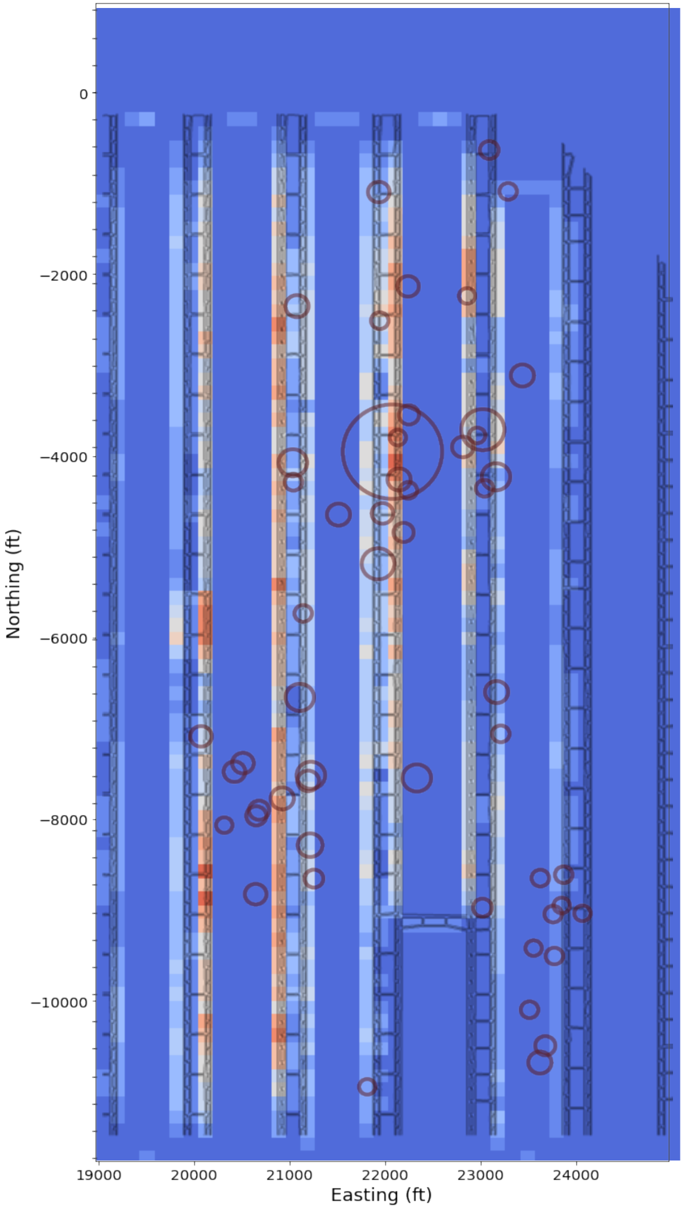

Seismic potential maps for a deep longwall mine

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Pittsburgh Mining Research Division

Background

- **Problem statements:**
  - Massive seismic events are known to pose a risk to the safety of miners and the stability of workings

- **Concept:**
  - Seismic monitoring is becoming a common mining instrumentation practice used to record millions of events, containing data on a rock state, but their interpretation is challenging
  - Modern numerical techniques account for complex effects of structural elements and mining processes, but measurement data are limited
  - The advantage of one tool may be the shortcoming of another

- **Long-term objective: Integrating seismic monitoring with geomechanical analyses**
  - Methodologies to generate seismic potential maps for longwall mines.

- **Approach:**
  - Seismic events in conventional geomechanical models cannot be identified
  - One approach is to monitor energy components in a model

- **Case study:**
  - A longwall mine in Virginia with history of mining-induced seismicity
  - Three anomalous events 3.7 M_L, 2.5 M_L, and 1.9 M_L occurred in July 2016

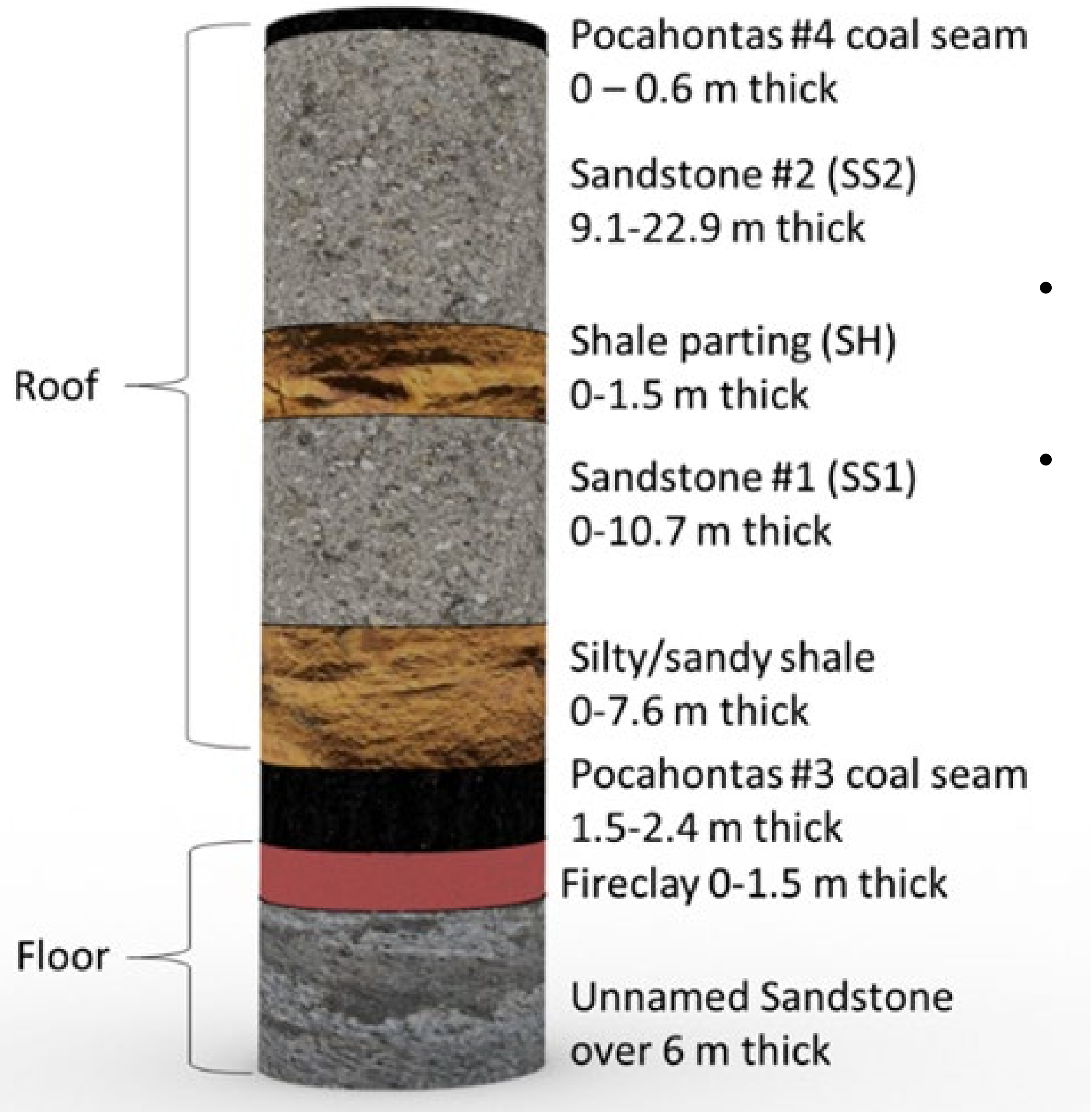
Case study: 2.5 M_L event - July 13, 2016

Case study: 3.7 M_L event - July 18, 2016

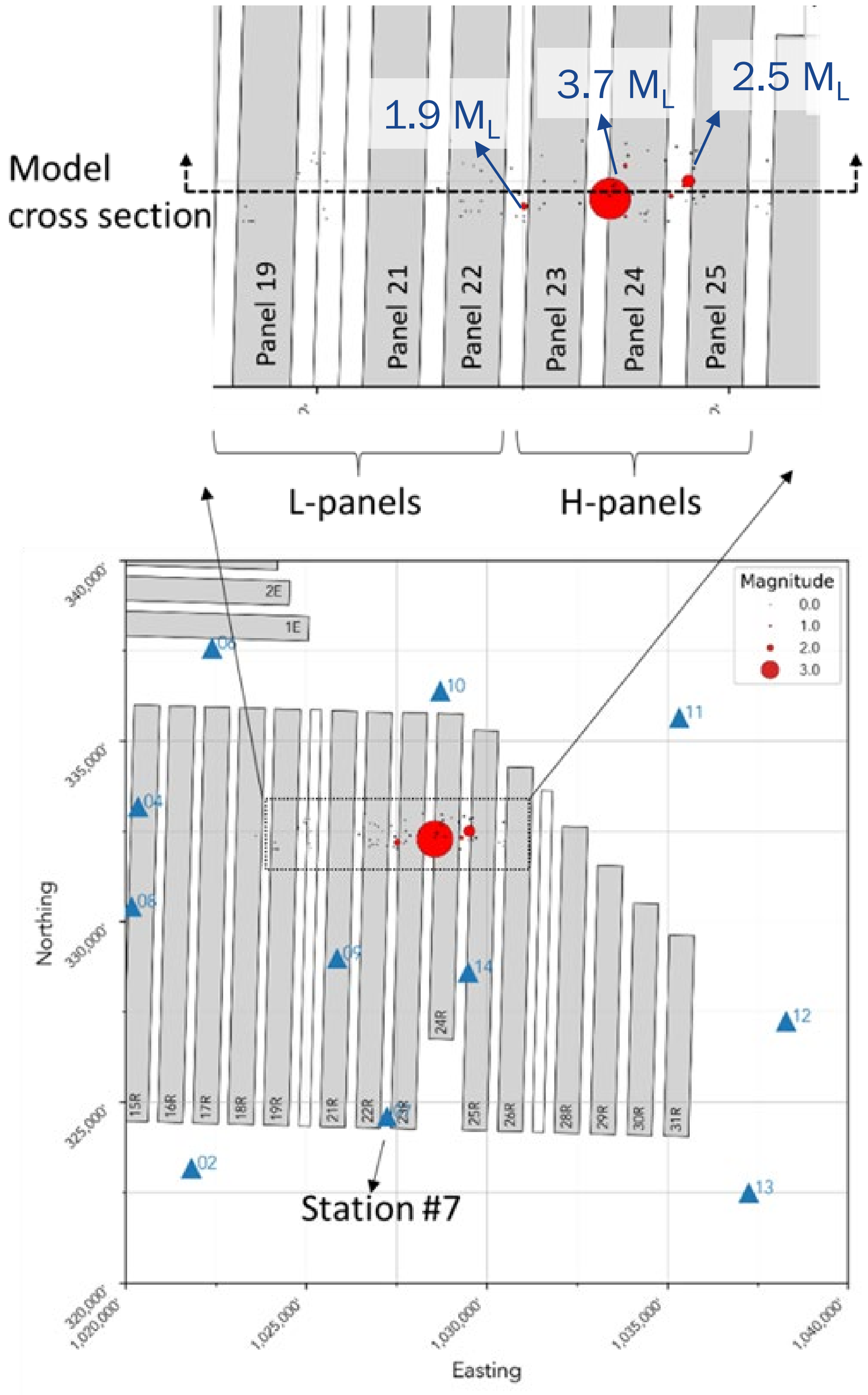
Case study: 1.9 M_L event - July 20, 2016

Methodologies

Collect geologic, seismic, and mining data

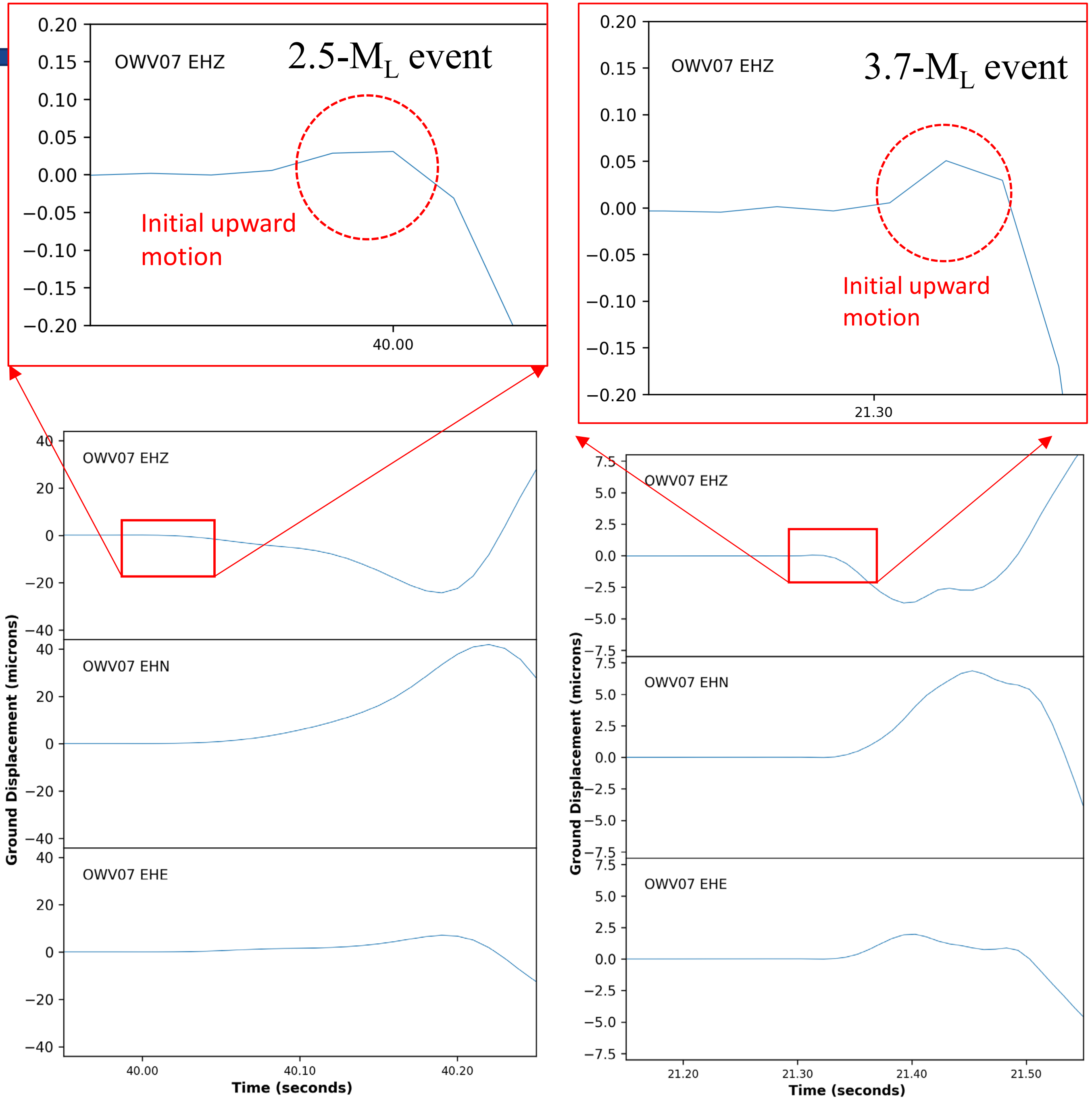


- Select areas with low-seismic activities
- Select areas with high-seismic activities



Methodologies: Mechanisms

- Most of events at the mine exhibit dilatational first motions at surface stations,
- Source is essentially isotropic and consistent with a downward displacement of rock mass.
- Some events, mostly larger than 1 M_L, show a small compressional first motion
- This indicates a small seismic slip on a plane of failure occurring at its initiation time.
- This non-isotropic contribution to the energy release varies in size for different events but is typically small compared to the overall size of the event.

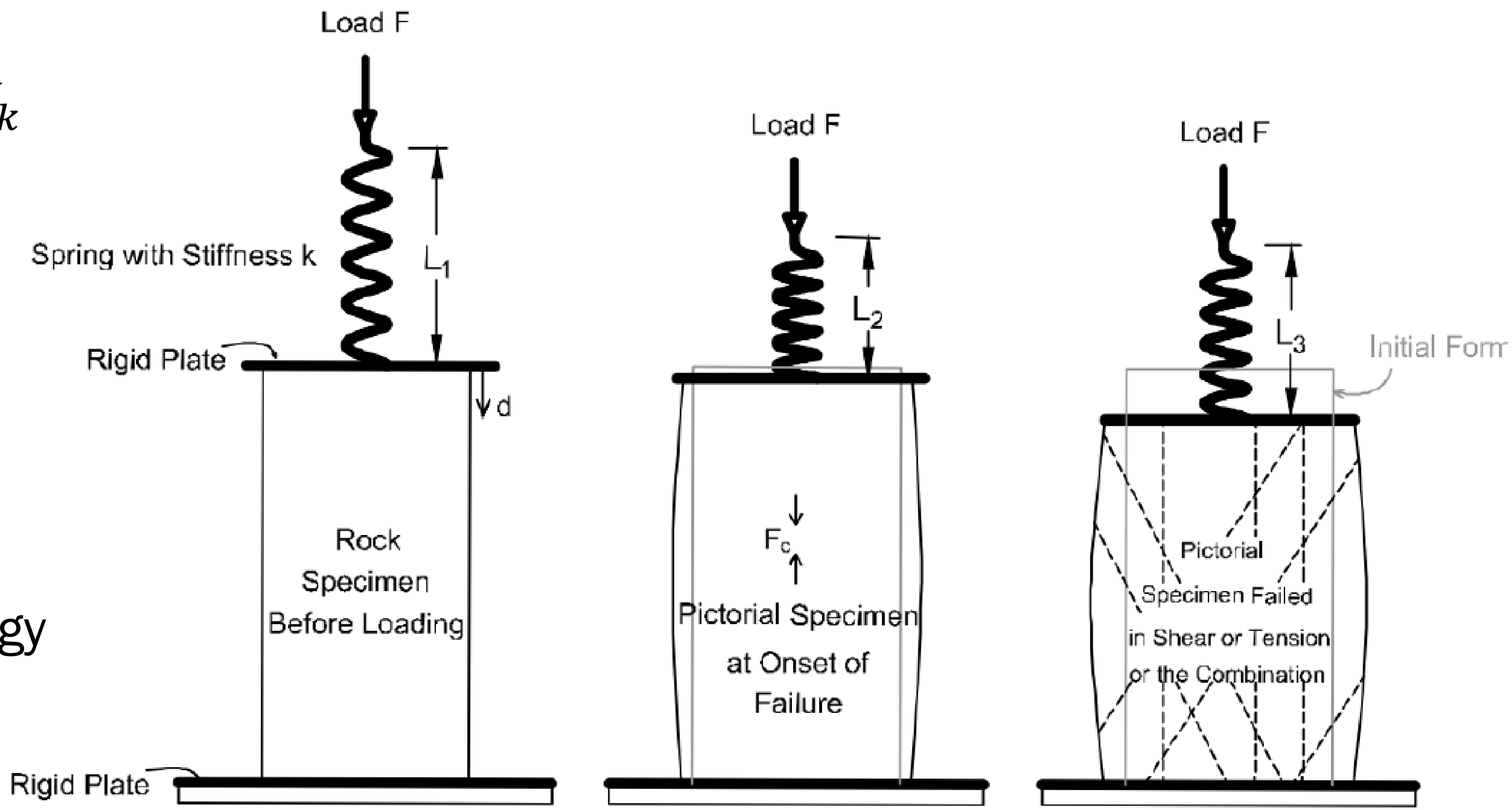


Methodologies: Seismicity in compressive failure

Energy released depends on the loading system's stiffness and rock's capability to absorb energy

$$W + U_i = W_p + U_r + W_k$$

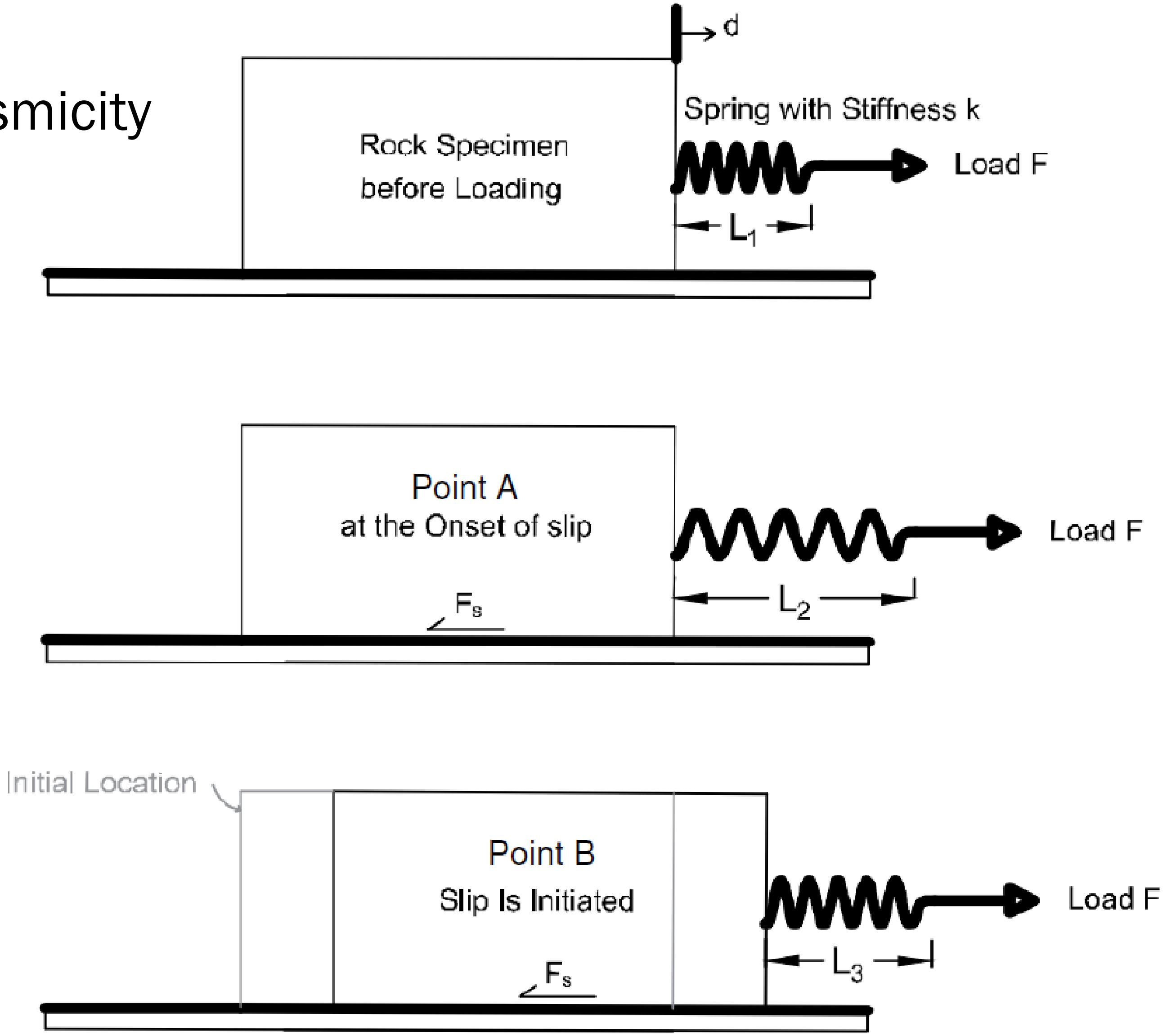
W : External work
U_i : Initial strain energy
W_p : Plastic work
U_r : Residual strain energy
W_k : Seismic energy



Methodologies: Seismicity in shear slip

Box-spring experiment shows how energy stored in a loading system can cause seismicity

$$W + U_i = W_p + U_r + W_k$$



W : External work

U_i : Initial strain energy

W_p : Plastic work

U_r : Residual strain energy

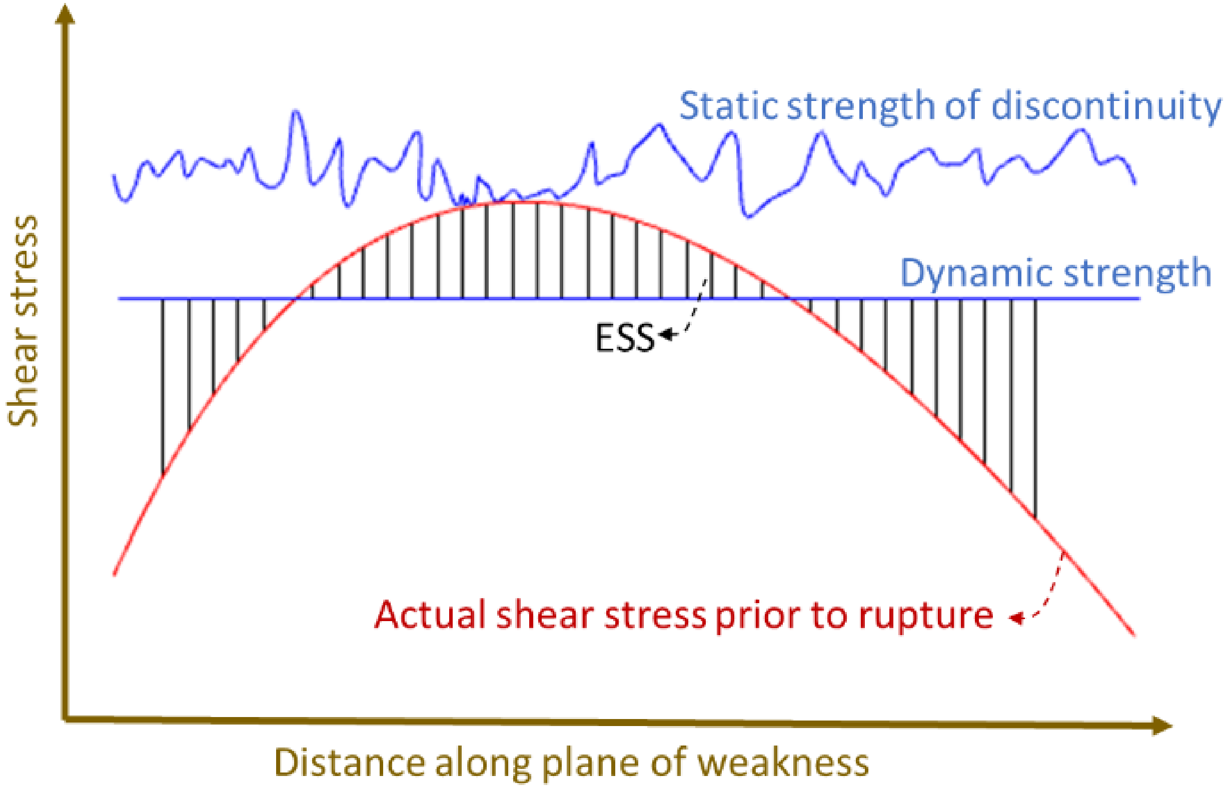
W_k : Seismic energy

Methodologies

	Compressive-type Events	Slip-type Events
Occurrence	Compressive Stress Concentration	Excess Shear Stress
Intensity	Strain Energy	Seismic Energy

Compressive Stress Concentration $\frac{(\sigma_1 - \sigma_3)}{UCS} > 0.7$ (Castro et al., 2012)

The change in the strain energy (Ui-Ur) and slip seismic energy (Wk) compared to the pre-mining state of the model is averaged over the seismogenic volume of rock



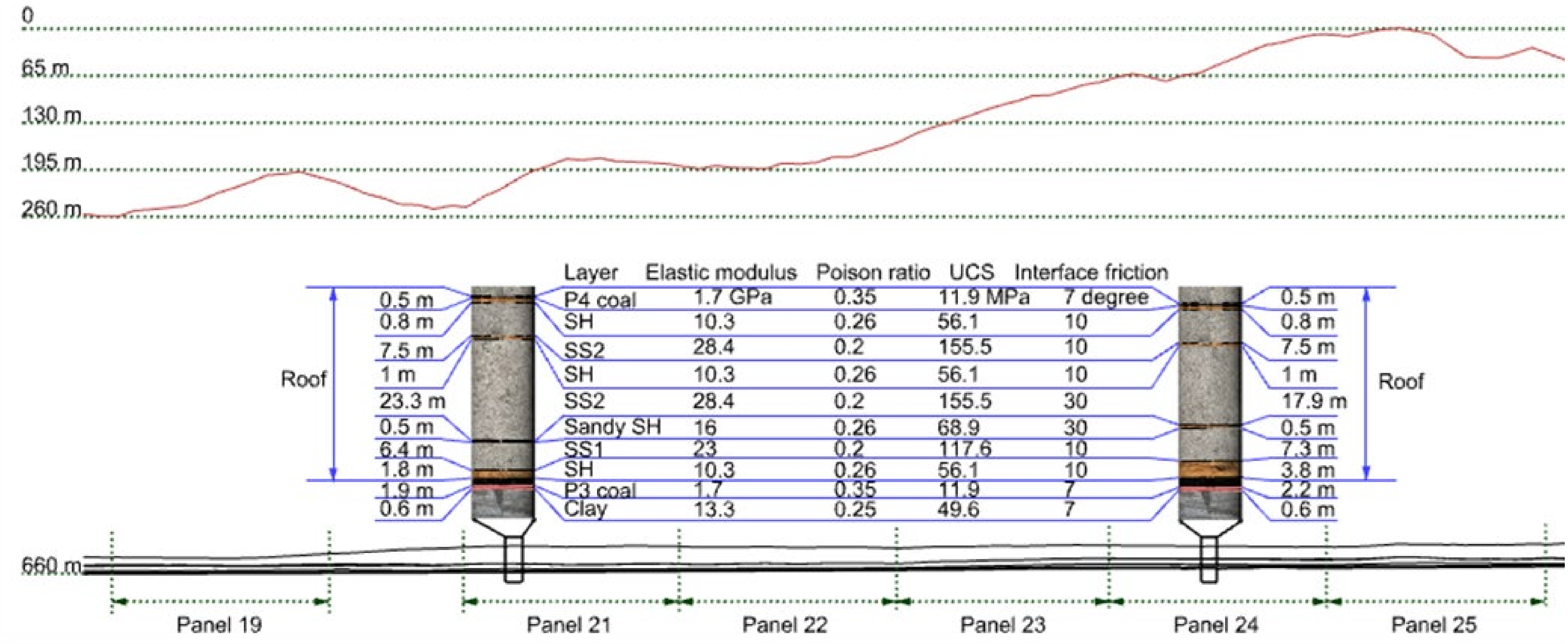
Shear Stress Concentration: Excess Shear Stress (ESS) > 5 MPa

ESS= shear stress prior to slip – dynamic shear strength

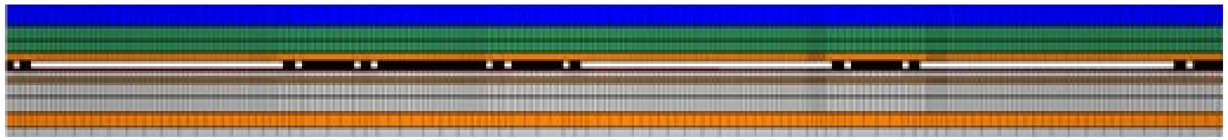
ESS >5MPa: Destructive seismic events are likely

$M_o = 2.25\, \tau_e\, a^2\, L$ $\quad W_k = \frac{M_o \tau_e}{2G}$ (Ryder, 1988)

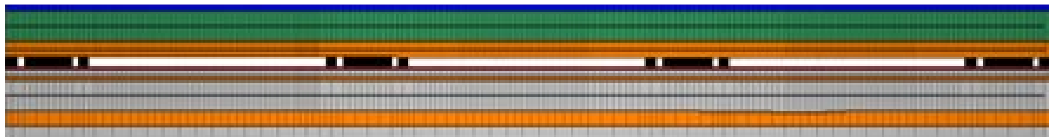
Methodologies: 2D Geomechanical model



L-panels in 3DEC model

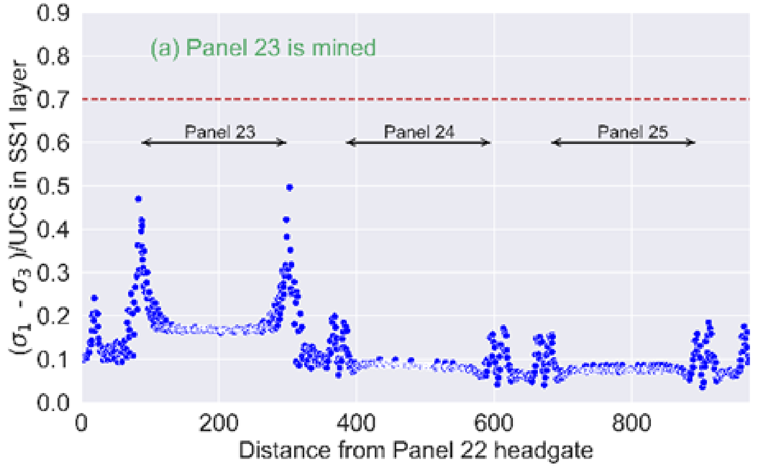


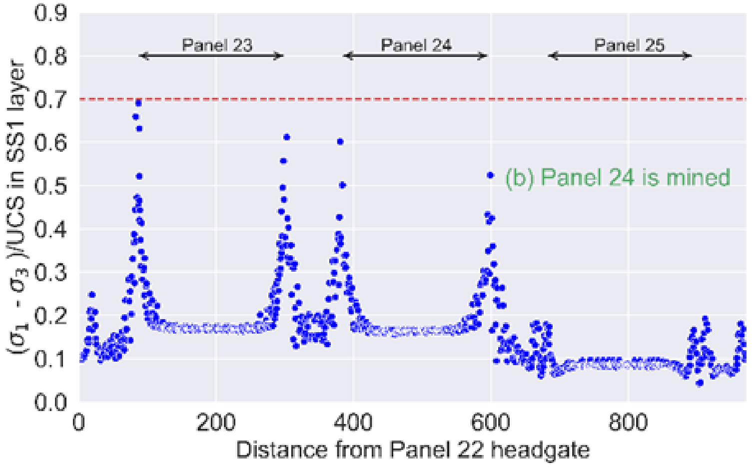
H-panels in 3DEC model

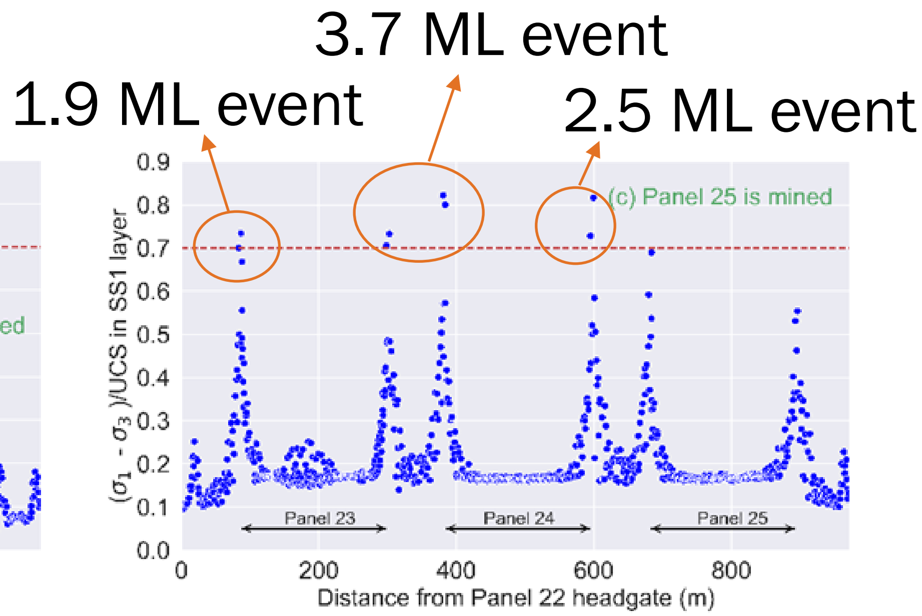


2D model results: Event occurrence in SS1 in H-Panels

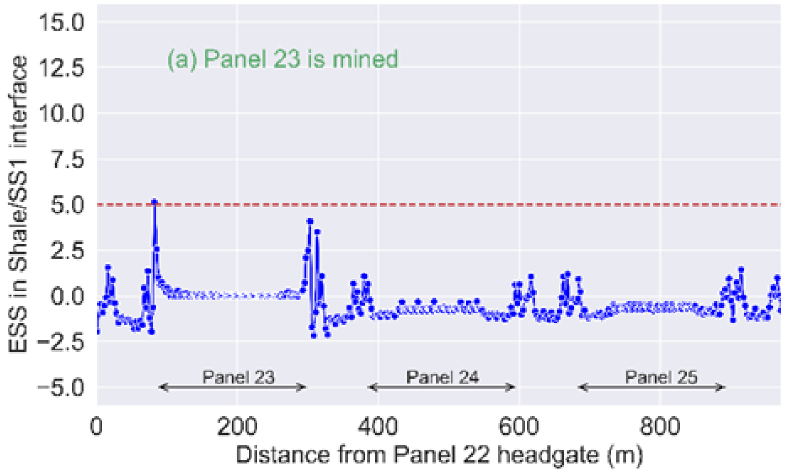
- **Compressive-type events: Occurrence**

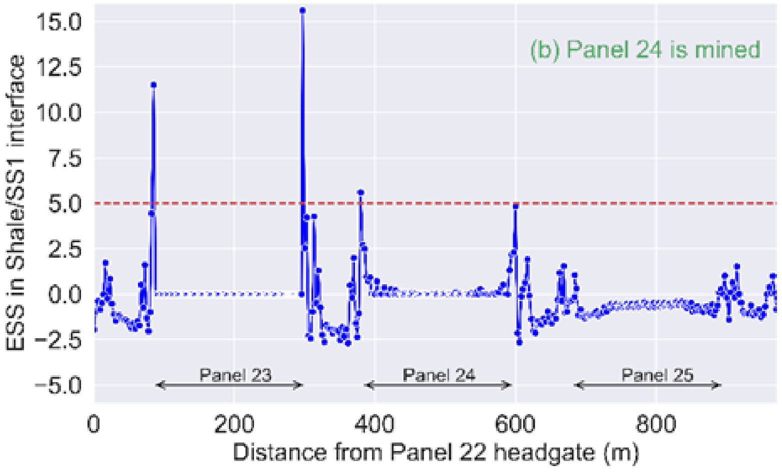


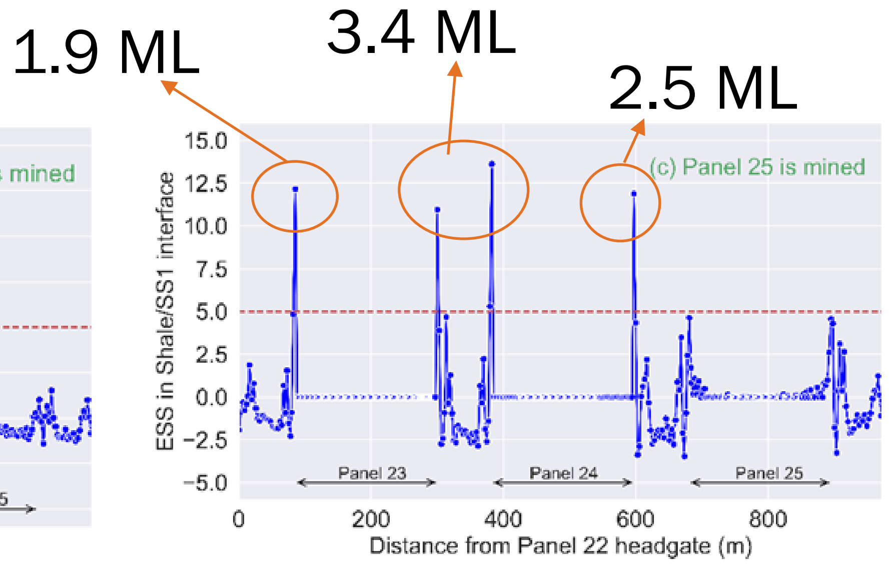




- **slip-type events: Occurrence**

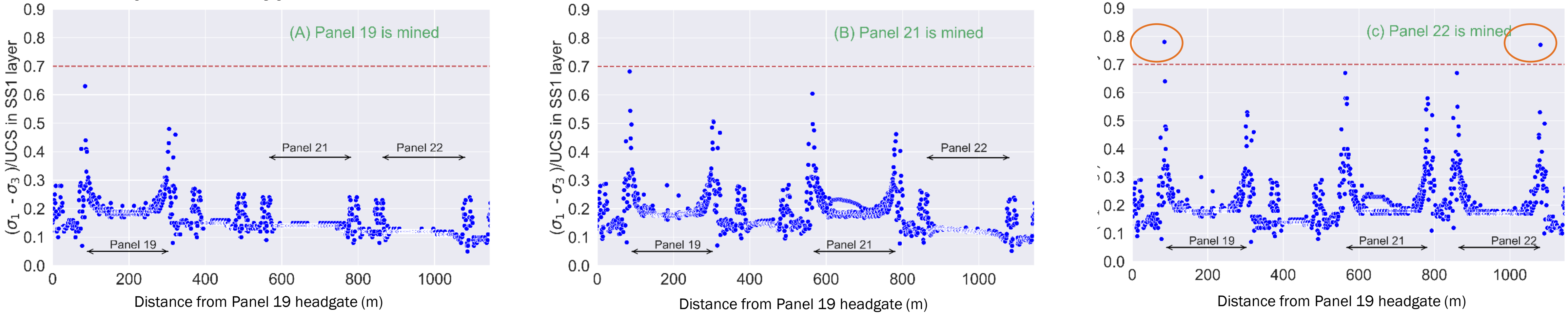




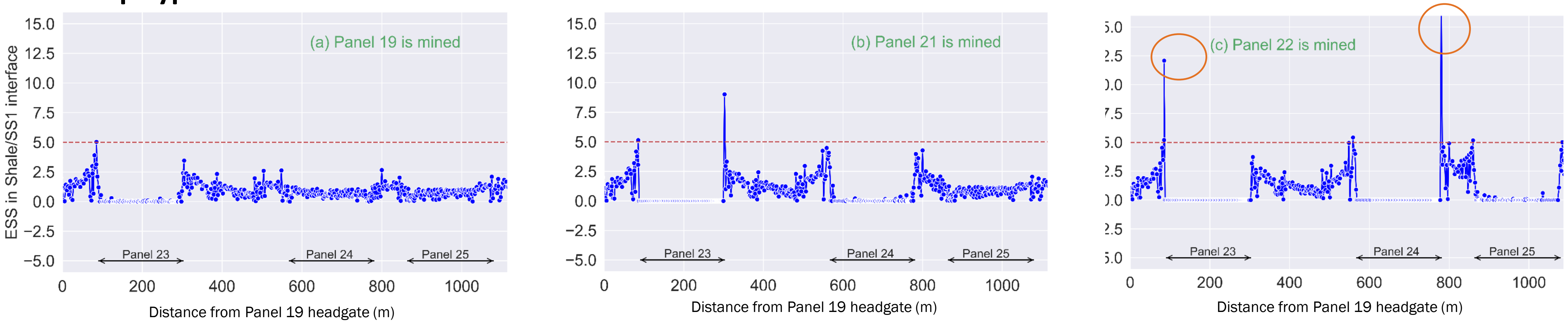


2D model results: Event occurrence in SS1 in L-Panels

- **Compressive-type events: Occurrence**



- **Slip-type events: Occurrence**



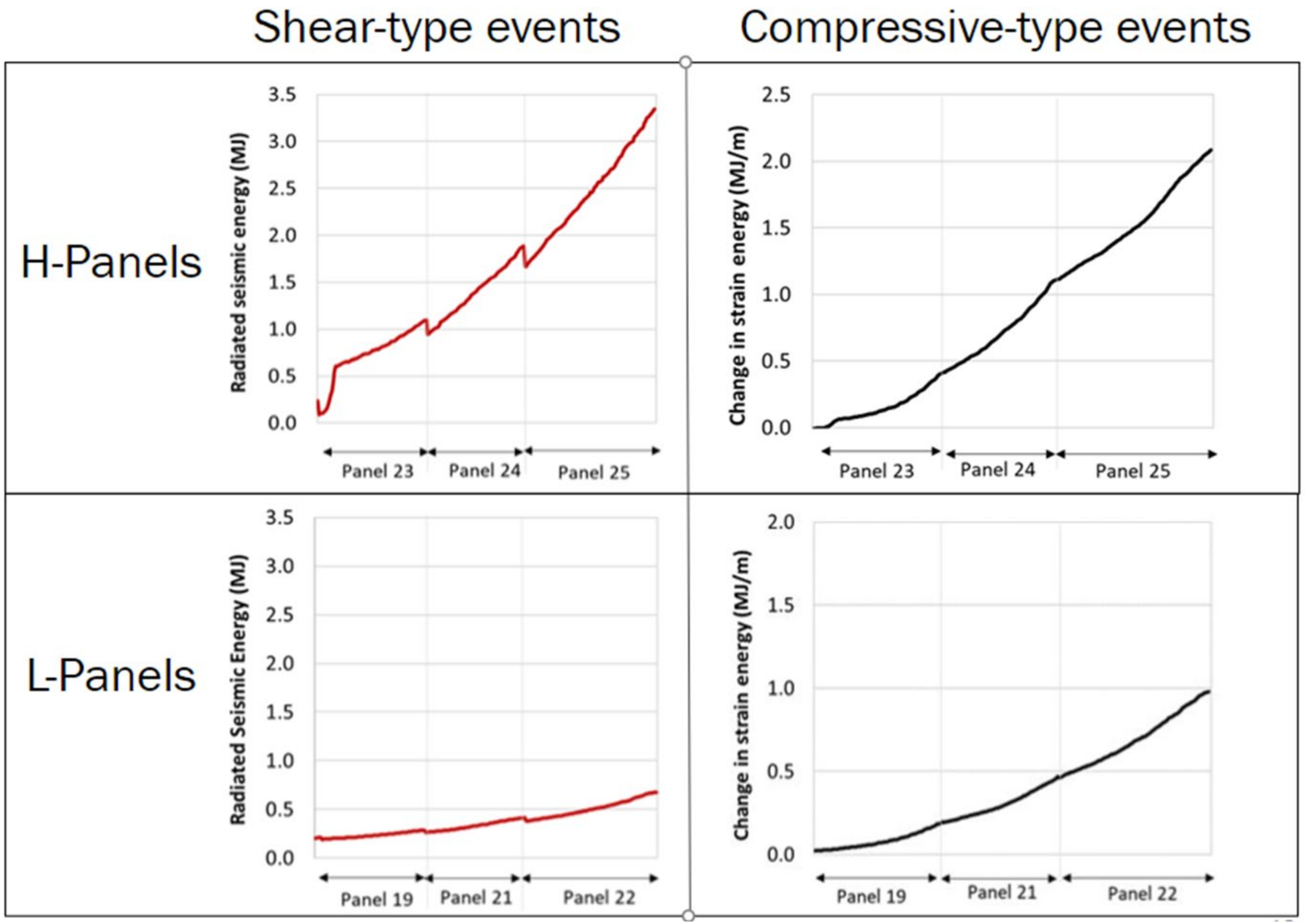
2D model results

- ✓ Confirmed the methodology for forecasting the approximate timing and location of potential events as observed in the mine

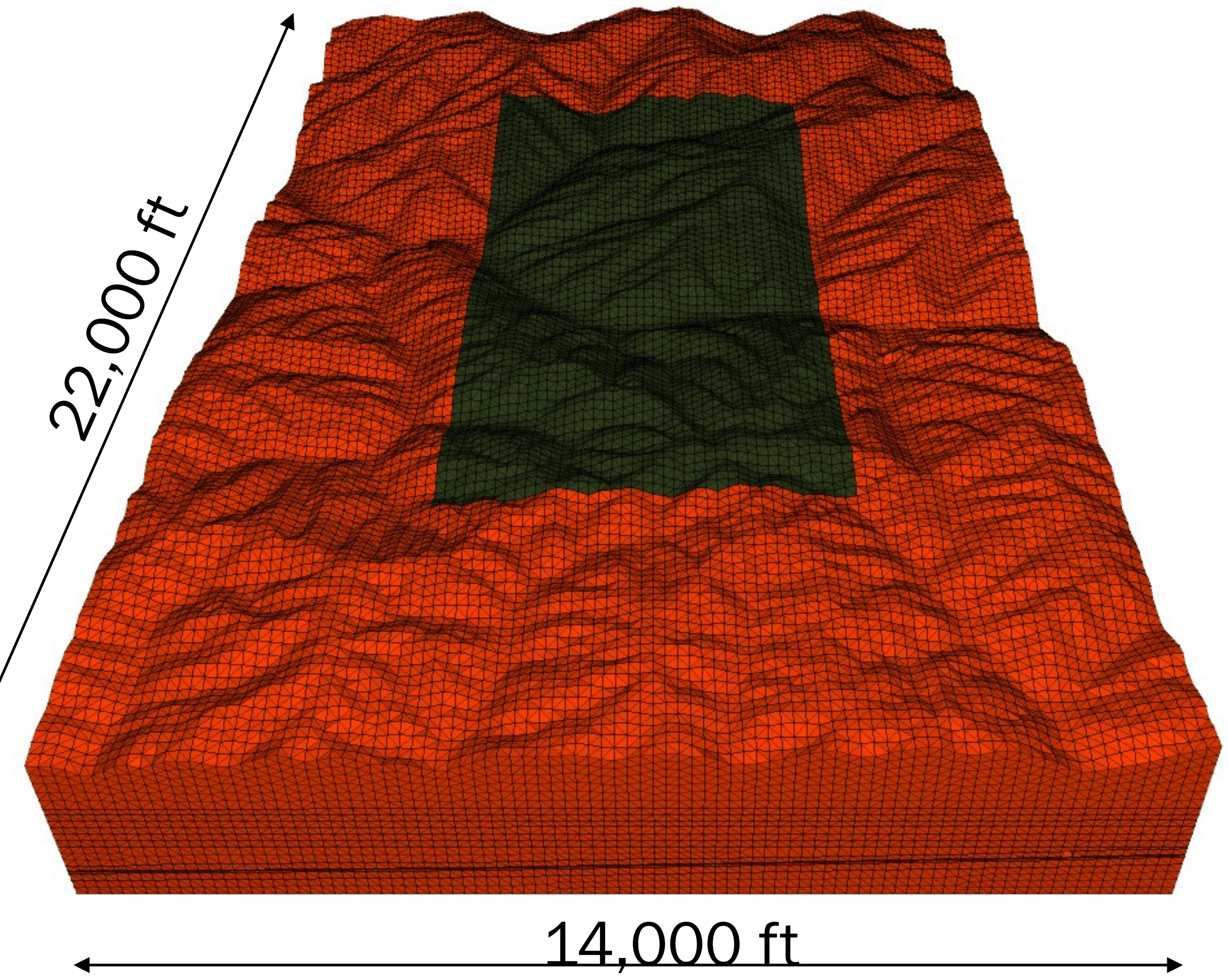
- Compressive-type events:
  Intensity: change in strain energy

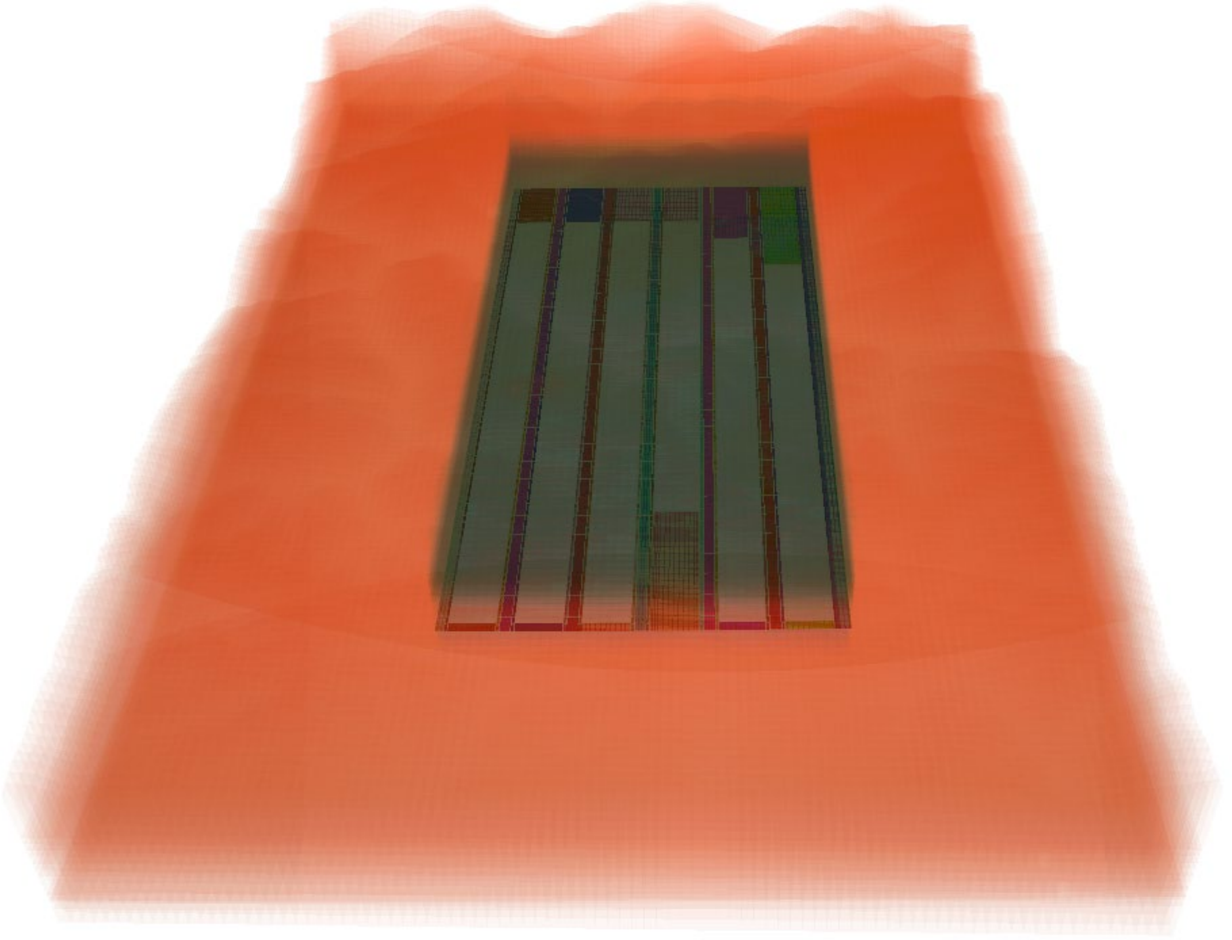
- slip-type events:
  Intensity: rupture seismic energy

- ✓ A 3D model is needed for generating a map for seismic potentials



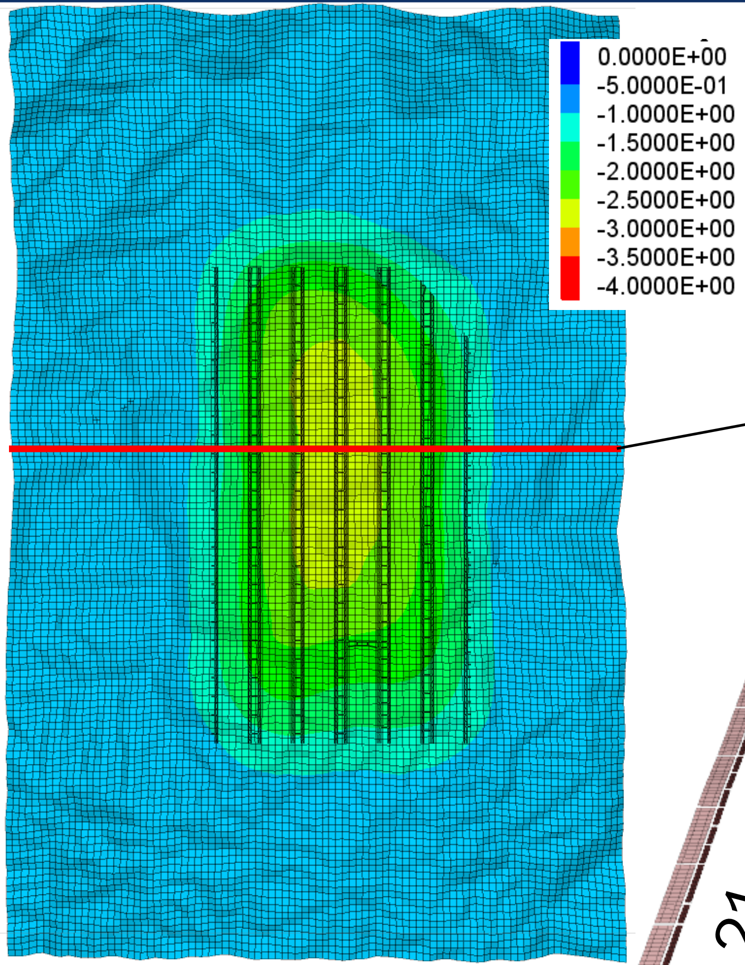
3D model geometry



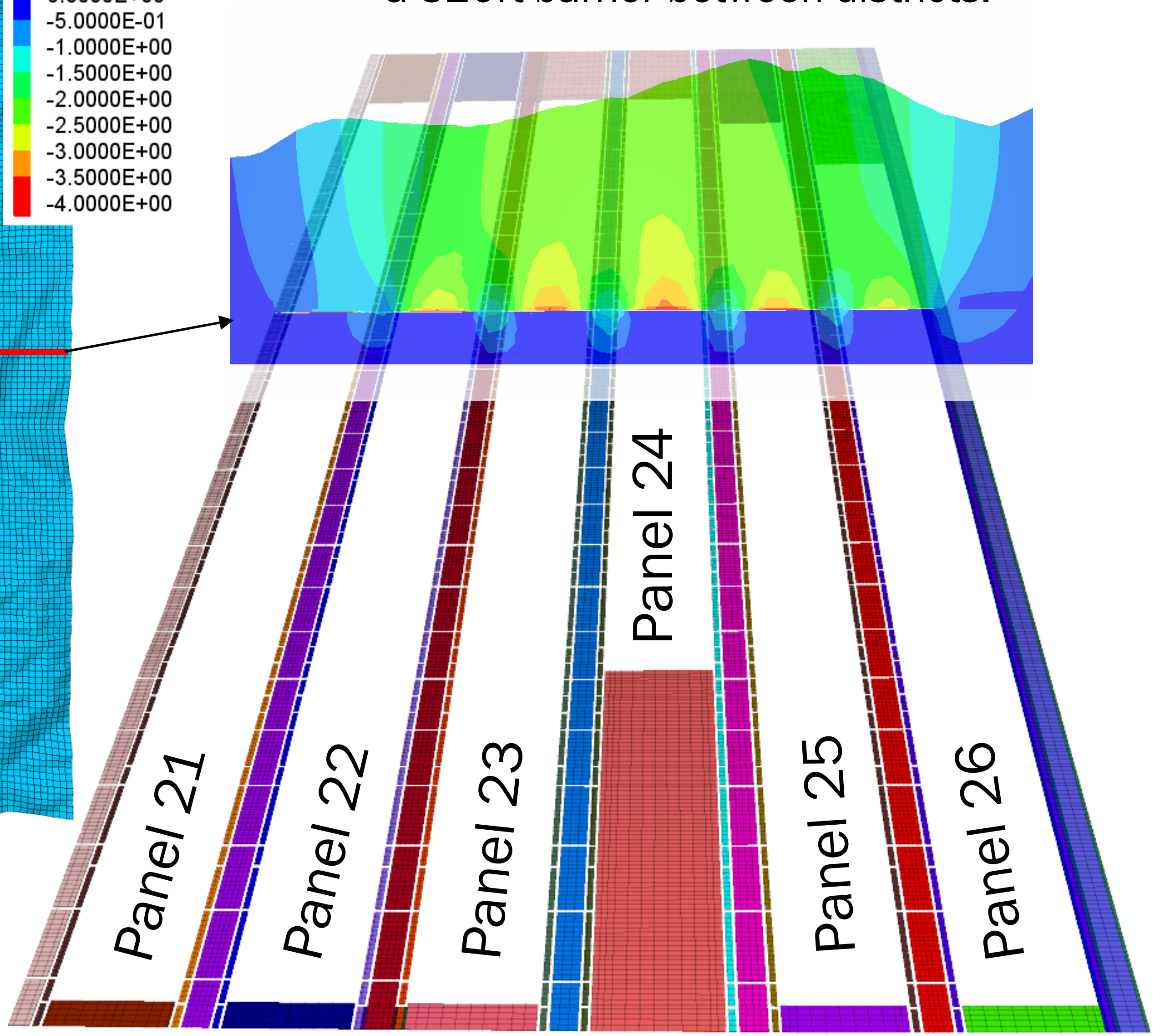


3D model geometry

- Varying thickness of strata is modeled
- Model geometry and excavation follow actual mine layout and mining sequence
- Smallest zone is 6 ft with aspect ratio of 1 to 5.

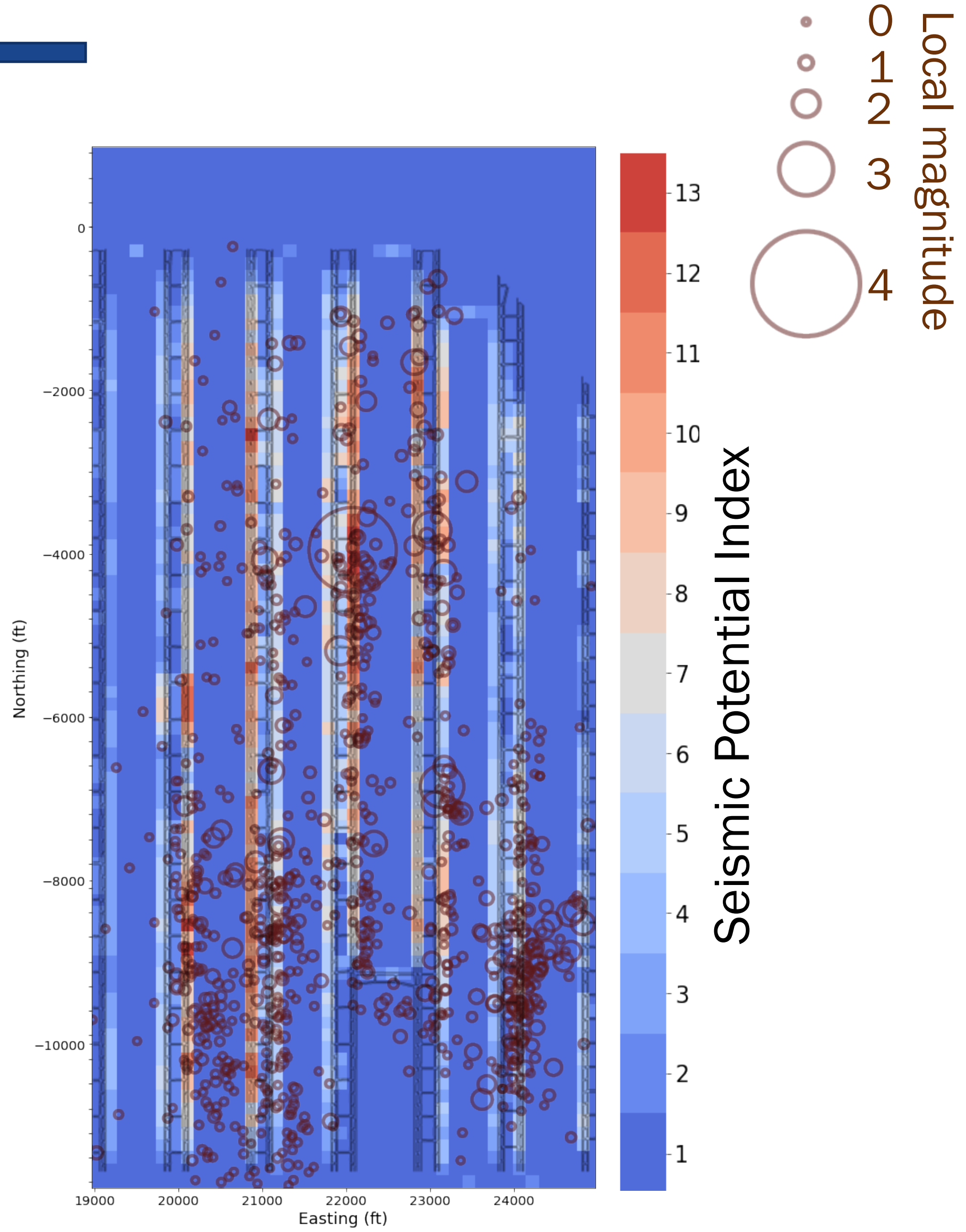


- 4-entry and 700ft wide longwall with 5-6 panels in a district and a 320ft barrier between districts.

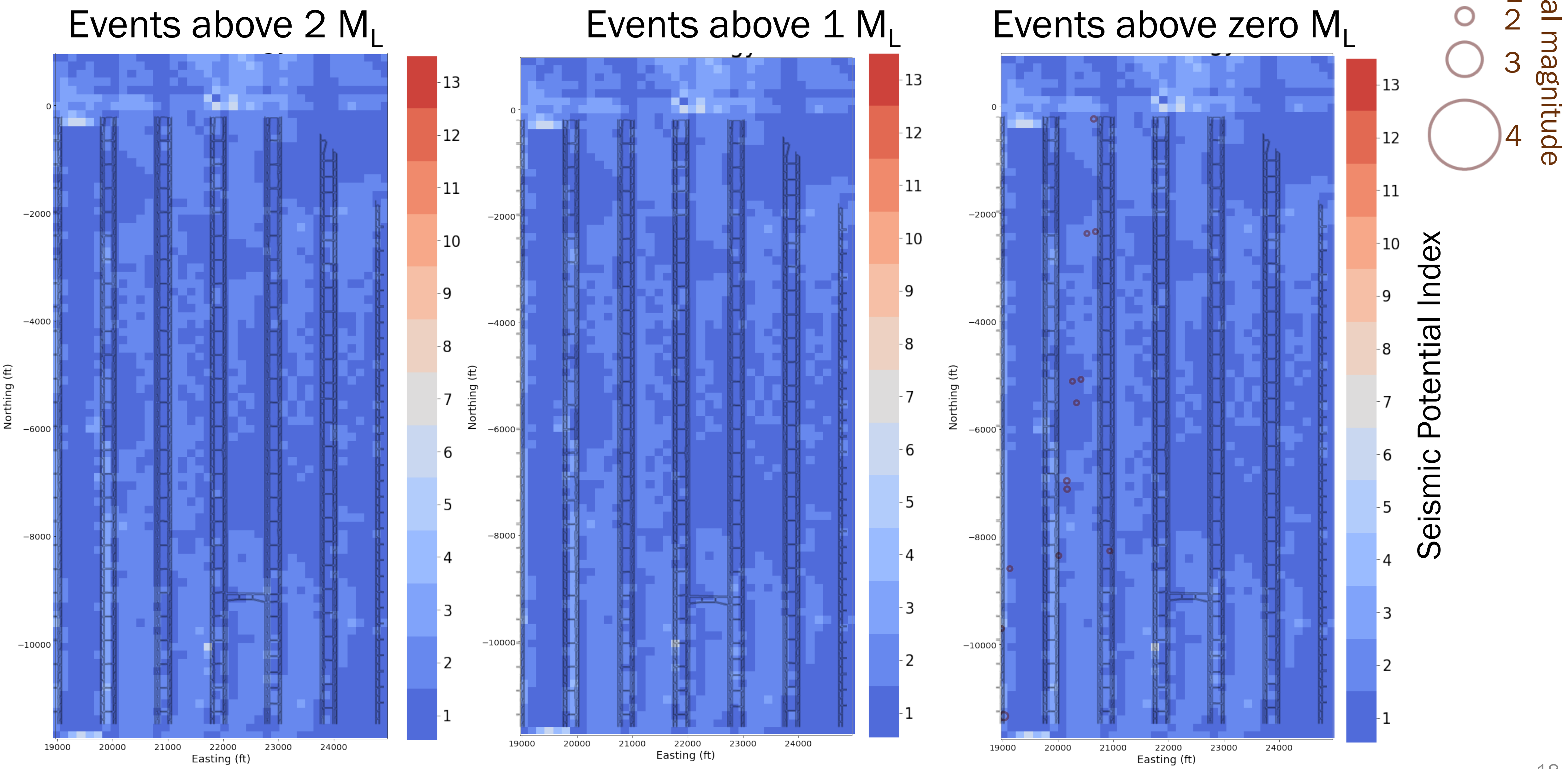


Seismic potential maps

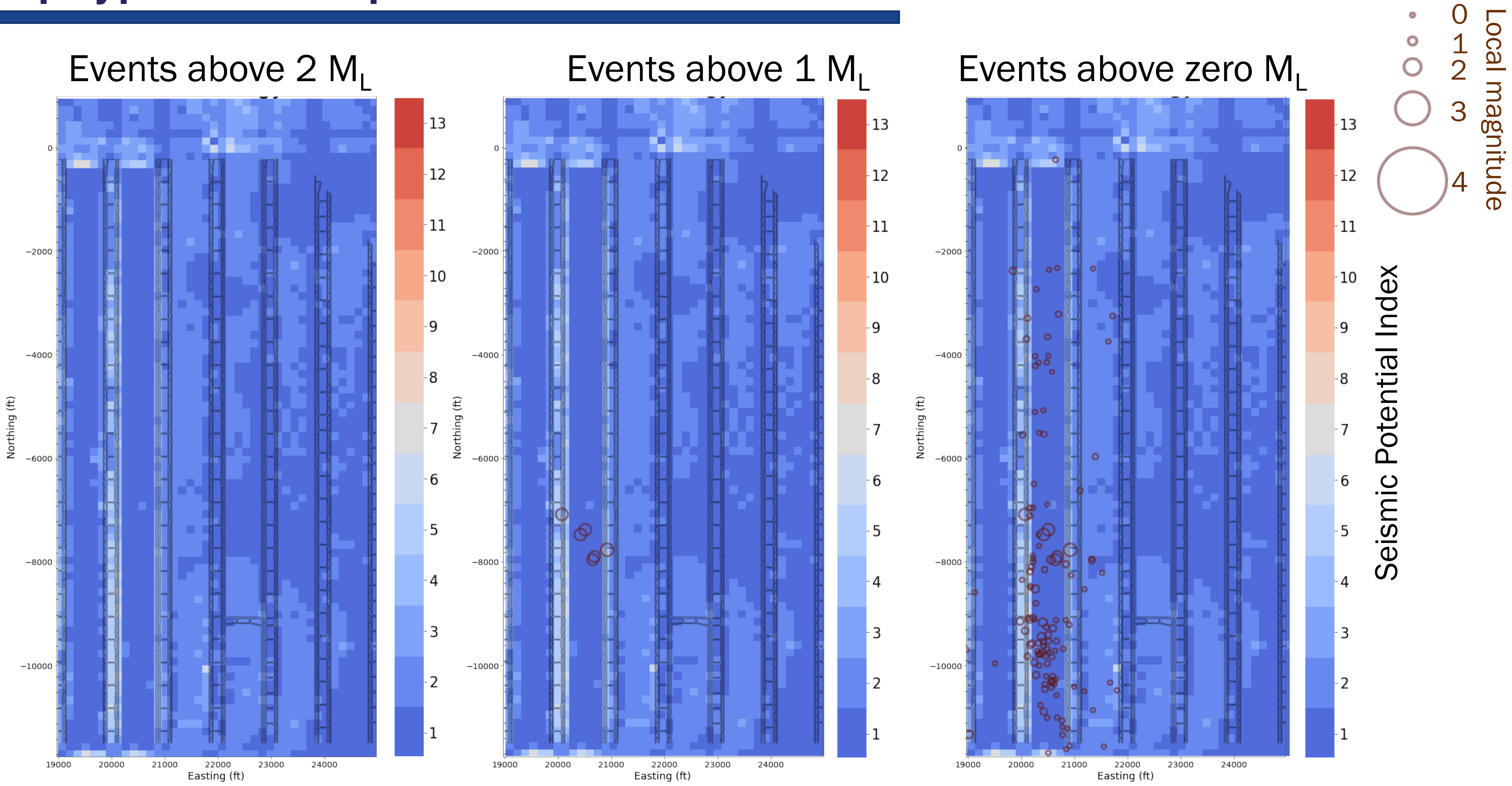
- Stress index for occurrence of events are calculated
- Energy index for intensity of events are calculated for each zone
- Seismic potential is obtained for each zone
- An index between 1 and 13 is defined with 13 showing the highest and 1 showing the lowest seismic potential
- Recorded events in the mine is superimposed on the seismic potential map in three categories (>0 M_L, >1 M_L, >2 M_L)



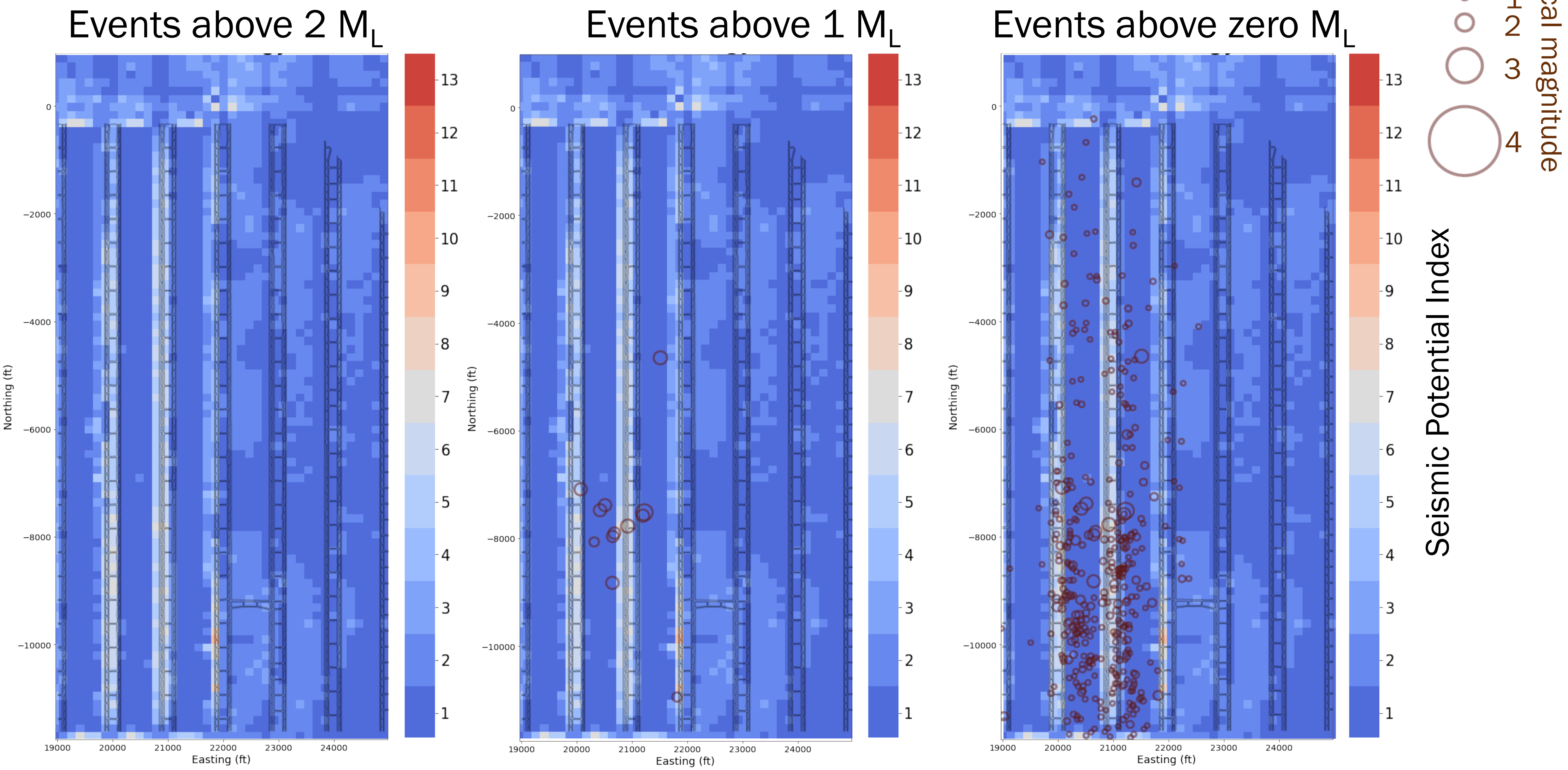
Slip-type seismic potential: Panel 21 mined



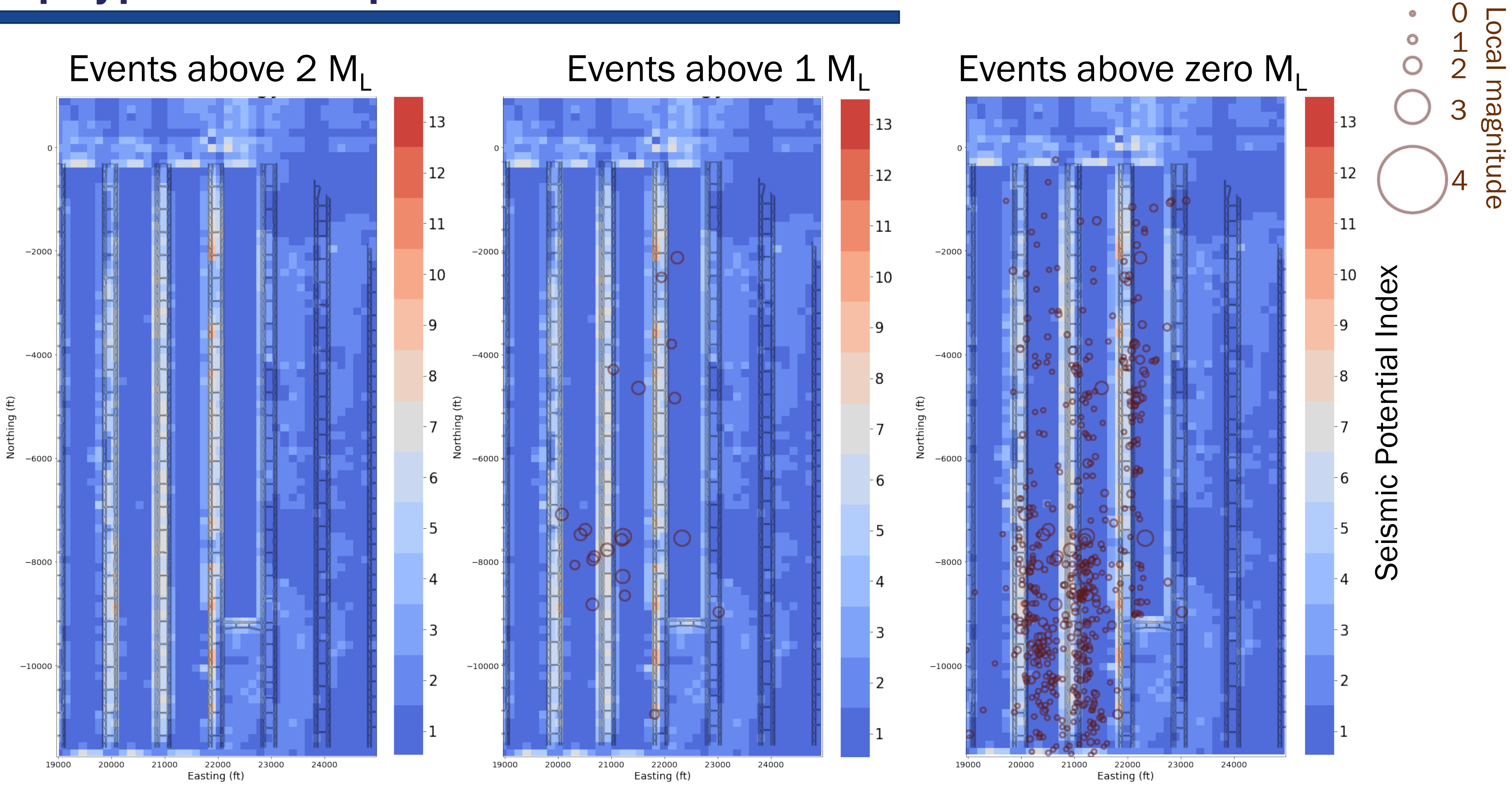
Slip-type seismic potential: Panel 22 mined



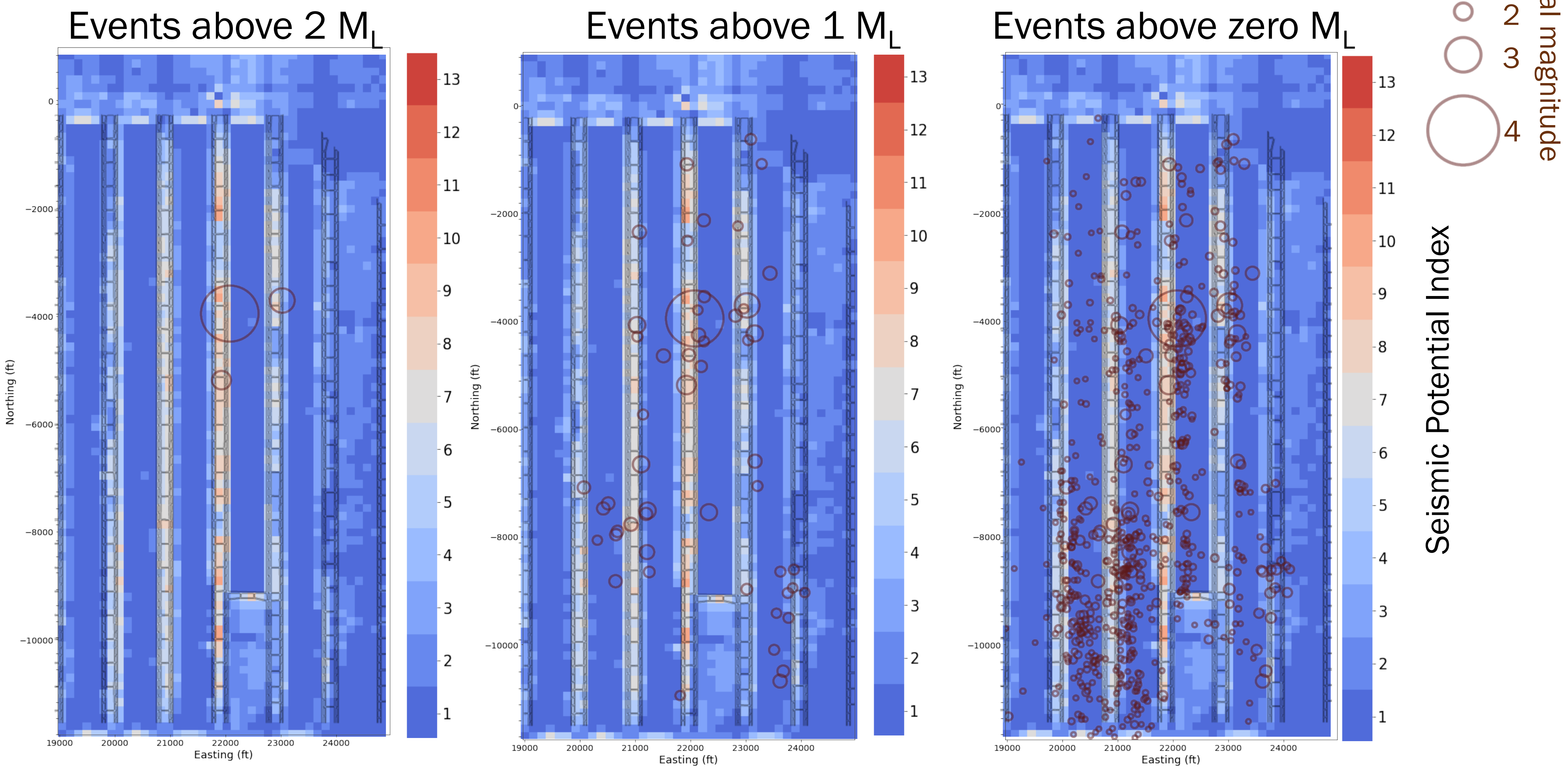
Slip-type seismic potential: Panel 23 mined



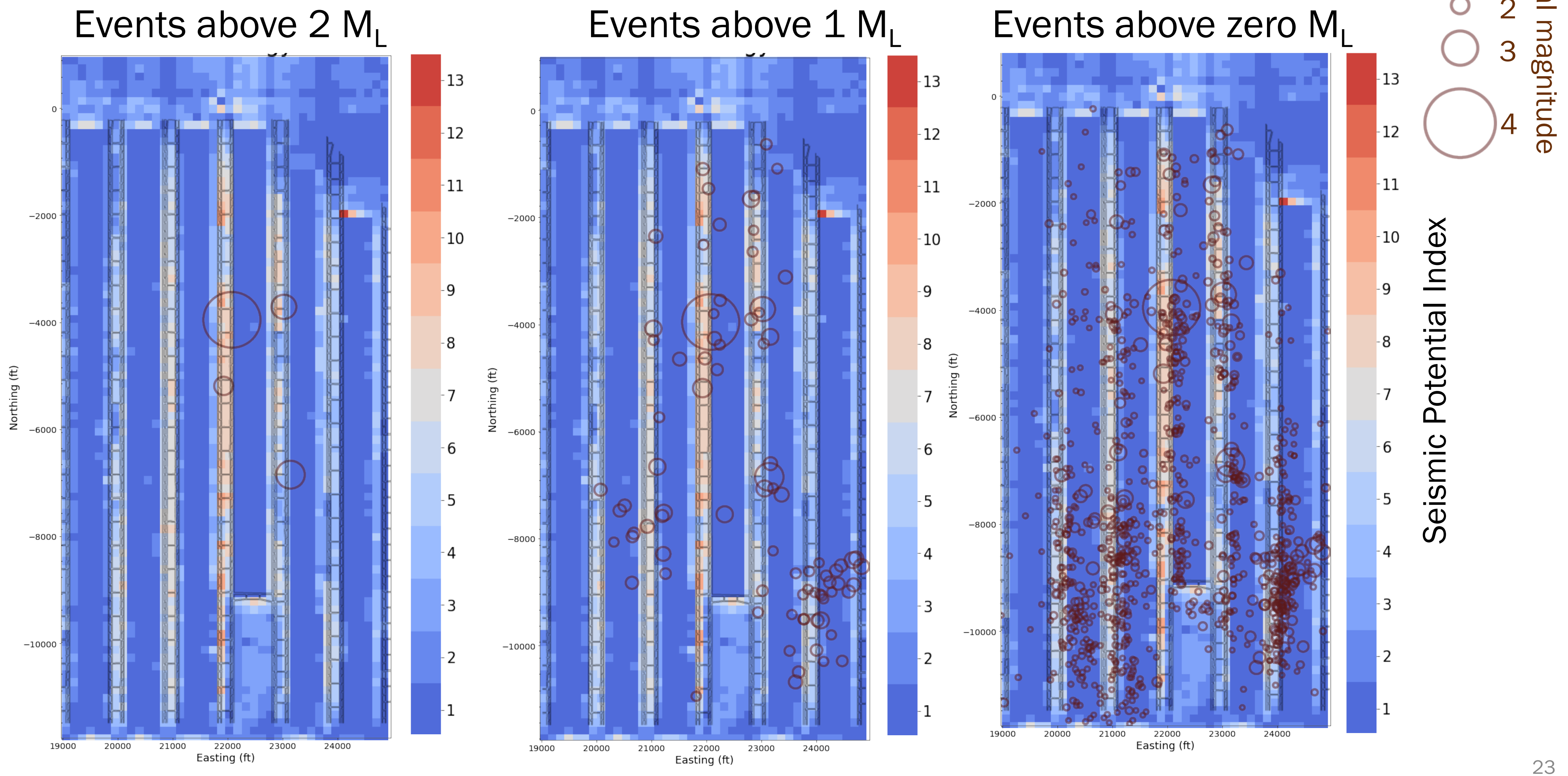
Slip-type seismic potential: Panel 24 mined

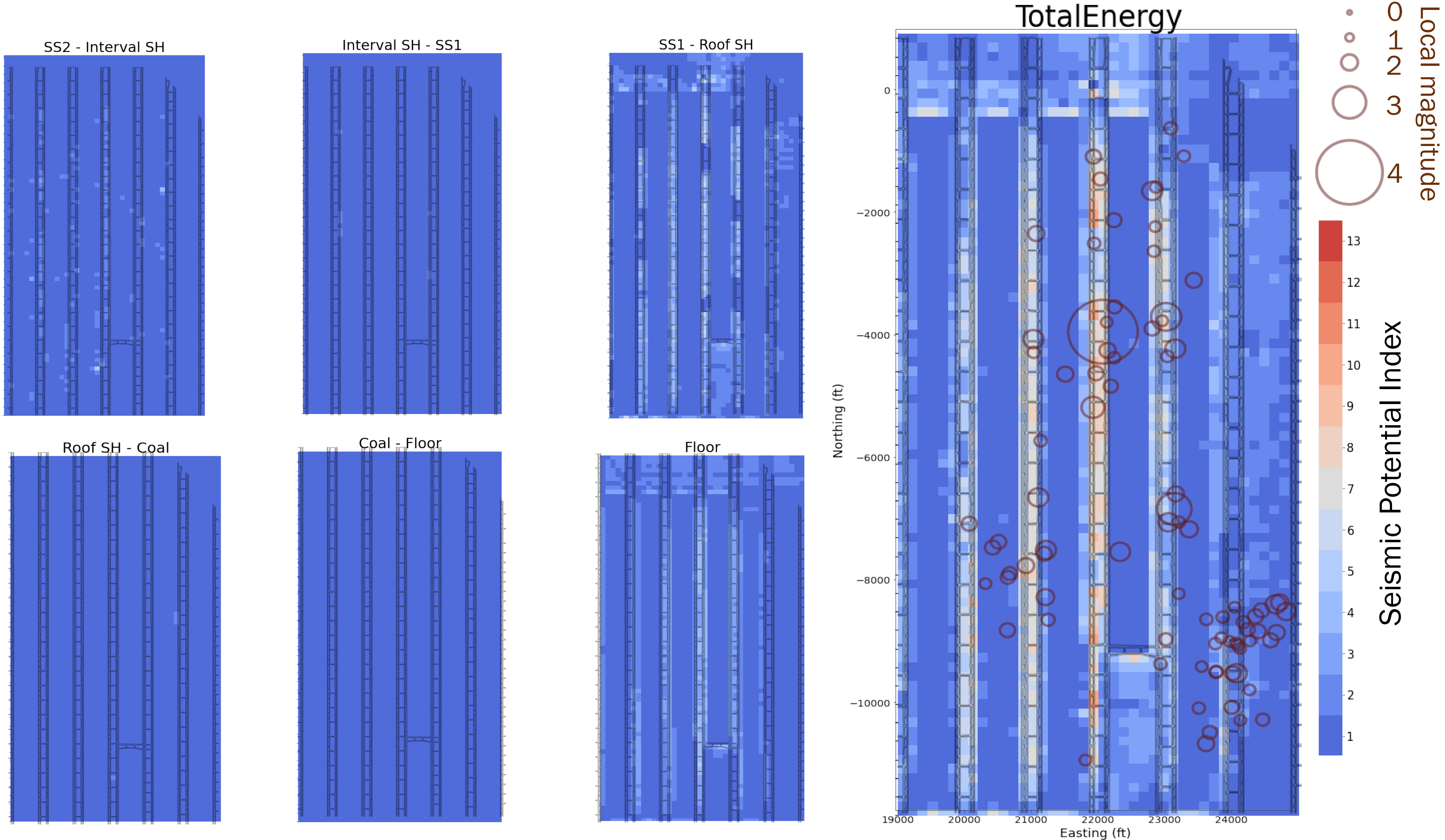


Slip-type seismic potential: Panel 25 mined



Slip-type seismic potential: Panel 26 mined

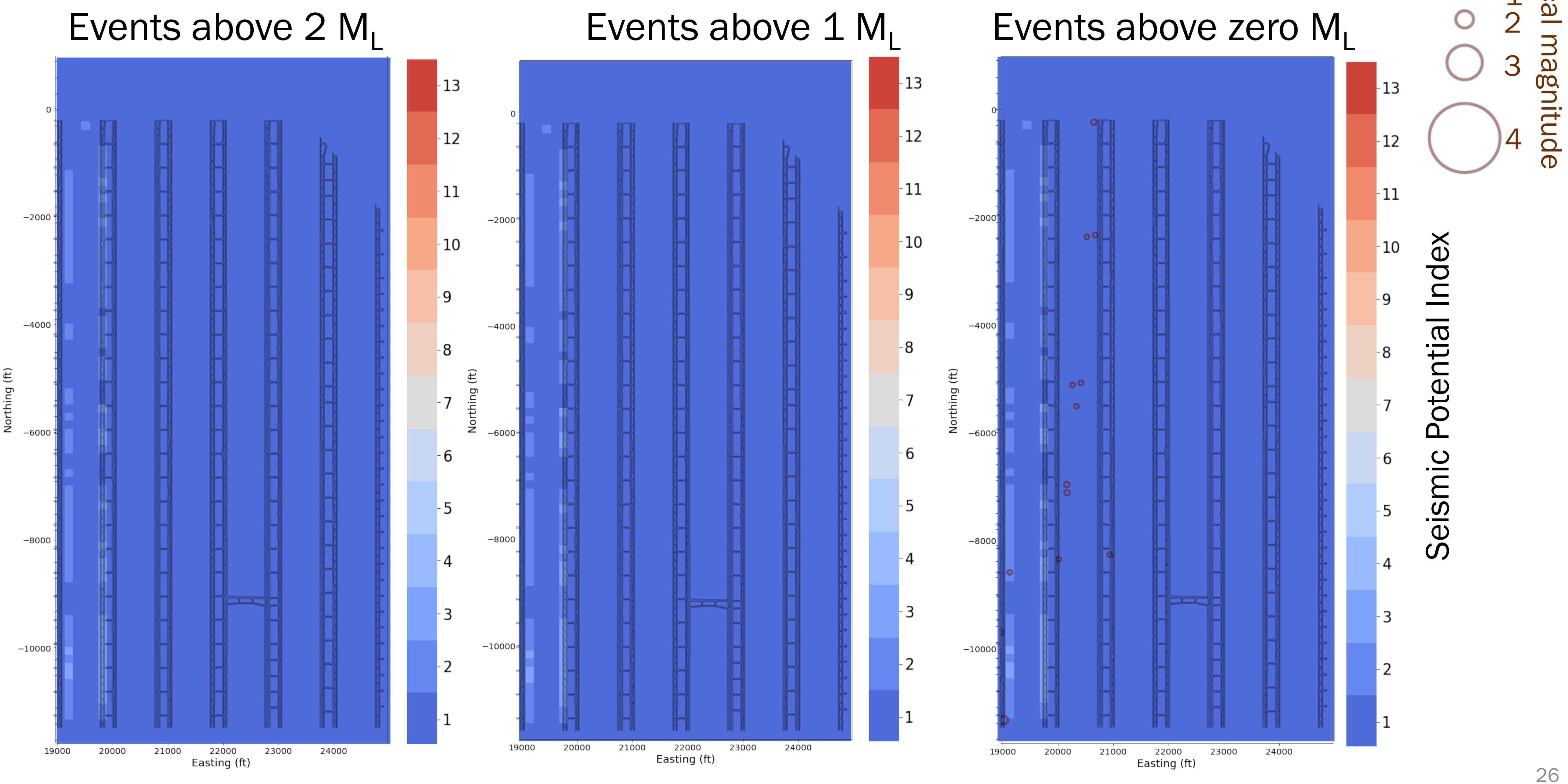



SS2 - Interval SH
Interval SH - SS1
SS1 - Roof SH
Roof SH - Coal
Coal - Floor
Floor
TotalEnergy
Northing (ft)
Easting (ft)
Local magnitude
Seismic Potential Index

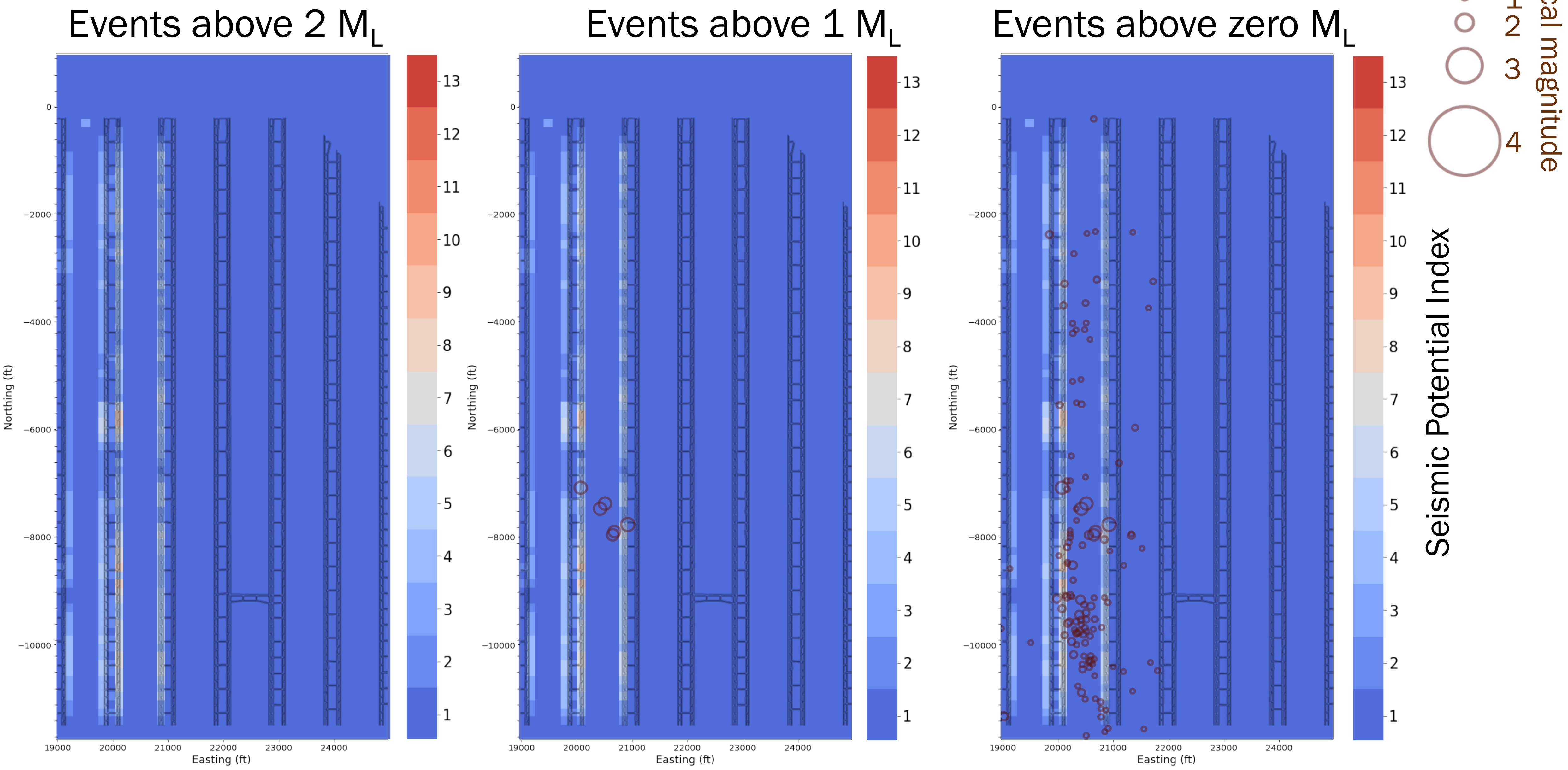
Slip-type seismic potential: Summary

- Slip-type seismic potential maps (SPM) can offer information on timing and approximate location of potentially large events.
- Most slip type seismic energy is released from the interface between SS1 and SS2 or SH interval
- From arrival waveforms, majority of events show dilatational first motion.
- This shows although slip might be the trigger, mainly the compressional failure contributes to the energy release.

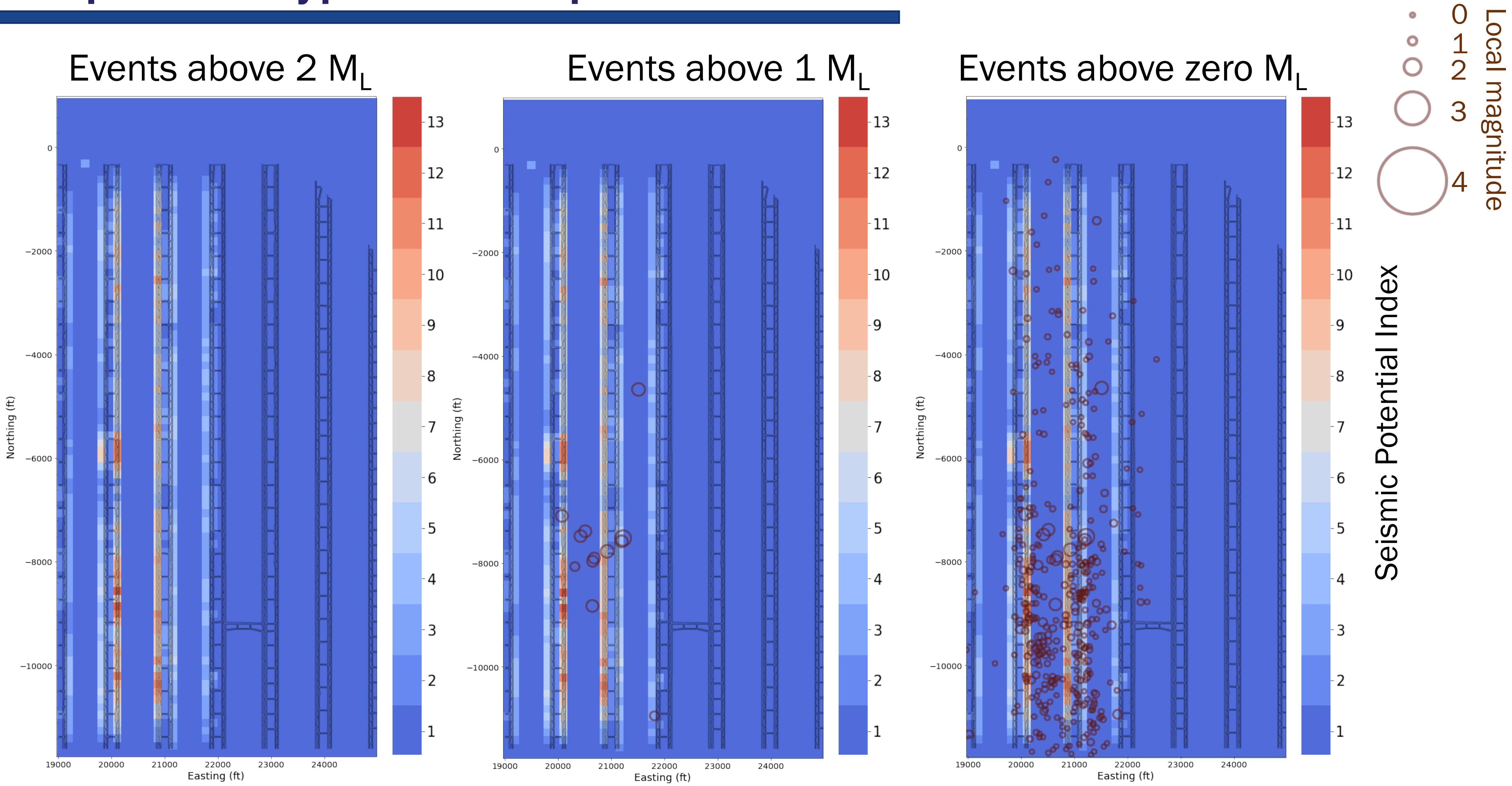
Compressive-type seismic potential: Panel 21 mined



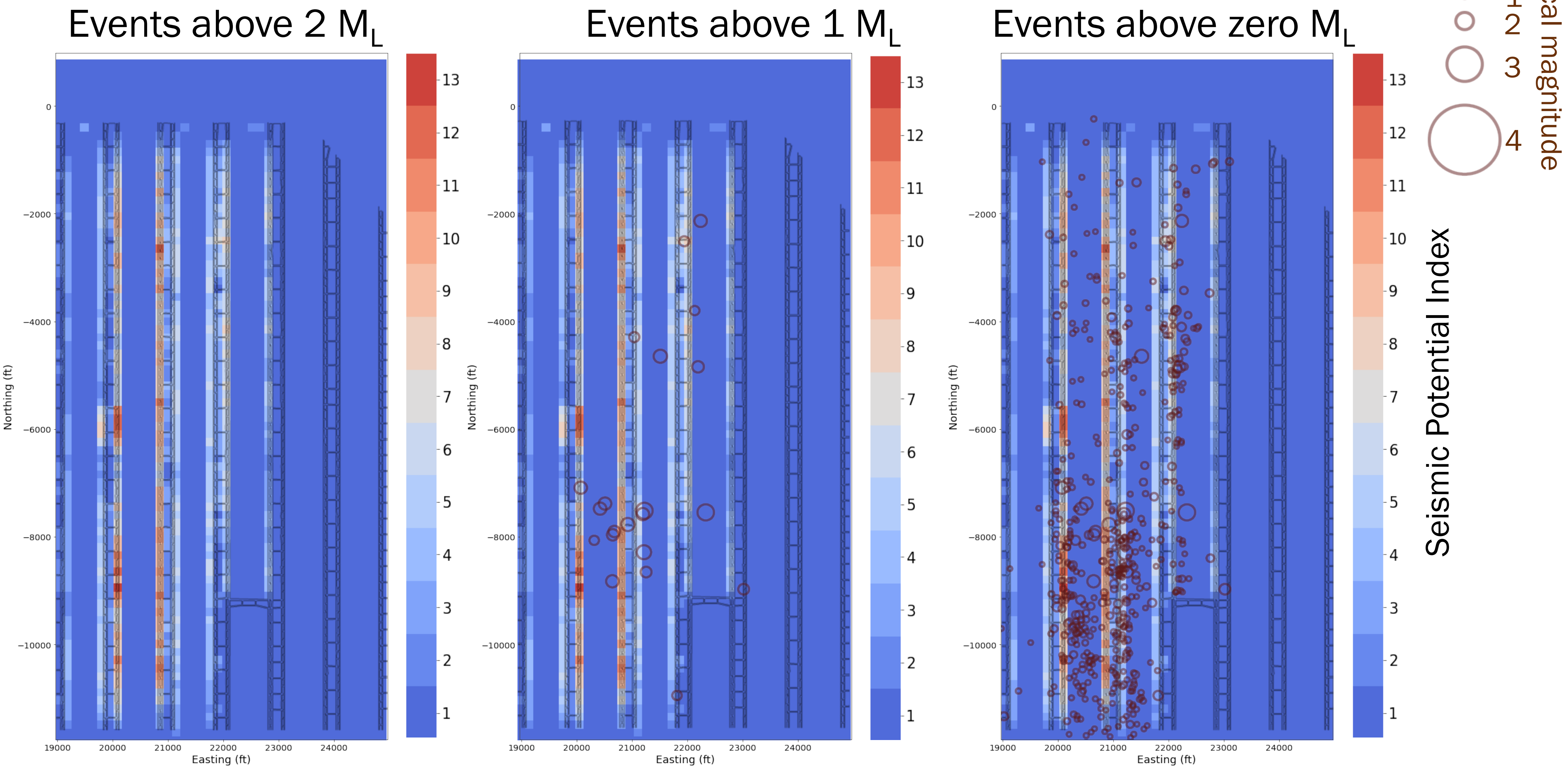
Compressive-type seismic potential: Panel 22 mined



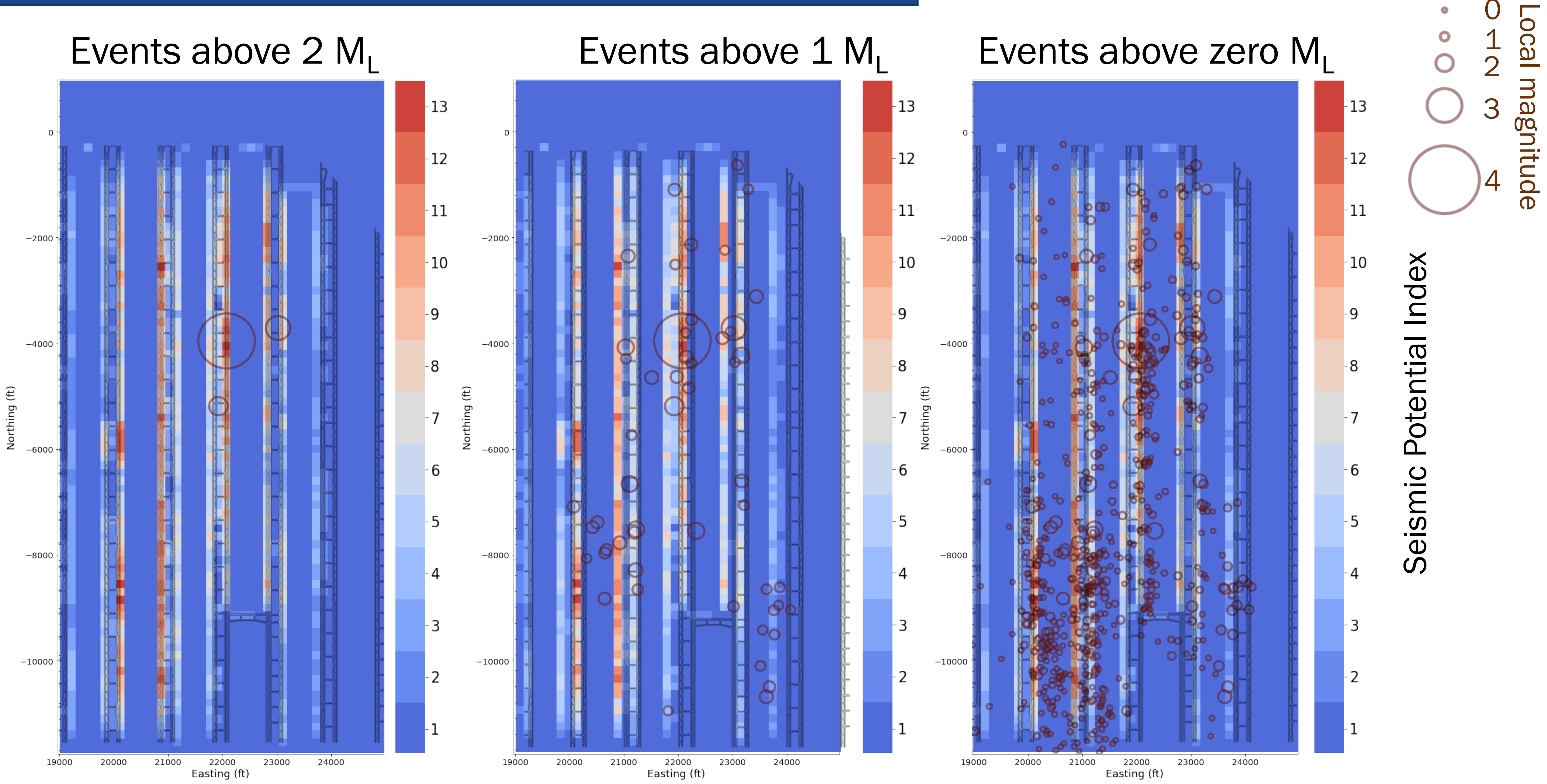
Compressive-type seismic potential: Panel 23 mined



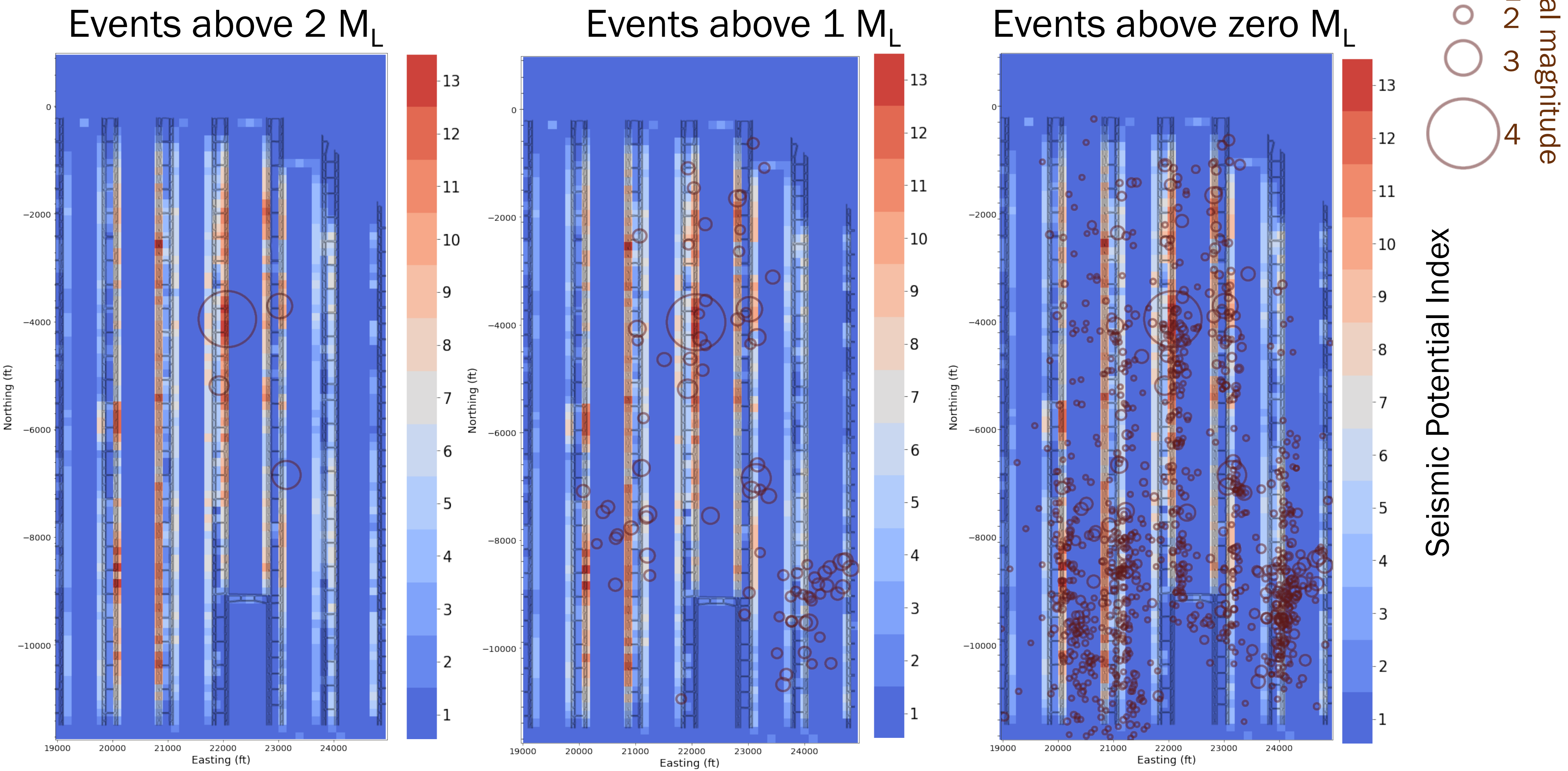
Compressive-type seismic potential: Panel 24 mined

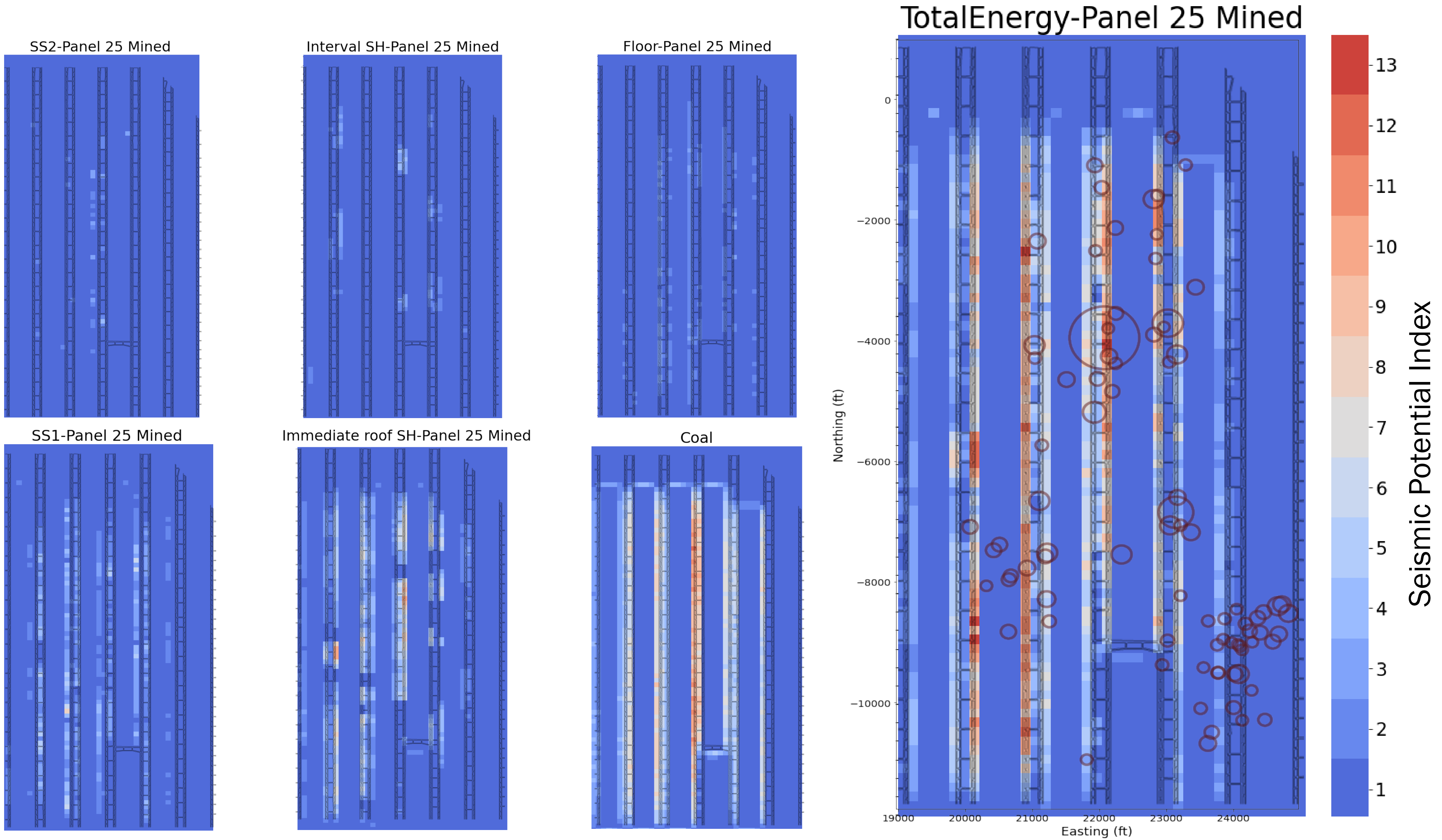


Compressive-type seismic potential: Panel 25 mined



Compressive-type seismic potential: Panel 26 mined




SS2-Panel 25 Mined
Interval SH-Panel 25 Mined
Floor-Panel 25 Mined
SS1-Panel 25 Mined
Immediate roof SH-Panel 25 Mined
Coal
TotalEnergy-Panel 25 Mined
Northing (ft)
0
−2000
−4000
−6000
−8000
−10000
Easting (ft)
19000
20000
21000
22000
23000
24000
Seismic Potential Index
1
2
3
4
5
6
7
8
9
10
11
12
13

Compressive-type seismic potential: Summary

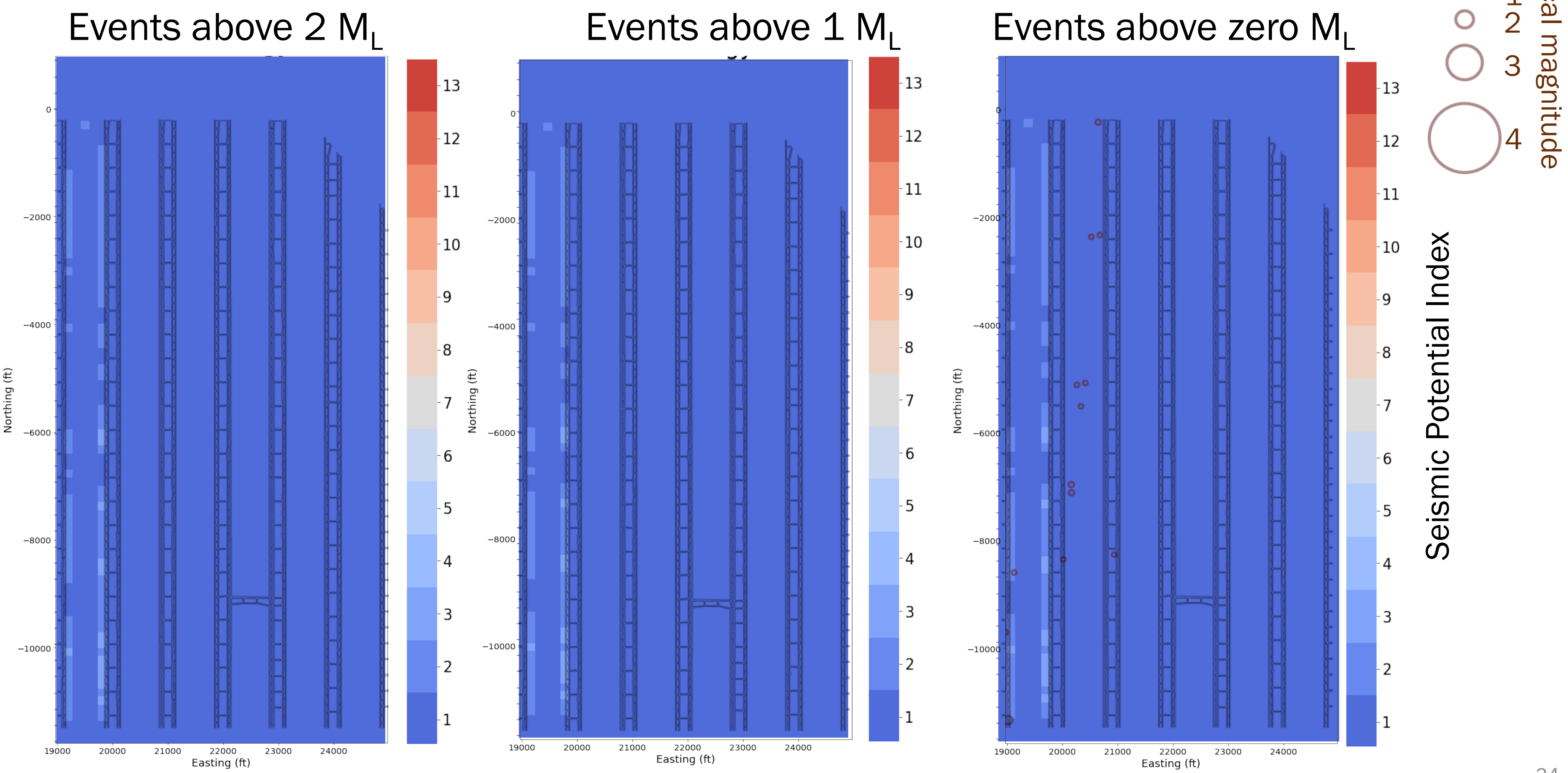
- Compressive-type seismic potential maps (SPM) can offer information on timing and approximate location of potentially large events.

- Most of energy is stored and probably released from SS1 shale, roof, and coal

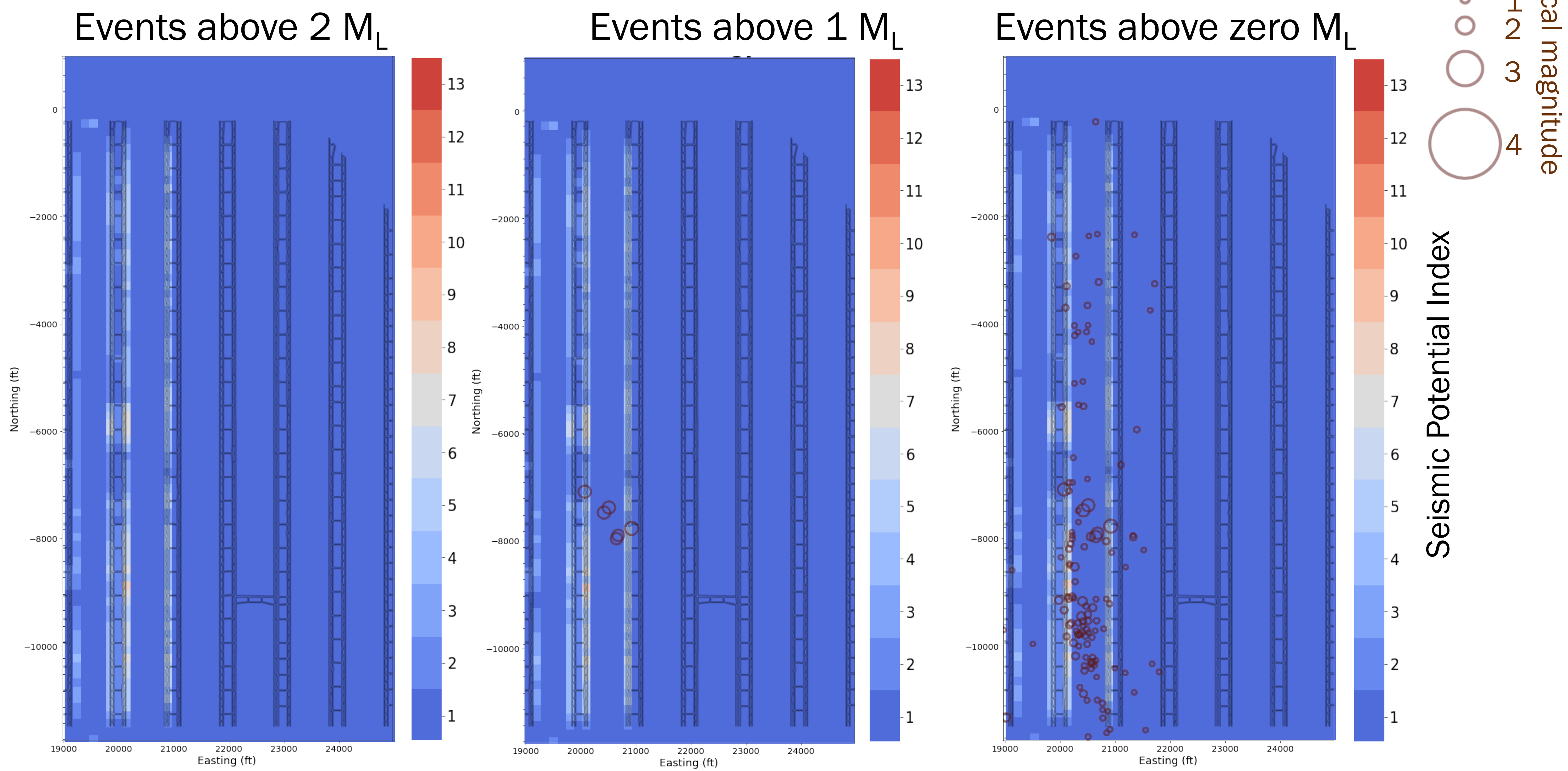
- High seismic potential during mining panel 23 was forecasted that was not on the slip SPM. Corresponding events are small magnitude but in large numbers

- It seems both maps are needed to understand the location and timing of large events; can we combine?

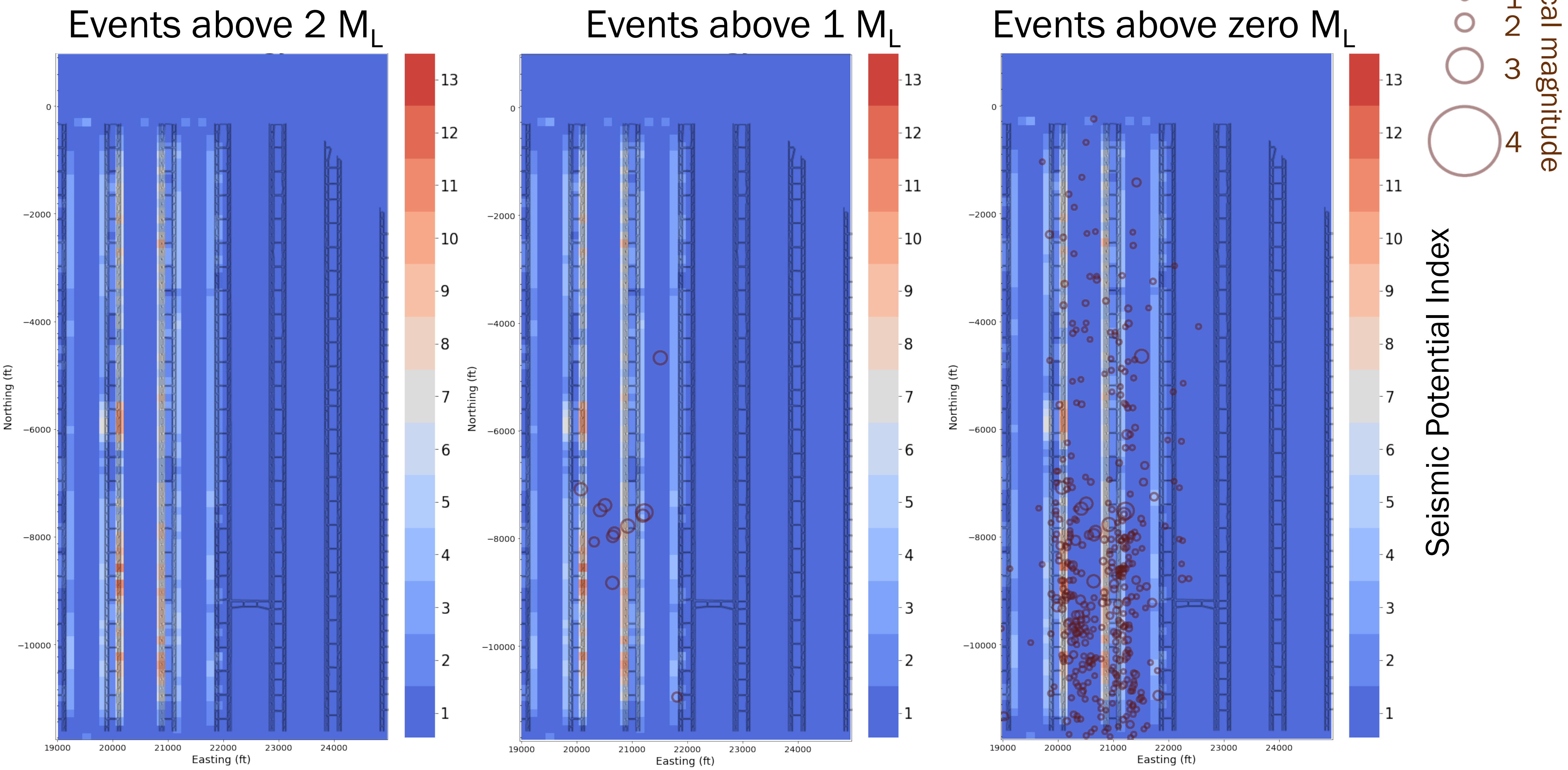
Combined seismic potential: Panel 21 mined



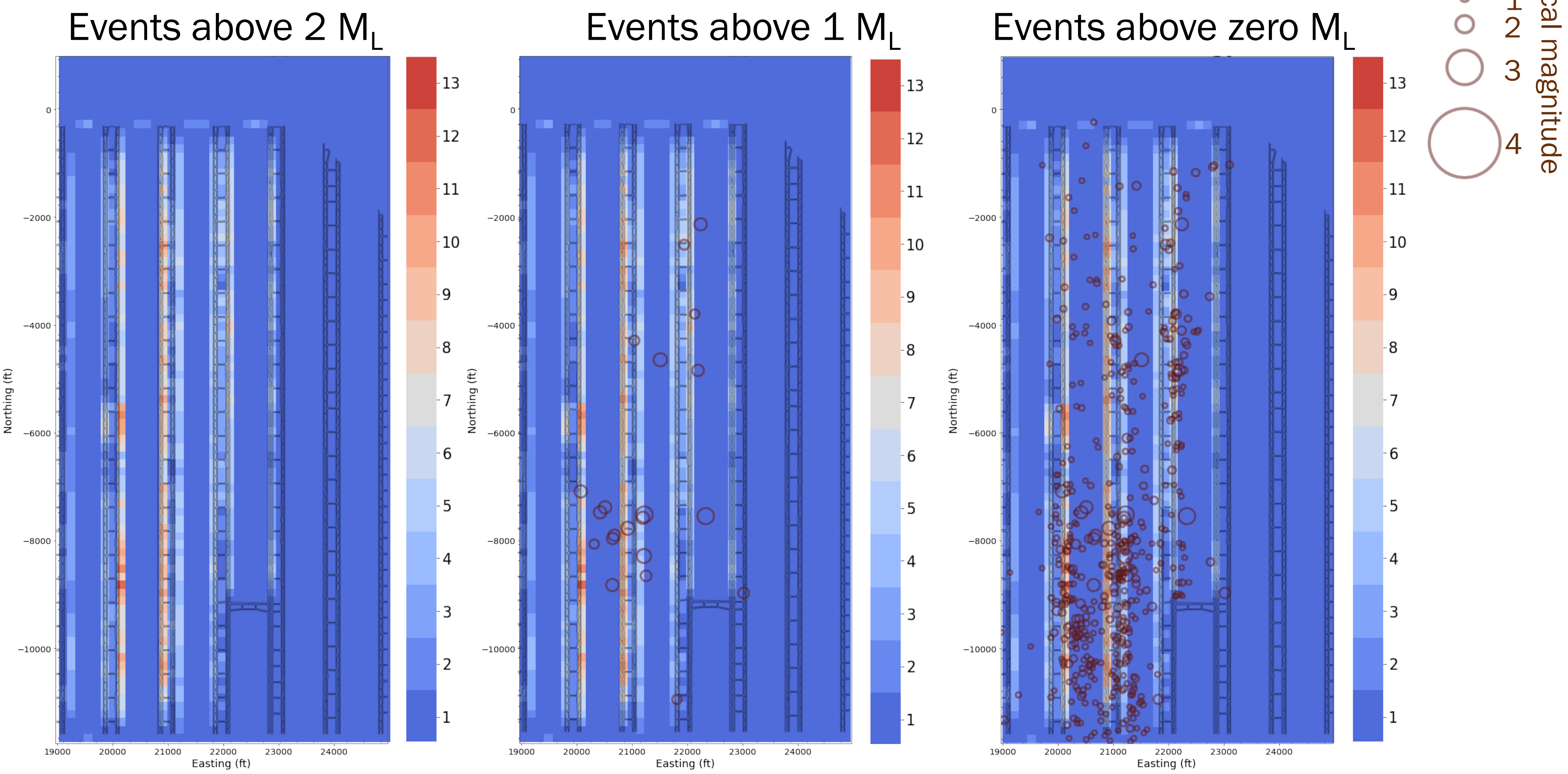
Combined seismic potential: Panel 22 mined



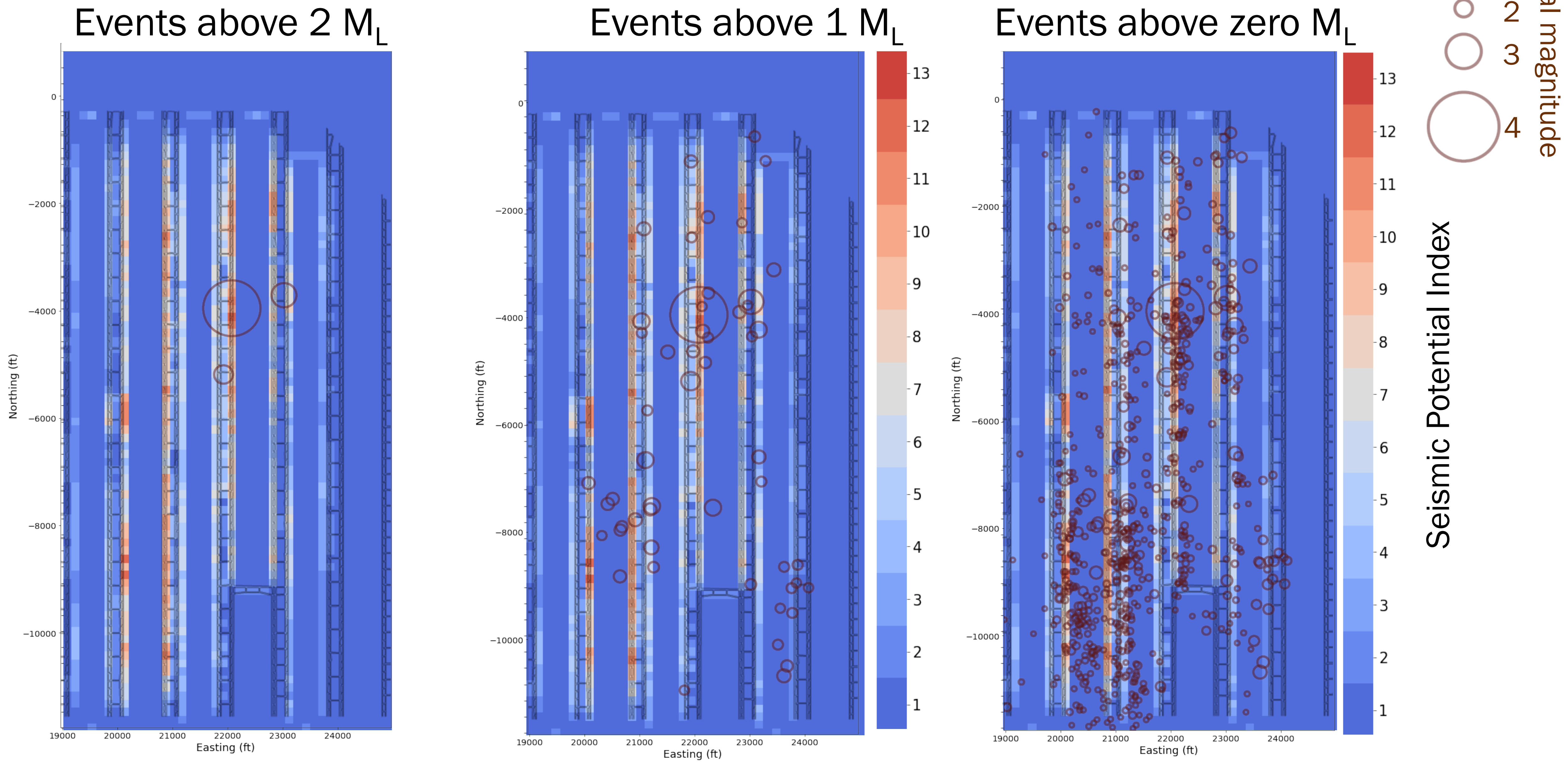
Combined seismic potential: Panel 23 mined



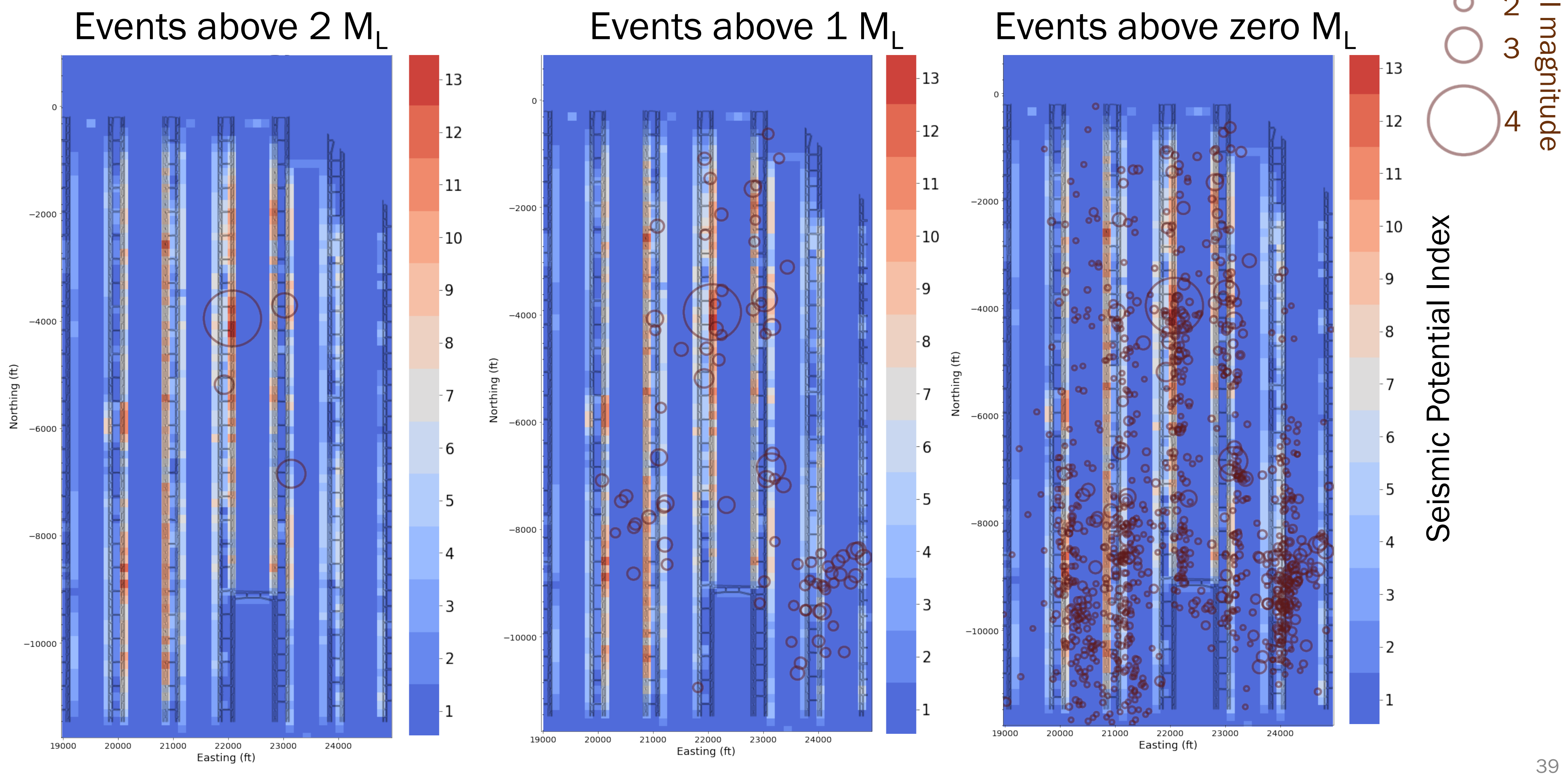
Combined seismic potential: Panel 24 mined

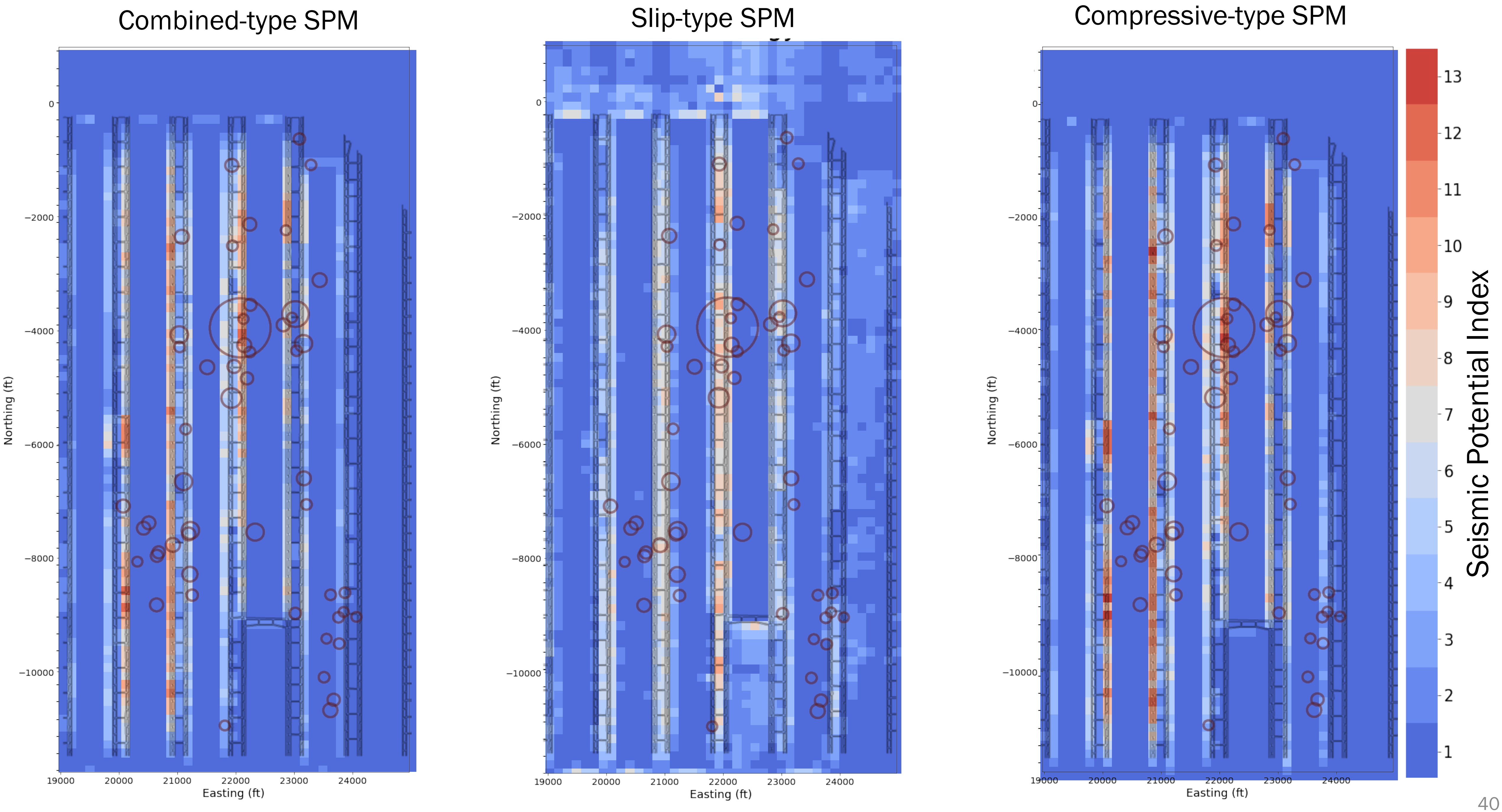


Combined seismic potential: Panel 25 mined



Combined seismic potential: Panel 26 mined



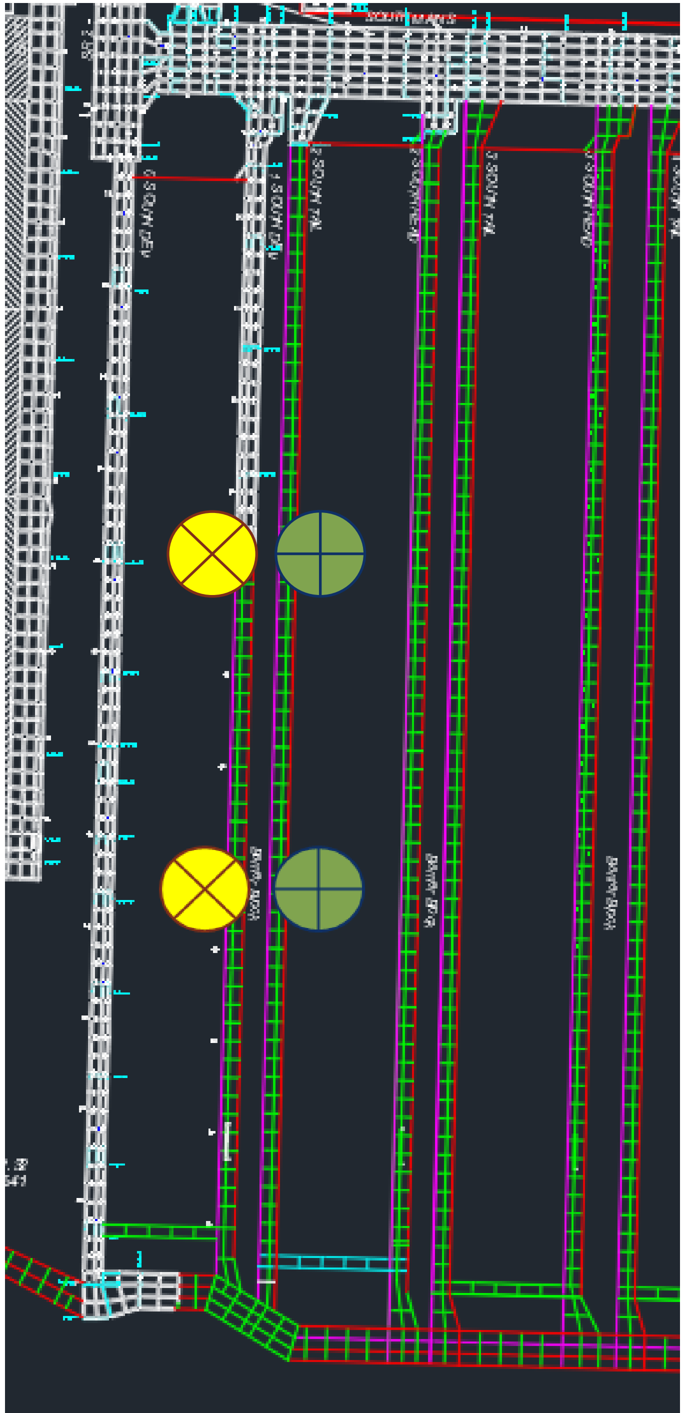

Combined-type SPM
Slip-type SPM
Compressive-type SPM
Northing (ft)
Easting (ft)
0
−2000
−4000
−6000
−8000
−10000
19000
20000
21000
22000
23000
24000
Seismic Potential Index
1
2
3
4
5
6
7
8
9
10
11
12
13

Combined seismic potential: Summary

- Combined-type seismic potential maps (SPM) can offer information on timing and approximate location of potentially large events.
- Considering both maps reduces false positive zones. At locations where both types showed high potentials, large events were reported from the field.
- The methodologies are validated for generation of initial SPM
- SPMs can be improved by fully solving energy balance equations in the model
- This requires lab testing and field measurements
- The SPM will be generated and tested for the new mine design

Field instrumentation: in progress

- New mine layout has no historic seismic data
- The old mine design with a 4-entry, 700ft wide longwall with 5-6 panels in a district and a 320ft barrier between districts.
- The new design with 1000-ft wide longwall faces with a 3-entry system and a 200ft wide barrier between each panel.
- Four monitoring sites to monitor the stress transfer over the barrier from a shale to a sandstone dominated roof geology.



Field instrumentation: in progress

- Roof displacement
  - ✓ Conventional extensometers
  - ✓ Distributed Optical Fiber Sensing (Missouri S&T).
  - ✓ LiDAR scanning
- Pillar pressure
- Cable bolt load

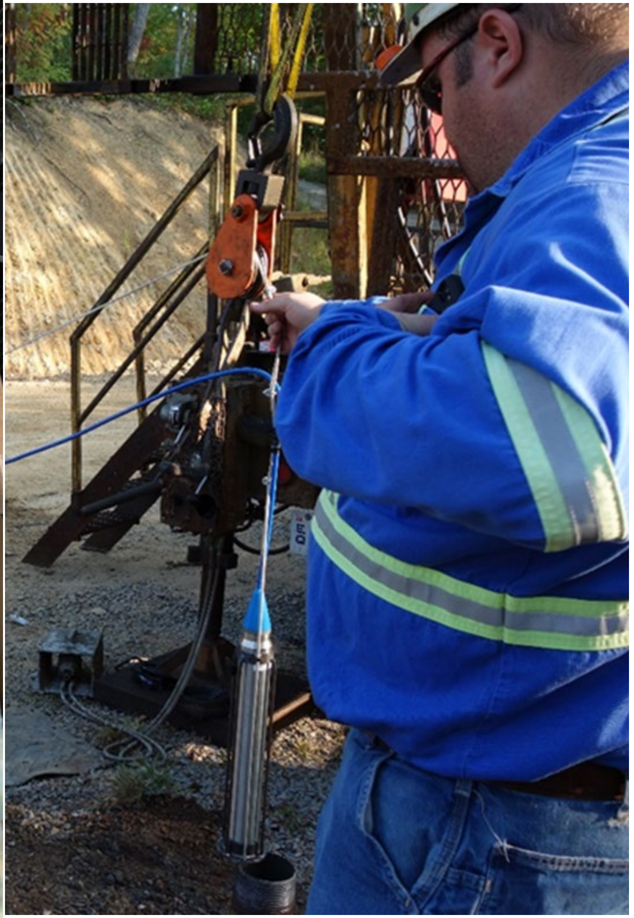
Seismic monitoring: in progress

The performance of SPM will be evaluated by seismic monitoring

A surface network with 20 stations over the first three panels

Three bottom-hole triaxial seismic sensors installed at depths around 1000 ft through gas wells

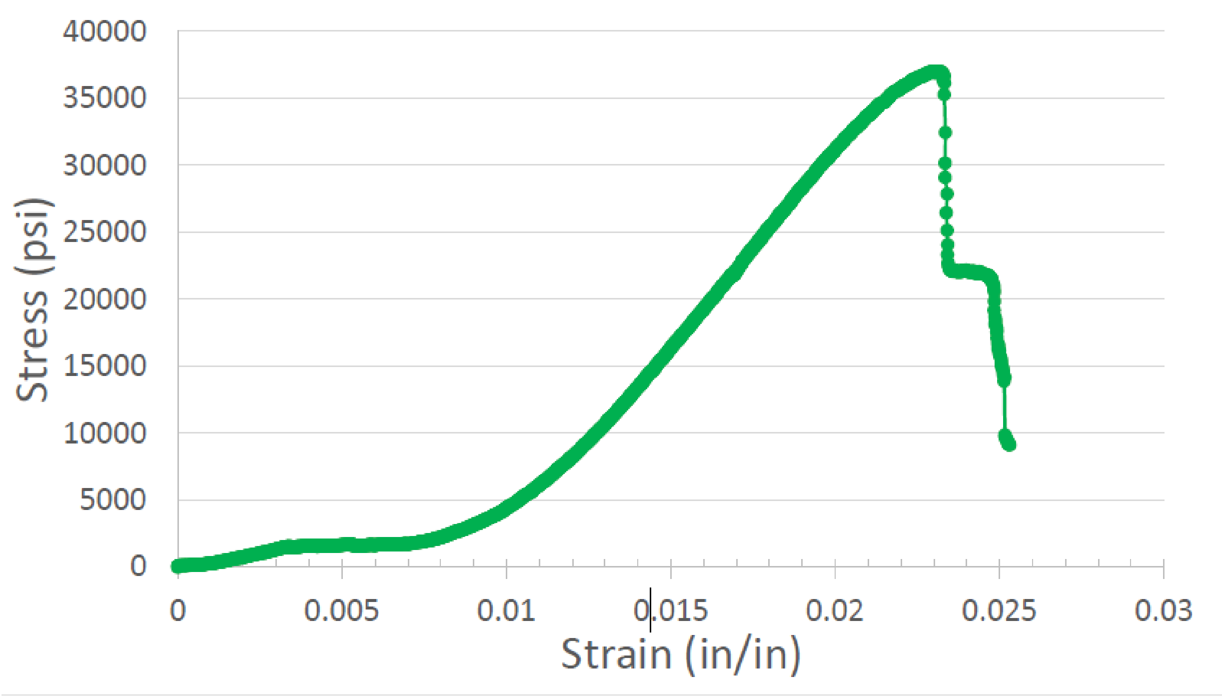
Distributed Acoustic Sensing cables through the gas wells



Lab testing: Completed

Lab Testing (University of Kentucky):

- Confined and unconfined compressive tests for capturing post-failure response of SH, SS1, and SS2



Final Summary

Completed milestones

- ➢ Developed preliminary modeling methodologies for hazard map generation
- ➢ Predicted location and timing of elevated seismic potential agrees with the historic data

Milestones in progress

- ➢ Quantify false positive and false negative forecasts
- ➢ Fully solving energy balance equations in the model
- ➢ Rock testing for capturing post-response of rock
- ➢ Field instrumentation to calibrate stress transfer over barrier pillars
- ➢ Seismic monitoring to improve elevation component of events

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Subsidence at SS1 and shale horizons versus recorded seismic events

No apparent relationship between roof vertical displacement and recorded events