Sample interval. 0.5ms

Trace interval, 1m

Bottom of the fibre optic is at 3237ft (seems to be trace 1155 of 1280 traces)

Gauge length. 10m

fMax. = Velocity / (2 * Gauge length)

fMax (Vp=5800) = 290Hz

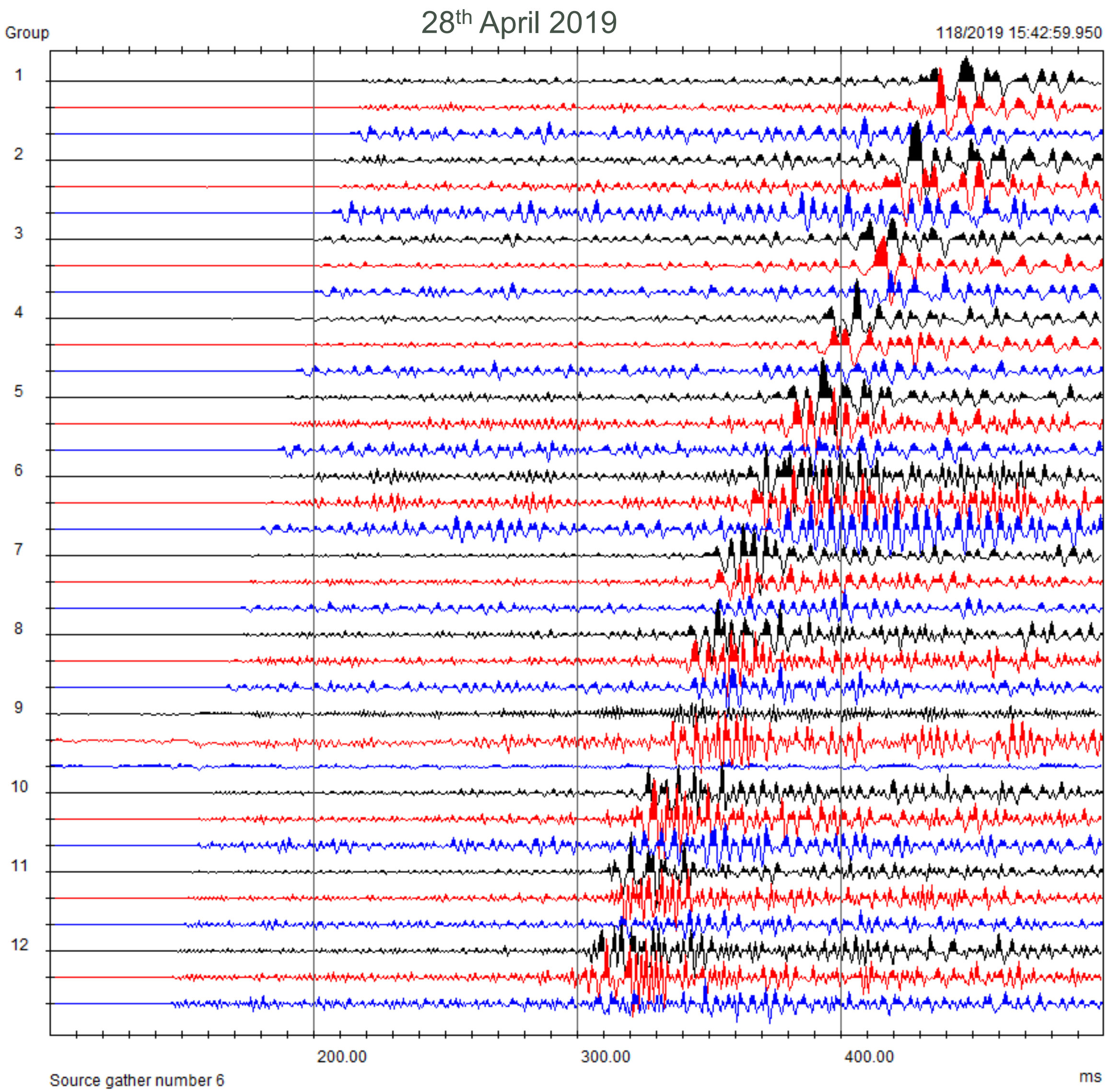
fMax (Vs=3350) = 167.5Hz

-1.4 to -0.5Mw. 41 events

12 level, 3C Schlumberger VSI string at 100ft intervals. 0.5ms sample interval. Green disks.

-2.0 to -0.5Mw. 424 events

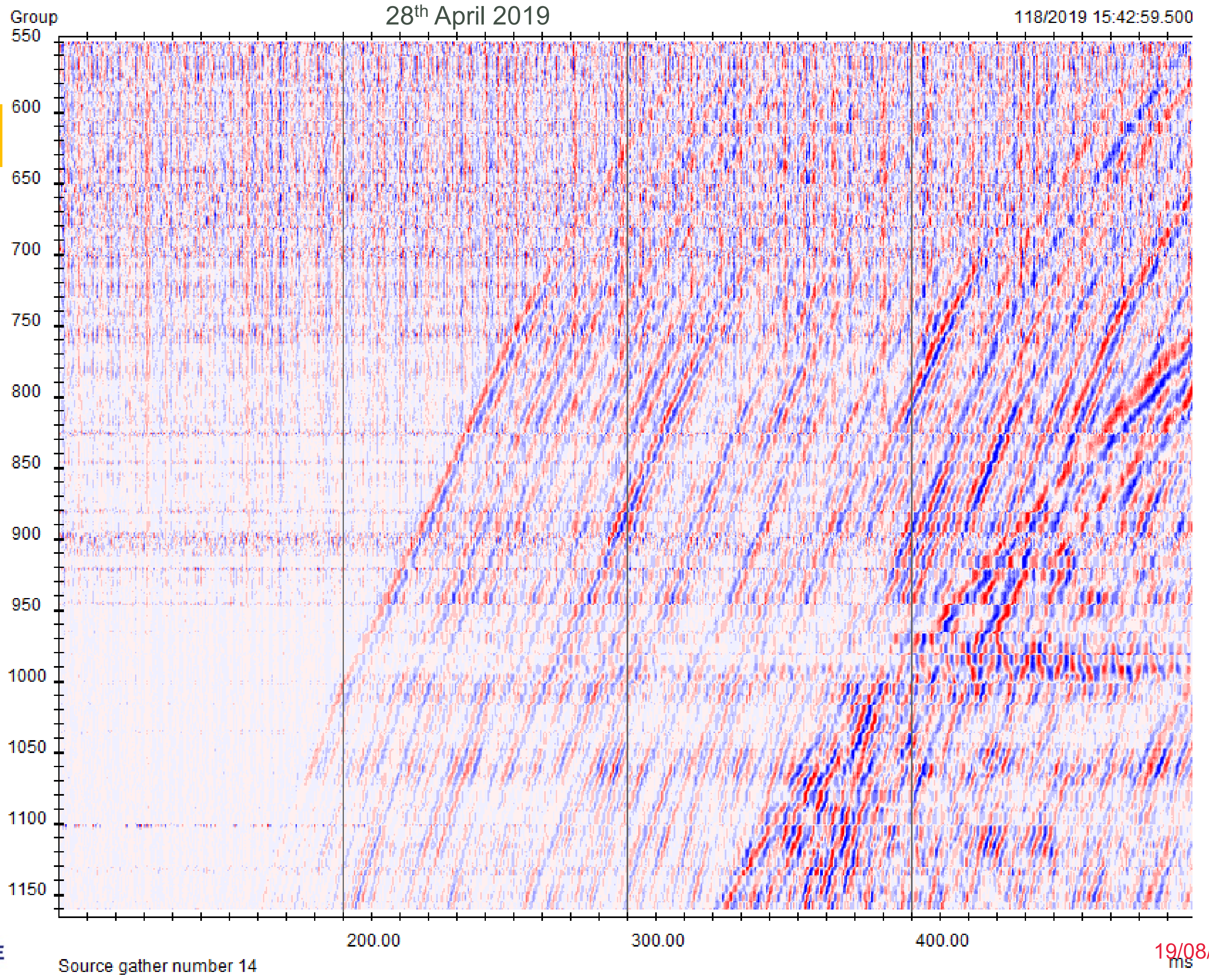
One of the Largest Events. -0.54Mw. 3C Chain



P wave S/N >200

One of the Largest Events. -0.54 Mw. DAS

P wave S/N ~2.0-2.5



Innovative Tools – 3C Fibre Optic Sensors

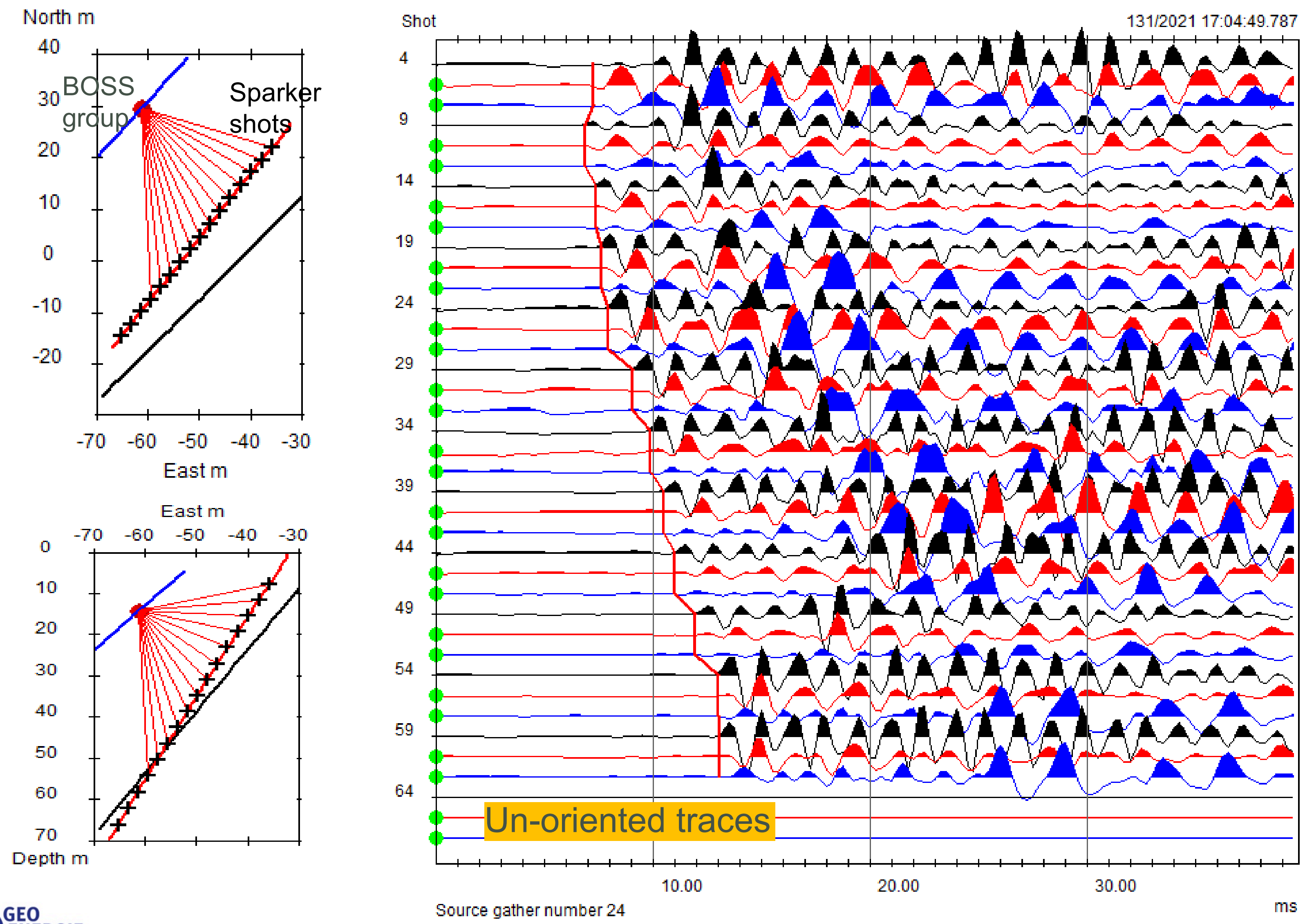
Avalon Borehole Optical Seismic System (BOSS)

- 200°C tool spec. Higher is possible
- No downhole electronics
- Metal to metal seals
- Single shot clamping arm with time release mechanism
- 3C fibre optic sensor groups
- Three levels at 5m intervals - fixed
- 1-1600Hz, 0.25ms sample interval

The string cannot be re-configured or repaired in the field

DAS in the wireline

BOSS – Bedretto Calibration Crosshole



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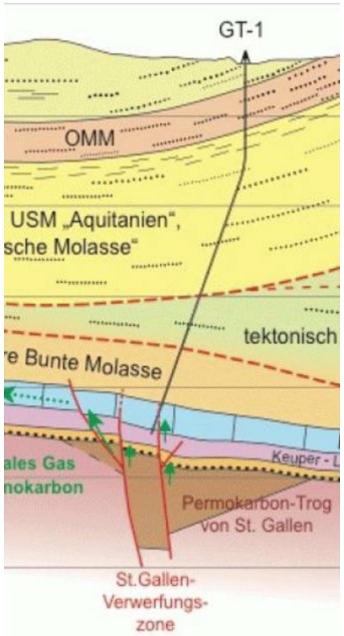
Mitigation of seismic risk

- Learn from previous mistakes!

- Basel 2006
  - Seismic risk was not really considered as an issue
    (2 pages for construction permit)
  - Comprehensive risk study done after the project (SERINAEX)

- injection into large faults can be dangerous
  - St. Gallen (2013) M=3.6 -> aborted
  - Pohang (2017) M=5.5 -> aborted (also no risk study)
  - Near Strasbourg (2021) M=3.9 -> aborted



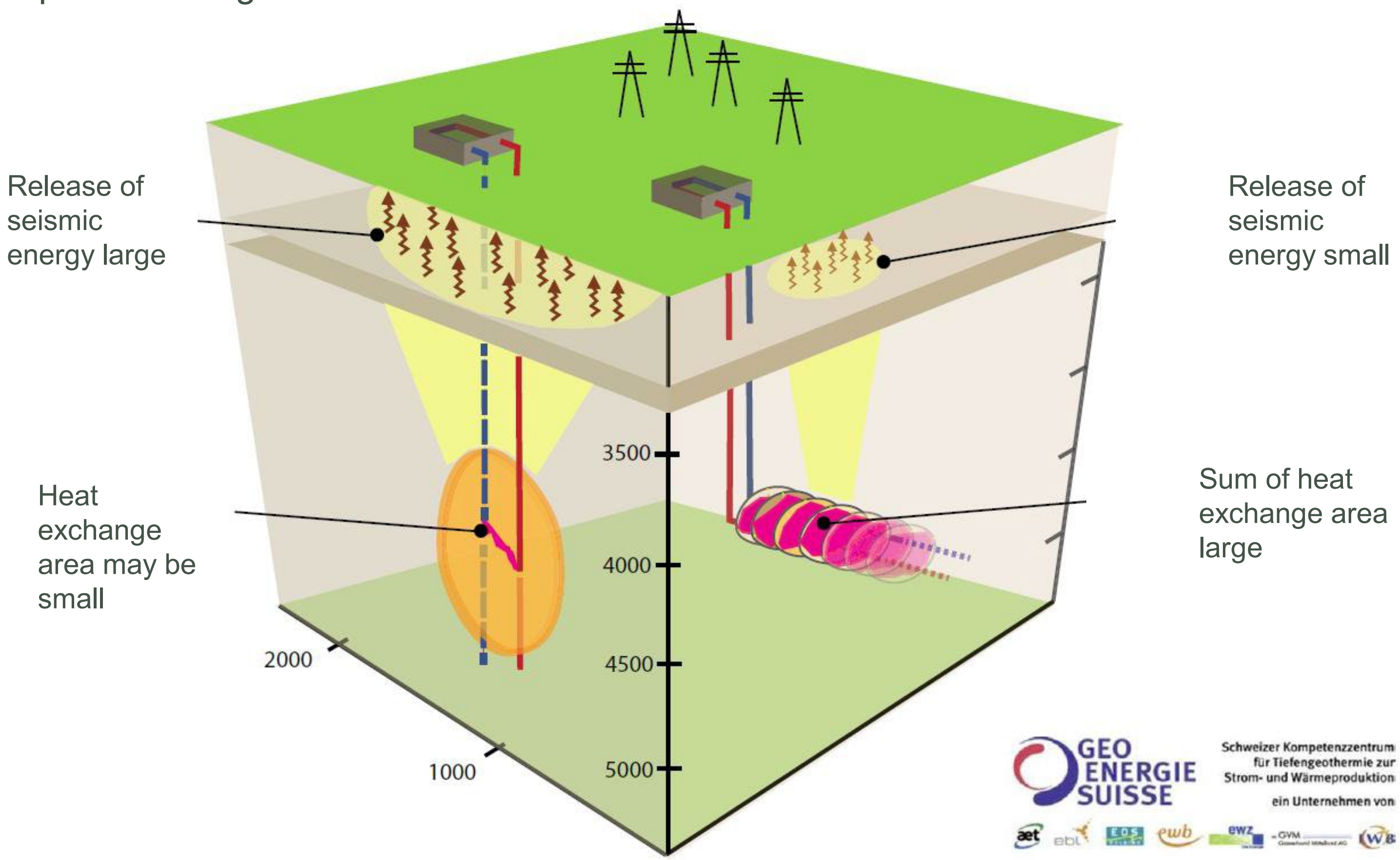
- Mitigation: change the concept!

Lessons learned Basel and consequences

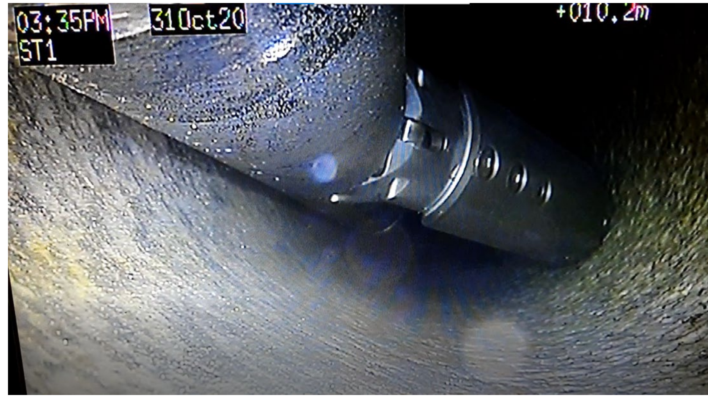
- Basel: A massive stimulation is less economic and bears a higher seismic risk

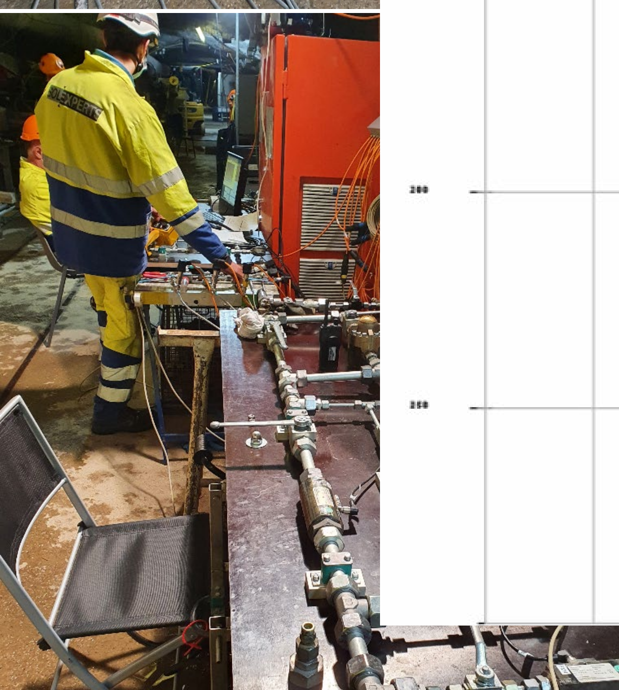
Concept
“deep heat mining Basel”

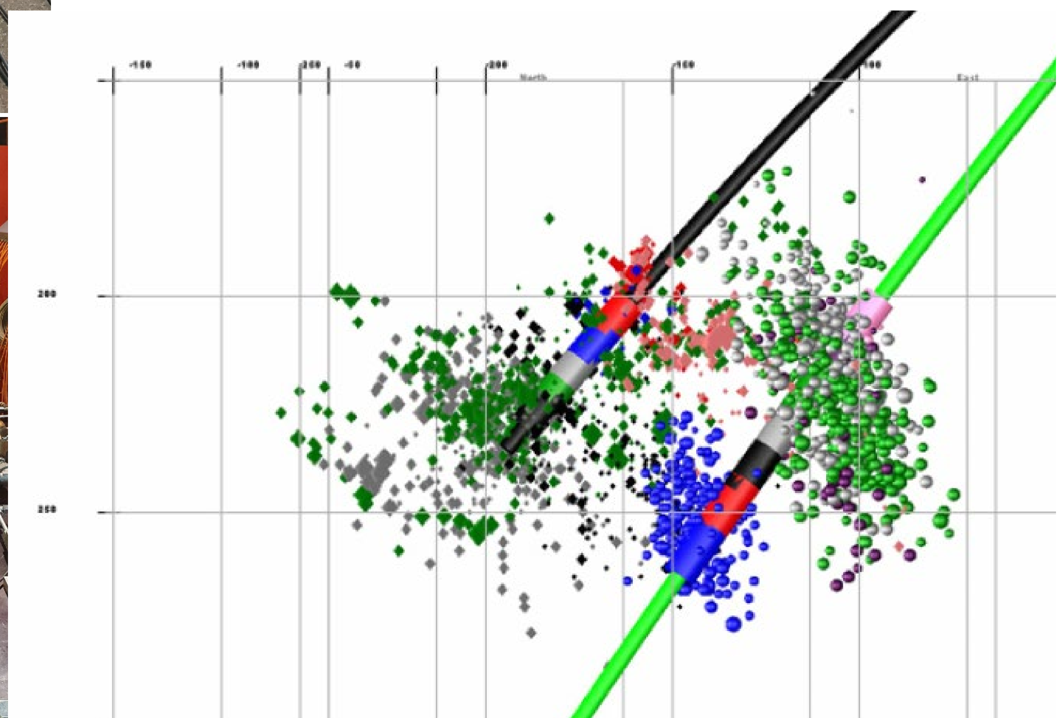
Concept
“multi-stage system” (FORGE, GES)

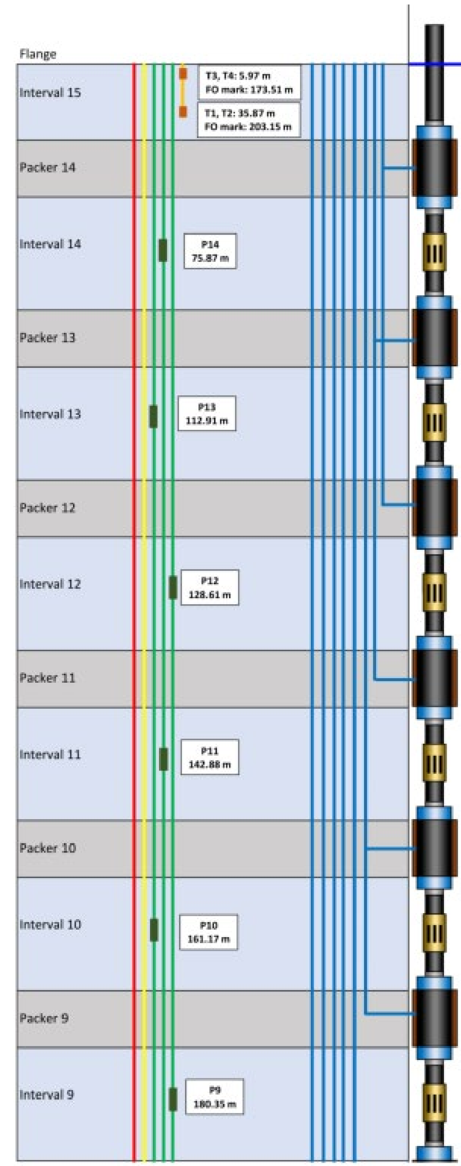


New concept applied to Bedretto Lab









Mitigation measures and issues

- Traffic light system (TLS)

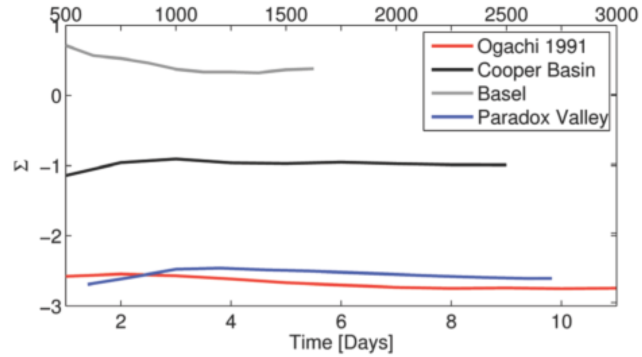
M_L		Pumping	Injection pressure	Report	PGV (cm/s)
2.0 ← 4.1	Stage 5	Stop	Bleed off excess pressure	Alarm to H.S. team Report to research institutions Report to local and project related institutions (KMA, Pohang city hall, MOTIE, KETEP)	2.0
1.7 ← 3.8	Stage 4	Stop	Bleed off excess pressure	Alarm to H.S. team Report to research institutions (SNU, KICT, KIGAM, POSCO, INNOGEO)	1.0
1.4 ← 3.4	Stage 3	Reduction or stop	Reduction or constant pressure	Alarm to H.S. team (H.S. team, M.S. monitoring team, Boards of Nexgeo)	0.5
1.0 ← 2.4	Stage 2	Constant flow rate	Constant pressure	Report to hydraulic stimulation team (H.S. team, M.S. monitoring team)	0.08
	Stage 1	Regular operation	Regular operation	Regular report (Microseismicity monitoring team)	

* Flow rate and injection pressure would be regulated dependently during hydraulic stimulation.

Fig. 9. The traffic light system for Pohang EGS project.

Lesson learned TLS- enhance TLS concept

- Consider post-injection effects (subtract a threshold)
- Make sure you can follow your action plan
- Get your magnitudes straight (Mw, ML, ‘official’ vs. project magnitude)
- Do a stimulation test (small stimulation until you have enough data)



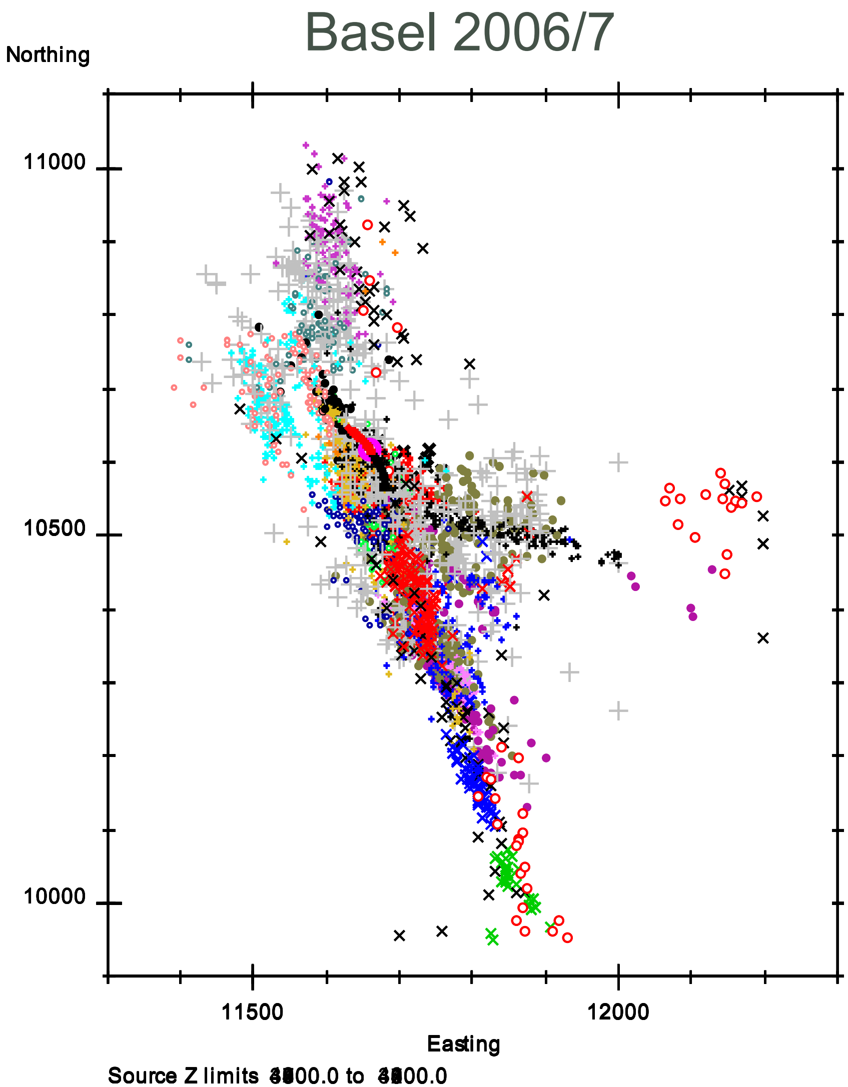
Shapiro et al. 2010

- Think about failure probabilities of your TLS
- Be proactive (adaptive / advanced traffic light system)

Application to FORGE

- Adaptive traffic light system
  - Real-time calculation of b-value
    - Forecasting of exceedance probabilities (yellow, red, …)
  - Real-time clustering –
    - cross correlation to existing events
  - Real-time relative locations
    - identification of (far) structures

100m Depth Slices Through the Event Clusters



Multiplet Parameters

- *S waves on H1/H2 at 4 stations*
- *LP filter at 60Hz*
- *Correlation level >0.75*

Results

- *18 multiplets*
- *81% (2860) events in multiplets*

Multiplet Benefits

- *Higher resolution locations*
- *Potential to identify discrete fractures for hydraulic modelling*
- *Possible solution to FPS N-S or E-W faulting ambiguity*

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Long range target & outlook

In collaboration with

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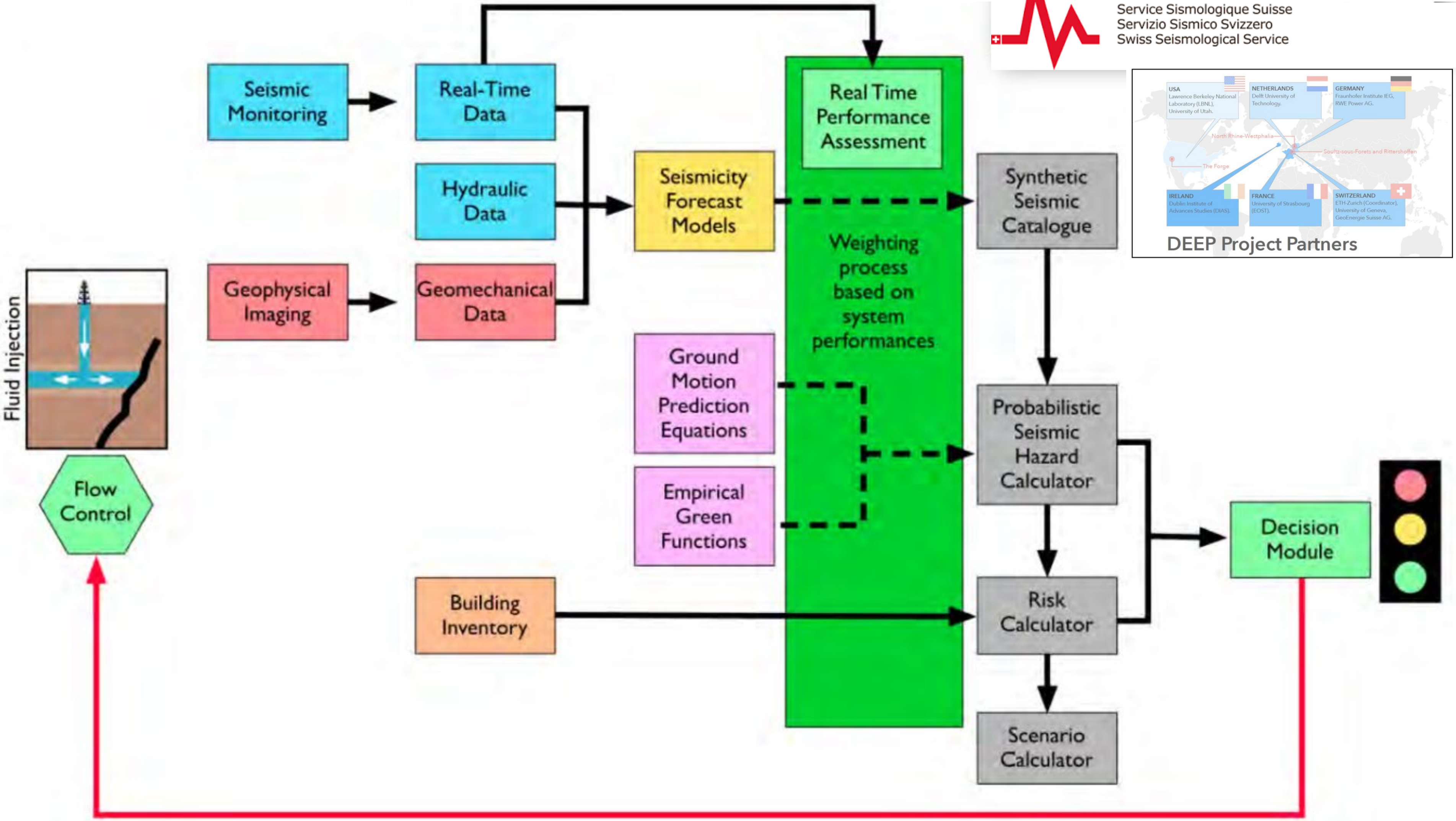

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