SIM 140301 *Technology transfer on minimising seismic risk in platinum mines*

Output 4: Learning materials for rock engineering personnel in seismically active platinum mines

Manual

Woodmead Business Park, B7 Maple North, 145 Western Service Rd.
Woodmead T/F (011) 656 1797/8 *www.mhsc.org.za*

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Introduction

The rock mass conditions found in the platinum mines of the Western Bushveld Complex (BC) are to some extent very similar to the Witwatersrand gold mines: flat dipping reefs embedded in a hard rock environment.

Generally rock strengths in the commonly occurring Pyroxenites, Anorthosites and (Leuco-) Norites are lower, regional faults and dykes are less frequent, k-ratios are higher and the horizontal stress component is more variable than in deep gold mines. The stress field is more complex and stress levels are lower than those the ultra-deep gold mines have to accommodate.

The common mining strategy in the deeper operations of the BC is scattered mining, in some cases with regional dip stabilising pillars, down to an approximate depth limit of 2 300m below surface. Extraction of the Merensky reef is seen as almost exclusively responsible for triggering the seismic response.

To manage the rockburst risk in the BC, the quality of information relating to this specific risk is essential. Such information would include: rock strength, rock mass quality, field stresses, geology, mining practice and micro-seismicity. Seismic data of sufficient accuracy are particularly important since high quality data are required to identify all source mechanisms reliably.

The chapters in this training manual are based on the recommendations made by SIMRAC project SIM100301, each with a number of sub-headings on specific, pertinent issues. The main themes are:

- Analysis of rock types and their properties; stress conditions and rock mass properties to enhance seismic hazard and rockburst risk assessments.
- Optimal mining practice to reduce seismic failure (avoidance of sources of seismic energy emissions).
- Precautions to reduce rockburst damage where seismic failure occurs (control of damage severity).
- Improved seismic monitoring practice and rockburst risk quantification.

In Chapters 1 to 7 we provide context, motivations and explanations on each of these issues. Where necessary, we make reference to visual materials contained in a separate slide show, or to external sources such as handbooks, web sites or other training materials such as the SiM manual on specific outcomes for the Rock Engineering Certificate (REC).

We recommend that readers also make use of the MQA sponsored education materials for the REC exams, especially for Papers 1, 2 and 3.1.

F Essrich (SiM) and J. Hanekom (Middindi)

Table of Contents

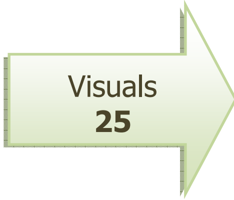
Introduction	3
Chapter 1 Geotechnical environment • Rocks and minerals • Stress field • Rock mass quality	9
Chapter 2 Potential for geotechnical environment to affect seismic failure • Rock type, strength, quality and stiffness • Stress distribution and fracturing • Geological structures • Rock mass behaviour	13
Chapter 3 Mining practice to reduce seismic failure potential • Mining directions and sequencing • Multi-reef mining • Confinement • Pillars	19
Chapter 4 Mining practice to reduce the potential of seismic damage • Stable ground conditions • Support practice • Safe off-reef areas	23
Chapter 5 Seismic monitoring - Planning • Monitoring objectives • Sensor configuration • Location accuracy • Velocity model • Local vs. regional coverage • Capacity • In-house expertise	27

Chapter 6 Seismic system operation • Source parameters • System timing • Sensor and station health • Status reporting • Principal sites • Data back-up • System optimisation • Quality control • Practice reviews	33
Chapter 7 Seismic monitoring – Value-add • Incident data base • Rock burst analysis • Rock burst risk ratings • Risk reduction	39

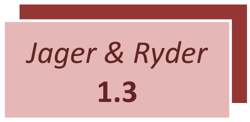
Source icons

Throughout this manual icons, that refer the reader to other sources of information (such as the slides in the visual materials, text books and research reports), are placed next to text. The first four icons refer to sources that are included on the CD in the back of this manual.

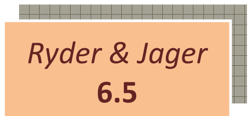
Relevant slide in PowerPoint presentation



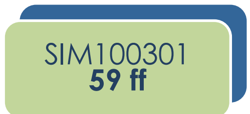
Relevant chapter in the Jager & Ryder handbook



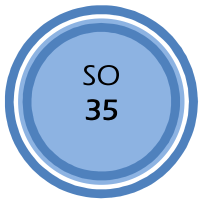
Relevant chapter in the Ryder & Jager textbook



Relevant pages in a research report

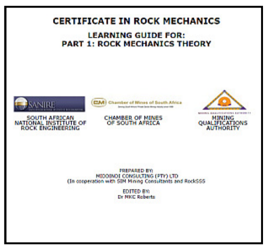


Specific Outcome in the SiM manual[1]



Websites

Readers are also advised to make use of the learning guides for exam papers 1, 2 and 3.1 for the Chamber of Mines Certificate in Rock Mechanics.



[1] *Specific Outcomes for Mine Seismology, 4th Ed.*, Manual based on the 2007 CoMREC Syllabus, ©2016 SiM Mining Consultants (Pty) Ltd.

1 Geotechnical environment

The following summary describes the geological and geotechnical environment in which platinum mining takes place in the Western Bushveld region. This includes the rock types exposed during mining operations, the rock mass quality encountered and the prevalent stress conditions. Chapter 1 provides some background information on these topics while the following chapters focus on how these issues can affect the potential for seismicity to occur or contribute to the associated damage.

Rocks and minerals

The rock types constituting the environment around the Merensky Reef are shown in Figure 1. Two major Merensky (Swartklip and Rustenburg) facies exist, but in general the rock types encountered in the different facies are very similar visually and petrographically.

Visuals
8-15

The Merensky unit (which contains the Merensky Reef) consists of a basal pegmatoid overlain by a pyroxenite layer that grades into Norite and then into Anorthosite. The footwall of the Merensky Reef consists of various types and grades of Norite and Anorthosite, while the hangingwall is a succession of Pyroxenite, Norite and Anorthosite (Figure 1).

SO
57

The different materials surrounding the reef are generally not separated by distinct planes but rather grade into each other. In spite of this gradual change, the main rock types vary in appearance (Figure 1) and have distinctly different properties. Generally, the dynamic failure behaviour (seismic) of materials is linked to their individual properties and it is important to know which materials make up on-reef pillars and are exposed in off-reef excavations.

Jager & Ryder
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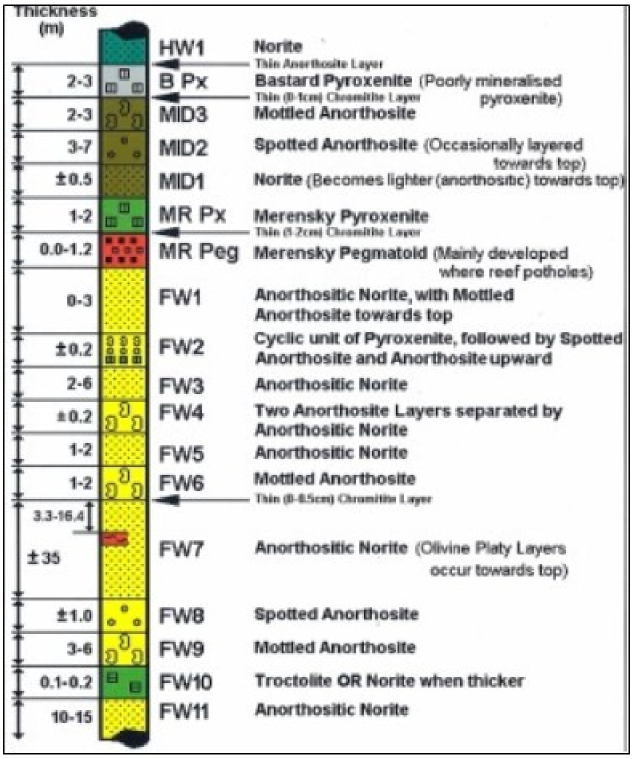

Figure 1: *Material succession around the Merensky reef*

Although it is possible to broadly link certain rock types to seismic or non-seismic behaviour, this may not be totally applicable to all areas on all platinum mines. Such a general approach would include the common opinion that the Merensky Reef environment is prone to bursting whilst the UG2 reef environment is not. However, recent seismic occurrences in one part of the platinum industry have indicated that under certain conditions bursting also occurs close to the UG2 horizon. Therefore, if one wants to understand the seismic response to mining, it is critical to take cognisance of the occurrence of the different materials in and around workings.

Ryder & Jager
1.3

Recommendation: *Determine the rock types present in pillars to identify which rock types play a central role in seismic failure or damage; include mapping of rock exposures and changes in composition and material thickness over short distances.*

Stress field

Visuals
16-18

Several authors have reported the results of stress measurements in the BC, but in relation to the areal extent of mining in this region the number of tests conducted is very limited. The application of test results to the entire BC, or even portions thereof, is not possible due to substantial variations in the stress field found across the different areas. Reported k-ratios vary from well below 1 to far above 2.

These variations include situations where geological structures appear to influence the stress field in their close proximity. As an example, the presence of near-horizontal thrust faults have resulted in substantial k-ratio variations such as an on-reef k-ratio of 0.65 and an off-reef k-ratio of 1.53 in the same area, resulting in considerable gothic arching (Figure 2). Other variations have also been reported and include the following situations:

Ryder & Jager
9.4

Figure 2: *Impact of large horizontal stress on footwall development (York et al, 1999).*

- The dyke swarm created by the formation of the Pilanesberg Complex has pushed aside the host rock where the swarm passes east of Rustenburg, creating high horizontal stress fields.
- The change in strike in the BC may have caused the footwall material to compress towards the centre of the area.
- Evidence exists that drill cores retrieved from below major pothole structures exhibit high-density discing, which may be related to the tectonic release of high horizontal stress.

Other measurements from a section of the BC have suggested that:

- The vertical component appears to be depth related with lower variability than the horizontal component, and
- The horizontal stress is generally higher, but also more variable than the vertical stress, even at depths in excess of 1 000 m below surface.

Anecdotal evidence suggests that the k-ratio is highly dependent on the rock type, with higher k-ratios being reported for the leucocratic (noritic) rock types.

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56

Since stress is the driver of seismic failure behaviour, it seems logical that the vertical and horizontal in-situ stress fields have an impact on the on-reef stress distributions and also the final pillar stress levels. These stress distributions are likely to be reflected in the nature and characteristics of seismicity.

The variability in the vertical and horizontal stress fields makes it difficult to successfully interpret the data with respect to the driving forces behind seismic activity. It is therefore critical to acquire accurate and reliable stress measurement data on a regional scale across the BC, but also locally for specific mining areas.

Recommendation: *Conduct stress measurements to determine principal stress directions, k-ratios and their changes over short distance.*

Rock mass quality

Rock mass ratings are routinely performed on most of the platinum operations. The results indicate that Q-values on and around the Merensky reef horizon typically range between 0.1 and 20 (from very poor to good rock mass quality). These Q-ratings confirm the general perception of significant variability in rock mass quality on and around the Merensky reef horizon.

Visuals
19-21

The general consensus in the industry is that levels of seismic activity in areas with poor rock mass quality are less significant than in good quality rock material. The reason lies with the tendency of a jointed, blocky rock mass to deform more easily during loading and not to accumulate as much strain energy as a high quality rock mass. High Q-values have been reported for Anorthosite and are due to lower joint density (the Q-rating focuses on joints), but this rock type is also well known for intense stress fracturing. This results in poor rock conditions that are not normally reflected by rock mass quality systems such as Q-Index.

The resulting rock mass quality (including the presence of stress fracturing) is related to the strength and the stiffness of the rock mass (its ability to limit strain under stress). It therefore also affects the capacity of a pillar to accumulate strain energy (i.e. the pillar strength) which potentially influences the seismic behaviour of the pillars.

In the context of rock mass quality, the following is of significance:

- Fall of ground potential increases as rock mass quality in the hangingwall decreases.
- Pillar punching potential increases as rock quality in the footwall decreases as this also reduces the material strength.

Ryder & Jager
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Recommendation: *Determine rock mass quality of pillar, hangingwall and footwall exposures on a routine basis and relate to seismic behaviour, punching and observed damage.*

Your notes:

Check your progress

I have studied the material and can answer the following questions:	
What are the main rock types found in the BC?	
What influences the variations in the stress field?	
What impact will varying k-ratios have on pillar loading, as well as confinement levels in pillars?	
What impact does reef dip have on the importance of the k-ratio variations with regards to pillar loading?	
Which factors determine rock mass quality?	

2 Potential for seismic failure

Several mining related issues increase the probability for seismic failure. These include exposure of certain rock types that are more prone to brittle failure (typically the stiffer materials) and the stress fields along abutments or within pillars. These issues affect the behaviour of the rock mass or more specifically the behaviour of a single pillar and should be considered when evaluating seismic failure potential.

Rock type, strength, quality and stiffness

Seismically-active platinum mines show a wide range of rock types, strengths and other properties. Several literature sources (Ryder and Jager, 2002 and Jager and Ryder, 1999) provide rock property information from various mining environments in the platinum industry. Extreme variations in the results are found, with the following implications:

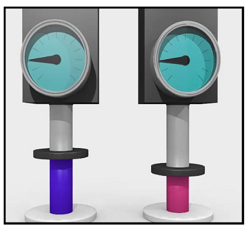
SIM100301
25 ff

Visuals
23-24

- There is a danger that differences in rock materials may be disguised when the rock strength values obtained for a single material type are averaged. Such material property differences could assist in understanding the occurrence of seismic events and the damage experienced. In other words a complete statistical and probabilistic approach should be adopted.
- It is necessary to look at the properties in more detail on every operation as part of understanding local rock mass behaviour, assuming that material variations could occur within an operation's boundaries, allowing variable rock mass responses.

Merensky Reef material appears weaker than both the hangingwall and the Footwall. The following should be noted:

- The lower strength of the reef package suggests that the fracturing and slabbing of pillars may occur at lower stress values than what is generally required for pillar foundation failure, and that foundation failure therefore becomes improbable.
- Weaker reef material strengths indicate that footwall punching of pillars should not form part of the seismic event process.



- Since foundation failures have reportedly occurred, it follows that significant strength variations are possible across the BC or even across a single mining operation.
- Limited footwall heave around pillars has been observed but the low level of occurrence across the BC and even across single operations confirms the variation of material strengths.

Underground observations of stress fracturing of excavation walls confirm that variable footwall strengths exist. This suggests that off-reef excavations could behave very differently over a few linear metres where subjected to stress.

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Test results from random samples confirm strength and material property variations. The UCS tests results in Table 1 provide the suggested average material unconfined strength as well as the elastic material properties 'E' (Young's Modulus) and 'v' (Poisson's Ratio). Even though the UCS results appear to be similar to the generally accepted values, the material stiffness is much lower whilst the suggested Poisson's Ratio is much higher. These results confirm the highly-variable rock properties and motivate the need for extensive rock testing programmes.

Rock Type	Strength (UCS) MPa	Tangent Elastic Modulus @ 50% UCS GPa	Secant Elastic Modulus @ 50% UCS GPa	Poisson's Ratio Tangent @ 50% UCS	Poisson's Ratio Secant @ 50% UCS
FW Norite	124.85	53.10	30.10	0.40	0.14
HW Norite	155.06	64.40	38.70	0.39	0.16
HW Pyroxenite	117.81	81.50	48.60	0.27	0.10

Table 1: *Uni-axial test results with elastic moduli*

Using tri-axial rock sample test results, material strength parameters should be established for each of the major rock types around the Merensky Reef as shown in Table 2.

Rock type	Hangingwall Norite	Footwall Norite	Hangingwall Pyroxenite
Cohesion (MPa)	6.8	10.55	10.6
Friction angle	39.5°	46.3°	31.8°
Mi	16.1	50.0	4.7
Mb	4.610	14.325	1.787
s	0.021	0.021	0.062
a	0.502	0.502	0.501

Table 2: *Material strength parameters*

Compared to values available from literature and as reported above, these confirm the highly variable nature of the rock material around the Merensky Reef. Since failure criterion parameters usually govern the failure conditions, the large differences between rock types and the variability within each individual rock type complicates the understanding of the behaviour of the material.

Recommendation: *Develop detailed knowledge of the rock type properties of each specific area including strength, stiffness and strength parameters and correlate with seismic behaviour.*

Stress distribution and fracturing

Stress is the underlying driving factor behind seismic events. The significant differences in virgin stress fields found on different platinum mines are thought to have an impact on the stress levels induced on mining faces, abutments and pillars. This could partly explain why the seismic response to mining (occurrence and severity) in different areas is so diverse.

Visuals
25-26

Stress fracturing is a function of stress levels and rock strengths. Experience has shown that the fracture density is related to high stresses, poor rock strength and the impact of time-dependant fracturing. The orientation of the stress fracturing is usually controlled by the principal stress directions.

Figure 3: *Dense fracturing of exposed Norite leading to collapse.*

Observations indicate that the local rock type makes a significant difference to the occurrence of seismic damage. The exposure of noritic material in stope hangingwalls or above pillars intensifies stress fracturing and damage potential. In some operations, the rock is referred to as 'white' rock and, where exposed, has been related to seismic damage on many occasions (see Figure 3).

The fracture orientations are affected by the original state of stress (virgin stress field) and the geometry of the excavation. The varying stress field and large range in rock strengths would therefore potentially result in different stress fracture patterns, while their impact on stability could also vary greatly. Norite often fractures into thin, curved slabs or sheets with sharp edges, and differs from Pyroxenite, which tends to break into blocks. Fracturing in these two rock types could potentially show:

Visuals
8, 51

- Flat dipping fracturing that aggravates the fallout severity (Figure 4),
- Fracture patterns that illustrate the shape, intensity and complexity of the stress field (Figure 5, 6), and
- Complex fracture patterns in some areas and particular materials (Figure 4).

Jager & Ryder
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Figure 4: *Flat dipping fractures in Pyroxenite*

Figure 5: *Dense, steep dipping and blocky fracturing in Pyroxenite*

Figure 6: *Dense, curved fracturing of exposed Norite*

Part of the impact of the stress state within pillars also includes the loss of confinement due to fracturing. This could induce sudden failure as the pillar strength decreases and its post-failure behaviour may change unfavourably.

Recommendation: *Develop knowledge and understanding of stress distributions around workings through numerical modelling and correlation with rock types and their properties, as well as recorded stress fracture densities and orientations.*

Geological structures

The most common geological structures in the platinum environment include jointing, domes, potholes, faults, dykes and, in certain areas, IRUP (Iron Rich Ultramafic Pegmatite). Underground observations often fail to indicate any clear correlation between these structures and seismic activity or damage.

SO
58-59

However, during internal and external studies conducted on mines such as the SIM100301 project it was found that, where potholes are approached, the possibility of experiencing higher joint density, shallower dipping joints and the risk of exposing noritic material increases.

Visuals
27

The role played by faults and dykes in affecting the seismic rock mass response to mining appears to be small when compared to the gold mining sector. Most faults mapped on mine plans have throws of centimetres, rarely metres. Therefore, their potential to slip significantly is low, reducing the magnitude of the largest events to be expected. The largest fault in the Rustenberg mining area, the Hex River Fault, has not generated any tremor larger than approximately M=2 even where mining took place in its vicinity

SIM100301
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Intrusions, mostly in the form of narrow, steep dipping lamprophyre and dolerite dykes, appear to not pose a significant threat since they are too thin (less than 1m) to accumulate large amounts of strain energy.

Recommendation: *Identify and record the presence of joints, dykes and faults and record their history in terms of location, frequency, severity and the likely source of energy release or zone of weakness.*

Rock mass behaviour

Visuals
28

Rock mass behaviour is a function of the stress field and the rock mass properties. Across the BC and its mining operations, the pre-failure stiffness of pillars changes as a consequence of rock type variation whilst the post-peak pillar behaviour is affected by the stress distribution within pillars. As a result, the pillar behaviour can be variable and complex.

Behaviour of the different rock types exposed during mining, such as stress fracture density and orientation, should be better quantified and understood because:

- The formation of fractures in pillars can affect the seismic behaviour of the pillar; the presence or absence of highly stressed pillar cores (not fractured) influences seismic activity.

Ryder & Jager
2

- The exposure of fractures in hangingwalls could affect the type and extent of damage experienced due to seismicity related vibrations.
- The exposure of Norite in the hangingwall of stopes appears to affect the stability of the excavations negatively when these exposures are subjected to seismic activity. This is due to the fracture density and flat dipping orientations that are significantly different from those formed in Pyroxenite.

Understanding the rock mass behaviour to improve seismic risk management at any operation requires knowledge of the variations in each of the issues discussed above, as they apply to a specific operation or area on the operation.

Recommendation: *Investigate and record rock mass behaviour on a routine basis and evaluate regularly to identify trends.*

Your notes:

Check your progress

I have studied the material and can answer the following questions:	
Which rock conditions increase the probability of seismic failure?	
Explain the importance of a rock strength testing program to inform the design of pillars.	
Explain the impact of weak footwall material on pillar behaviour.	
Why is it important to correlate material strength, the stress field and underground pillar behaviour?	
Why is it important to gather information on fracture density and orientation?	
How do fractures affect rock mass behaviour?	
Are rock properties fairly homogenous across the BC or do they vary significantly?	

3 Mining practice to reduce seismic failure potential

The implementation of appropriate mining practices is an extremely useful tool to reduce the potential for seismic failures. However, if these practices are ignored or not implemented correctly, the probability of creating seismic emission sources is substantial. Due care should be taken when implementing appropriate mining practices as a preventative measure.

Mining directions and sequencing

Mining sequencing includes situations in a conventional panel-and-pillar mining method where:

- advancing panels can create long abutments,
- stopping lines are ignored between raises, or
- excessive or insufficient leads and lags between panels are allowed.

Visuals
30-31

All these different situations raise one common concern: the creation of higher stressed panels or remnants that could create conditions conducive to seismic failure. However, these conditions can be prevented by improving the mining sequences implemented on a large scale (between raise lines) and on a smaller scale (leads and lags between panels).

A number of improvements can be made during mining sequence planning that affect seismic behaviour. They are listed below:

- Investigate the mining sequence practices that historically have impacted on seismic activity in platinum mines.
- Scrutinise local seismic activity and seismic damage reports to evaluate each practice. Identify those practices that appeared to have raised the level of seismicity or resulted in damage in a specific mining area.
- Further improve the practices within the operation or a specific mining area to reduce the likelihood of seismic activity.
- Monitor the mining practices implemented by means of plans and underground visits.

Jager & Ryder
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The results of a study conducted on a set of mining plans, combined with a number of underground visits, listed the following practices as having an effect on the occurrence of seismic events or the degree of damage experienced (see SIM100301 report):

- Mining directions: Within the same reef block mining directions were often not consistent, but included breast, down-dip, up-dip and diagonal mining.
- Abutments: Mining sequencing was not always well controlled and resulted in the creation of a number of long abutments or highly-stressed remnants.
- Stopping lines: Long strike gullies indicated that panels were mined well beyond the normal practice of halfway between raise lines, creating poor overall sequencing.

Visuals
32-34

SO
94

SIM100301
41 ff

- Sidings: Sidings were often left far behind the advancing face and where they were close to the face, the sidings were brought closer by down-dip mining.
- ASG hangingwalls were often carried higher than the stope hangingwall due to strike gullies being too shallow, or where developing the strike gully was at too high an angle above the strike direction.
- Lead and lags: In many instances the recommended practices were not followed and resulted in very poor face shapes.
- Holing between panels when mining from different raise lines resulted in final reef blocks constantly decreasing in size while the stress loading increased.

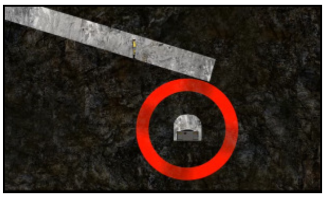
Although the above examples are not necessarily conclusive, they do indicate that generally accepted good mining practices can yield lower seismic hazard. Sound mining practices should be applied in the platinum industry, in spite of the perception that practices such as proper sequencing, co-ordinated mining directions, leads and lags, gully sidings etc. are intermediate depth gold mining practices and are therefore not applicable to platinum mines.

Recommendation: *The design and control mining directions, leads/lag distances, remnant formation, abutment creation, holing practices and mining sequences should be considered.*

Multi-reef mining

Visuals
35-37

At low middlings, the extraction of more than one orebody can result in stress field changes on the lagging mining faces leading to increased pillar loading and increased potential for unwanted pillar behaviours. This situation is exacerbated where mining one ore body is below a high-stress area on another orebody, such UG2 mining below Merensky remnants. The potential for pillar crushing, as well as pillar bursting of slightly larger pillars, increases substantially in this scenario.



Recommendation: *Ensure the proper sequencing of multi-reef mining environments.*

Confinement

Visuals
38

Confinement of footwall material within and around a pillar on the Merensky reef horizon can be increased by maintaining an intact footwall, or reduced when positioning a deep strike gully close to a pillar (i.e. a very shallow siding).

Similarly, confinement can be increased by leaving a larger than required pillar or by leaving substantial amounts of blasted ore or scaling in-situ around the pillar. The opposite effect, i.e. weakening, results from the removal or the cleaning of pillar scaling around a pillar.

The hangingwall conditions can have either a favourable or unfavourable effect on confinement: confinement is increased by an intact, stable Hangingwall; or reduced where the ASG is poorly positioned, for example in fractured or otherwise unstable ground (breaking of the Hangingwall).

The mechanism through which confinement impacts on the behaviour of pillars are likely to include the following:

- Material above and below the reef could increase in strength where confined, creating strong platens between which the weaker, less-confined reef rock (pillar) is compressed, resulting in extreme crushing and slabbing of the reef material pillars.
- Low material strength above or below the reef could allow punching of the pillar into the surrounding rock.
- Increased confinement of the pillar is known to change its post-peak (or post-failure) behaviour. As confinement increases, the pillar deformation behaviour becomes ductile and a reduction in confinement could result in a more brittle behaviour (sudden loss of strength), possibly leading to a pillar burst.

Mining practices such as the ASG hangingwall position, siding depth and pillar dimension all potentially affect the confinement within and around pillars, resulting in any of the abovementioned behaviours, including that of sudden pillar failures.

Implementation of good mining practices around pillars can assist in favourably affecting their failure behaviour.

Recommendation: *Ensure acceptable levels of confinement in and around pillars by following good mining practices.*

Pillars

Seismic pillar failures are related to the local field stress since bursting pillars are often situated in areas where the extraction ratio is higher than the designed value. Even though the role of stress in pillar bursts is accepted, pillar behaviour is also governed by the dimensions, position and shape of the pillar. Mining practices that ensure that pillars are cut according to standards in terms of size, position and shape are critical to managing pillar behaviour.

Visuals
39-45

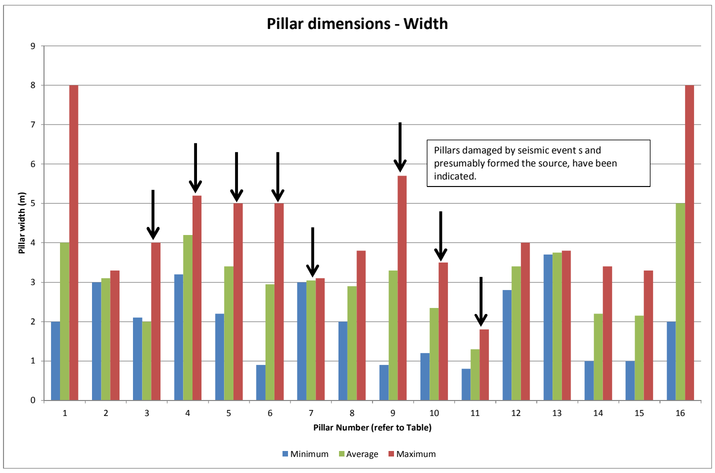


Figure 7: Pillar width of burst pillars (arrows)

Figure 7 shows that pillar behaviour often included pillar bursts when pillar widths were within a certain range. Whilst small width pillars crushed and large-width pillars remain very stable, it was the intermediate pillar widths that posed an increased burst risk.

Ryder & Jager
6.5

The fact that both anecdotal evidence and rockburst analyses point to slightly oversized pillars as being largely responsible for Rock bursts, allows the conclusion that final pillar widths must be managed well.

SO
60-62

Recommendation: *Prevent larger-than-designed, poorly shaped and ill-positioned pillars through good pillar cutting and mining discipline.*

Your notes:

Check your progress

I have studied the material and can answer the following questions:	
How are mining directions and sequencing related to seismic failure potential?	
Why is the implementation of a good planning system important to manage seismicity?	
Explain how incorrect gully layouts can affect pillar behaviour.	
How does a small middling between excavations affect the local stress field?	
Are over- or undersized pillars more prone to sudden bursting?	

4 Mining practice to reduce seismic damage potential

In addition to the potential for mining practices to reduce the probability of seismic events, some of these practices are also valuable in reducing the likelihood and severity of seismic damage when a seismic event does occur. Implementation of appropriate mining practices now also become actions that remedy the potential effects of seismic events and should always be considered for implementation on this basis alone.

Stable ground conditions

Stress fracture orientation and density are not only a function of the mining depth, and also of the gully layout (lead / lag) and the siding's shape and depth.

Visuals 47-49

Since fracturing could affect the local rock mass response to vibrations caused by a seismic event, it is critical to ensure stable ground conditions in and around gullies. This can be promoted by the following:

- Mining sidings in line with panel faces in areas where stress fracturing occurs.
- Sidings that are cut deep enough to ensure that scaling of the gully sidewalls does not negatively affect the pillar behaviour and that gullies do not reduce confinement of the footwall around the pillars.
- Selection of a suitable gully direction in relation to the reef strike direction to limit the damage to the hangingwall caused by gully development, and by maintaining deep gullies.

Jager & Ryder 3.4

Hangingwall stability is an even greater concern where the exposed rock type is Norite. As mentioned earlier, noritic material often results in flat dipping, high density stress fracturing, a condition prone to instability during seismic events. The flaking of Norite into thin sheets with sharp edges is likely caused by the low tensile strength of this rock type.

Recommendation: *Implement good gully and siding mining practices to prevent the creation of unstable fracturing. Prevent the exposure of the noritic material.*

Support practice

When approaching potholes, the risk of exposure of noritic material in the hangingwall increases, and thereby the risk of seismic damage also increases. The planning of mining in and around potholes, including the design and implementation of appropriate support practices, is critical to limiting this risk.

Ryder & Jager 7.2

Using support to address specific mining conditions in an attempt to ensure stable mining excavations is a well-known practice, and not a simple exercise. The most common methodologies to design support that are appropriate and likely to reduce rockburst damage from seismic activity include methods that will:

Visuals 50-51

- ensure sufficient support resistance to the rock walls, whilst at the same time,

Jager & Ryder
4

- ensure that the support unit has sufficient energy absorption capacity to maintain its integrity and the excavation stability, even during seismically induced displacement or deformation.

The application of these methods and the selection of appropriate support units for a specific environment are critical. Together with the implementation of sound mining practices these methodologies contribute to the stability of mine workings.

Recommendation: *Design and implement adequate support practices.*

Safe off-reef areas

The panel-and-pillar layouts generally applied in the platinum industry requires the positioning of access tunnels in the footwall of the ore body. These tunnels are often exposed to mining induced stress changes due to mining in its vicinity. Except for the impact of these stress changes, risk is added where these tunnels are situated close to an on-reef pillar or a long abutment, such as those created along the bottom of a panel set.

Jager & Ryder
5.4

It has been shown that seismic events tend to occur along abutments and that significant damage is inflicted on tunnels that are situated too close to these abutments. Avoiding the placement of tunnels within the direct zone of influence of current or future mining abutments is thus critical for their protection.

Where crosscuts and travelling ways are placed too close to on-reef pillars, the increased stress levels around pillars could impact on the stability of access tunnel in the following ways:

Visuals
52-53

- Stress fracturing around the tunnels may increase, requiring an increase in support installation.
- Seismically induced damage can be severe where tunnels are placed too close to a pillar or remnant that eventually bursts.

Rock mass modelling and analysis of past mining practice could assist in deciding on safe minimum distances between tunnels and on-reef mining areas.

Recommendation: *Place footwall access excavations in areas of low stress levels, away from abutments and on-reef pillars or -remnants.*

Your notes:

Check your progress

I have studied the material and can answer the following questions:	
Which of the practices to prevent seismic events and seismic damage are the most important to implement?	
What is the recommended practice in terms of gullies and sidings to ensure pillar stability?	
Where should access ways be positioned to reduce the likelihood of rockburst damage?	
Why are abutments potential sources of large events?	

5 Seismic monitoring - Planning

The following issues are critical to achieving optimum seismic monitoring practice. A seismic monitoring programme should, in its design, accommodate the main elements of quality management. The programme should start with an assessment of needs followed by a seismic network layout to satisfy these needs. After implementation and commissioning of the initial network, data quality should be assessed and meaningful data analysis should be performed regularly, continuously improved, failed practices abandoned and successful practices further enhanced.

The focus should always be on reducing seismic hazard and, where possible seismic risk. Thus, monitoring leads to data collection which feeds into data analysis, which in turn results in a better understanding of weaknesses in the programme, which can then be systematically removed or reduced.

Good practice in terms of the following items will likely contribute to successful seismic risk reduction.

Monitoring objectives

Prior to any installation of seismic equipment, the objectives of monitoring should be clearly defined. Depending on the history of seismicity, the size of the area affected, the severity of the associated losses and the projected time frame, a strategy is needed that will answer the following questions:

- Where does seismic failure occur?
- Which are the failure mechanisms and their underlying causes?
- Which trends and patterns are found in basic parameters (activity rate, locations, M_{max} etc.)?

SO
28

It is advisable to involve a system manufacturer in the design of the network, but an independent view from an unbiased expert is required to avoid over-design.

In general, when seeking answers to the above questions, the approach should be from coarse to fine, i.e. a mine that was never covered by a seismic system should begin with a small set of widely-spaced sensors that can provide basic information first, rather than starting the monitoring with a dense array of highly sensitive transducers.

Jager & Ryder
9.2

There is already a standard set of seismic hazard assessments developed for and widely adopted by deep-level gold mines (see SIM050302 project report). There, a distinction is made between short-, medium- and long-term assessments and the detailed study of unusual, large events (back-analysis). Another objective is to attempt the forecasting of large, potentially damaging

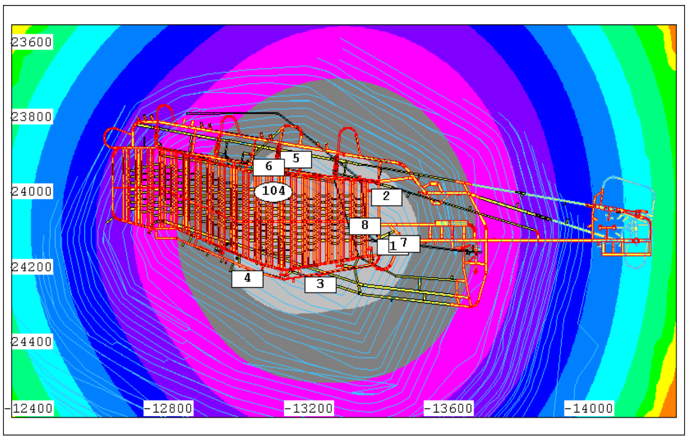


Figure 8: *3D-location accuracy of M=-1.0 events*

SIM050302
9 ff

events, also referred to as 'prediction'. The seismic system is then designed to provide data for short-, medium and long-term analysis. Medium-term usually means four to six weeks with results being presented at regular monthly planning meetings.

A different approach to deriving monitoring objectives would be to sub-divide a mine into areas of low, medium and high seismic response, so-called Seismic Hazard Districts (SHDs). The concept is similar to Ground Control Districts for support design purposes and results in associations between seismic hazard levels and seismic system requirements:

Visuals
55-58

Class I – *High production area* (high hazard):

High system reliability and quality of raw data: minimum location accuracy in plan equal to 1-2 panel lengths; sensitivity better than the minimum magnitude of damaging events; quick location and quick magnitude enabled[2]; MT enabled[3]; data throughput sufficient for daily instability evaluation.

Class II – *Low-density or remnant mining* (intermediate hazard):

Minimum location accuracy in plan equal to 3-4 panel lengths; sensitivity and better than minimum magnitude of damaging events; quick location and quick magnitude enabled; MT enabled.

Class III – *Back area* (low hazard):

Mainly large events: minimum location accuracy in plan equal to source size of potentially damaging events; sensitivity better than minimum magnitude of damaging events.

Once the appropriate Class has been assigned to each SHD, the network is configured to provide the required sensitivity and location accuracy. Class I sets the highest targets in terms of sensor density and configuration, whereas Class III has the lowest targets.

Appropriate software allows the modelling of network performance for a given sensor layout (Figure 8). The contour plot in this figure shows the improved location accuracy for a n 8-station network when sensor 104 is added.

Recommendation: *Seismic network design should be preceded by a needs analysis and the formulation of monitoring objectives according to these needs.*

Sensor configuration

Visuals
59-61

SO
34

The seismic systems deployed on platinum mines of the BC belong to a category named "store-and-forward systems". These systems digitally sample the recorded ground motion, declare a 'trigger' when the ground motion exceeds a certain threshold and triggered a minimum, pre-defined number of stations, and store the signal until a central server on surface requests the data for further processing.

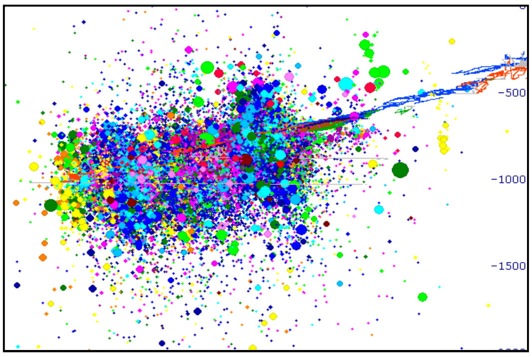


Figure 9: *High vertical location error around a tabular reef horizon*

[2] Ground-motion relation regularly updated; quick magnitude and location in under 2min;
[3] MT=Moment Tensor; Quality index of configuration >0.5, min. 10 stations, at least 2 stations near pole.

Theoretical considerations suggest that location errors can be reduced by:

- a 3D network layout that surrounds the source region of interest,
- an accurate knowledge of the seismic velocities in the region, and
- the accuracy of seismic station locations.

SIM100301
48 ff

Planar networks, where all sensors are close to a tabular reef, produce large location errors in the direction normal to the reef (Figure 9). Placing seismic sensors outside the rock volume that is seismically active generates high overall inaccuracies (apart from low sensitivity).

Recommendation: *Additional shallow and deep sensor sites should be placed to reduce location error in depth; linear and planar layouts should be avoided; sensors should surround the seismically active rock volume.*

Location accuracy

SO
7-8

The standard method of calculating the location of seismic events is by triangulation. The seismic network sensors (photo courtesy IMS) deliver a set of arrival times of waves radiated from the source. Then, assuming wave velocities in the rock mass and using the 3D position of the sensors, the system determines the source location that matches the observed arrival times. In principle, this is the same algorithm that is used by GPS satellite based locating methods.

Figure 10 below shows a seismogram, a recorded wave-form comprising a Primary (P-wave) and a Secondary (S-wave) arrival.

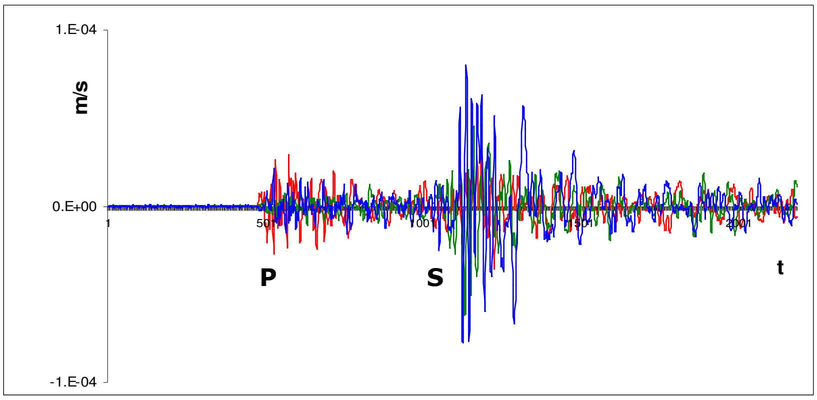


Figure 10: *Seismogram with arrival of P- and S-wave (horizontal axis = time)*

sensor

In the case of mine seismic networks, the input data is to some degree inaccurate. Among others, the exact seismic wave velocities are unknown; the arrival time at the sensor has a certain error margin; in many cases, the wave path is not straight but curved; the sensor position and orientation in the mine's survey co-ordinate system is associated with an error in the region of 1 metre. And there are additional deviations which arise from the rock mass not being a homogenous, isotropic and perfectly elastic medium.

SO
35

The above inaccuracies add up to a location error, which should be reduced as far as possible by adhering to certain standards. Increasing the number of stations used for location is one possibility. Another is a more accurate wave velocity model (see below). A third is the use of tri-axial sensor

Visuals
62-65

sets instead of single uni-axial sensors. This will allow the direction of the wave to be calculated as it enters the seismic sensor set. As a result, location is not only based on travel times but also on ray path information.

Ryder & Jager
5.3

Recommendation: *Locations of seismic events in 3D determined from tri-axial sensor sets; choose a three-dimensional sensor configuration (see below). See SIM050302 Phase 2 OP3 Table 10.1 for more details on reducing location error.*

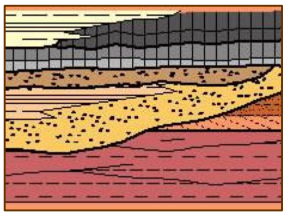
Velocity model

SO
14-16

Elastic wave velocities correlate roughly with rock density and rock strength. It is generally assumed that seismic waves travel along straight ray paths and with constant velocity between source and sensor, but on mines encompassing rock types with starkly contrasting properties a more sophisticated approach needs to be taken. Such mines would benefit from a series of calibration blasts to estimate the average seismic wave velocities for different sections of the mine.

Visuals
66-67

The estimation of P- and S-wave velocity is fundamental to reducing the location error, and calibration blasts are a common method to estimate true wave velocities. With the distance between blast and station a known quantity, the measured travel time from source to sensor translates directly into a propagation velocity, which is input into the location algorithm.



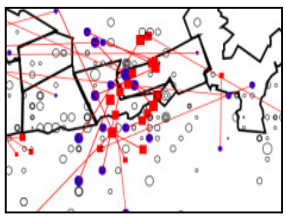
Where elastic wave velocities are found to vary by more than approximately 5% across the mine, and where a simplified, layered 3D model can be developed, it is recommended that the seismic system be configured such that it uses this model for location purposes rather than assuming a single, homogenous half space.

Recommendation: *A 3D velocity model is preferred, over a homogeneous half space with fixed and constant velocities.*

Local vs. regional coverage

Visuals
68

Mines, especially in the western BC, do not operate in isolation. Large mining houses such as Impala Platinum and Anglo Platinum each operate several shafts with a number of independently run seismic systems. In addition, the Council for Geosciences has some of its National Seismic Network (SANSN) stations installed near active mines, all of which record varying portions of the mining induced seismicity in the region.



SO
81

Thus, parts of the western limb of the BC are covered by a regional and several mine-based (local) seismic systems, and it is in the interest of mine safety that the operators exchange information on the recorded seismicity. To facilitate the information exchange, the 'language' spoken should be a universal one that every stakeholder can understand. Language refers to time, location, seismic energy, moment, magnitude and other event parameters that are routinely used for the quantification of seismic sources.

SIM100301
38

This can be achieved when the network managers agree on a basic set of source parameters so that events that are recorded by all three systems are characterised in a common language. This would also allow for the data sets from different networks to complement each other as, due to the different technologies deployed, mine seismic networks are better suited to recording smaller events accurately (up to approximately M=2..3), and the SANSN is more suitable for larger tremors (above M=2..3).

Recommendation: *Standardisation of reported magnitude and other basic source parameters across the region and in line with CGS standard; mix of mine network coverage and SANSN operated sensors.*

Capacity

Every mine, that is reliant on instrumentation and other sophisticated equipment to collect data for operational purposes, requires a certain set of resources to install, operate and maintain this equipment. In this context, capacity refers to the financial resources, competent personnel, skills and knowledge, and to safe access to the equipment. It also includes the management capacity that will ensure that needs are identified and problems overcome to obtain the data with the requisite quality.

Visuals
69

The main issues that a mine should consider when deciding on whether it has sufficient capacity to monitor seismicity on its operation are:

- Sufficient budget for system design and installation
- Assignment of responsibilities for network administration
- Sufficient funding for maintenance and repair
- In-house expertise in mine seismology
- Technical expertise in instrumentation technology
- Knowledge and understanding of seismic hazard

SIM050302
12 ff

It is important that mine personnel, especially rock engineers, have an understanding of the concept of seismic hazard and the mitigation of seismic risk. Where principles of mining induced seismicity are not well understood, the benefit of operating a seismic system is in jeopardy. The value derived from collecting seismic data lies in the reduction of seismic failures, especially potentially damaging Rock bursts, by avoiding the conditions that have been found to result in seismic failures. (See SIM050302 OP3 Ch. 7.1)

Recommendation: *Employment of critical skills; training in mining induced seismicity; capacity for prompt sensor repair or replacement where necessary (within less than three months).*

In-house expertise

The mining houses in the BC have varying management structures and levels of in-house expertise to manage their respective sets of seismic monitoring equipment. The levels seem partly related to the severity of seismic risk, but also relate to varying mine management decisions, the willingness to in- or outsource, and the availability of suitably qualified and experienced personnel in this specialised sector of the labour market.

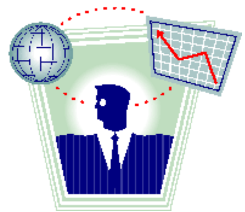
SIM050302
12 ff

In the case of Impala Platinum, a team to provides technical support and maintenance, data processing and mine seismology expertise, and is in charge of several independent seismic systems at four shafts. The systems are still being further expanded. In the case of Anglo Platinum and Northam, the system maintenance, data processing and analysis, and reporting are outsourced, but overseen by experienced mine seismologists and several rock engineers familiar with ultra-deep gold mining.

In the majority of other, smaller operations that have not experienced seismic hazard on any significant level, no staff qualified in mine seismology are deployed or in charge of networks.

Experience from deep-level gold mines indicates that some form of in-house expertise may be beneficial, for several reasons:

- Overall responsibility for the network is assigned to an employee of the mine; his or her performance is subject to an employment contract and task agreement.
- Expertise is allocated to oversee the performance of service providers and equipment suppliers.
- Decisions taken reflect the interests of the mine, not those of the supplier.
- To speed up repairs, installations and expansions, a person of requisite authority can allocate budgets and issue instructions to assist with the process.



Where in-house expertise is allocated, networks are more likely to be designed, implemented and maintained according to the mine's needs.

Recommendation: *Mine seismology expertise to be created in-house (where appropriate).*

Your notes:

Check your progress

I have studied the material and can answer the following questions:	
Which are the five standard monitoring objectives for deep mines?	
How does one measure seismic network performance?	
What is the purpose of a Seismic Hazard District?	

6 Seismic system - Operation

This chapter focuses on the challenges associated with the operation of seismic systems, for example the maintenance and repair of equipment, ensuring high levels of data quality, and adjusting and possibly expanding the network in line with the mine's changing requirements.

Source parameters

Visuals 71-73

The number of triggers (NoT) associated with an event is important for valid and accurate locations. For reliable source parameters such as seismic energy, seismic moment, magnitude, stress drop etc. a minimum set of wave spectra must be available, as these parameters are determined from the spectral content of the wave forms emitted by the seismic source.

Parameter
Location: South West Up
Local magnitude
Seismic moment [N·m]
Radiated energy [J]
Energy S / Energy P
Apparent stress [MPa]
Corner frequency [Hz]

The more seismic sensor sets that are deployed and in good working order, and the more wave forms that area recorded with low background noise levels, the more reliable are the calculated source parameters. This, in turn, ensures a better understanding of the seismic source mechanism, i.e. slip or burst, the source dimensions, the state of stress in the surrounding rock mass and other parameters that allow a quantitative and qualitative analysis of the source.

SO 26, 63

There is one factor that limits the number of triggers used for source calculation: the further away sensors are from the source, the lower is the recorded wave amplitude and the less accurate is the information contained in the wave form. This is the reason for large network operators to limit their maximum NoT to 20-25, i.e. they exclude the stations in the network furthest from the recorded source (see calibration blast results, F Essrich, 1996).

SIM100301 51 ff

Recommendation: *Quantification of source parameters from at least four P- and four S-spectra using tri-axial sensor sets; at least four triggers for location purposes, including directional information (wave angle of incident).*

System timing

Since the time travelled by a seismic wave between source and sensor is the basis for location calculation, it is essential that the electronic timing devices in seismic stations are synchronised to an accuracy below 10^{-6}s, i.e. the time must be the same in all stations and throughout the network.

SO 33

For event times to be accurate across several networks, all have to be on the same time scale, which is referred to as the global time. The solution to this problem is provided by satellite based time information that is received by all system computers on surface and passed on to all stations within each network.

Large tremors that are recorded by several mine networks and possibly by the SANSN are referred to as regional events. These can only be located using seismograms from several networks if the system clocks of these networks have been synchronised which is best achieved using satellite based GPS data.

Visuals 74

Recommendation: *Synchronisation of system clocks (regional events).*

Sensor and station health

SIM050302
26 ff

It is clear that the purpose for which mine seismic systems are designed – the monitoring of mining-induced seismicity and its quantification in time and space – can only be achieved within certain limits. Seismic processes happen continuously, 24 hours per day, in varying locations and with differing intensities. Seismic networks have an upper and a lower sensitivity limit, their coverage is finite and they transmit only a certain band of frequencies and amplitudes.

SO
39

These are serious limitations especially since, in practice, a certain percentage of stations can also be faulty at any given time (roughly 10-30%), which affects the system performance negatively. Already during the planning phase and when designing a new network or upgrading an existing network, should the resources to maintain the stations, data communication infrastructure and data processing and storage facilities be planned.

Visuals
75

The budget required to maintain a mine seismic system is equal to approximately 10% of its initial installation costs, per year of operation. It requires human resources and expertise within the mine's engineering department and from the rock engineering department.

Recommendation: *At any given time at least 80% of all seismic stations should be fully operational, i.e. are equipped with healthy sensors and are reliably recording ground motion on a 24/7 basis.*

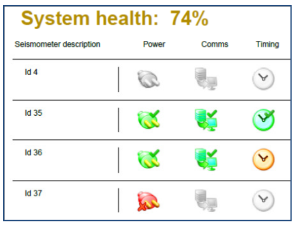
In combination, the above measures are likely to result in seismic data which are more complete, accurate and relevant and which contribute more meaningfully to the management of seismic hazard and rockburst risk. Where they are considered together the issues below, they can significantly increase the value of seismic data to the management of rock related risks on a platinum mine.

Status reporting

The overall performance of a seismic network is a function of its ability to meet the monitoring objectives. Where detailed information is required daily for a number of spatially limited areas, the network needs to supply the underlying data in sufficient detail in both space and time. The core issues found to be impacting on network performance are:

Visuals
76-78

- sensor health,
- seismogram quality,
- location error and sensitivity,
- reliability of data communication,
- expertise of technical staff,
- budget and review processes.



Sensor health is a central issue with some networks, depending on the manufacturer of the sensors and the care taken during their installation.

Based on experience, sensors deteriorate over time and are not always replaced or repaired at the rate at which they fail. The technical support function is often outsourced and lacks proper supervision. As a result, sensitivity and location accuracy are reduced and the quality of seismograms suffers.

It is therefore important to regularly report on the health of network components and the main factors that impact on seismic data quality. A common report format assesses a range of factors, determines a score for each seismic station and summarises the results in a table format.

For reporting purposes, a distinction is made between sensors being off-line (no data recording and no data communication) and a sensor being on-line but not fully functional. The latter may be due to partial failure of the sensor itself, an impaired data recording unit underground, or due to unreliable data communication between station and surface. Hence, a fully functional seismic station has to have a healthy sensor, a reliably functioning data recording unit, and consistent data transfer to surface.

Recommendation: *Report daily and monthly on sensor health to the mine personnel in charge of network operation.*

remember:

no process without **data collection**

no data collection without **data analysis**

no analysis without **decisions**

no decisions without **action**

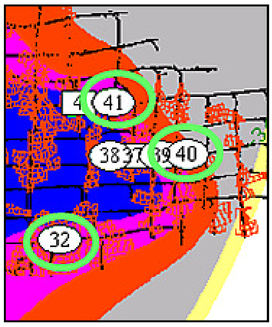
Principal sites

Principal stations (or sensor sites) are network stations that are critical in terms of seismic monitoring coverage of the mine and that should receive the highest priority with respect to fault finding and repair. Critical sites provide basic, essential coverage in the case of large, potentially damaging events. These sites must always be in operation and should therefore receive priority in terms of repair and upgrade.

Visuals **79**

The process of identifying the critical stations in a network consists of:

- Identifying those parts of the mining operation that need to be monitored for potentially damaging seismicity at all times;
- Determining the magnitude threshold of damage from rockburst reports;
- Selection of at least three, or even better five, candidates among the existing stations with easy access and on different depth levels to cover the critical areas of the mine;
- Modelling the sensitivity and location accuracy of the pre-selected group of priority sites and either adding to or reducing the number of principal sites accordingly.



To ensure 24/7 operation, and in addition to being prioritised in terms of repairs, principal stations should be equipped with UPSs or built-in batteries, and with an additional cable pair for horizontal communication between seismic box and shaft station in case of the loss of communication.

Recommendation: *Identify 'principal sites' required for basic coverage of critical mining areas; ensure sufficient location accuracy and sensitivity for the minimum rockburst magnitude, i.e. the smallest events known to cause damage.*

Data back-up

Mining operations in the BC have life spans of several decades. Data and information relating to rock related hazards within these operations have to be saved and stored for extended periods of time to be available should the need arise.

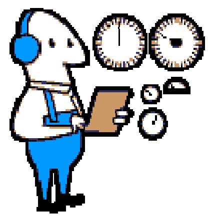
Seismic data, the history of the seismic system and its operation, seismic data analysis results and relevant reporting, and all decisions based on the collected seismic data should be stored and regularly backed up to external locations to avoid loss of data through fire or other natural hazards.

Part of ensuring long-term use of seismic data is the conversion of historic data to newly introduced standards and, when applicable, to new storage technology. An example is the development of high-density digital data storage devices from floppy disk to stiffy, from there to magnetic tape and finally to CDs, DVDs and then high capacity hard disk drives. All of these storage media have a life span after which the stored information can no longer be retrieved.

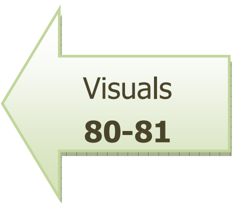
Recommendation: *Reliable seismic database back-up procedures including data migration across software versions.*

System optimisation

A modern digital seismic system has hundreds of parameters that need to be set at the time of installation and commissioning to ensure optimal operation, ranging from rock mass properties to digitising algorithms and the calculation of source parameters. Each mine site is different, not only with respect to the geotechnical environment, but also in terms of network configuration, data transmission, sensors deployed, source quantification, data processing and the reporting of seismic data analysis results to mine personnel.



One set of parameters directly impacting on the quantification of the observed seismicity relates to the way seismic waves are recorded, filtered, digitised and stored for subsequent processing and analysis. These parameters should be adjusted such that they are optimally suited for the type of seismic failure occurring with the reach of the seismic system, especially the frequency range of the waves emitted by the local seismic sources.



The smaller the sources, the higher are the wave frequencies emitted by these sources, and the higher the required sampling rate and the capacity of the network to transmit and store information. As an example, a mine experiencing seismicity mainly associated with blasting and generally in the magnitude range below M=0, has to set noise filters to a higher frequency band, digitising speeds to higher rate, and data transmission speed to a higher bandwidth than a mine experiencing the occasional large event on geological features.

Recommendation: *Filter settings, sampling rate and data communication speed (bandwidth) to be aligned with the event magnitude range of interest.*

Quality control

To instil confidence in the outcomes of seismic data analysis, it is important to have qualified personnel in charge of the system operation and data interpretation. This will also ensure that the quality of the seismic raw data collected by the network meet certain pre-set quality criteria.

For this purpose, each trigger set recorded by the system should be scrutinised for validity and only those representing a dynamic rock mass failure recorded by a defined minimum number of sensor sets (also referred to as the minimum NoTs) should be recorded. Note the definition of quality:

DEFINITION

Quality:

Totality of features and characteristics of a service or product that bear on its ability to satisfy stated or implied needs [ISO 8402, 1986]

We note that quality is defined in relation to the needs and expectations of the customers, which may vary from one client to the next.

It is the responsibility of the quality control process to verify that each event has fulfilled the requirements in terms of minimum NoTs and spectra recorded, and other site specific criteria, which tend to differ from mine to mine depending on the needs.

The higher the demands in terms of data quality, the more reliable are the data analysis results and the more relevant will be the conclusions and possible corrective action drawn from seismic data analysis. The ratio of accepted to rejected events may be small: it is not uncommon in ultra-deep gold mines that the proportion of rejected triggers due to quality concerns is above 50%.

Recommendation: *Only valid seismic events are used for data analyses that meet the minimum quality standards (excluding blasts).*

Practice reviews

SO 88

On seismically active platinum mines with a discernible seismic risk, mine employed rock engineers are the primary customers of seismology services. They are in charge of controlling the contracts with service providers receive the seismic data analysis results for review and recommend remedial action when required.

There are four task groups that rock engineers have to cover in such an environment:

1. Input into mine planning: Design of support pillars and bracket pillars; optimal face layout and mining sequence, production rate and face configuration; optimal design and placement of stability pillar etc.

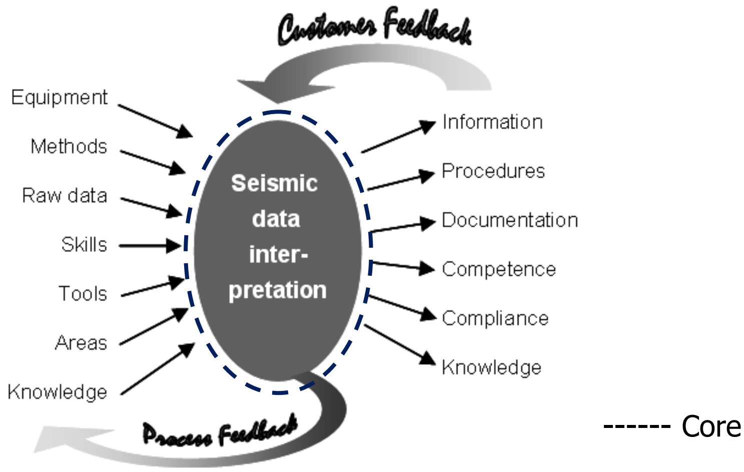
2. Support systems design: Evaluation of rockburst information and peak ground motion estimates to recommend suitable excavation support.

Visuals 82

3. Hazard identification: Correlating trends and patterns in seismicity with information from other disciplines (geology, production, safety and health) for detection of potentially hazardous developments.

4. Contract management: Liaison with suppliers; reviews and audits; quality control and other functions required to administer contracts with seismic service suppliers.

Procedures adopted by a mine need to ensure good communication, compliance with legal and operational requirements and adequate response to the information received.



The core process, seismic data interpretation, receives various forms of input and delivers several outputs to customers. The co-operation of recipients of seismic information with network suppliers and those conducting data analysis and evaluation is essential for the successful management of seismic risks. Customer feedback to seismologists in charge of the core process is used to feed back to the input side to ensure continued exchange and improvement of the overall process.

Feedback can be continuous or through a periodic, scheduled review process. Customers occupy the most important role and should be the ones to drive the review process. Criteria should be identified that allow the quantification of efficiency and effectiveness of the processes with the aim of improving these processes over time.

Recommendation: *Regular practice reviews and quality management procedures should be implemented.*

Your notes:

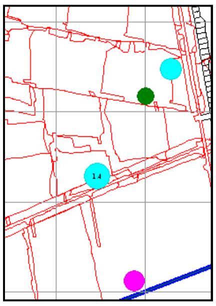
I have studied the material and can answer the following questions:	
Why is the quality of seismic data essential for successful monitoring?	
Name the criteria to measure and quantify the health of seismic stations.	
What is the function of a principal site?	

7 Seismic monitoring – Value-add

Extracting value from data collected by the seismic network, and other sources such as incident reports, is the overall objective of monitoring. Analysis and interpretation of collected information should lead to improved practice and a reduction in seismic hazard and risk.

Incident data base

To accommodate the wide range of factors that can contribute to Rock bursts and seismic injuries, it is advisable to set up a database that allows the analysis of the information in a convenient and quick way. Relating to rockburst incidents, the key questions are:



- What type of seismic event causes what type of damage?
- Are there events with a higher probability of injuring workers than others?
- Can the rockburst and injury frequency be related to geotechnical areas or to mining sections?
- Are there certain layout parameters that seem to reduce damage frequency?
- Do Rock bursts or injuries occur predominantly during the night or the day shift?
- Does the support type influence the severity of injuries?

SO
71-75

A deeper understanding of the causes of rockbursts would likely lead to potential remedial measures, which would most likely lead to a reduction in seismic hazard in a mining operation affected by induced seismicity.

Visuals
84

Recommendation: *Rock burst data bases need to be consistent, complete and accurate for a given reporting period and in a format that allows statistical analysis, e.g. spreadsheets or relational data base.*

Rock burst analysis

Recalling the process defined by *network design - data collection - data and information analysis - risk reduction*, the analysis of rockburst related information forms part of the second last step before hazards and risks can be reduced. Rock burst incident analysis enables mine management, production personnel, rock engineers and mine planners to develop a deeper understanding of the conditions that lead to dynamic rock mass failure, which in turn may result in damage to excavations.

SIM100301
42 ff

The recommended practice is to gather and store information relating to four main topics when attempting rockburst analyses (Durrheim et al, 2006):

1. General such as date, time, work place, incident number,
2. Seismic source parameters,
3. Mining and geology in the affected area,
4. Experienced losses, i.e. on- or off-reef, FOG size, damage type and extent etc.

To create a detailed record of rockburst incidents and the conditions under which they occur, a well-structured database is essential. Optimally, the database should be a relational database structured in such a way that these four groups of entries are accommodated (See Output 2, Chapter 5 of SIM100301).

The objectives of the analysis of rockburst data are twofold:

Visuals
85-89

1. To understand in detail the causes and contributing factors in each individual case; and
2. To detect patterns and common characteristics, amongst the recorded cases that reveal vulnerabilities and offer opportunities for future prevention. Where these can be identified, such as pillar dimensions and their placement or certain geological conditions, corrective action can be implemented.

Recommendation: *Rock burst analysis to specify source, failure and damage mechanisms, location and the mining and rock conditions under which failure occurred.*

Rock burst risk ratings

SO
92

Rock burst risk ratings make use of the rockburst incident analysis results by choosing leading indicators that point towards a vulnerability. For example, rockburst related data from platinum mines indicate that certain pillar cutting practices along gullies on the Merensky reef horizon in a depth range beyond 800m may increase the level of rockburst risk. The leading indicators identified in this scenario are: deep gully, narrow siding, oversized pillar and irregular pillar shape.

Visuals
90-91

As rock conditions and mining practices vary, each operation would have to evaluate their respective incident records to identify the risk factors. Then, applying these to the working places in operation at a given time, risk ratings could be assigned which, if chosen well, could reflect the likelihood of a certain panel or access tunnel to experience damaging seismicity.

Recommendation: *Rock burst risk ratings based on factors contributing to potentially damaging seismicity and to rock conditions that increase damage probability.*

Risk reduction

Risk reduction is the final step in the process of seismic data analysis for improved rock related risk management. The causes and factors identified during rockburst analysis should be systematically and effectively addressed to reduce both sources of seismicity and exposure to Rock bursts.

Visuals
92

Rock burst risk reduction is as much a matter of reducing the hazard, i.e. preventing some or all of the identified seismic failures to occur, as it is a matter of preventing damage and reducing exposure. The latter can be achieved by improving support measures, removing workers and equipment from seismically active areas, reducing the extraction of ore reserves under unstable conditions and the use of access ways in seismically active parts of an operation.

Once precautionary measures have been decided upon their implementation should be monitored. A change in practice often requires motivation, training, demonstrations and follow-ups, including evidence that the new practice has benefits and warranted the effort to change. Such evidence is found in the rockburst incident data base, which should reflect fewer incidents or a reduction in severity. Where either incident frequency or severity has dropped or possibly both, the risk mitigation measures can be considered successful.

Recommendation: *Periodic analysis of rockburst data bases to extract guidelines for improved mining methodology; follow up on successful implementation.*

Your notes:

Check your progress

I have studied the material and can answer the following questions:	
Which are the incident details that should be captured in a rockburst data base?	
How are rockburst risk ratings calculated?	
How can the risk of rockbursts be systematically reduced?	

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GLOSSARY

ASG	Advanced strike gully
BC	Bushveld Igneous Complex
CGS	Council for Geoscience
GPS	Global Positioning System
IRUP	Iron Rich Ultramafic Pegmatite
MER	Merensky reef horizon
M_{max}	Magnitude of the largest event
NoT	Number of Triggers
P-wave	Primary wave (compressional)
S-wave	Secondary wave (shear)
REC (COMREC)	Chamber of Mines Rock Engineering Certificate
SANSN	South African National Seismic Network
SIMRAC	Safety in Mines Research Advisory Committee
SHD	Seismic Hazard District
UCS	Uni-axial Compressive Strength
UG2	Upper Group 2

For other rock engineering and mine seismicity related terms and abbreviations please refer to the glossary on pages 125 – 128 in the SiM manual.