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Progression and management of seismic hazard through the life of Telfer sublevel cave

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Abstract

Telfer gold mine consists of both open pit and underground operations, including a mature sublevel cave. Changes to mine design, the addition of subsequent sublevels, level footprint and increasing depth have all resulted in a changing seismic hazard, which is managed using a combination of seismic exclusions zones and dynamic ground support. The seismic hazard associated with high-stress slot development and production is well understood, but the progression of seismic activity into areas of low expected seismic hazard required a systematic upgrade to support.

A common theme is that changes to mine design have resulted in additional and changing seismic hazards, with areas of existing infrastructure no longer adequately designed or supported for the future expected demand. Understanding how changes to mine planning, addition of sublevels, footprint size and depth all effect the evolving seismic hazard, have been key to managing the hazard.

Keywords: *hazard management, seismicity, sublevel cave*

1 Introduction

The Telfer gold mine (Telfer), owned by Newcrest Mining Limited, is located in the Great Sandy Desert 400 km east-southeast of Port Hedland, and approximately 1,300 km northeast of Perth. The Telfer deposit was discovered in 1971, when anomalous gold and copper values were returned from outcrops in what is now known as Main Dome. In late 2000, the operation was put into care and maintenance after producing approximately 6 Moz of gold. A feasibility study was undertaken in 2002 that established the strategy for mining and processing ore from the surface and underground deposits. This led to the re-establishment of open pit mining operations in 2004, and underground operations in 2006.

Telfer is currently producing from the Main Dome and West Dome pits, and the underground operations, which consist of a sublevel cave (SLC), narrow vein, long-hole open-stoping (M Reefs) and long-hole retreat stoping (Western Flanks). The SLC was initiated in late 2006, at the 4650 Level, 850 m below surface. The cave broke through into the Main Dome open pit in late 2009. The footprint of the cave is approximately 1,000 m by 250 m, with the current SLC extraction levels some 1,085 m below surface.

The open pit is currently mining at rates in the order of 50 Mtpa of ore and waste, while the underground is hoisting in the order of 6 Mtpa. The ore sources combine to feed a mill that treats approximately 24 Mtpa.

2 Mine geology

Telfer's geology is divided into two main geological domes, namely West Dome and Main Dome, with underground mining operations occurring in the Main Dome. The Main Dome formation is a large, oval-shaped, double-plunging open fold, consisting of a sedimentary stratigraphic sequence (Figure 1).

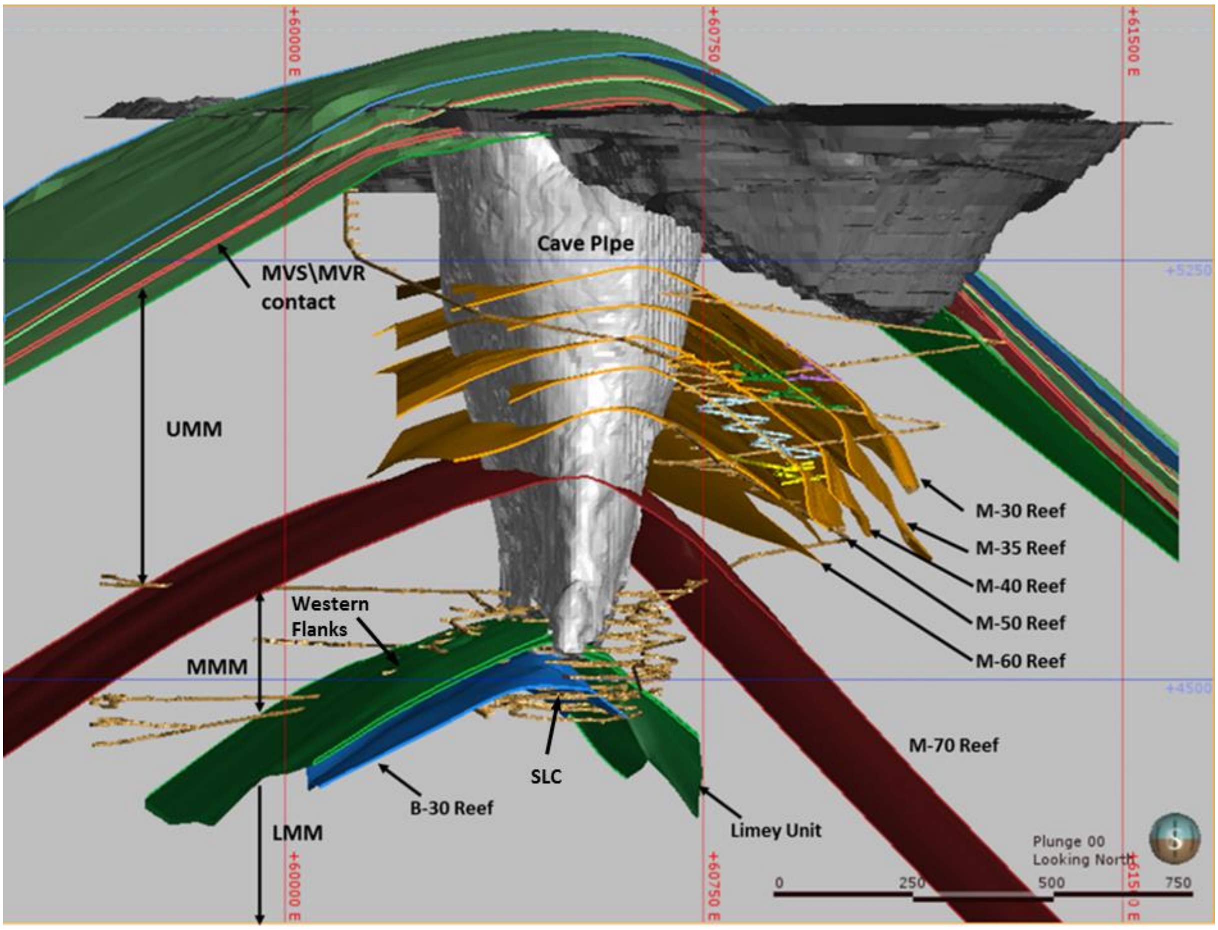


Figure 1 Overview of geological units at Telfer, looking northeast

The current underground operation is constrained within the Malu Formation, which is a massive sandstone and quartzite unit with thinly interbedded pelitic strata. The Malu Formation is divided into three major members; the Upper (UMM), Middle (MMM), and Lower (LMM) members, that have undergone moderate to intense sericite and silica metasomatism.

A large regional fault zone, the Graben Fault, exists on the eastern flank of the main orebody, which is intersected by mine development. A number of large fault structures are related to the Graben Fault.

2.1 Rock mass characteristics

The regional faulting, folding and subsequent thrusting has resulted in slip between sedimentary layers. The slip has caused brecciation of the weaker siltstones, facilitating the formation of both reef and shear units throughout the entire mine stratigraphical sequence. This has resulted in frequent and pervasive jointing, decreasing the overall rock mass strength, making it amenable to caving.

The intact rock strength is generally very high (greater than 200 MPa), with the exception being the major ore units (around 80 MPa), with a generally fair quality rock mass, with rock mass rating (RMR) values between 50 and 60.

The major principal stress has been measured to strike roughly northwest–southeast, dipping around 20° to the southeast. Nine stress measurements have been taken at various depths using the HI Cell over-coring method, AE techniques and borehole slotting. The calculated results are displayed in Table 1.

Table 1 Principal stress orientation (D = depth below surface in metres)

Principal stresses	Magnitude (MPa)	Orientation	
		Dip (°)	Bearing (°)
Major	0.046D + 6	20	130
Intermediate	0.032D + 0	40	22
Minor	0.019D + 0	43	240

3 Mine design

3.1 Mine history

The feasibility study for underground mining was completed at the end of 2002, with the mine layout based on that used at Ridgeway, with cave propagation in an east to west direction. Following a review of the layout in 2004, the cave advance was changed to west to east, to promote cave initiation and propagation.

The SLC is based on a transverse layout, with crosscut centres spaced at 14 m (9 m pillars and 5 m wide crosscuts) and sublevels spaced at 25 m. The slot drive is on the western flank of the orebody, with production retreating in a 'V' shape towards the eastern flank, where perimeter drives and ore passes are located (Figure 2). The crusher and shaft is located on the western side of the SLC, requiring the haulage drive to pass under the SLC.

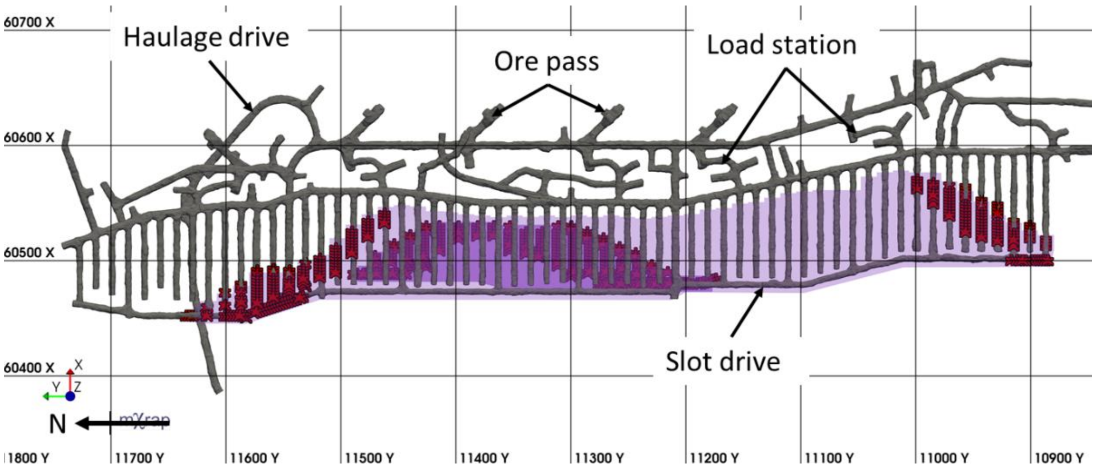


Figure 2 Telfer Mine transverse layout and mining front, 4475 Level and 4440 Level mining front

Caving was initiated at the 4650 Level and planned to progress seven levels to the 4500 Level, with the haulage drive and orepass infrastructure located on the east of the 4475 Level, passing under the SLC.

The 4650 Level had a footprint of 315 × 185 m, with levels progressively increasing in size and stepping out to the north and south, as far as the 4525 Level (1010 × 165 m). Below the 4525 Level, the footprint began to reduce in north–south extent (Figure 3).

3.2 Change to mine design

In 2013, the 4475 Level was added to the mine plan resulting in a bypass of the haulage drive under the SLC, and the addition of load stations to the 4475 Haulage Drive. The inclusion of the 4475 Level production drive and loading stations between the 4475 Haulage Drive and production footprint resulted in numerous pillars with a 1:1 ratio (Figure 2).

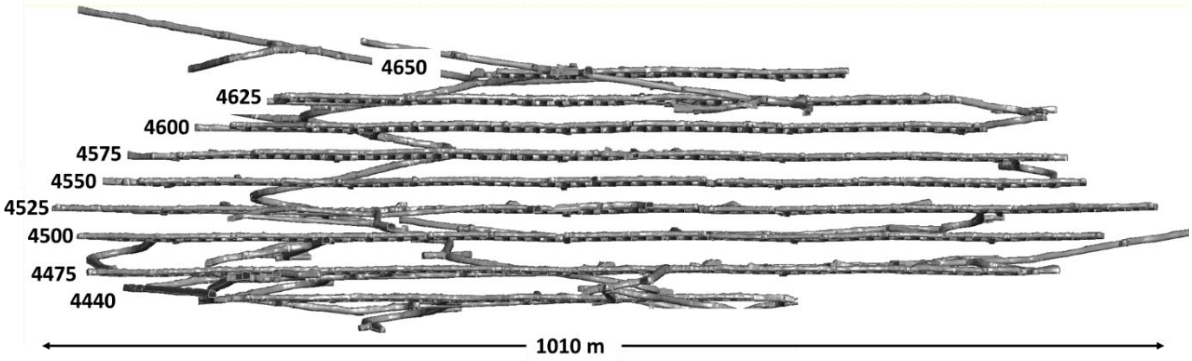


Figure 3 Telfer Mine SLC level footprint

Below the 4600 Level, the SLC stepped in to the east to target higher grade reserves. However, the southern part of the 4475 Level stepped back to the west of the above levels, resulting in the cave being pushed into the high-stress abutment, with an increase in seismic activity around the slots drives post-2016 (Figure 4).

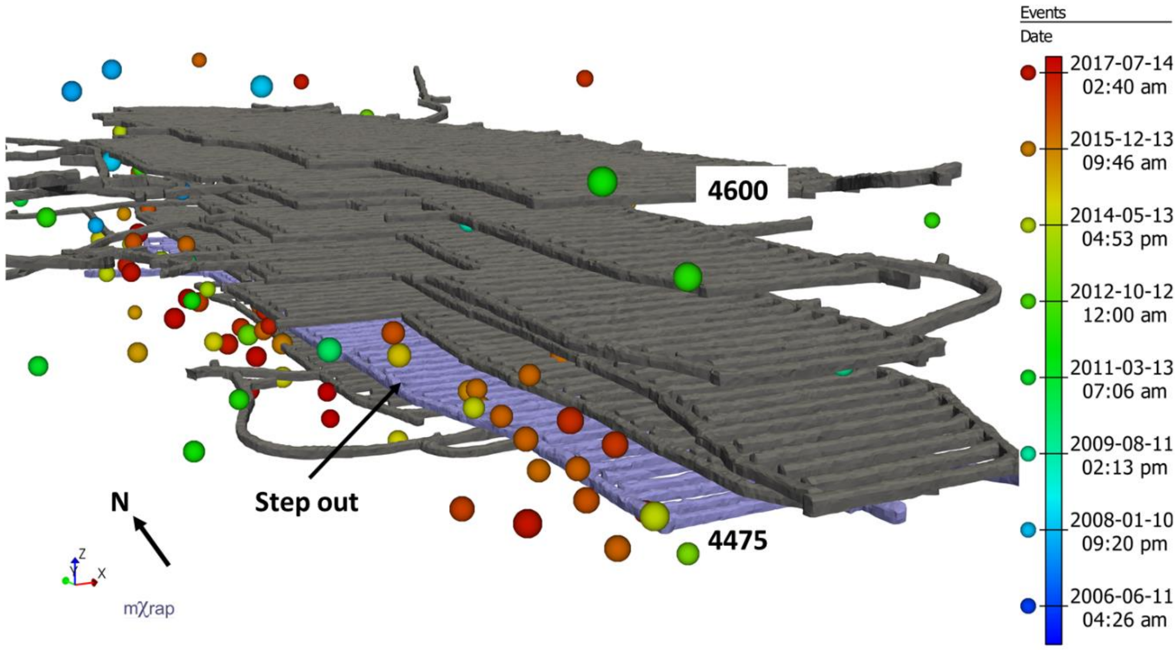


Figure 4 4475 Level step out to the west and seismic events over +1 M_L coloured by time

The 4440 Level was added to the mine plan in 2015, with the footprint reducing significantly to 455 × 85 m, located in the north and central section of the SLC footprint.

4 Seismic system

The Telfer seismic system was initially installed and commissioned in late 2005, and has since been upgraded and expanded to include 43 operational triaxial geophones of different natural frequency; 22 4.5 Hz and 21 14 Hz geophones. This allows for the estimate of seismic source parameters and local magnitude, with the seismic system providing real-time data transfer via the underground fibre optic network.

The sensor array took advantage of mine infrastructure to locate sensors at different depths and locations around the SLC (Figure 5). The system layout and sensitivity was designed for location accuracies of less than 30 m, and recording of all events greater than local magnitude (M_L) -1.5. Due to the development layout and expected seismic hazard, a large proportion of sensors are located on the western side of the SLC, resulting in higher system sensitivity and location accuracy on the western abutment of the SLC.

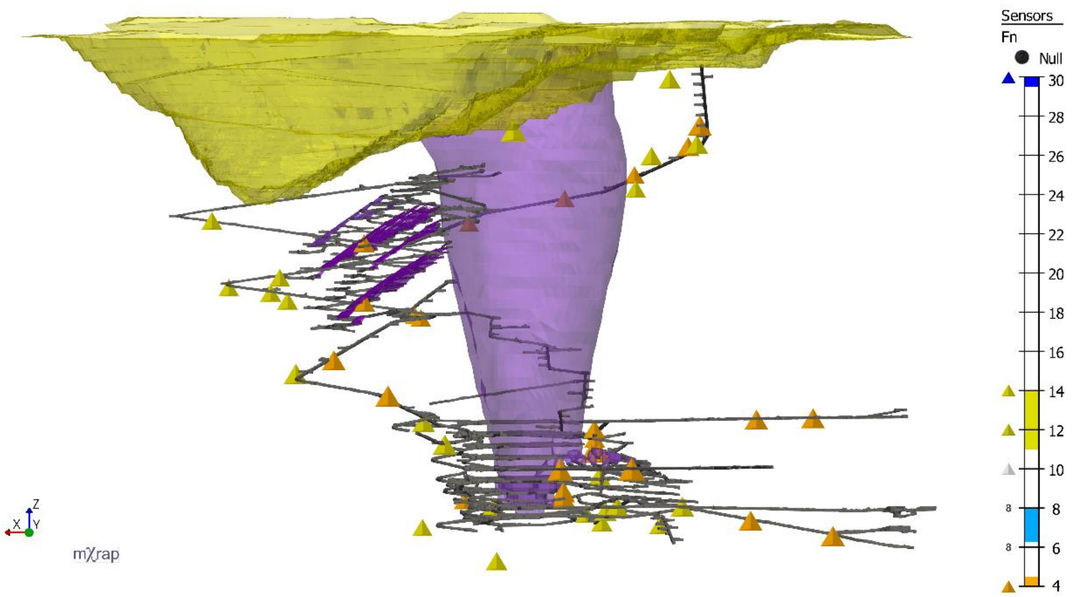


Figure 5 Telfer Mine seismic system layout, looking south - 2018

5 Seismic history

The seismic and mining history for the SLC is outlined in Table 2 and Figure 6. The seismic activity rate was highest during cave propagation and breakthrough to the Main Dome pit.

Table 2 Telfer SLC and seismic history

Period	Mining activity	Events (M_L > -1)	Average events/day (M_L > -1)	Largest event (M_L)
2005–2006	First production and early stages of cave initiation	751	~20	1
2007–2008	Cave established and mostly propagated to the surface	43,252	~460	2.3
2009–2010	Cave breaks through to the surface and growth steps out in both the northern and southern limbs (4600 and 4575 Levels)	70,372	~460	1.9
2011–2012	Continued cave growth in the northern limb (4550 Level)	33,046	~170	2.4
2013–2014	Cave growth steps out in both the northern and southern limbs (4525 Level). Production begins on the 4475 Level	23,615	~130	2.9
2015	Cave growth on the western side of cave. 4475 production mines through the western truncation of the SLC	15,173	~190	1.8
2016	Production on 4500 steps out in the north	12,887	~160	1.9
2017	Production of 4475 and 4440, and start of Western Flanks mining	9,545	~95	2.1

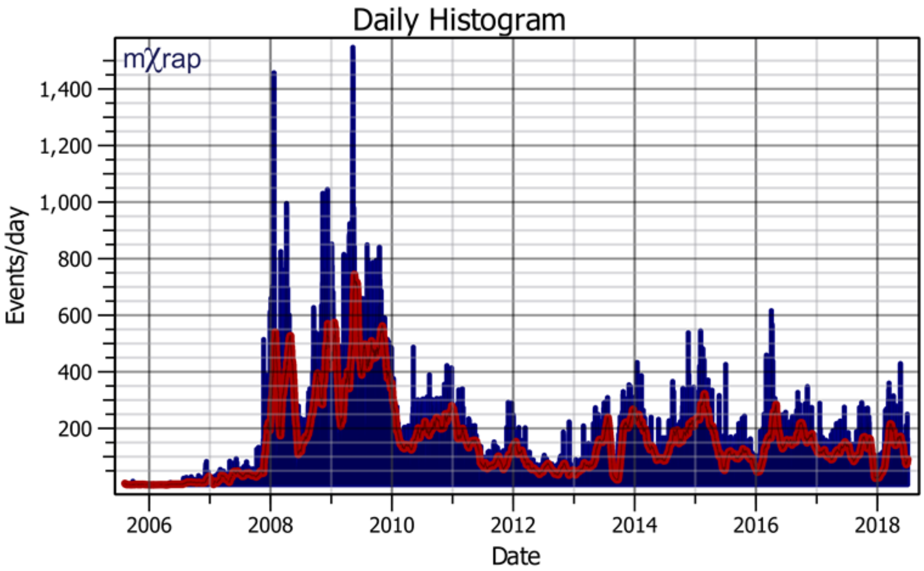


Figure 6 Historic of seismicity >M_L-1.5 at Telfer, 2005 to 2018, including 30 day moving average

5.1 Cave growth

Following breakthrough to the Main Dome open pit in 2009, the concentration of cave growth seismic activity has been located in the north-east and south-west of the SLC – the areas of maximum stress concentration (Figure 7).

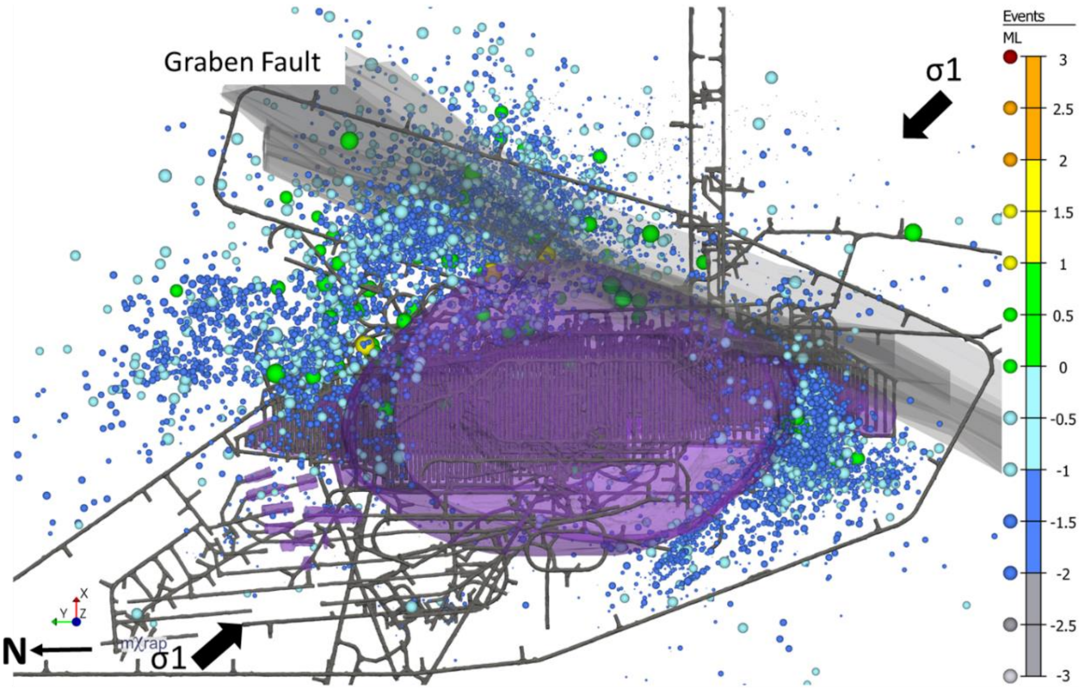


Figure 7 Three months of seismic activity demonstrating stress concentration around the cave column

Since 2016, activity on the northeastern side of the SLC, up to approximately 4700 Level, has increased, which appears to be a result of stress redistribution on the northeastern flank, with subsequent cave break-back. This area also coincides with a confluence of major structures and rock units.

5.2 Understanding of seismic hazard

The pattern of seismicity at Telfer has generally been that the western side of the SLC has predominantly experienced high-stress, large events, generally coincident with and adjacent to slot advance, with the eastern side shadowed by the slot, resulting in low-energy cave growth events. Figure 8 displays a plot of energy index for the 4475 Level that illustrates this understanding.

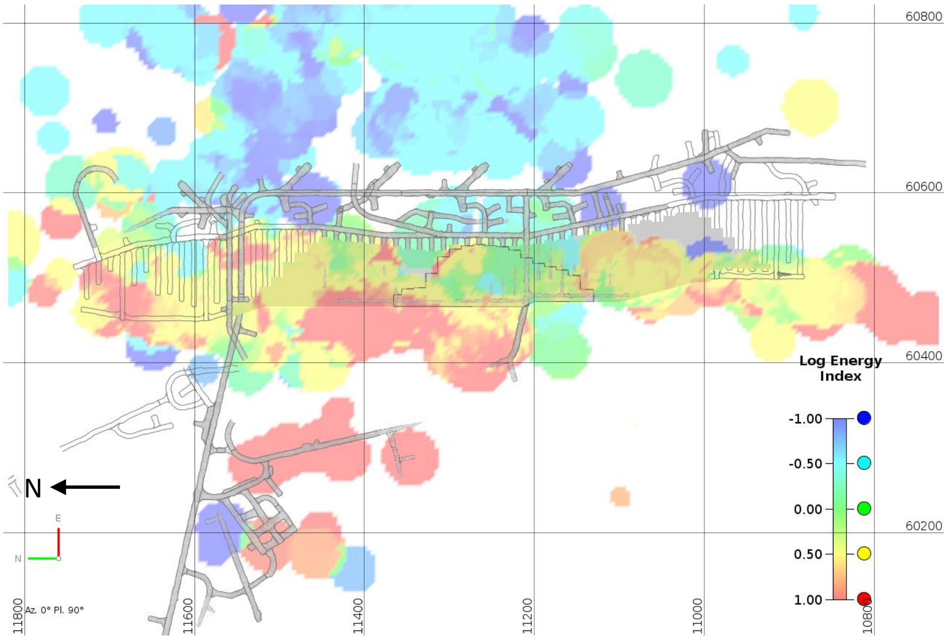


Figure 8 Plan of the 4475 Level showing energy index (pers. comm., Institute of Mine Seismology November 2017)

The majority of damaging seismic events has been located on the western side of the SLC, with most of the damage associated with the slot drives.

A recent report by Beck Engineering (2015), indicates that a reducing footprint means subsequent levels are less 'shadowed' by levels above, and at times, slotting induces large movements and energy release. At some other mines, such as Perseverance in Western Australia, shrinking level sizes have evolved a similar pattern of seismicity encroaching on work areas with large seismic events and rockbursts occurring more frequently.

5.2.1 Blasting and seismicity

Historically, large seismic events have been associated with slot firings on the western abutment of the SLC, with an increase in activity as the slot advance pushes into the major stress concentration to the north and south. This is noticeable in the magnitude/time charts. The example in Figure 9 shows the seismic response between October 2017 and April 2018, with a noticeable reduction in seismicity during the SLC shutdown between November and December 2017. Also noticeable is the seismic response to slot firing, with a coincident jump in number and magnitude of events.

5.2.2 Production and seismicity

The overall number of seismic events and cave growth is strongly influenced by production from the SLC, as demonstrated during the suspension of SLC production, where there was an instant reduction of seismic activity (Figure 9).

The relationship between more subtle production rate changes and seismicity is less apparent. Production rate has gradually reduced over time. However, during the same period, the rate of occurrences of events over $M_L > 0$ has increased, with a greater rate of increase for events $M_L > 1$ (Wesseloo, pers. comm., 14 December 2017).

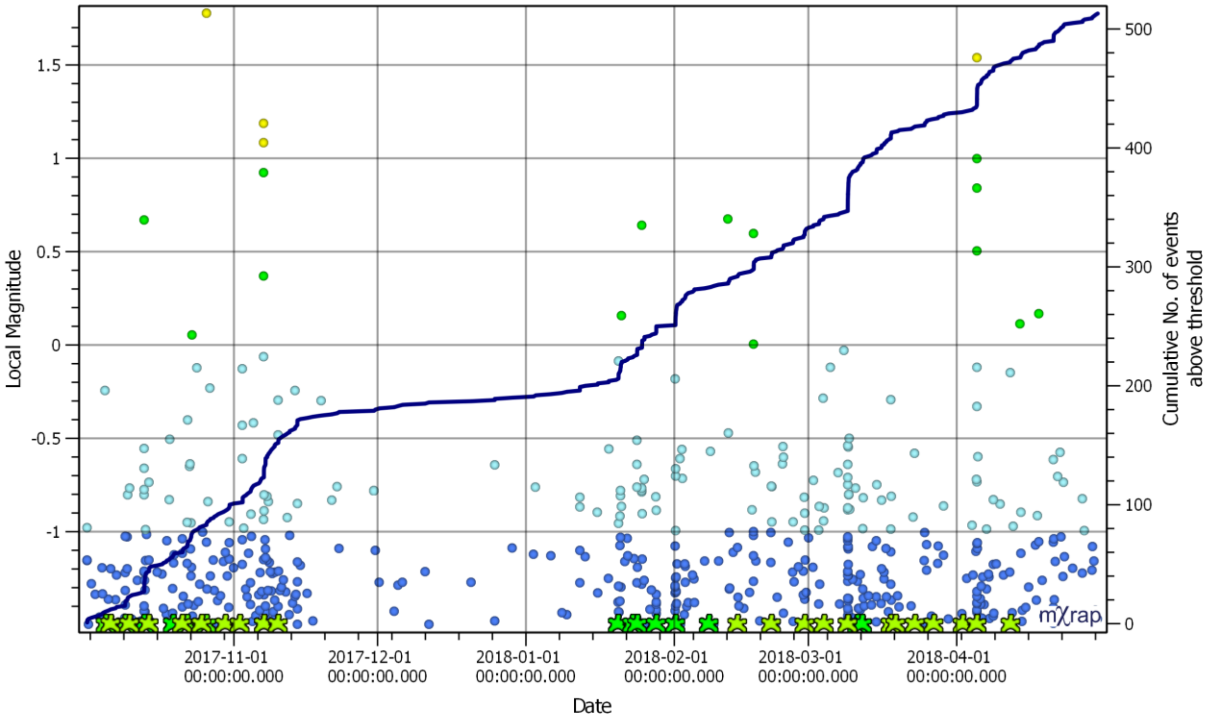


Figure 9 Magnitude/time chart, with cumulative number of events line, displaying response to firing. The green stars along the bottom indicate SLC slot firing blasts

5.2.3 Seismicity and structural influence

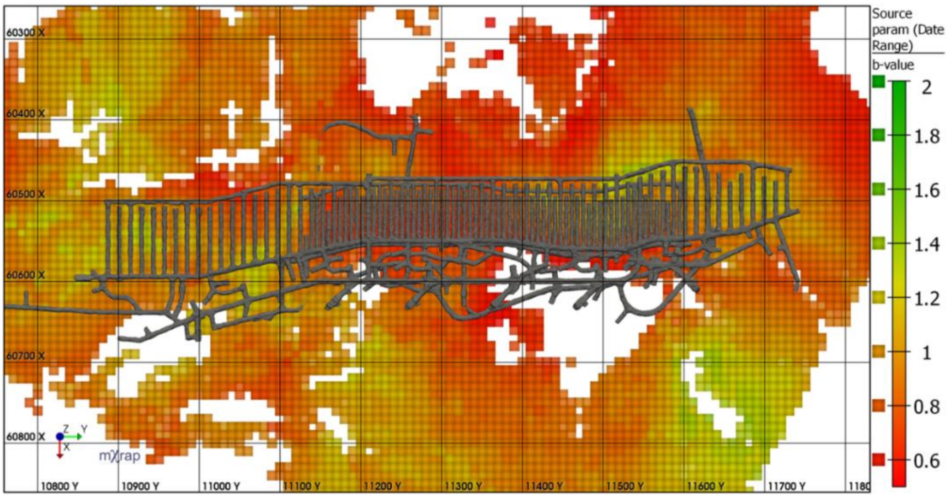
Other than the Graben Fault, no identified structures appear to dominate seismicity, and seismic hazard appears to be driven by mining-induced stress on local structures within the rock mass. Over time, the seismic hazard migrates, due to local stress changes caused by the mining front and larger scale stress redistribution as the rock mass zones around and under the SLC yield and shed load to other areas of more competent rock (Wesseloo, pers. comm., 14 December 2017). This has resulted in seismicity now exhibiting less blasting-dependant behaviour, occurring outside blasting and exclusion practices, as the cave zone enlarges.

Since 2016, the magnitude of the seismic hazard has increased on the eastern side of the cave. This appears to be associated with a yielding of pillars on structure within the 4475 Level, and a subsequent redistribution of stress onto the eastern abutment. A general drop in the b-value in the eastern abutment (Figure 10) indicates a possible mechanism change, from a crushing-dominated failure mode to a shearing-dominated mode (Wesseloo, pers. comm., 14 December 2017). Around the western side of the cave an increasing b-value appears to indicate greater rock mass damage.

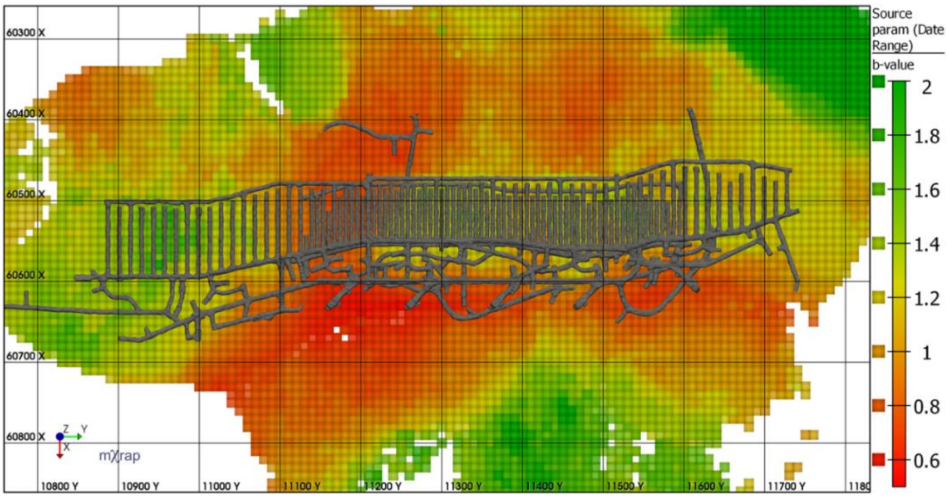
5.3 Large events

Large events have historically been associated with slot firing, and have occurred simultaneously with, or directly following, firing in the western abutment (Figure 11).

The largest event to date was M_L+2.9 in November 2014, located in the northwest abutment, occurring simultaneously with a production firing in the 4500N slot drive. The likely mechanism was unclamping of the B30 Reef and a number of intersecting structures.



(a)



(b)

Figure 10 Plot of b-value (a) 2012–2016 at the 4430RL; and, (b) 2017 onwards, showing higher b-values to the west and lower b-values in the east

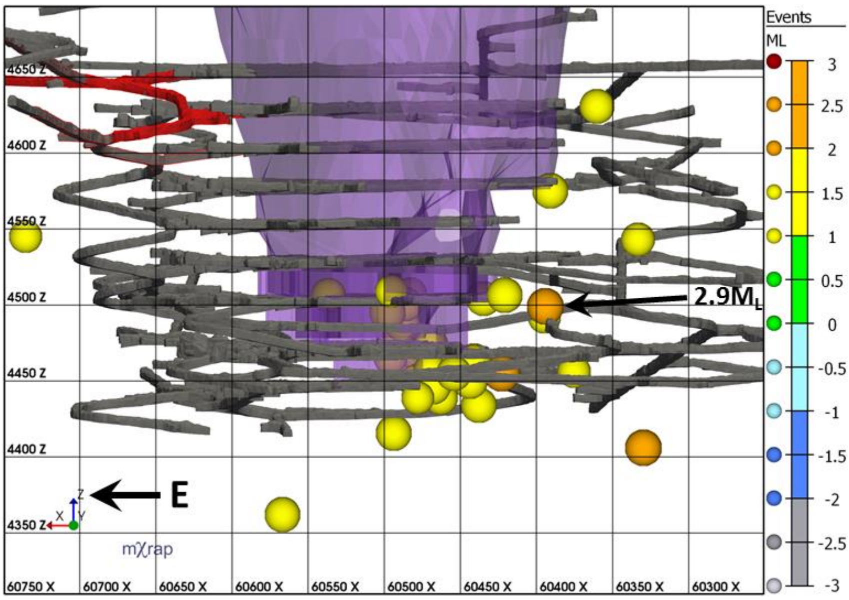


Figure 11 Seismic events greater than +1.5 M_L clustered around the 4475 and 4440 slot drive

6 Managing seismicity

Seismicity is managed through a hierarchy of controls, with the objective that hazards should be removed, with protection measures or just-in-time forecasting techniques adopted only as a last resort.

Control measures can be categorised as either tactical or strategic:

- Tactical applications are typically operational in nature, such as ground support, seismic exclusion practices and seismic response trigger action response plans (TARP) for large events or rockbursts.

  The TARPs detail the actions, communication and response required in the event of a large seismic event experienced in a number of locations, or a local rockburst, respectively. This includes immediate actions to be taken and reporting, as well as investigations and any remedial action required.

- Strategic applications typically relate to mine planning and sequencing activities, such as shadowing areas and pillar sizes. These are outlined in the Telfer Seismic Risk Management Plan.

6.1 Exclusion practise

Seismic exclusion practices are implemented at Telfer for slot firings and stand-up firing of crosscuts, with exclusion zones based on Omori analysis of slot firings in different quadrants of the SLC. Minimum exclusion practices are three hours, but must be reviewed by the geotechnical engineer prior to lifting.

6.2 Ground support

Ground support practices have evolved with the increasing seismic hazard, with dynamic ground support installed in the slot drive, final 20 m of SLC crosscuts, and North Abutment zone. Ground support in these areas consists of 50 mm fibre-reinforced shotcrete (FRS), mine mesh and 2.4 m de-bonded Posimix bolts, with 25 mm FRS sprayed over the mesh. Mesh sheets are overlapped by 1.5 m, securing the overlap with two Posimix bolts, reducing the potential for overlap failure (Figure 12). De-bonded Posimix bolts are installed using 1.5 m resin cartridges to limit the guillotine effect during shear loading and increase the amount of deformation the bolt can withstand before failure.

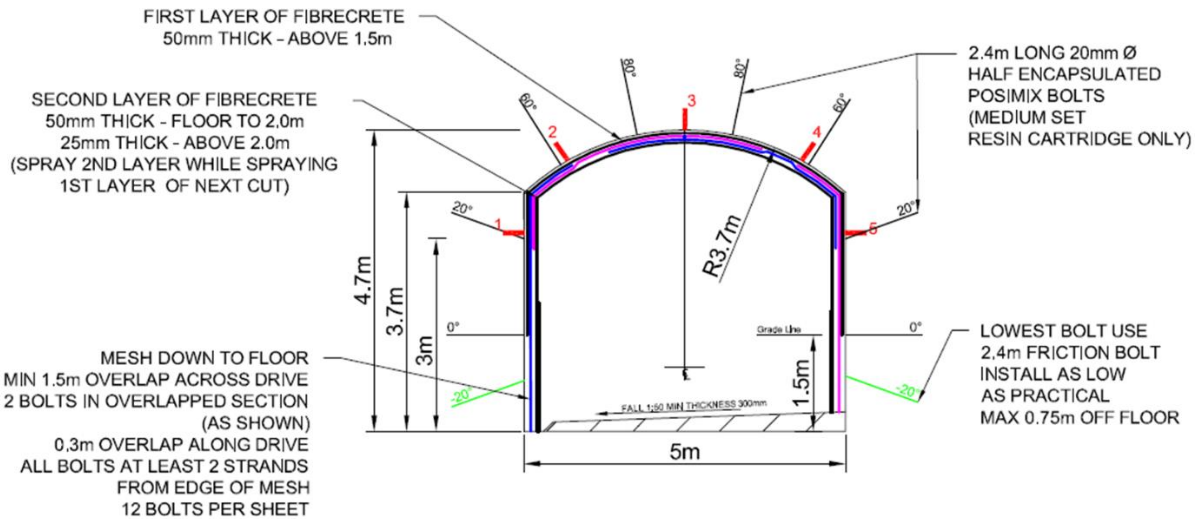


Figure 12 Dynamic ground support scheme used in the slot drive and high seismic hazard areas

Within the SLC, outside of the above domains classified as requiring medium to high dynamic ground support, the ground support standard was 50 mm FRS and fully bonded Posimix bolts.

6.3 Production management

Production rules are implemented to protect development, where possible, with the slot drive shadowing the subsequent development. SLC crosscuts are held 12 m short of the slot drive until the slot is fired past the next crosscut, shadowing the area, before the pillar is closed and stand-up fired (Figures 13 and 14).

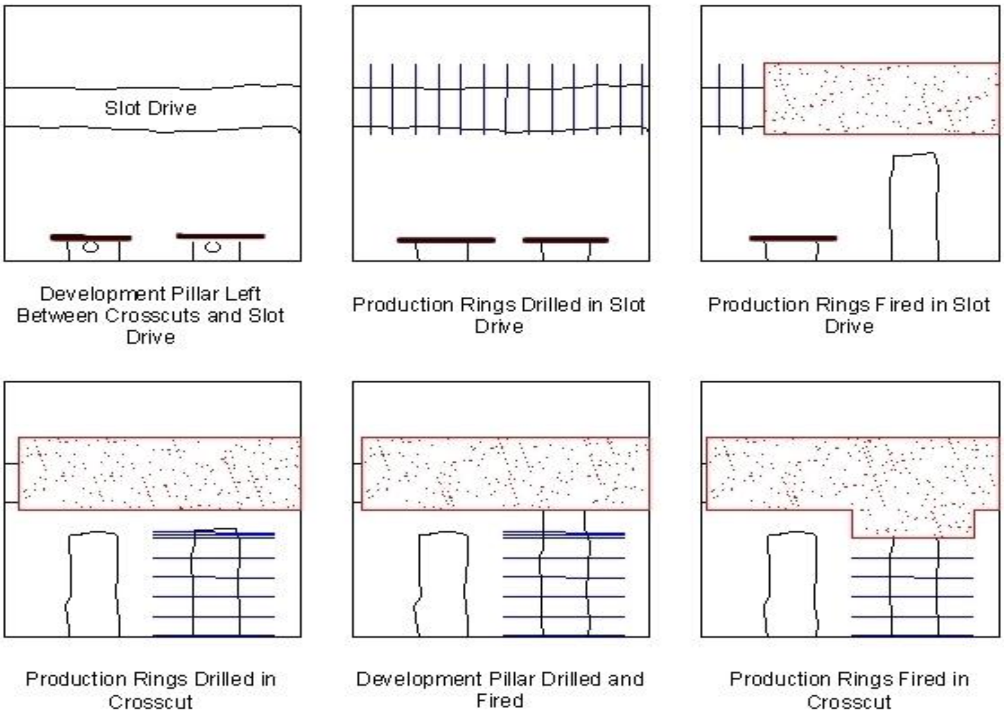


Figure 13 Plan of development and production sequence to shadow crosscut development and pillars

Slot drives on subsequent levels maintain a minimum 40 m lead-lag, to reduce interaction between levels, and crosscut lead-lag rules to maintain the production front between 0 and 45°.

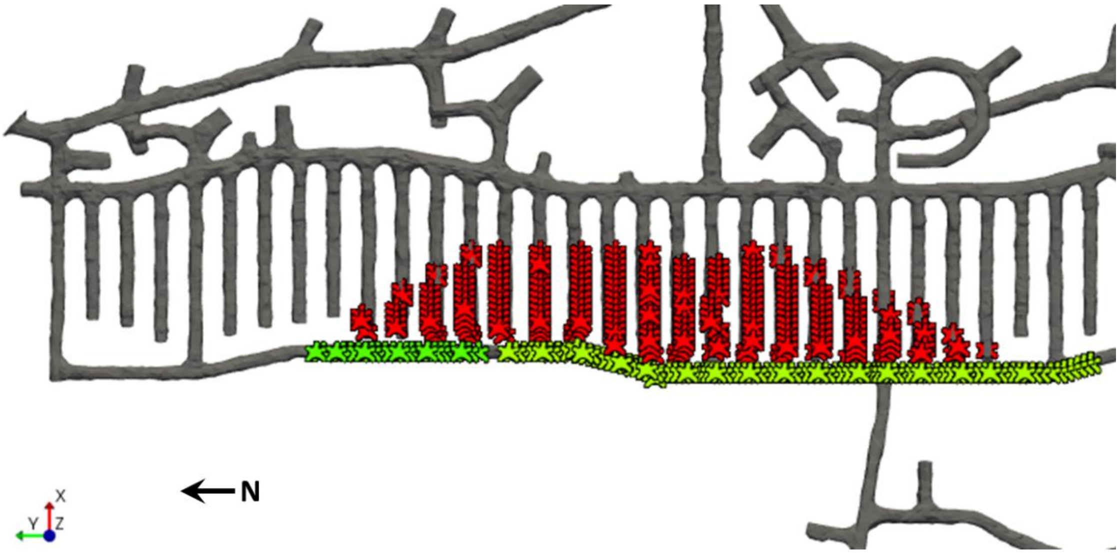


Figure 14 Plan of 4440 Level showing crosscut firings in red, demonstrating the slot drive firings in green passing the crosscuts before they are developed past their hold point

7 Upgrade to sublevel cave ground support

7.1 Identification of high-risk areas

A significant amount of development on the eastern side of the SLC was completed with low energy absorption ground support schemes and, with the changing pattern of seismicity, required upgrading to match the future expected demand. A targeted response to support upgrade was developed, reducing disruption.

7.1.1 Damage mapping

Underground inspection and mapping was completed to identify the installed ground support capacity, corrosion and damage. The Kaiser support damage scale (Kaiser et al. 1992) was used to rank the level of support damage, along with a site-based, six-stage corrosion scale, from no corrosion to extreme corrosion. Ground support standards were also assigned, based on the dynamic capacity of the reinforcement and surface support. Of particular concern were areas that had only FRS surface support, with no weld mesh, existing damage or high corrosion. The results of the mapping were recorded using the mXrap damage mapping application (Harris & Wesseloo 2015) (Figure 15).

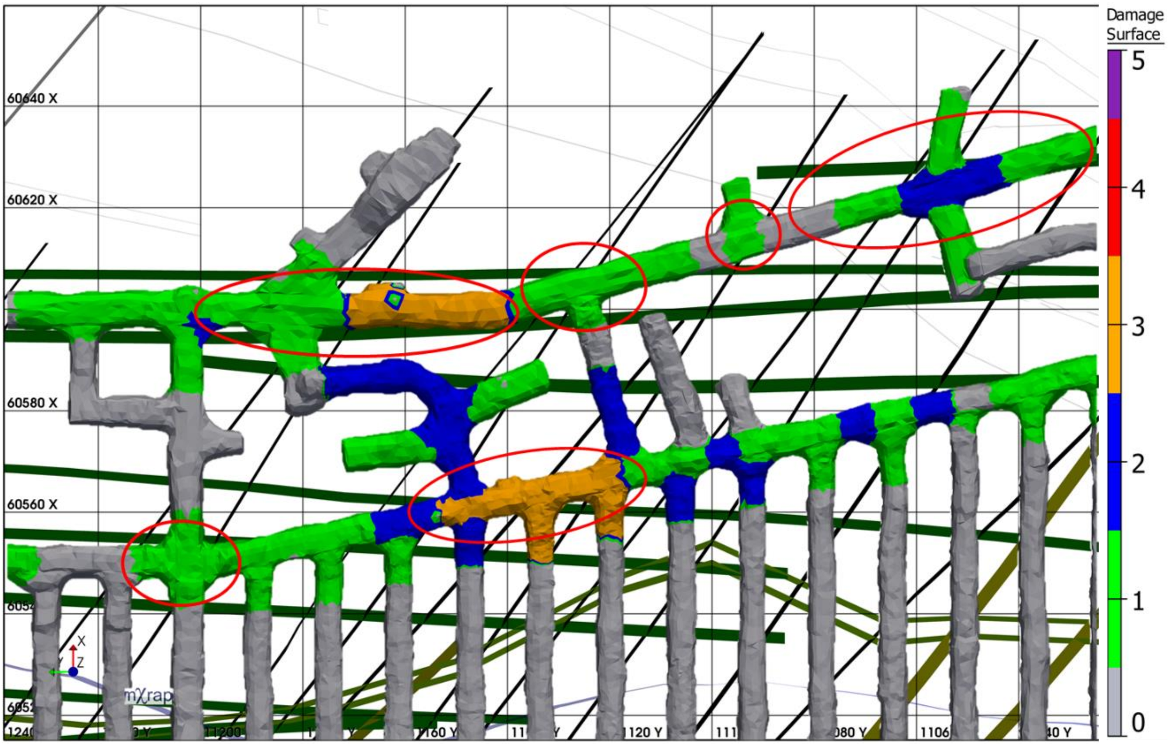


Figure 15 Section of the 4475 Level with identified structures and damage mapping recorded in mXrap

7.1.2 Structural geology review

A review of the structural model and historic fall of ground data identified that damage is associated with certain structures and that certain combinations of structures are particularly prone to instability. Falls of ground have tended to occur most frequently along the intersection of reefs (or bedding planes) with southwest-dipping veins (SWDV), northwest-trending veins (NWV) and south-dipping joints (SDJ).

The majority of these falls of ground have occurred close to the production front, well after development, suggesting that these structures are not immediately activated. This information was used as the starting point for identification of areas requiring upgrade (Figure 15).

7.2 Upgrade requirements

Information from the above sources was collated and combined to identify areas requiring upgrade, as per the flow chart in Figure 16.

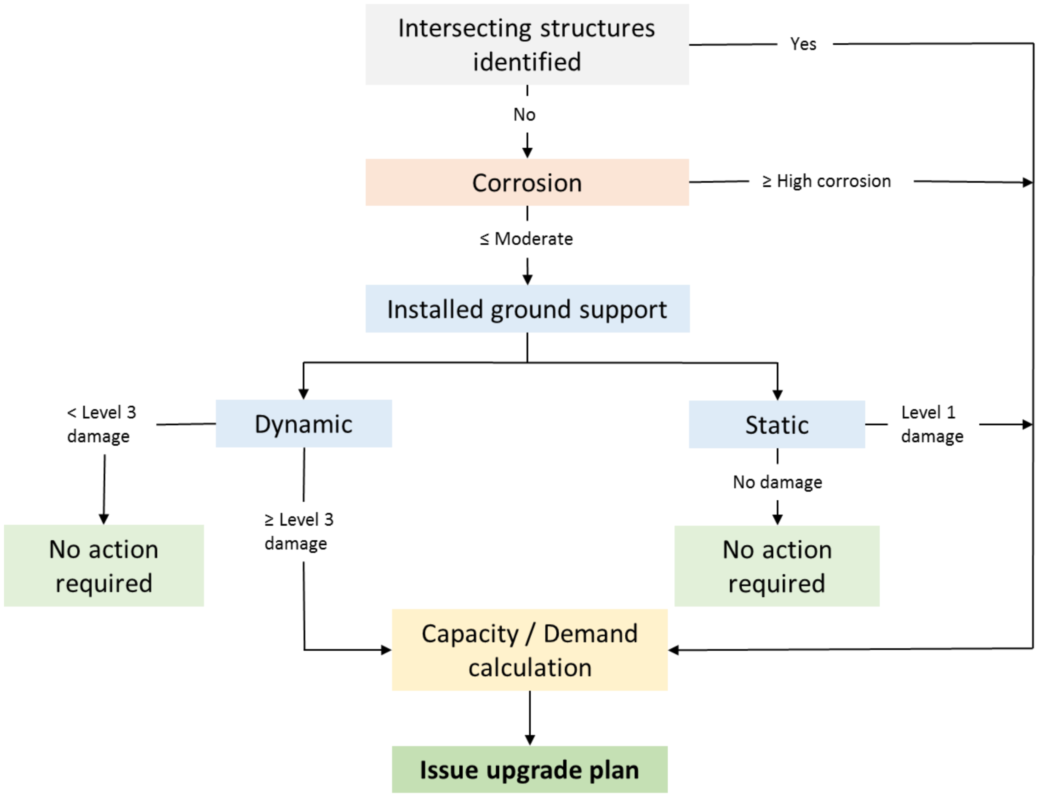


Figure 16 Decision flow chart to identify support upgrade requirements using Kaiser's support damage scale rating 1–5 (Kaiser et al. 1992)

Ground support upgrades utilised a combination of strengthened overlap mesh, Sandvik MD bolts and MDX bolts, and cable bolts. Strengthened overlap mesh is described by Louchnikov et al. (2014), where the product comprises a standard 5.6 mm weld mesh with the addition of two wires of the same diameter along the edge of the sheet. This results in stronger and stiffer overlaps and reduces the risk of mesh failure at these locations. The MDX bolt is a modification of the MD bolt, with a greater energy absorption and deformation capacity, developed in conjunction with Telfer, as described by Darlington et al. (2018). The MDX bolt allows for a more efficient installation, while providing greater than 25 kJ capacity (Darlington et al. 2018).

8 Conclusion

The evolving seismic hazard at Telfer has been well managed through an extensive seismic monitoring network, TARPs and the implementation of the seismic risk management plan. The hazard has increased with the addition of extra sublevels and mine design changes, as well as increasing cave size, but has not experienced a step change in activity. However, the predictability of seismicity and its association with blasting and slot firings is decreasing with time, as more seismicity is associated with stress redistribution around and under the cave.

A common theme is that changes to mine design have resulted in additional and changing seismic hazards, with areas of existing infrastructure no longer adequately designed or supported for the future expected demand. Understanding how changes to mine planning, addition of sublevels, footprint size and depth all effect the evolving seismic hazard is key to managing the hazard.

Acknowledgement

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