# Rockburst Analysis Outcome

SANIRE 2019
2nd Rockburst Workshop

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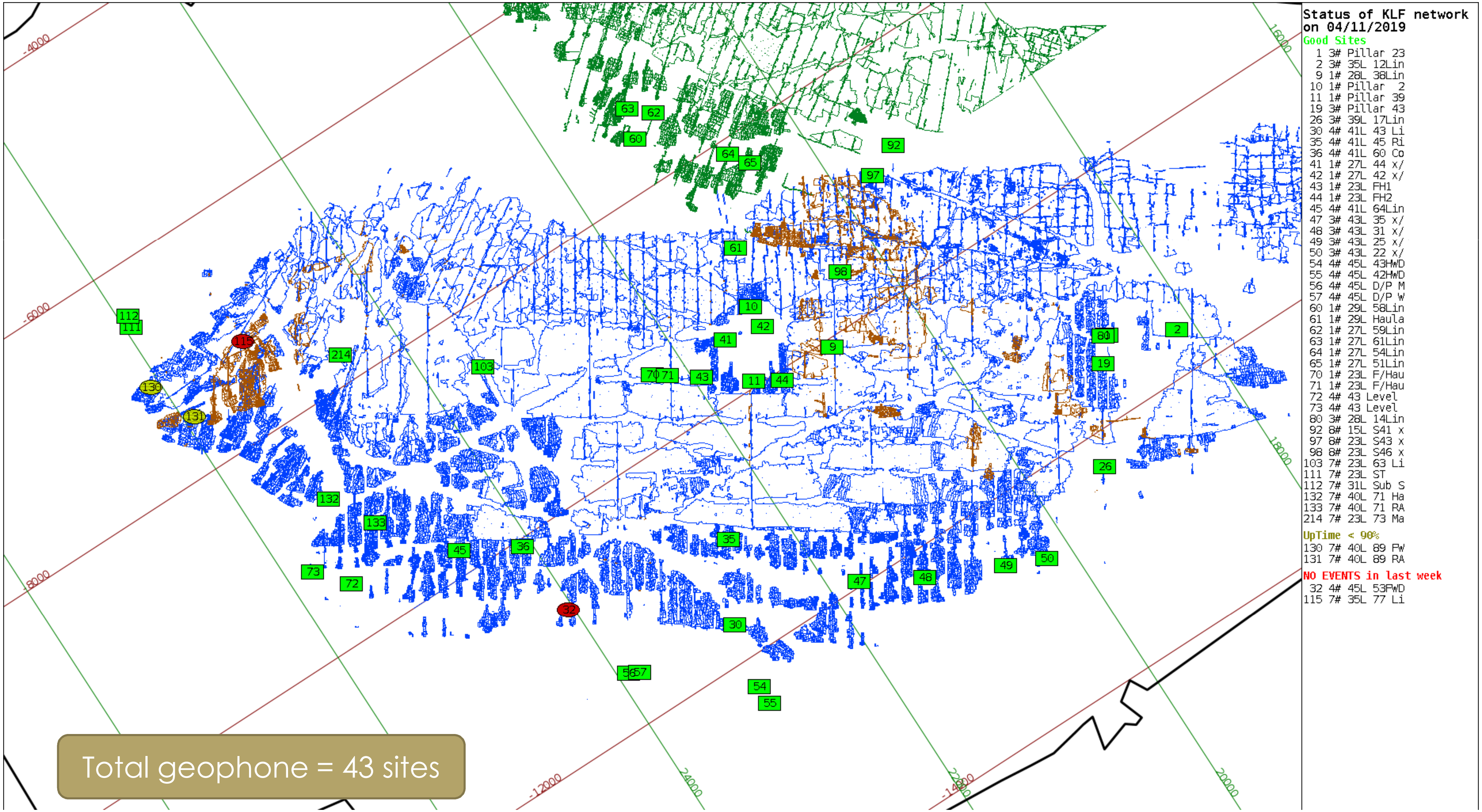
# Rockburst

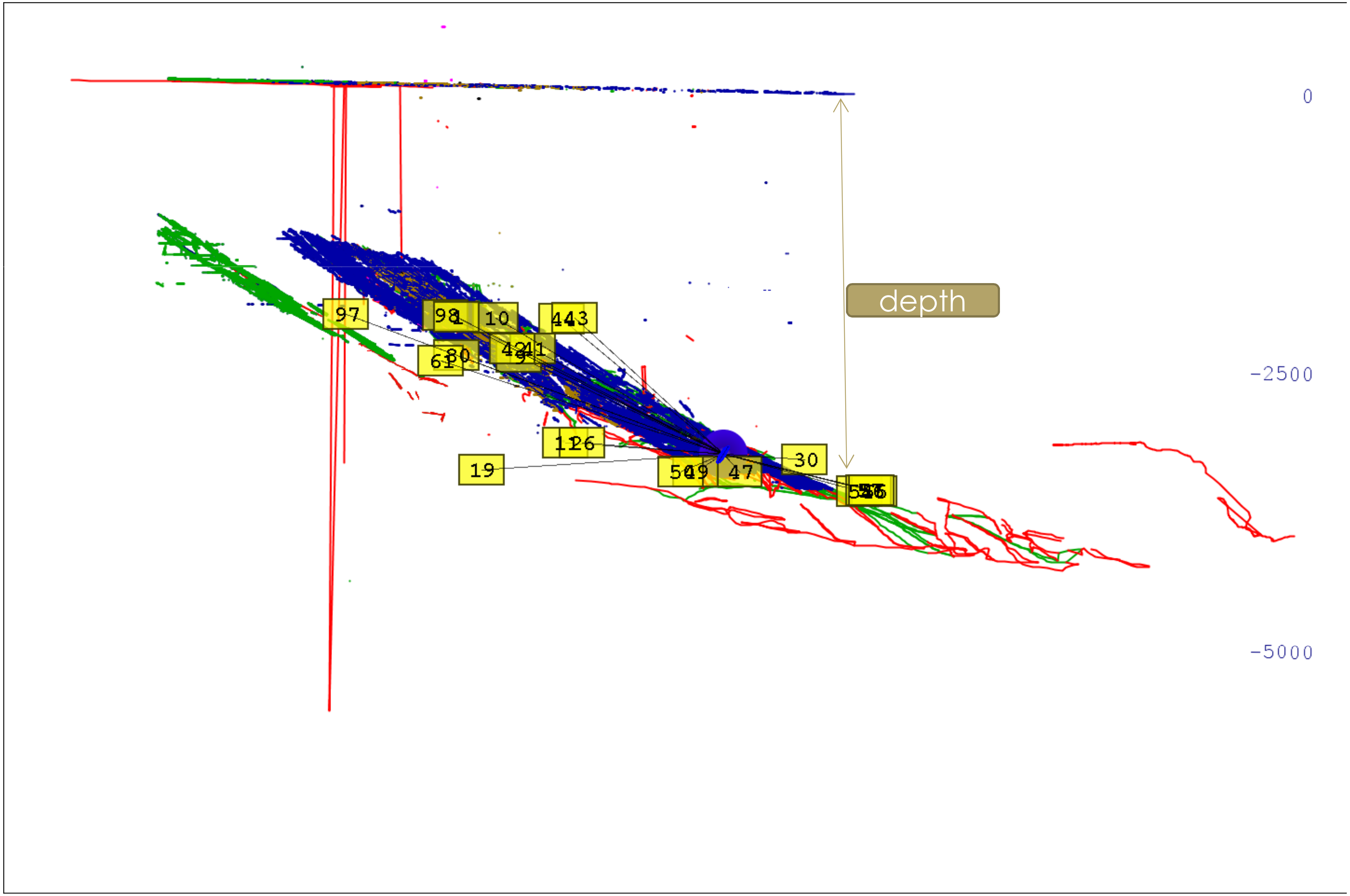
- Rockbursts continue to be a major contributor to mine accidents and cause of damage to mine excavations, particularly at great depth.
- Attempts have been made in the past to mitigate the impact of rockbursts, with rock support remaining the ultimate method for providing stability in rockbursting environments.
- The problem has been present for more than a century, and although much research has been carried out, a solution is still elusive

# Seismic Coverage

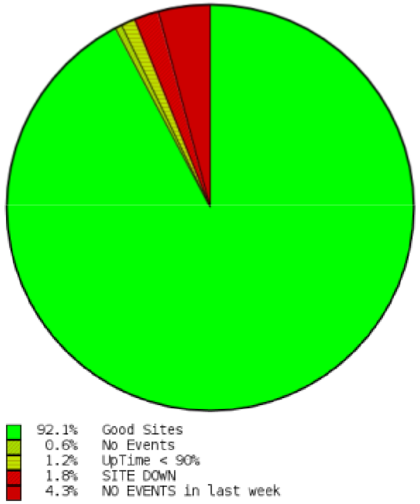



Total geophone = 43 sites

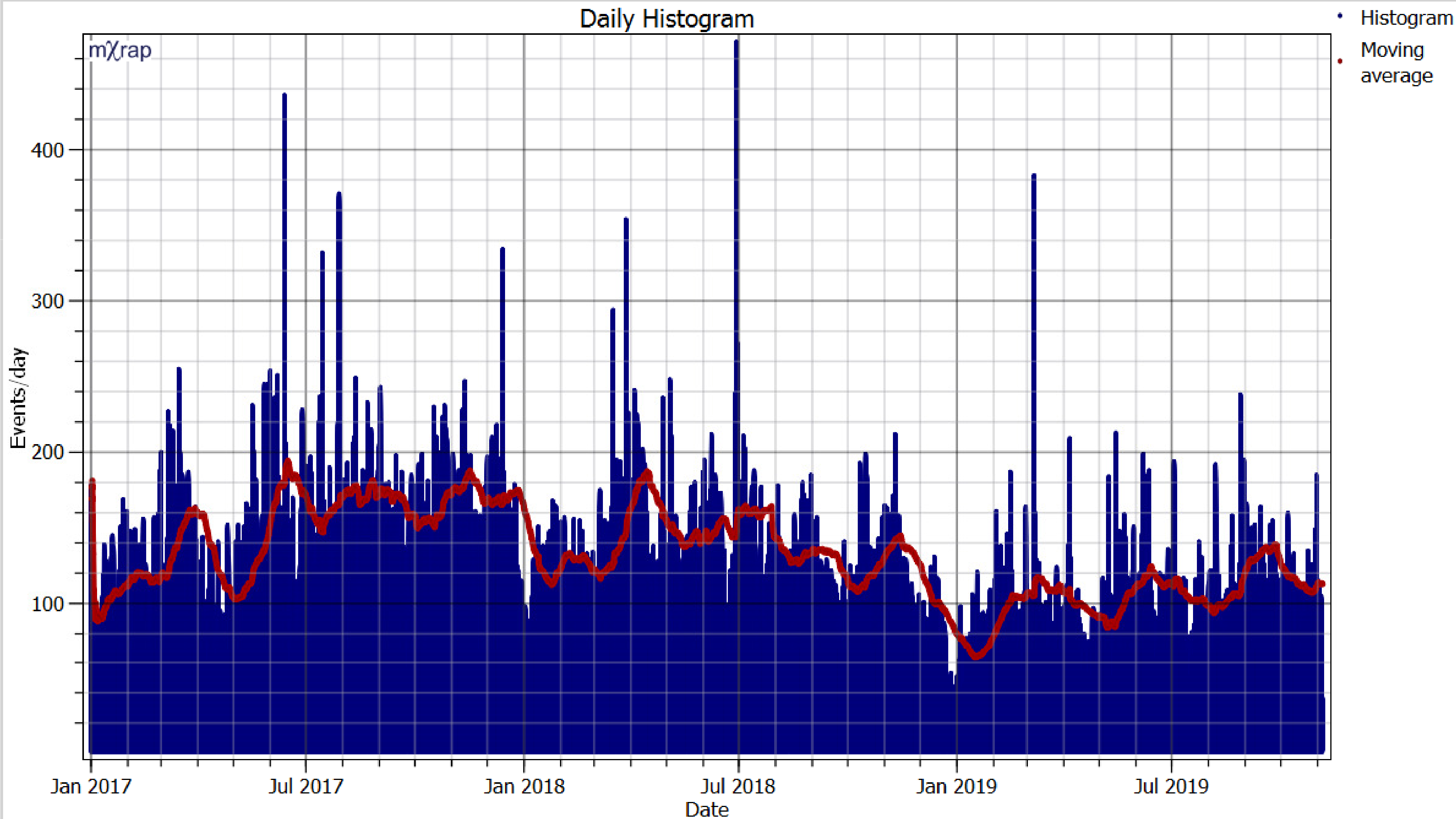
# Section View (sensor array)



# Health of the system



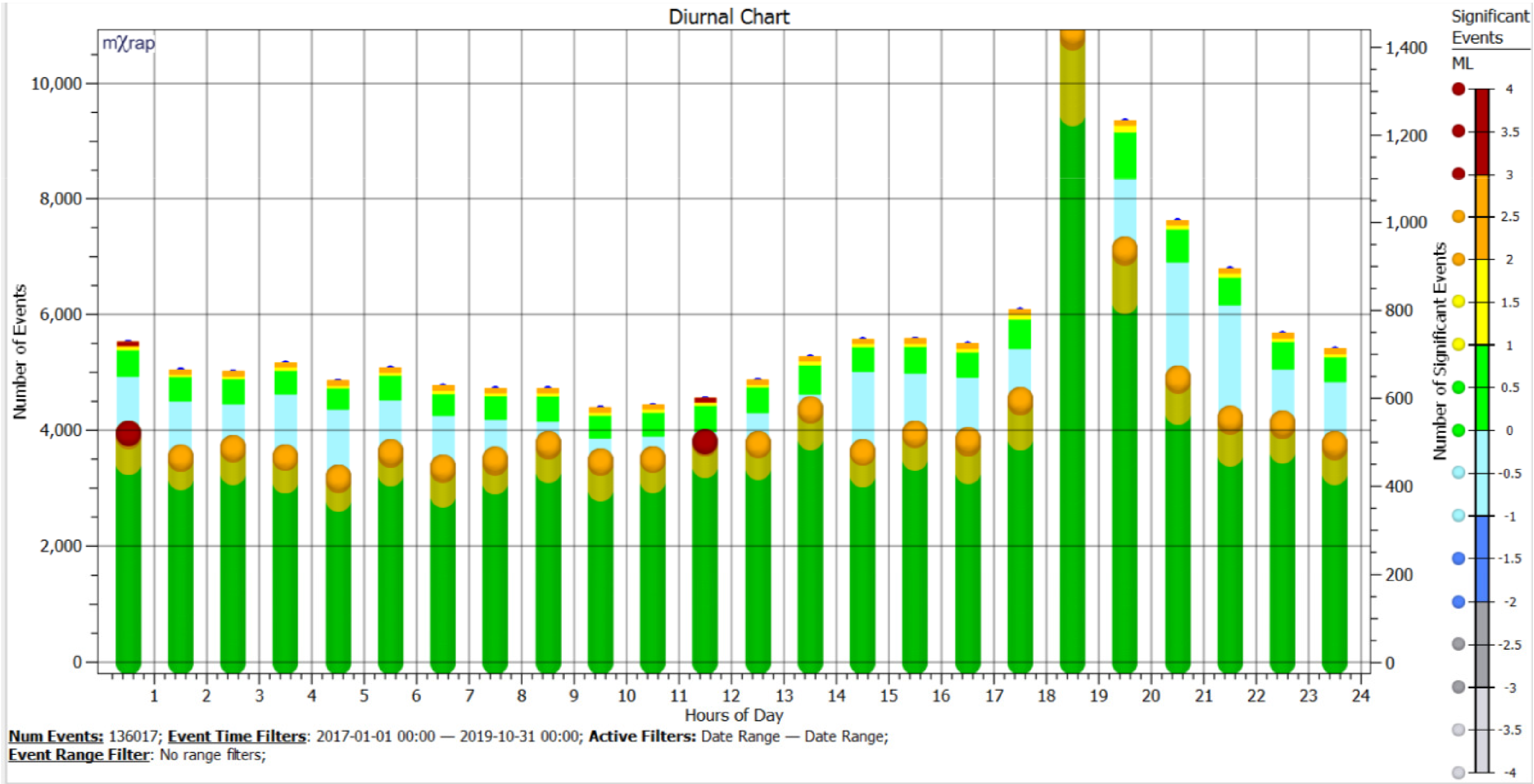

# Daily Histogram (30 days moving average)



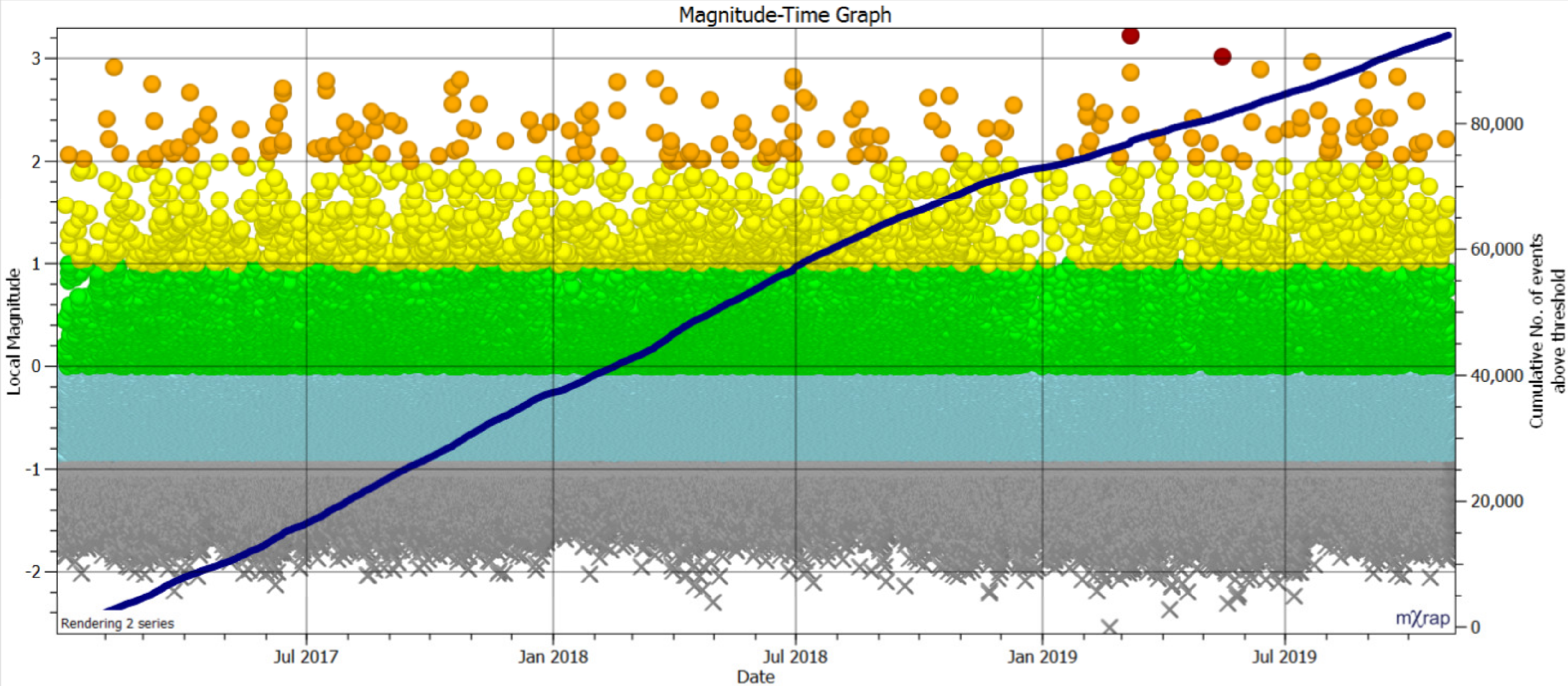

**Moving Window Average** = 30 days;

**Num Events:** 136670; **Event Time Filters**: 2017-01-01 00:00 — 2019-11-05 10:40; **Active Filters:** Date Range — ...;
**Event Range Filter**: No range filters;

# Diurnal chart



# Diurnal chart

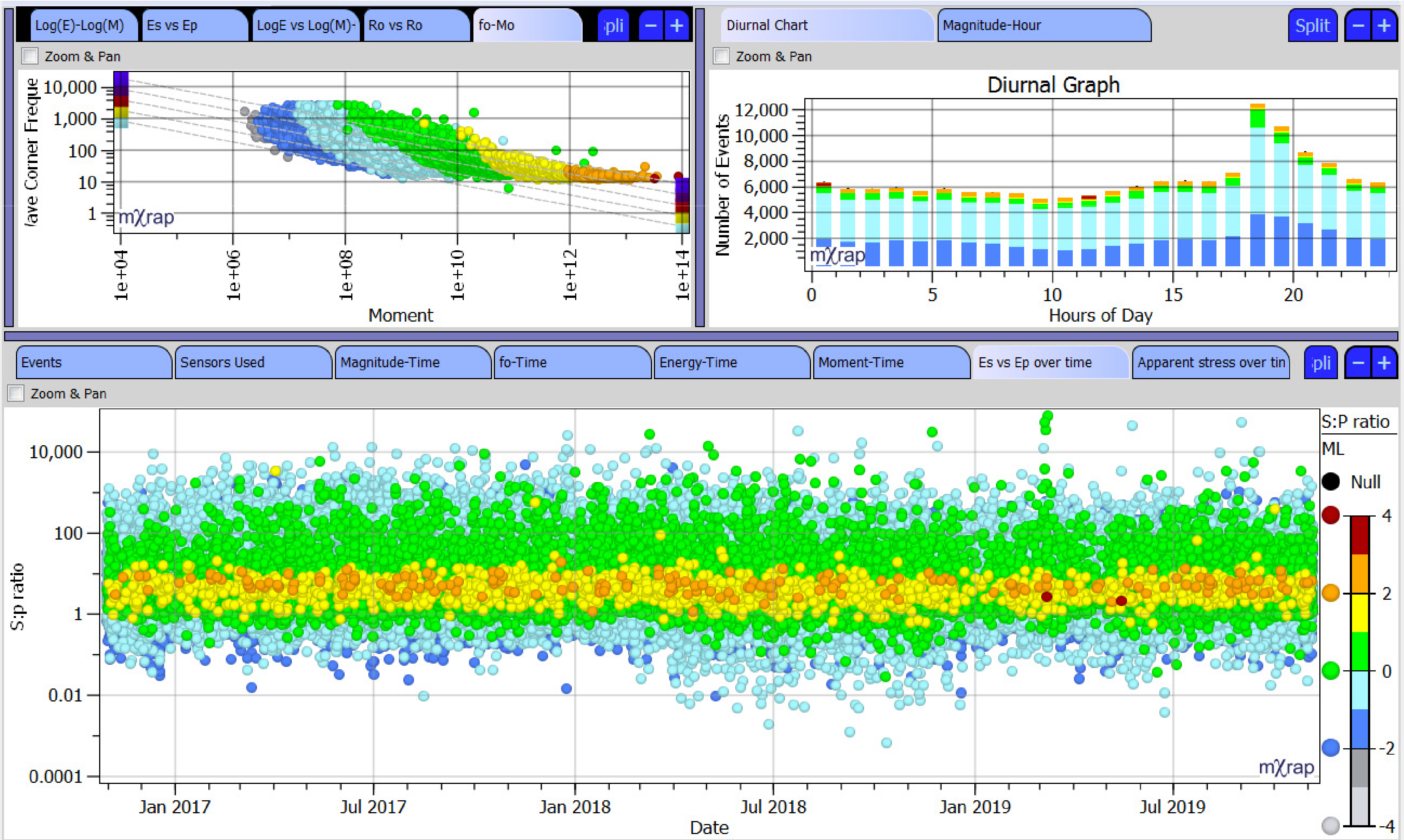


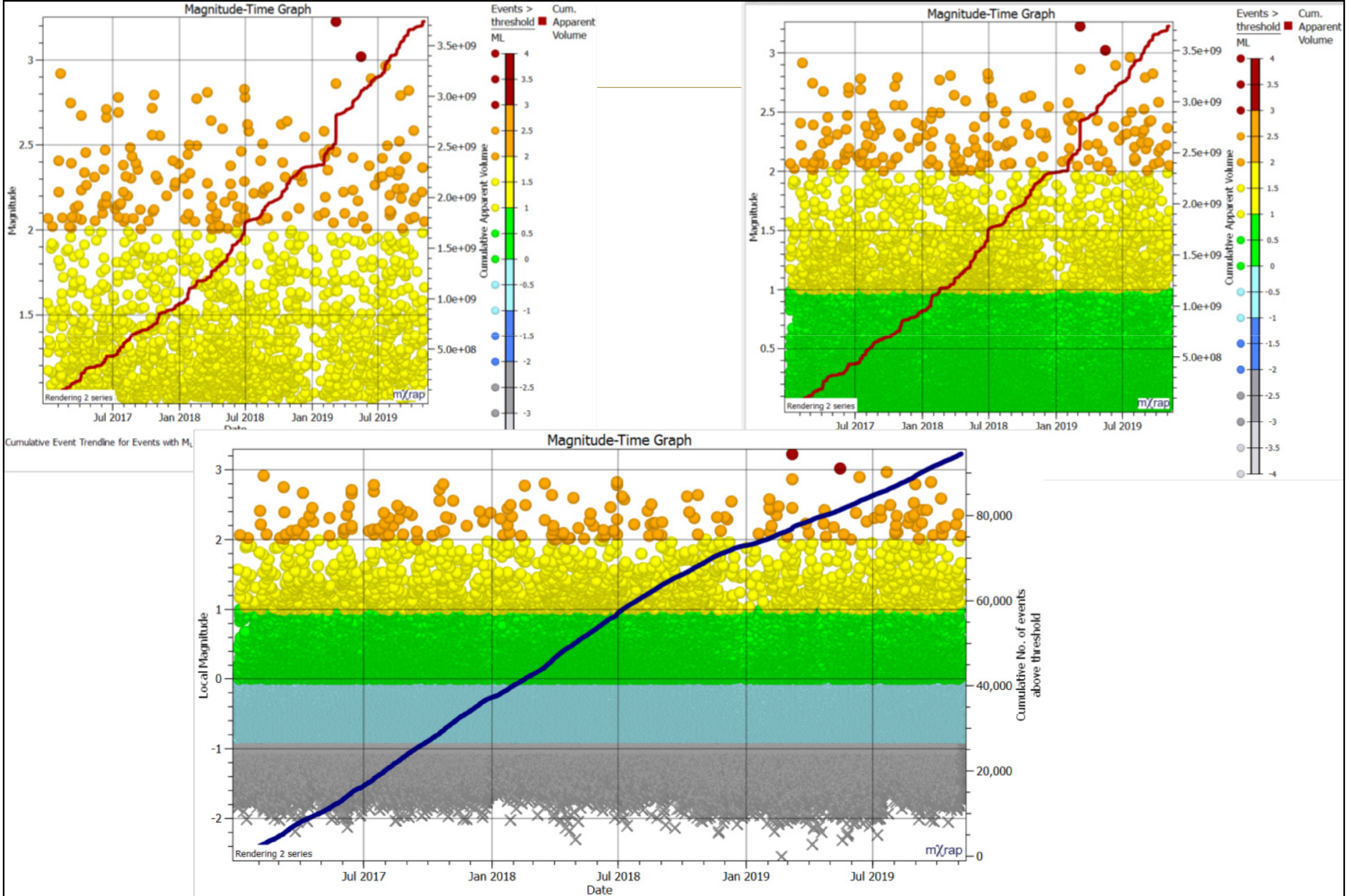

Cumulative Event Trendline for Events with $M_L \geq -1$;

**Num Events:** 136017; **Event Time Filters**: 2017-01-01 00:00 — 2019-10-31 00:00; **Active Filters:** Date Range — Date Range;
**Event Range Filter**: No range filters;

**Blast Filter**: No blasts in the database:

# S:P ratio and the Duration

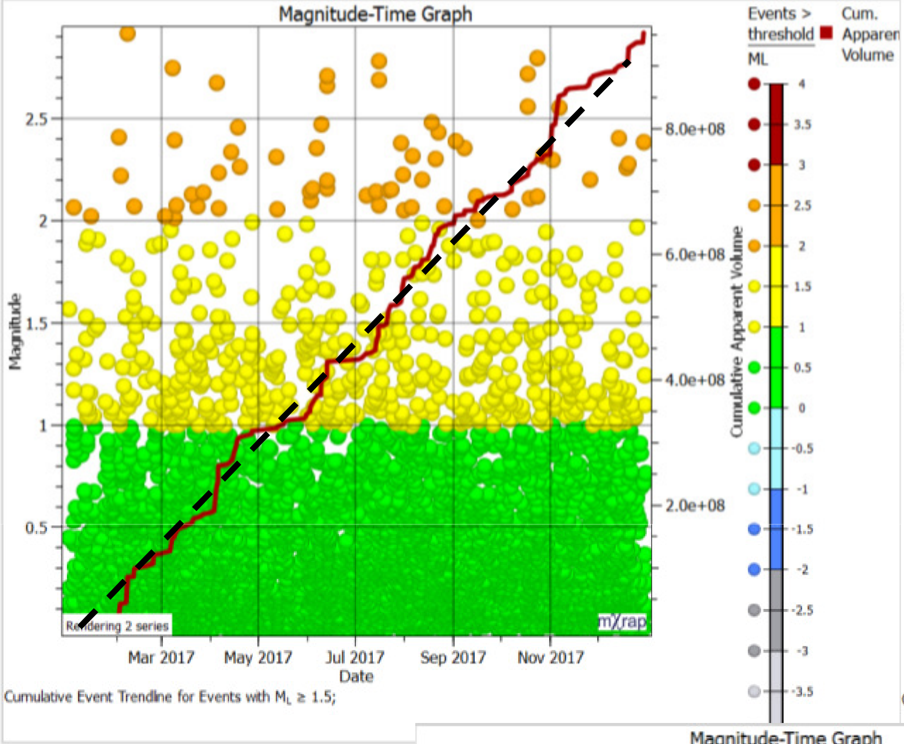


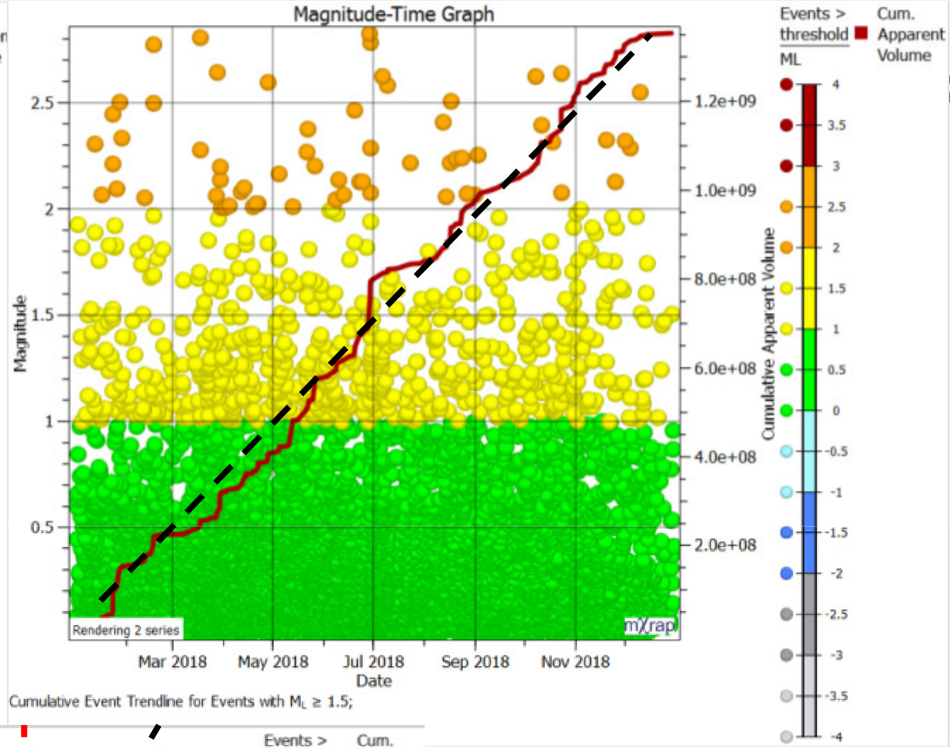


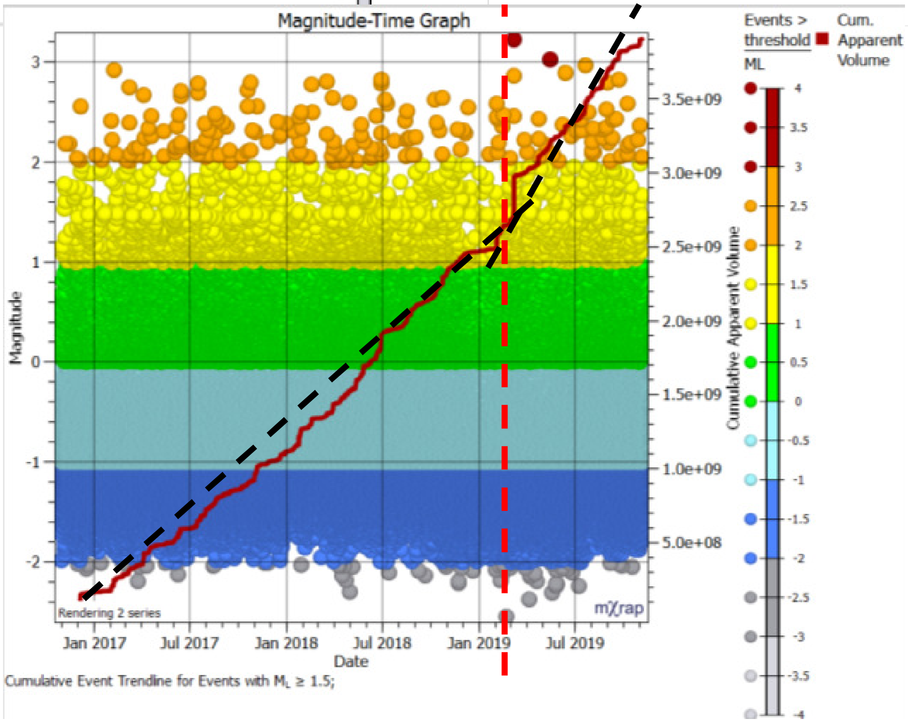

Cumulative Event Trendline for Events with $M_L \geq -1$;

**Num Events:** 136670; **Event Time Filters**: 2017-01-01 00:00 — 2019-11-05 10:40; **Active Filters:** Date Range — …;
**Event Range Filter**: No range filters;

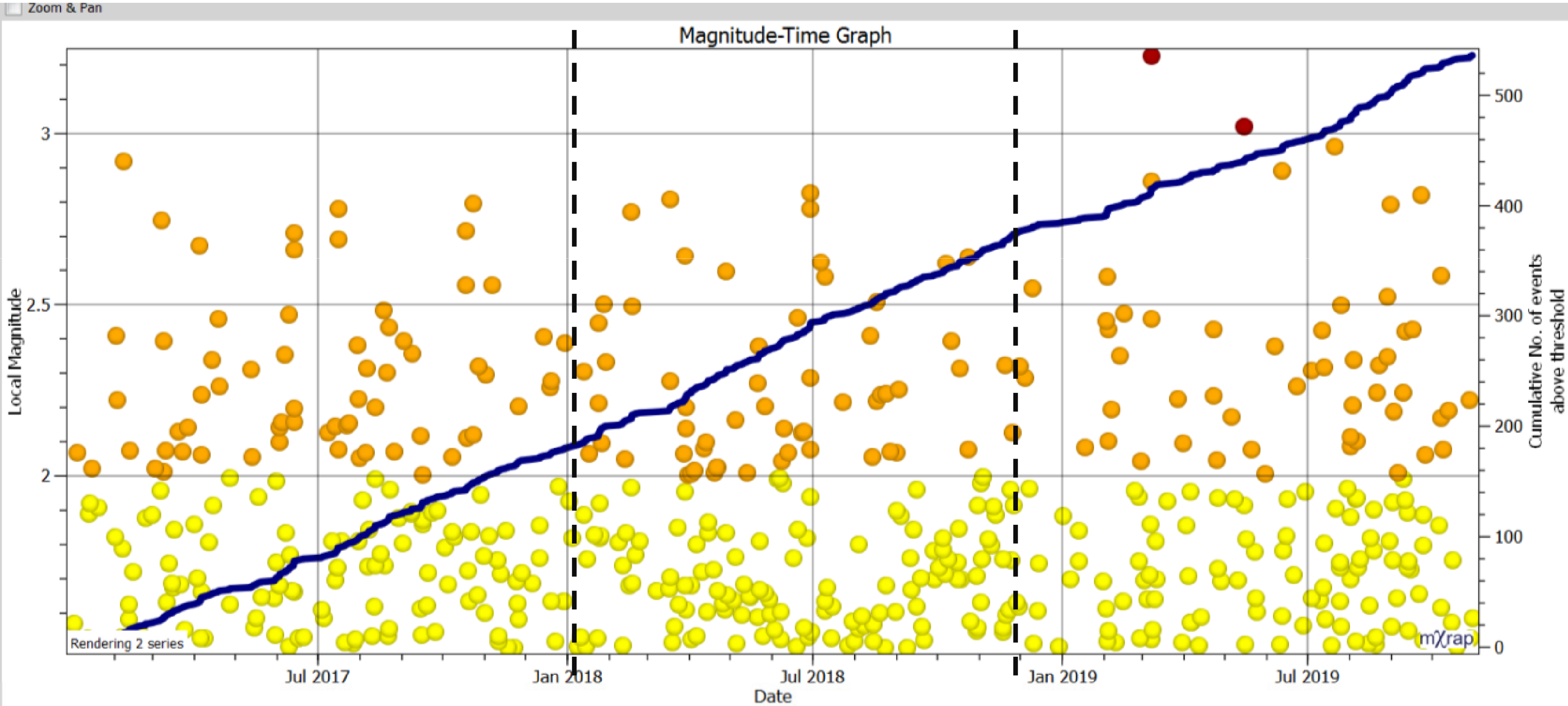
**Blast Filter**: No blasts in the database;


Magnitude-Time Graph
Magnitude
Cumulative Apparent Volume
Date
Mar 2017
May 2017
Jul 2017
Sep 2017
Nov 2017
Events > threshold
Cum. Apparent Volume
ML
Rendering 2 series
mXrap
Cumulative Event Trendline for Events with $M_L \geq 1.5$;


Magnitude-Time Graph
Magnitude
Cumulative Apparent Volume
Date
Mar 2018
May 2018
Jul 2018
Sep 2018
Nov 2018
Events > threshold
Cum. Apparent Volume
ML
Rendering 2 series
mXrap
Cumulative Event Trendline for Events with $M_L \geq 1.5$;


Magnitude-Time Graph
Magnitude
Cumulative Apparent Volume
Date
Jan 2017
Jul 2017
Jan 2018
Jul 2018
Jan 2019
Jul 2019
Events > threshold
Cum. Apparent Volume
ML
Rendering 2 series
mXrap
Cumulative Event Trendline for Events with $M_L \geq 1.5$;

# M≥1.0

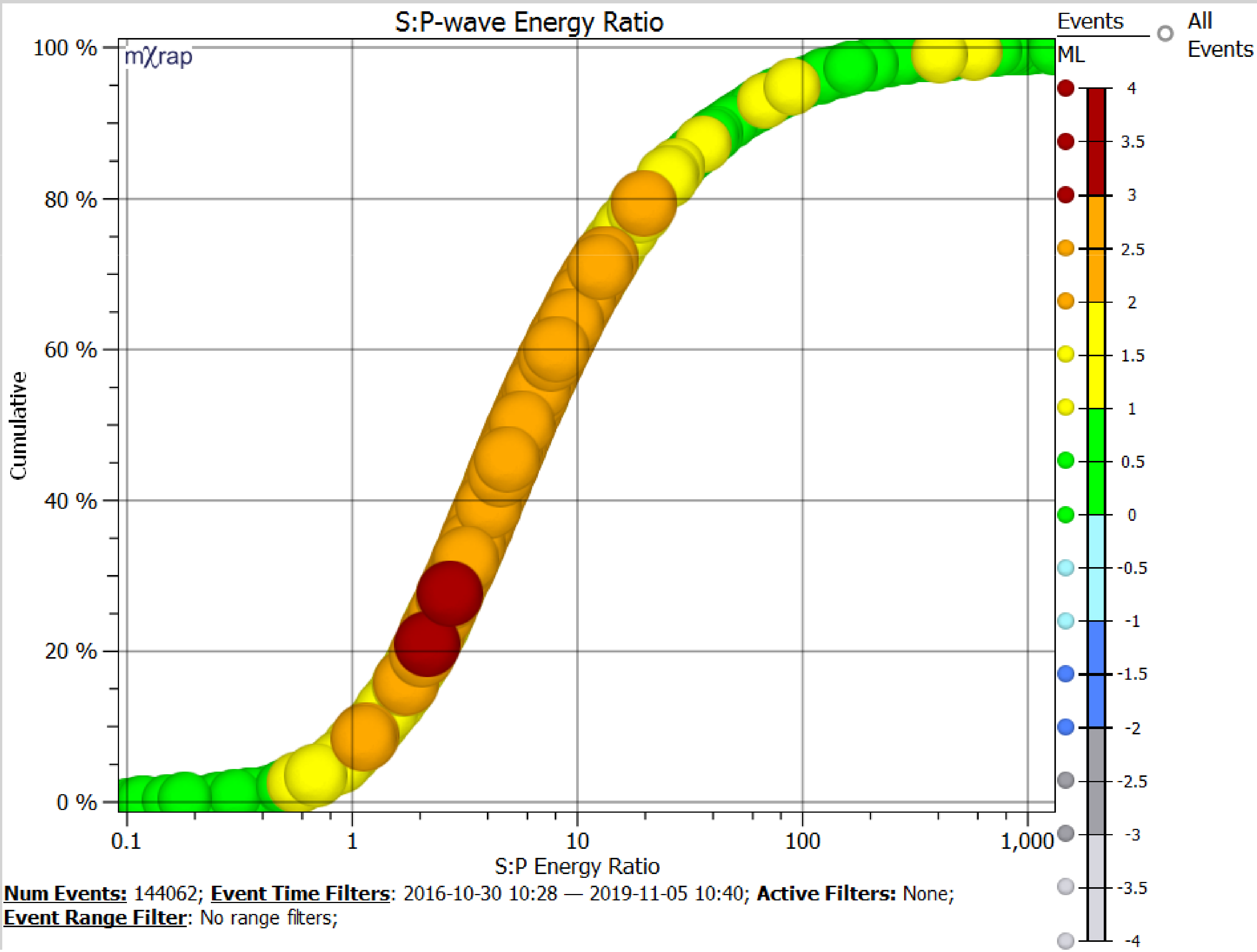



Cumulative Event Trendline for Events with $M_L \geq -1$;

**Num Events:** 536; **Event Time Filters**: 2017-01-01 00:00 — 2019-10-31 00:00; **Active Filters:** Date Range — Date Range;
**Event Range Filter**: $M_L$: 1.5 — ...;

**Blast Filter**: No blasts in the database;

# S:P wave Energy ratio




**Num Events:** 144062; **Event Time Filters**: 2016-10-30 10:28 — 2019-11-05 10:40; **Active Filters:** None;
**Event Range Filter**: No range filters;

# 3D seismic reflection and Mining Induced seismicity

- The 3D seismic reflection profiling and the earthquake seismology are often used as methods to study the structure and subsurface of the earth
- The two methods use different approaches with different objectives although they share the same fundamental principle of wave propagation and are rarely used together.
- It is intended that the integration of 3D seismic reflection data with mining induced seismic data will provide better understanding and interpretation of the seismic sources in this structurally complex area of the Witwatersrand Basin.

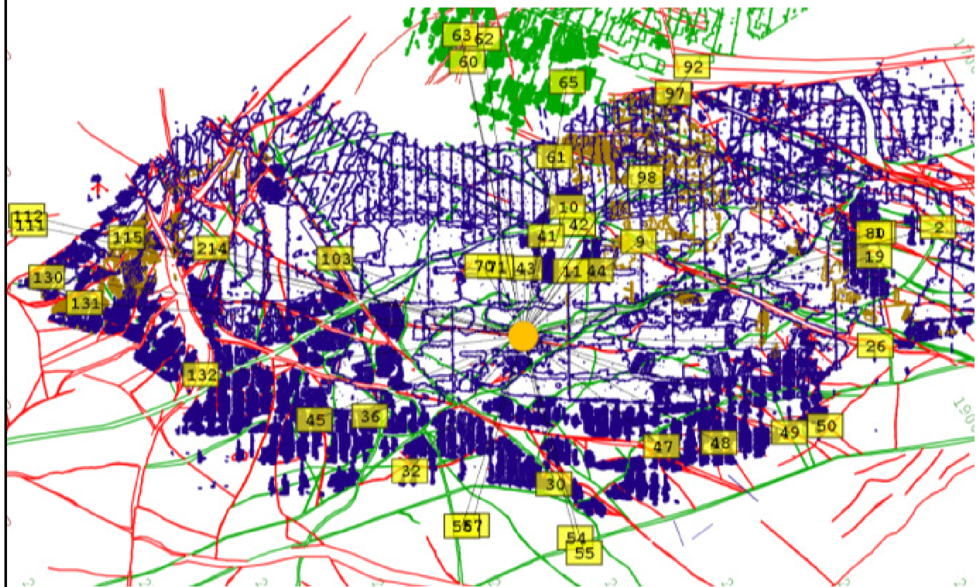
# Objectives of the two Methods

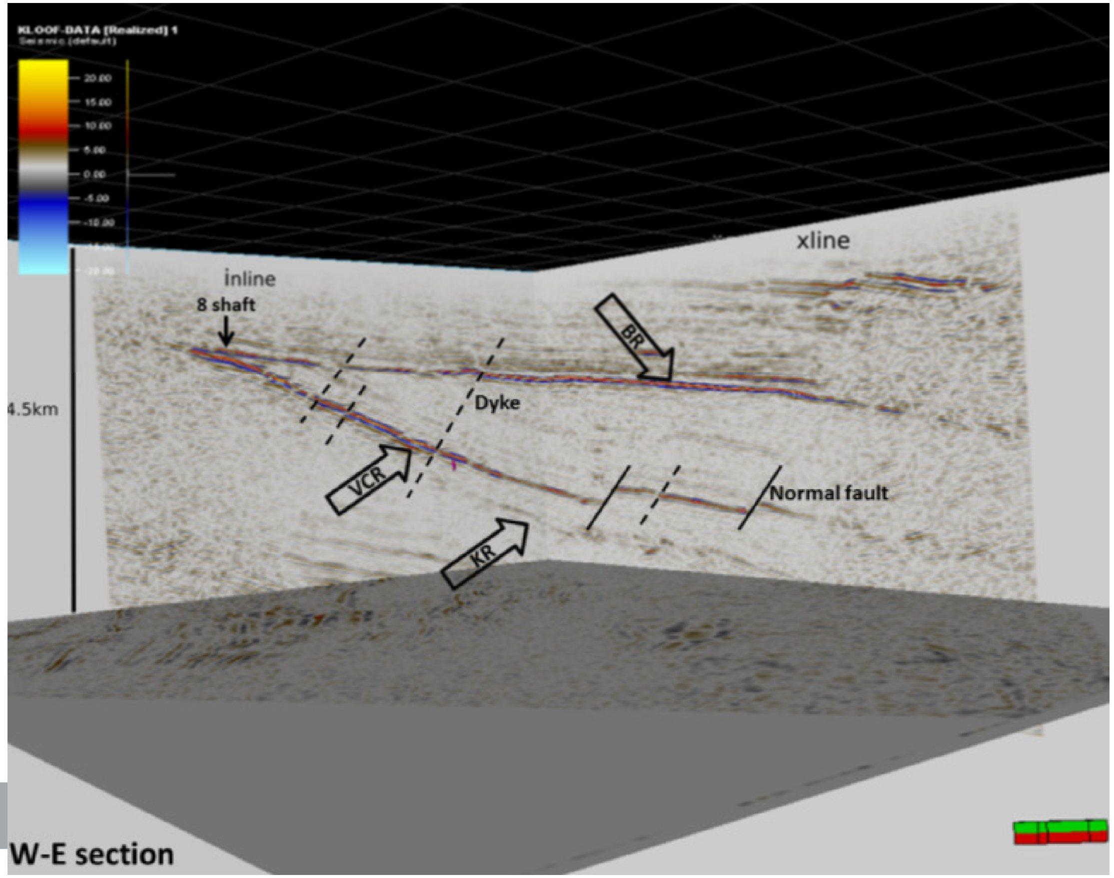
Processing of data

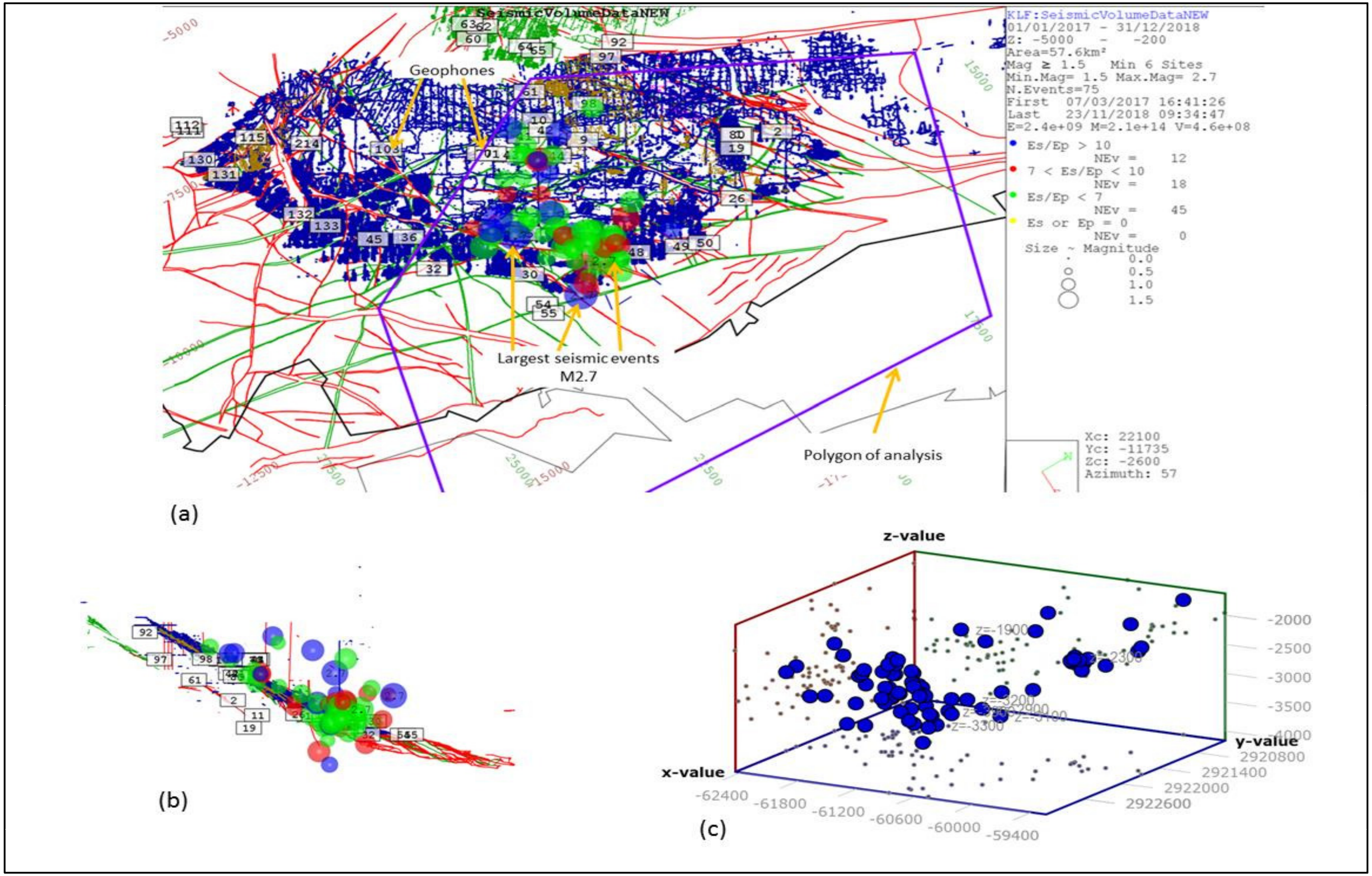
- The main objective of 3D seismic data processing is to
  - suppress noise,
  - enhance the reflected signal,
  - move (or migrate) seismic reflections to their true positions in time and space, and thus produce the best possible image of the subsurface.
- The main objective of Mining seismic data processing is for
  - Accurate Location
  - Moment Tensor Calculation (First arrivals)

# Criterion of selection (75 seismic events)

- Moment magnitude  above M1.5
- At least 20 sites (geophones)  triggered around the seismic event (selection based on the dense network)
- Seismic events with location falling within the volume covered by the in-mine seismic network and the 3D reflection volume.

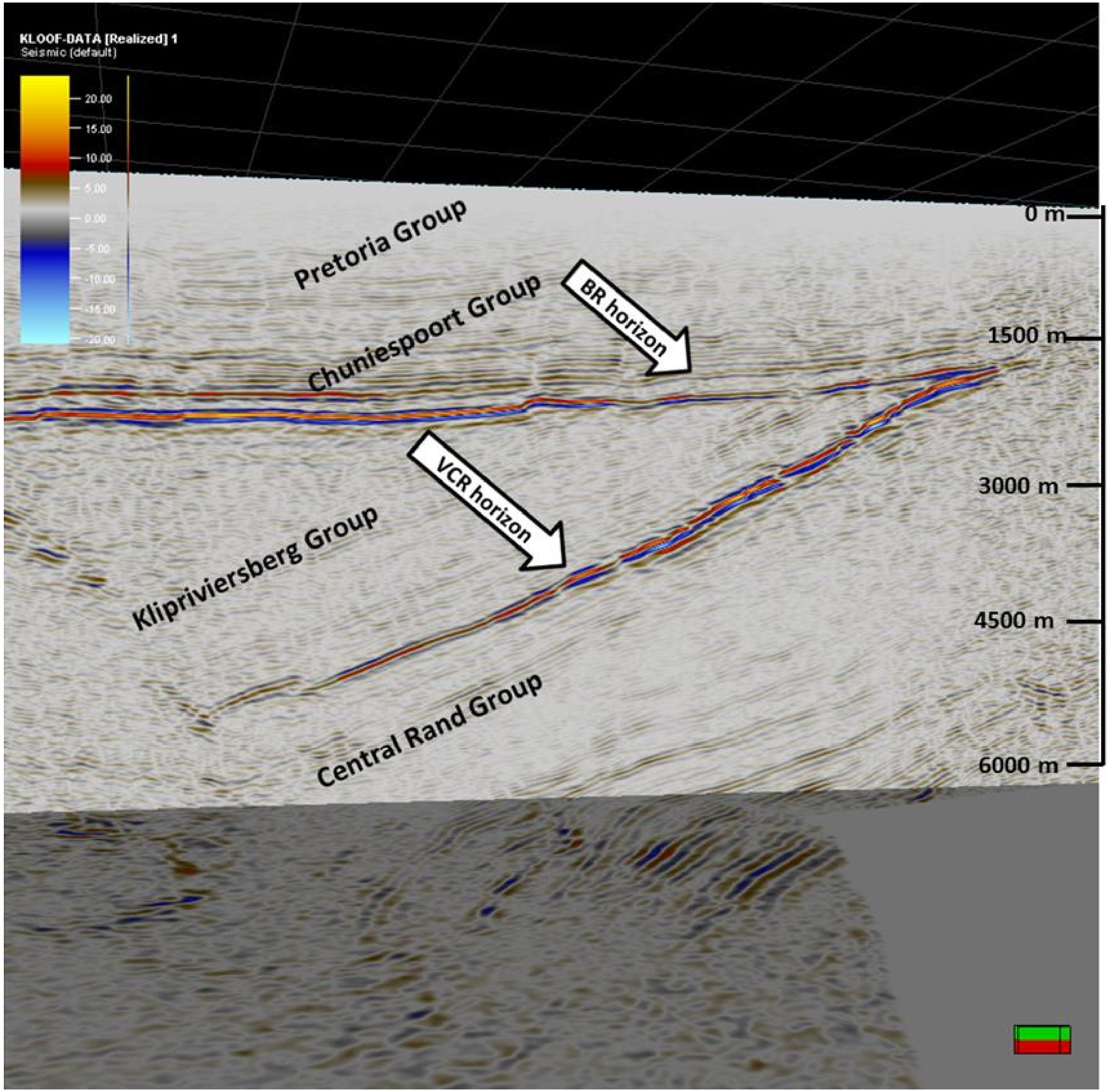




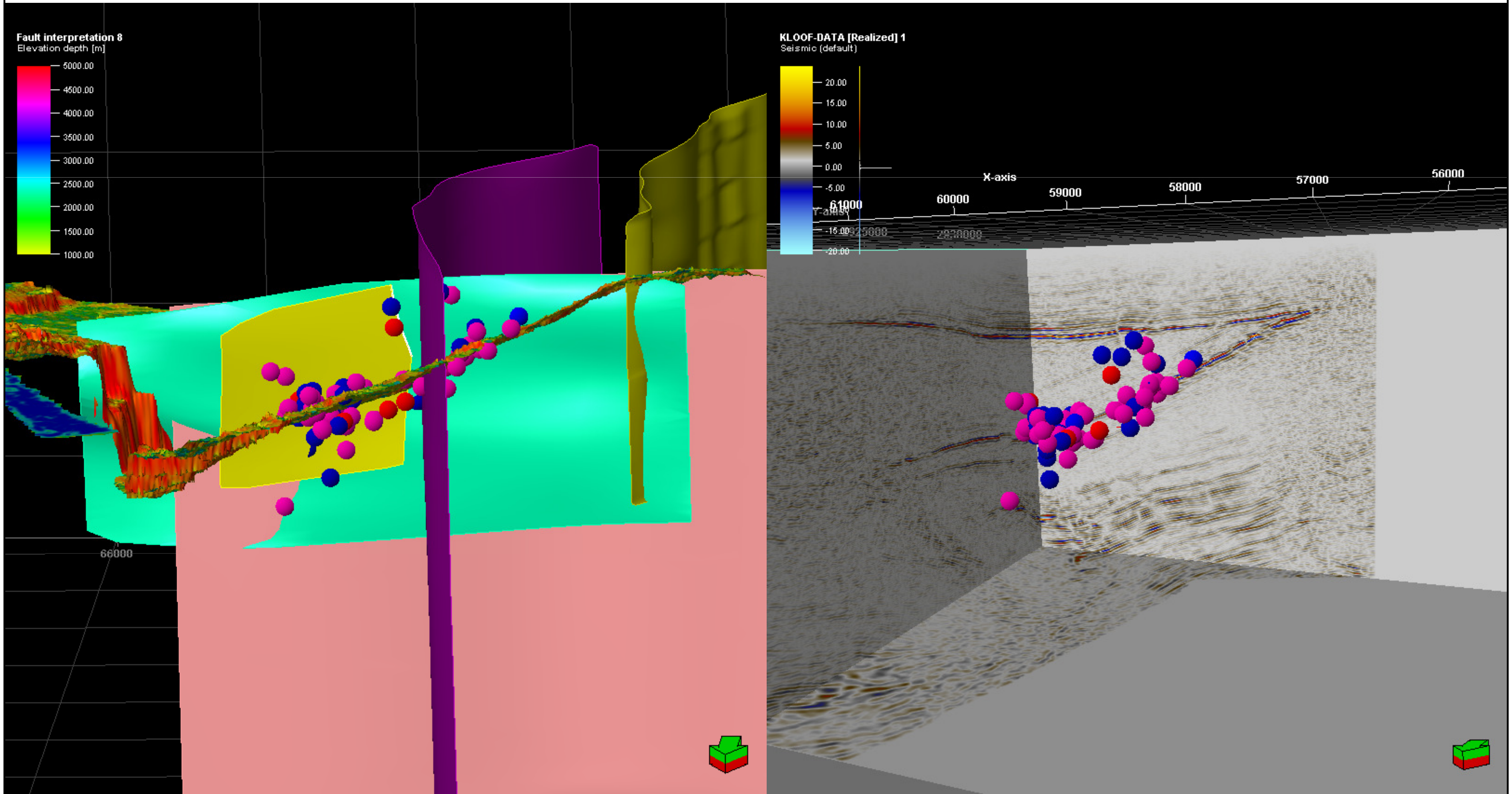


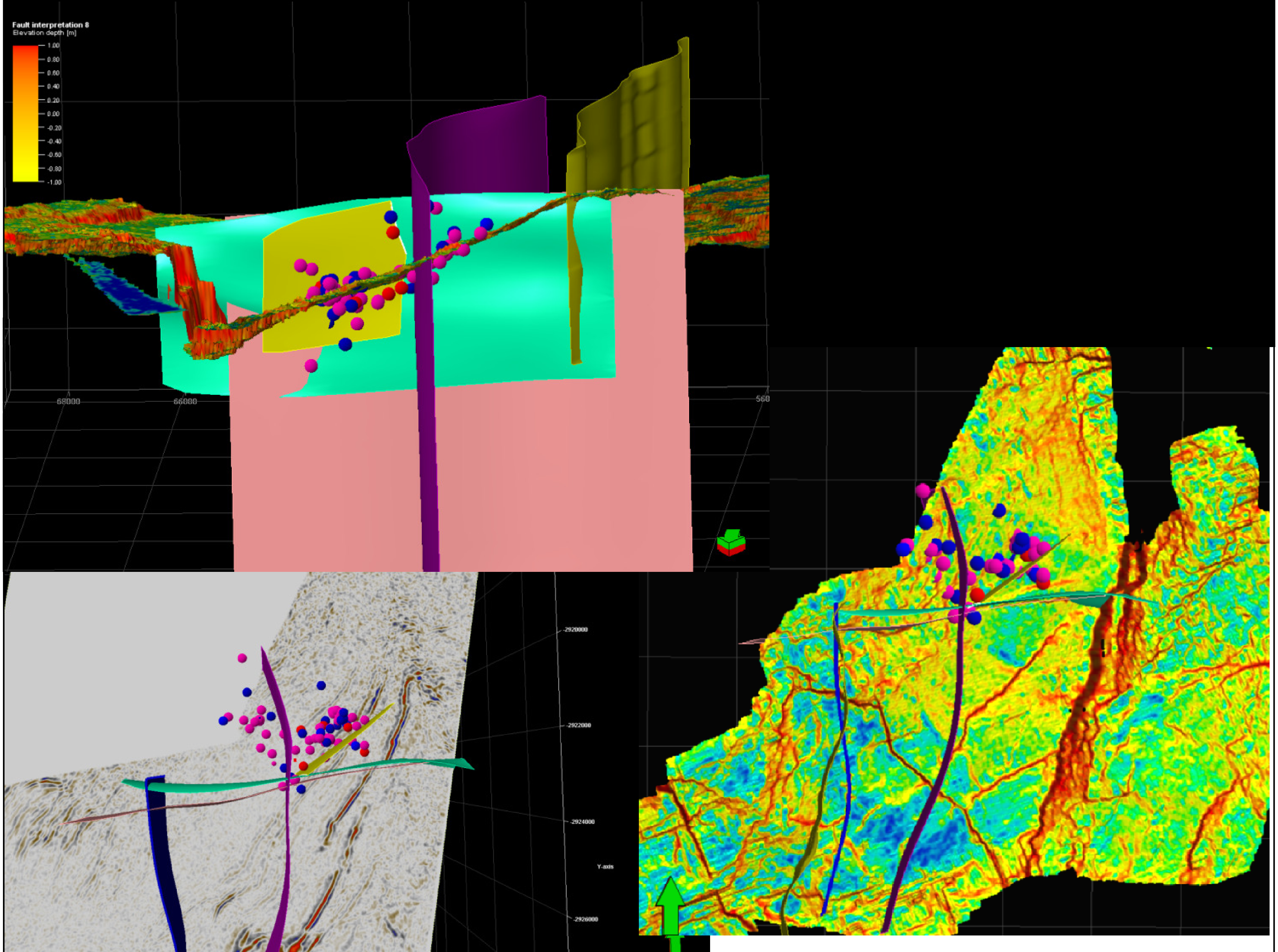

*(a) 2D Plan view of Kloof mine, South Africa, with the location of the in-mine geophones (rectangles) and the 75 seismic events (blue, green and red circles) considered in this. Purple polygon indicates the location for the analysed 3D seismic reflection Volume (b) Cross section view indicating the geometry of geophones and (c) 3D view of the events within the purple polygon.*

# 3D seismic reflection



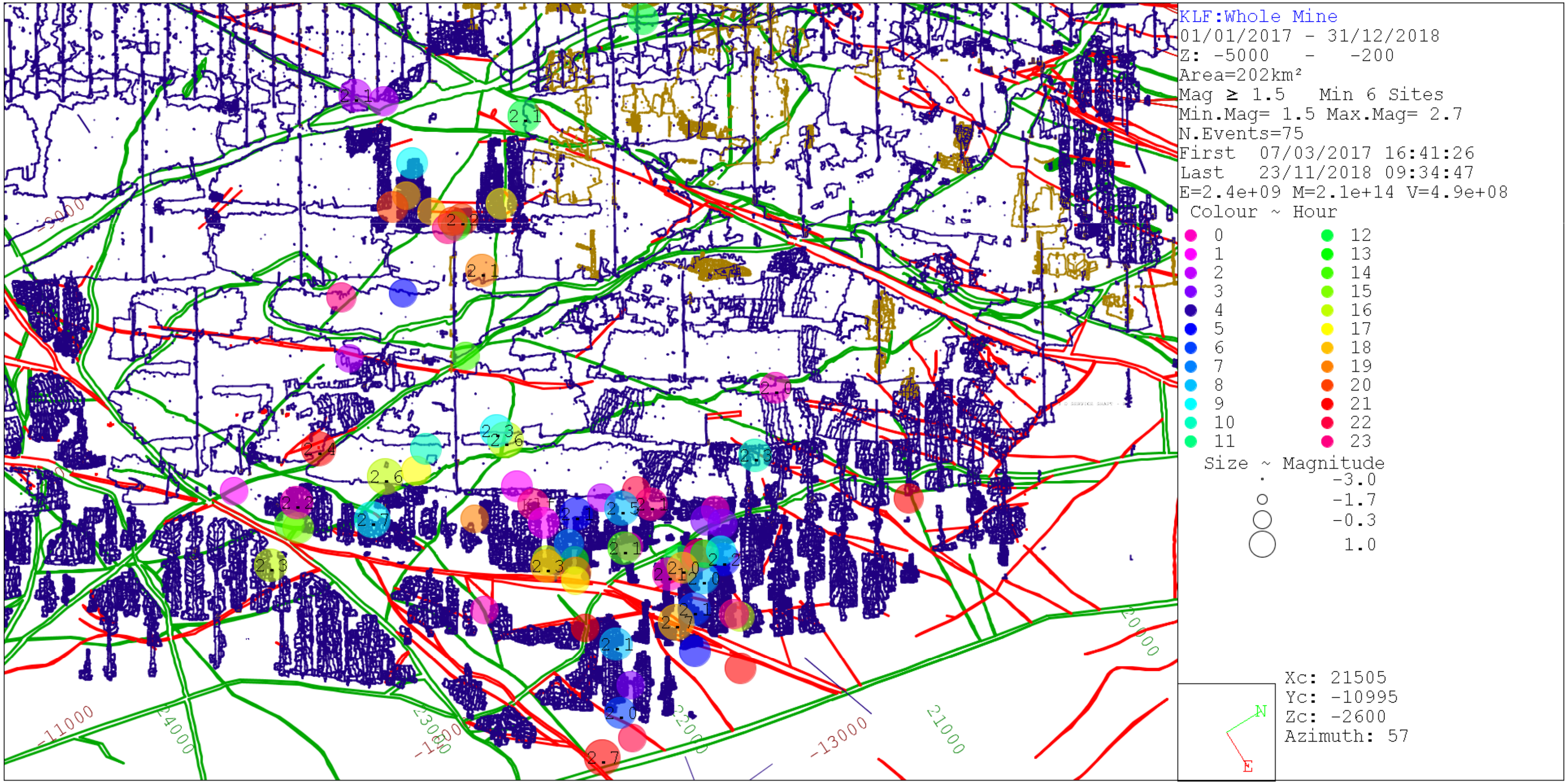
# Cross section and the 3D fault interpretation

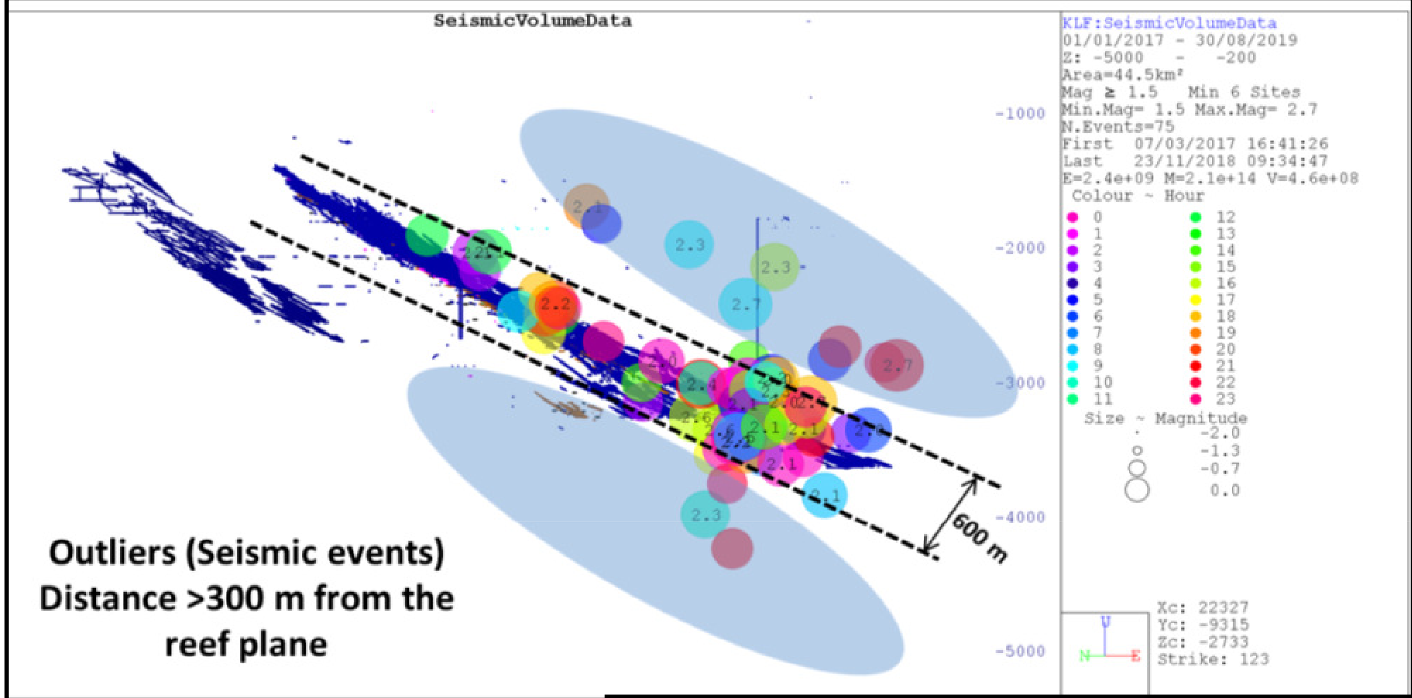


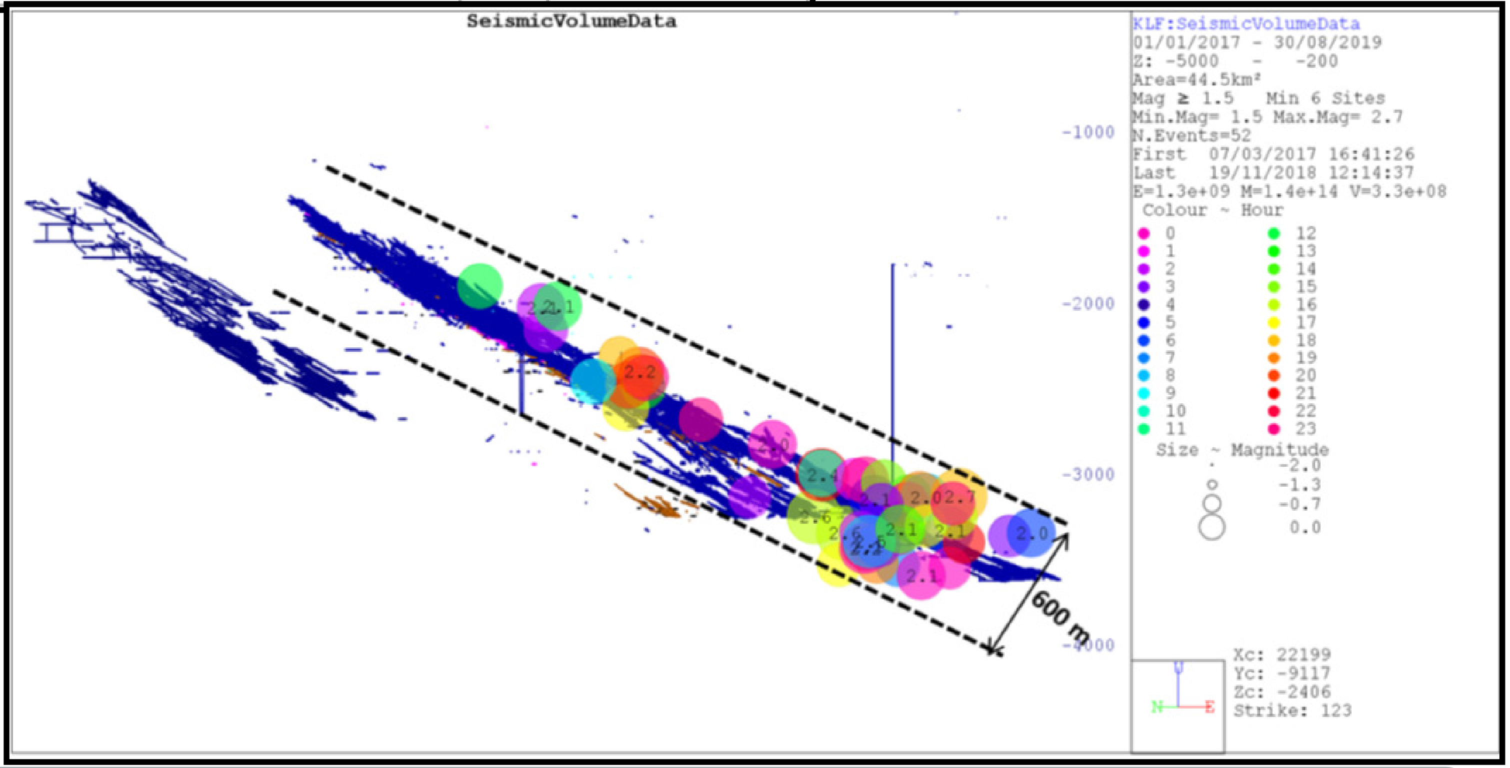


Fault interpretation 8
Elevation depth [m]
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
68000
66000
-2920000
-2922000
-2924000
-2926000
Y-axis

# Spatial Distributions (75 seismic events)




SeismicVolumeData
KLF:SeismicVolumeData
01/01/2017 - 30/08/2019
Z: -5000 - -200
Area=44.5km²
Mag ≥ 1.5 Min 6 Sites
Min.Mag= 1.5 Max.Mag= 2.7
N.Events=75
First 07/03/2017 16:41:26
Last 23/11/2018 09:34:47
E=2.4e+09 M=2.1e+14 V=4.6e+08
Colour ~ Hour
Size ~ Magnitude
-2.0
-1.3
-0.7
0.0
-1000
-2000
-3000
-4000
-5000
600 m
Xc: 22327
Yc: -9315
Zc: -2733
Strike: 123
Outliers (Seismic events)
Distance >300 m from the
reef plane


SeismicVolumeData
KLF:SeismicVolumeData
01/01/2017 - 30/08/2019
Z: -5000 - -200
Area=44.5km²
Mag ≥ 1.5 Min 6 Sites
Min.Mag= 1.5 Max.Mag= 2.7
N.Events=52
First 07/03/2017 16:41:26
Last 19/11/2018 12:14:37
E=1.3e+09 M=1.4e+14 V=3.3e+08
Colour ~ Hour
Size ~ Magnitude
-2.0
-1.3
-0.7
0.0
-1000
-2000
-3000
-4000
600 m
Xc: 22199
Yc: -9117
Zc: -2406
Strike: 123

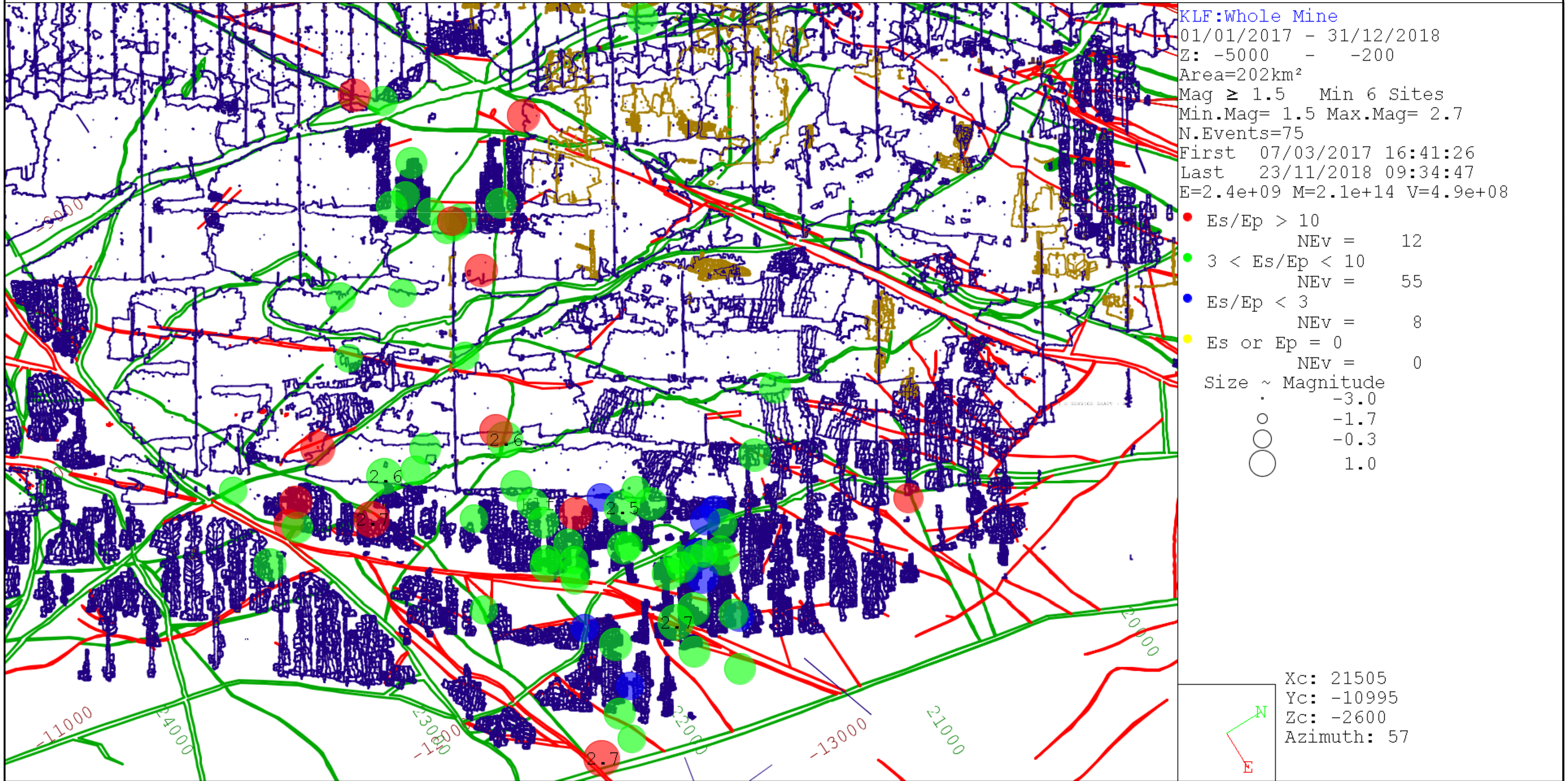
## Literature on mining-induced seismicity reveals many studies assigning diagnostic value to Es/Ep .

- $\frac{E_s}{E_p}$ value generally in Mining as important indicator of focal mechanism

Tensile model (Sato, 1978) Es and Ep are approximately equal
Gibowicz and Kijko (1994) - suggest tensile failure component with Es/Ep <10 )
Boatwright and Fletcher (1984)- suggest pure shear corresponds with Es/Ep > 10 )
Hudyma and Potvin (2010)-suggest that for events with Es/Ep < 3, the mechanism is non-shear
Es/Ep > 20 (Pure shear)- some authors

| Es/Ep | Mechanism interpretations |
|---|---|
| <1 | Pure tensile |
| 1–3 | Non-shear |
| 3–10 | Mixed |
| >10 | Shear |

# Focal mechanism(Es/Ep ratio)



# Moment Tensor inversion -Problems

- Proving that the results provide an accurate reflection of reality
- Verification can be reliably undertaken by obtaining fracture mapping (comparing location and orientations of the computed fault-plane solution with those of mapping)
- Even then, the conclusion often remain speculative

# Source Parameters and Moment Tensor Components

| Event ID | Local Magnitude ($M_L$) | DEV | ISO | Misfit | QI | Es/Ep ratio | $M_{xx}(10^{12})$ | $M_{yy}(10^{12})$ | $Mzz(10^{12})$ | $Mxy(10^{12})$ | $Mxz(10^{12})$ | $Myz(10^{12})$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20180902 061326 | 2 | 92.9 | 7.1 | 0.42 | 0.53 | 7.6 | -0.04 | 0.18 | 0.07 | 0.57 | 0.63 | 0.18 |
| 20180816 183153 | 2 | 63.3 | 30.7 | 0.37 | 0.71 | 7.1 | -0.28 | 0.06 | -0.71 | 0.11 | -0.44 | -0.25 |
| 20180526 083550 | 2 | 57.0 | 43.0 | 0.39 | 0.65 | 2.3 | -0.45 | -0.10 | -0.75 | 0.06 | -0.34 | 0.16 |
| 20181017 144042 | 2.1 | 91.7 | 8.3 | 0.38 | 0.43 | 4.2 | 0.27 | 0.40 | -0.92 | 0.42 | -0.31 | -0.01 |
| 20171219 050805 | 2.1 | 89.2 | 10.8 | 0.25 | 0.43 | **19.9** | -0.23 | 0.54 | 0.01 | 0.14 | -0.39 | -0.57 |
| 20180317 191617 | 2.1 | 82.4 | 17.6 | 0.33 | 0.95 | **12.5** | -0.34 | 0.82 | 0.05 | 0.49 | -0.08 | 0.00 |
| 20180113 023808 | 2.1 | 79.1 | 20.9 | 0.42 | 0.71 | **11.8** | -0.42 | 0.21 | -0.42 | -0.30 | 0.39 | 0.39 |
| 20181119 121437 | 2.1 | 74.1 | 25.9 | 0.25 | 0.82 | **10.5** | 0.28 | 0.23 | 0.26 | 0.23 | -0.07 | 0.67 |
| 20180628 233131 | 2.1 | 73.2 | 26.8 | 0.31 | 0.51 | 5.0 | 0.27 | -0.33 | -0.74 | 0.25 | -0.31 | -0.74 |
| 20180129 004428 | 2.1 | 72.8 | 27.2 | 0.27 | 0.69 | 4.9 | -0.18 | -0.19 | -0.86 | 0.07 | -0.33 | -0.86 |
| 20171027 080443 | 2.1 | 72.4 | 27.6 | 0.34 | 0.57 | 8.8 | -0.36 | -0.10 | -0.37 | -0.34 | 0.37 | 0.35 |
| 20171220 064504 | 2.1 | 55.2 | 44.8 | 0.17 | 0.43 | 4.0 | -0.40 | -0.15 | -0.80 | 0.04 | -0.34 | -0.80 |
| 20170729 202255 | 2.2 | 74.2 | 25.8 | 0.31 | 0.60 | 8.9 | -0.25 | 0.13 | 0.63 | 0.42 | -0.05 | 0.54 |
| 20171214 050211 | 2.2 | 63.6 | 36.4 | 0.34 | 0.72 | 8.0 | -0.48 | -0.06 | -0.55 | 0.02 | -0.47 | -0.55 |
| 20180522 003124 | 2.2 | 60.3 | 39.7 | 0.37 | 0.57 | **11.1** | -0.39 | -0.48 | -0.32 | 0.27 | -0.27 | 0.35 |
| 20170818 090901 | 2.3 | 94.8 | 5.2 | 0.39 | 0.90 | **10.8** | 0.29 | 0.25 | -0.69 | -0.22 | -0.22 | 0.69 |
| 20180127 184558 | 2.3 | 82.8 | 17.2 | 0.40 | 0.54 | 3.7 | -0.54 | -0.54 | 0.54 | -0.11 | 0.25 | -0.20 |
| 20170822 105230 | 2.3 | 74.9 | 25.1 | 0.29 | 0.65 | 9.4 | -0.23 | 0.71 | 0.27 | -0.02 | -0.23 | -0.45 |
| 20180217 163457 | 2.3 | 60.7 | 39.3 | 0.34 | 0.91 | 5.7 | -0.41 | -0.53 | -0.23 | -0.01 | -0.39 | -0.40 |
| 20171017 211230 | 2.4 | 76.3 | 23.7 | 0.35 | 0.48 | **11.3** | -0.40 | 0.27 | -0.64 | -0.14 | -0.42 | -0.19 |
| 20181007 082527 | 2.5 | 88.6 | 11.4 | 0.29 | 0.48 | 7.0 | 0.19 | 0.08 | -0.61 | 0.28 | -0.56 | 0.22 |
| 20170715 162357 | 2.6 | 95.3 | 4.7 | 0.32 | 0.48 | 4.7 | -0.26 | 0.51 | -0.57 | 0.15 | -0.57 | -0.14 |
| 20170307 164126 | 2.6 | 88.5 | 11.5 | 0.34 | 0.56 | 6.6 | -0.36 | 0.41 | -0.66 | 0.21 | -0.45 | 0.01 |
| 20171023 094245 | 2.7 | 71.8 | 28.2 | 0.26 | 0.80 | **10.6** | -0.10 | 0.77 | 0.18 | 0.33 | -0.25 | 0.18 |
| 20180317 214226 | 2.7 | 66.0 | 34.0 | 0.33 | 0.75 | **10.5** | -0.15 | -0.31 | -0.56 | 0.30 | -0.49 | -0.08 |
| 20180628 181056 | 2.7 | 45.3 | 54.7 | 0.26 | 0.74 | 4.6 | -0.39 | -0.43 | -0.82 | 0.06 | -0.26 | -0.22 |

# Corresponding Fault-Plane Solution

These results show both deviatoric and isotropic components

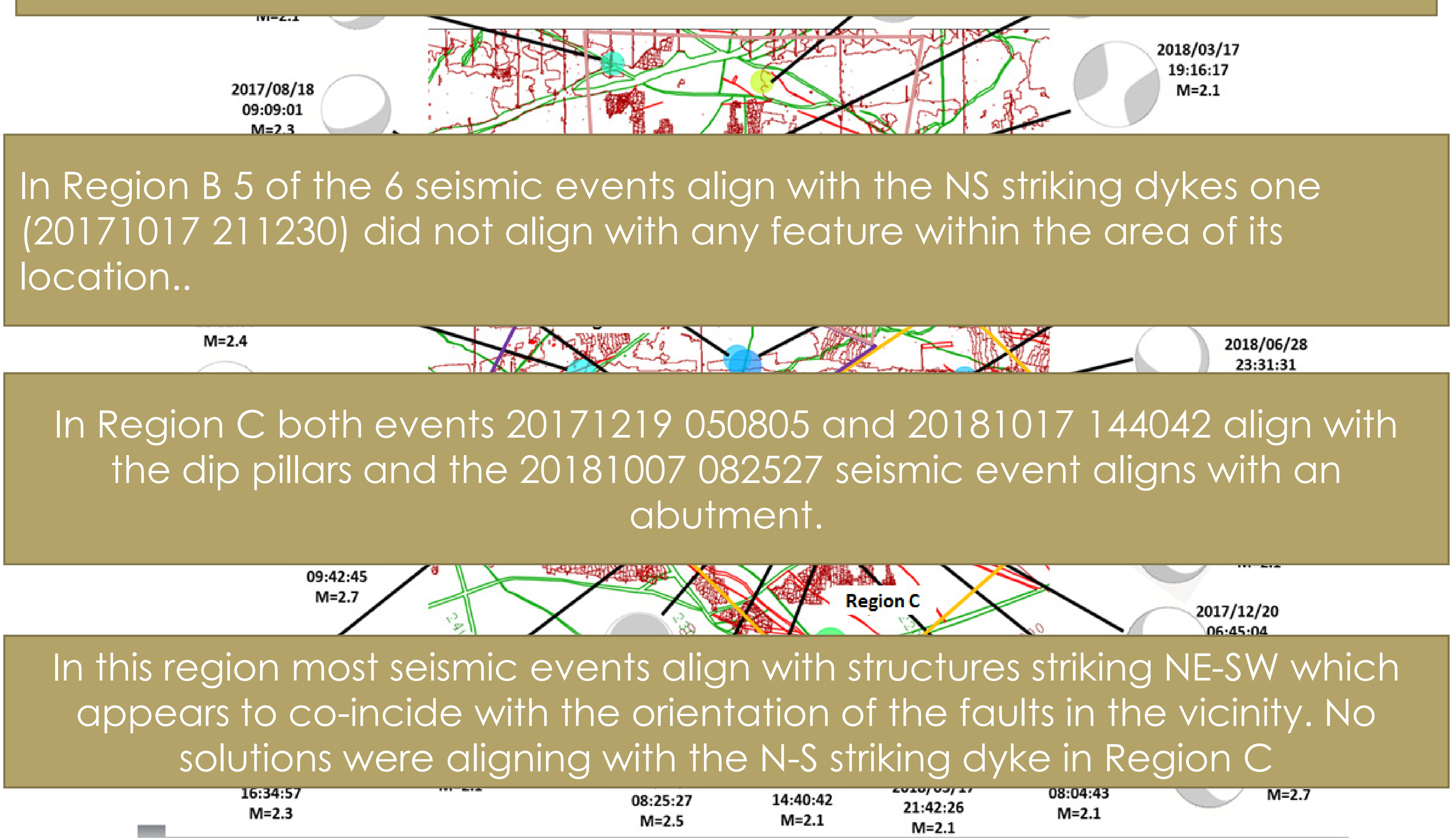
| Event ID | Local Magnitude ($M_L$) | DEV % | ISO % | Fault-Plane Solution 1 (degrees) Strike | Dip | Rake | Fault-Plane Solution 2 (degrees) Strike | Dip | Rake |
|---|---|---|---|---|---|---|---|---|---|
| 20181017 144042 | 2.1 | 91.7 | 8.3 | 126 | 53 | -107 | 333 | 40 | -68 |
| 20171219 050805 | 2.1 | 89.2 | 10.8 | 139 | 84 | -117 | 38 | 27 | -12 |
| 20180317 191617 | 2.1 | 82.4 | 17.6 | 115 | 86 | -174 | 25 | 84 | -4 |
| 20180113 023808 | 2.1 | 79.1 | 20.9 | 10 | 60 | -128 | 247 | 47 | -44 |
| 20181119 121437 | 2.1 | 74.1 | 25.9 | 90 | 19 | 177 | 184 | 89 | 71 |
| 20180628 233131 | 2.1 | 73.2 | 26.8 | 317 | 43 | -42 | 81 | 63 | -124 |
| 20180129 004428 | 2.1 | 72.8 | 27.2 | 310 | 25 | -74 | 113 | 66 | -97 |
| 20171027 080443 | 2.1 | 72.4 | 27.6 | 247 | 47 | -16 | 349 | 78 | -136 |
| 20171220 064504 | 2.1 | 55.2 | 44.8 | 133 | 68 | -112 | 1 | 30 | -46 |
| 20170729 202255 | 2.2 | 74.2 | 25.8 | 354 | 32 | -33 | 114 | 73 | -117 |
| 20171214 050211 | 2.2 | 63.6 | 36.4 | 18 | 26 | -19 | 125 | 82 | -115 |
| 20180522 003124 | 2.2 | 60.3 | 39.7 | 66 | 14 | 123 | 213 | 78 | 82 |
| 20170818 090901 | 2.3 | 94.8 | 5.2 | 236 | 23 | -64 | 28 | 69 | -101 |
| 20180127 184558 | 2.3 | 82.8 | 17.2 | 116 | 50 | 68 | 327 | 45 | 113 |
| 20170822 105230 | 2.3 | 74.9 | 25.1 | 318 | 87 | 135 | 51 | 45 | 5 |
| 20180217 163457 | 2.3 | 60.7 | 39.3 | 317 | 84 | 84 | 180 | 9 | 133 |
| 20171017 211230 | 2.4 | 76.3 | 23.7 | 157 | 63 | -132 | 41 | 48 | -37 |
| 20181007 082527 | 2.5 | 88.6 | 11.4 | 329 | 33 | -39 | 93 | 70 | -117 |
| 20170715 162357 | 2.6 | 95.3 | 4.7 | 13 | 26 | -41 | 141 | 73 | -110 |
| 20170307 164126 | 2.6 | 88.5 | 11.5 | 354 | 42 | -32 | 109 | 69 | -127 |
| 20171023 094245 | 2.7 | 71.8 | 28.2 | 119 | 51 | -171 | 23 | 83 | -39 |
| 20180317 214226 | 2.7 | 66.0 | 34.0 | 343 | 27 | -29 | 100 | 77 | -114 |
| 20180628 181056 | 2.7 | 45.3 | 54.7 | 307 | 18 | -92 | 129 | 72 | -89 |

Region A has indicated some alignment to two events close to nearby dykes (20180113 023808 and 20181119 121437).

In Region B 5 of the 6 seismic events align with the NS striking dykes one (20171017 211230) did not align with any feature within the area of its location..

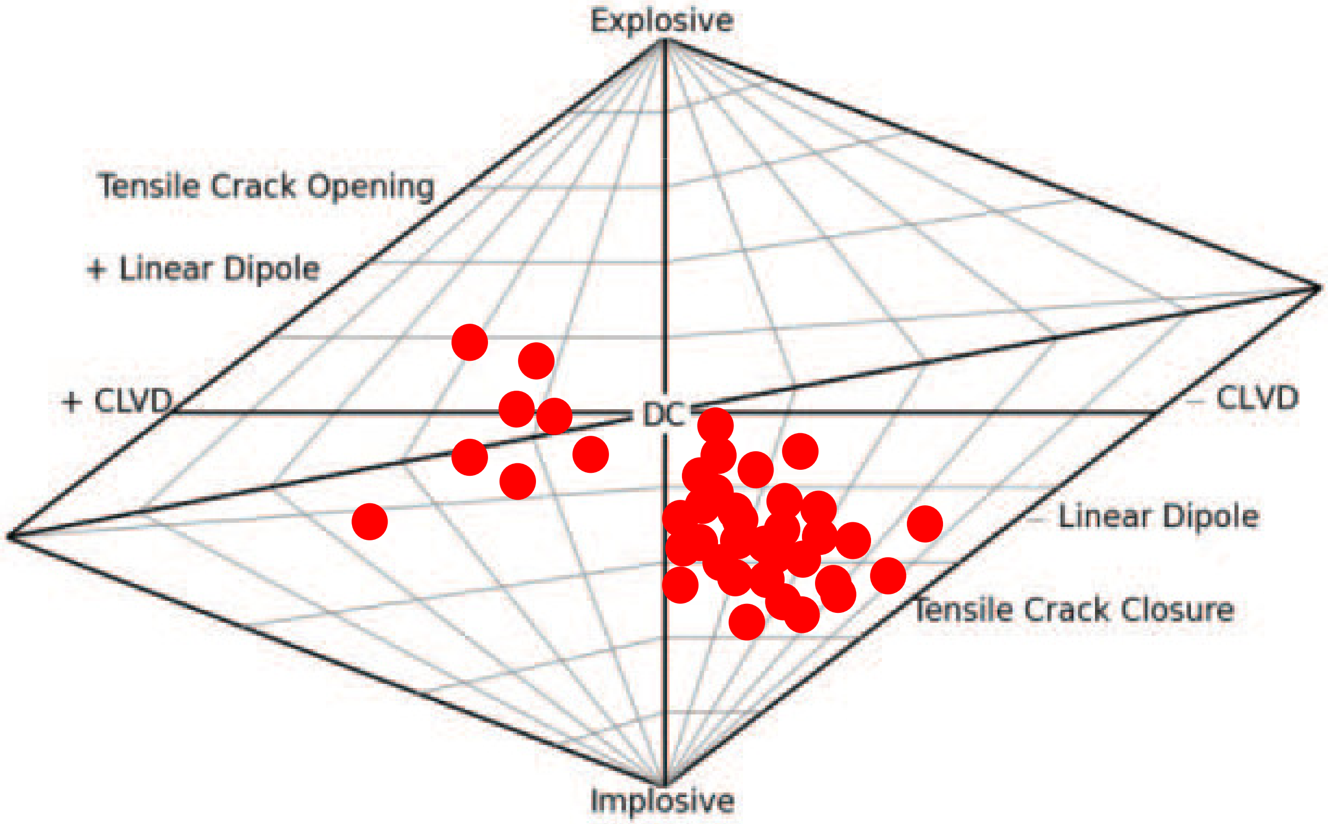
In Region C both events 20171219 050805 and 20181017 144042 align with the dip pillars and the 20181007 082527 seismic event aligns with an abutment.

In this region most seismic events align with structures striking NE-SW which appears to co-incide with the orientation of the faults in the vicinity. No solutions were aligning with the N-S striking dyke in Region C



# Hudson-Diagram (source type)

- Kloof Data indicates more implosive source type indicating the Tensile crack closure within the rockmass

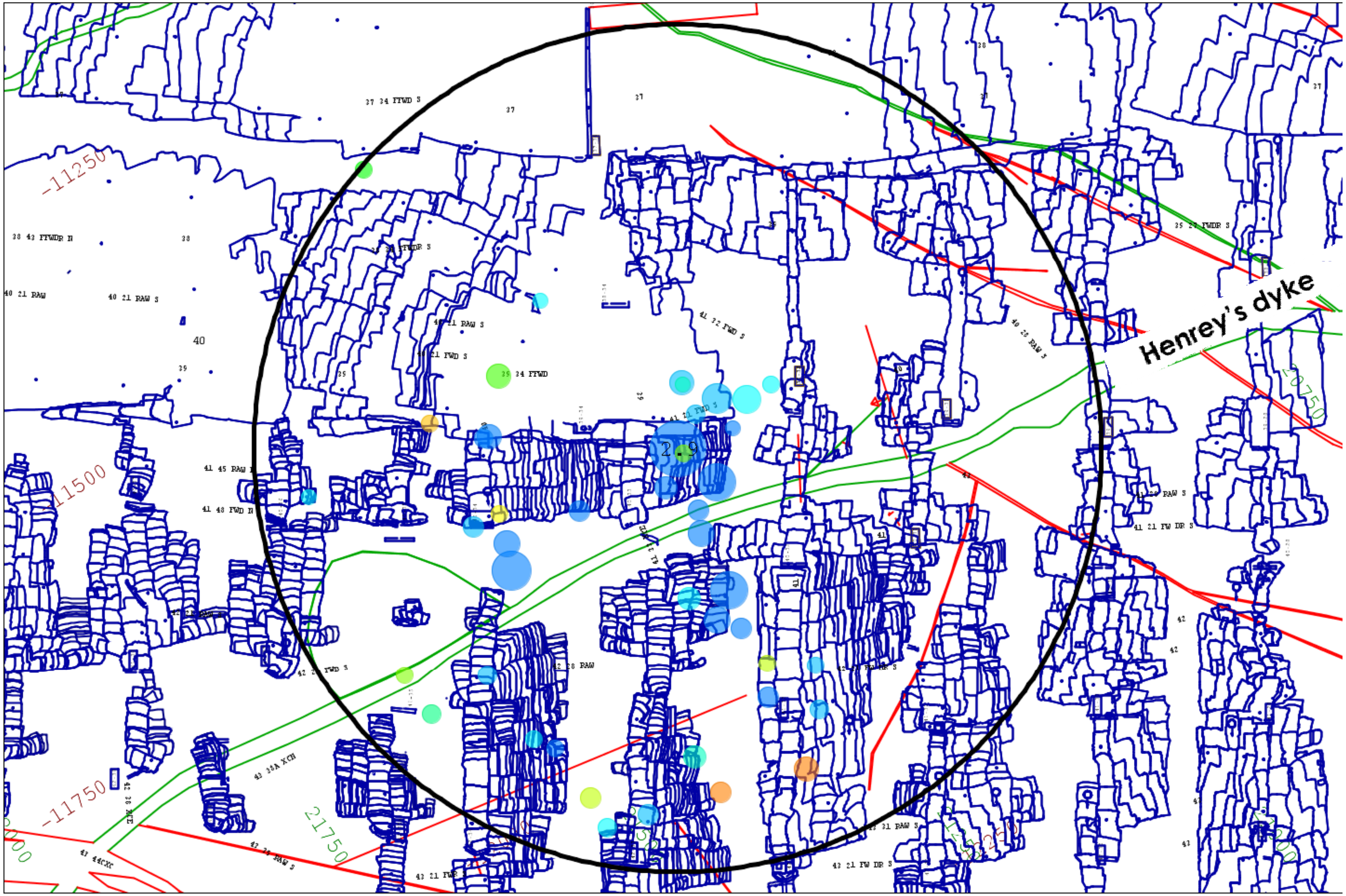


## conclusion:

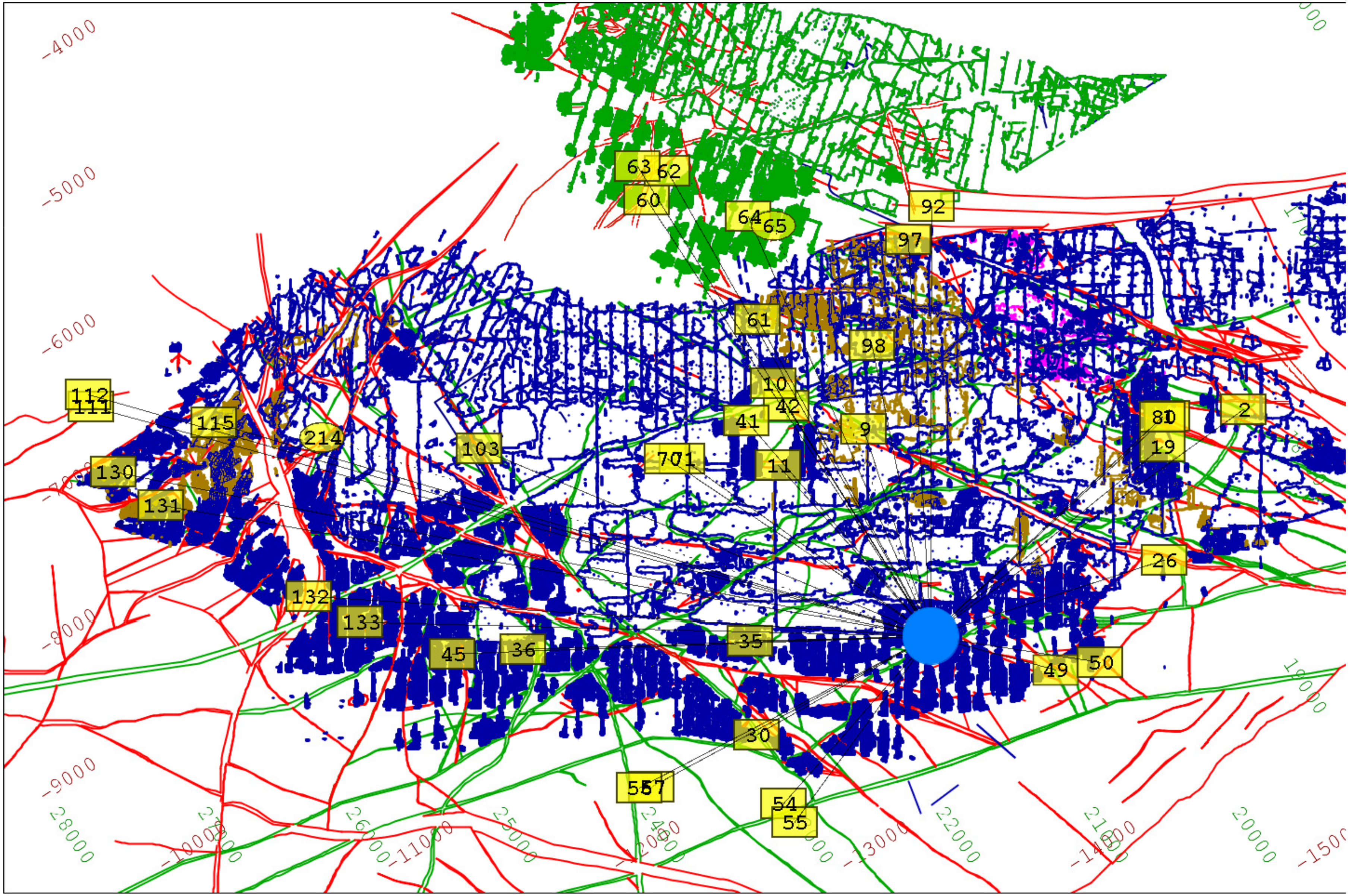
- The data has shown that the implosive component dominates the source mechanism of the majority of the events.
- Moment Tensor inversion indicates that the dominating source mechanisms is of the Shear type and show near vertical and near horizontal nodal planes.

# CASE STUDY : Seismic Information Pertaining to the M=2.9 on Henrey’s dyke

# 1Day in R=400m



# M=2.9 and the Associated triggered sites



# Henrey's Dyke- Moderate to High Seismic Potential

| Name Of Structure | Dip | Reef plane LOI (Line of Intersection) Strike | Type / infilling / width / thickness / etc (down-throw in brackets) | N events (>=$M_L$1.5) Within ~100m of structure | P($M_L$2.0) In 30 days | $M_{max}$ Recorded / expected | Relative seismic potential (high = top 1/3 Low = bttm 1/3 |
|---|---|---|---|---|---|---|---|
| Babydyke1 | - | - | - | 98 | 15% | 2.7/3.0 | High |
| Jock's Extension | 85 | NE-SW | Mylonite (35m) | 59 | 8% | 3.0/3.2 | High |
| Fault and dyke zone | - | - | - | 19 | 2% | 1.8/2.1 | Low |
| Frans dyke | - | NE-SW | 90m | 43 | 15% | 3.2/3.5 | High |
| Henrey's dyke | 80 | N-S | 4m | 59 | 5% | 2.6/2.9 | Moderate |
| Phantom dyke | - | N-S | 30m | 4 | 1% | 1.8/2.1 | Low |
| Running dyke | 80 | N-S | No throw | 121 | 15% | 3.2/3.5 | High |
| 37-15 fault | 80 | NE-SW | Mylonite (20m) | 12 | 5% | 3.2/3.5 | Moderate |
| Libanon dyke | | N-S | No throw | 22 | 4% | 2.5/2.8 | Moderate |

Henrey's dyke recorded the highest $M_{max}$ seismic event

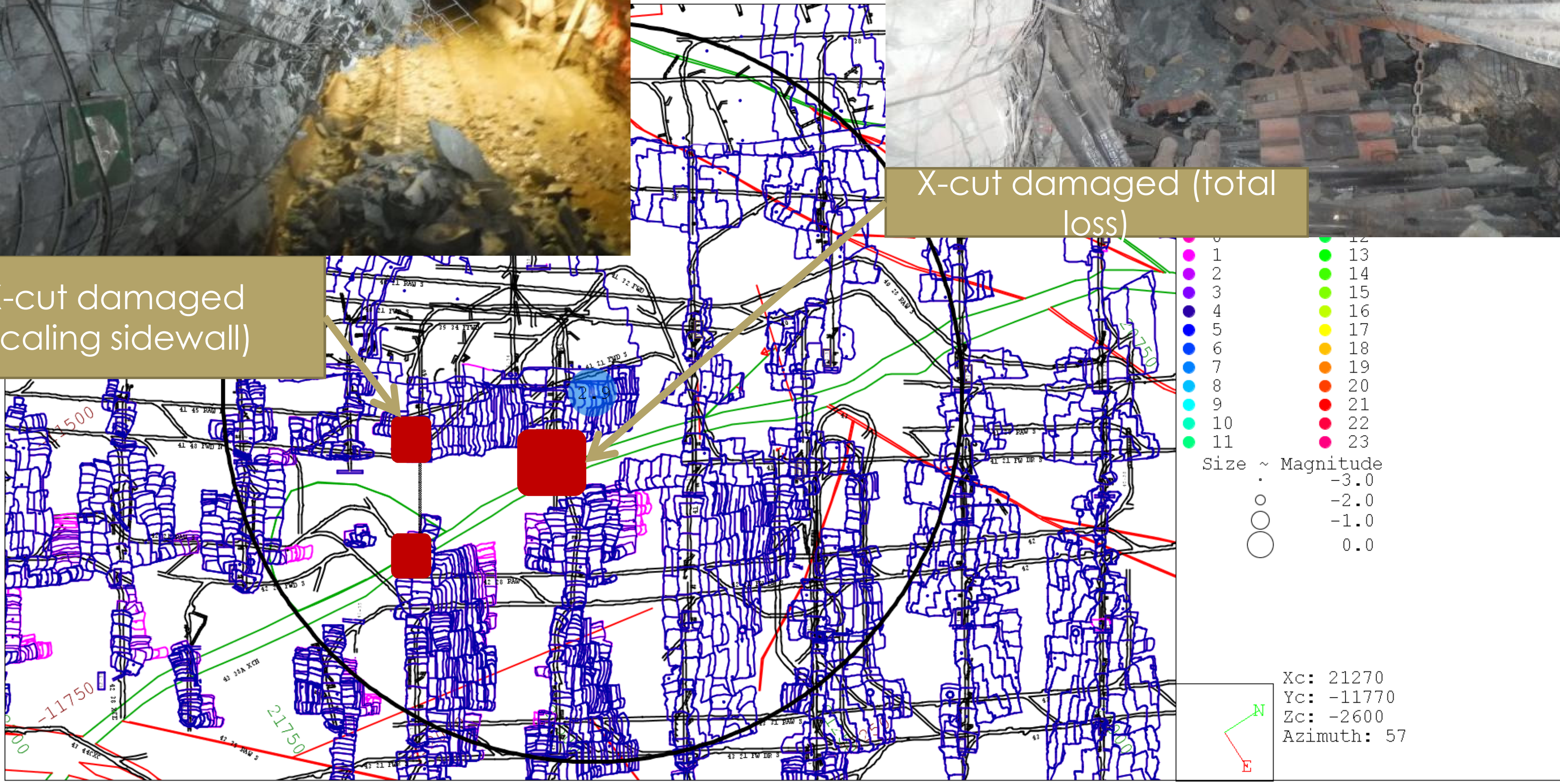
# Fault Plane Solution(FPS):


FPS
Burst type event

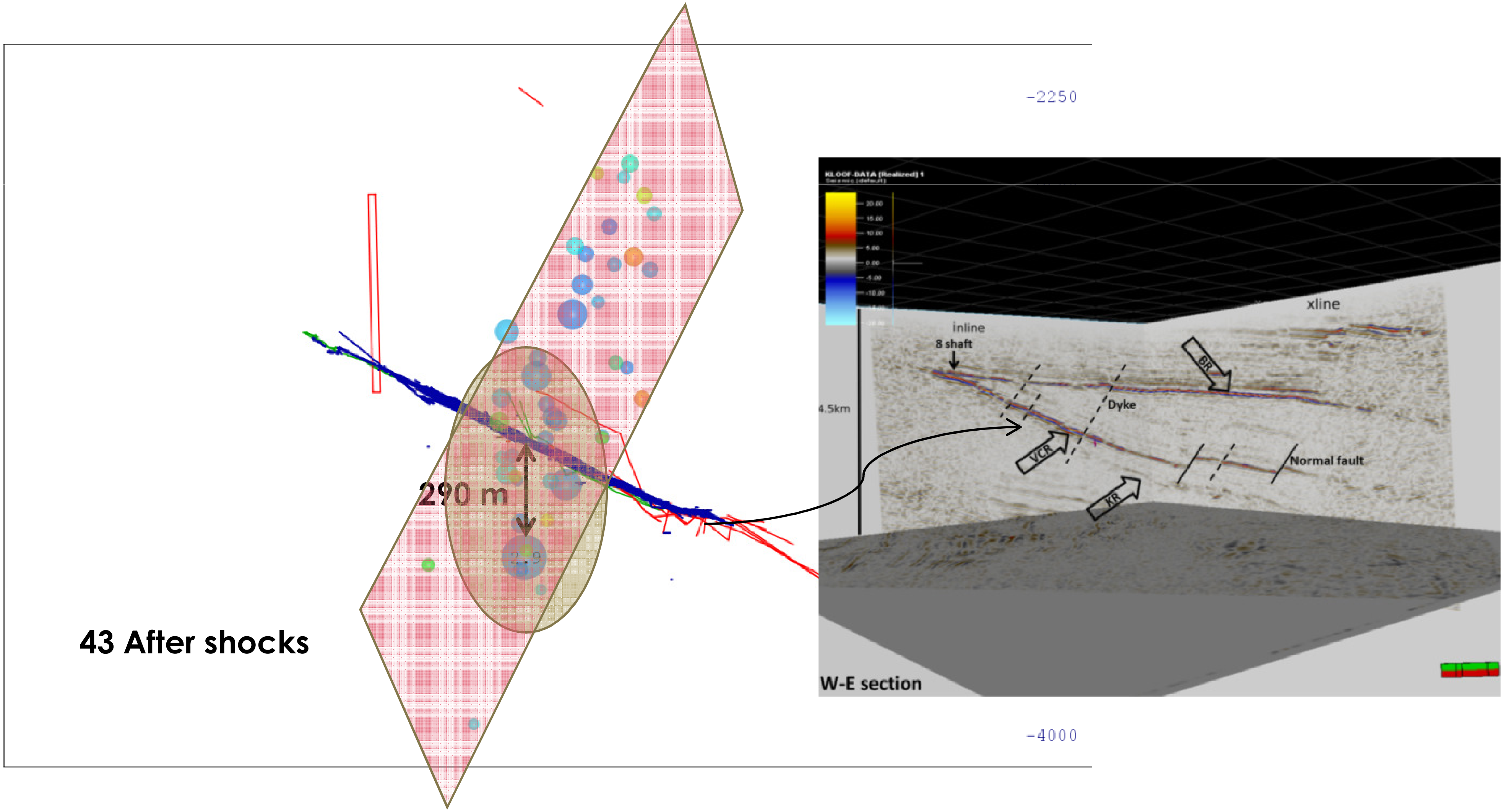
**Aligns with the North-South (strike) and dipping at $80^0$(West)**

X-cut damaged (total loss)

X-cut damaged (scaling sidewall)



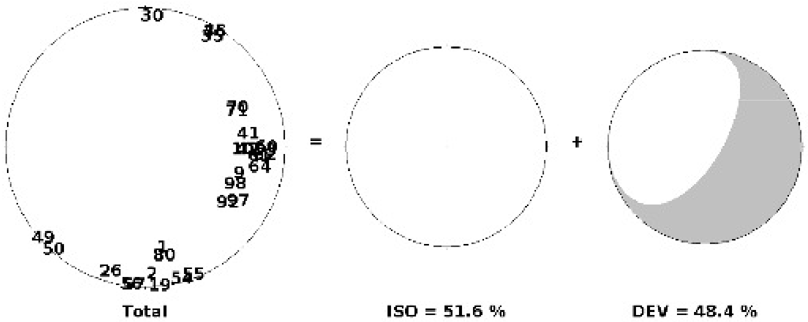
# Section View- Foot wall seismic event (1day)



# Moment Tensor Solution

$$\begin{bmatrix} -0.454 & 0.151 & -0.207 \\ 0.151 & -0.461 & 0.321 \\ -0.207 & 0.321 & -0.633 \end{bmatrix} \times 1.099 \times 10^{14}\ \mathrm{P[m^3]} = \begin{bmatrix} -0.15 & -0.16 & -0.43 \\ -0.16 & 0.24 & -0.32 \\ -0.43 & -0.32 & 0.50 \end{bmatrix} \times 1.072 \times 10^{3}$$

**Decomposition**




**Principal Axes**

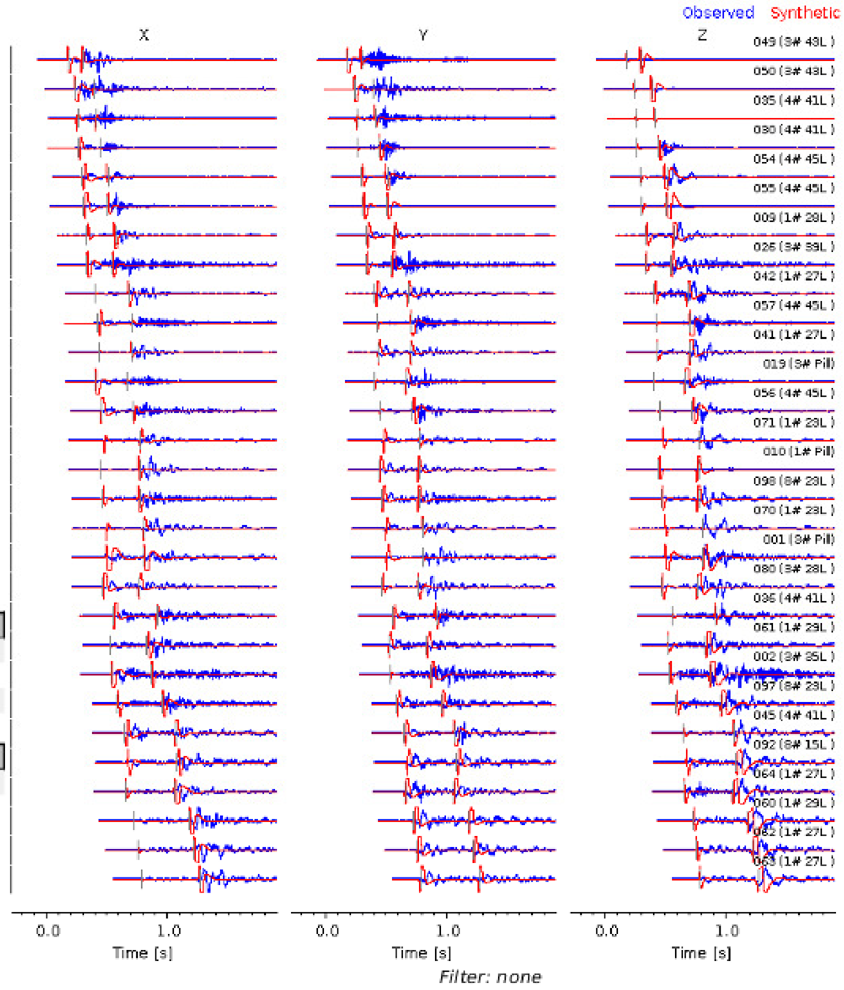
| Axis | Azimuth [deg] | Plunge [deg] |
|---|---|---|
| T | 93 | 38 |
| P | 308 | 46 |
| B | 198 | 18 |

**Nodal Planes**

| Num | Strike [deg] | Dip [deg] | Rake [deg] | Comment |
|---|---|---|---|---|
| 1 | 19 | 86 | -72 | Normal slip |
| 2 | 122 | 18 | -167 | Right lateral strike slip |

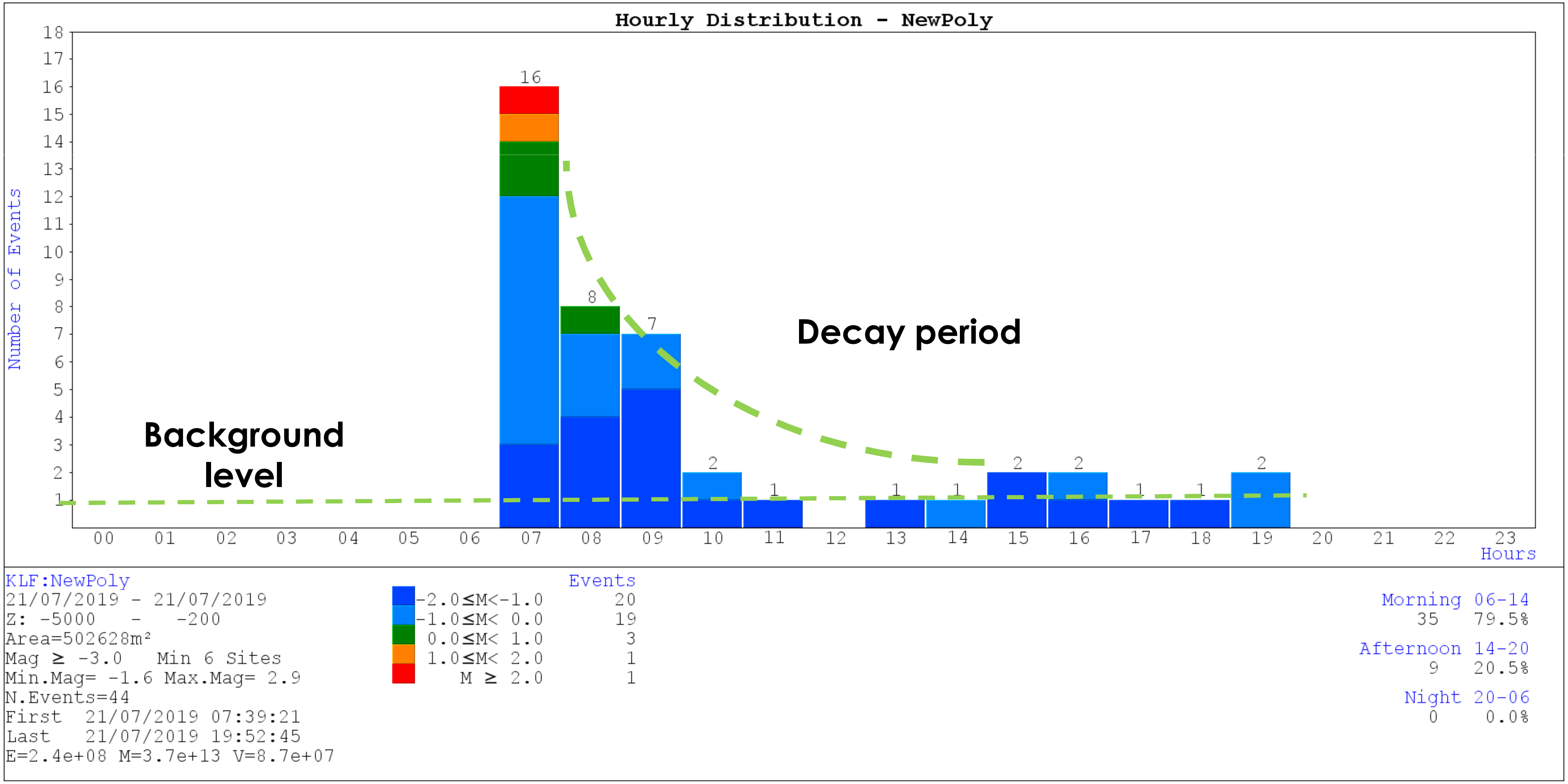
Non-DC Parameters: T = 0.75 k = -0.52

Inversion misfit [0..1] : 0.33



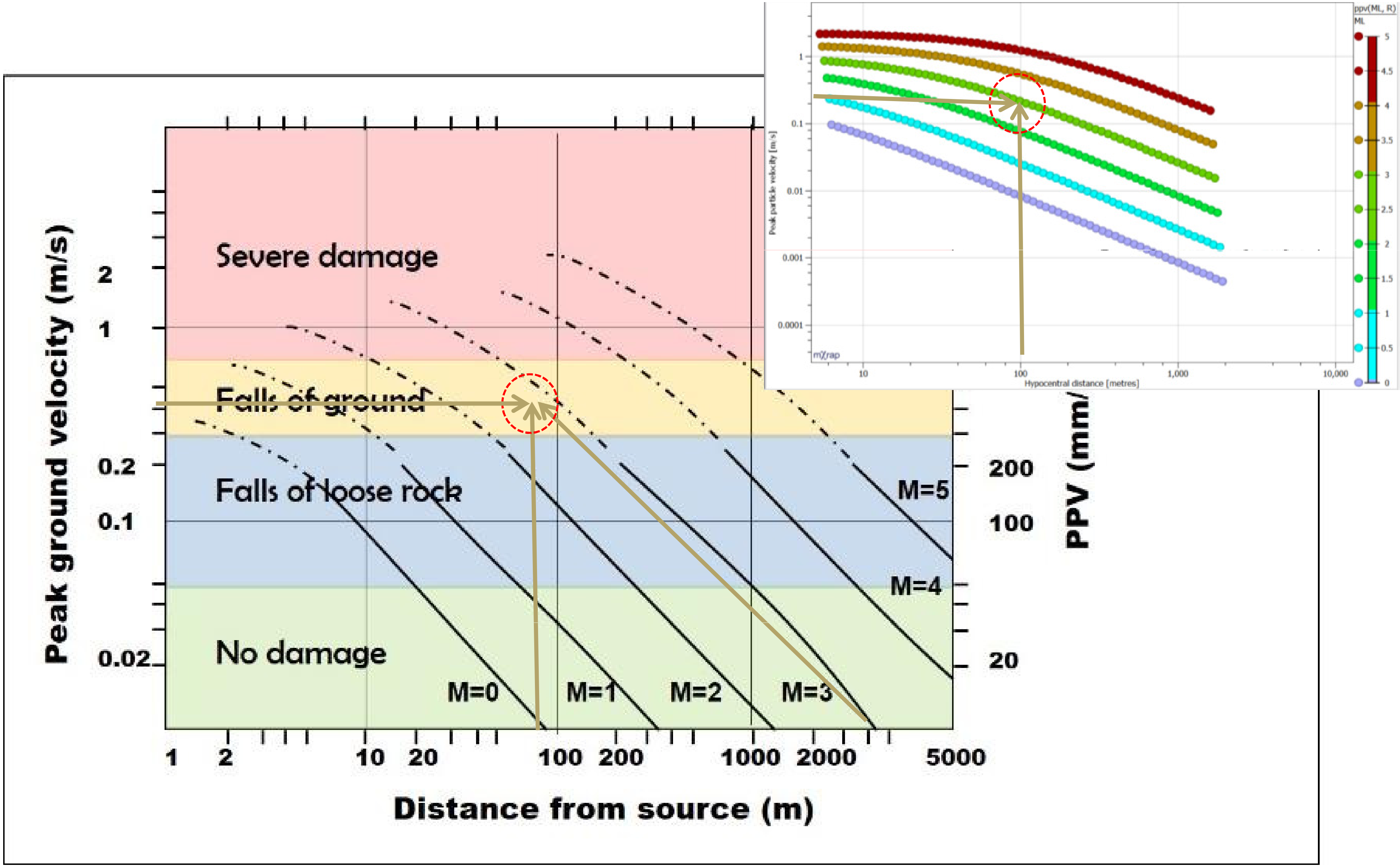

Implosive source type

# Seismicity: Diurnal Distributions (R=400m)



# PPV-Magnitude–Distance Plot & Expected damage.

Sibanye Stillwater
we are one



# Summary on the event

- The M= 2.9 seismic event is located 65 m away from the **North-South** trending Henrey's dyke .
- The induced seismic event is likely to be associated with the geological feature in the vicinity of its source location trending North-South .
- It is likely to be the burst on Henrey's dyke according to the Energy ratio (Es/Ep =4.4) and location error margin
- FPS indicates plane 1 correlates with the dip of the dyke.
- The PPV plot for the M=2.9 seismic event was 0.7- 1.0 m/s at the 41level x-cut (total lost) and 43 level x-cut, which correlates with the damages within the source radius of the seismic event.
- The expected damage for these values of PPVs coincided with the oberved damages underground.
- Henrey's dyke is transitioning from a quite stage (less aseismic) to being seismically active dyke.