Passive Seismic imaging of Discrete Fracture Networks

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ITASCA UK

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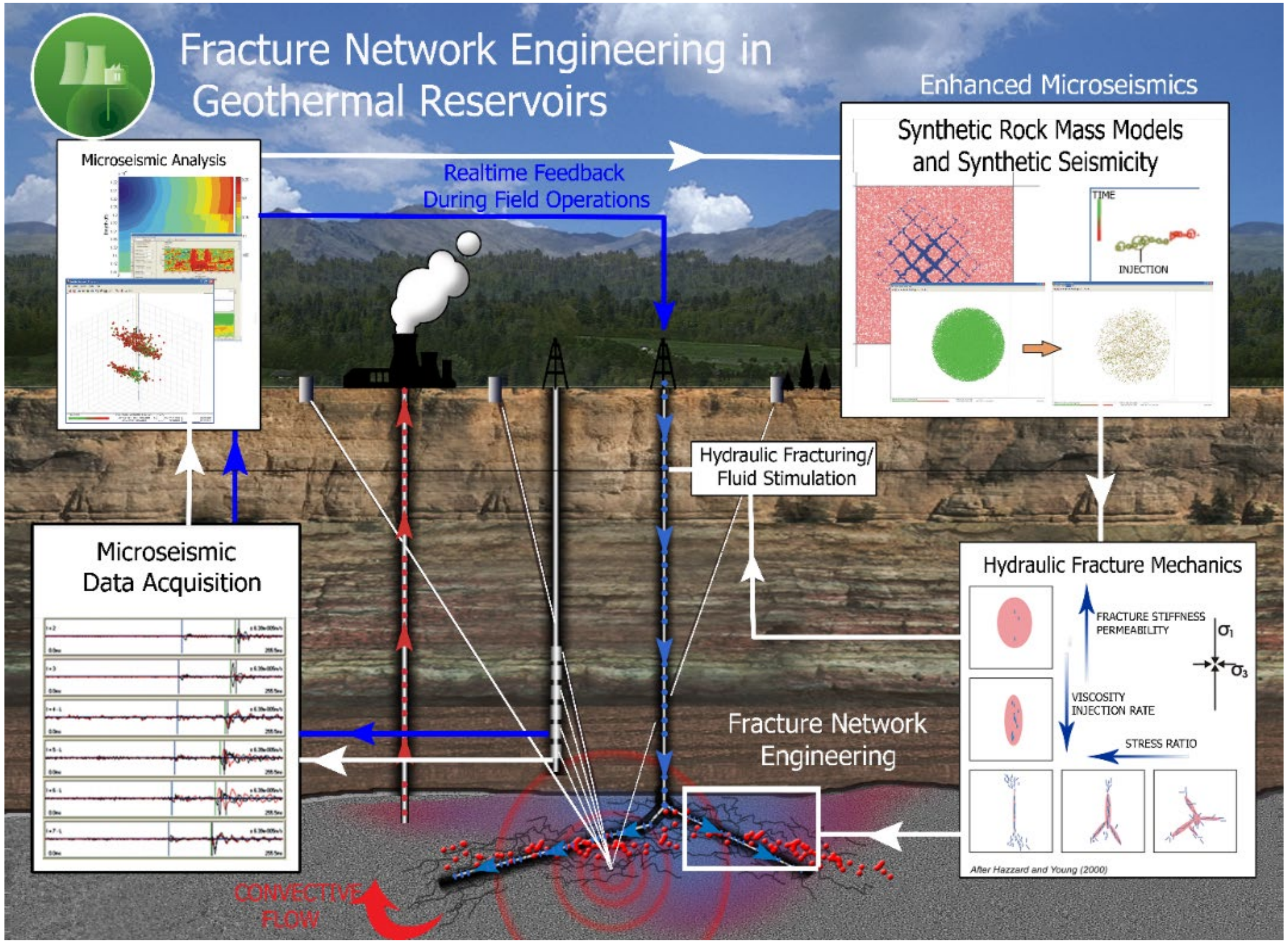
Vienna, 18th February 2020

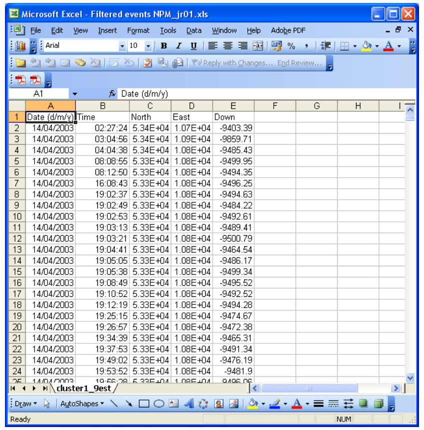
Fracture Network Engineering



Seismic monitoring: Fracture imaging

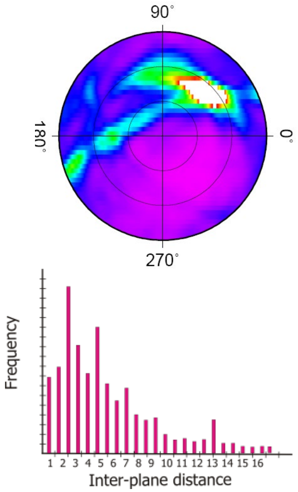
- Passive microseismic monitoring is a unique technology to image fracturing processes associated or induced by different engineering operations
- The analysis of seismic catalogues beyond timing and location and the analysis of full waveform records can provide further insights into the geometry and nature of the induced or mobilised fracture network

MS catalogue

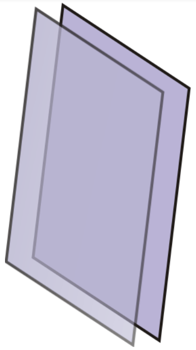

Microsoft Excel - Filtered events NPM_jr01.xls

	A	B	C	D	E
1	Date (d/m/y)	Time	North	East	Down
2	14/04/2003	02:27:24	5.34E+04	1.07E+04	-9403.39
3	14/04/2003	03:04:56	5.34E+04	1.09E+04	-9859.71
4	14/04/2003	04:04:38	5.34E+04	1.08E+04	-9485.43
5	14/04/2003	08:08:55	5.33E+04	1.08E+04	-9499.95
6	14/04/2003	08:12:50	5.33E+04	1.08E+04	-9494.35
7	14/04/2003	16:08:43	5.33E+04	1.08E+04	-9496.25
8	14/04/2003	19:02:37	5.33E+04	1.08E+04	-9494.63
9	14/04/2003	19:02:49	5.33E+04	1.08E+04	-9484.22
10	14/04/2003	19:02:53	5.33E+04	1.08E+04	-9492.61
11	14/04/2003	19:03:13	5.33E+04	1.08E+04	-9489.41
12	14/04/2003	19:03:21	5.33E+04	1.08E+04	-9500.79
13	14/04/2003	19:04:41	5.33E+04	1.08E+04	-9464.54
14	14/04/2003	19:05:05	5.33E+04	1.08E+04	-9486.17
15	14/04/2003	19:05:38	5.33E+04	1.08E+04	-9499.34
16	14/04/2003	19:08:49	5.33E+04	1.08E+04	-9495.52
17	14/04/2003	19:10:52	5.33E+04	1.08E+04	-9492.52
18	14/04/2003	19:12:19	5.33E+04	1.08E+04	-9494.28
19	14/04/2003	19:25:15	5.33E+04	1.08E+04	-9474.67
20	14/04/2003	19:26:57	5.33E+04	1.08E+04	-9472.38
21	14/04/2003	19:34:39	5.33E+04	1.08E+04	-9465.31
22	14/04/2003	19:37:53	5.33E+04	1.08E+04	-9491.34
23	14/04/2003	19:49:02	5.33E+04	1.08E+04	-9476.19
24	14/04/2003	19:53:52	5.33E+04	1.08E+04	-9481.9

cluster1_9est

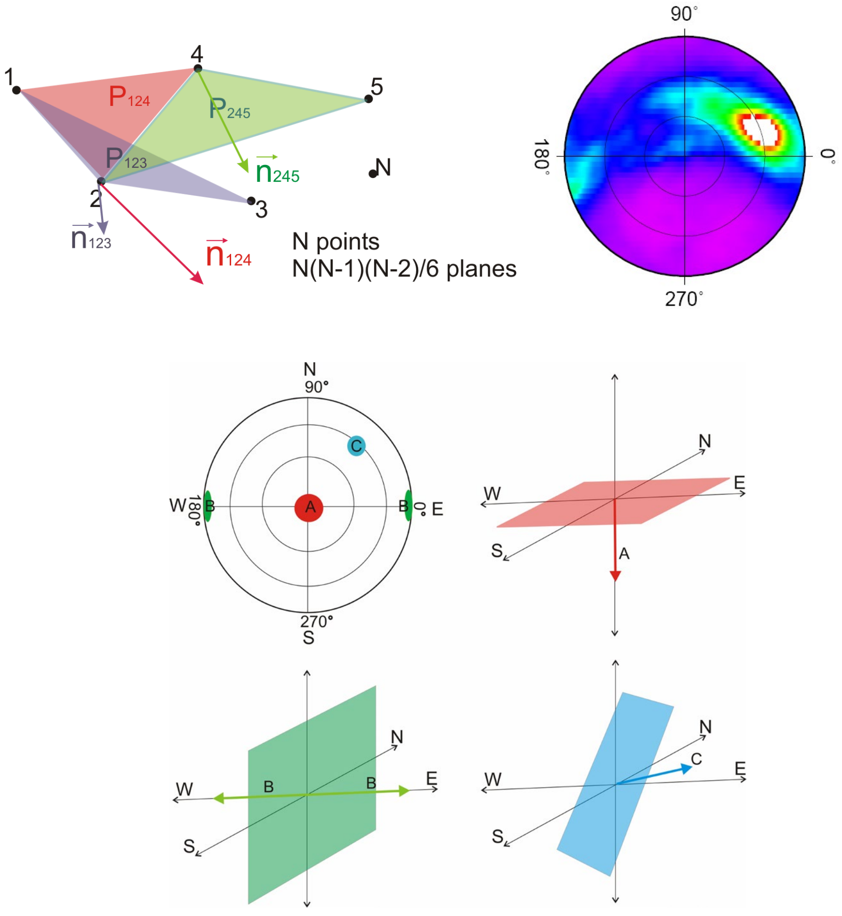


Characterization of induced fracture network



Analysis of fracture network: three-point method

- The statistical analysis of the spatial and temporal distribution of located MS events allows identifying dominant structures and provides the orientation, persistence and spacing of the dominant fracturing (e.g. Reyes-Montes et al. 2007b).
- The statistical technique calculates the planes that fit every unique combination of three events. The poles of the calculated planes can then be plotted on a stereogram. A high density of poles will reveal any preferential orientation.
- The multiple sampling makes this method less sensitive to a Gaussian error in the events location than studies based on interevent distributions.



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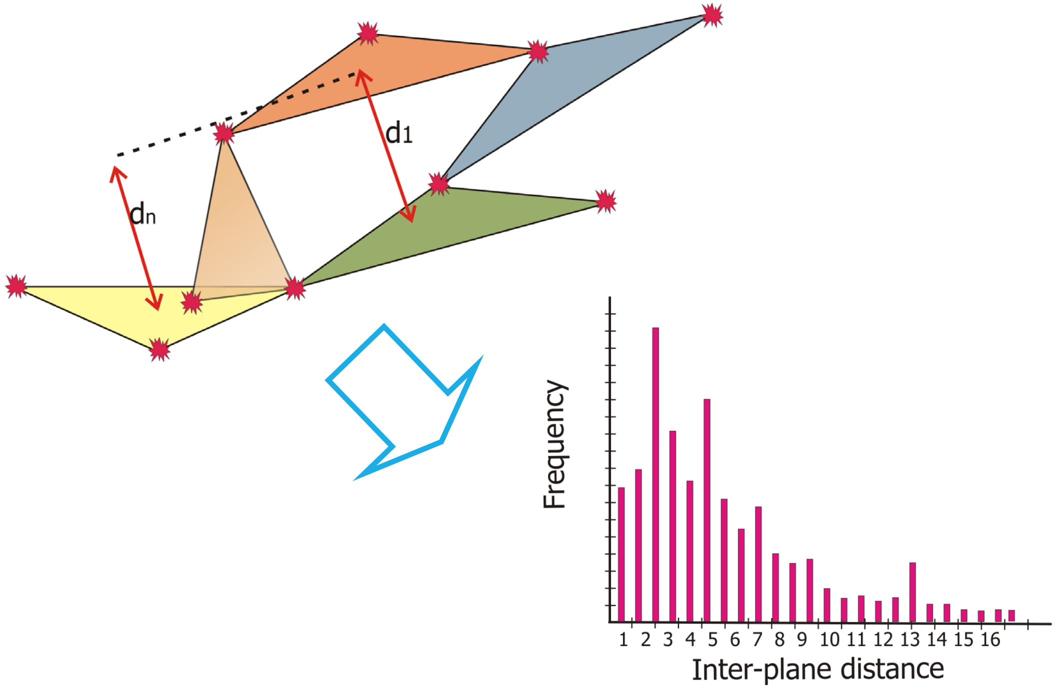
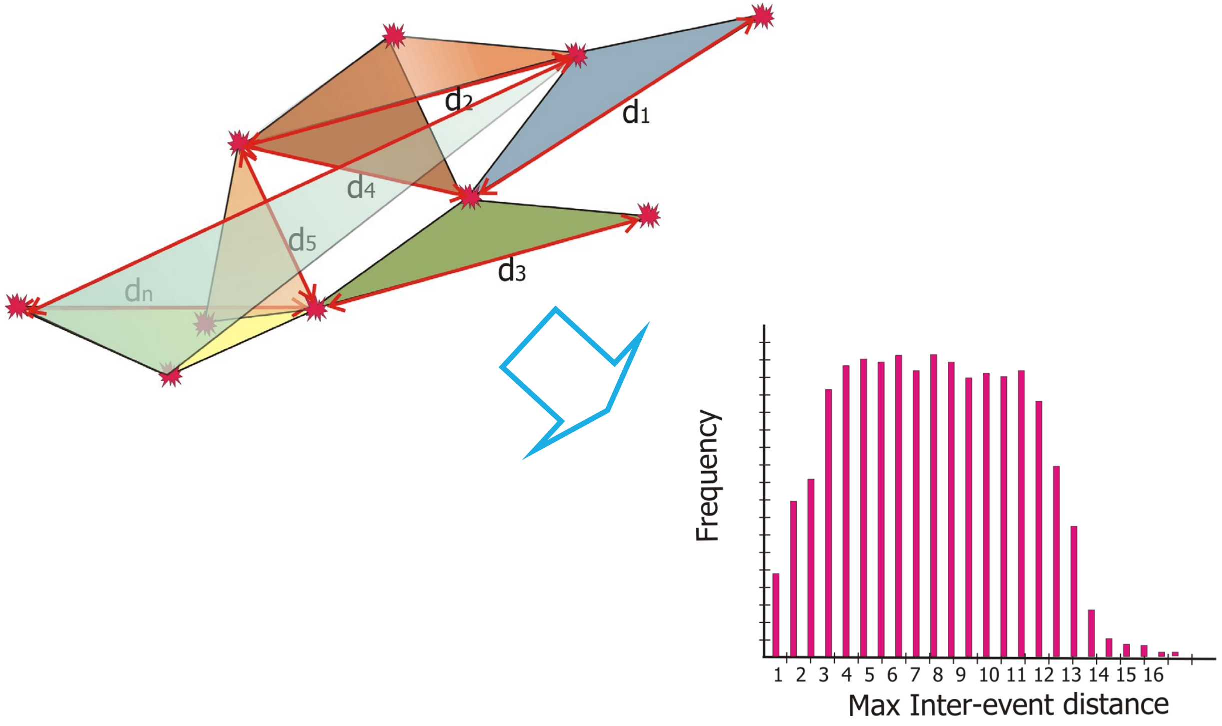
Macrofracture spacing and persistence

- The spacing is inferred from the distribution of values of separation, measured along the direction normal to the dominant direction, between centroids of parallel planes (formed by triads of MS events)

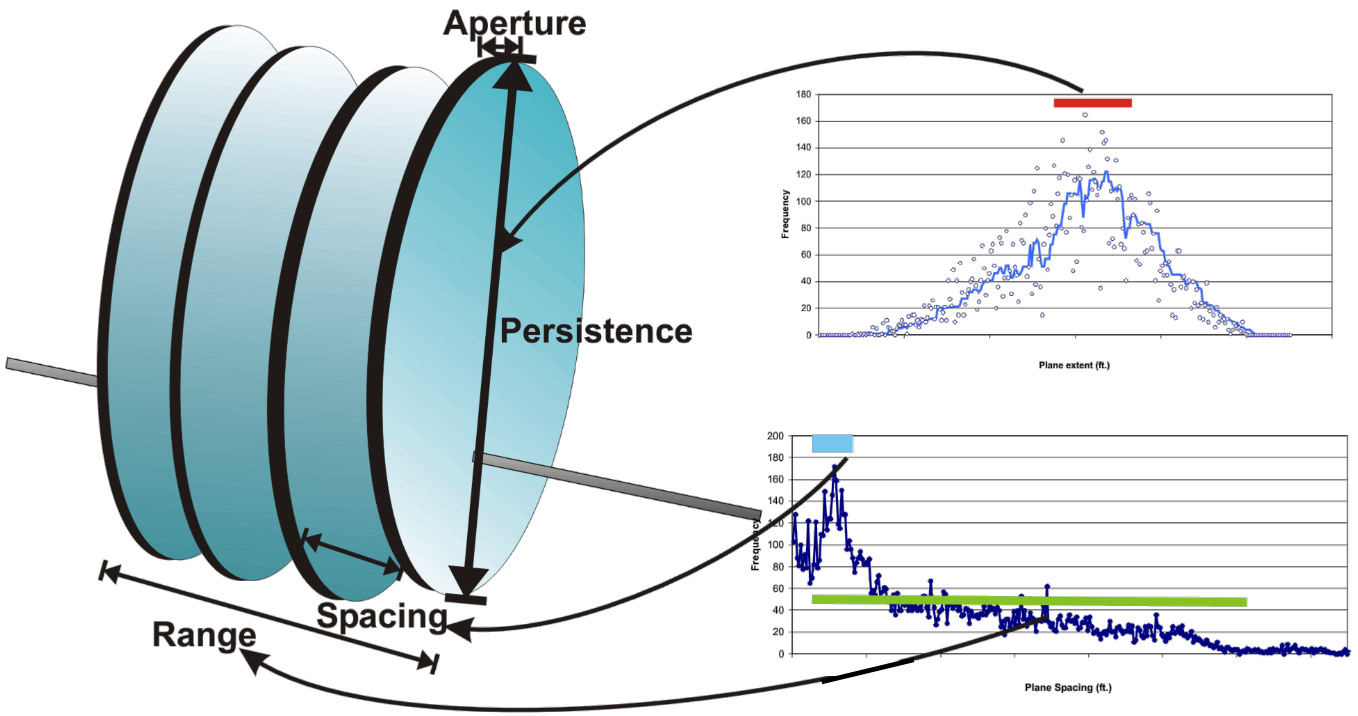


- The persistence is inferred from the distribution of values of maximum inter-event separation between MS events forming each of the triads

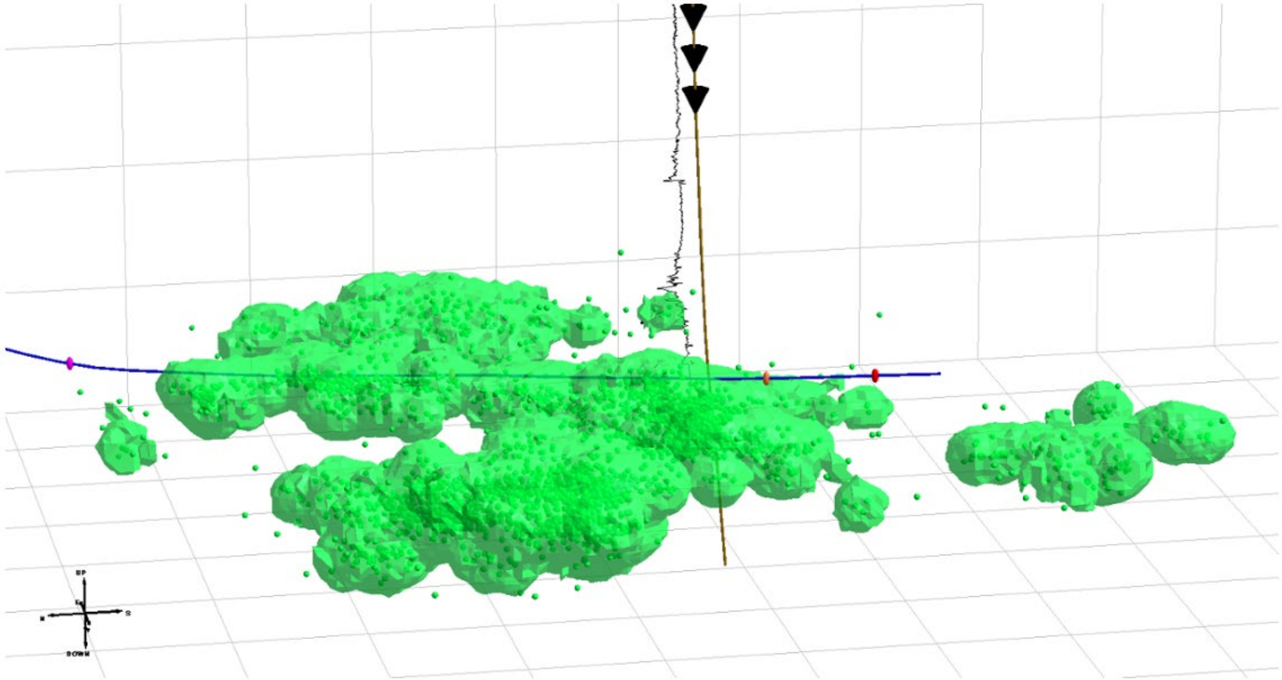


Fracture Network Interpretation

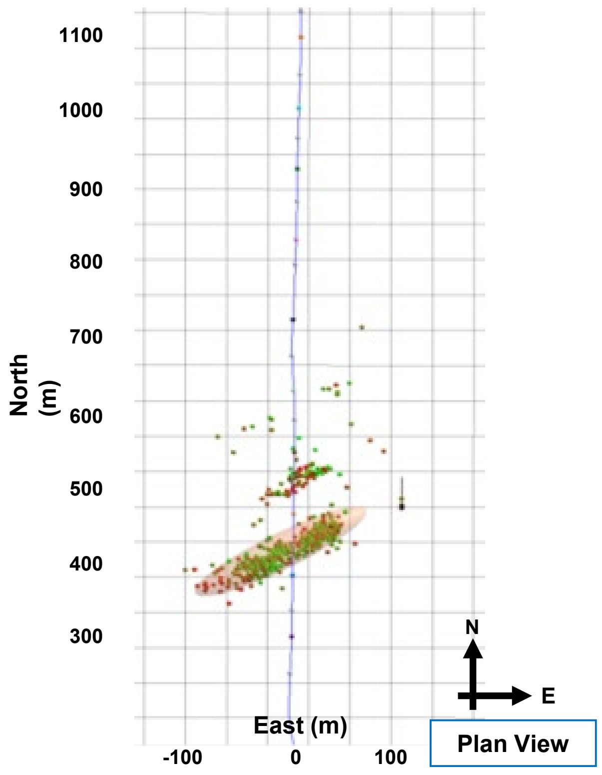
- Interpretation of fracture network spacing and persistence from the inter-plane and inter-event separations within example events fitting planes following the observed dominant orientation.

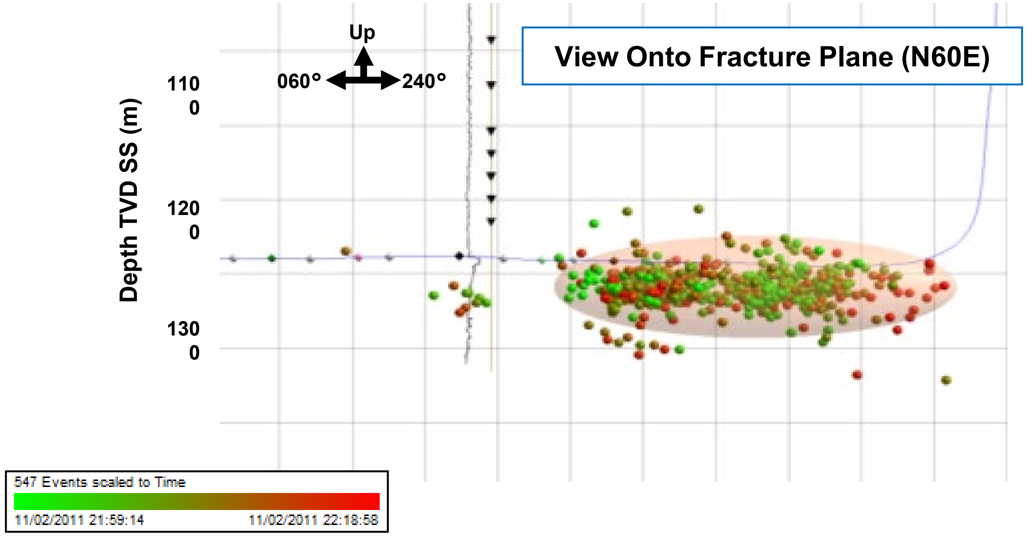


Monitoring Fracture Development



Fracture Network Geometry

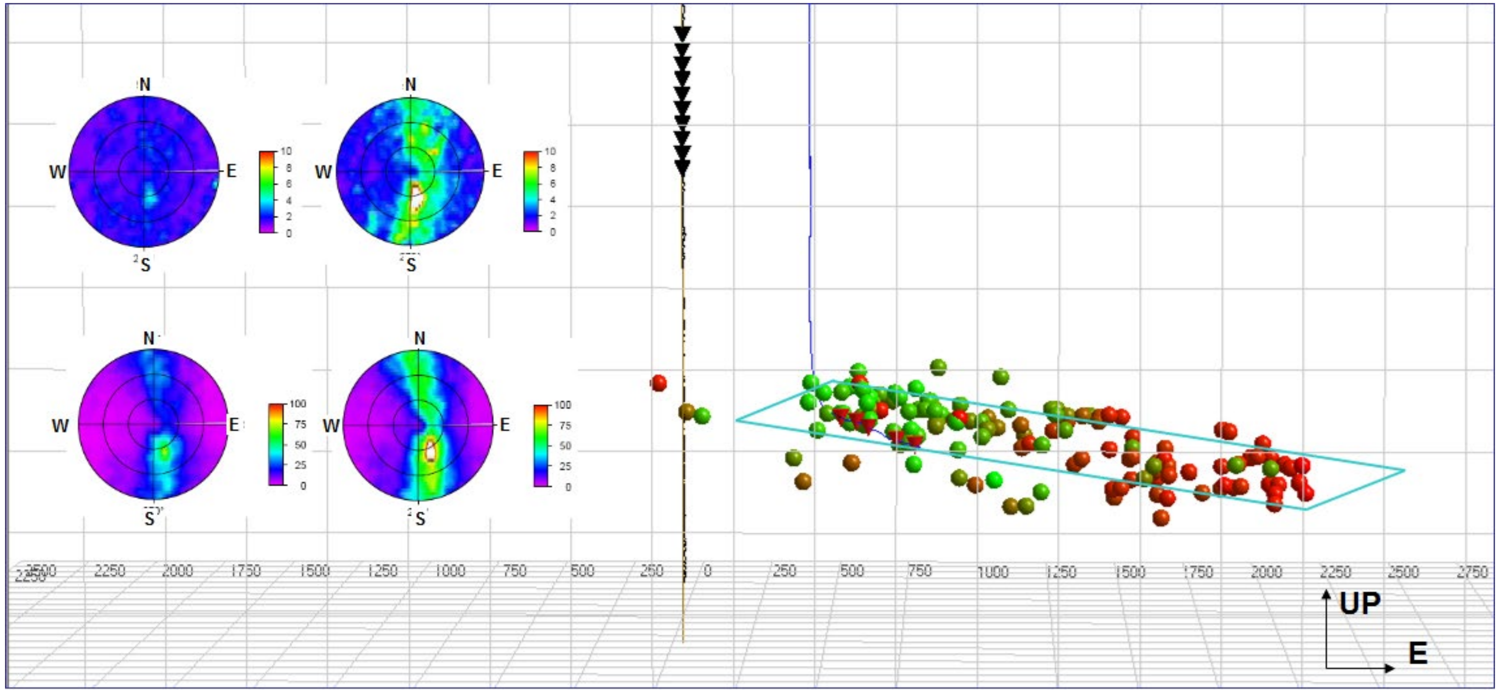




Single Wing	No
Breakthrough	No
Fracture Network Wing Length	135 m (NE-wing)
Fracture Network Length	240 m
Fracture Network Height	70 m
Fracture Network Width	50 m
Fracture Network Top	1,174 m TVDSS
Fracture Network Bottom	1,244 m TVDSS
Fracture Network Azimuth	60 degrees E of N
Fracture Network Plunge	0 degrees
Fracture Network Volume	440x10^3 m^3

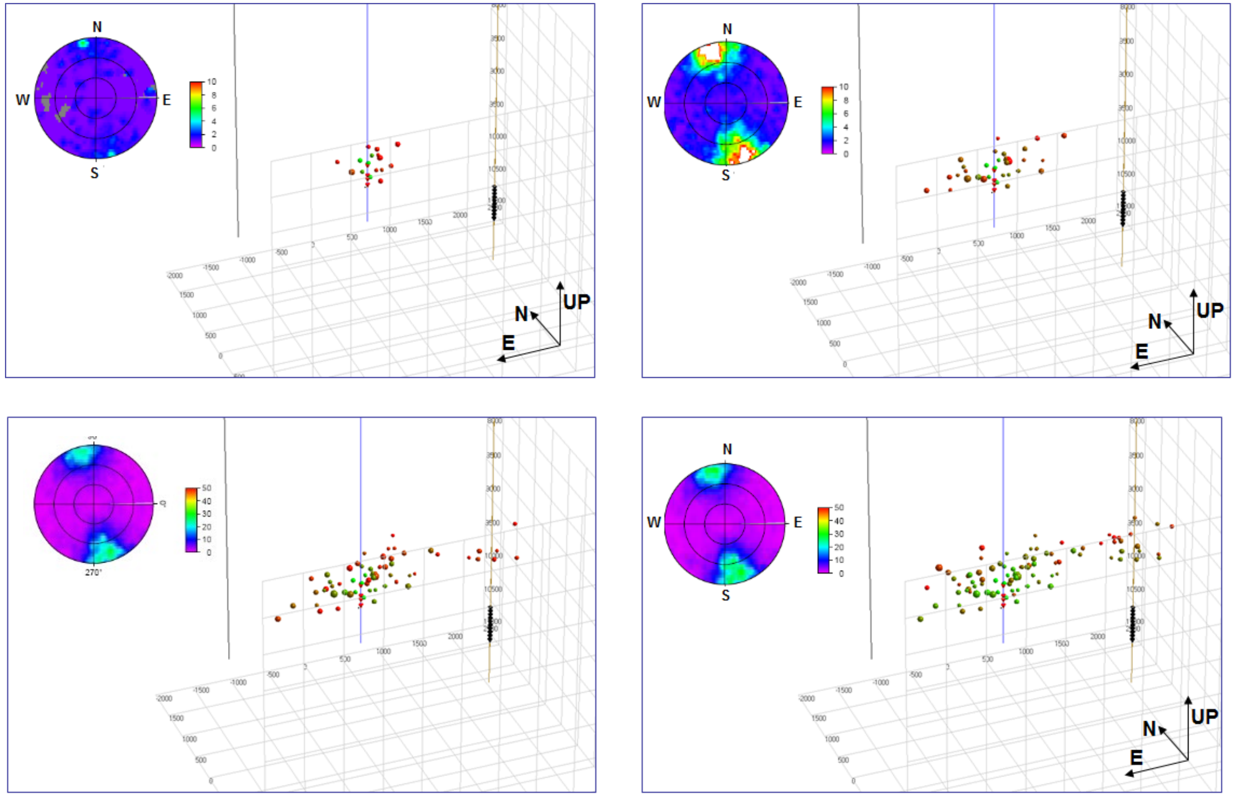
Hydraulic Fracturing: Induced DFN

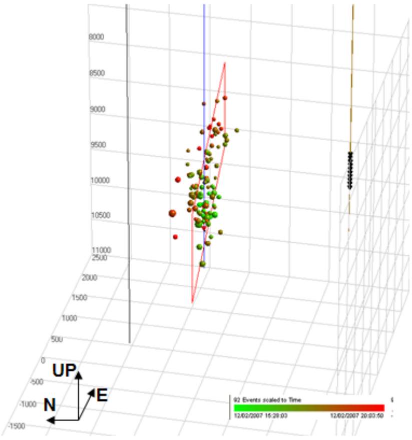
- The identified dominant structures can be correlated with mapped pre-existing fractures for an interpretation of the effect of the treatment.
- This analysis complements the information on fracture extent provided by the spatial distribution of the induced microseismicity with information on the direction and intensity of major induced fracturing associated with potential enhanced paths for fluid communication.



Reyes-Montes, J.M., Pettitt, W.S., and Young, R.P., 2009. "Enhancement of Fracture Network Imaging from Microseismic Monitoring of Hydraulic Fracturing Treatments," Canadian Society of Exploration Geophysicists Microseismic Workshop, Calgary, November 2009.

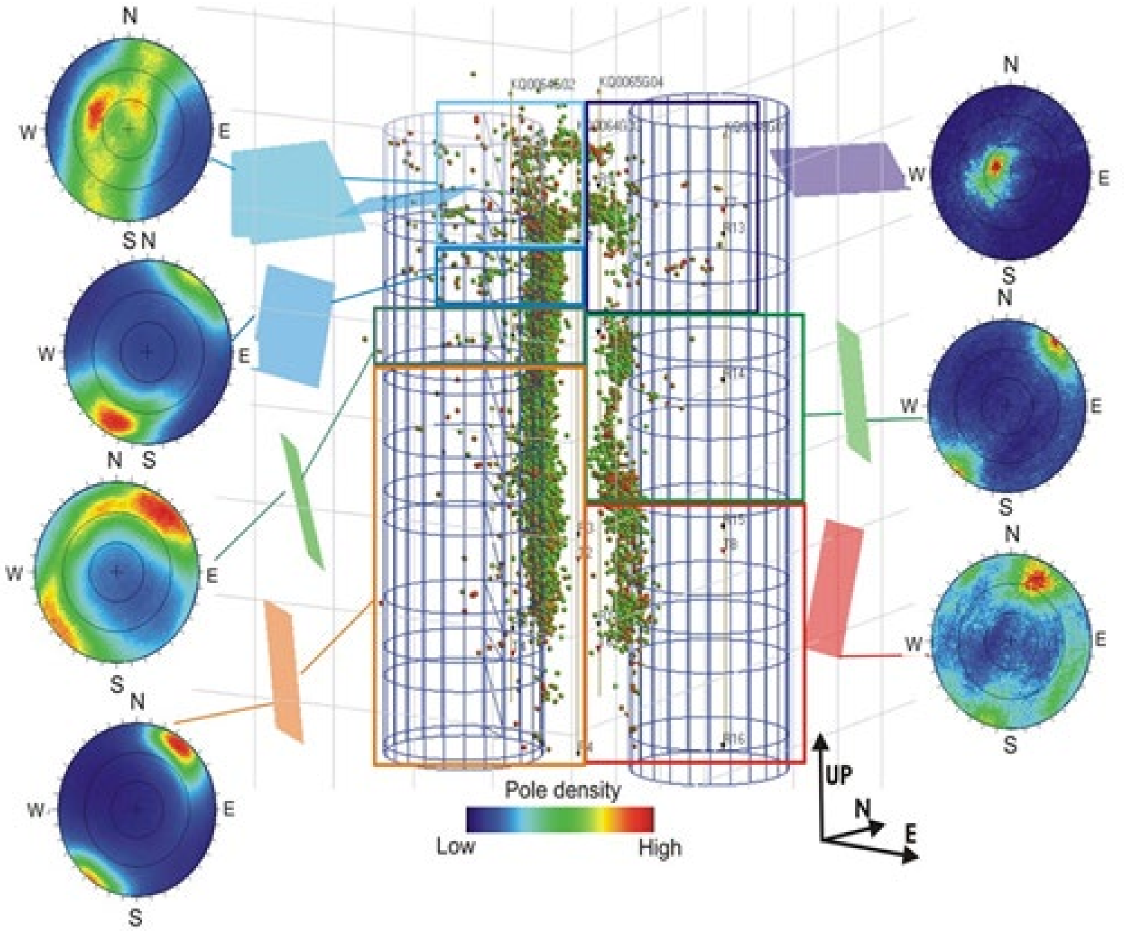
Hydraulic Fracturing: Induced DFN





- The evolution in the induced or mobilized fracture network during a single-stage injection can be characterized with the analysis
- The vertical fracture propagating in the E-W direction is evident from early stages of the injection

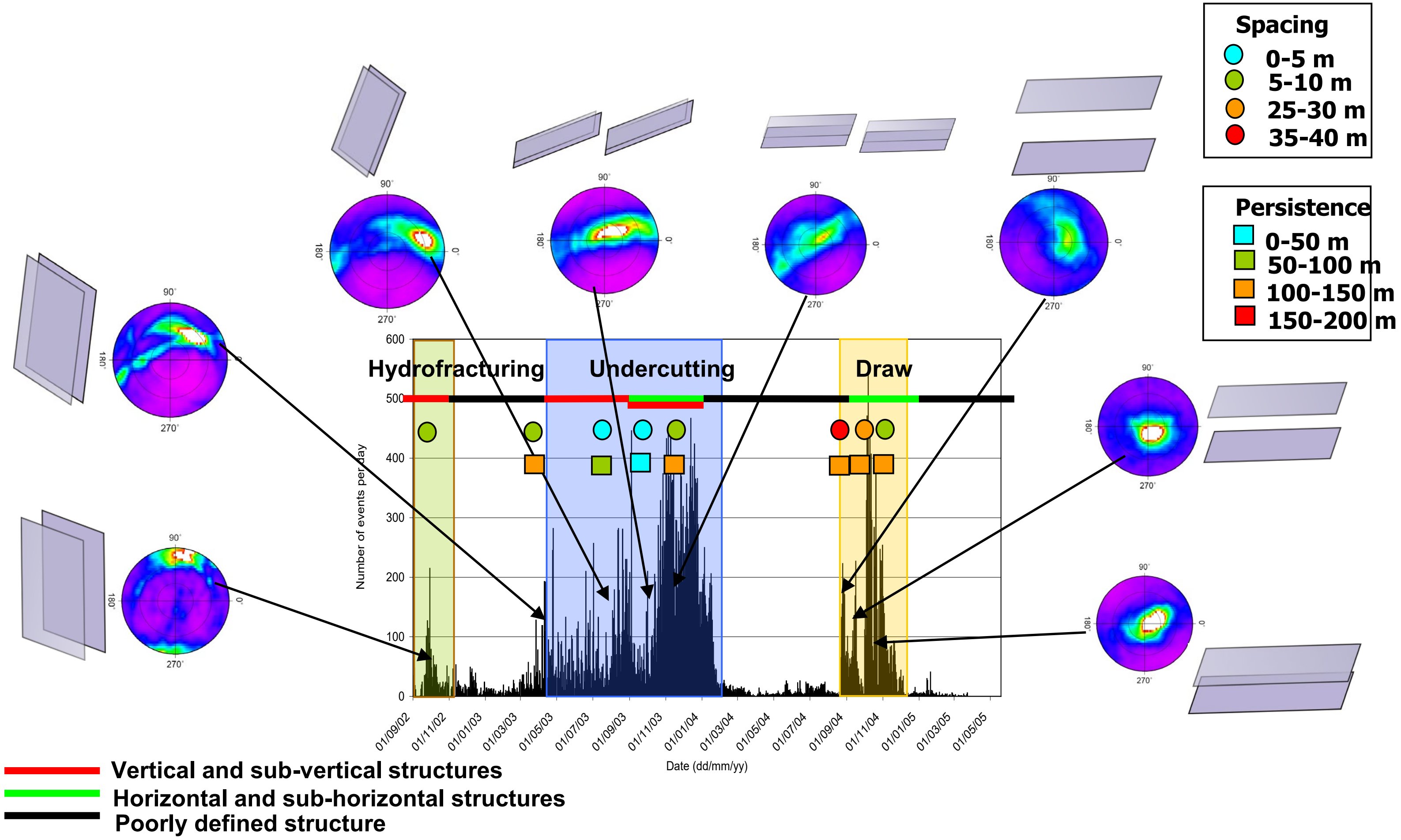
Excavation and Thermal-induced fracturing



- 15,198 AE events induced around two test deposition holes excavated in diorite at SKB's Äspö Hard Rock Laboratory
- The analysis of split clusters show fracturing dominated by a network of sub-vertical well-defined fractures oriented sub-parallel to the hole's walls, with well-defined shallow dipping
- planes on the upper section (reactivation of in-situ fractures)
- Structure more clearly defined around the unconfined deposition hole indicating a better developed fracture network (sub-vertical slabbing).

Moretti, H.C., Reyes-Montes, J.M., Haycox, J.R. and Young, R.P., 2013. **Temporal analysis of fracturing using acoustic emissions at the Aspö Pillar Stability experiment.** Rock Mechanics for Resources, Energy and Environment- Proceedings of EUROCK 2013 - The 2013 ISRM International Symposium Wroclaw, Poland, 23-26 Sept 2013, pp 627-631.

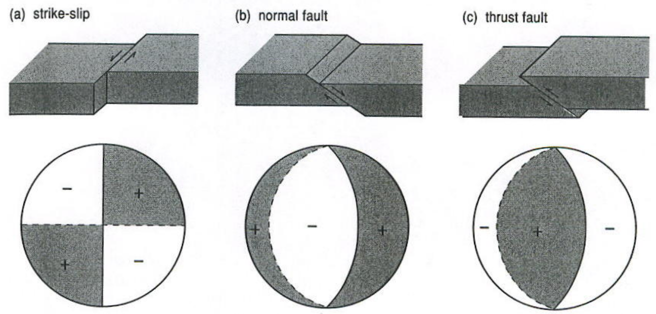
Evolution of slip/fracturing in Cave Mining

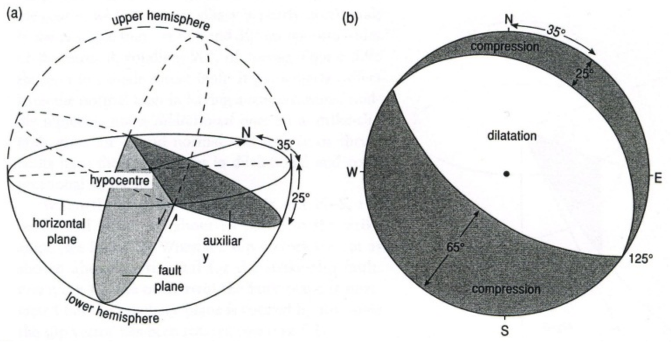


Reyes-Montes, J.M., and Pettitt, W.S., 2010. Microseismic Validation of Jointed Rock Models in Cave Mining. in ***Proceedings, 44th U.S. Rock Mechanics Symposium (5th U.S.-Canada Rock Mechanics Symposium, Salt Lake City, Utah, June 2010)***, Paper No. 10-273. Alexandria, Virginia: ARMA

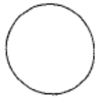
Source mechanism inversion

- The inversion of source mechanism from waveform amplitude and polarisation provides one of the most complete sources of information for the imaging of the fracturing process, particularly fracture plane orientation, source radius and information on the in-situ stress and strain.
- The calculation is based on the measurement of P- and S-wave relative amplitudes, variables controlled by the radiation pattern associated with a type of rupture along a particular plane (e.g. Zhao and Young, 2011).
- Typically, the mechanism of shear events can be described by the motion of P-wave arrivals plotted in a lower-hemisphere stereographic projection of the space surrounding the source, known in seismology as beach balls. These beach balls provide information on the orientation of the shearing plane, corresponding to the active fracture.



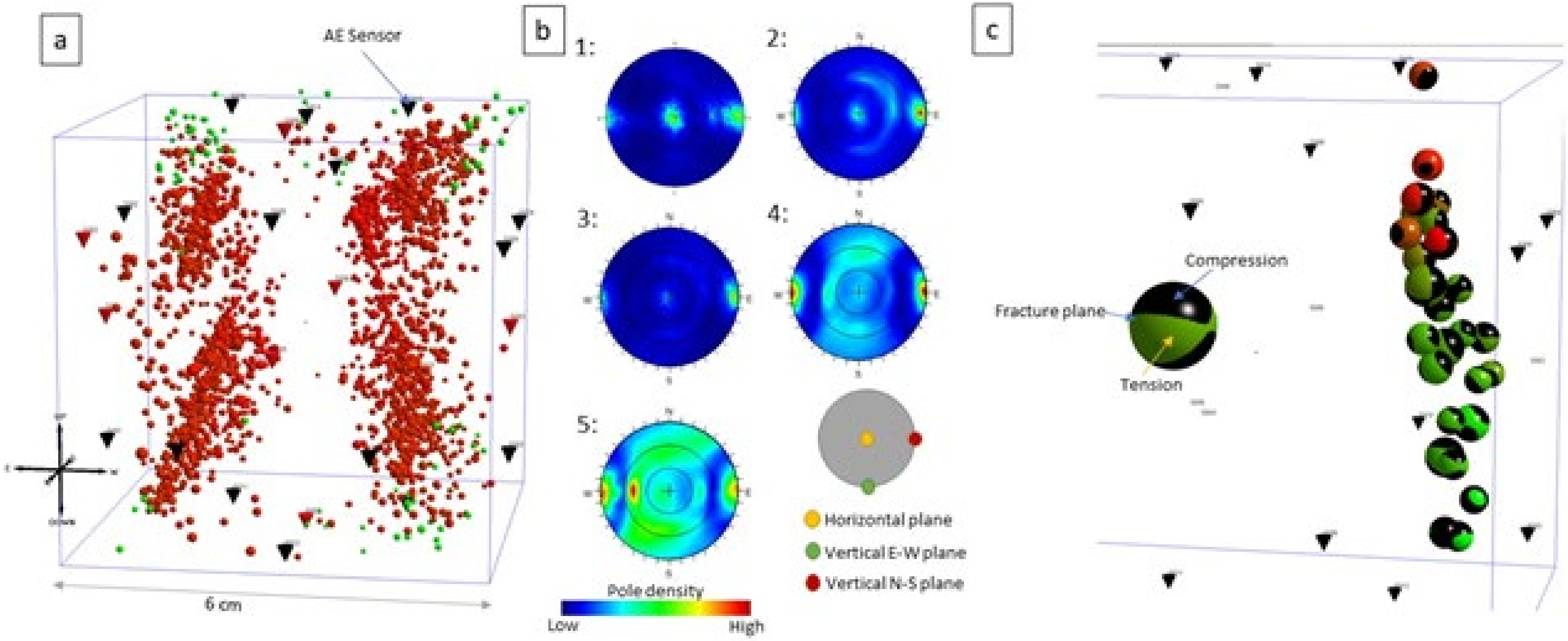


Source Mechanism

Moment Tensor	Beachball	Moment Tensor	Beachball
$\frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}$		$-\frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}$	
$-\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&0\\0&0&1\\0&1&0\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&0\\0&1&0\\0&0&-1\end{pmatrix}$	
$\frac{1}{\sqrt{2}}\begin{pmatrix}0&1&0\\1&0&0\\0&0&0\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&1\\0&0&0\\1&0&0\end{pmatrix}$	
$\frac{1}{\sqrt{2}}\begin{pmatrix}1&0&0\\0&-1&0\\0&0&0\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}1&0&0\\0&0&0\\0&0&-1\end{pmatrix}$	
$\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&-2\end{pmatrix}$		$\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&-2&0\\0&0&1\end{pmatrix}$	
$\frac{1}{\sqrt{6}}\begin{pmatrix}-2&0&0\\0&1&0\\0&0&1\end{pmatrix}$		$-\frac{1}{\sqrt{6}}\begin{pmatrix}-2&0&0\\0&1&0\\0&0&1\end{pmatrix}$	

Selected unit moment tensors and associated beach-Balls (2D).

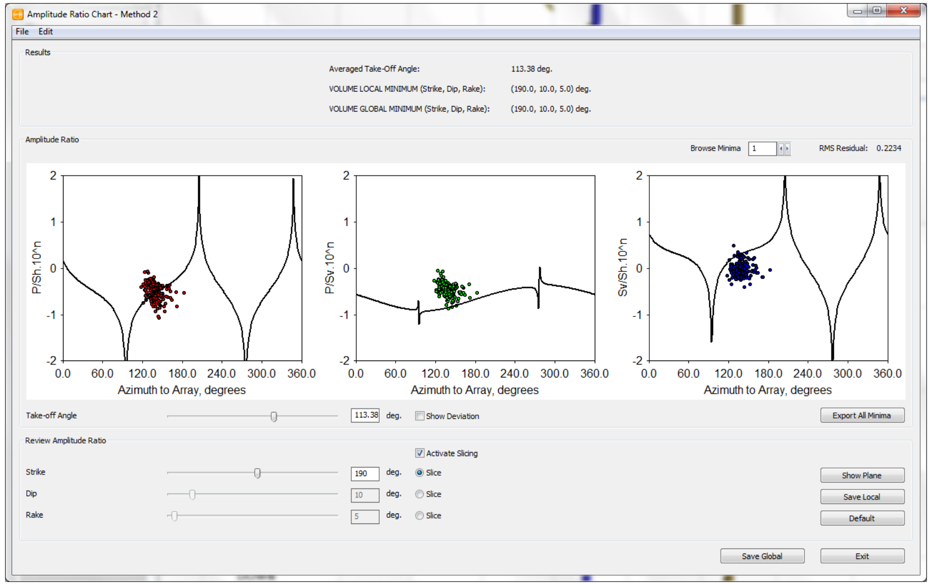
Imaging True-Triaxial rock fracturing test



After King, M., Pettitt, W., Haycox, J. and Young, R. (2012), Acoustic emissions associated with the formation of fracture sets in sandstone under polyaxial stress conditions‡. Geophysical Prospecting, 60: 93-102. doi:10.1111/j.1365-2478.2011.00959.

Composite MS Discrete Fracture Network

- A robust inversion of the mechanism at the source requires a good azimuthal coverage, with seismic sensors ideally surrounding the seismic source,
- A monitoring array with a limited azimuthal coverage of the source volume restricts the estimation of waveforms P-wave polarities, and hence the inversion of its source mechanism.
- Grouping events for a composite solution can overcome this limitation. The grouping is typically performed based on the ratio of amplitudes for the different phases, i.e. P, SH and SV arrivals measured as a function of the angle of incidence connecting source and receiver. The comparison of this distribution with modelled radiation patterns allow to constrain the most likely source mechanism for the group of events and defining a fracture plane.



MS Discrete Fracture Network

- A search in the space of (Strike, Dip, and Rake) can be used to find the best fracture plane that fits the observed amplitude ratios (P/SH, P/SV, SV/SH) for a set of events

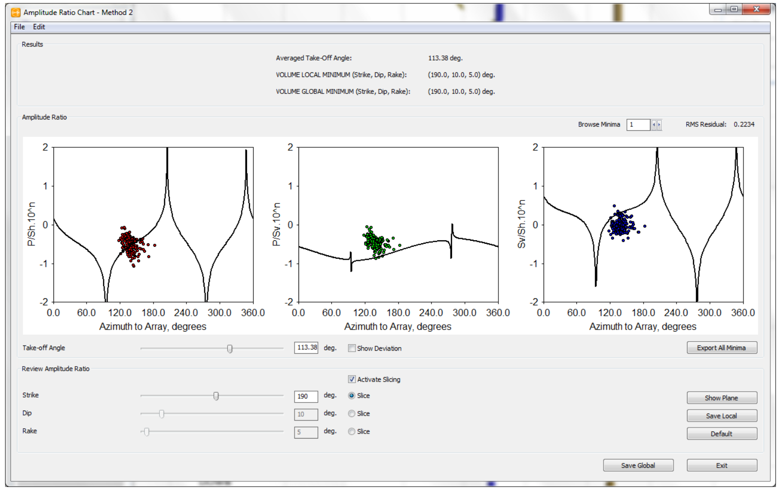
- Depending on the coverage and quality of data the method uses different levels of assumption on the ray path take-off angle:

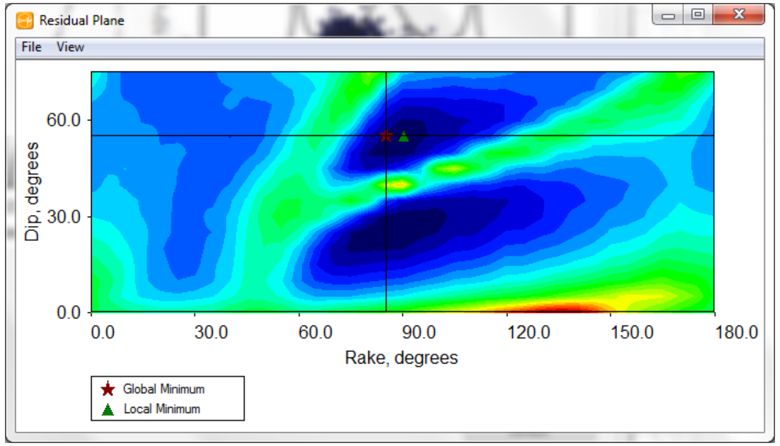
a. Single take-off angle for all events - a single value take-off angle averaged across all source- receiver pairs is used.

b. One take-off angle for each event - the take-off angle averaged across the receiver array for each event is used.

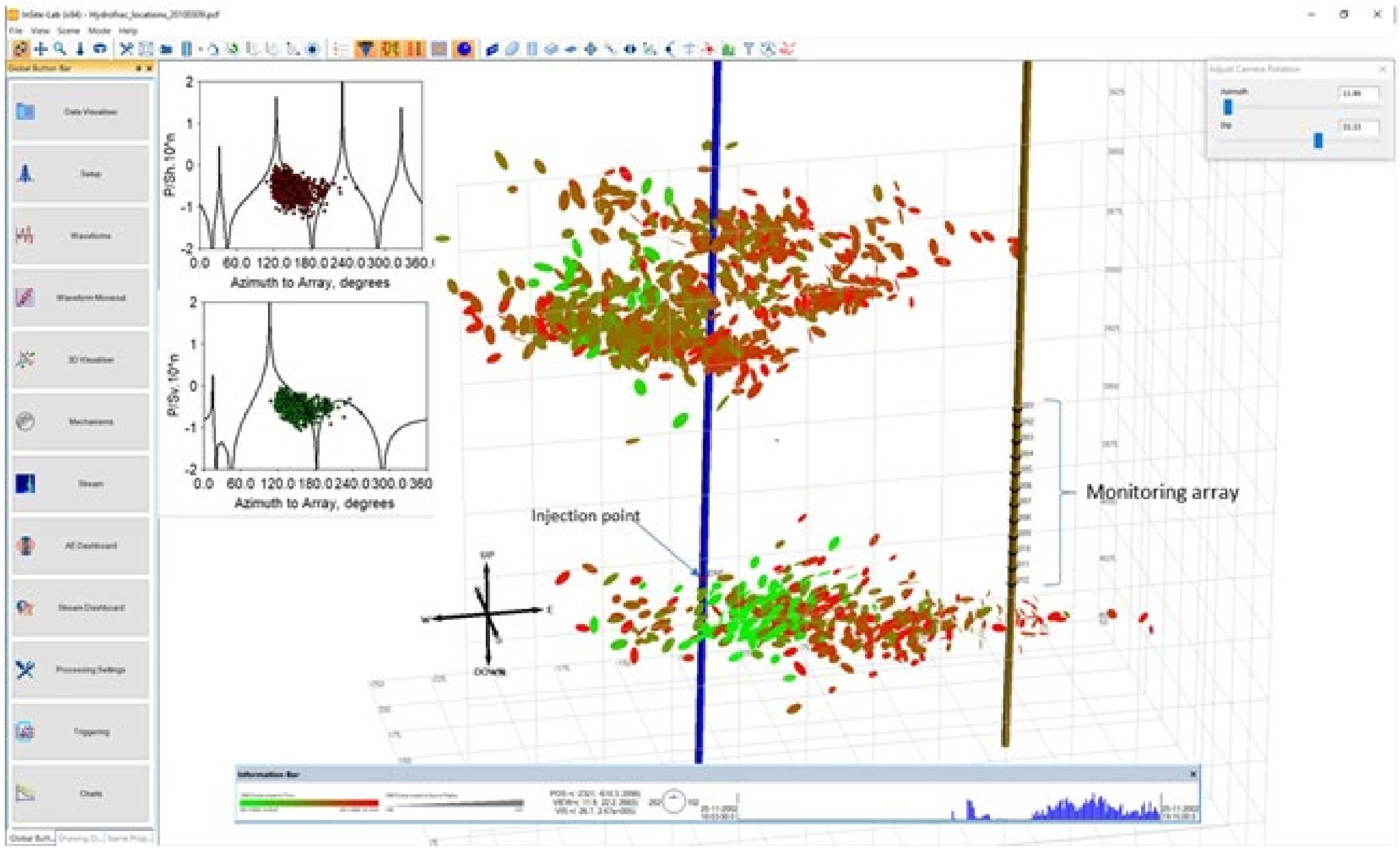
c. One take-off angle for each event-receiver - one take-off angle for each pair of source and receiver is used. No averaging is performed, and this method takes more processing time than other two methods.

- The method calculates the optimized curve for the observed amplitude ratio and the optimum orientation of the fracture plane is chosen from the global minimum in the misfit plane





Imaging HF-induced DFN



InSite Seismic Processor

InSite HF

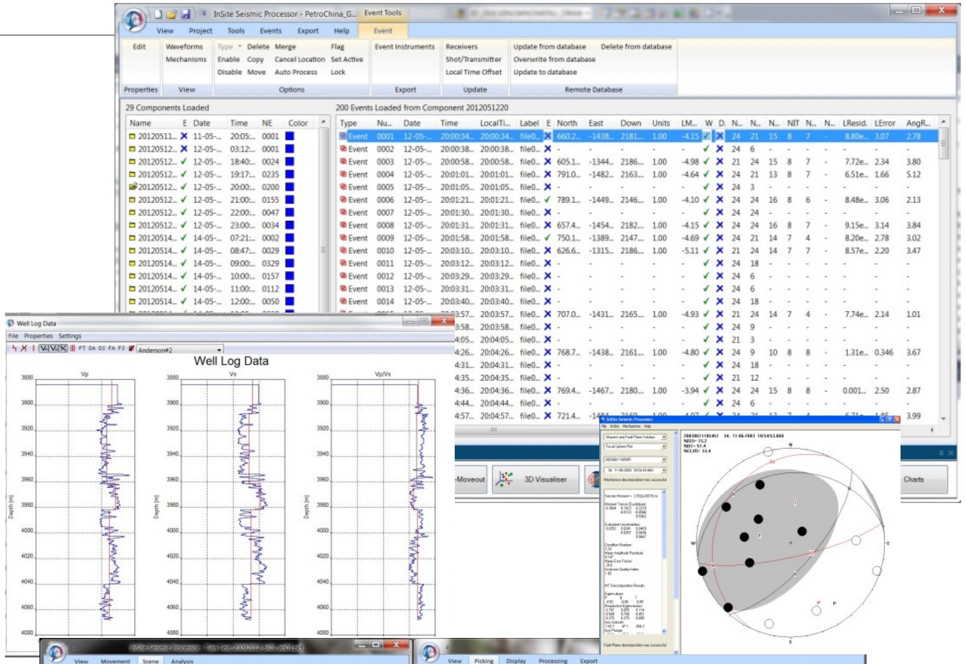
InSite Geo

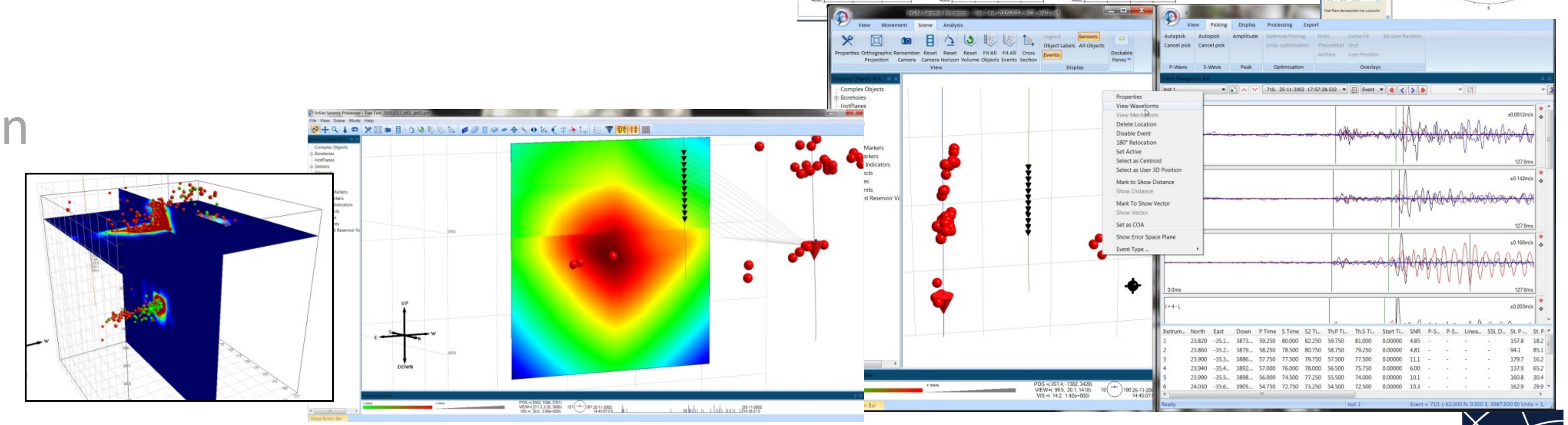
InSite Lab

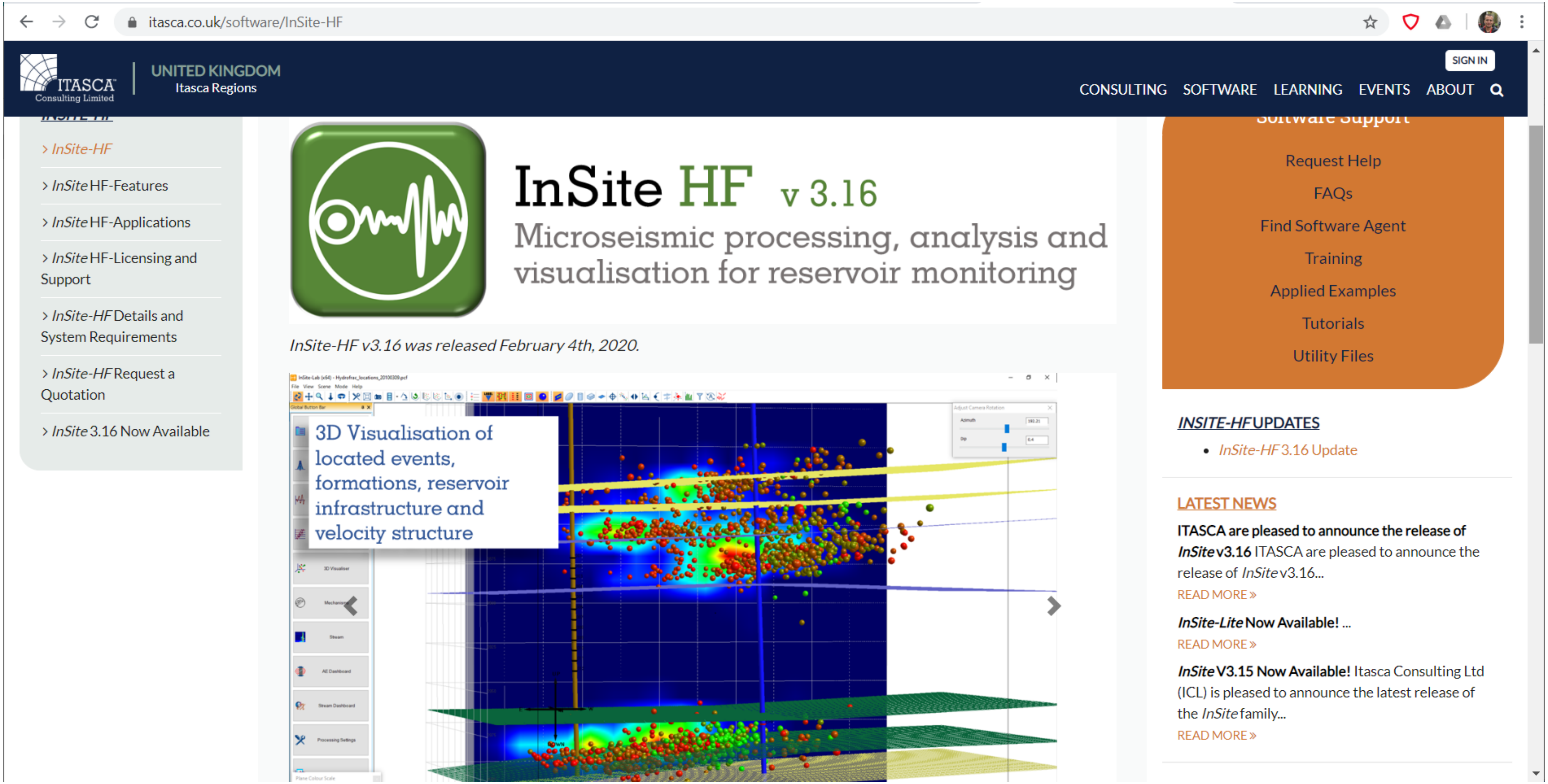
InSite Design

InSite Lite

- Integrated data processing, management and visualisation software.
- Process seismic data (from lab-scale to field-scale).







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Microseismic processing, analysis and visualisation for reservoir monitoring

InSite-HF v3.16 was released February 4th, 2020.

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