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Seismological and Numerical Characterisation of Stability Pillar Behaviour at South Deep Mine

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Seismological and Numerical Characterisation of Stability Pillar Behaviour at South Deep Mine

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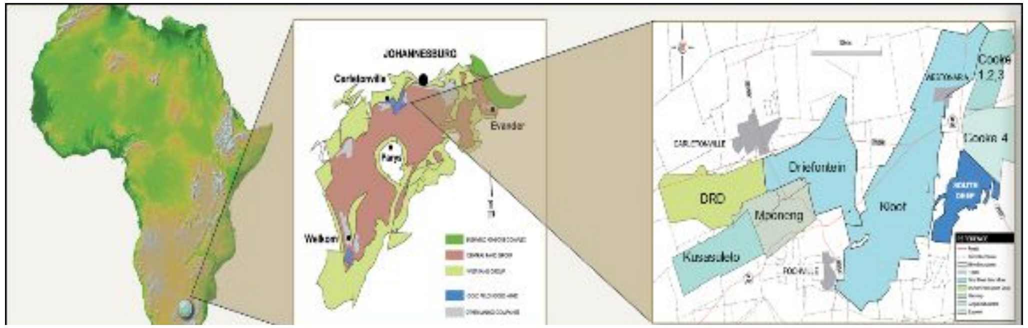
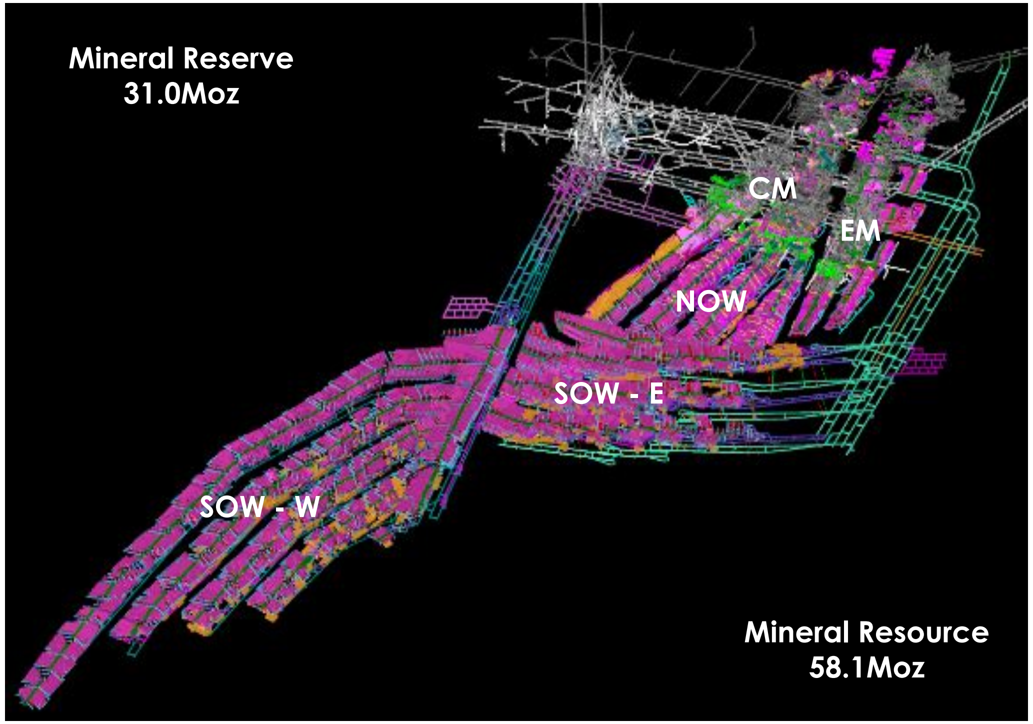
PRESENTATION OUTLINE

1	STUDY FOCUS OVERVIEW
2	GEOLOGY
3	MINING METHOD
4	STUDY RATIONALE
5	STUDY OBJECTIVES
6	METHODOLOGY
7	RESULTS
8	DISCUSSION & CONCLUSION

INTRODUCTION – STUDY FOCUS OVERVIEW



Located ~70km south-west of Johannesburg in the Witwatersrand basin



OREBODY

Mining focused on **Massive Elsburg sedimentary reefs**	Mineral Reserve (2023) **31.0Moz**	Mineral Resource (inclusive) (2023) **58.1Moz**

LOM

Current LOM
~ 70 years

ACCESS

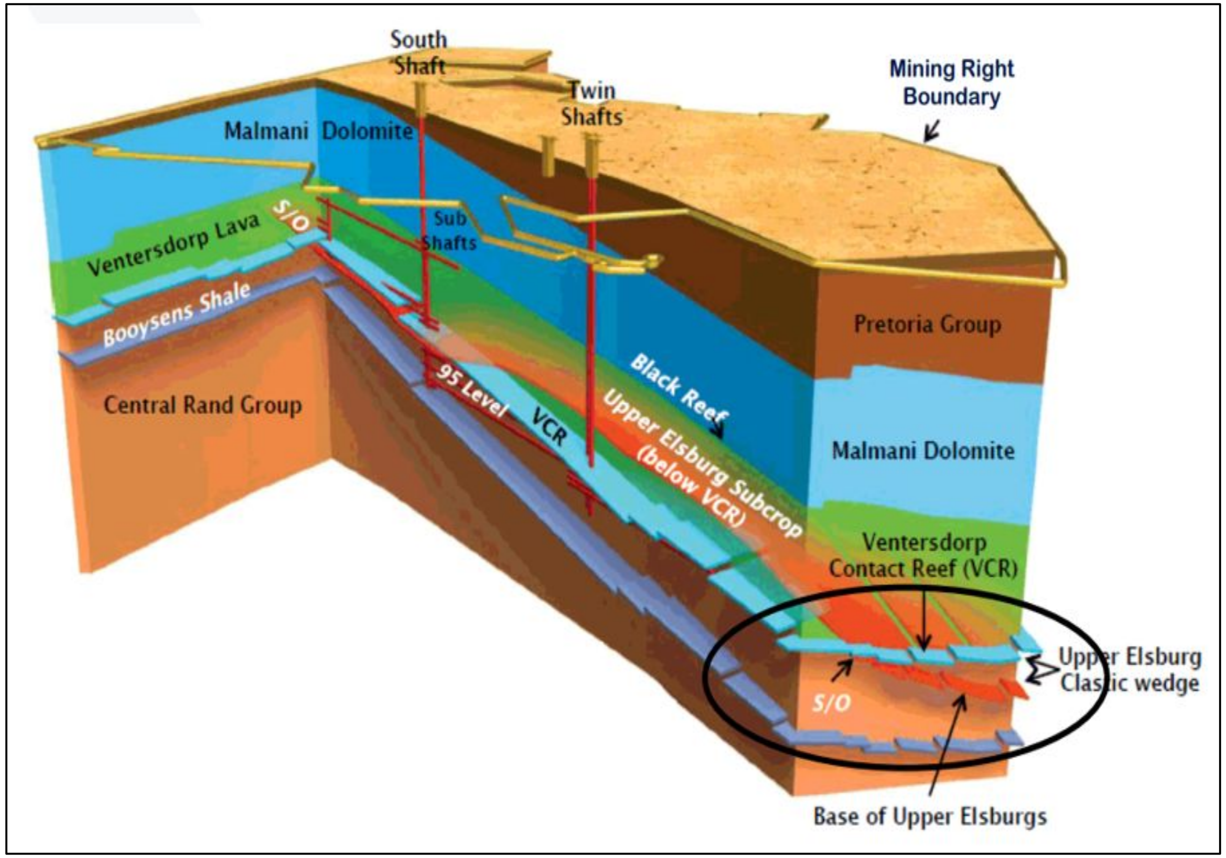
Operations accessed by **two shaft systems:** • Twin Shaft Complex • South Shaft Complex	**Deepest single drop shaft** in the world **~3km**	Average depth of operations: **2.8km - 3.4km**

MINING METHOD

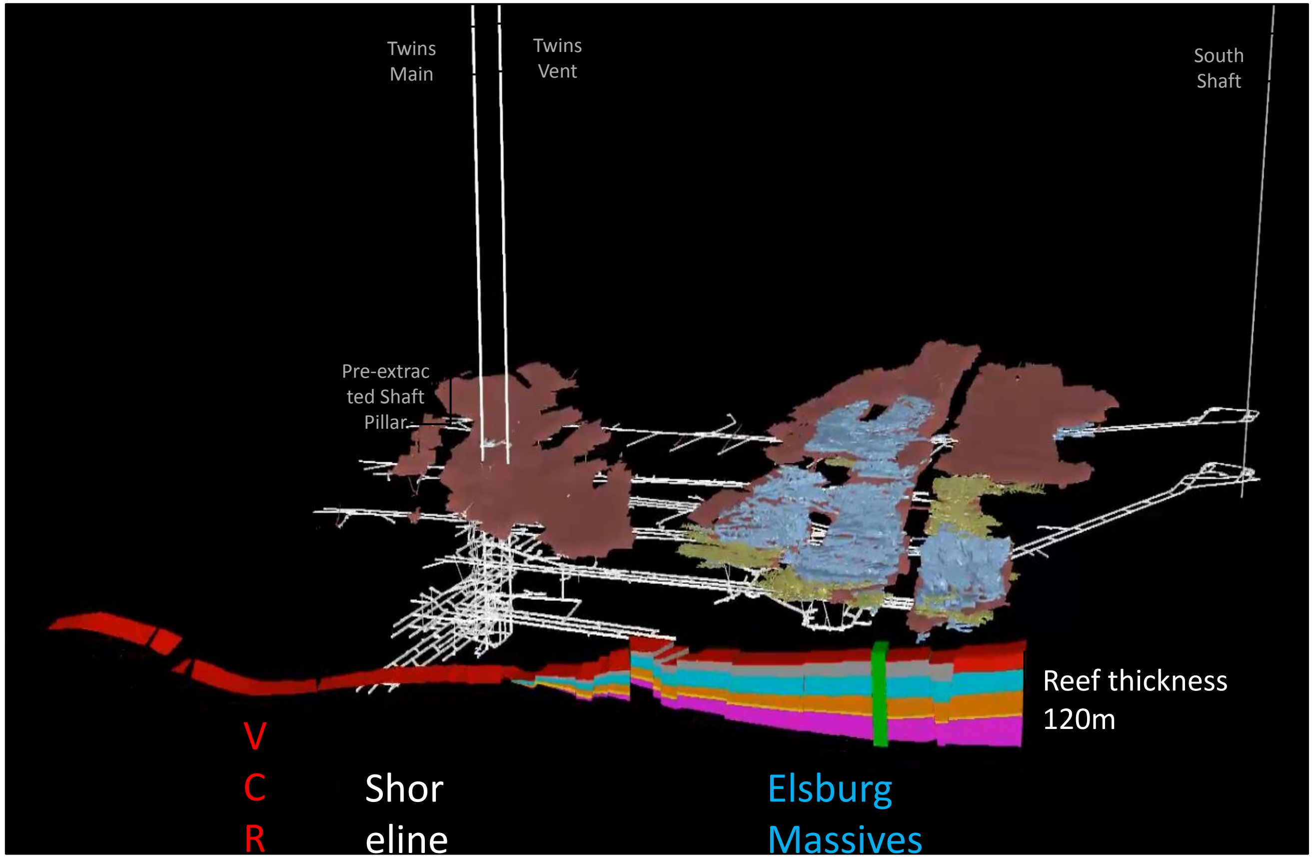
Horizontal **destress**	**Longhole** stoping	**Bulk mechanised** mining methods

INTRODUCTION – GEOLOGY

Regional Geology

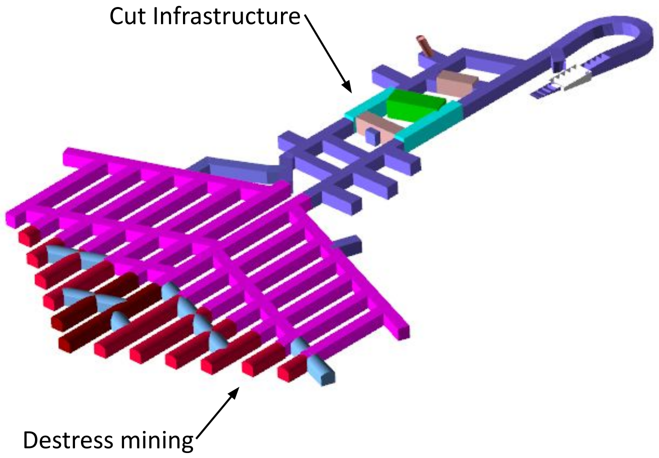


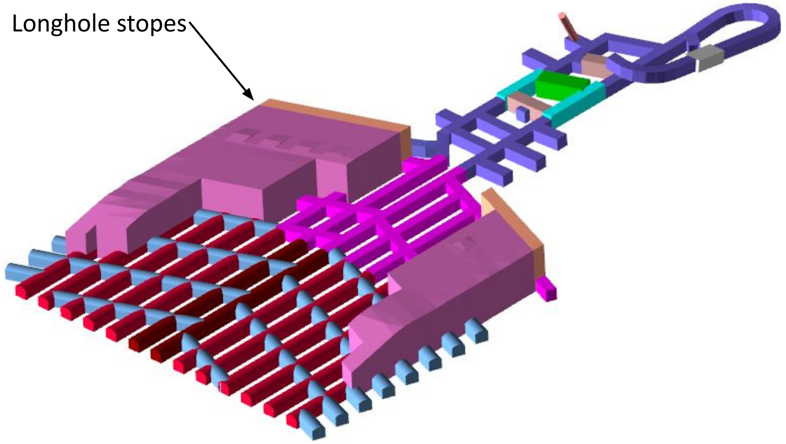
Local Geology

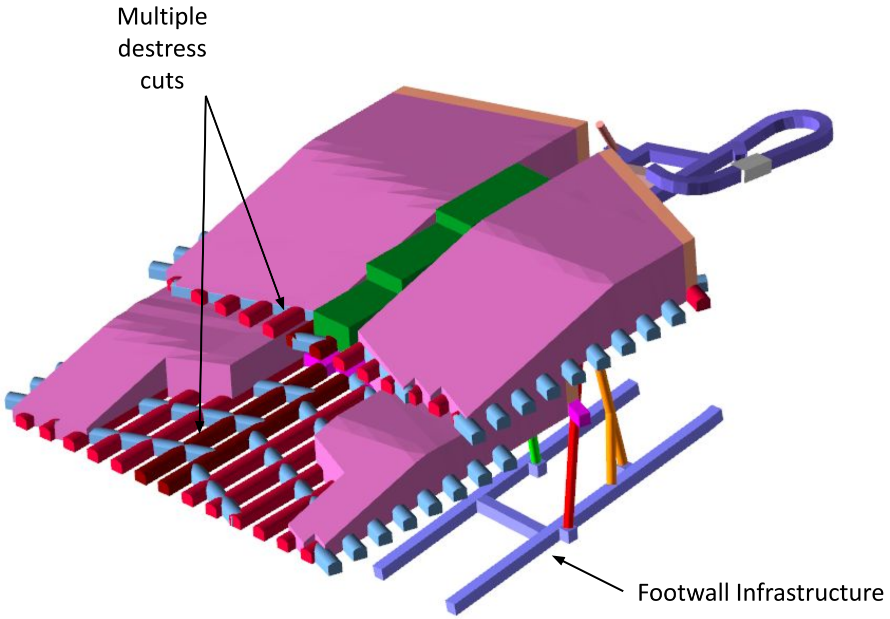


- Orebody lies within the Central Rand Group of the Witwatersrand Supergroup.
- The Ventersdorp Contact Reef (VCR) and Upper Elsburg reefs are the most economically important units.

INTRODUCTION – MINING METHOD







Cut Infrastructure and Destress mining

- The initial phase of mining consists of establishing infrastructure to support the mining activities in a cut.
- Once the base of the targeted reef is reached a destress cut (6.0m(w) x 5.5m(h)) is mined towards the top of the target
- This reduces the in-situ stress and allows us to mine large excavations (stopes of 13m(w) x 15m (h))

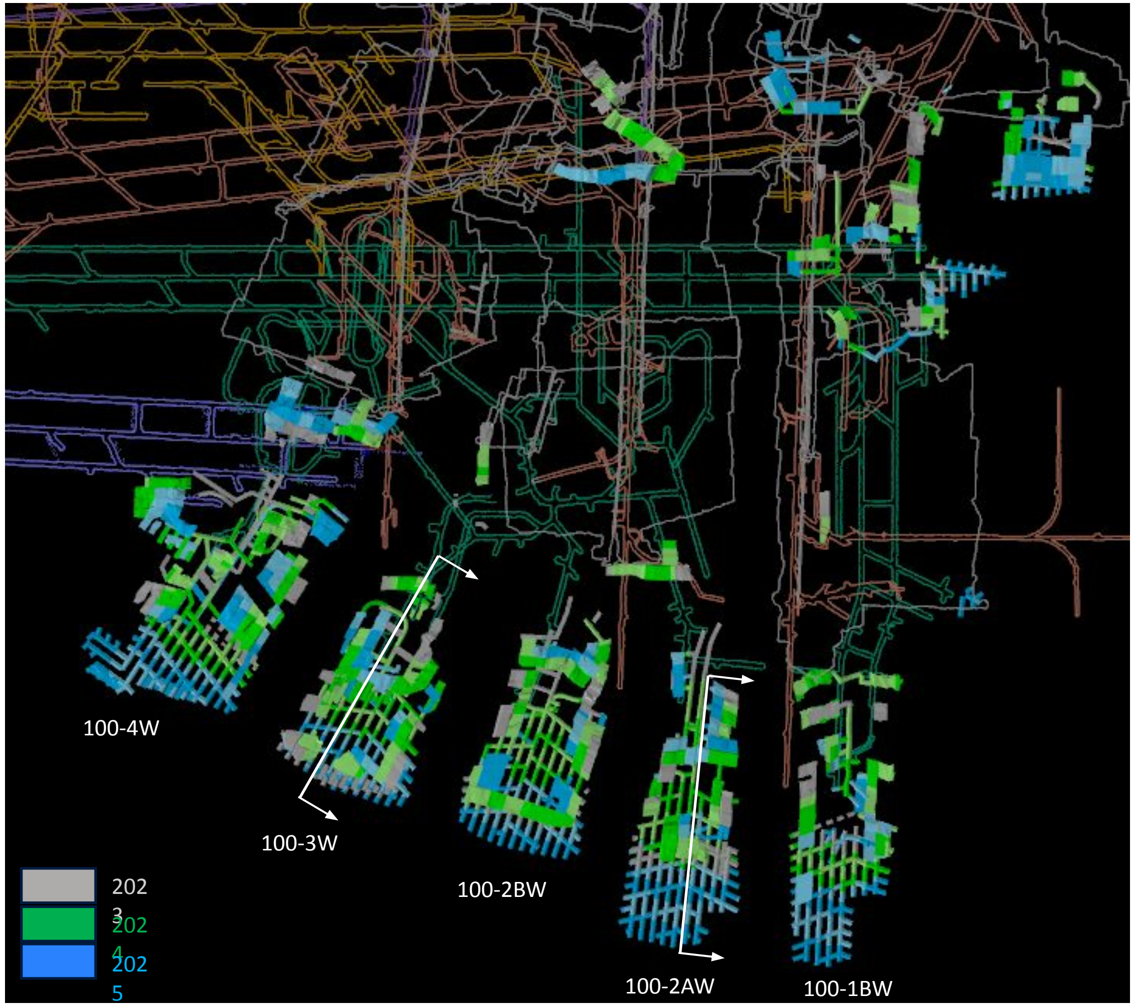
Longhole Stoping

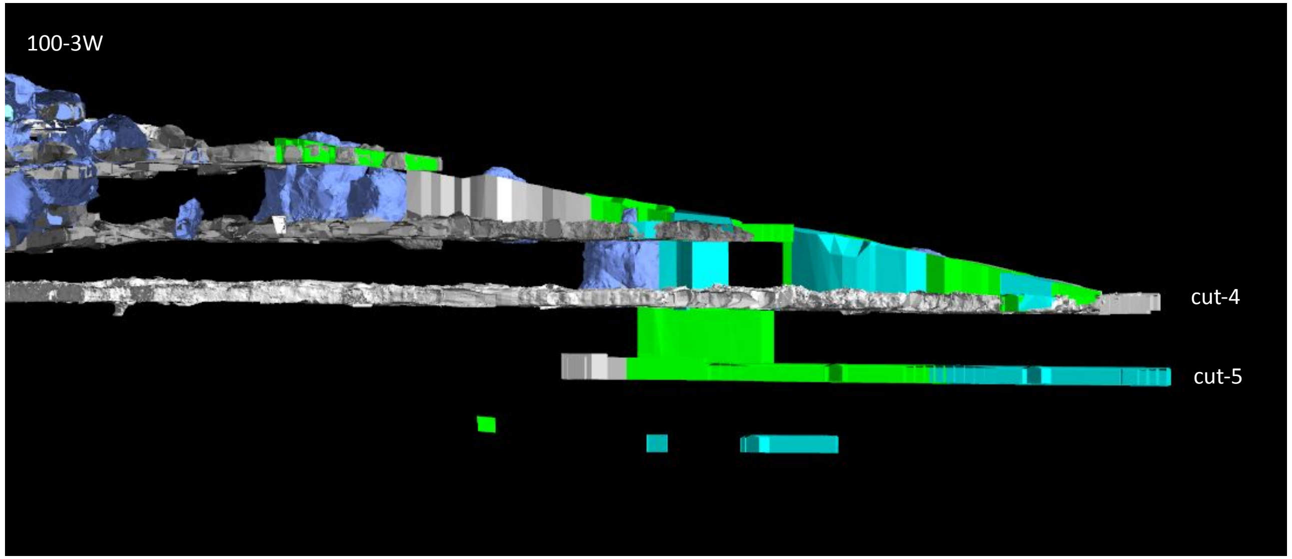
- Longhole stopes are then mined and backfilled sequentially towards the centre accesses

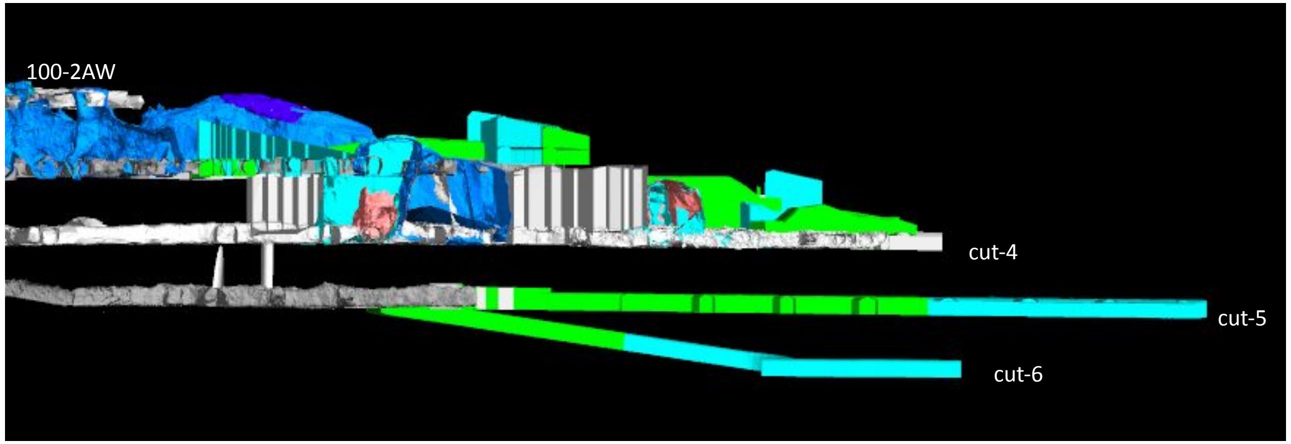
Multiple Cuts and Footwall Infrastructure

- This sequence is repeated to follow the -15° dip of the reef
- Cuts are spaced vertically at 15m (based on drilling accuracy and stress characteristics)
- The activities in the reef horizon is supported by footwall infrastructure (rock handling and airways)

INTRODUCTION – MINING METHOD







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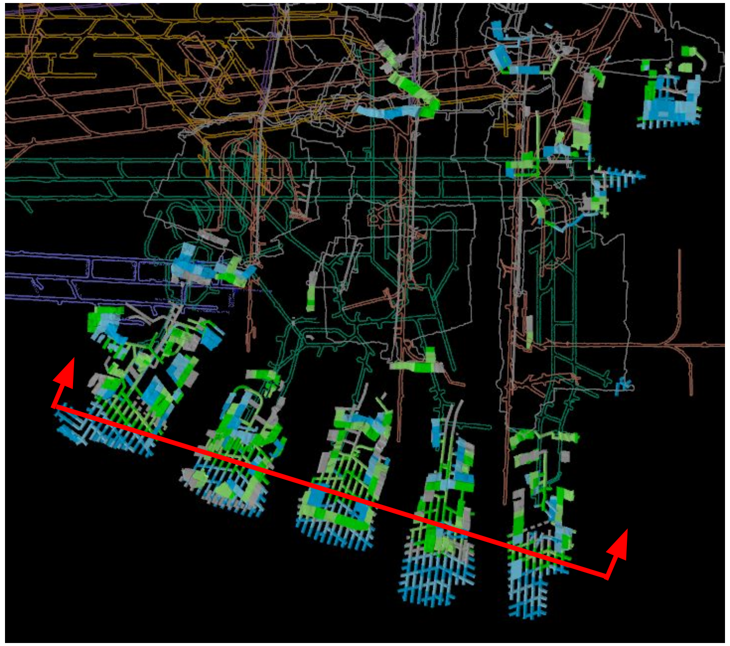
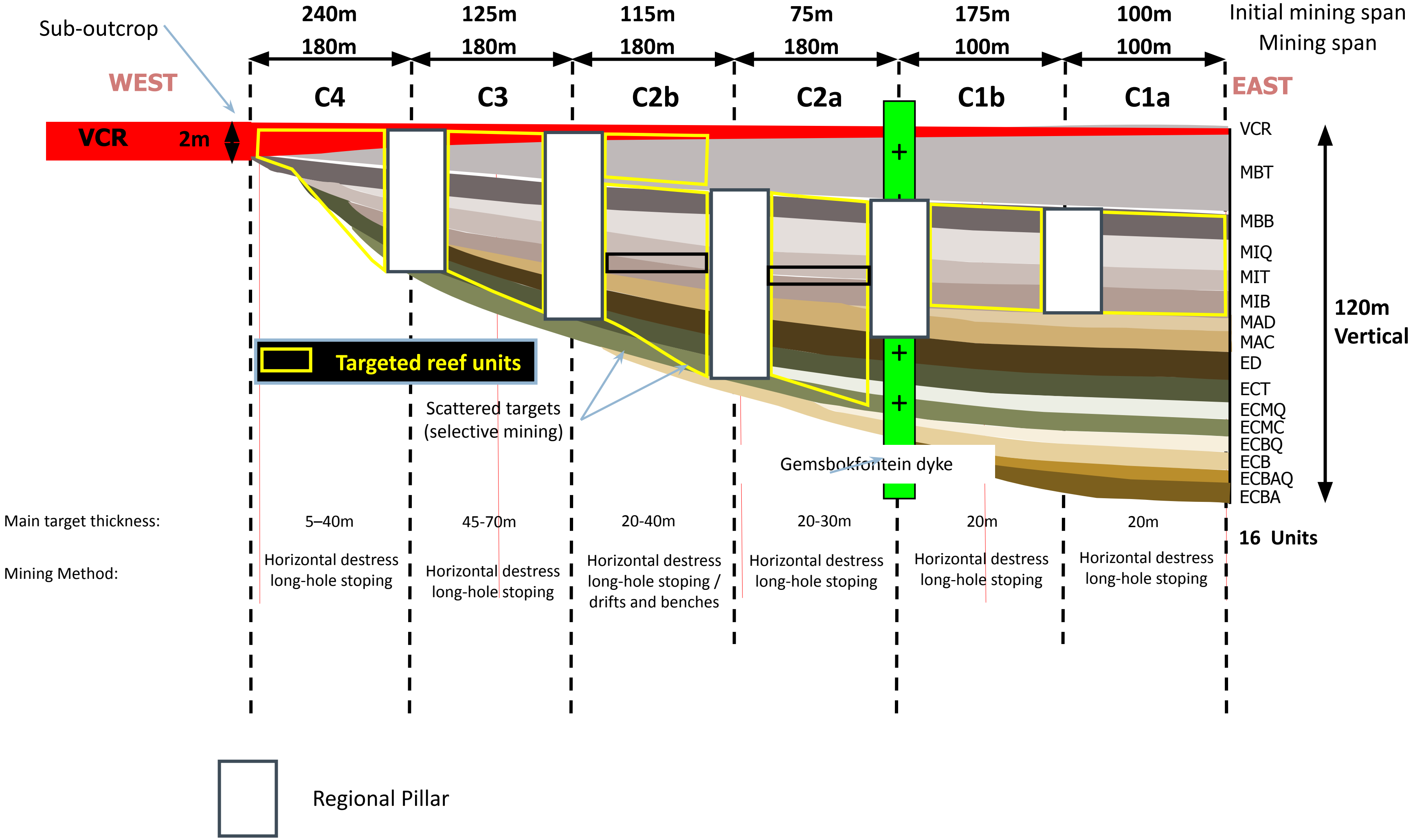
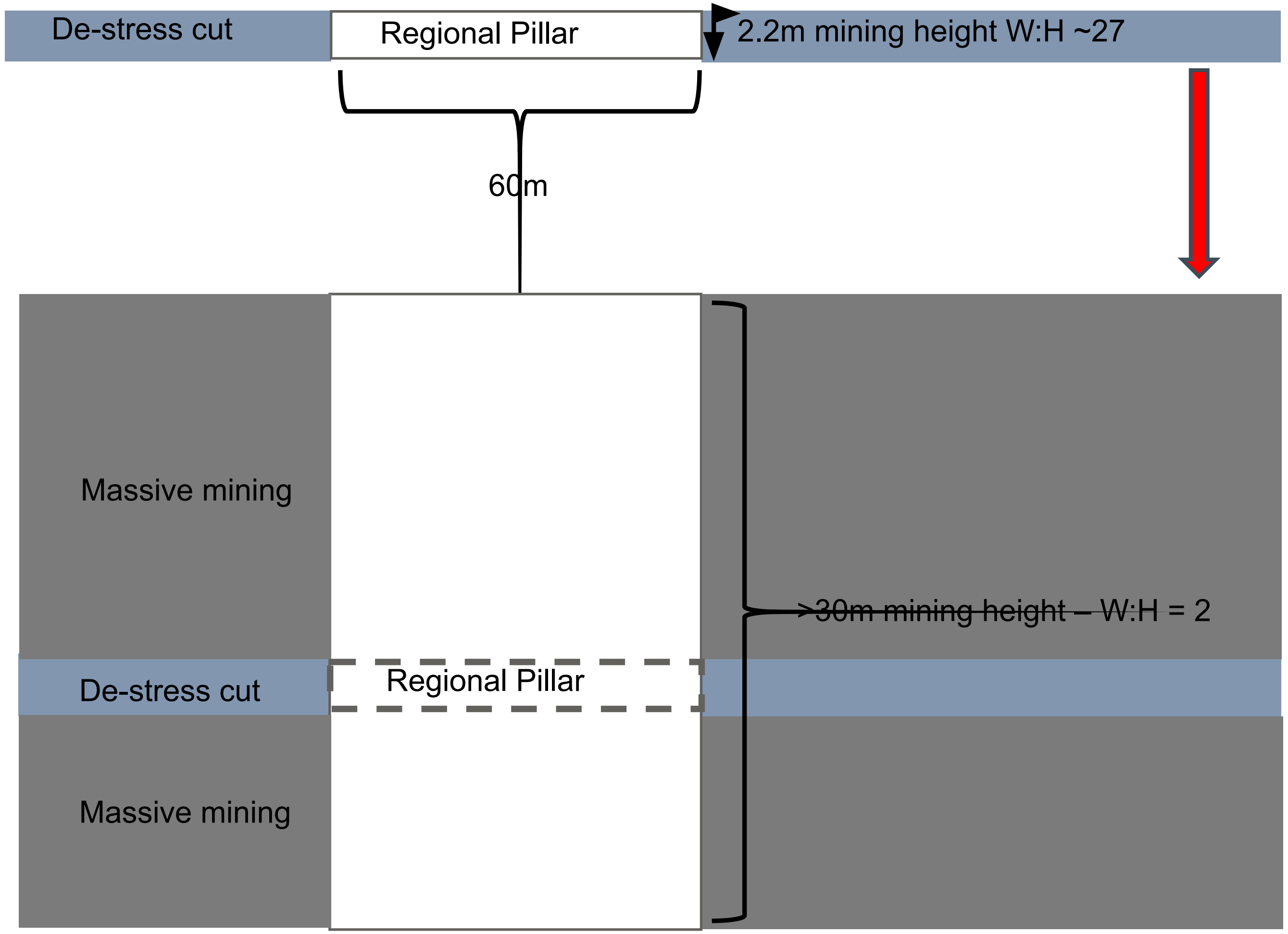




STUDY RATIONALE



progressive massive mining (long hole open stoping) reduces pillar width-to-height ratio

Increased susceptibility to yielding and failure – **Understanding pillar behaviour under such conditions is critical for risk mitigation**

STUDY RATIONALE

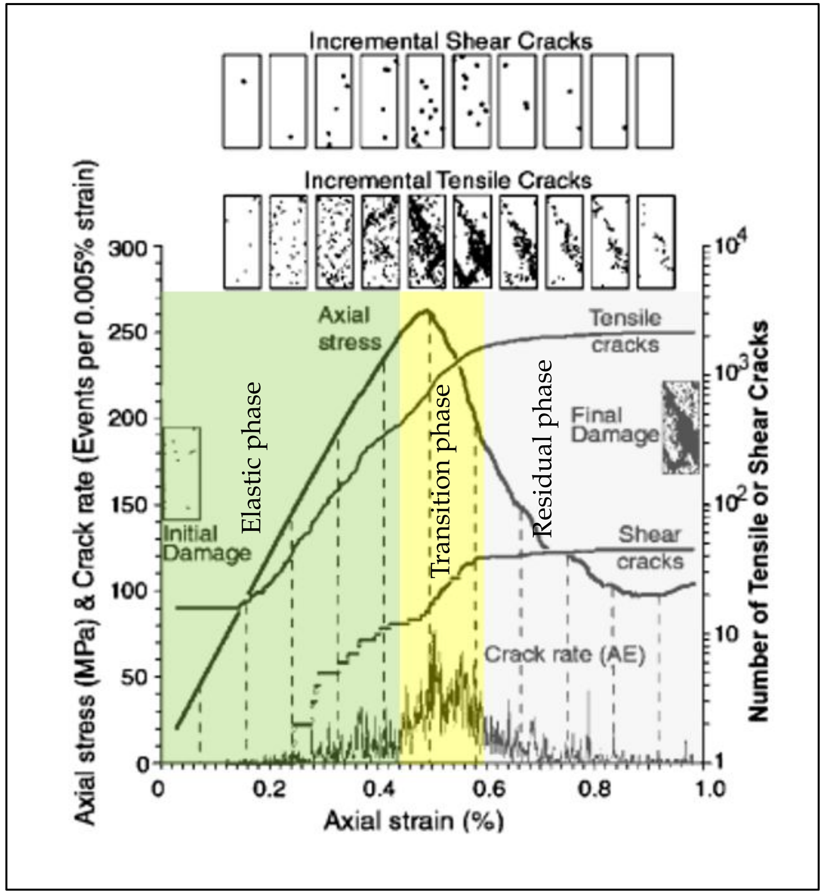


Figure 1: Stress-strain stages (Diederichs et al., 2004)

- Study builds on methodologies from Ollila and Brown (2022), who demonstrated seismology's efficacy in tracking sill pillar yield
- Diederichs et al. (2004) illustrated rock damage progression through a simulated stress-strain curve, identifying three stages:
  1. Elastic phase (Pre-peak), where stress increases within elastic limits, accompanied by rising acoustic emissions.
  2. Transition phase (Peak to post-peak), where stress plateaus then decline with peak crack rates (acoustic emissions) signalling inelastic strain.
  3. Residual phase where Stress stabilizes at lower levels, with reduced cracking.
- Ollila and Brown (2022) linked these stages to seismological indicators:
  1. Strain hardening (high Energy Index (EI), low Cumulative Apparent Volume (CAV) which reflects elastic stress accumulation.
  2. Strain softening (low EI, high CAV) which denotes stress release.

- This study extends their framework by correlating numerical stress-damage models with seismic data to evaluate a stability pillar at South Deep Mine.

STUDY OBJECTIVES

Understanding pillar behaviour under such conditions is critical for risk mitigation

Aim	**Synthesise numerical modelling and seismological analysis to characterize pillar response as W:H decreases**		
Objectives	**Numerical Analysis**	**Seismological Analysis**	**Behaviourr Characterisation**
	Quantify stress and damage evolution via Finite Element (FE) modelling	Identify strain hardening/softening phases in the pillar using EI and CAV.	Correlate numerical and seismological findings to predict failure mechanisms.

METHODOLOGY – Numerical Modelling

1 Numerical Modelling Framework

- **Non-Linear Finite Element Modelling (Abaqus Explicit Solver)**
- **Simulated stress and damage evolution during 2010–2016 mining sequences**
- **Model focused on pillar with:**
    - 60 m width
- **Progressive reduction in width-to-height (w/h) ratio:**
    - From ~27 (2.2 m HD slot)
    - To ~2 (30 m open stope condition)
- **Results used to assess stability and potential damage mechanisms over time**

2 Input Parameters – Stress field

- **Based on stress measurements performed at South Deep**

Principal stress component	Magnitude gradient (MPa/km)	Dip	Dip azimuth	σ_i/σ_{zz}
σ_1	27.0	90	000	1
σ_2	24.0	00	000 = 180	0.89
σ_3	16.0	00	090 = 270	0.59

Cartesian stress tensor at 1,000 metres:

$$\begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{zx} \\ \sigma_{xy} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{yz} & \sigma_{zz} \end{bmatrix} = \begin{bmatrix} \sigma_{EE} & \sigma_{EN} & \sigma_{UE} \\ \sigma_{EN} & \sigma_{NN} & \sigma_{NU} \\ \sigma_{UE} & \sigma_{NU} & \sigma_{UU} \end{bmatrix} = \begin{bmatrix} 16.0 & 0 & 0 \\ 0 & 24.0 & 0 \\ 0 & 0 & 27.0 \end{bmatrix} \text{MPa}$$

3 Input Parameters – Material properties

- **Based on TCS and UCS tests on quartzites and the hangingwall lava**

Number	Domain	Code	Density (kg/m³)	UCS (MPa)	GSI	Stage	Plastic strain	E (GPa)	ν	s	m	a	d
1	Pretoria Group	PG	2,752	100	65	Peak	ε_0 = 0.0%	20.9	0.25	2.76E-03	1.77	0.5	0.25
						Transition	ε_1 = 2.2%	20.9	0.25	2.76E-03	1.77	0.5	0.25
						Residual	ε_2 = 3.8%	10.5	0.25	1.26E-03	1.16	0.5	0.09
2	Malmani Dolomite	DOL	2,752	100	65	Peak	ε_0 = 0.0%	20.9	0.25	2.76E-03	1.77	0.5	0.25
						Transition	ε_1 = 2.2%	20.9	0.25	2.76E-03	1.77	0.5	0.25
						Residual	ε_2 = 3.8%	10.5	0.25	1.26E-03	1.16	0.5	0.09
3	Ventersdorp Lava	VENT	2,752	100	65	Peak	ε_0 = 0.0%	20.9	0.25	2.76E-03	1.77	0.5	0.25
						Transition	ε_1 = 2.2%	20.9	0.25	2.76E-03	1.77	0.5	0.25
						Residual	ε_2 = 3.8%	10.5	0.25	1.26E-03	1.16	0.5	0.09
4	Westonaria Formation	WAF	2,900	79	54	Peak	ε_0 = 0.0%	16.5	0.25	1.30E-03	1.19	0.5	0.20
						Transition	ε_1 = 2.5%	16.5	0.25	1.30E-03	1.19	0.5	0.20
						Residual	ε_2 = 4.4%	8.3	0.25	7.44E-04	0.92	0.5	0.07
5	Ventersdorp Contact Reef	VCR	2,680	56	57	Peak	ε_0 = 0.0%	11.7	0.23	7.39E-04	1.00	0.5	0.14
						Transition	ε_1 = 2.9%	11.7	0.23	7.39E-04	1.00	0.5	0.14
						Residual	ε_2 = 5.0%	5.9	0.23	3.43E-04	0.65	0.5	0.05
6	Elsburg Reef package	EREEF	2,780	200	75	Peak	ε_0 = 0.0%	50.0	0.20	5.70E-02	3.00	0.5	0.50
						Transition	ε_1 = 0.8%	50.0	0.20	5.70E-02	3.00	0.5	0.50
						Transition	ε_2 = 1.5%	25.0	0.20	1.50E-02	1.23	0.5	0.18
						Residual	ε_3 = 10.0%	1.5	0.20	1.00E-04	1.00	0.5	0.18
7	Footwall quartzite	FWQ	2,780	157	65	Peak	ε_0 = 0.0%	32.8	0.25	1.29E-02	3.12	0.5	0.39
						Transition	ε_1 = 1.6%	32.8	0.25	1.29E-02	3.12	0.5	0.39
						Residual	ε_2 = 2.7%	16.4	0.25	3.49E-03	1.82	0.5	0.14

METHODOLOGY – Seismological Analysis

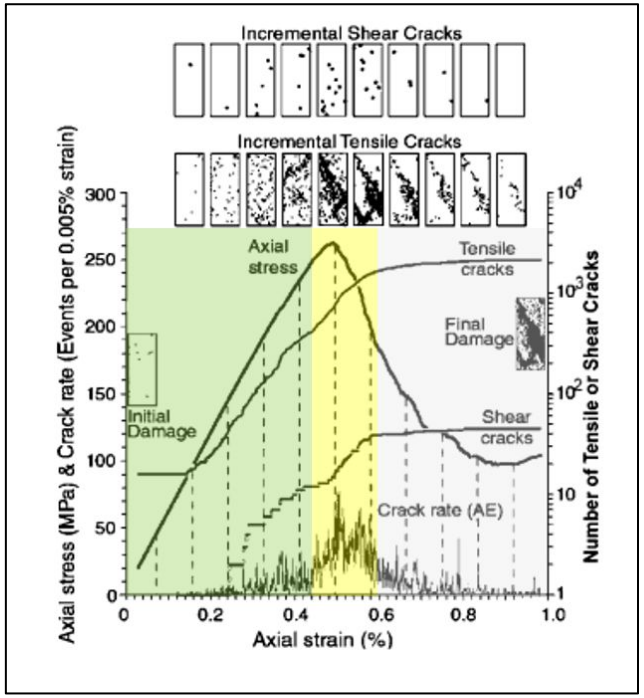
1 Seismic Data

- **Seismic data (2009–2025) were filtered (ML > -0.5) to exclude non-failure events (e.g., blasting)**

Figure 2: Stability pillar under consideration (area of interest, circled in red) and associated seismic events over 15 years (2009 to 2025).

2 Data Analysis

- **EI (stress proxy) and CAV (strain proxy) used to infer stress path changes and track pillar behavior. Three phases were defined:**
  1. Hardening: High EI, low CAV.
  2. Transition: Rapid EI decline, CAV rise.
  3. Softening: Low EI, high CAV.



RESULTS – Numerical Modelling

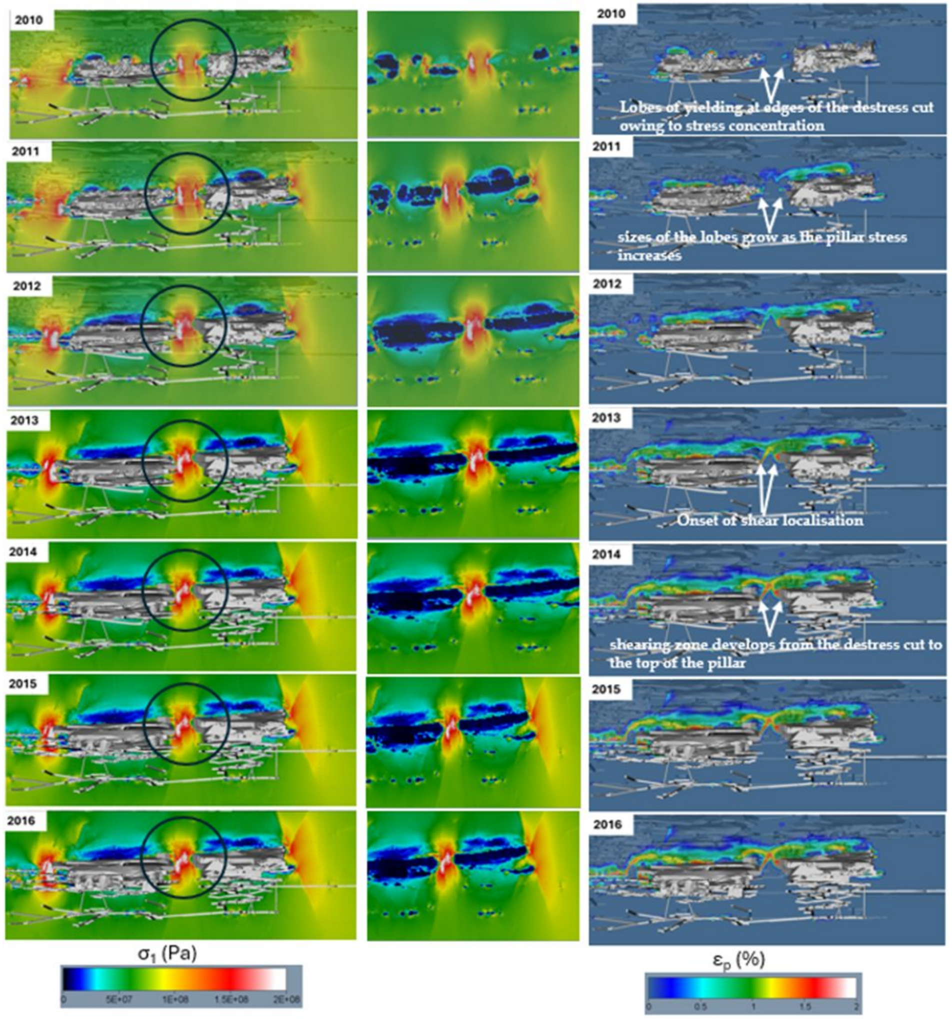


Figure 3: Evolution of major principal stress (left) and plastic strain (right) from 2010 to 2015

Stress and Damage Progression in Pillar Core (2010–2016)

- **Pillar stress:**
  - 2010 - Relatively low stress (~100MPa) in pillar core. Predominant mining was 2.2m HD cut.
  - 2012 – 2016 – pillar core stress increased markedly to >200MPa. Massive mining.

Damage Progression Stages:

- **2010–2011:** Pillar Edge Yielding
  - Lobes of yielding on pillar edges due to localized stress concentrations - Edge yielding **(elastic to hardening phase)**
- **2012–2013: Core Stress Accumulation**
  - Moderate damage evolving within the pillar
  - Massive mining activities advanced
  - Stress buildup approaching **peak strength**
- **2014–2016: Coalescing Plastic Zones and Bearing-Type Failure**
  - Shear-type damage evolved near the hanging wall (top of pillar), initiating in WAF lava
  - Plastic zones coalesced from HD cut to pillar top
  - Interpreted as bearing-type failure **(softening and damage propagation)**

RESULTS – Seismological Analyses

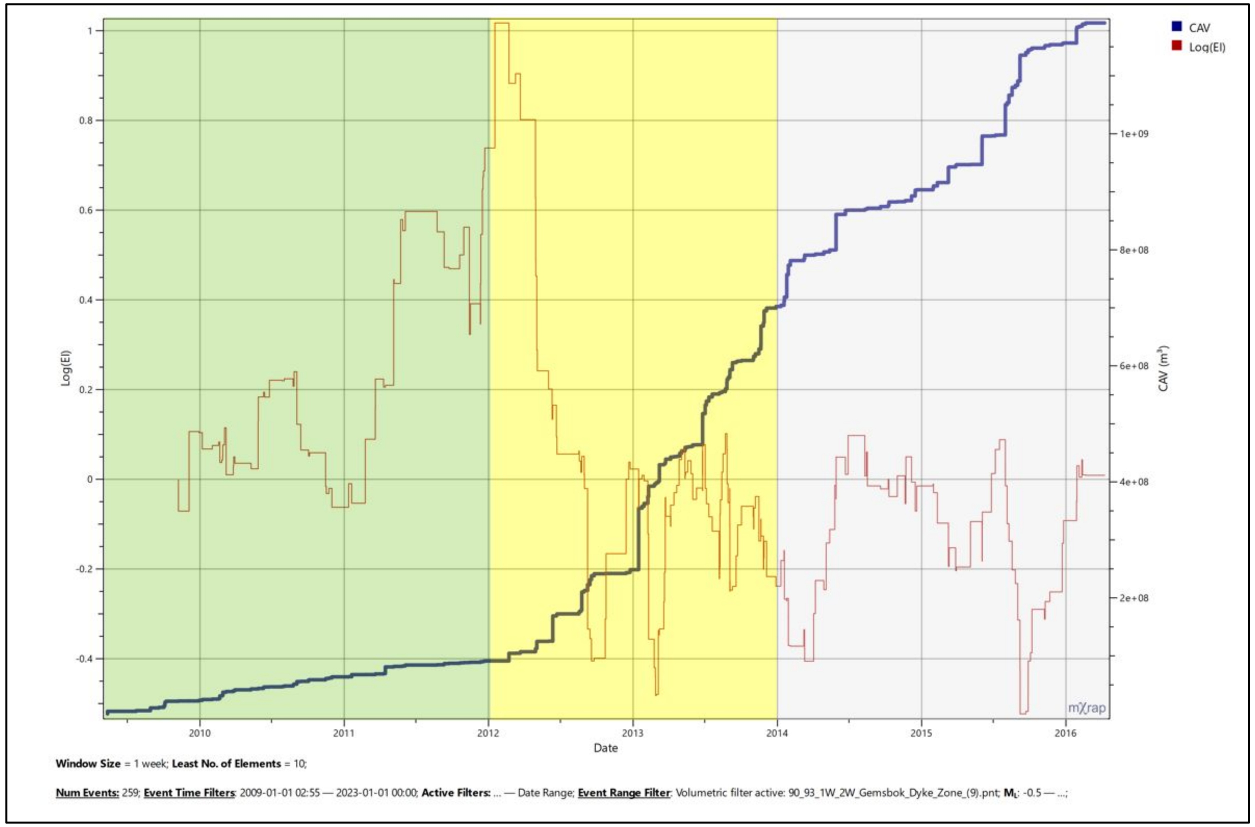


Figure 4: EI/CAV phase transitions.

Pillar Behaviour from Seismological Analysis (EI/CAV Chart – Figure 4):

- Pillar response tracked as W:H ratio decreased due to massive mining
- EI/CAV chart highlights three distinct behavioural phases:

1. Strain Hardening Phase (Green Region)

- High Energy Index (EI), low CAV
- Indicates elevated stress with minimal yielding
- Consistent with confined, high-stress rock mass

2. Transition Phase (Yellow Region)

- Sharp drop in EI and increase in CAV
- Occurred between 2012 and 2014
- Suggests onset of damage and stress redistribution

3. Strain Softening Phase (Grey Region)

- Low EI, high CAV
- Signifies stress release and increased deformation
- **Pillar yielding inferred** from:
  - Sustained low EI and minimal seismicity. May also reflect reduced mining activity in the area

RESULTS – Seismological Analyses

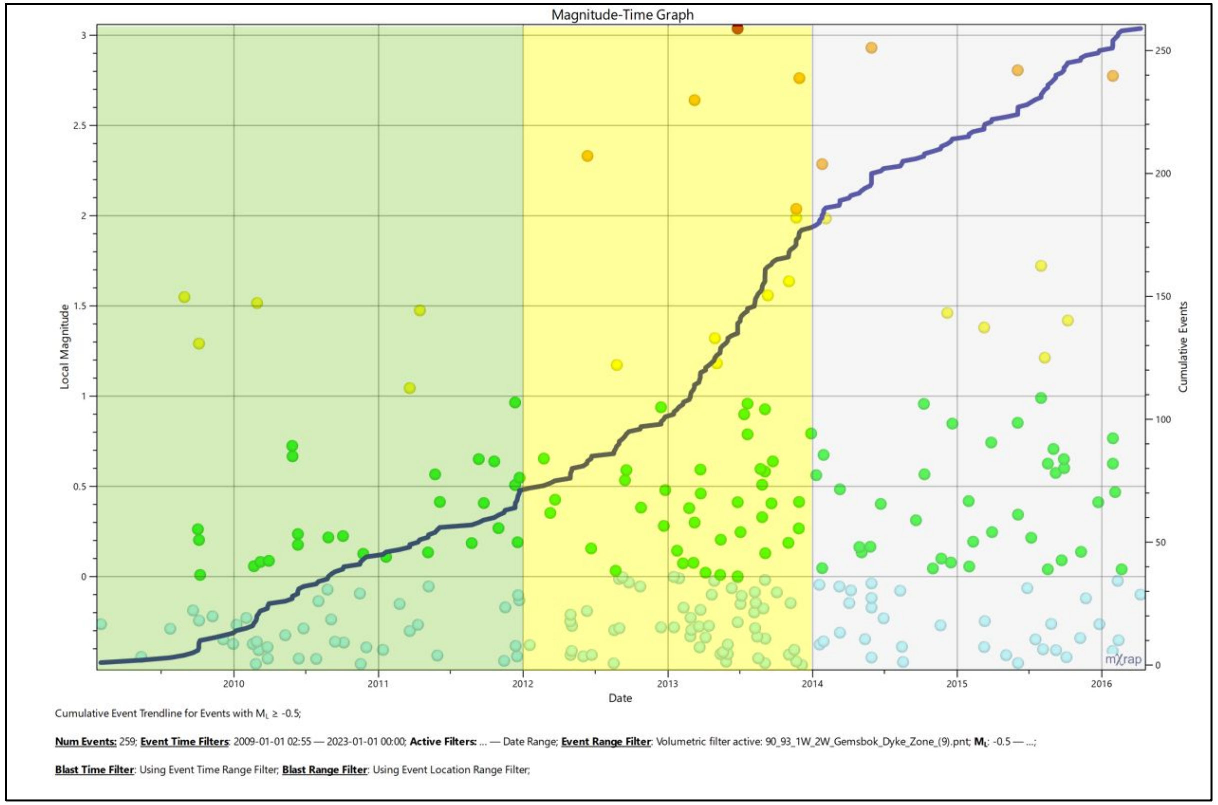


Figure 5: Magnitude-time plot for events in the stability pillar (blue line represents cumulative events).

Seismic Activity Over Time (Figure 5):

- **Rapid acceleration in event rate** from early 2012
    - Included several **larger magnitude events**
- **Deceleration observed** from early 2014
    - Events of **smaller magnitude** dominate
- Pattern is **consistent with a yielding rock mass**
- The larger seismic events occurred when the pillar started losing its load-bearing ability, similar to the findings of Mendecki *et al*. (1999).

DISCUSSION – Pillar Behaviour Analysis

Integrated Methodology

Combined **numerical modelling** and **seismological analysis** can provide an in-depth understanding of pillar behaviour in deep mines

Numerical Analysis

- Highlighted the width-to-height (W/H) ratio as a key factor in stress control and damage evolution.
- Predicted foundation yielding (bearing failure) under decreasing W/H ratios

Seismological Analysis

- **Strain Hardening**: High Energy Index (EI), Low Apparent Volume (CAV) → resistance to deformation
- **Strain Softening**: Low EI, High CAV → onset of deformation and stress release
- Patterns aligned with numerical predictions

Key Takeaway

Integration of tools enhances monitoring, understanding, and management of pillar stability in deep mining.

CONCLUSION – Implications & Future Work

01

Key Findings:

- Stability pillars transition from hardening to softening as W/H ratios decrease.
- These transitions are identifiable via EI/CAV trends and numerical damage models

02

Practical Impact:

- Supports failure prediction and safer mining strategies.
- Provides a framework for real-time pillar stability management

03

Future Work:

- Incorporate additional monitoring tools – active source monitoring, microseismics
- Improve model calibration and validation for enhanced predictive accuracy

THANK YOU