ASC
Applied Seismology Consulting

Seismic and microseismic applications for the mining industry

Open pit monitoring

Slope stability monitoring and analysis
Open pit - underground interaction
Wireless instrumentation

Risk monitoring

Subsidence risk monitoring
Induced seismicity
Rockburst monitoring

Consultancy

Seismic array design
Fracture analysis from seismic catalogues
Validation of geomechanical models

Underground monitoring

Fracture imaging and characterisation
Cave mapping
Imaging rock damage
Wireless instrumentation

Seismic monitoring is an established technology in mines generally applied for safety monitoring, rockburst prediction and imaging the extent of damage induced by the mining operations. Microseismic monitoring, provides an insight into the location and extent of fracturing induced by the stress changes associated to mining processes in general. The spatial characteristics of the observed microseismicity provide valuable validation for the back analysis of fracturing processes such as caving, preconditioning, etc. through numerical models (e.g. Pierce et al. 2006; Sainsbury et al., 2008). It also provides a tool for the future validation of forward cave models that predict the extent and location of the seismogenic zone and the transmission properties of the damaged rock.

The post-process analysis of seismic catalogues or seismic record or real-time analysis can provide feedback for:

- Early warning on localised induced damage to mine infrastructure.

- Slope stability in open-pit mines

- Extent and positioning of damage zones in underground operations

- Imaging the cave progress and extent in underground caving mines

- Imaging the persistence, spacing and mechanism of induced and mobilised fractures

- Progress of subsidence zones above underground operations

- Effectiveness of preconditioning operations

ASC Services

ASC has developed a series of novel analyses that enhance the information provided by existing microseismic catalogues to monitor the evolution of the fracturing processes and provides the following services for mining stakeholders:

- Advanced post-processing, analysis and interpretation of client data using a range of techniques and software functionality developed in-house to identify fracturing modes, the fraction of newly opened and reactivated fractures and provide a full geometrical characterisation of fracturing.

- Active and passive source tomography for imaging of damage induced by mining operations

- Acquisition system-independent seismic processing software for automatic, real-time processing of induced seismicity

- In-depth understanding of fracture mechanisms through the integration of acquired data and "Synthetic Rock Mass" models built with Itasca's Particle Fluid Code (PFC) and site-scale degradation models.

- Structure imaging and velocity inversion combining the illumination capability of controlled seismic sources and passive seismic events.

- P- and S-wave time-lapse tomography to image the degradation of host rock and structures in terms of elastic modulus and fracture density.

- Temporal and spatial clustering of microseismic events to quantify damage accumulation and identify areas of localised fracturing.

- Fully-featured microseismic training courses focussed on the principles behind the technology, processing algorithms and hands-on experience of using processing software.

- Design, optimisation and quality check of seismic monitoring arrays.

Case studies

Mass Mining Technology Project: Validation of SRM models

ASC participated in phases I and II of the Mass Mining Technology Project (MMT), an International Collaborative mining research project coordinated by the University of Queensland focused on critical reviews of conventional caving design approaches, collation of common caving practice, and advancing the understanding of the caving fundamentals. ASC's role focused on enhancing the information extracted from MS data collected from case study mine to use MS events in the imaging of the fracture network as an essential validation tool for geomechanical models.

Innovative processing methodologies were developed to improve the understanding of the evolution of the fracture network as the rock mass undergoes undercutting and caving.

SRM (Synthetic Rock Mass) experiments were used to model the effects of undercutting and caving on the rock mass using the results from case studies (Northparkes mine, Palabora mine, Kiruna mine, Ridgeway mine) as a basis for the validation of the SRM approach.

The analysis of the evolution of the spatial distribution of MS events to was correlated to mining operations in the different identified domains to test the validity of using SRM tests as a means to predict rock mass response to undercutting and caving.

The statistical approach presented by Reyes-Montes (2005) was used to investigate the distribution of MS events along non-random planar structures. This method made use of the three-point method to identify preferential fracture orientations.

The mine was categorised into geomechanical domains, the seismic behaviour of each of the domains was used to characterise the difference in the nature fracturing and degree of yielding.

SRM's from each domain underwent tests resulting in the sample exhibiting over 100,000 cracks each. Two different techniques were used to study the macroscopic cracks, the first used examination of contiguous blocks to see how the initial rock disintegrates, visualising the fractures that lead to the disintegration.

The second technique used the three-point method to fit planes to clouds of cracks in a similar way to its use on the mine data. Individual cracks were grouped into PFC seismic events, events consisting of less than four cracks were filtered out before the three-point method was employed.

Case studies

The second technique allowed easy comparison of the fractures inferred from seismicity in the mine and those predicted by the SRM as a way of validating the predictive capabilities of SRM tests.

The results from the SRM investigations agreed well with the dominant structure inferred from seismic data analysis indicating that SRM testing may be used for prediction of rock mass response to undercutting and caving.

The study allowed to track the fragmentation of each SRM sample as it fractured which was similar to average fragmentation observed in the mine.

Further exploration of the SRM approach could be undertaken as a potential means to estimate primary fragmentation.
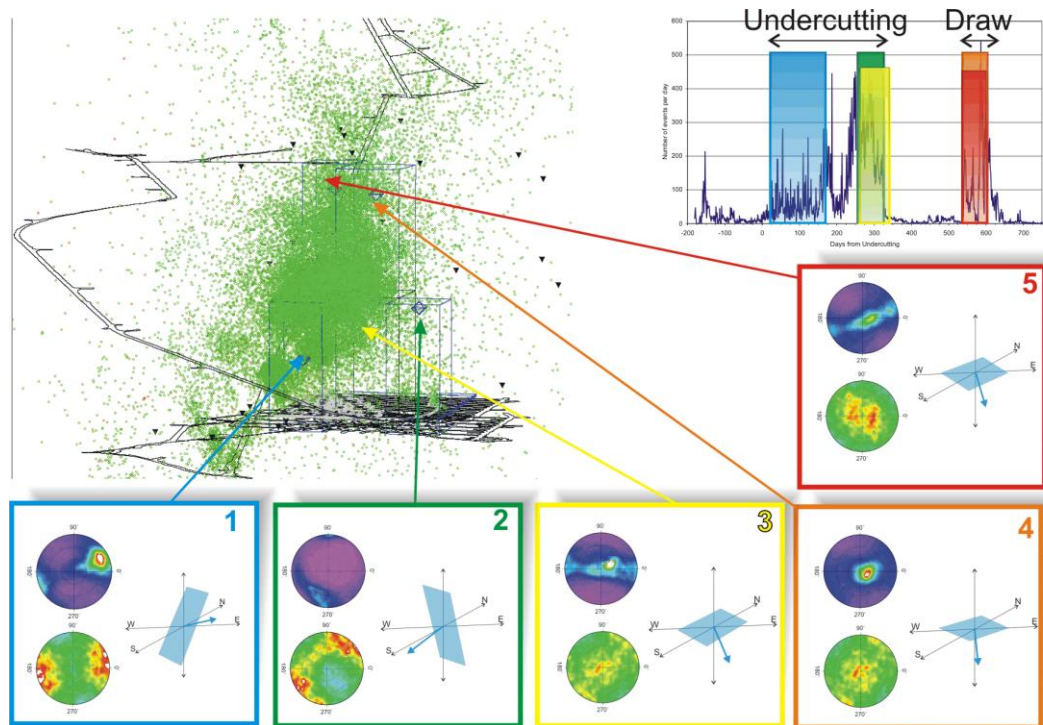

Figure 1: Stereographs showing the relative density of poles to the planes fitting the microseismic events induced at different stages of cave development at Northparkes Mine. The time period and the corresponding mining operation are shown in the histogram of daily seismic activity rate shown in the top-right corner. In each pane, the upper stereograph represents the density plot calculated for in-situ induced microseismicity while the lower stereograph is calculated for the synthetic model constructed for the corresponding geomechanical domain. The results show a good correspondence between in-situ and synthetic seismicity. The diagrams show the interpreted dominant planar structures.

Microseismic tools for the analysis of the interaction between open pit and underground developments

As part of the Mass Mining Technology project, the seismic catalogue from different mines, representing different challenges in cave development were analysed, in order to enhance the information extracted from the seismic record. A case study consisted on the seismicity recorded during undercutting and production at Palabora Mine leading which lead slope failure in the open pit above the cave. The transition from surface to underground mining presents a series of technical and operational challenges, in particular those arising from the interaction between the cave and the overlying pit. Seismic monitoring provides a unique means to obtain near real-time information about the development of the fracturing process induced by the mining operations. The temporal, spatial and source size patterns in the seismicity recorded during undercutting and production at Palabora Mine were investigated in order to identify associations between seismic parameters and the subsequent slope failure that could serve as a forecast tool in other mines.

The analysis made use of b-values and the cluster index (CI), a parameter quantifying the degree of interaction and clustering in events. The results showed a good correlation between high degrees of clustering, changes in the slope of b-value distribution and the development of major failure in the area above those areas with highly clustered seismicity. The conclusions showed that the back analysis of the seismic data provides a prediction technique that could now be employed during the planning stages of a mining operation. It is hoped that by employing these techniques it would be possible to incorporate results from predicted fracture network behaviour into engineering designs in similar future mining operations and thus provide a means to predict and mitigate against large scale failure as observed at the Palabora Mine.
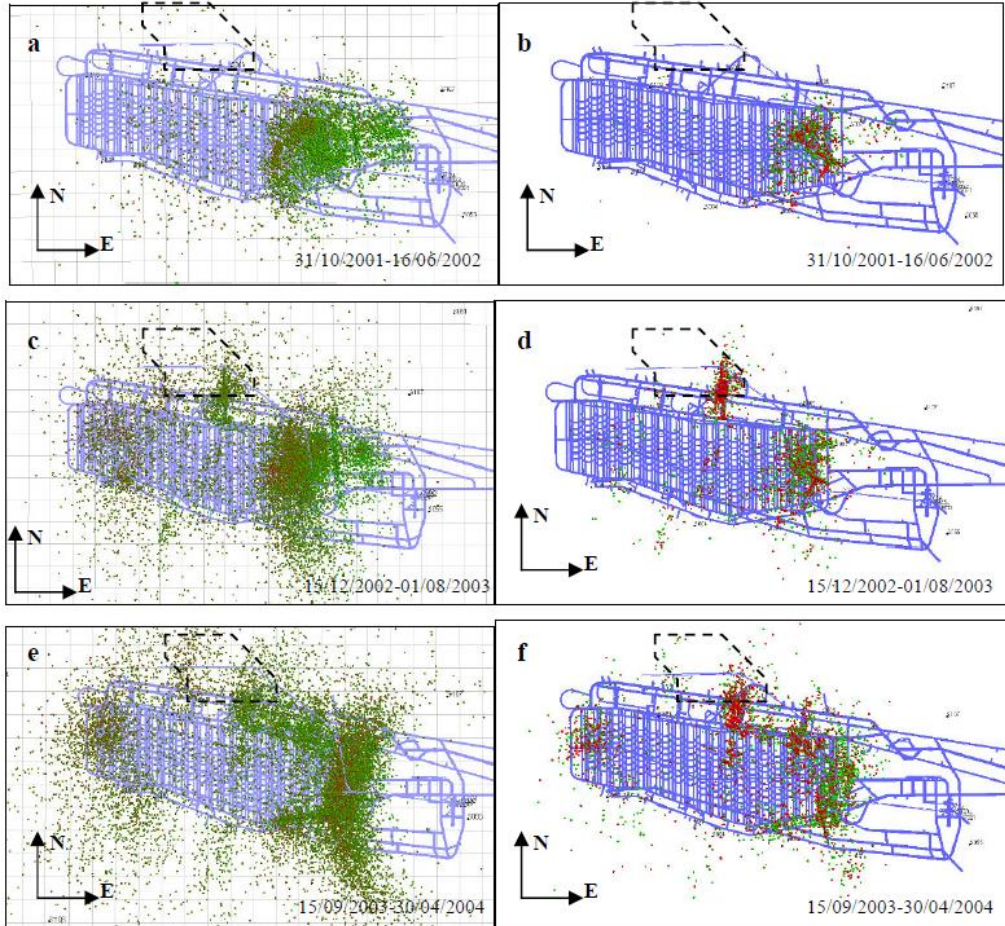
Case studies

Figure 2: Plan view of the seismicity at Palabora mine in different periods preceding the Open pit North wall failure in November 2003 (a-d) and post failure (e-f). Left column (a,c,e) shows all events scaled to moment magnitude, Right column (b,d,f) shows only events with CI>0 scaled to CI. The dashed outline represents the projection of the open pit mobilised zone.

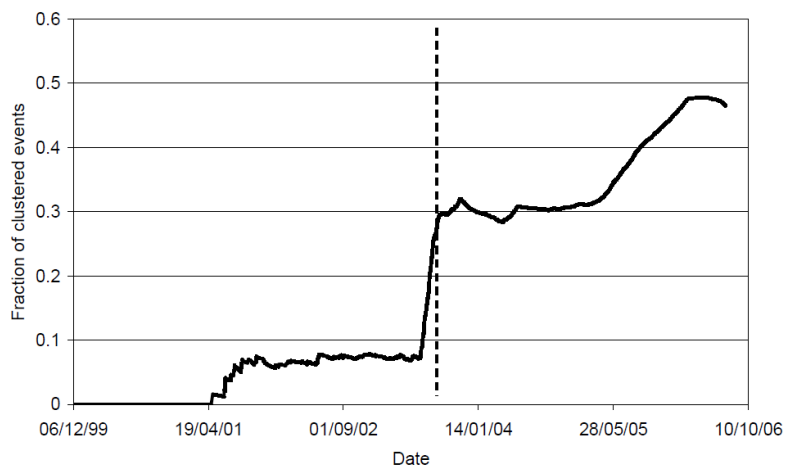*Figure 3: Evolution of the relative abundance of clustered events during the undercut and production of Palabora underground cave. The vertical dashed line marks the time of the slope failure in the open pit initiated at upper levels.*
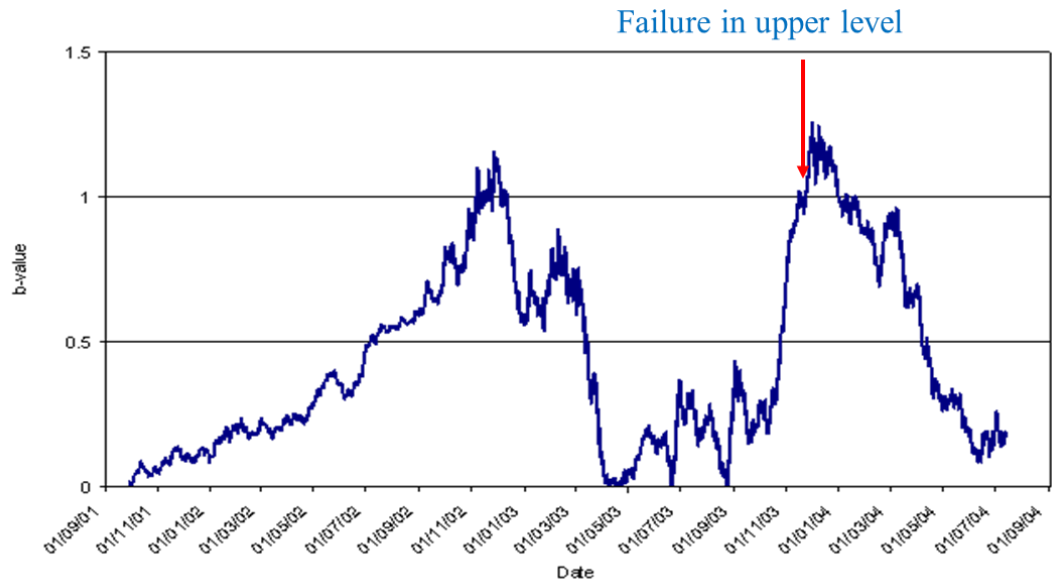
Figure 4: Evolution of b-values for the seismicity recorded

Quantification of preconditioning efficiency in cave mining

Hydraulic fracturing preconditioning has been applied as a means to induce cave propagation into unfractured rock volumes within underground caving mines. ASC analysed the processed microseismic events induced during preconditioning of an area within Northparkes mine to evaluate the effectiveness of the process and quantify the damage imposed by the hydraulic fracturing treatment. By combining the location of induced microseismic events with their source dimension, interpreted from the frequency content, it is possible to interpret and quantify the damage and degree of interaction between the induced fractures. The spatial and temporal evolution of the degree of interaction is provided by the cluster index, which allows the characterisation of events in terms of their potential interactivity.

The patterns of damage accumulation in different geomechanical domains of a caving production were analysed through a series of Synthetic Rock Mass samples subject to the same stress disturbance expected in the field and the analysis of the induced microseismicity. The analysis focuses on the comparison of damage and fracture propagation in caved volumes and a domain that failed to cave following the removal of the undercut and was subject to hydraulic pre-conditioning in order to stimulate cave development into the volume. In particular, the cluster index was calculated for sets of microseismic events induced during the hydraulic treatment of a non-caved rock volume and volumes previously caved. The degree of interaction between microseismic events and the evolution of source parameters such as moment magnitude and P and S-wave energy ratio appear to correlate with different behaviour in terms of cave propagation in the different rock volumes monitored in this study and can therefore provide feedback on the effect achieved on a preconditioned rock volume.
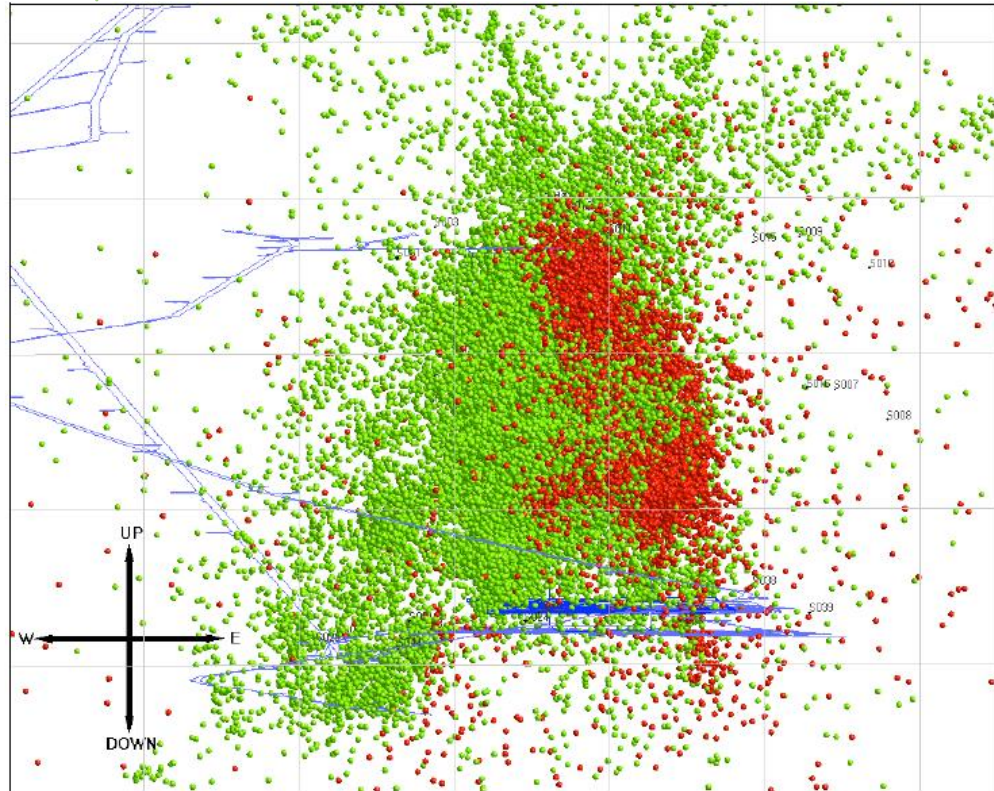
Figure 5: Microseismic events induced during the caving of volume E26 of Northparkes Mine. In green, events induced during the caving of the volume, in red, events induced during the preconditioning of the uncaved volume.
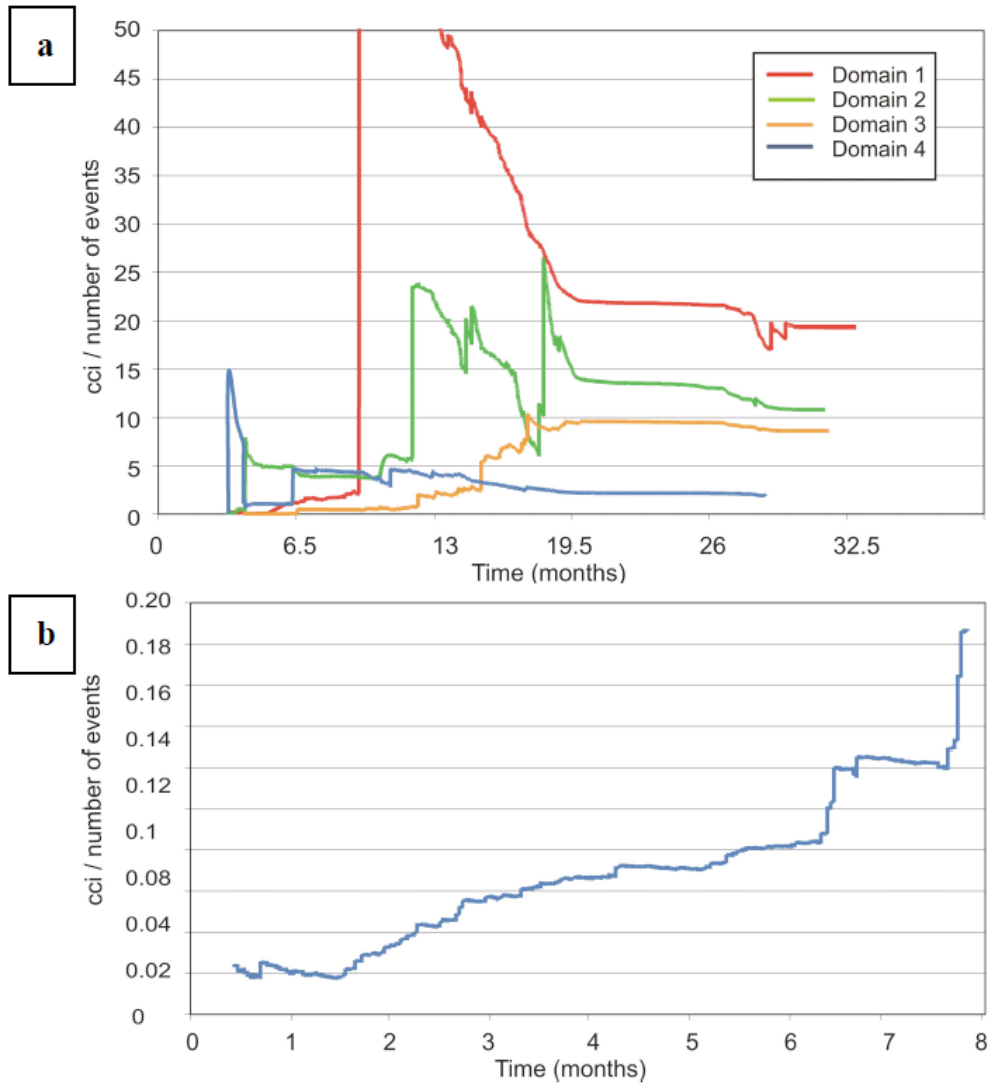
Figure 6: Evolution of the cumulative cluster index normalised to the number of events and cumulative number of located MS events for the events induced during the caving of four example domains (a) and the preconditioning of the uncaved volume (b).

Application of cave-scale rock degradation models in the imaging of the seismogenic zone

Microseismic monitoring provides insight into the location and extent of rock-mass fracturing induced by cave mining, enabling interpretation of the cave profile and validation of predictive numerical models. Source location uncertainties can lead to misinterpretation of the inferred characteristics of the fracture network. One principal source of uncertainty is the velocity model used to invert the location algorithm. Large-scale 3D numerical models of modulus changes across a caved mass can represent such complexities in the location algorithms, allowing more accurate interpretation of the microseismic activity. A Northparkes mine case study applies this advanced approach to microseismic data interpretation. The implementation of a nonlinear modulus-softening relation in a large-scale caving analysis was conducted at Northparkes mine. The model results were used to process the microseismic data and locate the seismogenic zone during cave propagation. A comparison of the predicted and observed microseismic events was completed to validate the seismic location and ray-tracing algorithms outlined herein.

Wavefront construction was used to forward-model travel times through a velocity model discretised as voxels that reproduce the damage distribution due to mining activities. This method can use predictive cave-scale numerical models of moduli distribution interpreted in terms of elastic wave-transmission velocities. Location of microseismic events using a cave-scale modulus model provides a more realistic description of the velocity structure and, hence, allows a higher resolution and level of confidence in the location and definition of the seismogenic zone. Model fit quality was assessed by comparing measured and modelled travel times. The quality of the fit between measured and modelled travel times for high-quality seismic events provides a means of validating cave-scale moduli-distribution predictions.
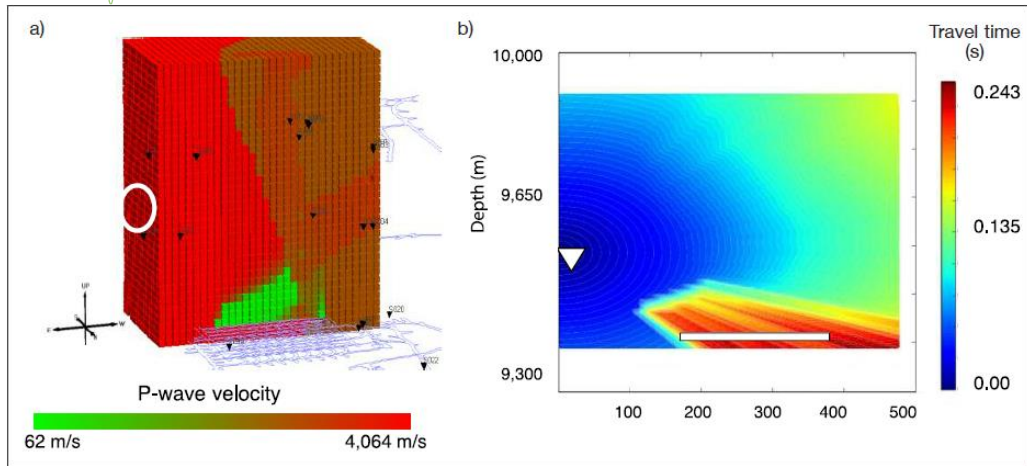
Case studies

Figure 7: Example vertical section of the wave-transmission model built from the FLAC3D™-based predictions of modulus/density variability for early drawing stages at Northparkes lift 2. Voxels are colour scaled to P-wave–transmission velocity. b) Contour plot of travel times calculated through ray-tracing from the station circled in a) a white triangle in b) to the points in the chosen east-west section. The colour scale represents the travel time, with warm colours indicating higher travel time values. The white box shows the approximate position of the undercut.
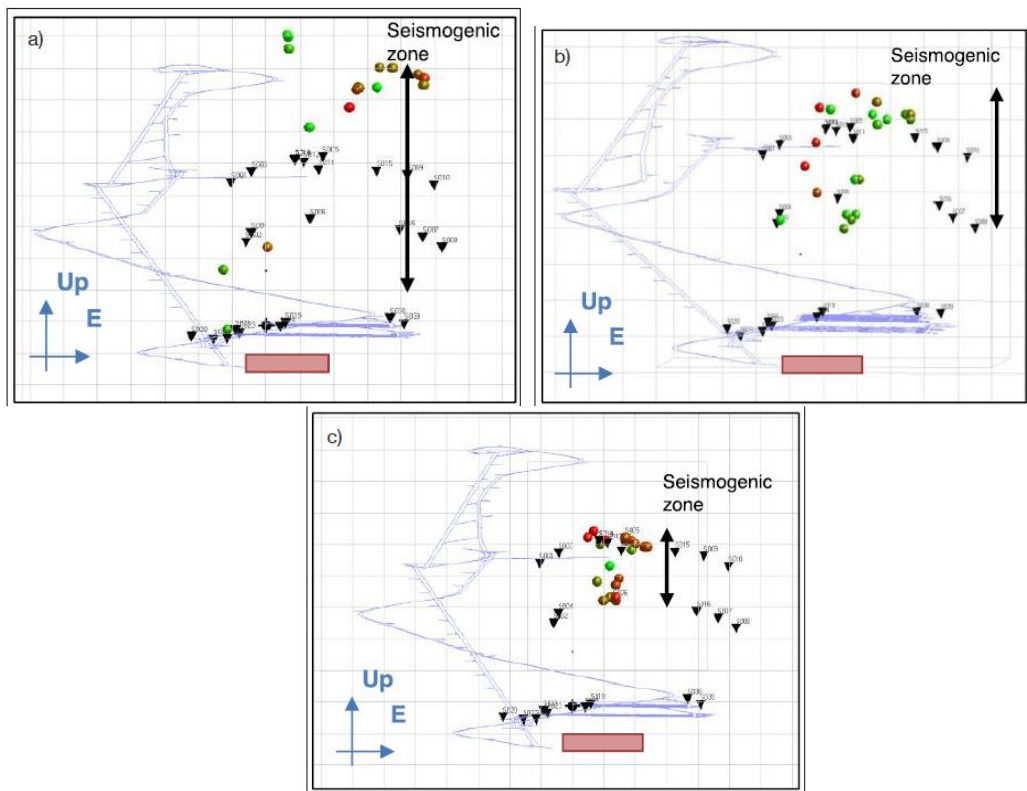

Figure 8: Location of sample high-magnitude microseismic events from early undercut development of volume e26 at Northparkes mine. Events were located using three velocity models: a) a homogeneous-isotropic velocity model, b) a coarse damage model (model 1), and c) a velocity model using the cave-scale yield predictive model (model 2). grid size is 50 m. Note: The red box represents the progress of the undercut at this stage

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Publications

Seismic processing and Quality Control

ASC offers a fully integrated service for real-time and post-processing of seismic data. We have reviewed, quality checked and analysed third-party seismic and microseismic datasets from a wide range of applications. Our seismic and microseismic processing quality control service focuses on the review of location uncertainty and source parameter calculation, specifically sensitivity to velocity uncertainty, tool orientations, location algorithm and phase identification.

Our fully integrated microseismic processing service can provide:

- Monitoring of fracturing operations
- Site and regional seismic characterisation
- Monitoring of regional natural and induced seismicity
- Quality control of acquisition settings and seismic dataset
- Full Post-processing and enhanced analysis
- Seismic risk assessment
- Software Training and Consulting

Our consulting services on project design cover many applications such as:

- Microseismic monitoring array design
- Provision of optimal seismic instrumentation from our partners
- Geomechanical modelling
- Pre-analysis of structural deformation of the host rock

For more information on any of our products or services please visit us on the web at:

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