STRUCTURAL MECHANISMS CONTRIBUTING TO LARGE-SCALE HANGINGWALL INSTABILITIES ON THE UG2 REEF HORIZON

A.G. HARTZENBERG

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I hereby declare that this dissertation is my own unaided work. It is being submitted for the degree MSc. Mining at the University of Pretoria, Pretoria. It has not been submitted before for any degree or examination in any other University. This document represents my own opinion and interpretation of information received from the mine or people on the mine.

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A.G. HARTZENBERG

Dated this _____day of _____ 2019

ABSTRACT

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A.G. HARTZENBERG

Supervisors: Dr M. du Plessis

                     Prof D.F. Malan

Department: Mining Engineering

University: University of Pretoria

Degree: MSc Mining

Structural complexities, including regional geologic structures, low-angle structures, ramp structures and alteration zones contribute towards large-scale hangingwall or structural (pillar) instabilities experienced in many UG2 chromitite mines. The associated anomalous behaviour of the rock mass caused by these structures may result in significant ore reserve write-offs. The inability of technical and underground mining personnel to pro-actively identify and treat these geologic structures and associated failure mechanisms has resulted in ongoing instabilities experienced in many mines. Anomalous behaviour is mostly as a result of the exposure of numerous low-angle structures on various scales, commonly known as 'doming'. These low-angle structures are treated simplistically or go unnoticed. Also, the presence of pegmatite veins, which is a common joint characteristic, causes problems and is generally ignored as the potential for instability. Furthermore, the presence of alteration zones is typically unnoticed as it is not common. The exposure of these prominent structures or a combination of these structures can impact on the exposed hangingwall conditions, panel span, support- and pillar behaviour. In some instances the impact have resulted in multiple fatalities and total mine closure.

Case studies were conducted by the author at the Lonmin Marikana Operations where large-scale instabilities have been experienced. These findings were related to other similar study sites in the Bushveld Complex and the Great Dyke in Zimbabwe. The investigations confirmed some of the findings made by

previous studies. However, new information gained from this study provided an improved understanding of the formation, interaction and potential instabilities if these structures are exposed by mining. The formation of the Bushveld Complex and geologic structures contributed to the anomalous conditions experienced in some underground mine workings. With the application of a new technology by the author (a sub-surface profiler), for the first time, the presence and location of these anomalous structures could be verified in the hangingwall. This contributes to an improvement in the spatial interpretation of these structures and confirmed that it should be considered in the mining strategy and support design processes.

The learnings from the study will assist with the early detection of specific structural conditions which may contribute to the mitigation of potentially unstable conditions. Suitable remedial strategies were developed by the author from the site investigations and are discussed in detail. This includes the application of preferred mining layouts, mining direction, spans and support strategies where these structures are present. This work may significantly reduce the risk of large-scale instabilities and is therefore considered a significant contribution towards improving safety and the understanding of these anomalous structures at the mines in the Bushveld Complex.

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LIST OF SYMBOLS AND ABBREVIATIONS

Ga	Billion years
Ma	Million years
km	kilometres
m	metres
cm	centimetres
mm	millimetres
kN	kilonewtons
MN/m	millinewtons/metre
m/s^2	metre per second square
SF	Factor of safety
MPa	Megapascal
GPa	Gigapascal
mbs	meters below surface
σ_c	Pillar Strength
t	Tonnes
GPR	Ground Penetrating Radar
PGMs	Platinum Group Metals
UG2 Reef	Upper Group Number 2 chromitite Reef
kg/m^3	Density of rock type, kilograms per cubic metre

DEFINITIONS

Alteration zones: See shear zones.

Layer-parallel structure: Fault, joint or shear (alteration) zone that occurs parallel to the stratigraphic layering of the Bushveld Complex.

Lineaments: Large-scale linear structures visible from aeromagnetic images, striking approximately WNW-ESE at Lonmin.

Marikana structures: WNW-ESE striking structures, dipping at approximately 60˚ towards the south at Lonmin with a pegmatite infill. These are classified as regional structures as they cross cut the stratigraphic layers. The structures have the same orientation as the lineaments and are very often associated with large-scale instabilities experienced along the Bushveld Complex.

NNW-SSE clusters: More than one joint/fault in close proximity (< 1 cm spacing) to other joints/faults trending in a NNW direction at Lonmin. The structures have a similar orientation than the trend of the major fault structures. Major contributor towards instability. Causes slabbing along pillars where an alteration zone is present.

Pegmatite veins: Linear structures with an infill composed of quartz, feldspar and mica. It has a similar silicic composition as granite. It is approximately 1.15 - 1.1 Ga old feldspathic veins formed from rest fluids of the Bushveld Complex. Prominent weakness contact, cut across the stratigraphic layers.

Pongola rift faults: Basement structures that formed during the assemblage of the Kaapvaal Craton and has been affected by reactivation. The structures are believed to be the source along which the Bushveld Complex intruded.

Ramp structure: The layer-parallel segments connected by a step or ramp structure where fault, joint or shear (alteration) zones cut obliquely across the competent stratigraphic layering in the Bushveld Complex. Also referred to as a flexural slip thrust fault, flat ramp and/or a non-planar curved structure. The structures ramp from one weakness contact to another, cross-cutting the stratigraphic layers, creating small- or large-scale low-angle structures, which may form a weakness boundary, contributing to instabilities.

Regional structures: Structures cutting across the stratigraphic layers occurring within a large region such as the Bushveld Complex. Can also be identified from aeromagnetic images. The Marikana structures also fall within this classification.

Secondary structures: Davis and Reynolds (1996) explained that these structures form in igneous rocks after lithification. These are joints, shear fractures, faults, folds, cleavage, foliation, lineation and shear zones.

Seismotectonics: The study of the relationship between the earthquakes, active tectonics and individual faults of a region.

Shear zones: Davis and Reynolds (1996) describe a shear zone as a strained, sheet like and planar or curviplanar zone in comparison to the adjacent rocks. These zones form a network consisting of individual shear zones that can be subparallel sets, deflect towards one another and link up in an anastomosing pattern. It can also cross-cut or displace one another. The shearing cause fractures to form that allow for fluids to pass through. The hangingwall pyroxenite, which has been exposed to hydrothermal fluid flow, serpentinization, and layer-parallel shearing, is defined as the alteration zone. Other terms used: 'clay-like' layer, fault gouge, 'mud layer'. Essentially the term 'alteration zone' will be used in this study to describe this weak layer/contact.

The alteration zone is altered pyroxenite units in the hangingwall, along the top reef contact, within the UG2 Reef or within the footwall of the reef or along the contacts of the ramp structures.
It creates a weak contact along either the footwall 5/footwall 6 shear, footwall of the UG2 Reef, UG2A markers and along the hangingwall 1A/hangingwall 2 contact. It can be a:

- Source of pillar instability.
- Hangingwall fallouts.
- Large-scale hangingwall instability.

CONTRIBUTIONS MADE BY THE AUTHOR

During the period of the study, various papers were published by the author to share the research findings. The publications are listed below:

Hartzenberg, A.G. (2014). An Investigation of the ground conditions and extraction strategy of the UG2 chromitite layer in the vicinity of the Elandsdrift Fault Zone at Lonmin's Newman Shaft. *Proc. 8th South African YGE Conference*, Stellenbosch, South Africa.

Hartzenberg, A.G. and Du Plessis, M. (2014). The influence of regional structures associated with the Bushveld Complex on the mechanism driving the behaviour of the UG2 hangingwall beam and in-stope pillars as identified on Lonmin. *Proc. of the SAIMM Platinum Conference*, Sun City, South Africa.

Du Plessis, M., More O'Ferrall, G.C. and Hartzenberg, A.G. (2015). Rock mass instability associated with the formation of regional geologic structures along the Bushveld Complex as encountered during the extraction of the UG2 chromitite layer at Lonmin Plc. *Proc. ISRM 2015 Conference*, Montréal, Canada.

Hartzenberg, A.G., Du Plessis, M. and Friese, A.E.W. (2016). Structurally-related hangingwall alteration zones contributing to UG2 stope instabilities at Lonmin. *Proc. 2016 ISRM International Symposium, Rock Mechanics and Rock Engineering from the Past to the Future*, Cappadocia, Turkey, p.997-1002.

Hartzenberg, A.G. and Du Plessis, M. (2017). Unravelling the structural mysteries of the 'Bermuda Triangle' at Lonmin's Saffy Shaft. *Proc. ISRM International Symposium, Rock Mechanics for Africa*, Cape Town, South Africa, p. 933-945.

Hartzenberg, A.G. and Du Plessis, M. (2018). Investigating the mechanism contributing to large-scale structurally driven hangingwall instabilities on the UG2 Reef horizon. *Proc. ISRM European Rock Mechanics Symposium*, St. Petersburg, Russia.

A key contribution made by the author was a first attempt to integrate a detailed knowledge of geologic structures with practical rock engineering solutions in platinum mines. These two subjects are typically treated in isolation, but it is clear from this study that it needs to be more closely integrated for the design of stable mining excavations in the platinum industry.

MOTIVATION FOR THIS STUDY

1. INTRODUCTION

Mining operations expose major geologic structures (faults and dykes) as well as secondary geologic structures (joints and shear zones) that are associated with the deterioration of ground conditions. The structures in the layered Critical Zone of the Bushveld Complex, which have significantly contributed to layout instability on various mining operations, have been investigated in this study. These structures include layer-parallel faults and shears as well as ramp faults with curved slip planes and prominent striations. Also, major WNW-ESE striking faults and joints have been exposed at the sites of instability investigated in the Marikana lease area. These structures, as well as the shear zones (alteration zones) along the pyroxenite units in the vicinity of the UG2 Reef, contribute to major instability and hazardous ground conditions in the mining environment. Different terms have been used to describe this weak layer/contact throughout the industry and these are: fault gouge, layer-parallel structures, shear zone, 'clay-like' layer and 'mud layer'. In this study, it will be referred to as an alteration zone. The behaviour of this alteration zone and its contribution to rock mass instability has not been properly investigated in the past. This is mainly due to a lack of knowledge of the historical cases of a similar type of instability which have occurred throughout the Bushveld Complex. In many mines, the affected areas were typically barricaded and new panels established regardless of the fact that the contributing mechanism is not understood and mitigated using an appropriate layout or design. The objective of the research was to create awareness of and to provide guidelines to treat the risk related with the alteration zones and the resulting rock mass conditions.

The impact of the 'anomalous' geologic structures provides a challenge for mining with regards to hazard identification and the associated risk classification. 'Anomalous' refers to the regional large-scale structures, layer-parallel shears, ramp structures and alteration zones. The effect these structures has on the rock mass stability may influence the choice of appropriate mining method, layout, orientation, support strategies, mining rate and available ore reserves that was planned to be mined (long-term planning and short-term planning).

This study was motivated by a number of large-scale instabilities that occurred in the Bushveld Complex (Figure 1.1). This includes, but is not limited to, Lonmin Marikana Operations, Impala, Aquarius and Everest Mine. Similar large-scale instabilities have also been reported in the mines of the Great Dyke (Zimplats). These instabilities have resulted in fatalities, production losses, significant ore reserve write-offs and even mine closure. The case studies and investigations revealed that various similarities may be expected to exist along the entire Bushveld Complex as well as other sites along the Great Dyke.
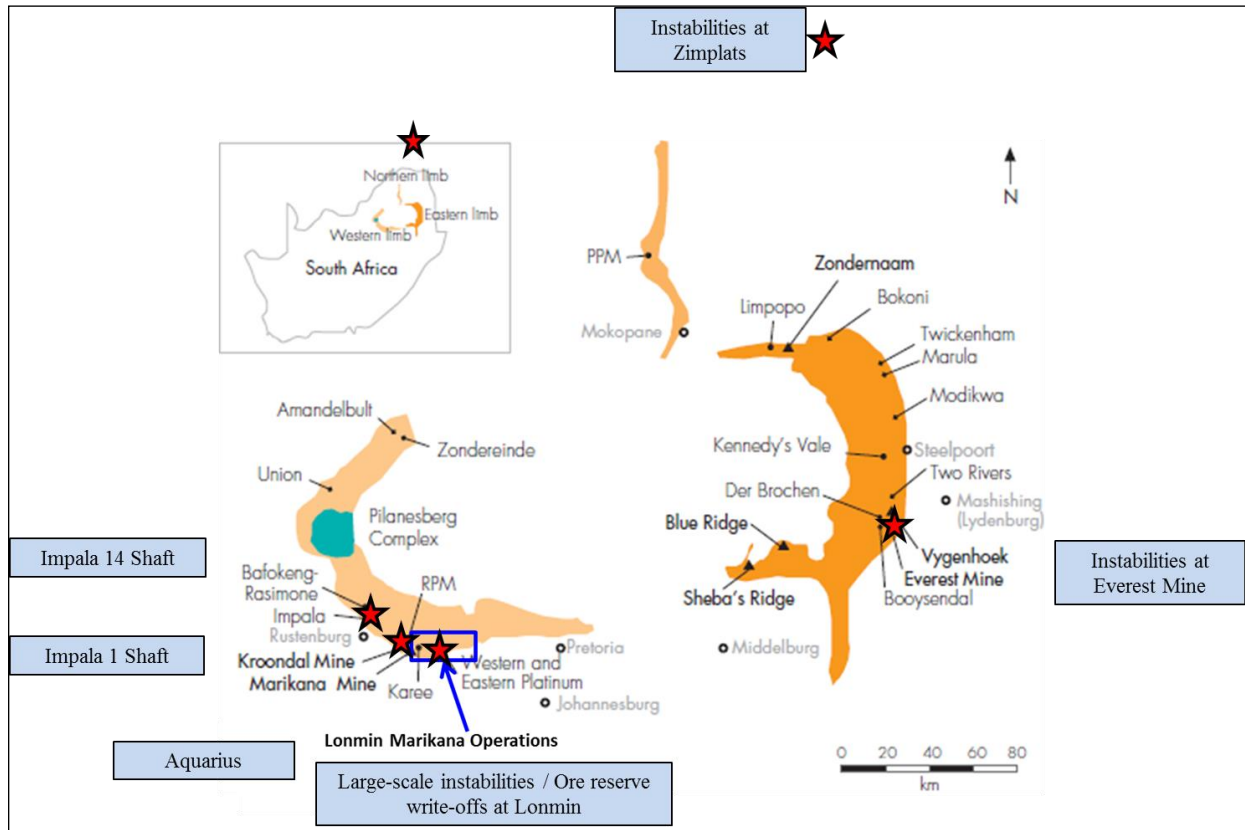
Figure 1.1: Areas where large-scale instabilities occurred in mines in the Bushveld Complex. It also occurs in the Great Dyke in Zimbabwe.

The impact of these instabilities can be detrimental. Lonmin's Marikana Operations (Figure 1.2), where the majority of the site investigations for this study was conducted, experienced a lot of large instabilities over the past 15 years. More O' Ferrall and Du Plessis (2017) described the large-scale instabilities that were first observed at the structurally complex Eastern Platinum Limited 2 and 3 Shafts in 2003. Ongoing investigations at Hossy and Saffy Shafts identified anomalous pillar behaviour due to the presence of alteration zones along the top contact of the pillars, large-scale unravelling along belt drive protection pillars and it also impacted on the stability of the stoping panels. Instabilities were also identified at 4 Belt Shaft when mining intersected structurally complex areas in 2009 and 2017. Large falls of ground and resulting ore reserve write-offs at Newman Shaft (2013), occurred due to alteration zones exposed along or within the immediate hangingwall layers. Falls of ground due to hangingwall alteration and anomalous pillar behaviour was recorded at Rowland Shaft in 2014 and 2018. During 2017, footwall heave was experienced at K3 Shaft, caused by alteration zones present along the footwall units. This resulted in support failure and large-scale hangingwall instability. Recently, hangingwall instability at Saffy Shaft (2017 to 2018) caused unexplained support failure and hangingwall unravelling.

Owing to the author's intimate knowledge of the instabilities at Lonmin (Figure 1.2), this area was used as the primary investigation site for this research on the Upper Group 2 (UG2) chromitite Reef horizon. There was a need to investigate the occurrences of the instabilities and resulting impact on mining layouts (i.e. span, orientation and pillar behaviour) and support.

Instabilities related to geologic structures have also occurred in other areas. An article by Karombo (2014) explained that a large-scale instability at Zimplats' Bimha Mine in 2014 resulted in the loss of approximately 45 000 ounces of platinum group metals (PGMs) for that year. The mine collapse was 'triggered by the accelerated deterioration of ground conditions' associated with shear zones which impacted on the stability of the pillars. The mine was subsequently closed with more than a year of redevelopment required to re-establish access beyond the affected area. Similarly, Everest Mine, located on the Eastern Limb of the Bushveld Complex experienced large-scale pillar collapse resulting in mine closure. A new portal had to be developed to give access to the ore reserves for future mining. Furthermore, two of Impala's Rustenburg Shafts and one of the Kroondal Aquarius Shafts experienced, structurally related collapses resulting in multiple fatalities (3 events; 17 people).

During exploration and underground drilling, geologic structures should be identified and accurately logged and captured to create a ground control district or risk plan for each shaft. In many cases, these structures, specifically the alteration zones along the pyroxenite layers, have not been identified by Geologists and Rock Engineers. This is mostly due to a lack of knowledge and experience. Alteration zones are commonly captured as a 'core loss'. The failure to pro-actively identify these structures has major consequences as it may not be considered as part of the mining and support strategies. As a result, the short- and long-term planning processes of the shafts will be impacted as possible ore reserve write-offs could be unavoidable.

In summary, the pro-active identification of geologic structures, the rock mass behaviour and potential failure mechanisms is of utmost importance to implement the most suitable mining method, mining layout and support strategies. This will improve the overall safety and production at shafts where adverse geotechnical conditions prevail.

The following two sub-sections describe the geology and mining layouts at Lonmin's Marikana Operations. An overview is provided as most of the findings in the study have been conducted at the Lonmin sites. It provides a general background which can be compared with other sites.

1.1. Geology

The Merensky Reef as well as the UG2 Reef is extracted at the Marikana Operations (Figure 1.2). Both reef horizons occur stratigraphically in the Upper Critical Zone of the Rustenburg Layered Suite (Kruger, 2005),

striking in an E-W direction with an average dip of 10˚ to the north. Both ore bodies are consistent over several kilometres. The planar continuity of the orebody however, is disrupted by geologic structures, including faults, dykes, potholes, rolling reef, secondary geologic structures (jointing, layer-parallel and ramp structures) and iron-rich ultramafic pegmatites (IRUPs). The UG2 Reef extracted has an average thickness of approximately 1 m. This study only focused on rock mass conditions associated with the UG2 Reef horizon.

The Lonmin Marikana Operations, extracting the UG2 Reef and Merensky Reef Horizons

1-Spruitfontein Fault   4-Saffy West Fault   7-Harties West Fault
2-Marikana Fault   5-Saffy East Fault   8- Roodekopjes Fault
3-Elandsdrift Fault Zone   6-Turffontein Faults
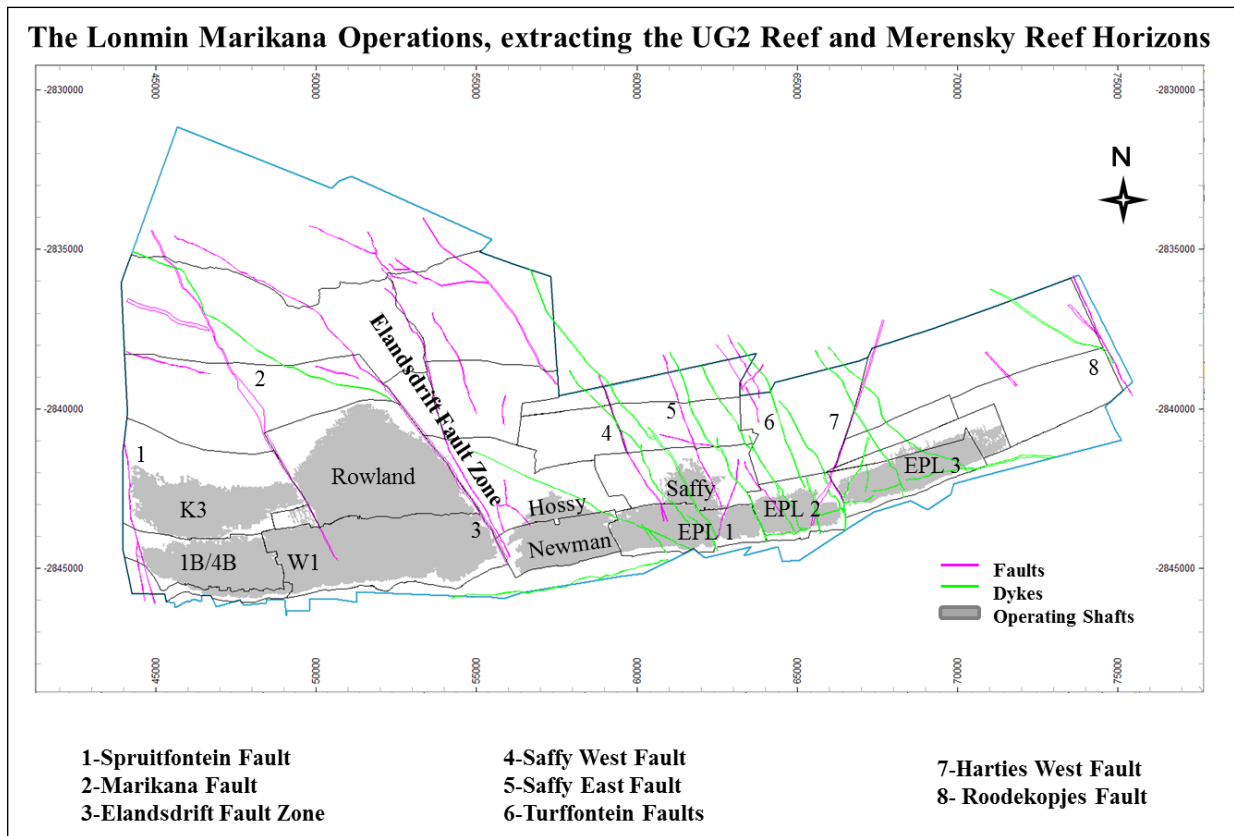
Figure 1.2: Lease area of the Lonmin Marikana Operations.

Figure 1.2 shows the mined out areas, current operating shafts and main geologic structures which create the natural boundaries between the operating shafts. The grey areas are mined out. The current operating shafts are indicated. Magenta coloured lines represent the major fault structures and the green lines illustrate the major dykes across the property. Major trends are in a NNW-SSE and NNE-SSW direction. The Elandsdrift Fault Zone is a major fault that forms the natural boundary between Rowland Shaft to the west and Newman and Hossy Shafts to the east. The main geologic structures as well as the associated secondary structures may lead to problematic ground conditions that provide a challenge for extracting the reef layers.

1.1.1.   Mining layouts and support design

The majority of shafts at Lonmin use conventional mining methods. Access to the reef horizon is through incline shafts or vertical shafts (maximum depth of 1 100 m). A non-yield pillar system is used at Lonmin to support the overburden to surface. Inter-pillar spans are limited to 30 m for the UG2 Reef and 31 m for the Merensky Reef. Site specific variations exist where the prevailing structures impact on the beam behaviour. Here the spans are adjusted to 25 – 27 m. Rock bolts are used in development ends. In-stope rock bolting, elongates and/or grout pack support is used as support elements in the mining panels. At increased depth, crush pillar systems with yieldable support elements are considered.

Strike haulages, located approximately 20 m in the footwall of the respective reef horizons provide access to the stopes by means of short travelling ways. The declines are developed in footwall 5 or footwall 6 which may expose the footwall 5/footwall 6 shear (Figures 1.3 and 1.4) or other shear zones located in the footwall (Figure 1.5).

The mining layouts practised at Lonmin consist of the following:
•   Split up-dip and down-dip.
•   Long panel up-dip and down-dip.
•   Breast mining layout.

Figure 1.3 shows the geologic succession of the UG2 Reef at Lonmin and is considered in the general layout and support design to accommodate the mining method and ore transport systems. The immediate stope footwall consists of either pegmatoidal pyroxenite or mottled anorthosite. The footwall pegmatoidal pyroxenite can be altered (Figure 1.6) which may have an effect on the footwall of the stopes (footwall heave) and the pillar behaviour. The hangingwall beam that should be considered in the span and support design includes the hangingwall 1B, UG2A markers and hangingwall 1A. Alteration zones have been identified along the top contact of the UG2 Reef (Figure 1.6) as well as in the vicinity of the UG2A markers and hangingwall 1A/hangingwall 2 contact which may affect the hangingwall stability. The stope spans are designed to be stable and internal stope support units provide additional hangingwall stability (hangingwall 1B and UG2A markers) to prevent local instability (Figure 1.7) where anomalous geologic conditions exist (More O'Ferrall and Du Plessis, 2017). In the case that the hangingwall 1B beam is stable, then the overlying hangingwall 1A beam should remain stable.
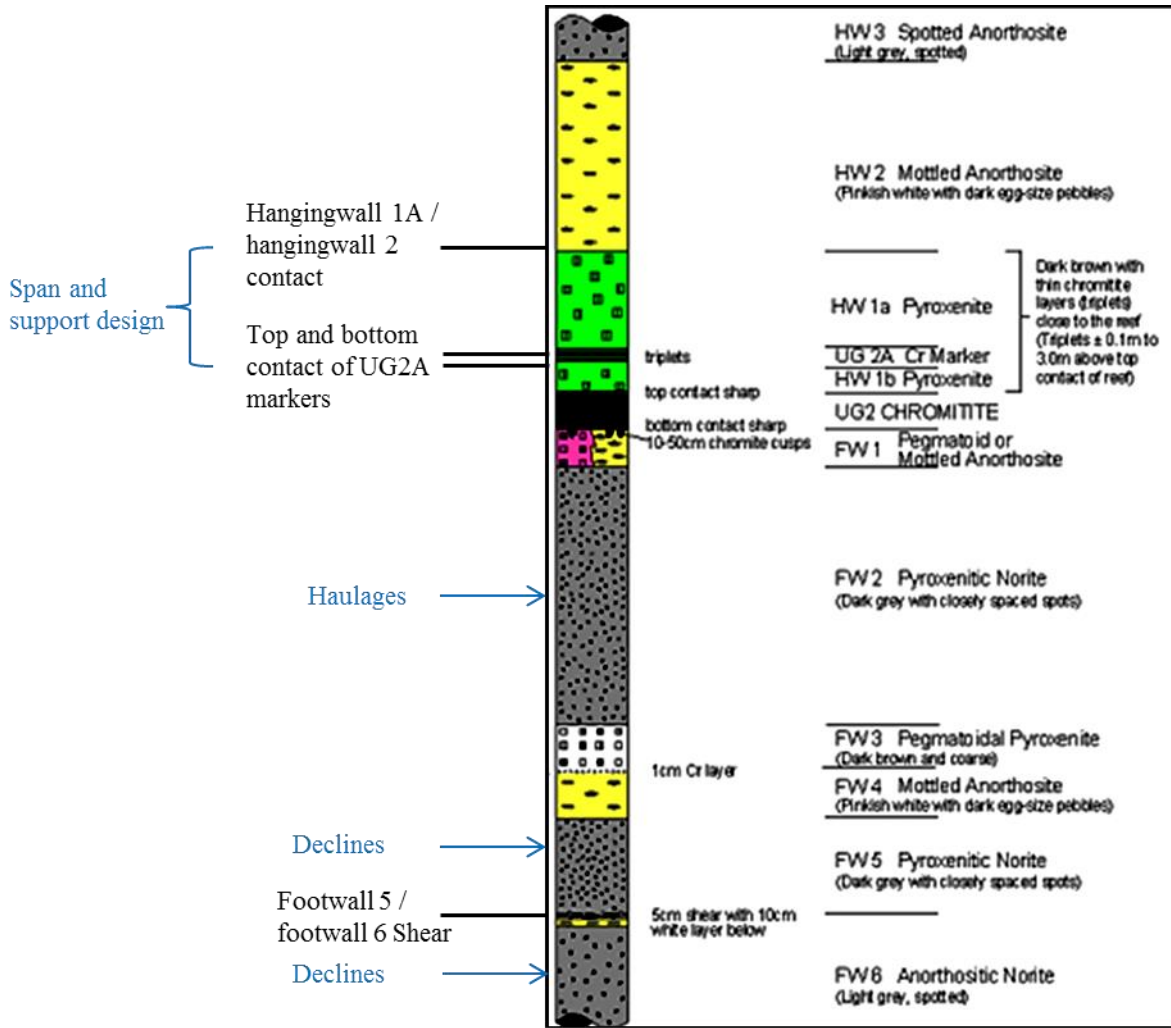
Figure 1.3: Geologic succession of the UG2 Reef. From case studies it is confirmed that potential parting planes exist at the UG2A markers and hangingwall 1A/hangingwall 2 contact at the Lonmin Marikana Operations. These potential parting planes should be considered in the mine and support design (Lonmin, 2011).

Figure 1.4: Footwall 5/6 shear exposed in an off-reef development excavation (a decline) at an Eastern Platinum Limited Shaft.

Figure 1.5: Footwall shear exposed in off-reef development (a decline) at a shaft in the Bushveld Complex where the stratigraphic layers are steeply dipping.
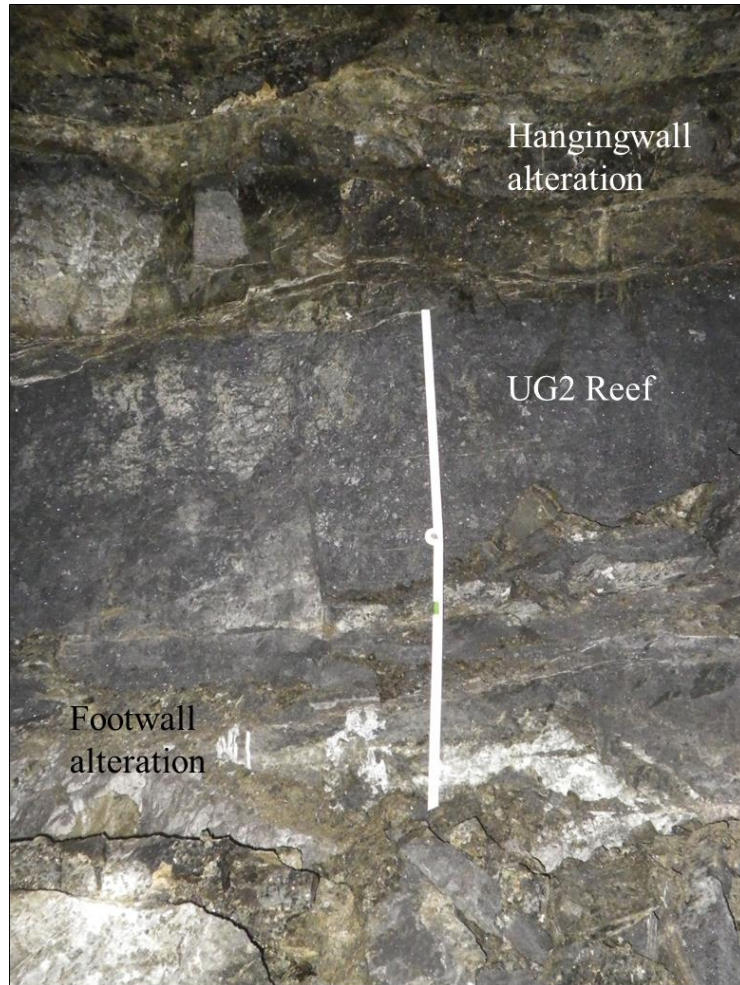
Figure 1.6: Alteration zones along the hangingwall and footwall pyroxenite units of the UG2 Reef.

Figure 1.7: Separation in the hangingwall caused instabilities. Crushed grout packs and buckling of timber elongates can be observed. The stoping width (1.2 m) was reduced to 30 cm.

1.2. Problem statement and scope of the study

The key objective of this study is to identify and understand the influence of prominent regional and secondary geologic structures, including alteration zones, on the mechanisms affecting UG2 hangingwall stability and in-stope pillar behaviour.

From the literature survey described in the next chapter, it appears that regional large-scale geologic structures, ramp structures (Figure 1.8) and layer-parallel shears (alteration zones) or a combination of these structures is the main contributors towards significant underground instabilities. The study focused on the pro-active identification of these structures on the UG2 Reef and investigated how it contributed to the observed instabilities. Figures 1.8 to 1.12 are examples of these instabilities. The identification of these structures and an improved understanding of the associated behaviour will assist in implementing appropriate mining and design strategies to prevent future instabilities.

The need for this study was clearly highlighted by Malan and Napier (2011) when they wrote the paper *'The design of stable pillars in the Bushveld Complex mines: a problem solved?'* This paper describes the large-scale pillar collapses that occurred in the Bushveld Complex and emphasised that there is currently no accepted design methodology for pillars when alteration zones are encountered. This study is an important first step in developing such a methodology.

This study was divided into two components namely:

- The impact of regional large-scale and secondary geologic structures, including interlinking ramp structures.
- Alteration zones along the pyroxenite layers of the UG2 Reef.

These two specific areas will be addressed in the literature review and in subsequent chapters.

Figure 1.8: Unstable hangingwall conditions along a ramp structure. The only support on the edge of the brow was in-stope rock bolt support. The structure ramped up to the position of the UG2A markers (located at 3 – 4 m in the hangingwall). A large fall of ground occurred in the panel face where another ramp structure was intersected. This resulted in the panel being abandoned.

Figure 1.9: Panel instability shown in the red ellipse. The entire panel was affected along a regional large-scale WNW-ESE trending fault structure. Separation occurred at approximately 12 – 15 m in the hangingwall (along the hangingwall 1A/hangingwall 2 contact). The panel had to be re-established.

Figure 1.10: Large-scale instability showing the loading and failure of the support units. The support units were loaded as a result of separation along the hangingwall 1A/hangingwall 2 contact (12 – 15 m in the hangingwall). The peak support capacity for elongates are 27 t and for the 1.2 m diameter grout packs are approximately 500 t. The panel was abandoned and had to be re-established.
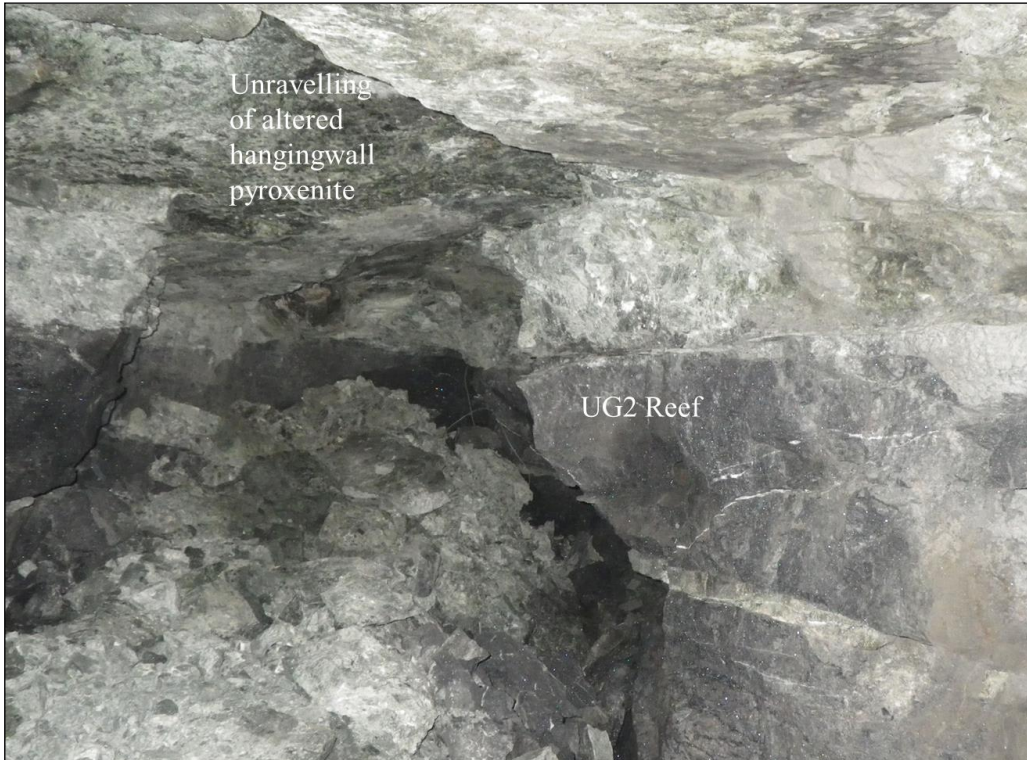
Figure 1.11: Alteration zone along hangingwall pyroxenite, causing unravelling between installed support units. This development end was abandoned and had to be re-established.
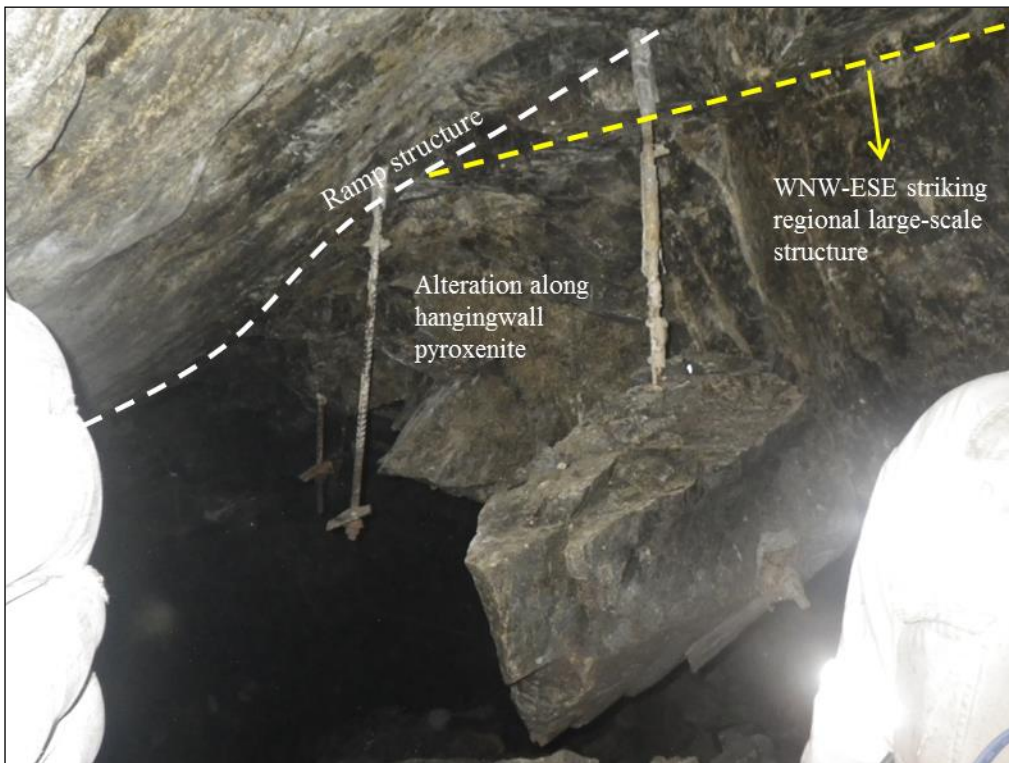
Figure 1.12: Catastrophic failure where geologic structures and a hangingwall alteration zone were exposed, causing falls of ground. This ledge was abandoned and a new panel had to be established.

The scope of the study included the following items:

- To obtain a better understanding of these prominent geologic structures at Lonmin as well as the occurrence of similar structures at other operating shafts. The intent is to create awareness across the Bushveld Complex and in future expand the study towards other areas.

- Examine the nature and origin of the structures in order to gain an improved understanding of their distribution, morphology and geometry, specifically in the vicinity of the UG2 Reef.

- An improved understanding of the spatial distribution of the structures in three dimensions and how they impinge on the mining excavations and hence the determination of the preferential mining direction and mining spans. The improved understanding, mapping and detection of structures may reduce panel instabilities due to improved mine layout, mining direction as well as support strategies.

- The identification of potential further research topics to investigate anomalous pillar behaviour, span behaviour and support in areas where the geologic structures have a detrimental impact on the stability of mining excavations.

1.3. Methodology

The geologic structures have specific structural behaviour and potential failure mechanisms are associated with these. It is difficult to pro-actively identify these structures. A comprehensive literature study was conducted for sites where structurally-related large-scale instabilities, alteration zones as well as abnormal pillar behaviour have been reported.

Underground site investigations were conducted by the author in areas where regional large-scale structures, ramp structures and/or alteration zones were exposed. The objective was to determine the formation and potential failure mechanisms. Sites where alteration zones have been exposed along the pyroxenite units were investigated. At some sites a combination of these structures are present. The impact of these structures on excavation stability and pillar behaviour was explored.

The objective of the outcomes from the literature review and underground investigations was to highlight the main contributing factors to the large-scale instabilities, adverse hangingwall conditions and abnormal pillar behaviour. The structural conditions, associated behaviour and failure mechanisms should be considered when implementing the most suitable support strategies, mining layout and mining direction.

The improved knowledge gained from these studies was used to suggest improved support strategies and layout modifications to ensure panel stability in areas where these geologic structures are present.

1.4. References

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LITERATURE SURVEY

2. LITERATURE SURVEY

This chapter discusses the history of major instabilities recorded in stopes of the UG2 Reef in the Bushveld Complex and the Great Dyke. The formation of the layered intrusions and geologic structures, associated behaviour and potential failure mechanisms were determined from historic literature. This knowledge will contribute towards an improved understanding of the mechanisms of failure and will assist to develop strategies to prevent the large-scale collapses. The flow diagram below summarises the topics that will be discussed in this chapter. This was included to assist the reader with the link between the large number of topics included in this chapter.
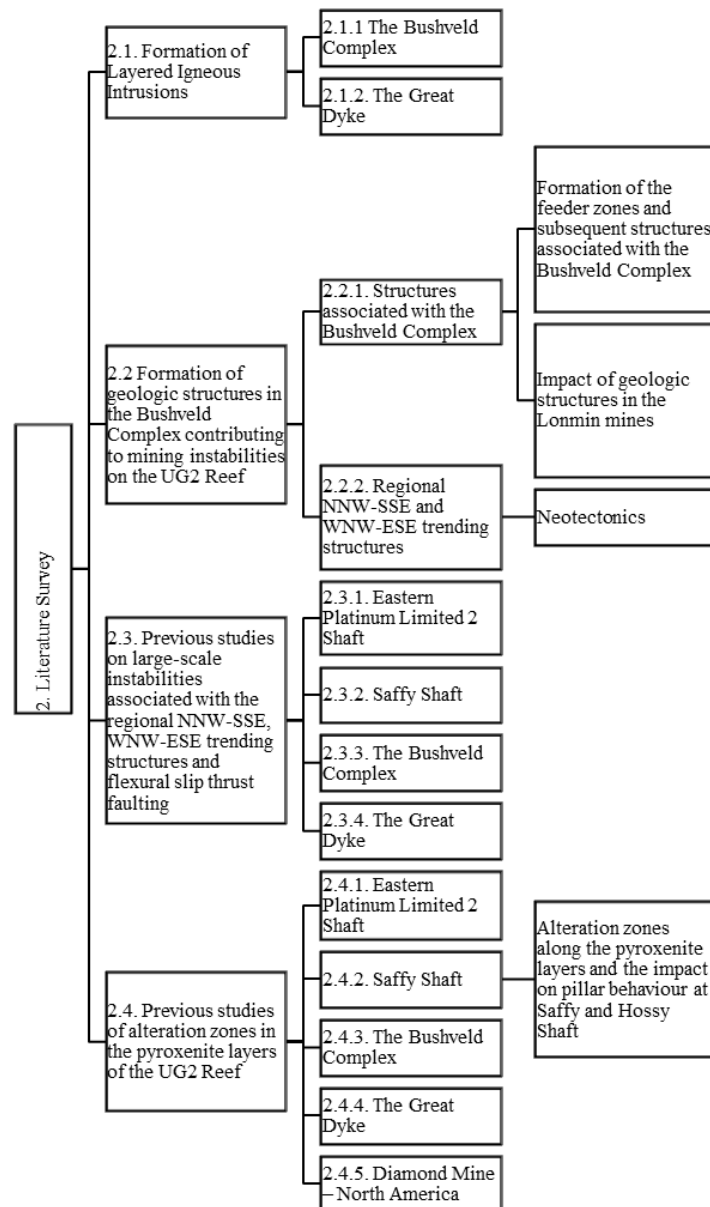
2.1. Formation of Layered Igneous Intrusions

Schouwstra *et al*. (2000) stated that the four major layered igneous intrusions that are currently dominating the platinum and palladium supply market include the Bushveld Complex of South Africa, the Stillwater Complex in the United States of America, the Great Dyke in Zimbabwe and the Noril'sk/Talnakh Complexes in Russia. These layered intrusions formed as molten magma which cooled slowly deep within the earth's crust. The mineral's compositions were altered with the slow drop in temperature in the magma caused by the cooling process. As the cycle of magma intrusion repeated, several thousand meters of solid rock have formed. The resultant layering controlled the distribution of the ore deposits.

Two areas where major instabilities have been recorded, namely the Bushveld Complex and the Great Dyke, will be discussed in more detail in this study. The purpose of the literature review is to describe the formation of the geologic structures exposed in the underground mining environment and the rock mass behaviour caused by these structures.

2.1.1. The Bushveld Complex

The 2.06 Ga (Billion years) old Bushveld Complex (Figure 2.1) is the world's largest layered intrusion. It is up to 9 km thick and more than 350 km in diameter (Roberts and Clark-Mostert, 2010). Many of the other layered intrusions are often compared to it in literature owing to its unique character. At current levels of erosion, a Western-, Eastern- and Northern Limb of the Bushveld Complex has been exposed. According to (Perritt and Roberts, 2007), the Bushveld Complex intruded at the boundary between the overlying Rooiberg Group and the underlying Transvaal Supergroup and basement rocks of the Kaapvaal Craton.

Figure 2.2 show that the large-scale layers form the basis for a simple subdivision (Marginal-, Lower-, Critical-, Main- and Upper Zone). The layers are laterally continuous to a large extent, but are disrupted by major fault and dyke structures as well as downward magmatic erosional discontinuities known as potholes (Roberts and Clark-Mostert, 2010). The Critical Zone is characterised by the presence of well-developed layers of chromitite seams and repeated cyclic units consisting of pyroxenite, grading upwards through melanorite and leuconorite into anorthosites (Eales *et al*., 1993; Schurmann *et al*., 1998). The largest concentration of Platinum Group Elements (PGMs) is hosted in the Upper Critical Zone of the Bushveld Complex, including the Upper Group Number 2 (UG2) chromitite Reef, Merensky Reef and Platreef.

Faults, dykes and planar jointing occur throughout the Bushveld Complex, but their frequency of occurrence varies. Roberts and Clark-Mostert (2010) also indicate the presence of other structures described as flexural slip thrust faults, containing fault gouge material. It represents two major risks to underground mining activities, namely falls of ground and potential unpredictable pillar behaviour. Roberts and Clark-

Mostert (2010) stated that the gouge material found in the affected pillars was compressed and that it caused the pillars to fail in tension.
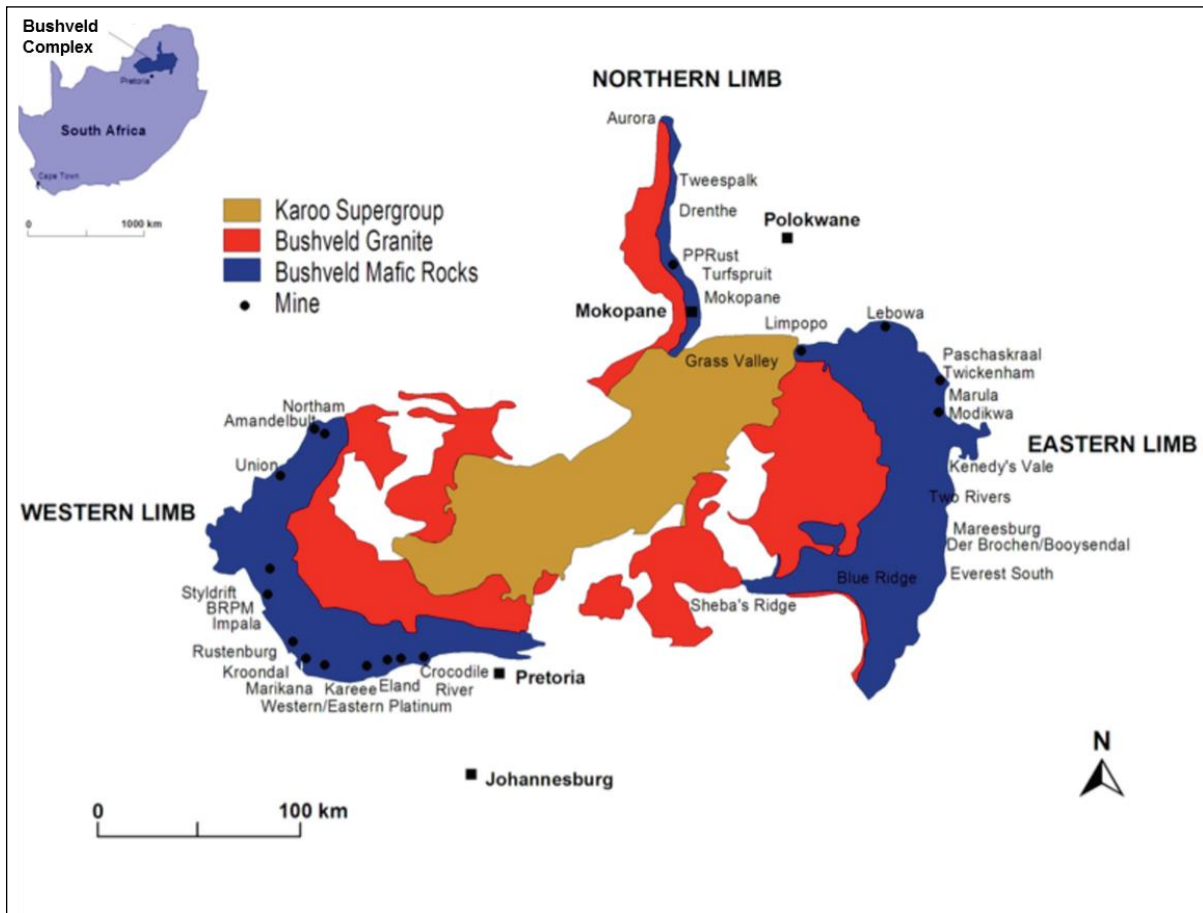
Figure 2.1: Regions of the Bushveld Complex and its location in South Africa (Roberts and Clark-Mostert, 2010).
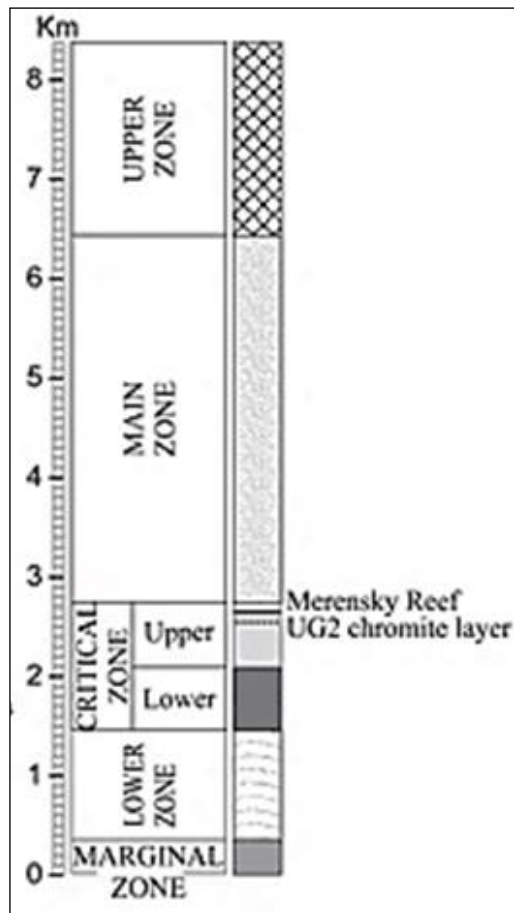
Figure 2.2: Layers of the Bushveld Complex (Godel *et al.,* 2006).

Figure 2.3 is a three-dimensional illustration of the emplacement of the Bushveld Complex between approximately 2.06 – 2.054 Ga (Friese, 2003). Magma ascended along the pre-existing geologic structures, including the Pongola rift faults (basement structures) as well as the Thabazimbi-Murchinson Lineament, feeding dykes and sills at mid-crustal depths. At approximately 4 km in the crust, a critical level was reached where the magmatic pressure equalled the lithostatic pressure that allowed the intrusion of the massive 'sill-like' Bushveld Complex.
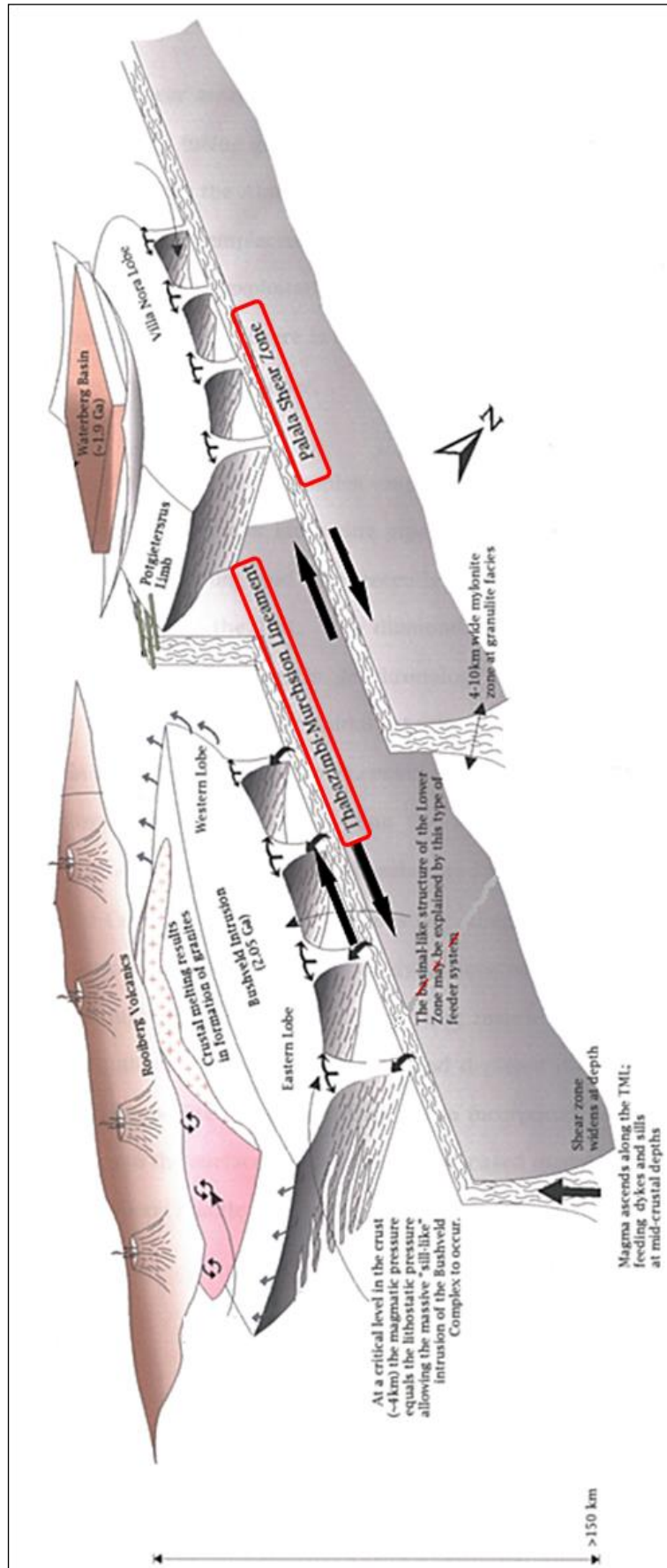
Figure 2.3: Three-dimensional illustration of the emplacement of the Bushveld Complex (Friese, 2003).

2.1.2. The Great Dyke

The Great Dyke in Zimbabwe (Figure 2.4) is described by Wilson (1992) as a linear shaped layered intrusion that is 2.59 Ga old. The layered intrusion strikes NNE for a distance of 550 km and varies in thickness from 4 km to approximately 11 km. The Great Dyke consists of a slightly curved, locally faulted line of five layered ultramafic to mafic complexes. This intrusion cuts through the Archaean granites and greenstone belts of the Zimbabwe craton.
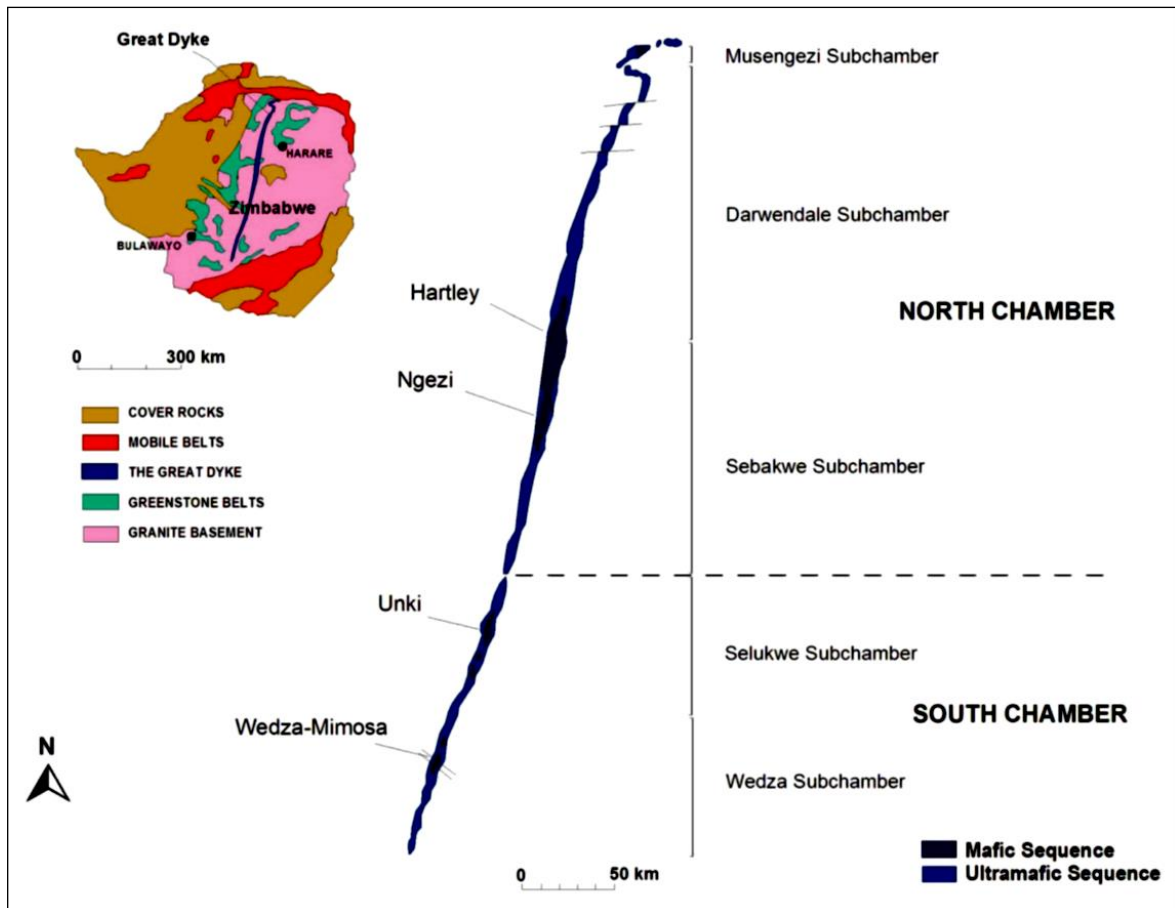
Figure 2.4: Location of the Great Dyke in Zimbabwe (Roberts and Clark-Mostert, 2010).

In section, this intrusion is trumpet-shaped where the layers dip at shallow angles towards the centre (Figure 2.5). The Main Sulphide Zone contains both PGMs and nickel. NNE striking, sinistral Popoteke faults and WNW trending Mtshingwe faults have been exposed sub-parallel to the Great Dyke. Planar jointing is abundant throughout this intrusion. Ramps or flexural slip thrust faults with slickensides have also been exposed in underground mine workings (Roberts and Clark-Mostert, 2010).
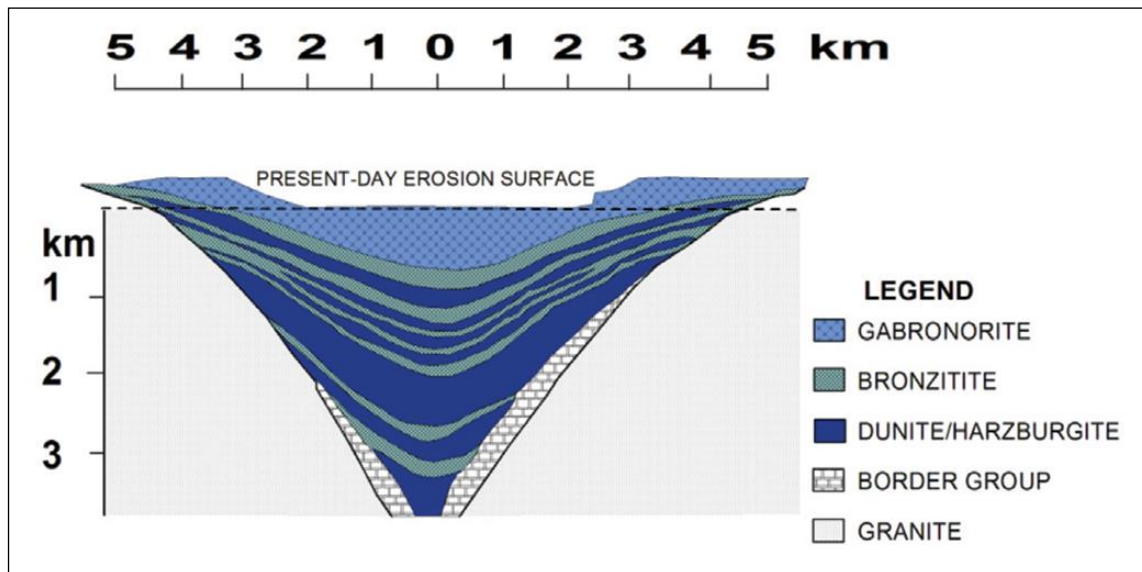
Figure 2.5: Cross-section of the Great Dyke (Roberts and Clark-Mostert, 2010).

2.2. Formation of geologic structures in the Bushveld Complex contributing to mining instabilities on the UG2 Reef

This section gives an overview of the formation of geologic structures that contribute to problematic rock mass conditions during the extraction of the UG2 Reef. The following sub-sections are dealt with, discussing the formation and occurrence of:

- Regional large-scale structures, including NNW-SSE and WNW-ESE striking structures and ramp structures.
- Alteration zones along pyroxenite layers and specifically their impact on pillar behaviour.

Case studies in the Bushveld Complex and Great Dyke indicate that these structures are common throughout the various mining areas. It is important to understand the formation of these structures to develop an understanding of potential failure mechanisms encountered in the underground mining environment.

2.2.1. Structures associated with the Bushveld Complex

The literature survey involved the study of the assemblage of the Kaapvaal Craton. The structures in this area can be explained by the Pongola rift faults (basement structures) that formed during the assemblage of the Kaapvaal Craton and were also reactivated during the intrusion of the Bushveld Complex. The Kaapvaal Craton of South Africa (Figure 2.6) is one of the oldest continental fragments that formed and stabilized between 3.7 and 2.7 Ga years ago (De Wit *et al*., 1992). The formation of this type of craton can be related to the process of modern-day plate tectonics through the addition of new material by subduction-related processes and the accretion of pre-existing terranes (De Wit *et al*., 1992). The Thabazimbi-Murchinson Lineament and the Magaliesburg-Barberton Lineament are two distinct lineaments, striking in a WSW-ENE direction (Figures 2.3 and 2.6). It is important to note that the NNW-SSW trending Colesberg Lineament

(Figure 2.6) formed as a result of the eastwards accretion of the Kimberley Block onto the Kaapvaal Craton at 2.88 Ga years ago (Eglington and Armstrong, 2004). The structures contained between the Thabazimbi-Murchinson Lineament and Magaliesburg-Baberton Lineament predominantly trend in an N-S to NNW-SSE direction, which coincide with the structures (faults, dykes and jointing) occurring in the Western Limb of the Bushveld Complex (Bumby *et al.,* 2011).
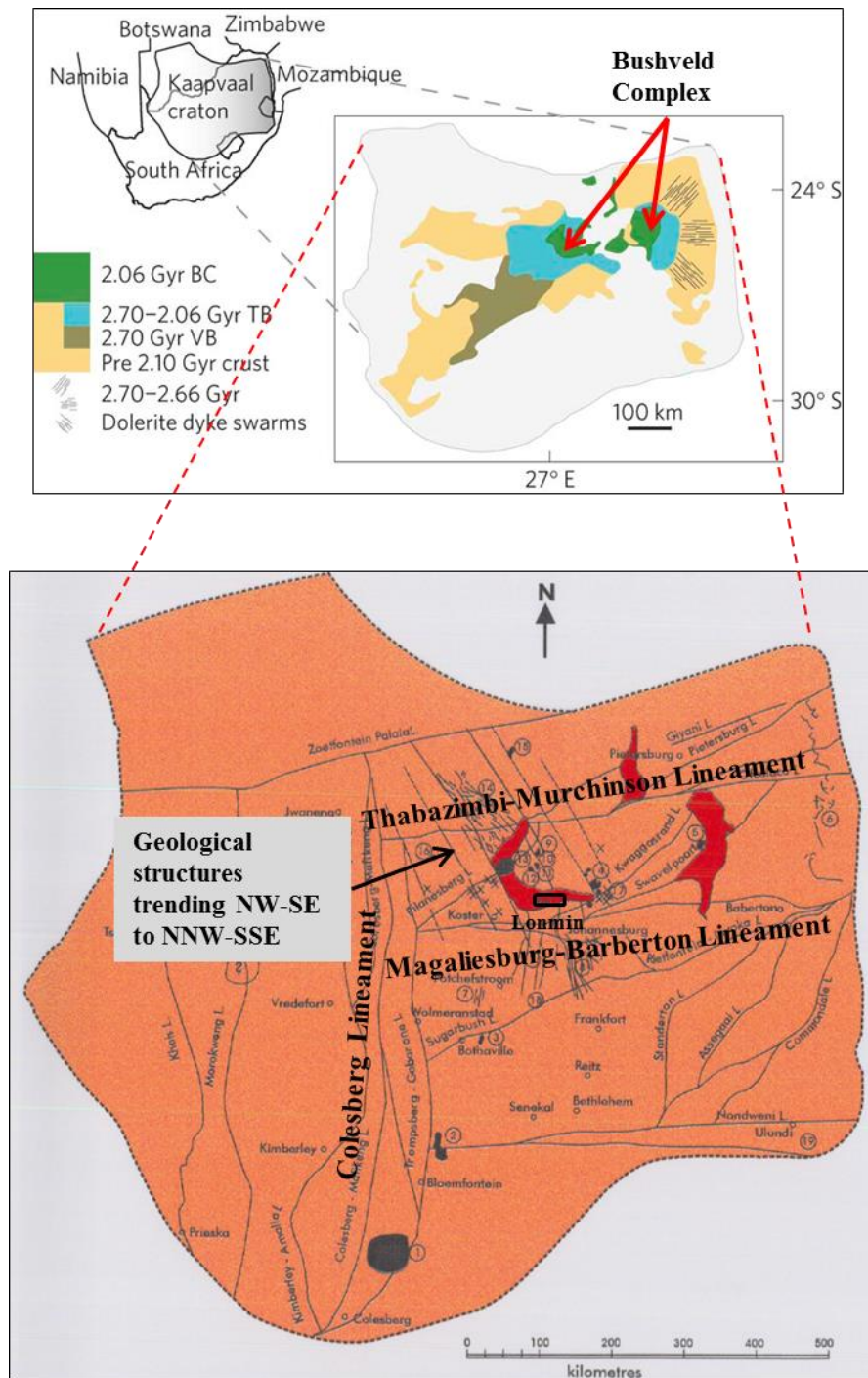
Figure 2.6: Location of the Kaapvaal Craton, associated structures and the position of the Bushveld Complex with reference to South Africa (Olsson *et al.,* 2011).

Formation of the feeder zones and subsequent structures associated with the Bushveld Complex

The tectonic evolution of the Bushveld Complex from 2.6 Ga to post-Bushveld is described by Andersen (2001). The Kaapvaal-Limpopo-Zimbabwe Block stabilized when the Kaapvaal and Zimbabwe Cratons collided 2.6 Ga ago. Extension dominated the early Proterozoic (approximately 2.5 Ga) forming intracratonic pull-apart sedimentary basins, including the Transvaal Supergroup basin (Erikson *et al.,* 1996). Trans-cratonic linear structures originated at this time, including the Thabazimbi-Murchinson Lineament and Magaliesburg-Baberton Lineament (Andersen, 2001). The Bushveld Complex was emplaced between 2.06 and 2.05 Ga.

Two distinct trends of weaknesses occur in the Kaapvaal Craton, ENE-WSW coinciding with the Thabazimbi-Murchinson Lineament and Magaliesburg-Baberton Lineament as well as NNW-SSE, coinciding with the Rustenburg and Brits Graben Faults. According to Bumby *et al.* (1998), little movement occurred along the faults after the Bushveld Complex intruded and the recrystallization associated with this event might have rheologically strengthened the neighbouring strata, preventing it from being refaulted. Bumby *et al.* (1998) proposed that the Pretoria Group sediments that occur in the vicinity of the Rustenburg Fault were deposited over an area with a pre-existing basement weakness that trends in a 330˚ orientation and was already susceptible to reactivation (Figure 2.7). It appears that the reactivation of the Rustenburg Fault occurred along a pre-existing plane of weakness that might have formed during the accretion of the Kaapvaal Craton. It strikes in a NNW-SSE direction.
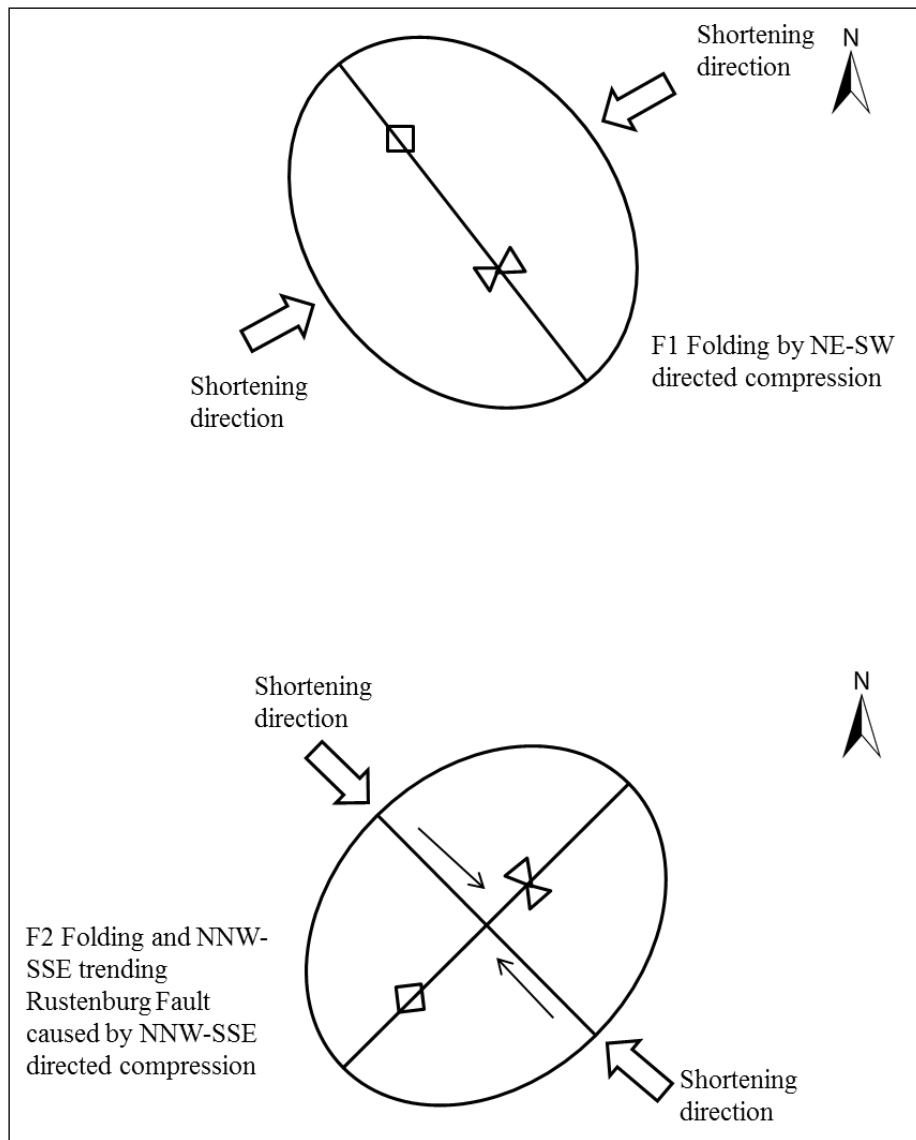
Figure 2.7: A possible model for the evolution of deformation recorded along the Rustenburg Fault Zone (after Bumby *et al.*, 1998).

Table 2.1 summarizes the sequence of geologic events that led to the occurrence of the geologic structures prevalent in the Bushveld Complex and those found in underground mine workings.

Table 2.1: The sequence of geologic events that contributed to the formation of geologic structures, the stress field and rock mass behaviour in the Bushveld Complex.

Geologic Event	Timeframe	References
Kaapvaal Craton formed and stabilized.	3.7 – 2.7 Ga	De Wit *et al.,* 1992
Magmatic accretion of blocks formed the Craton's nucleus.	3.547 – 3.225 Ga	Eglington and Armstrong, 2004
Blocks formed and combined to form a larger continental block.	Post 3.225 Ga	Lowe and Byerly, 2007
Formation of craton relates to the process of modern-day plate tectonics: addition of material by subduction related processes and accretion of pre-existing terranes.		Bumby *et al.,* 2011
Terrain accretion along two distinct ENE-WSW trending suture zones: Magaliesburg-Barberton Lineament and Thabazimbi-Murchinson Lineament.	3.23 and 2.9 Ga	Poujol *et al.,* 2003; Anhaesser, 2006; Robb *et al.,* 2006
Formation of NNW trending faults.	3.0 Ga	Friese, 2017
Colesberg Lineament trends NNW-SSE accommodated the accretion of the Kimberley Block.	2.88 Ga	Eglington and Armstrong, 2004
Formation of NE trending faults.	2.7 Ga	Friese, 2017
Kaapvaal and Zimbabwe Cratons collided and created a stable block, known as the Kaapvaal-Limpopo-Zimbabwe block.	2.6 Ga	Andersen, 2001
Early Proterozoic pull-apart sedimentary basins formed, creating trans-cratonic linear, Magaliesburg-Barberton Lineament and Thabazimbi-Murchinson Lineament.	2.5 Ga	Erikson *et al.,* 1996
Extension (rifting): Pongola rift system activated for 50 Million (Ma) years. Therefore continued for 10 Ma during the cooling of the Bushveld Complex. Faults act as feeder systems.	2.1 Ga	Friese, 2017
NNW-SSE compression. Movement on Rustenburg Trend and development of Brits Graben.	Pre-Bushveld 2.05 Ga	Andersen, 2001
E-W trending diabase dykes, coincide with axis of Bushveld Complex, (E-W compression).	Pre-Bushveld	Uken and Watkeys, 1997
Intrusion of the Bushveld Complex. Reactivation of	2.06 and 2.05 Ga	Bumby *et al.,* 2011

planes of weakness that were formed during the assemblage of Kaapvaal Craton.		
Bushveld intrusion: -Mafic phase -Felsic phase -Hydrothermal phase -Cooling phase	- 2.06 to 2.058 Ga - 2.058 to 2.056 Ga - 2.056 to 2.048 Ga IRUP and Dunite dykes	Friese, 2017
Out of the Bushveld thrusting. Referred to as deformation event 1 in this document.	Syn-Bushveld	Friese, 2017
The segmented appearance of Marikana Operations' major faults includes the Elandsdrift Fault Zone trending NW-SE to NNW-SSE direction.	Post-Bushveld	Mine Information System, 2014
Subsidence of the magma chambers towards feeders. Post consolidation. E-W listric faulting. N-S compression. Shallow angle footwall shears. NNW-SSE compression. S-directed thrusting forming E-W trending, normal and counter dipping joints. E-W compression. E-W dykes and steeply dipping E-W normal faults and joints. Strong dextral re-activation of the Rustenburg Trend. Formation of Spruitfontein Upfold.	Post 2.05 Ga	Andersen, 2001
Intrusion of Alkaline Complexes (calcite veins), Pilansberg and Pilansberg dykes trending NNW. Major principal stress: N-S orientation.	Approximately 1.25 Ga	Andersen, 2001
E-W Compression. Sinistral reactivation of Rustenburg Fault and Brits Graben.	Post 1.25 Ga	Andersen, 2001
Second generation of dyke swarms cuts through both the Goudini and Pilansberg Alkaline Complexes.	< 1.190 Ga	Andersen, 2001
Intrusion of mafic dykes. At the time of the dyke intrusions, normal dip-slip and sinistral strike-slip movement on pre-existing faults (reactivation). Feldspathic veins: rest fluids of the Bushveld Complex. Calcite veining.	approximately 1.15-1.1 Ga	Friese, 2017
NE-SW compression. Formation of NE-SW and NW-SE faults with displacement of all other structures.	Post 1.0 Ga	Andersen, 2001

Karoo aged dyke trending NW.	0.28-0.19 Ga	Lyons and Du Plooy, 2000
Subsidence of Bushveld Complex along ENE-WSW axis. Reactivation of E-W structures.	2 Ma	Andersen, 2001

Lonmin's Marikana Operations was used for the majority of the site investigations for this study as significant excavation instabilities have been reported in these mines over the past 15 years.

Impact of geologic structures in the Lonmin mines

The main structures that have an impact on the Lonmin mining operations (Figure 1.2) include the Spruitfontein-, Marikana-, Elandsdrift Fault Zones and dykes which coincide with the geologic structures contained between the Thabazimbi-Murchinson Lineament and Magaliesburg-Baberton Lineament. The Elandsdrift Fault Zone is a NNW-SSE trending fault which compartmentalizes the Marikana Operations into an eastern and western geotechnical domain (Figure 2.8). The fault zone has an estimated vertical displacement of 100 – 120 m (down-throw) to the east in the shallower part of the operations.

The eastern part of the mine lease area is intersected by a series of faults that includes the Saffy East, Saffy West, and Turffontein Faults with reef displacements of 10 – 20 m. The Harties West Fault has a displacement of up to 80 m. The Roodekopjes Fault, with a displacement of more than 500 m, forms the practical mining boundary on the eastern side of the Marikana Operations.

Dykes appear as linear geologic anomalies as defined by aeromagnetic surveys (Figure 1.2). According to Lyons and Du Plooy (2000), three ages of dykes have intruded the Marikana Lease Area:

- E-W trending diabase dyke that formed pre-Bushveld (Uken and Watkeys, 1997).
- NNW-SSE trending Pilansberg-aged dykes (Andersen, 2001).
- NW-SE striking Karoo-aged dyke (Lyons and du Plooy, 2000).

The dyke present along the southern boundary of the lease area (Figure 1.2) in the vicinity of Eastern Platinum Limited 2 and Eastern Platinum Limited 3 Shafts is the oldest and is displaced by NNW trending Pilansberg age dykes. The NNW trending dykes coincide with the strike direction of the pre-existing basement structures that were reactivated by the intrusion of the Bushveld Complex and Alkaline Complexes (Table 2.1). A north-westerly striking Karoo age dyke cuts across the entire Mine Lease Area (Eastern Platinum Limited 1, Hossy and to the north of Rowland Shaft) as indicated in Figure 1.2. Table 2.1 summarizes the sequence of geologic events that led to the formation and occurrence of the geologic structures prevalent on the shafts.

Figure 2.8 shows the Lonmin Marikana Operations with all the current operating shafts. The Elandsdrift Fault Zone forms the division between the western and eastern side of the property. The geotechnical environment with potential support strategies on the western and eastern side of the Elandsdrift Fault Zone at various depths is shown in the lower half of this figure. It should be considered during the mine and support design. The eastern side of the property is structurally complex with an increase in the thickness of the UG2 hangingwall beam between the UG2 Reef and the top of the UG2A markers (Figure 2.8) from the west (< 1 m) to the east (> 15 m) of the property. The UG2 Reef strikes from E-W with an average dip of 10˚ to the north across the Marikana Operations.

Figure 2.8: The Lonmin Marikana Operations where the Elandsdrift Fault Zone divides it in a western and eastern geotechnical domain.

Figure 1.3 shows the stratigraphy of the hangingwall and footwall units of the UG2 Reef and potential parting planes. The UG2A markers are thin chromitite layers which act as natural parting planes in the hangingwall. A thin chromitite layer can also be present along the hangingwall 1A/hangingwall 2 contact,

which also acts as a potential parting plane. Alteration zones (weak contacts) can be present along the pyroxenite layers of the UG2 Reef (Gebrekristos and Cheshire, 2012).

Figure 2.9 was compiled by Preston (2004) to describe the geologic structures exposed at Lonmin's Newman Shaft. Unfortunately at the time, the shafts were managed in isolation and the loss of key staff resulted in the loss of knowledge of the area. Similar ground conditions have been exposed at adjacent shafts, but the resulting rock mass behaviour was not anticipated due to a lack of knowledge of the occurrence and potential failure mechanisms associated with the geologic structures. Figure 2.9 provides a good generalised depiction of the structures' orientation. The presence of the 'J3' structure was identified in 2008 on Hossy Shaft (down-dip from Newman Shaft). However, it was only identified when anomalous pillar behaviour was observed. This reiterates the importance to pro-actively identify and treat these anomalous geologic conditions.

PLAN VIEW – RAISE LINES

SECTION – STOPE

HW1A — J3

UG2

J1: striking NNW-SSE; dips 90°; high frequency of talc chlorite infill (light green). Many closely spaced joints associated with the main joint, creating very blocky hangingwall conditions.

J2: most prominent; striking ENE-WNW (E-W; dip 60 – 80°); frequently associated with pegmatite infill (white) which is not always visible in the UG2 Reef. If water is present, extra caution must be applied to prevent falls of ground.

J3: undulating, layer-parallel joints in hangingwall pyroxenite dips less than 45° in all directions; high frequency of talc chlorite infill (light green); responsible for smaller falls of ground. Extra caution to be applied when water is present.

J4: striking NE-SW; dip 90°, talc chlorite infill or no infill is present.

J5: includes all other randomly orientated joints; they are not included in the diagram as no apparent trend has yet been identified.

Figure 2.9: Orientation of geologic structures and associated ground conditions as described by Preston (2004). Note that the structures have similar orientations to the major structures described in the previous section.

2.2.2. Regional NNW-SSE and WNW-ESE trending structures

The main structures exposed in Lonmin's underground mine workings are shown in Figures 1.2, 2.10 and 2.11. The NNW-SSE striking structures are associated with the Pongola rift faults that were reactivated during the intrusion of the Bushveld Complex.

Lyons and Du Plooy (2000) identified subtle WNW-ESE striking lineaments as shown by the blue lines in Figure 2.10. The lineaments are clearly visible (black dotted lines) on the aeromagnetic survey (Figure 2.11) of Eastern Platinum Limited. The structures are not defined as steeply dipping faults but rather sub-parallel structures from underground mapping done at Lonmin's Shafts. Figure 2.10 show the interpreted 'regional basement lineaments' in blue. Although it appears as discrete structures on the aeromagnetic image, it is more likely to define a broader zone. Lyons and Du Plooy (2000) explained that these structures cause adverse hangingwall conditions and terminate against NNW- and NNE trending, near-vertical structures. Underground a trend of structures has been identified to coincide with the orientation of the regional, large-scale structures of the Bushveld Complex. Although exact structures cannot be pin-pointed, an associated behaviour has been identified from historic instabilities at Eastern Platinum Limited 3 Shaft and Saffy Shaft (Du Plessis, 2009).
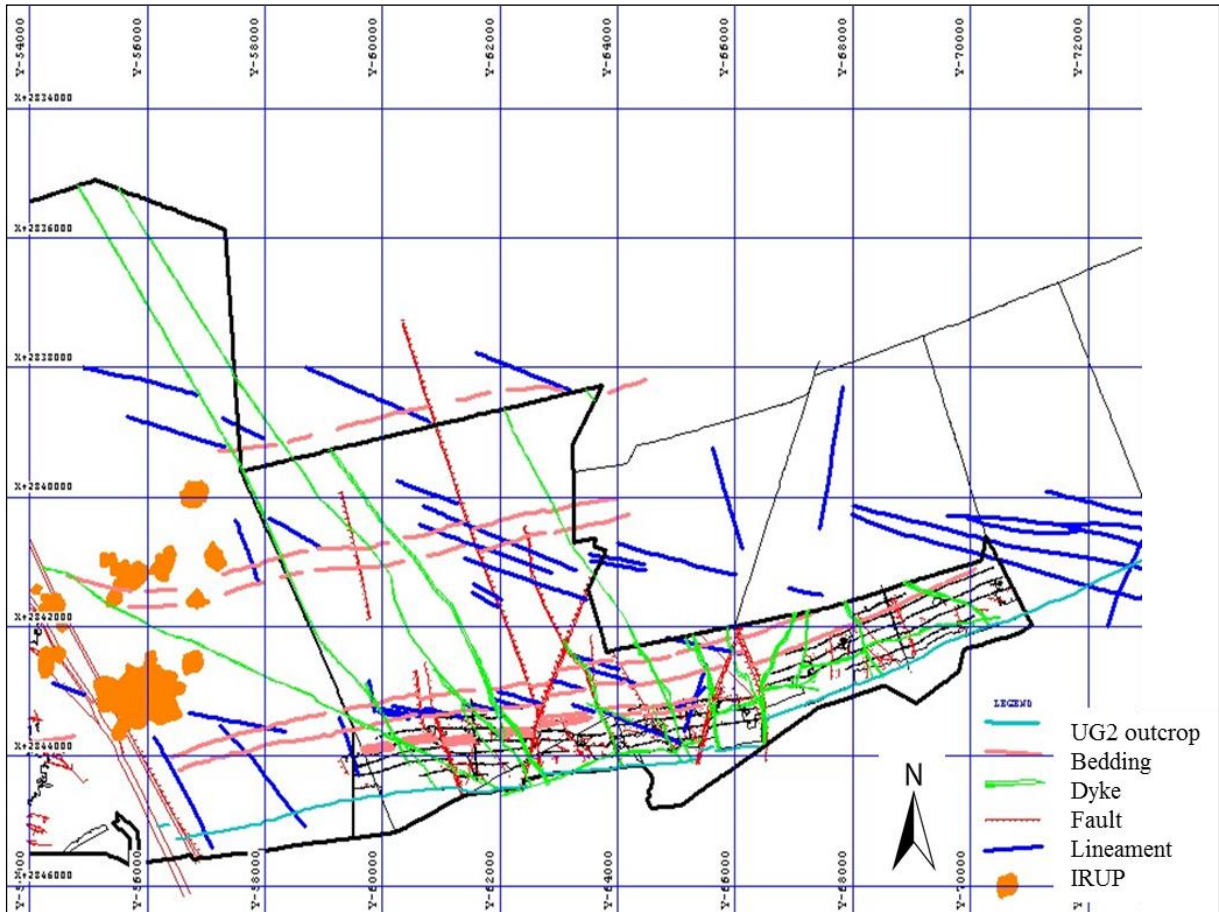
Figure 2.10: Mine plan illustrating the WNW-ESE trending lineaments along Eastern Platinum Limited, shown by the blue lines (Lyons and Du Plooy, 2000).
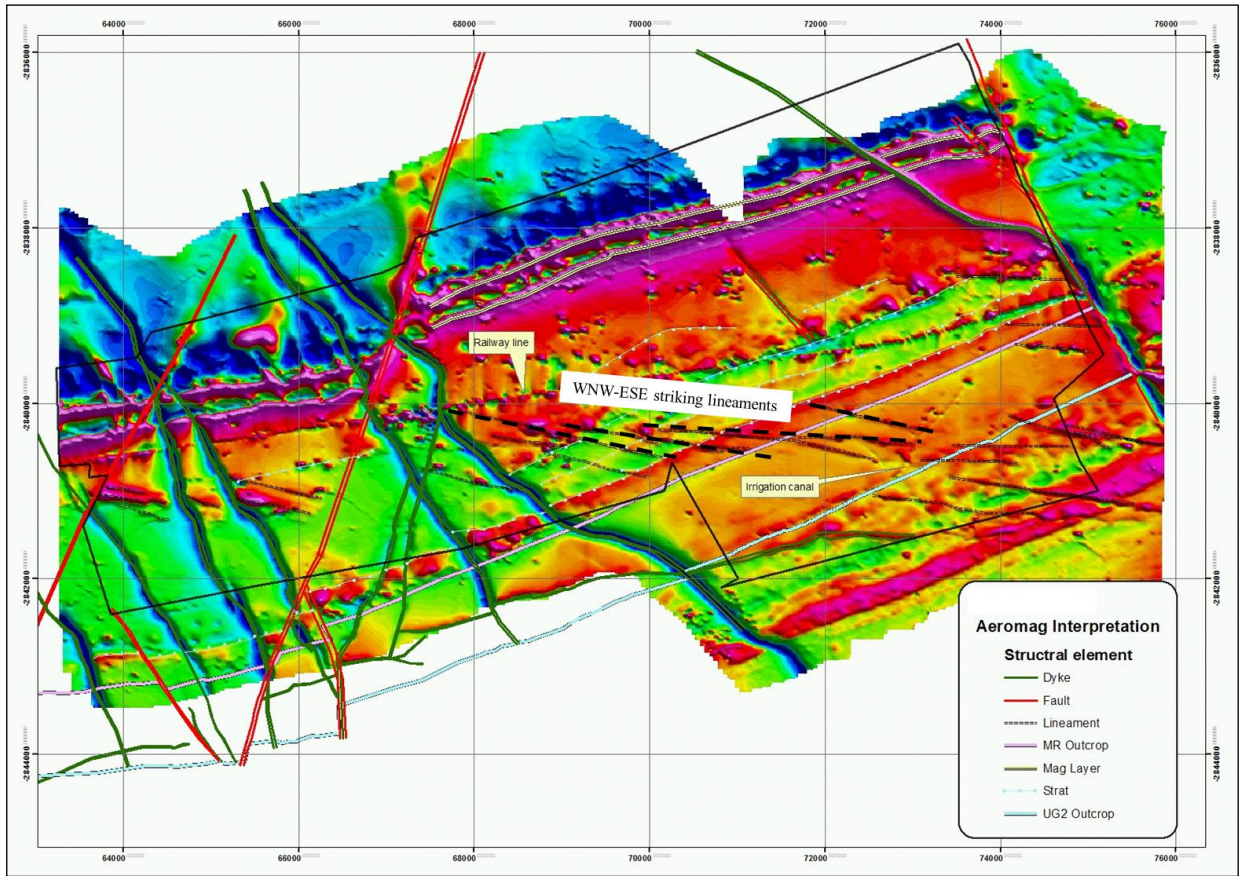
Figure 2.11: Aeromagnetic image of Eastern Platinum Limited, showing the major geologic structures, including the WNW-ESE trending lineaments (black dotted lines).

Neotectonics

Stewart and Hancock (1994) defined neotectonics as the branch of tectonics dedicated to the study of deformations and the effects are detectable in present-day landforms. Neotectonic activity in Southern Africa has been analysed in terms of known stress fields. The African plate south of the equator is divided in two zones of compressive stress orientation. The one zone of predominant NNE-directed trends which corresponds to the East African Rift system, and a second zone in southern and southwestern Africa (where the Bushveld Complex is located), but including the southwest Indian Ocean, characterized by NW- to WNW trends (Zoback *et al.,* 1989, Zoback, 1992 and Andreoli *et al.,* 1996). Most of South Africa is dominated by a NW- to WNW- trending horizontal compressive stress field (Figure 2.12) after Stacey and Wesseloo (1999). Andreoli *et al.* (1996) described this stress field as the Wegener Stress Anomaly.

Madi and Zhao (2013) discussed that evidence was found both offshore and onshore that South Africa is undergoing neotectonic activity. Neotectonics are strongly related to seismicity and although South Africa is in an intraplate setting, seismic events are common.

It should be considered that mining in high stress conditions may also be affected by the current seismotectonic environment. Neotectonic activity is characterized by reactivation of ancient faults, dykes and creation of new fractures. It could also play a role in the exploration of groundwater (Madi and Zhao, 2013).
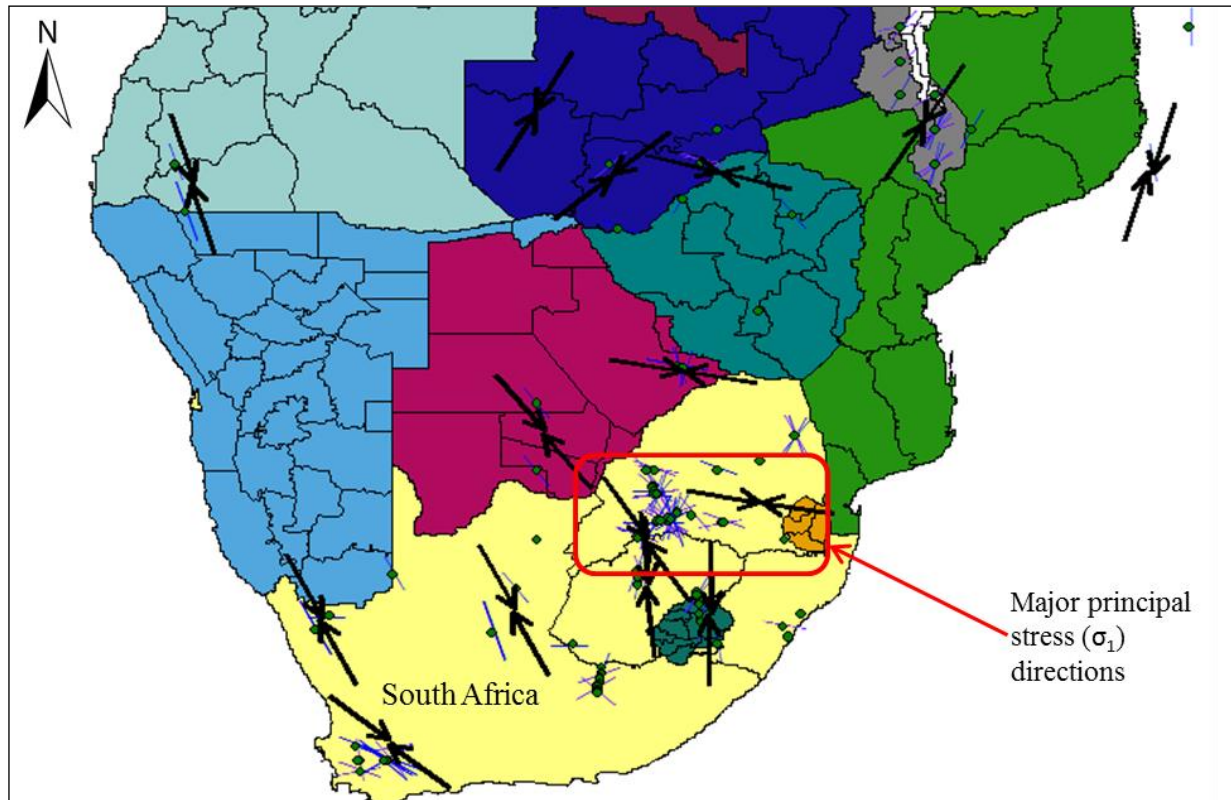
Figure 2.12: Neotectonic stress fields of Southern Africa (Stacey and Wesseloo, 1999).

2.3.   Previous studies on large-scale instabilities associated with the regional NNW-SSE, WNW-ESE trending structures and flexural slip thrust faulting

Large-scale instabilities and collapses have been recorded at various mines in the Bushveld Complex and Great Dyke. From previous studies conducted by various investigators, the geologic structures and failure mechanisms have been identified. The following section discusses the various recorded case studies.

2.3.1.   Eastern Platinum Limited 3 Shaft

In 2003, spalling along the top corner of a 15 m wide crown pillar was reported at a depth of 220 meters below surface at Eastern Platinum Limited 3 Shaft (Figure 1.2). Inspection of the working places that were mined out revealed that a large-scale collapse had occurred (Figure 2.13) with a size of approximately 360 m on strike and 130 m on dip (More O'Ferrall and Du Plessis, 2017). A non-yield pillar layout was implemented and the in-stope support consisted of timber elongates intended to ensure the stability of the

hangingwall 1B and UG2A markers, situated approximately 7.5 m above the UG2 top reef contact illustrated in Figure 1.3.
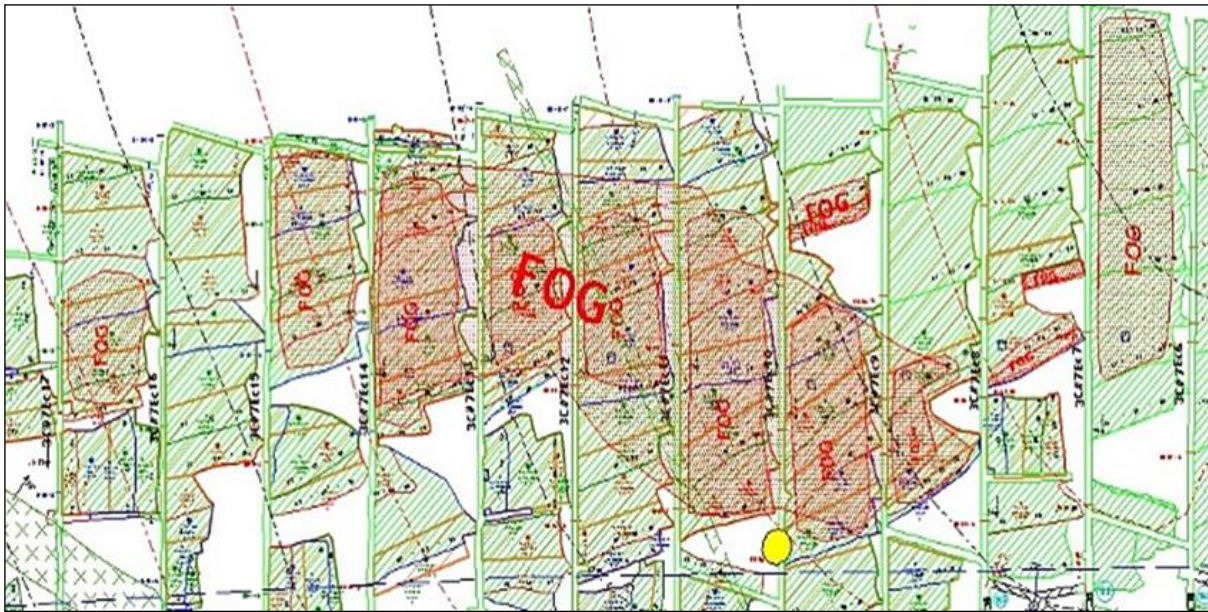
Figure 2.13: Falls of ground extending 360 m on strike and 130 m on dip at Eastern Platinum Limited 3 Shaft.

Figure 2.14a shows the onset of fracturing experienced close to the hangingwall contact of the UG2 Reef. In many instances, pillar slabbing (Figure 2.14b) was observed and in other instances total pillar failure had occurred. It was noticed during the investigations that the timber elongates were failing in compression. Prominent joint planes were open and dripping water was observed in the surrounding areas where the falls of ground had occurred.

(a)

(b)
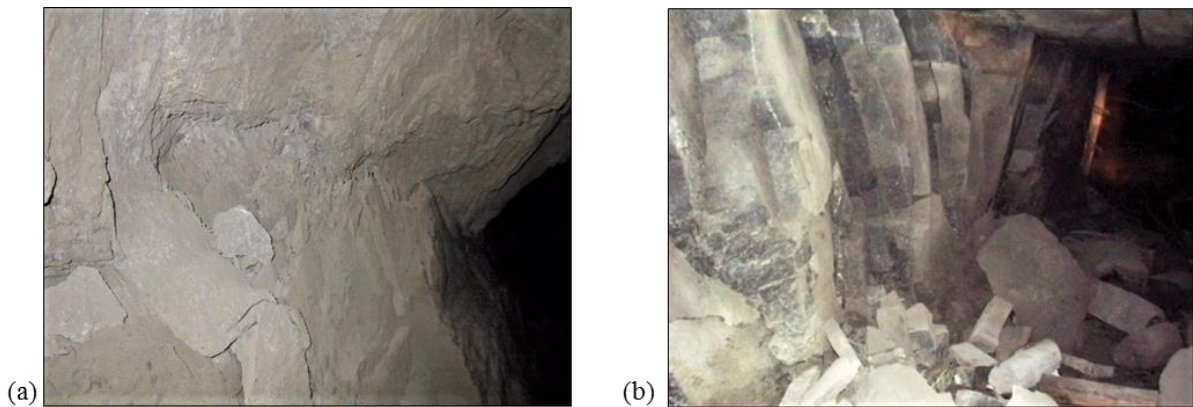
Figure 2.14: (a) Stress fracturing of the pillar; (b) pillar slabbing.

Boreholes drilled from surface into the collapsed area confirmed that the source of instability occurred at the hangingwall 1A/hangingwall 2 contact which caused a 13 m beam to detach (More O'Ferrall and Du Plessis, 2017).

More O'Ferrall and Du Plessis (2017) believed that the instability was caused by the failure of the entire hangingwall1 beam (hangingwall 1B, UG2A markers and hangingwall 1A) where the panels stripped along major, vertical dykes, striking approximately NNW-SSE. The possibility exist that the contact of the hangingwall 1A and hangingwall 2, in close proximity to the dyke on Eastern Platinum Limited 3 Shaft was weathered (altered). This resulted in a beam thickness of 13 m that was only supported by the timber elongates.

The detached blocks could not be supported by the timber elongate in-stope support, which was subsequently overloaded. This resulted in the collapse of the beam in the middle of the panel strike span (Figure 2.15b). Two types of pillar behaviour were identified. This included stress fracturing (Figure 2.14a) where no infilling (alteration) occurred at the UG2 Reef and hangingwall 1B pyroxenite contact, as well as pillar slabbing where a thin altered layer was present at the top reef contact (Figure 2.14b).

As an immediate remedial action, the mining spans were reduced and cementitious grout packs were introduced in the support design strategy to prevent the secondary effect of unravelling in the back area.
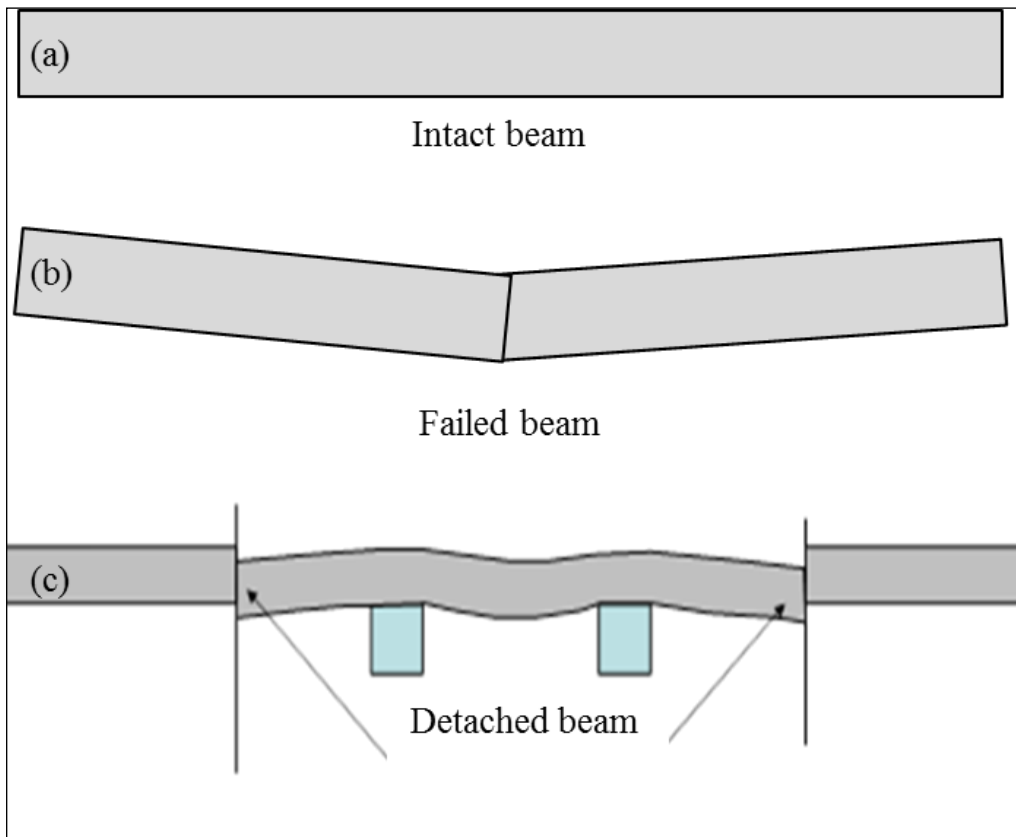
Figure 2.15: (a) Intact beam, no geologic structures; (b) Failed beam, near-vertical geologic structures, absence of low-angle structures and (c) Detached beam (modified after Du Plessis, 2010).

In 2009, 13 large-scale instabilities were recorded over a period of 18 months at Eastern Platinum Limited 3 Shaft (Du Plessis, 2009). The panel spans exceeded 30 m and in some instances the grout pack installations were delayed and could therefore not control the hangingwall deformation. Aeromagnetic surveys along Eastern Platinum Limited mines (Figure 2.11) show WNW-ESE trending lineaments and NNW-SSE striking dykes. The WNW-ESE striking lineaments were identified underground as fairly thick (50 – 200 mm) joints with pegmatite infill dipping between 30˚ and 60˚ to the south (Figure 2.16).

Figure 2.16: Underground image of a WNW-ESE striking, regional low-angle structure with pegmatite infill. These structures have been termed the Marikana structures in this study.

These structures were historically associated with major instability in the stoping panels as it traverses the entire hangingwall 1 pyroxenite package. Where these Marikana structures intersect the mining area, the hangingwall beam is cut off at one end (Figure 2.15c) and is simplified by some authors as a possible cantilever effect as shown in Figure 2.17 (Du Plessis, 2009). The detached beam reaches a critical span after which the convergence sustained by the deflecting rock cannot be absorbed by the timber elongates (Figure 2.17). Van der Merwe and Madden (2002) discussed the calculations to determine the deflection (δ), by applying equation 1, and the stress (σ_t), by applying equation 2.

$$\delta = \frac{(3/2) \cdot \gamma \cdot L^4}{E \cdot t}$$

(1)

$$\sigma_t = \frac{3 \cdot \gamma \cdot L^2}{t}$$

(2)

Where:

δ = Deflection (mm)

E = Young's modulus (GPa)

σ_t = Induced horizontal tension (MPa)

γ = Unit weight (ρ x g) measured in MN/m

ρ = Rock density (kg/m^3)

g = Gravitational constant (m/s^2)

t = Beam thickness (m)

Care should nevertheless by exercised when applying simple beam formulas as the rock is typically fractured and contains joints underground and the so-called 'beam' is not intact. Du Plessis (2009) noted that the lineaments could not be identified as individual structures. However, the associated rock mass behaviour is related with the formation of large detached blocks, dipping at low angles towards the south.

Figure 2.17: Buckling of timber elongates as identified during a 2009 study. The Marikana structure defines the edge of the brow.

During the 2009 study, an investigation in the open pit directly up-dip of Eastern Platinum Limited 3 Shaft revealed that an alteration zone exists at the hangingwall 1A/hangingwall 2 contact (Figure 2.18). This contact can also consist of a thin chromitite layer and it acts as a natural parting plane. This confirmed the findings that a weak contact exists at the hangingwall 1A/hangingwall 2 contact.

Figure 2.18: Open pit, up-dip of Eastern Platinum Limited 3 Shaft showing the alteration zone at the hangingwall 1A/hangingwall 2 contact.

More O'Ferrall and Du Plessis (2017) noted that historically at the Eastern Platinum Limited operations, a long down-dip panel (one panel mined per development end) layout was applied for areas where above average jointing and/or weathering (altered pyroxenite) conditions were identified. This layout improved stability and consequently safety. However, panel spans were limited to 25 m. The expected behaviour of the hangingwall layers was incorporated in the design of the panel strike spans. Du Plessis (2009) found that back breaks occurred when a dip mining span of approximately 50 m was reached (twice the panel strike span). These collapses could only be reduced by controlling the inter-pillar span.

Breast mining was the preferred mining orientation to accommodate the Marikana structures. The mining direction is further determined by the prevailing geologic structures that should be approached from the stable side. The identification of weak parting planes should be used to anticipate the potential behaviour of

the hangingwall layers and to ensure that the appropriate design criteria are implemented. In all instances the instabilities occurred when spans were increased to more than 27 m.

2.3.2. Saffy Shaft

Saffy Shaft (Figure 1.2) experienced large-scale (approximately 900 m^2) instabilities on the reef horizon (Figure 2.19) during December 2010 and January 2011 (Van Zyl, 2011). The UG2 Reef on the shaft strikes from E-W with an average dip of 11˚ to the north. Mining takes place at depths of approximately 300 – 800 mbs. A hybrid mining method was applied. This involved conventional stoping whereas all of the on-reef cleaning was conducted with a mechanised fleet of equipment (Liebenberg, 2017).

Figure 2.19: Fall of ground visible along a gully at Saffy Shaft where the support units failed when the hangingwall beam detached at a height of approximately 15 m at the hangingwall 1A/hangingwall 2 contact. This resulted in failed timber elongates and crushed grout packs.

Figures 2.20 and 2.21 show the major geologic structures exposed at Saffy Shaft. Structures are trending in NNW-SSE, NNE-SSW and WNW-ESE directions. The WNW-ESE striking Marikana structures coincide with the orientation of the lineaments identified at Eastern Platinum Limited 3 Shaft. The presence of these structures is indicative of possible instability in underground excavations. Significant water intersections along these major structures have been identified. The water intersected during drilling operations is the

maximum measured at the time of intersection (Knipe, 2016). Common practice is to seal the boreholes that intersect water.

From a study conducted by Du Plessis (2010), the cause of the falls of ground were due to the intersection of prominent geologic structures trending NNW-SSE and WNW-ESE Marikana structures with dips greater than 60˚. The infilling consisted of calcite, serpentine, talc, chlorite or pegmatite.
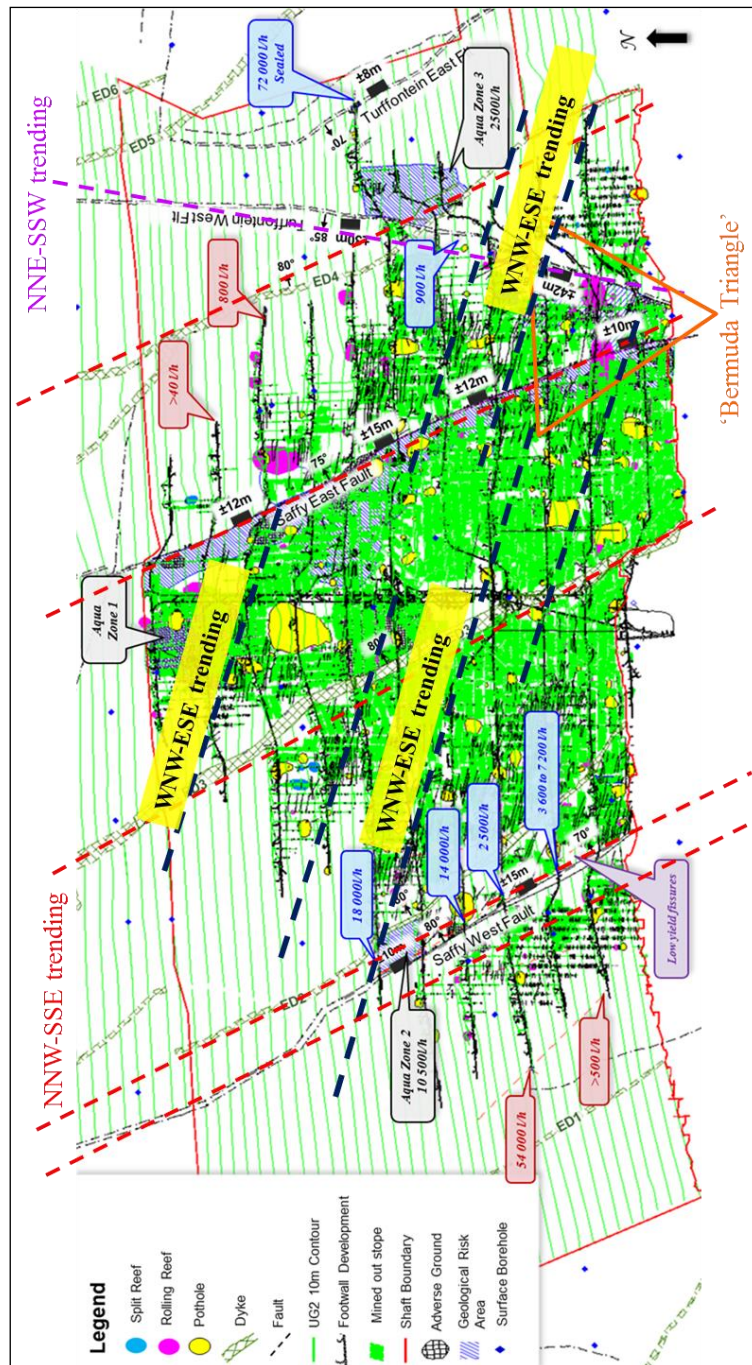
Figure 2.20: Structural plan of the Saffy Shaft block. The numerous smaller WNW-ESE striking structures are intersected by the more prominent NNW- and NNE striking structures.

Van Zyl (2011) used joint modelling software (JBlock) to generate possible combinations of key blocks which could result from the joint combinations in the hangingwall. A probabilistic assessment of the possible falls of ground was done, also taking into consideration, the excavation, mining direction and the evaluation of support effectiveness in the particular excavation. The findings from Van Zyl (2011) concluded that the least risky option for the particular stoping method was split down-dip panels (half a panel is mined on both sides of the development end) with the western face leading. Breast panels mining towards the east were also classified as a low risk option. Additional strategies applied to prevent the occurrence of associated large-scale instabilities was to limit the mining spans to 27 m (Du Plessis, 2009) and to apply a support system consisting of stiff, active support, including rock bolts, timber elongates and 5000 kN cementitious grout packs.
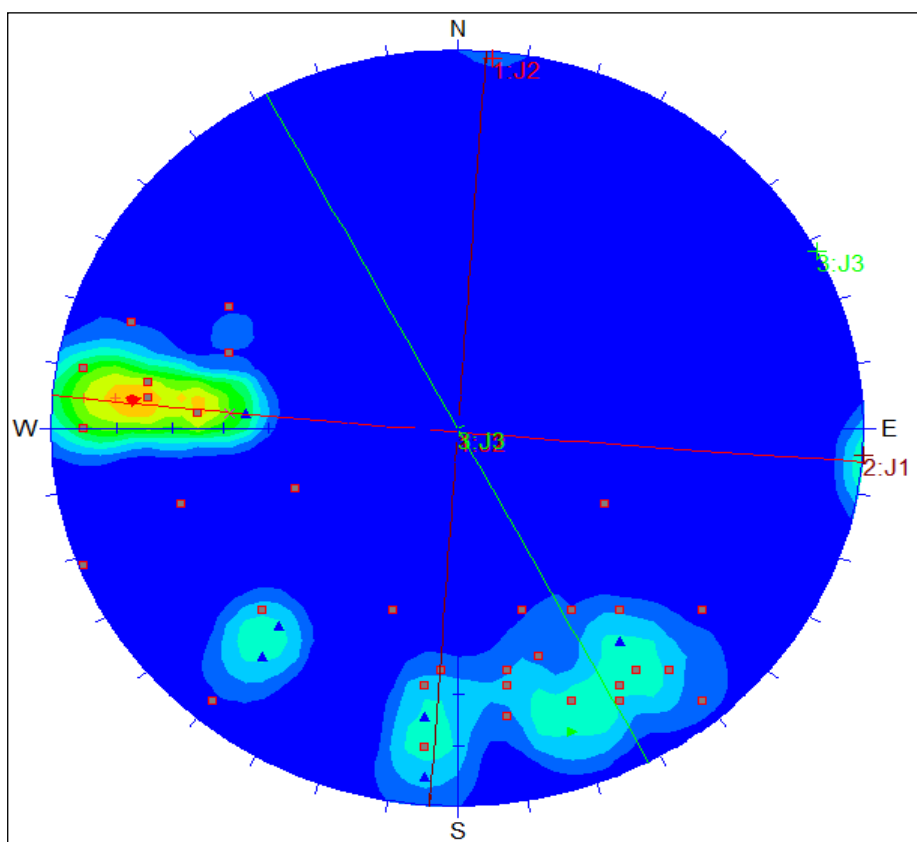
Figure 2.21: Polar plot of mapped joint sets (Van Zyl, 2011) showing WNW-ESE and NW-SE trending structures. Most of South Africa is dominated by this pervasive, NW- to WNW-trending (Figure 2.12), horizontal compressive stress field for which the term Wegener Stress Anomaly was proposed (Andreoli *et al.,* 1996).

2.3.3. The Bushveld Complex

Roberts and Clark-Mostert (2010) identified sites in the Bushveld Complex where flexural slip thrust faults occur. These faults have a reputation to be one of the main contributors to falls of ground. Two components make up the flexural slip thrust fault; the layer-parallel portion of the fault known as the flat and an inclined non-planar surface known as the ramp part of the fault (Figure 2.22). Roering and Berlenbach (1989) found that fault gouge, which forms a very weak contact, can be present along these ramp planes. These structures may therefore pose a significant fall of ground risk. The fault gouge is referred to as an alteration zone in this study.
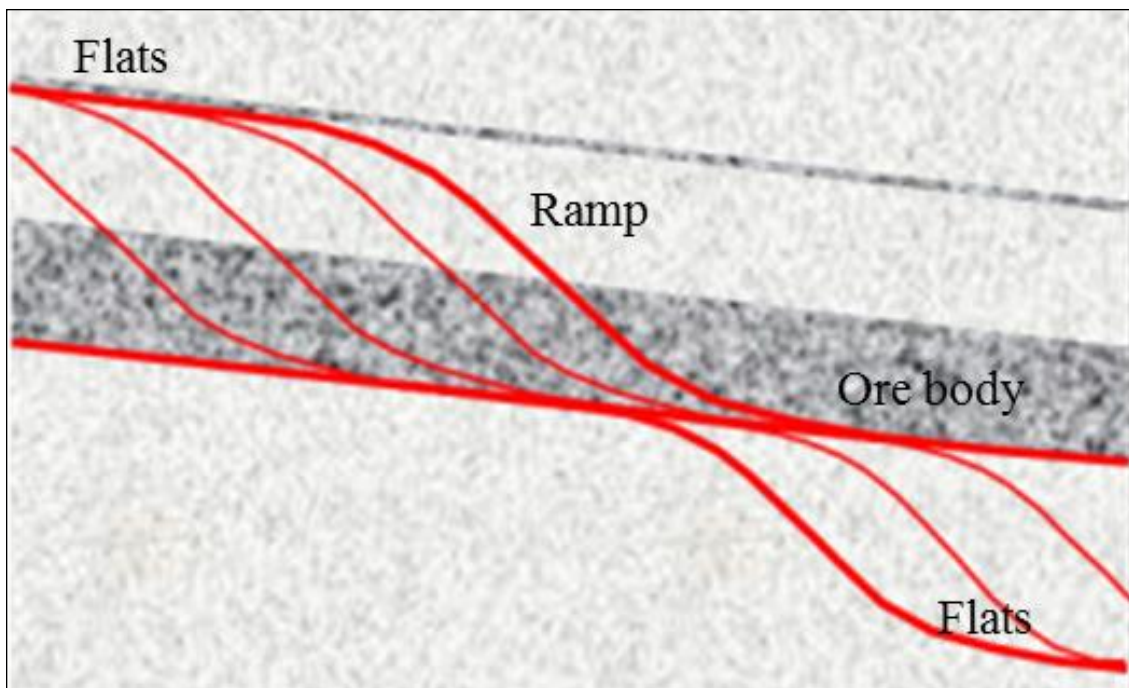
Figure 2.22: Section view of the ramp and flats in the vicinity of the ore body (Roberts and Clark-Mostert, 2010).

A large number of falls of ground fatalities in the platinum industry (especially on the UG2 Reef horizon) have been caused by the intersection of low-angle structures with steeply dipping joints, faults or pegmatite veins. Figure 2.23 show a fall of ground in a bord and pillar mine. Roberts and Clark-Mostert (2010) recommended that flexural slip thrust faults can be controlled by installing 4 m long, 400 kN cable anchors in a systematic pattern of 1.5 m x 1.5 m. This provides a support resistance of more than 200 kN/m^2. The bord widths in this environment can also be decreased. The visual identification of the low-angled structures nevertheless remains a challenge. Some mines have implemented the use of ground penetrating radar (GPR) and borehole cameras in an attempt to early identify flexural slip thrust faults, low-angle ramp structures, also referred to as deformation event 1 in Table 2.1. Roberts and Clark-Mostert (2010) found that the

application of grout packs in Bushveld Complex platinum conventional mines proved to be an effective support system to prevent falls of ground associated with these structures.

It is of utmost importance to understand the three-dimensional spatial occurrence of the structures and the impact it has on the mining excavation to effectively implement the most suitable mining direction, mining spans, orientation and support strategy.
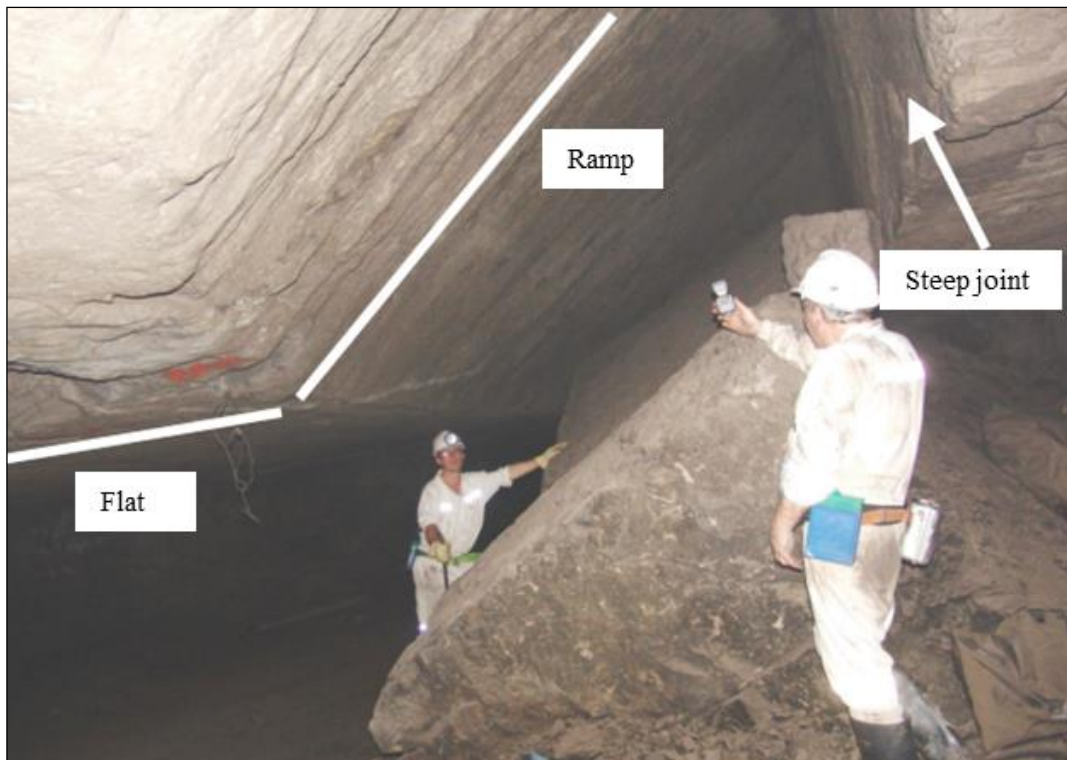
Figure 2.23: Flexural slip thrust fault (ramp structure) intersecting a steeply dipping joint (Roberts and Clark-Mostert, 2010).

Potential pillar instability exist if a large portion of the flat part of the flexural slip thrust fault, with a considerable amount of fault gouge present, is exposed approximately parallel to the reef and form the boundaries of the pillar contacts/foundations (Roberts and Clark-Mostert, 2010). There are three reported cases of mines in the Bushveld Complex where the entire mine or large portions of the mines were abandoned due to the presence of fault gouge in the vicinity of the reef (hangingwall contact) which resulted in large-scale instabilities.

This occurred at:
- A chrome mine in the Western Bushveld: fault gouge material in the same plane as the reef and parallel to the reef.

- A platinum mine in the Eastern Bushveld: gouge material located on top of the reef.
- A platinum mine in the eastern portion of the Western Bushveld: 20 - 30 cm gouge along top contact and within the pillars.

Roberts and Clark-Mostert (2010) believed that the pillar instabilities occurred as a result of the fault gouge being compressed, deforming the material and failing the pillars in tension (Figure 2.24). The pillars were effectively pulled apart. Consequently, when extensive pillar failure occurred, unravelling of the hangingwall was initiated and this led to widespread collapses. This failure mechanism is further investigated in Chapter 4.
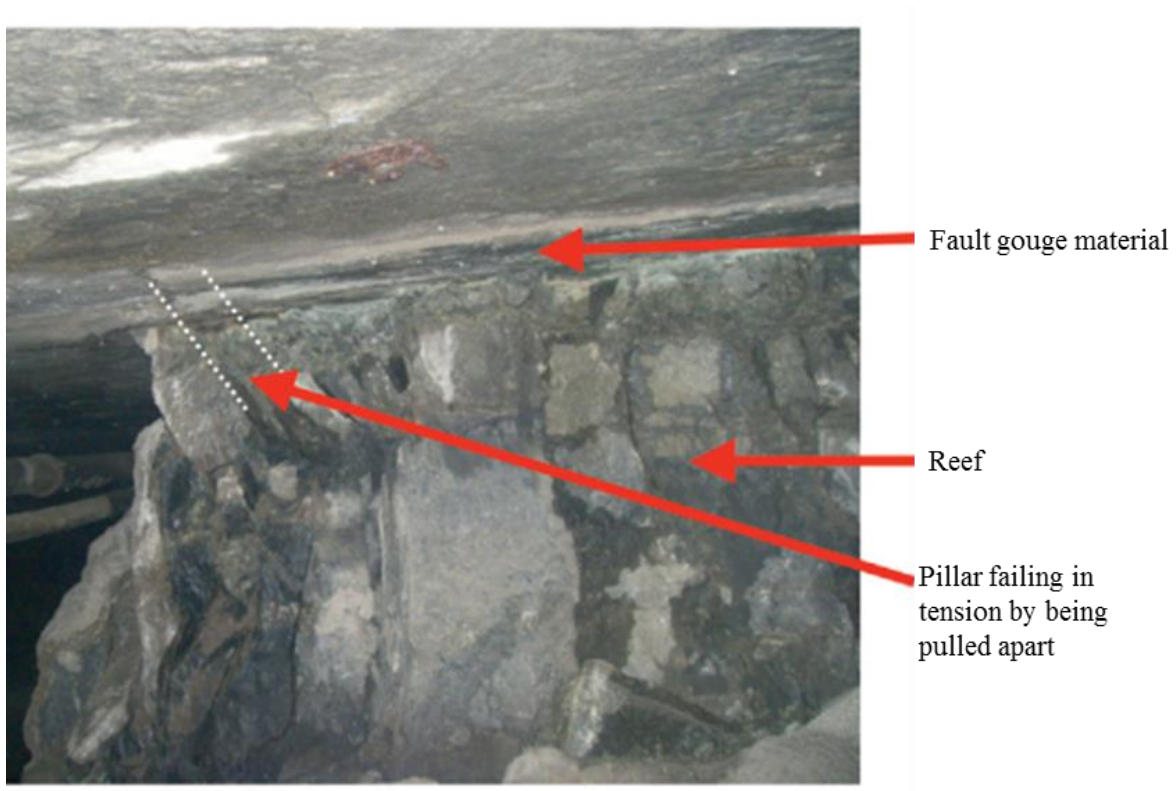
Figure 2.24: Pillar failure due to the deformation of the fault gouge material (after Roberts and Clark-Mostert, 2010).

As a result of this failure mechanism experienced when gouge is present along the contacts, the traditional method of determining the pillar strength using empirical formulae no longer applies. As the pillar strength (σ_c) is unknown, the factor of safety for the pillar system cannot be determined. Further work is required to determine pillar strength.

As a further complication, the fault gouge may be washed out during exploration drilling and would only be captured as a core loss of 20 - 30 cm. This is a major concern as the geotechnical logging would not identify this structure and it would only be discovered when it is exposed by the mining operations (Roberts and

Clark-Mostert, 2010). More O'Ferrall and Du Plessis (2017) explained that as a result, the Design Engineer may not carry knowledge of this structure or the risk of pillar failure. Consequently, the pillars may be incorrectly designed and fail over time. The pro-active identification of these structures are therefore of importance to apply an appropriate design criteria.

2.3.4. The Great Dyke

Some mining operations in the Great Dyke have excellent ground conditions where the bord spans (bord and pillar mining method) is 15 m and minimal support is installed. Mining is more challenging where the joint density increases and non-planar curved structures (Figure 2.25) are exposed. This results in a decrease of the bord widths (Roberts and Clark-Mostert, 2010).

Roberts and Clark-Mostert (2010) noted that the presence of curved structures presented a similar risk to the ramps of the flexural slip thrust faults observed in the Bushveld Complex sites. Also, slickensides were visible on the planes, indicating thrust movement. These structures have tentatively been identified as flexural slip thrust faults (ramp structures). These structures have not been recorded everywhere in the Great Dyke and no fault gouge was present along these curved structures.

Non-planar curved structure
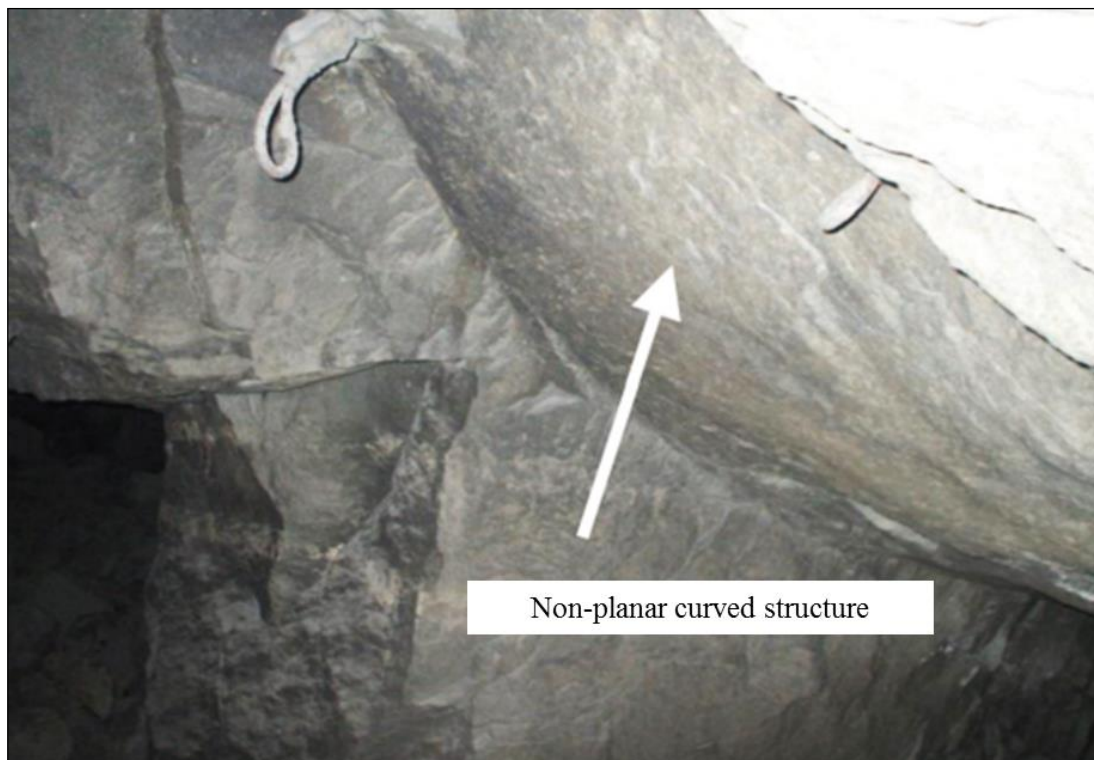
Figure 2.25: A non-planar curved structure (ramp structure) in a mine of the Great Dyke (Roberts and Clark-Mostert, 2010).

2.4.   Previous studies of alteration zones in the pyroxenite layers of the UG2 Reef

Davis and Reynolds (1996) describe a shear zone as a strained, sheet like and planar or curviplanar zone in comparison to the adjacent rocks. These zones form a network consisting of individual shear zones that can be subparallel sets, deflect towards one another and link up in an anastomosing pattern. It can also cross-cut or displace one another. The shearing cause fractures to form that allow fluids to pass through. The hangingwall pyroxenite, which has been exposed to hydrothermal fluid flow, serpentinization, and layer-parallel shearing, is defined as the alteration zone. The other terms used for this shear zone are: 'clay-like' layer, fault gouge and 'mud layer'. The term 'alteration zone' will be used in this study to describe this weak layer/contact as seen in Figure 2.26.

When these alteration layers are present, it poses a fall of ground risk as the rock may unravel around installed support units and it can also result in anomalous pillar behaviour. The occurrence of the weak contacts can easily be overlooked in geotechnical drill holes, due to the alteration material being washed out during the drilling process. The presence of alteration zones may also not be correctly identified by underground staff. Therefore, its presence may not be reported and the behaviour of these structures not necessarily recorded unless there was significant associated instability.

Figure 2.26: An alteration zone present at the top contact of the UG2 Reef.

The occurrence of the weak zones was initially identified as anomalous. It may, however, be explained by two theories resulting from studies conducted by Perritt and Roberts (2007) and by Gebrekristos and Cheshire (2012).

The first theory is based on paleomagnetic evidence (summarised by Eales *et al*., 1993) which suggests that the layers of the Bushveld Complex were originally deposited in a horizontal manner and the load of the Bushveld Complex and overlying granites caused crustal flexure/bending, leading to the formation of centripetal dips of 10˚ and 20˚ (Cawthorn and Webb, 2001). According to Perritt and Roberts (2007), the crustal flexure/bending caused the mobilisation and re-orientation of layers by means of a flexural slip mechanism (shear). This concept is illustrated in Figure 2.27.
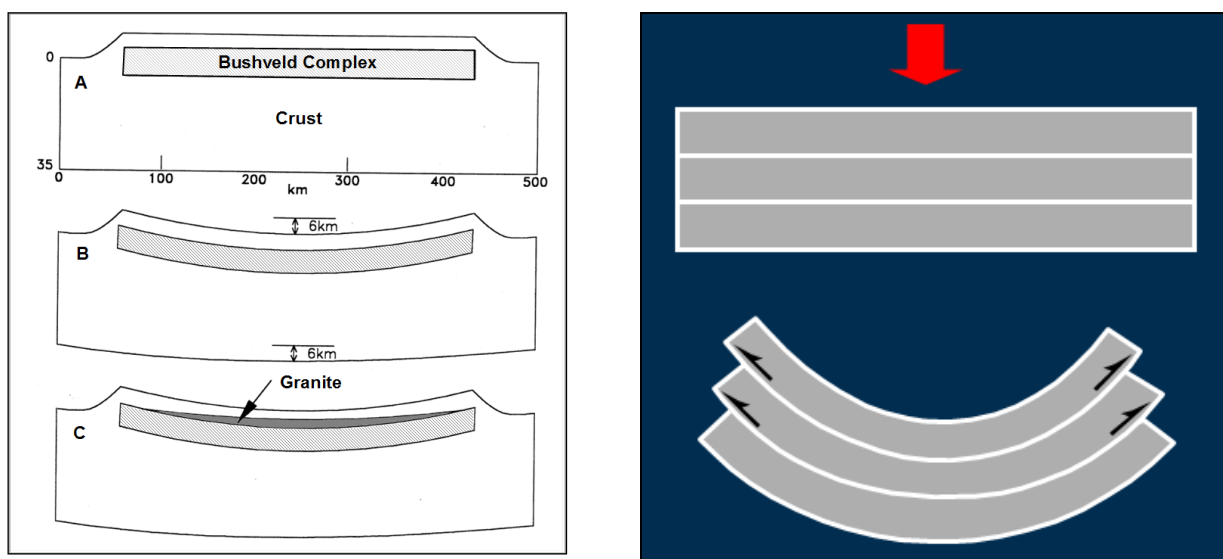
Figure 2.27: Simplified illustration of the Bushveld Complex and how the load from the Bushveld Complex and overlying granites caused crustal flexure/bending (Cawthorn and Webb, 2001; Perritt and Roberts, 2007).

The slip usually occurs along layer boundaries. Possible layer-parallel faulting occurs along the top contact of the UG2 Reef and at the chromitite-pyroxenite contacts (within the UG2A markers). The infilling can consist of chlorite and/or serpentine (Figure 1.3). The contacts of the UG2 Reef are not always sheared; therefore, faults do not always occur. In the case where layer-parallel faults occur along the contacts of the UG2 Reef, it varies in extent and can be present across several panels; i.e. approximately 50 m along strike. Falls of ground occur where these structures cut off against the joints with pegmatite infill (Marikana structures) that trend along the strike direction of the layering (Perritt and Roberts, 2007). These structures are important in relation to mining activities as it contributes to unstable hangingwall conditions. It may be present in other areas, but it is not necessarily exposed by the mining operations.

Low-angle structures and alteration zones are some of the most prominent structures exposed during the extraction of the UG2 Reef, but it is not pro-actively identified. There is a lack of knowledge and understanding regarding layer-parallel structures and alteration zones as well as the impact thereof on the design. It is only when these structures are exposed and anomalous conditions occur when mitigation strategies are applied (e.g. secondary support). Leading indicators may exist across several panels and should be pro-actively identified in order to prevent large-scale instability.

The second theory by Gebrekristos and Cheshire (2012) suggests that weathering in the hangingwall pyroxenite of the UG2 Reef can be pronounced by the unique aquifer properties of the UG2 pyroxenite in the area of the mining zone ($5 - 7$ m below the aquifer). These specific aquifer properties of the UG2 pyroxenite might have contributed to the formation of alteration zones ('clay-like' material). There is no clear explanation why the UG2 pyroxenite weathers more readily than norite and anorthosite, but it can possibly be explained by the layering as well as the specific mineralogical composition of the pyroxenites and the preferential chemical and physical weathering processes. The amount of weathering and tendency to form aquifers varies for different pyroxenites as the weathering is dependent on the composition of the pyroxene minerals. At a deeper fractured bedrock aquifer system, the infiltration and flow of ground water are mainly associated with small-scale faults and minor jointing rather than large-scale regional faults that were found to be comparatively dry (Titus *et al.,* 2009). The storage of ground water is mainly restricted to the UG2A markers above the UG2 Reef, because of the enhanced weathering along the boundary of the irrespective chromitite and pyroxenite layering.

2.4.1. Eastern Platinum Limited 2 Shaft

Alteration zones have been exposed at the Marikana Operations. Lyons and Du Plooy (2000) and Andersen (2001) referred to a structure known as a 'mud layer' (Figure 2.26). Lyons and Du Plooy (2000) mapped this structure (at the Marikana Operations) to determine the deformation event that contributed to the formation of this 'mud layer'. Deformation event 1 was a thrust movement towards the SSE (160˚), where after it was converted into a normal fault moving towards the NNW (335˚), defined as deformation event 2. Deformation event 3 was described as a stage of relaxation (see Chapter 3 for a visual description of these deformation events).

2.4.2. Saffy Shaft

Knipe (2016) did a study on the structural geology and geohydrology of Saffy Shaft (Figure 2.20). The strike of the most prominent sub-vertical structures at Saffy Shaft corresponds to the NNW trend of the Rustenburg Fault, Elandsdrift Fault Zone and Brits Graben Faults which forms a conjugate set with the NNE striking structures such as the Turffontein West Fault. Numerous WNW-ESE striking faults (less than 1 m displacement) and joints are also exposed in the underground mining operations (Figure 2.20).

Knipe (2016) indicated that several layer parallel shears (Figure 2.28) are observed on the shaft and tend to follow geologic contacts. These shears are best developed in specific stratigraphic positions (Figure 1.3) which is similar to the findings at other sites. The footwall 6 shear which occurs on the footwall 5/footwall 6 contact is approximately 42 m below the reef and is not exposed in the normal mining operations, except where decline systems are developed in this location. A second footwall shear is also known to occur towards the top of footwall 5 at the Eastern Platinum Limited Shafts, but it is only observed in the shallower operations. Here it can be very brittle with open fractures or is completely weathered (referred to as a 'mud layer' by Lyons and Du Plooy, 2002).

Figure 2.28: Occurrence of the alteration zone in the vicinity of the UG2 Reef.

The alteration zones (Figure 2.28) were also identified at the hangingwall 1A/hangingwall 2 contact, at the top UG2 Reef contact and / or at the UG2A markers (approximately 8 - 13 m above the top contact of the UG2 Reef). Recent alteration and possible brecciation was also observed at the bottom of the hangingwall 2 mottled anorthosite, directly west of 'Aqua Zone 1' (19 to 20 Level West in Figure 2.20). Relatively close to this area on 19 and 20 Level East, grout packs were observed to have failed (Figure 2.20). The presence of the alteration zone at the hangingwall 1A/hangingwall 2 contact could explain the failure of the grout packs. A thorough understanding of the alteration zones and deformation events at the bottom of hangingwall 2 and delineation of the affected area is essential.

Directly west of the Turffontein East Fault (Figure 2.20), intense layer-parallel shearing has been identified. These shears correspond to the geologic risk zone (approximately 100 - 180 m wide) characterized by localized areas of alteration. The shear seemed to have formed a secondary permeability along which hydrothermal fluids circulated causing argillic alteration of the pyroxenite.

The mineralogy of the alteration zones has been determined by (Davis, 2013) using optical microscopy and mineral geochemistry. The sheared chromite grains aligned, creating foliation planes parallel to the UG2 top reef contact. The fractures allowed for fluid to pass through and induce the alteration zone of olivines to serpentine. Other hydrous minerals such as talc and montmorillonite can also be observed in large amounts (Davis, 2013).The UG2 Reef and hangingwall contact thin section samples have evidence of structural influences. Figure 2.29 show the shearing along the top contact and the minerals present. Clay-like minerals have been identified in the alteration zone.
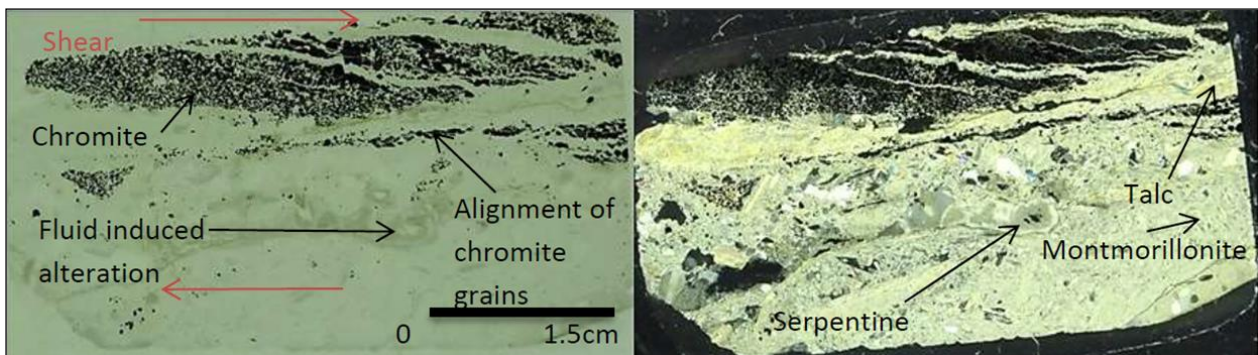
Figure 2.29: Images of the thin sections at the top contact of the UG2 Reef. The shearing caused the top contact to be fractured.

Water aquifers (Figure 2.20) have been intersected in the underground mining excavations and are structurally controlled fractured bedrock aquifers (Titus *et al.,* 2009). Table 2.2 explains the water fissures associated with specific structures and the potential risk to mining. The composition of the underground fissure water indicates that the water from the underground aquifers has been captured in the rock for a very long time and it will not be replenished (Titus and Rossouw, 2015).

Table 2.2: Aquifers and fissures associated with geologic structures (Knipe, 2016).

Geologic structures	Water intersections	Risk rating	Comments
Structures sympathetic to major NNW striking faults and dykes	Low	Low	Position of structures can be predicted.
Major NNW striking faults and dykes.	High	Medium	New intersections can be predicted and managed.
Layer-parallel structures	Low	Medium	Difficult to predict the occurrence and extent.
Smaller WNW-ESE striking faults.	Variable	High	Difficult to predict the occurrence and extent.

Alteration zones along the pyroxenite layers and the impact on pillar behaviour at Saffy and Hossy Shaft

Pillar slabbing (Figure 2.30) was studied by Malan (2008) at Hossy Shaft. Unexpected and abnormal pillar behaviour was observed on both Hossy and Saffy Shafts where pillar slabbing was observed for non-yield pillars. It was thought that this only occurred on pillars that were cut smaller than the specified size (possible over loading). It was suggested by Malan (2008) that the major contributing factor to the pillar slabbing was the very weak contact present between the hangingwall and UG2 pillars (Figures 2.31 and 2.32). Numerical modelling indicated that the impacted pillars had very high pillar stress (> 150 MPa). Malan (2008) suggested limiting the pillar stress to < 130 MPa and to apply a factor of safety > 2 to ensure that the unravelling pillars (slabbing phenomena) is accommodated. It will also ensure that the pillar does not fail and mine stability is ensured. Additional slabbing of the pillars in the back area could therefore possibly occur and routine observations in these areas would be required to identify potential instability.

Figure 2.30: Slabbing noted at the edge of a pillar. The slabs are defined by joint planes which are mobilised by alteration zones along the pyroxenite and chromitite contacts (i.e. Figure 2.31).

Figure 2.31: The alteration zone at the contact between the UG2 Reef and the hangingwall.

Figure 2.32: A fragment illustrating the alteration zone between the UG2 Reef and the hangingwall. Note the slickensided surfaces which indicate that movement has occurred along the top reef contact.

The pillar strength will significantly decrease when an alteration zone is present at the pillar and hangingwall contact. Laboratory experiments were done by Peng (1978) and he concluded that the strength can vary by up to 100% depending on the conditions at the interface of the rock-sample testing machine. Wagner (1980) confirmed this result and his tests indicated that if a soft layer is present at the rock / platen interface, the strength is reduced and the mode of failure changed. The mode of failure changes from 'hour glassing' (Figure 2.33a) and scaling on the edges for the higher friction angles to axial splitting (Figure 2.33b) for the lower contact friction angles.

(a)   (b)
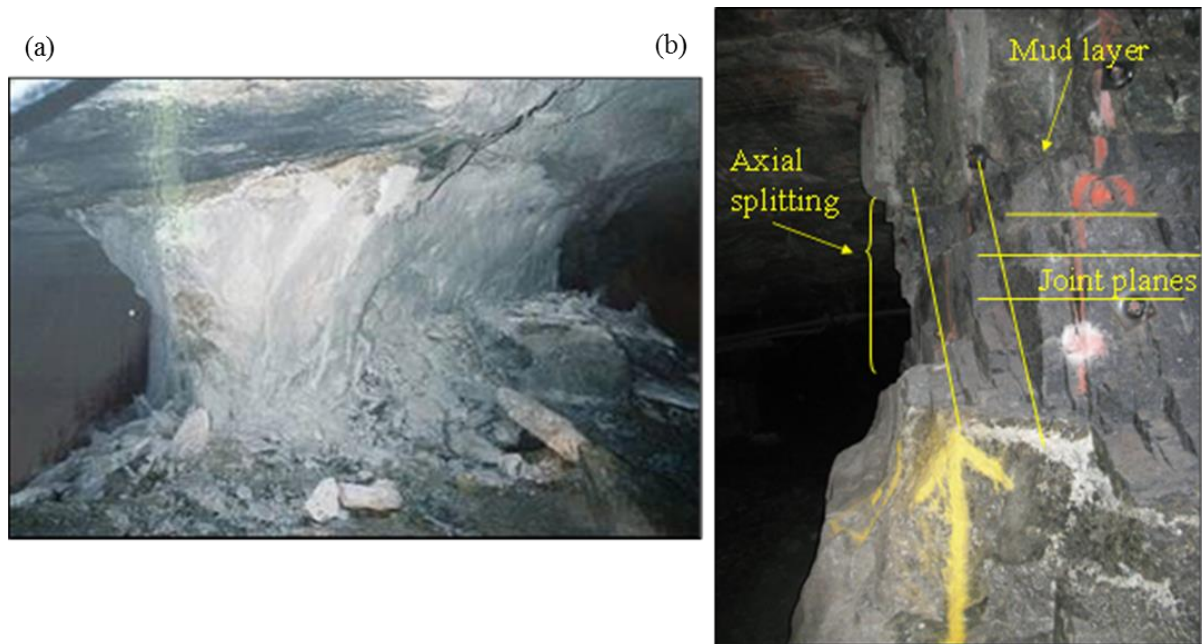
Figure 2.33: (a) Examples of pillar scaling in areas where no alteration zone is present at the interface between the pillar and the hangingwall. The typical 'hour glass' failure mode is evident (Malan, 2008); (b) Axial splitting is evident where an alteration zone is present along the top reef contact.

Rock engineering literature indicates that the alteration zones can reduce pillar strength significantly and that traditional pillar strength formulae are not applicable for these pillars. Additional work is required to establish an appropriate pillar strength formula (Malan, 2008).

As a well-established pillar strength formula for UG2 pillars is not available, the recent update of the power law strength formula after Hedley and Grant derived for a PlatMine project (Watson *et al.,* 2007) was used to obtain a first approximation of pillar strength. This formula should however be further investigated as it is still experimental and additional work is required.

$$P_{stress} = \sigma_v /(1-e)$$
(3)

$$\sigma_v = \rho \cdot g \cdot h$$
(4)

Strength formula

$$P_{strength} = DRMS \cdot W_{eff}^{\alpha} / H_{eff}^{\beta}$$
(5)

With

PlatMine (Watson *et al.,* 2007) UG2: α = 0.67, β = 0.32, based on UG2 pillars in the Western Limb.

DRMS$_{UG2}$ = 67 MPa, (Watson *et al.,* 2007) .

DRMS = Design rock mass strength. This is dependent on the rock strength and rock mass condition (MPa). The value is typically assumed equal to 1/3 x rock strength and can be as much as 2/3 x rock strength.

P_{stress} = Pillar stress (MPa)

σ_v = Virgin vertical stress (MPa)

e = Extraction ratio

ρ = Rock density (kg/m^3)

h = Mining depth (m)

$P_{strength}$ = Pillar strength (MPa)

H_{eff} = Effective pillar height (m)

W_{eff} = Effective pillar width (m)

Where

$$W_{eff} = 4 \cdot Pillar\ area / Pillar\ perimeter$$

(6)

H_{eff} = An increase of 7% above the regular stoping width accounts for adjacent excavations effecting the pillar height, Roberts *et al.* (2002).

$$SF = P_{strength} / P_{stress}$$

(7)

According to Du Plessis (2009b), in areas where the hangingwall has weak partings which influence the behaviour of the pillars, the factor of safety (SF) must be at least 2 (i.e. Saffy and Hossy Shafts).

It should be noted that the PlatMine calibrated values for equation 5 excludes the weakening effect when an alteration zone is present and additional work will have to be conducted to verify its applicability at Hossy and Saffy Shafts. Furthermore, this equation is based on data obtained mainly from Amandelbult, Union and Northam, placing further doubt on its applicability at the Lonmin mines (Malan, 2008). Therefore, the pillar strength could significantly be impacted upon when an alteration zone exists.

2.4.3. The Bushveld Complex

Lombard (2018) created an illustration (Figure 2.34) of the location of the alteration zones from core that was drilled across a mine in the Western Limb of the Bushveld Complex. In most instances, the altered material washed out and it was not captured during the core logging process and the weakening effect was not incorporated into the support design.

In the case where the alteration zone is located along the top reef contact, it will be a challenge to support this material as it unravels between and around the installed support units. Areal coverage will have to be considered. The unravelling of this material during blasting causes dilution (increase in stoping width) and if the grade is too low, mining will not be economically viable. It will also have an impact on the pillar behaviour.

In the case that the alteration zones are located within the hangingwall units, it contributes to a decrease in the friction angle of the alteration zones and other contacts. Large-scale instabilities can then occur. Stiff, active grout packs will be required to support to the highest possible parting plane.
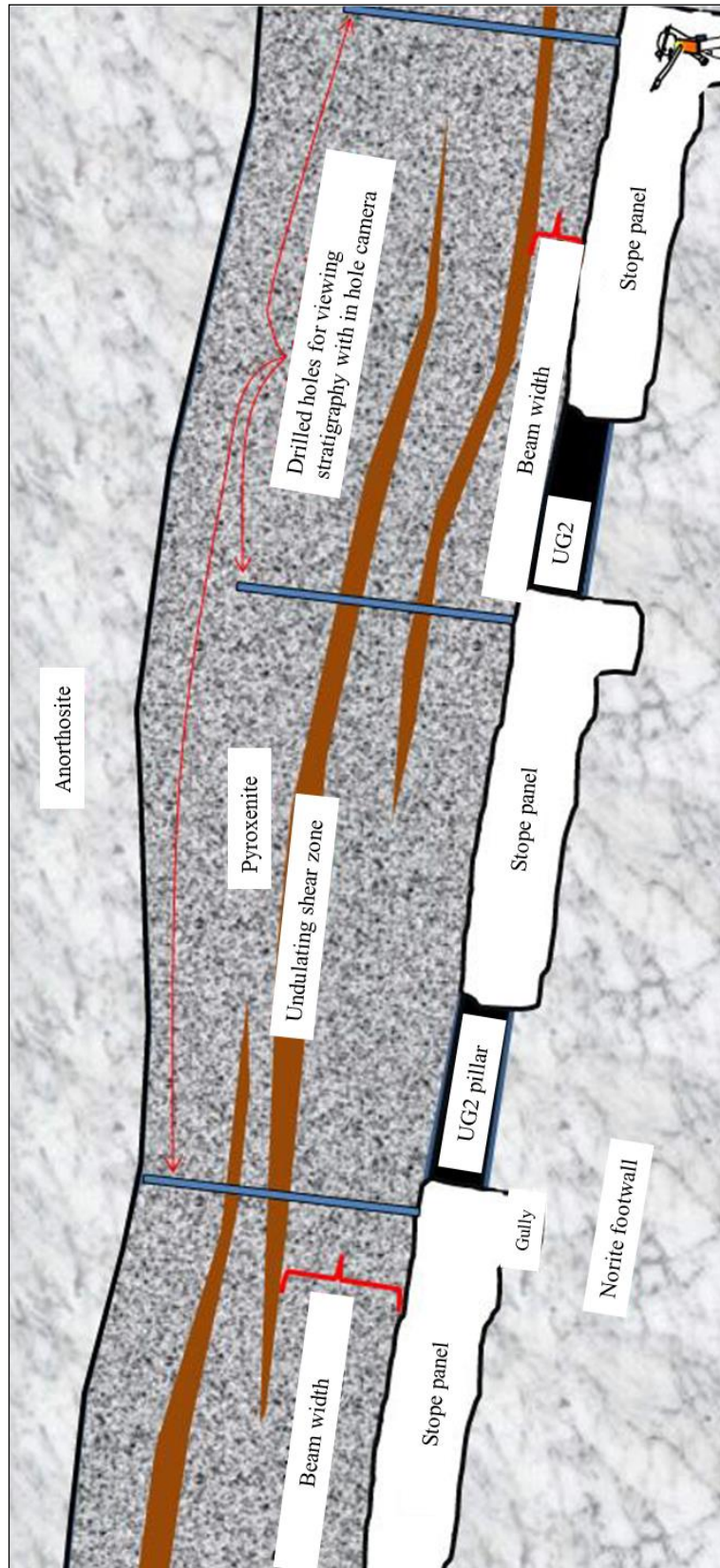
Figure 2.34: An illustration of the undulating nature of the hangingwall alteration zone and its potential effect on stope hangingwall beam stability as well as the in-stope support. The alteration zone may be more continuous as suggested by the picture (Lombard, 2018).

2.4.4. The Great Dyke

More O'Ferrall and Du Plessis (2017) did an investigation at Bimha Mine. At this mine, instability was associated with a weak layer that was present within the pillars or located in the pillar foundation. The stability of underground workings was compromised due to the deterioration in ground conditions associated with this major shear structure (Mutambara shear). This shear zone transgresses through half the mine area. More than 50% of the mine's footprint was compromised.

At this site, mechanised mining was conducted in a room and pillar layout. The mining height was approximately 2.25 m and pillar dimensions varied according to ground class. A large number of joint sets and possible shear zone configurations existed. The nature of the problem was therefore extremely complex. Regional and local stability was provided by non-yield pillars which support the load up to surface. In the shallow part of the operation, footwall heave and unravelling of blocks along joints from the pillar walls was observed (Figure 2.35).

Figure 2.35: Unravelling caused by joint planes in the pillar (More O'Ferrall and Du Plessis, 2017).

In the deeper section of the mine, the Mutambara shear (a few mm to 50 mm thick) was exposed along the hangingwall or within the pillars. Where exposed in the pillars, slabbing of the pillar walls, both above and below this shear layer, (Figure 2.36) occurred. The challenge was that this shear zone was not always identified in the borehole core logging. Additional logging of some boreholes indicated that the shear zone

was present in some of the boreholes, although not initially captured as such (More O'Ferrall and Du Plessis, 2017).

Muaka *et al.* (2017) described that large footwall heave occurred where the shear zone was located in the footwall. If the shear zone was located in the hangingwall, large falls of ground occurred. In the case where the shear zone was located within the pillar, tensile fracturing, bulging of pillar walls and large pillar lateral displacements were observed.

Figure 2.36: The mylonitic shear layer (Mutambara shear) within a pillar at Bimha Mine (More O'Ferrall and Du Plessis, 2017).

Three years after the initial observations were made, major instability was observed in the deeper section of the mine. Here the shear layer was located in the footwall of the pillars and this increased the occurrence of footwall heave. Pillar unravelling also occurred. Rehabilitation of the pillars was attempted with the installation of rock bolts and applying wire mesh and lacing to confine the pillars. This was not successful. It was also attempted to compartmentalize the instability by increasing the pillar sizes on strike and down-dip of the instability. Production was eventually stopped when surface subsidence occurred as a result of large-scale pillar failure. A new decline shaft had to be developed after this, in order to gain access to the remaining ore reserve. Substantial pillars were left to isolate the collapsed area (More O'Ferrall and Du Plessis, 2017).

A discrete fracture network (DFN) approach was utilised to investigate structural data from a mapping exercise conducted at the mine (Muaka *et al.,* 2017). The built-in DFN generator in the numerical software

program 3DEC was used to generate stochastically 3D DFNs from which 2D sections were cut and imported into the 2D program, UDEC. Owing to time constraints, only two DFNs (DFN 1 and DFN 2) were examined and were selected such that DFN 1 incorporated a low-angle random joint set. Four shear zone configurations were examined for each DFN including, shear in the footwall, in the hangingwall, in the orebody and a case without a shear structure (Figure 2.37).
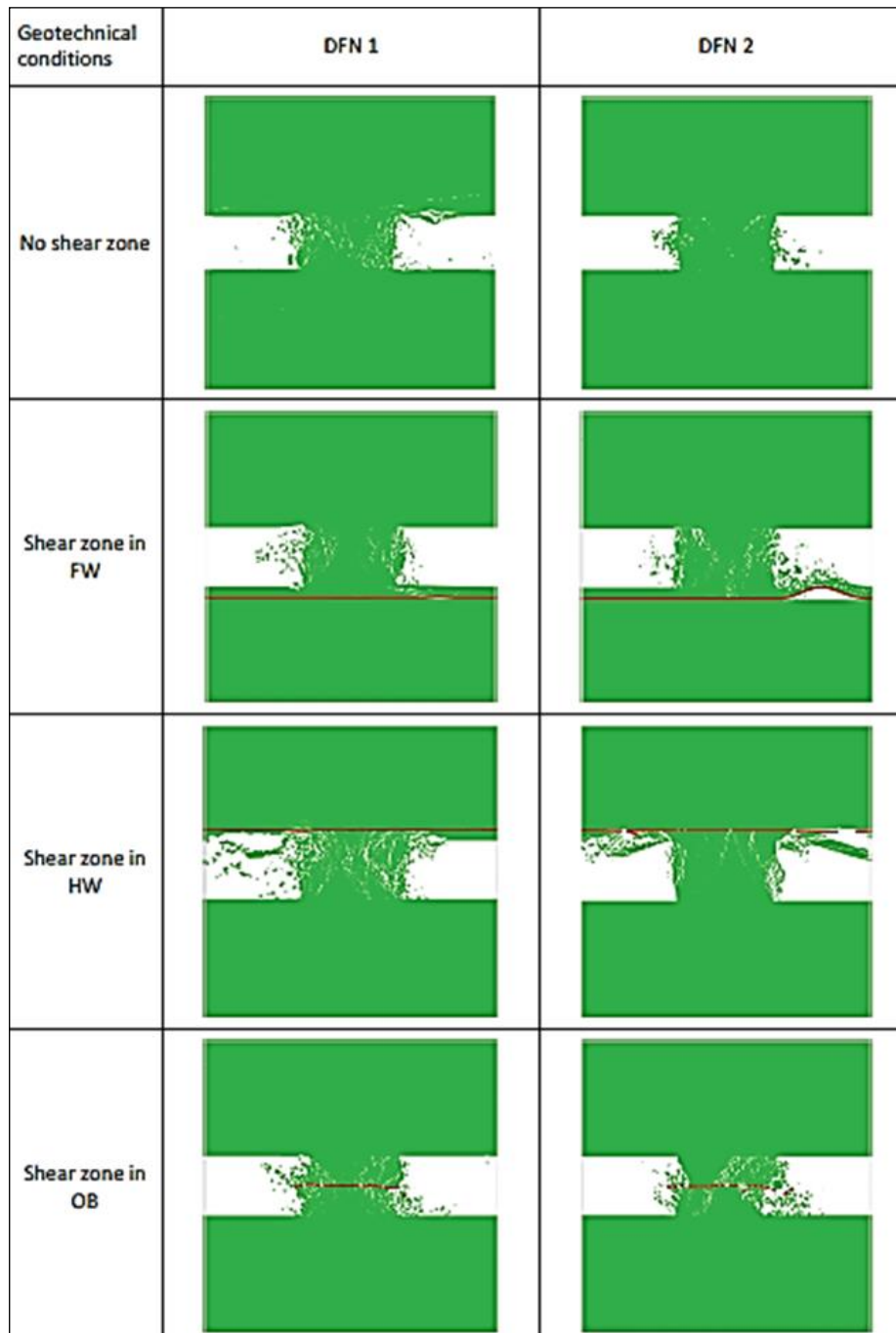
Figure 2.37: Simulated failure mechanisms in the pillars at Bimha Mine (after Muaka *et al.,* 2017) No shear zone, shear zone in the hangingwall (HW), footwall (FW) and within the reef (OB).

The modelling presented by Muaka *et al.,* (2017) was preliminary and the results therefore need to be verified. It seems as if most of the pillar failure mechanisms could be simulated. The approach may be useful to gain an improved understanding about the underlying failure mechanics.

2.4.5. Diamond Mine - North America

Although not directly related to the UG2 Reef problems described in this dissertation, the following example was included to illustrate that the problems caused by shear layers may be widespread in the mining industry. A study was done by More O'Ferrall and Du Plessis (2017) at a mechanised diamond mine in kimberlite sills. Owing to the unpredictable nature of the sills, a non-yield pillar design was investigated using a pillar width to height ratio and factor of safety (ratio of pillar strength to pillar load) analyses to determine the dimensions of the pillars. The planned mining height was 4 m and the drift spans 5 m. Figure 2.38 illustrates a typical fall of ground in the drift backs. The attention of technical staff controlling the local falls of ground and the pillar instability associated with the shear layer (Figures 2.39 and 2.40) went unnoticed.

Figure 2.38: Localised fall of ground (More O'Ferrall and Du Plessis, 2017).

Figure 2.39: Shear layer exposed in the underground workings.

Figure 2.40: Unravelling of the pillar wall below the shear layer (More O'Ferrall and Du Plessis, 2017).

The pro-active identification of the early signs of pillar instability, which included squeezing out of the kimberlite below the shear layer, slabbing of pillar walls and footwall heave was not conducted. Remedial actions were taken to limit the extent of instability. In most cases, the lack of identification, investigation and understanding of the failures which occur (small- or large-scale) will cause unpredictable or large-scale instabilities.

2.5.   Summary

This chapter discussed the geologic aspects and major instabilities of the Bushveld Complex and Great Dyke. The formation of the layered intrusions and geologic structures, associated behaviour and potential failure mechanisms were discussed as described in literature. Chapter 3 will discuss the site investigations conducted by the author to determine the impact of regional and secondary geologic structures on mine stability. Chapter 4 will focus on case studies conducted by the author on the impact of alteration zones in the pyroxenite layers of the UG2 Reef. The findings of this study will contribute towards an improved understanding of the mechanisms of failure and will lead to strategies to prevent the large-scale instabilities.

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THE IMPACT OF REGIONAL AND SECONDARY GEOLOGIC STRUCTURES ON MINE STABILITY

3. THE IMPACT OF REGIONAL AND SECONDARY GEOLOGIC STRUCTURES ON MINE STABILITY

Over the past 15 years, several large-scale collapses have been reported at various mining operations in the Bushveld Complex. Rowland, Saffy, Eastern Platinum Limited 2 and Hossy Shafts at Lonmin have experienced these instabilities. Perritt and Roberts (2007) explained that the layer-normal joints and WNW-ESE striking, regional, structures with pegmatite infill (Marikana structures), are orientated parallel to the strike of the layering, dipping towards the south. Flexural slip layer-parallel faults can be linked by lateral and frontal ramp structures (Figure 3.1). These structures are illustrated in three dimensions in Figure 3.2. Site investigations were conducted by the author of this dissertation in an attempt to understand the influence of these structures on the hangingwall stability at various mines across the Bushveld Complex. Of particular importance is the spatial distribution of these structures in three dimensions and how it impacts on the mining excavations. This study provides an improved understanding of the interaction and effect of these structures. This chapter describes the findings of the various case studies, the impact of the associated structures on mine stability as well as some key learnings and remedial strategies. This knowledge will assist with the early detection of specific rock mass conditions which may lead to unstable conditions. Suitable support and appropriate mining strategies may be used in these cases to reduce the risk of large-scale instabilities.
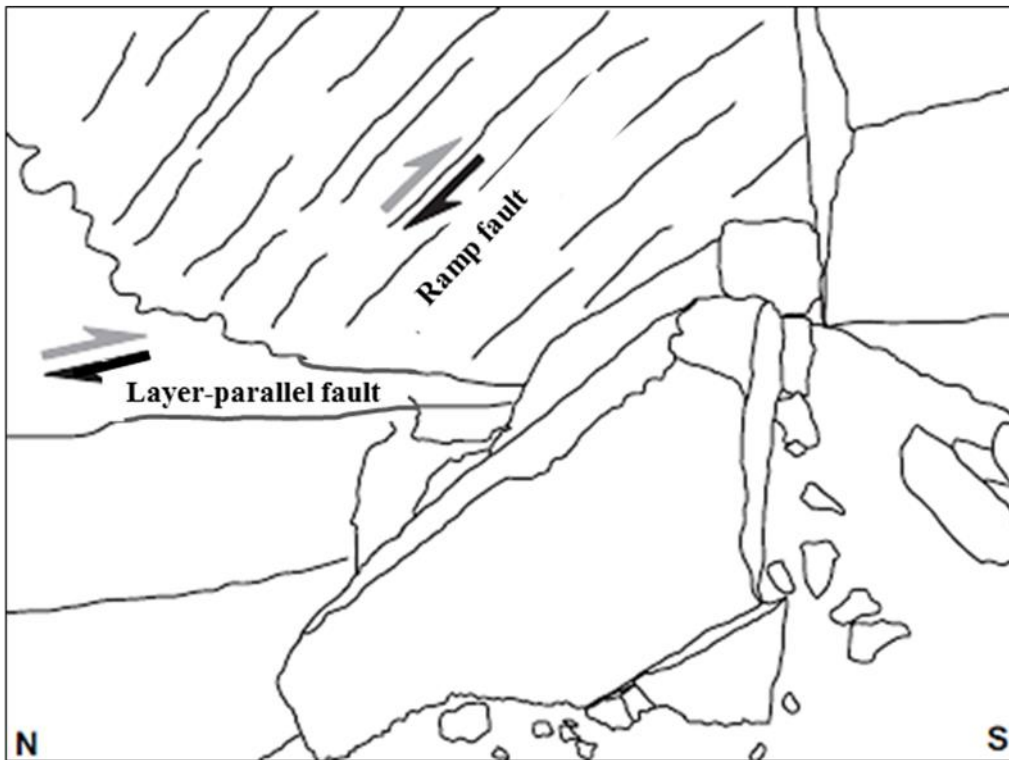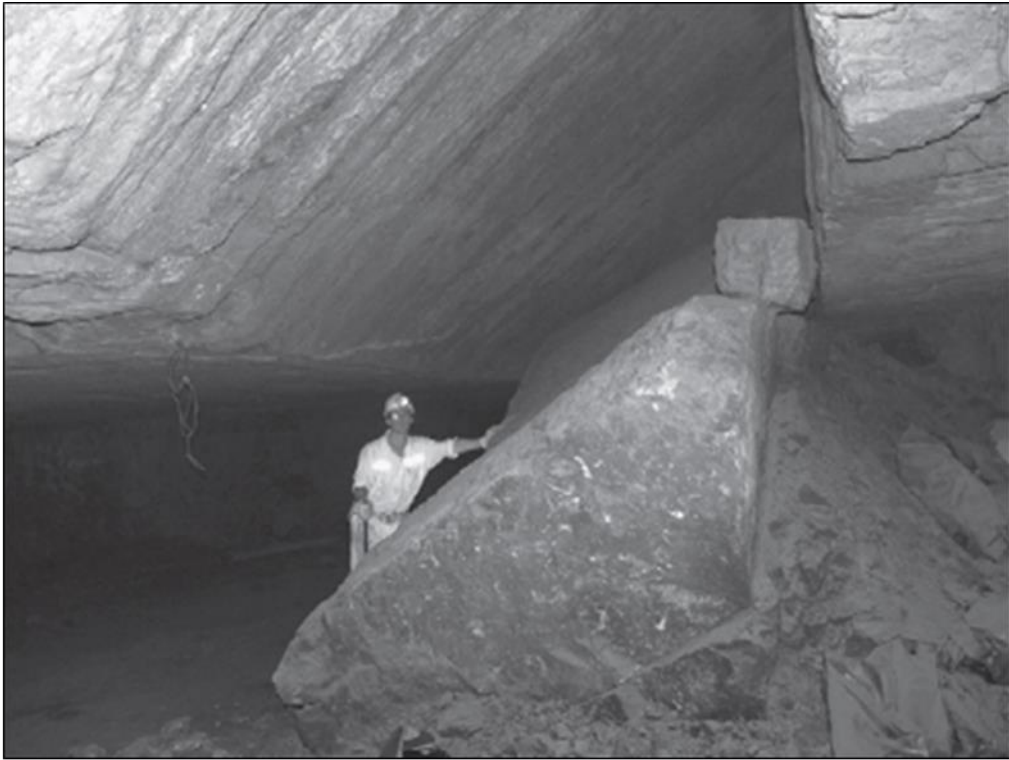
Figure 3.1: Photograph and interpretation of an underground exposure of layer-parallel faults and ramp faults (Perritt and Roberts, 2007).

3.1. Introduction

On many operations, mining layouts and support designs are inherited from best practices in industry or to accommodate a specific extraction method. In most cases, adverse ground conditions are not identified by mining personnel and the consequence of mining in these conditions is only realized once significant instabilities occur.

Figure 3.2 gives a three-dimensional representation of the major and associated secondary structures that contribute to large-scale instabilities on the UG2 Reef horizon. This diagram was compiled by the author from the knowledge presented in Chapter 2. Different cases have been reported where one of these structures or a combination of these have caused instabilities. As a first step, it was explored if seismicity contributed to the instabilities observed. Currently there is no seismic network at Lonmin. Figure 3.3 show the seismic events obtained from the Council of Geoscience (2018) that were plotted along the South-western Limb of the Bushveld Complex. This shallow mining environment, including the Lonmin Marikana Operations is known to be aseismic with no recorded events of mining induced seismicity. The plottings show that some of the seismic events can be traced along the NW- (purple and green lines) and WNW- (orange dotted lines and as per Figures 2.10 and 2.11) striking geologic structures, parallel to the Wegener Stress Anomaly. As Madi and Zhao (2013) explained, neotectonic activity is characterized by reactivation of ancient faults, dykes and creation of new fractures. It could also play a role in the exploration of groundwater. Figure 3.4 was constructed to illustrate plan views of the regional and secondary structures that may contribute to rock mass instability. Figure 3.5 is a photograph of an UG2 site showing interlinking ramp structures exposed along the UG2 Reef.
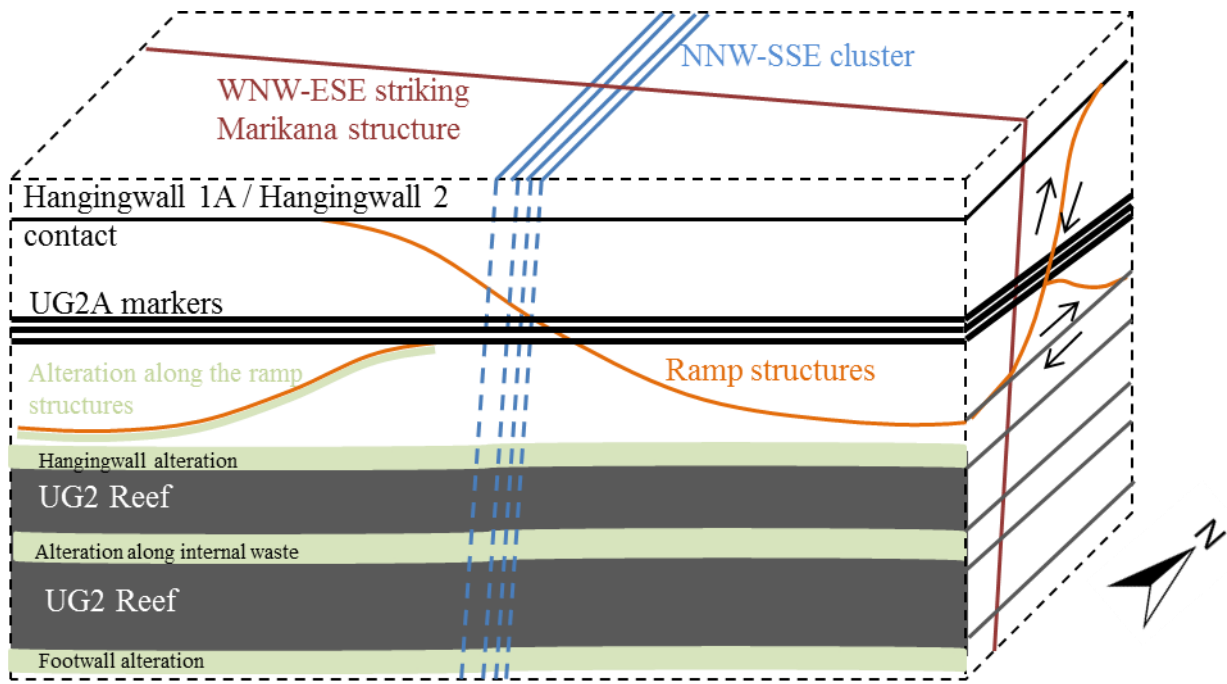
Figure 3.2: A three-dimensional representation of geologic structures that contribute to large-scale instabilities. The complex fabric of the hangingwall rock mass is evident in this figure.
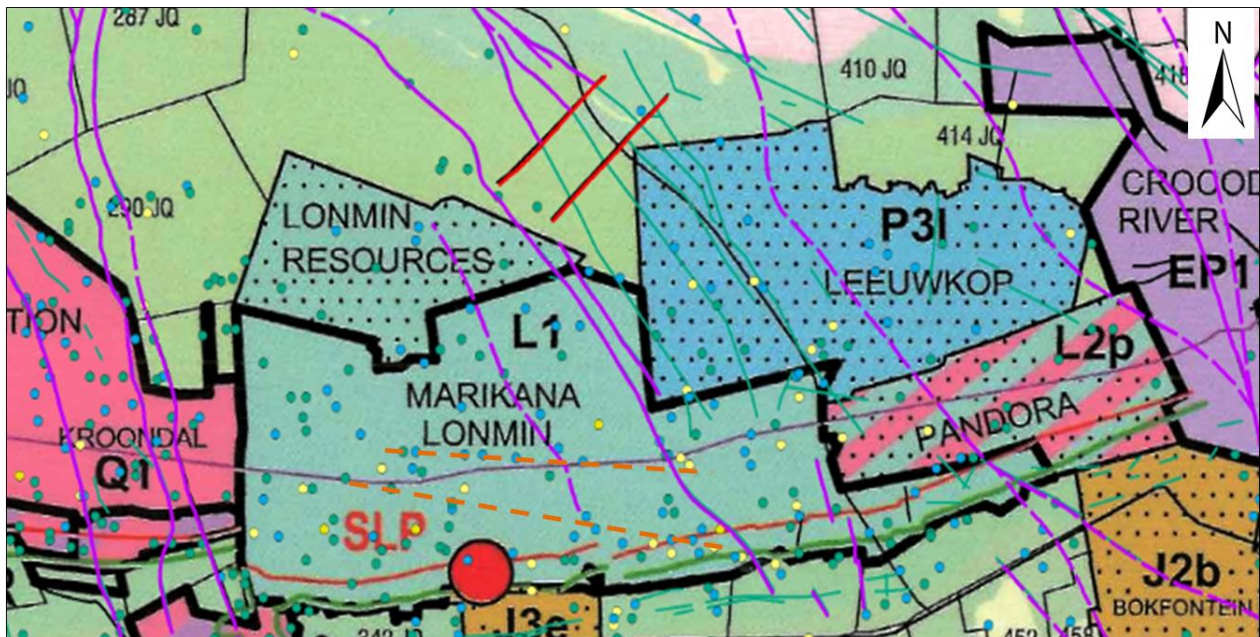
Southern Africa Seismic Events
Legend

● 0.1 – 0.99 ML	○ 2.5 – 2.99 ML	● 4.0 – 4.99 ML
● 1.0 – 1.49 ML	○ 2.5 – 2.99 Mb	● 5.0 – 5.99 ML
● 1.5 – 1.99 Mb	● 3.0 – 3.49 ML	● 6.0 – 7.2 ML
● 2.0 – 2.49 ML	● 3.0 – 3.49 Mb	● 6.0 – 7.2 Mb
● 2.0 – 2.49 Mb	● 3.5 – 3.99 ML	

Figure 3.3: Seismicity recorded along the South-western Limb of the Bushveld Complex (Council of Geoscience, 2018). Some of the plotted events occur along the NW- (purple and green lines) and WNW- (orange dotted lines) trending geologic structures, indicating reactivation of these structures trending parallel to the Wegener Stress Anomaly.
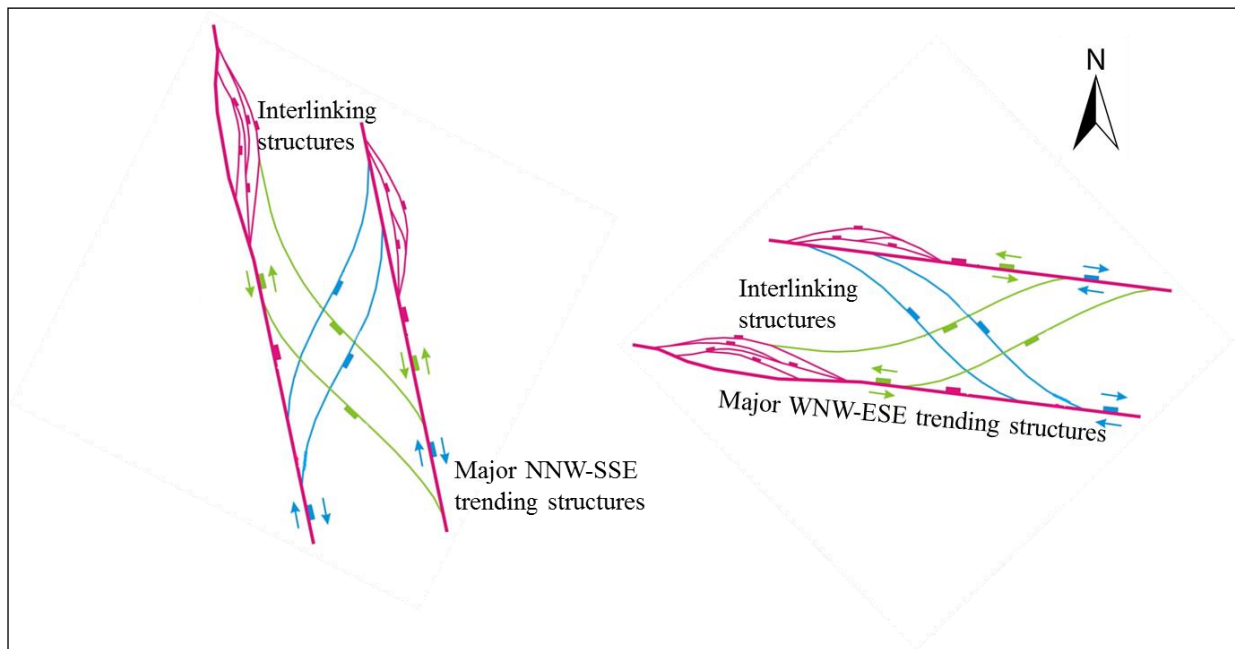
Figure 3.4: Plan views based on underground observations (Figure 3.5) by the author and Friese (2017). It shows the major and secondary structures typically associated with large-scale instabilities. The NNW-SSE trending structures run parallel to the basement structures (Figure 2.6). The WNW-ESE striking structures run parallel to the lineaments (Figure 2.10). Interlinking secondary structures formed between the major structures.

Figure 3.5: Interlinking ramp structures exposed along the UG2 Reef in a development end.

Detailed site investigations were conducted by the author at Rowland, Saffy, Eastern Platinum Limited 2 and Hossy Shafts where large-scale instabilities were recorded. The mining layouts consist of breast and dip panels with 27 – 30 m inter-pillar spans. The panel spans have been designed based on the expected behaviour of the hangingwall layers. A non-yield pillar layout is used on the stoping horizon (pillar widths vary with depth and is designed to support to surface). The hangingwall beam thickness is defined as the vertical distance between the top reef contact and the top contact of the UG2A markers (Figure 1.3), which is a known potential unstable parting plane. To provide sufficient support resistance for this beam of approximately 7 – 10 m, alternating rows of timber elongates and grout packs (or grout packs only at reduced spacing) are used as the primary in-stope support system. The role of the in-stope support system at Lonmin is to maintain stability of the hangingwall 1B pyroxenite, including the UG2A markers.

The installed support elements must meet the following requirements:

- Rock bolt support should cater for the typical fallout thickness (1.2 m). Additional support consisting of timber elongates and grout packs are also installed. The continuous hazard identification and risk assessment process should be applied by the underground mining personnel to minimize the risk of falls of ground.
- The design of the pre-stressed timber elongates must consider the tensile height resulting from the mining span, as well as to the height of the UG2A markers. Practical experience has shown however, that the height of fallout will be dictated by prominent parting planes.
  - The tensile zone is the region above a stope where the vertical stress is tensile in nature and conducive to parting separation and hangingwall instability. This is prominent in shallow and intermediate mining depths. The in-stope support should cater for this estimated height if it has a larger influence than that of the highest known parting plane.
- Grout packs must cater for the height of the UG2A markers (on shafts where only grout packs are installed). It should also prevent possible back breaks as a result of parting at the hangingwall 1A/hangingwall 2. The mining depth generally ranges between 200 – 1000 mbs.

Anomalous conditions were identified at the various investigation sites and these included:
- Unstable beam behaviour with separation occurring along prominent geologic structures.
- Buckling of the timber elongates.
- Crushing of cementitious grout packs.
- Slabbing occurring on the sidewalls of the in-stope pillars.

3.2. Site Investigations

Sites were identified at Lonmin where large-scale instabilities were recorded. The sites are structurally complex, where major dykes, faults and secondary geologic structures dissect the ore body. An assessment

of the general mining layout, support and geologic environment was conducted in the panels. The recorded conditions were also compared by the author to similar studies on adjacent operations.

Similarities exist between the sites that will be discussed in this chapter. Similar remedial strategies might therefore be appropriate. These strategies will be expanded on and will be referred to at other sites where applicable.

3.2.1.   Rowland Shaft

Rowland Shaft uses a conventional mining method within an up-dip and down-dip split panel configuration (half a panel is mined on both sides of the development end) at a stoping width of approximately 1.2 m. A large collapse (approximately 14 000 tonnes) occurred at 16 West Level (Figure 3.6) where a WNW-ESE striking, reverse fault and associated secondary structures were exposed.
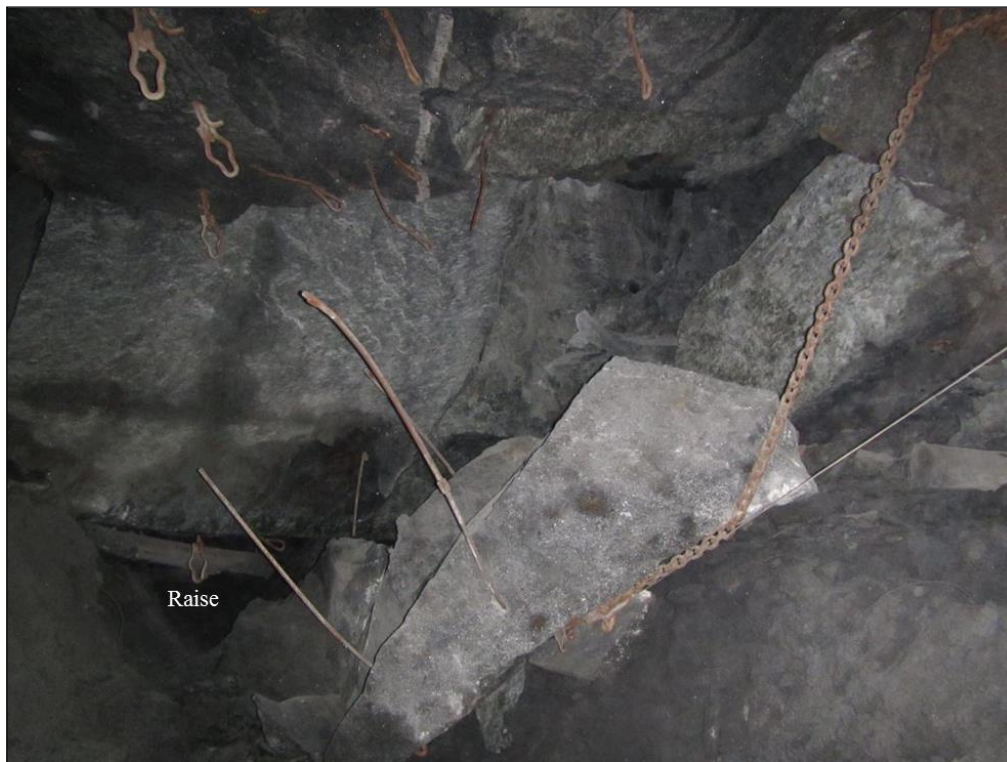
Figure 3.6: Fall of ground at 16 West Level, Rowland Shaft. Only approximately 0.5 m of the footwall raise is visible after the fall of ground occurred. The surface of the WNW-ESE trending down-dip boundary of the fall of ground is visible in the photograph.

The plan view in Figure 3.7 and section view in Figure 3.8 show the geologic structures that contributed to the collapse. These structures coincide with the structures shown in Figures 3.1, 3.2 and 3.4. A network of ramp structures dipping north and problematic WNW-ESE striking joints that dip towards the south

(Marikana structures) have been identified at this site. Instability was initiated where the low-angle structures ramped to the hangingwall 1A/hangingwall 2 contact. Only timber elongates and rock bolts were installed in this area. The instability resulted in timber elongates buckling due to excessive deadweight loading and others riding out due to wedge rotation (Figure 3.9). This collapse triggered the unravelling of the affected area. There is no history of similar collapses on Rowland Shaft. This area is mining in close vicinity to a major, low-angle reverse fault zone and a pothole was exposed up-dip of the site. The buckling of timber elongates and then the installed closure logger that triggered, indicated hangingwall instability. The pro-active decision making from the Mining and Rock Engineering personnel prevented injuries by removing the crews from this working place 4 hours prior to the collapse. Figure 3.7 illustrates that the instability occurred as the panel advanced for a distance of twice the panel span.
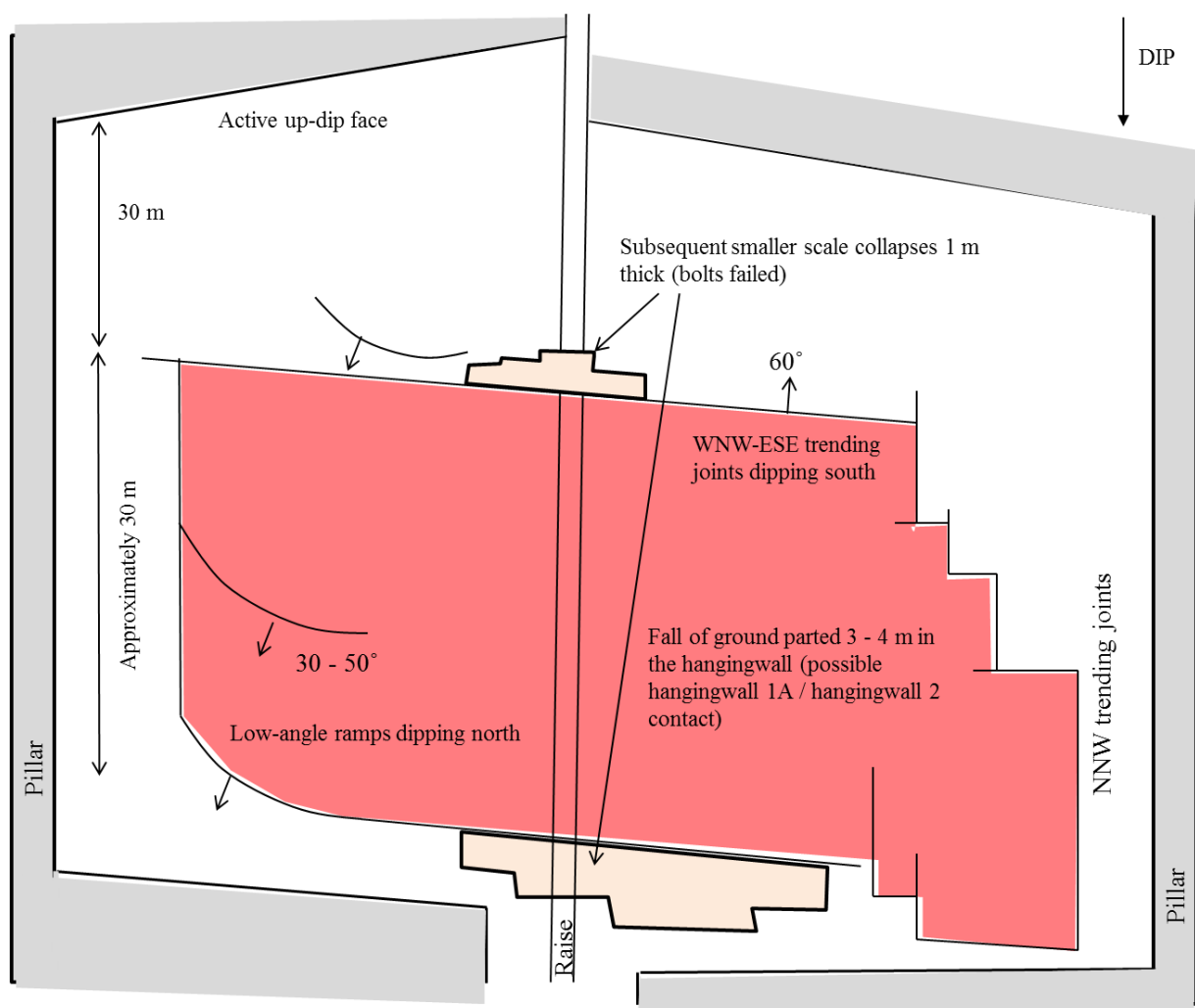
Figure 3.7: Plan view of geologic structures identified at the fall of ground site. The red hatching indicates the initial collapsed area and the orange show the subsequent unravelling. This panel has advanced approximately twice the panel span.

Figure 3.10 illustrates the most favourable dip mining layout and mining direction when intersecting the Marikana structures. In Figure 3.10, the structure cross-cuts the mining direction obliquely. Only a portion of the structure is exposed at a time (after each blast). The structure and associated behaviour can therefore be controlled by the timeous installation of the appropriate support. The span will only reach its maximum once the structure is fully exposed. Figure 3.10 shows that when only a half panel is mined at a time, the overall mining span is limited (controlled by leading and lagging panels). For a split-dip mining configuration, down-dip mining is more stable. The panel is mined from the stable side; the western face must lead to only expose half of the 'potentially' unstable structure. The eastern face supports the structure (unmined area). The support along the western panel must be installed in time before the lagging eastern panel face exposes the entire structure. Du Plessis (2009) suggested that by limiting the inter-pillar span to 27 m, the potentially unstable beam should not experience any deflection. The installed support units should therefore not be compromised and overall hangingwall stability should improve.
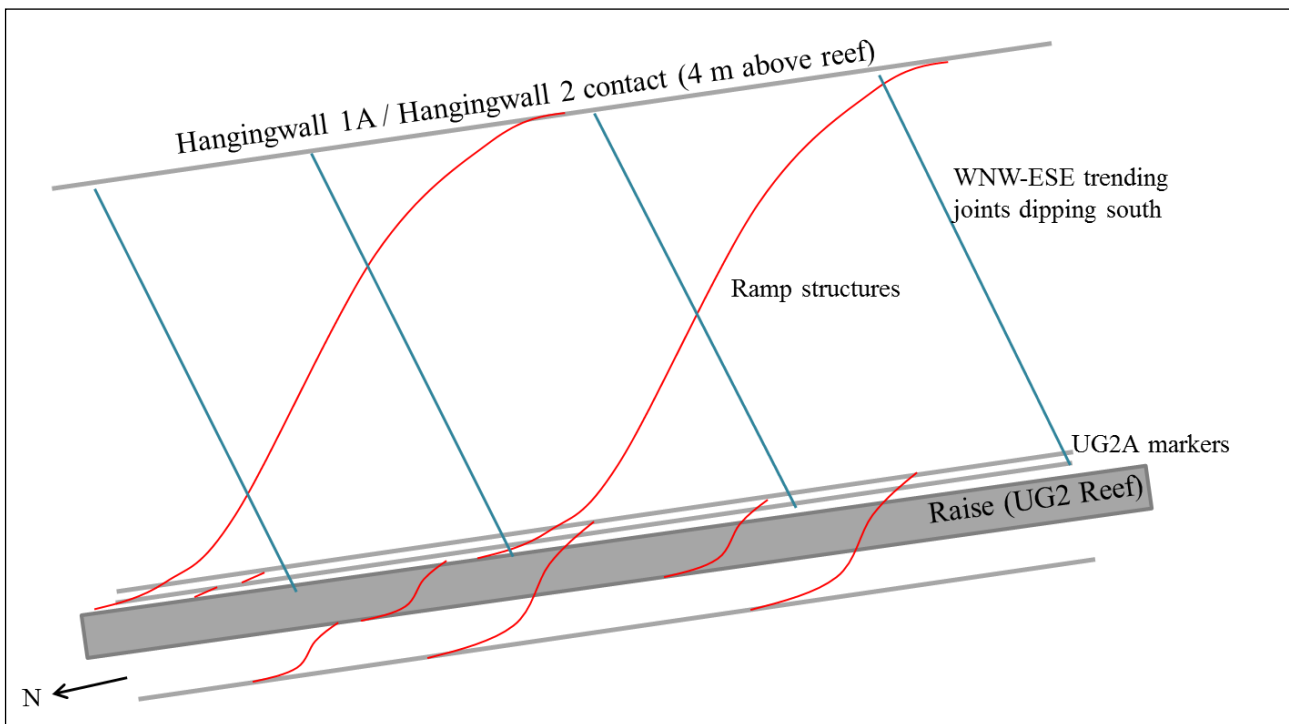
Figure 3.8: Section view of geologic structures, Marikana structures and interlinking ramp structures, identified at the fall of ground site.
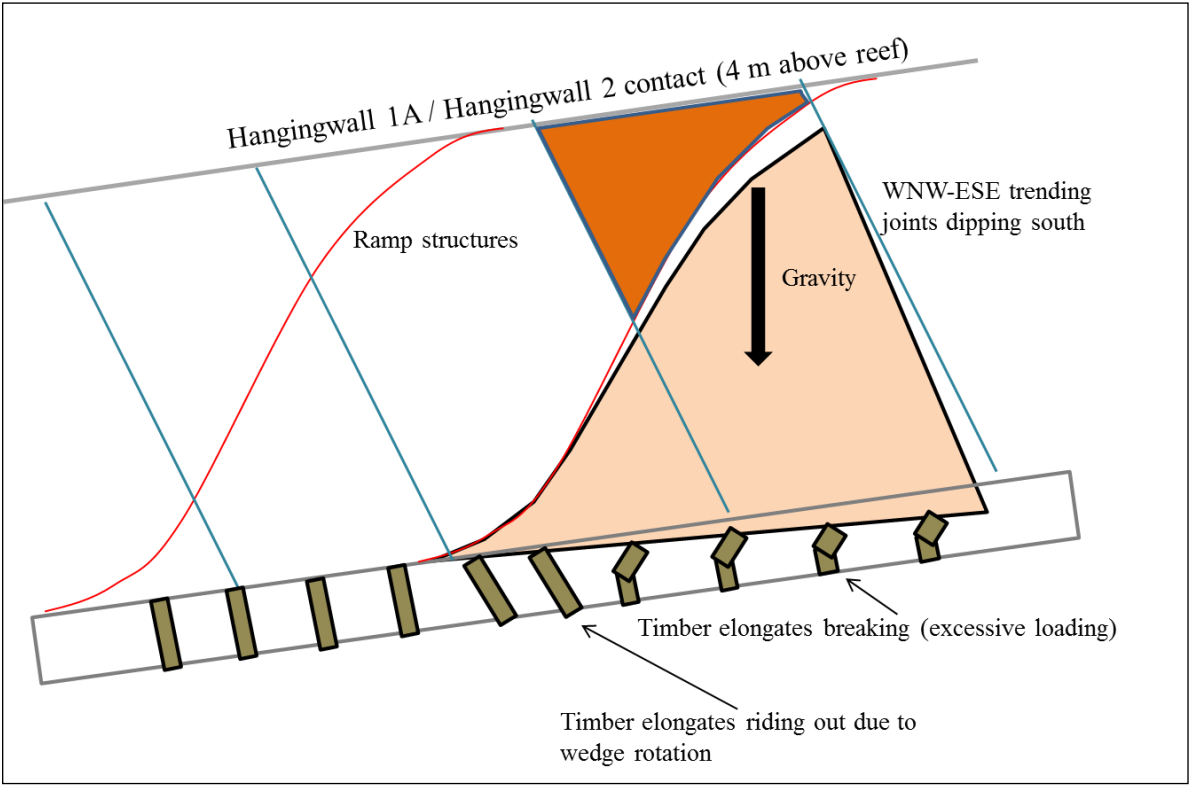
Figure 3.9: Section view illustrating the failure mechanism which resulted in the instability and subsequent collapse.

Dip mining configuration

Plan view

Mining down-dip with the western face leading

Panel span

Solid | Solid

Unstable | Unstable

Stable | Stable

Mined out | Mined out

≈ 60°

Raise line

A | A

Regional structure

Dip (N)

Hangingwall beam representation: A - A

Unstable

Stable

B

B

Section view: B - B

Hangingwall 1A / Hangingwall 2 contact

Regional Structure ≈ 60°

UG2A markers

Stable | Unstable

Panel

Separation along regional structure

Figure 3.10: Recommended split down-dip mining configuration, with the western face leading to control the associated behaviour when intersecting the regional (Marikana) structures.

At some sites with similar geotechnical conditions, a breast mining configuration (Figure 3.11) is applied. These sites (Saffy, Hossy and Eastern Platinum Limited 2 Shafts) are discussed later in this chapter. Van Zyl (2011) did extensive joint mapping and joint modelling (using JBlock) to consider the impact of the structures on the mining layout and support strategies. In the case where a breast mining configuration is implemented, the low risk option is to mine in an eastern direction, limiting the inter-pillar span to 27 m. The mining face will incrementally increase the span as the Marikana structure is exposed. Only a portion of the structure is exposed after each blast. The structure and associated behaviour can therefore be controlled by the appropriate support. The span will only reach its maximum if the structure is fully exposed by the mining span. Stiff, active support is required to support to the height of the potentially unstable beam. If grout pack support is considered, the grout packs must be stiff and active in order to provide high early strength close to the face and prevent back breaks.
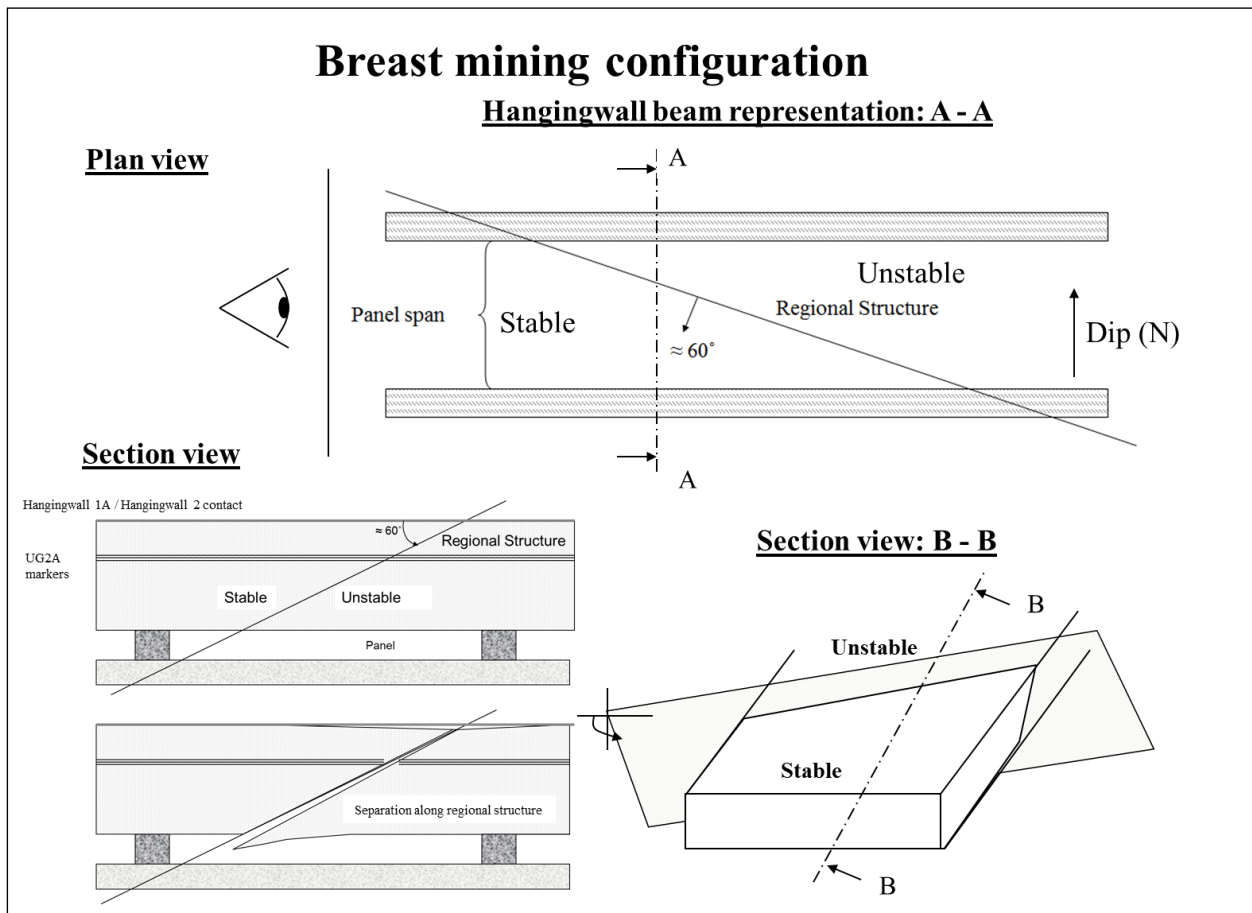
Figure 3.11: Recommended breast mining configuration, mining in an eastern direction to approach the regional (Marikana) structures from the stable side.

3.2.2. Saffy Shaft

Several panels were stopped at Saffy Shaft (red hatched areas in Figure 3.12) as a result of buckling of the timber elongates, crushing of grout packs, separation along joint planes and fracture of intact rock material along the hangingwall. No movement or loading of the pillars were observed at any of these sites. A breast panel configuration was used in these areas, mining predominantly towards the west with inter-pillar spans that ranged between 24 m and 35 m. The support configuration consisted of alternating rows of timber elongates (2 rows) and grout packs (1 row).
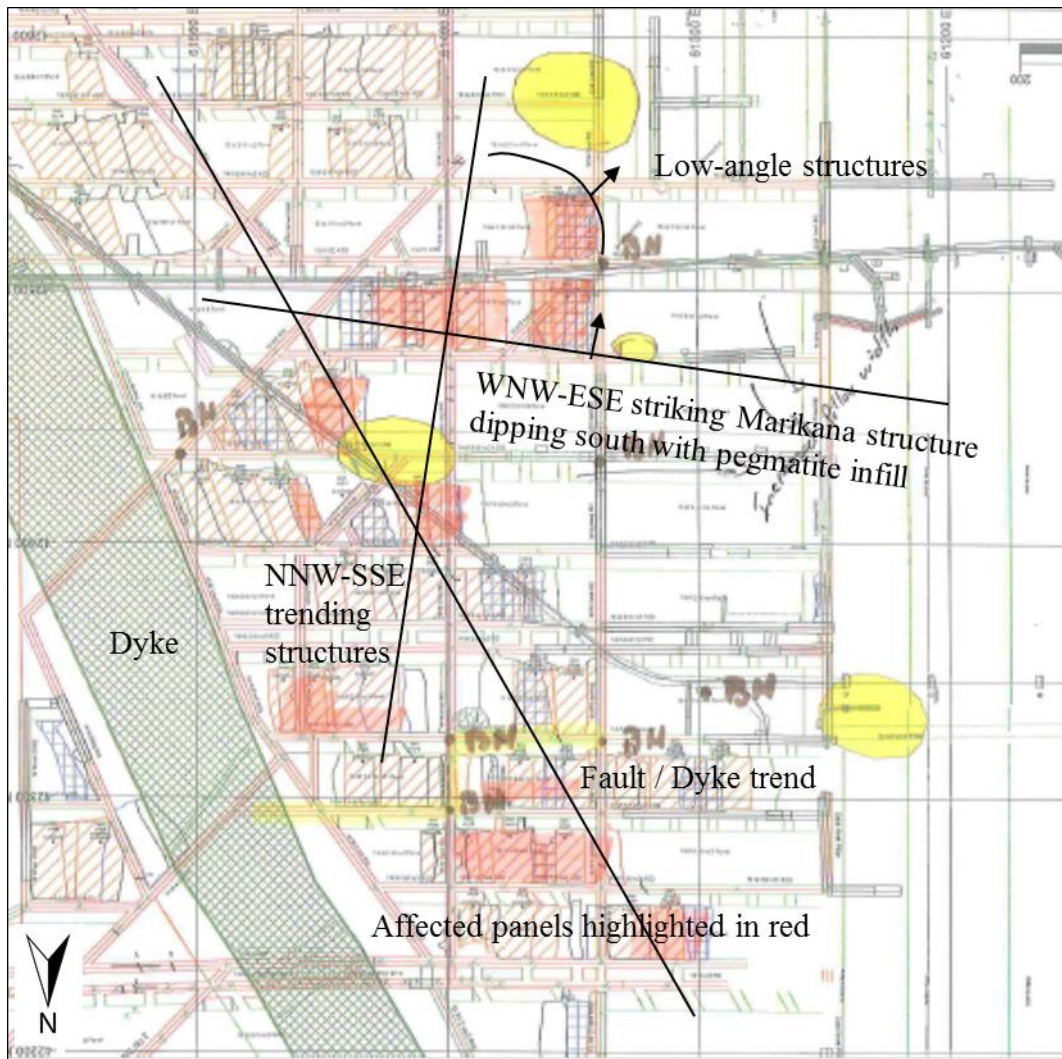
Figure 3.12: Plan indicating areas affected at Saffy Shaft (red hatched areas). Instabilities occurred in the red hatched areas and the panels were abandoned and barricaded off. The Pilansberg diabase dyke is indicated in green, striking NNW-SSE.

The investigation site was located between two NNW-SSE striking Pilanesberg diabase dykes (another dyke was situated approximately 300 m west from the dyke shown in Figure 3.12). The dykes by definition (Table 2.1) are younger in age and have intruded subsequent to the formation of the general strata.

The hangingwall beams are not continuous as a result of the dyke intrusions and the presence of regional structures. Figure 3.13 show the probable hangingwall behaviour through the interaction of dykes, jointing and ramp structures. The grout packs and timber elongates experienced excessive loading from the collapse of the beam (Figure 3.15).
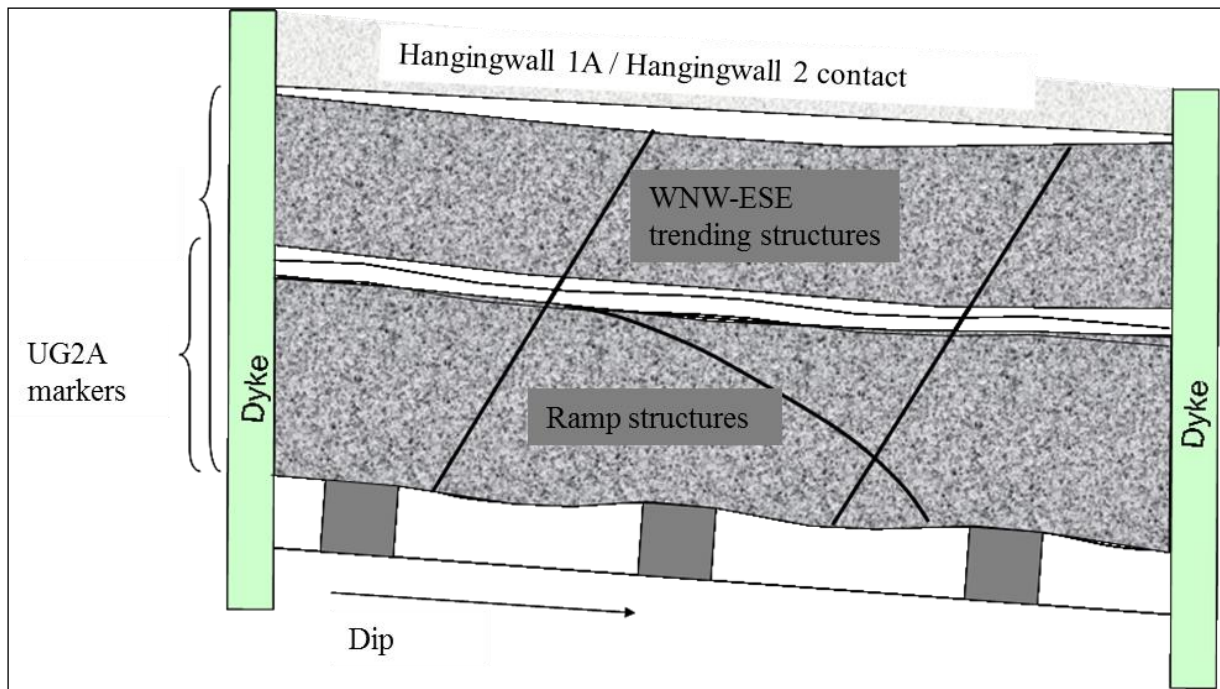
Figure 3.13: Hangingwall behaviour where it is cut off between the two dykes. It is hypothesised that this beam is in compression as discussed below. Major structures cause beam separation at the hangingwall 1A/hangingwall 2 contact, resulting in excessive support loading and failure in the panels.

Stress measurements have been conducted at the Marikana Operations, including Saffy Shaft. The measurements showed that the major principal stress across the Marikana Operations is approximately in a NNW-SSE direction (parallel to the Wegener Stress Anomaly and major fault structures across the property). However, an anomalous measurement in the vicinity of where the instabilities occurred at Saffy Shaft indicated that the major principal stress direction is approximately in a WNW-ESE direction (Figure 3.14). It was only after the instabilities shown in Figure 3.12 occurred that this measurement was considered as part of the investigation. It is hypothesised that the intrusions of the dykes increased the horizontal stresses (k-ratio of 1.8), resulting in hangingwall instability and support failure in the panels (Figures 3.13 and 3.15). The high horizontal stress may cause failure in the hangingwall in areas where flat dipping structures form a discontinuous beam.
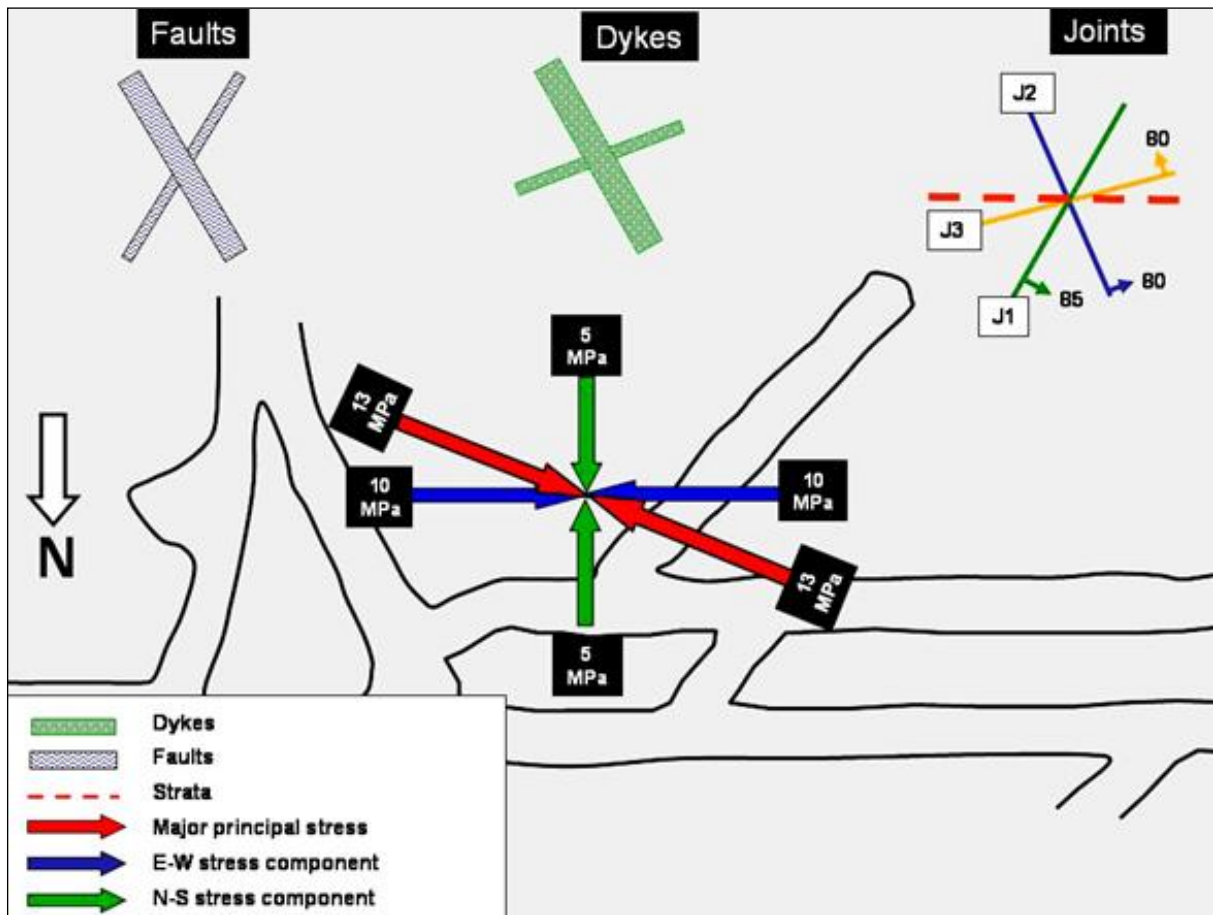
Figure 3.14: Stress magnitudes and orientations from a measurement at Saffy Shaft (Du Plessis, 2010). The measurement show high WNW-ESE stress in the vicinity of the dykes. It is assumed the magnitudes shown here is applicable to the area of instability in Figure 3.12.

Figure 3.15: Failure of grout packs and timber elongates owing to excessive loading from probable separation along the hangingwall 1A / hangingwall 2 contact.

From the investigations conducted by the author, it was concluded that the structures that contribute to the large-scale instabilities at Saffy Shaft include ramp structures, WNW-ESE striking and E-W striking faults as well as NNW-SSE striking faults. The understanding of the formation of these structures will assist in the pro-active identification of these risk areas to prevent the occurrence of the large-scale collapses.

E-W striking, flat north and south dipping ramp structures (Figure 3.16) are seen to splay from the major structures (Figure 3.4). These structures also contribute to the instabilities experienced. Two deformation events have been identified which are believed to be associated with the formation of the ramp structures. Deformation event 1 is characterised by layer-parallel, south-directed at Lonmin, outward flexural-slip thrusting from the centre of the Bushveld Complex along prominent lithological contacts during the cooling phase. Deformation event 2 refers to regional extension across the area of the Bushveld Complex towards the centre of the Bushveld Complex (north-directed at Lonmin).
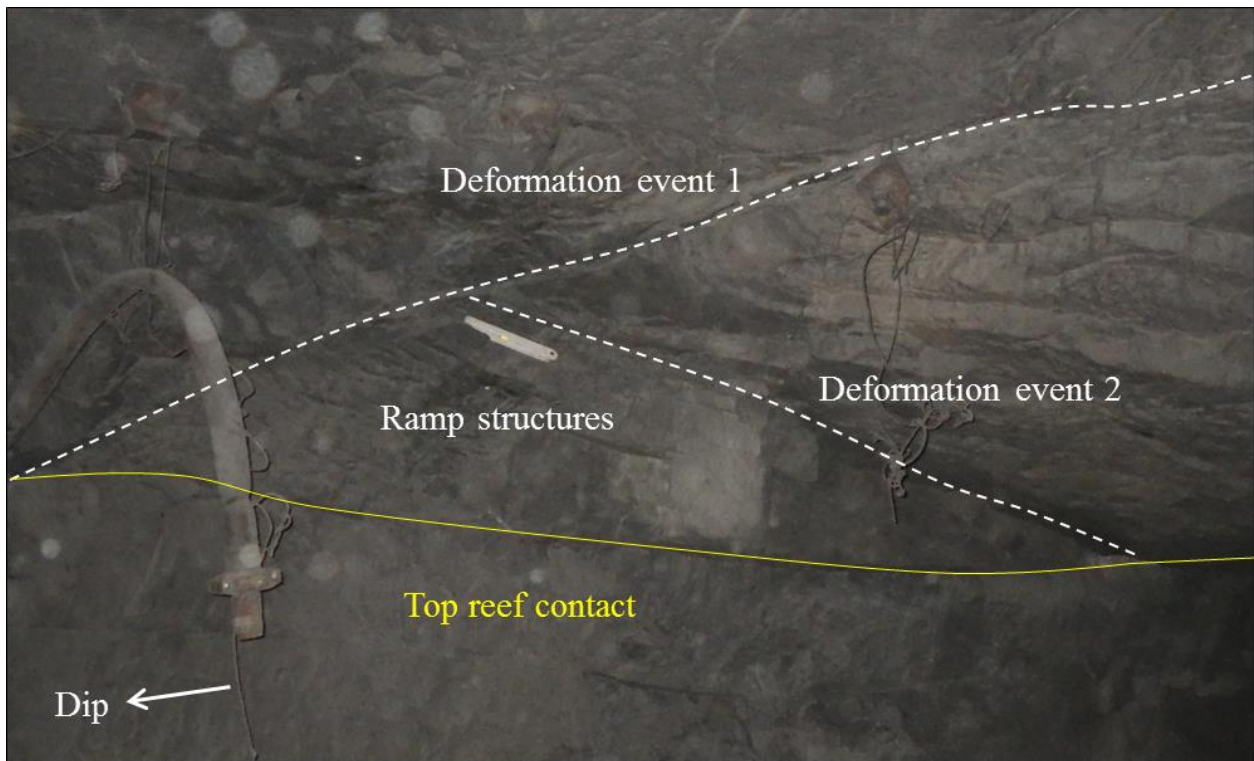
Figure 3.16: Ramp structures (Deformation events 1 and 2) splaying along the top reef contact into the hangingwall. These structures typically 'ramp up' to the next potentially weakness plane (UG2A markers or the hangingwall 1A/hangingwall 2 contact).

At the intersection of NNW-SSE clusters (Figure 3.17) and WNW-ESE or E-W striking geologic structures (Figure 3.18), structural wedges form. This results in poor hangingwall conditions and potential falls of ground. The fallout height of the falls of ground depends on where both structure sets intersect one another above the UG2 top reef contact. The wedges that formed grow in size where ramp structures (Figure 3.16) intersect the layer-parallel structures developed along the UG2A markers. At Hossy and Saffy Shafts these can be situated 7 – 10 m above the top reef contact.

The NNW-SSE (Figure 3.17) and WNW-ESE (Figure 3.18) striking structures are oriented approximately parallel to σ_1 orientation of the neotectonic stress fields, in the north-eastern part of South Africa (Figure 2.12). These structures trend parallel to the Wegener Stress Anomaly, where neotectonic activity is characterized by reactivation of ancient faults, dykes and creation of new fractures. It could also play a role in the exploration of groundwater.
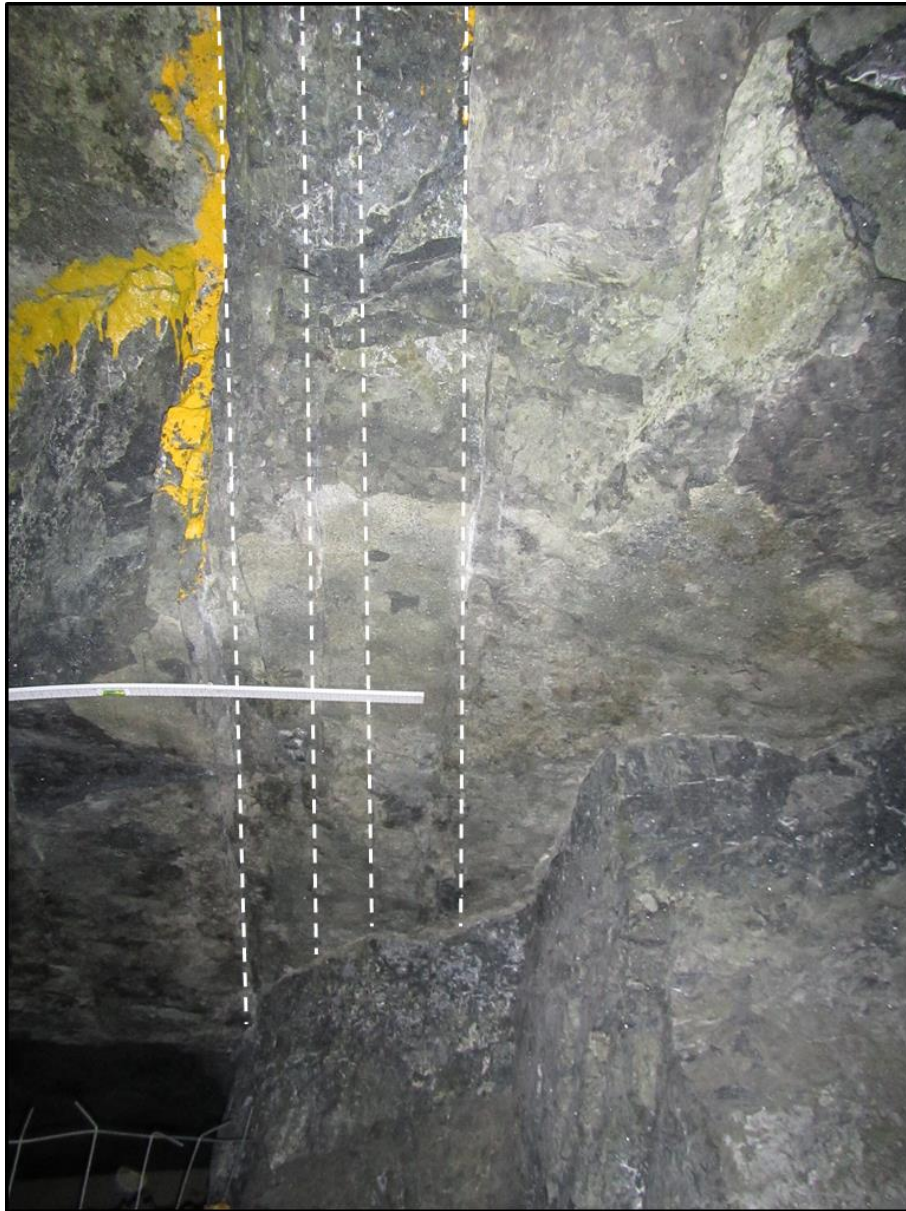
Figure 3.17: NNW-SSE striking cluster of joints exposed along the edge of a pillar that may contribute towards pillar slabbing.

Figure 3.18: E-W and WNW-ESE striking structures exposed in a panel.

Several remedial strategies have been implemented to stabilise the panels exposed to the conditions described above. These remedial strategies proposed by the author include:

- Denser timber elongates to support to the height of the UG2A markers.
- Replace the passive grout packs with the stiff; active new generation grout packs (Figures 3.19 and 3.20). More timber elongates (primary support) and high strength grout packs (secondary support) can be implemented or closely spaced high strength grout packs (as both primary and secondary, back area support) should be implemented. These new generation grout packs have fast curing time properties. These packs can therefore be installed closer to the face which will promote improved mining cycle times. These grout packs also have a pre-stress ability and provides high early strength which will increase the overall stability. Load data have been obtained from a MatlaMat (load cell) installed on two new generation grout packs, as shown in Figure 3.20. A pre-stress (approximately 40 tonnes) load was achieved by the packs through regular filling activity. The advantage of the system would be that, even if the hangingwall does unravel, as a result of separation along joint and faults, the packs will provide a secondary support function after a certain degree of compression and will stabilise the rock mass.
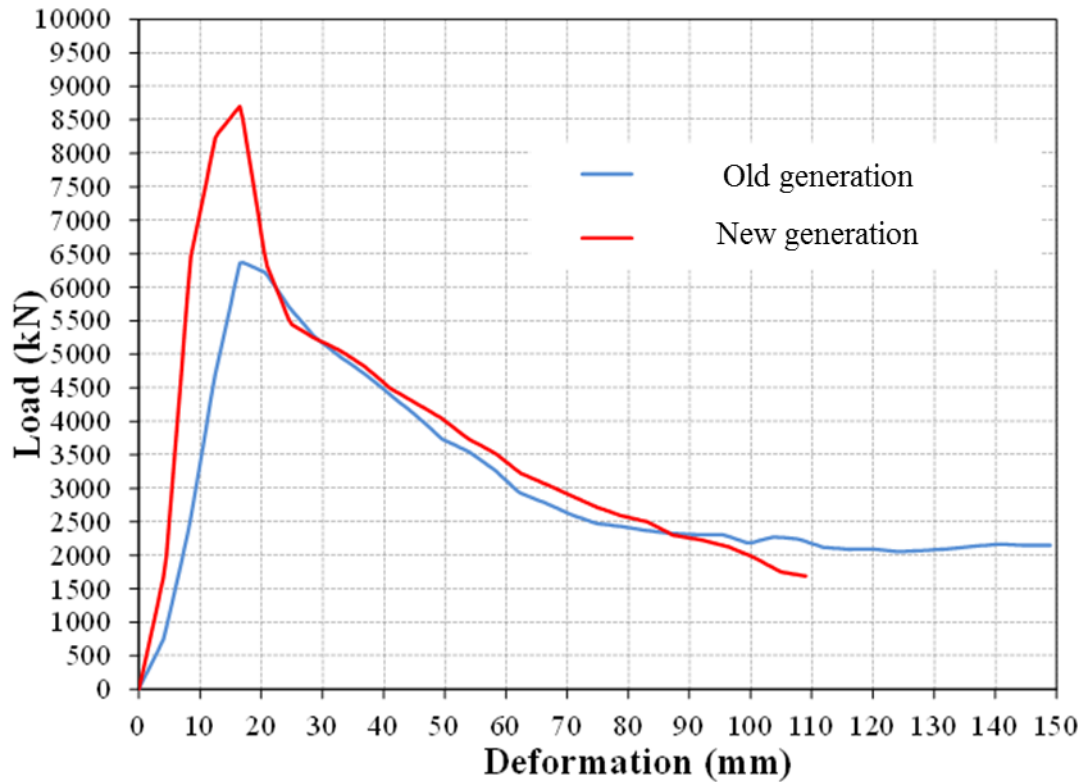
Figure 3.19: Load performance characteristics of the new generation grout pack versus the old generation grout pack filled with the same 16 MPa grout mix. Higher, early strength is obtained from the new generation grout pack. The new generation pack provided approximately 870 t and the old generation pack provided 600 t.

The instrumentation (MatlaMats) in Figure 3.20 results illustrates an increase in load after 50 – 60 m face advance. This confirmed observations made from case studies by the author on adjacent Lonmin Operations which indicated that back breaks typically occur where associated structures were intersected once the panel had advanced for approximately twice the panel span. This was confirmed at Rowland Shaft (Figure 3.7) as well as at Saffy and Eastern Platinum Limited 2 Shafts.
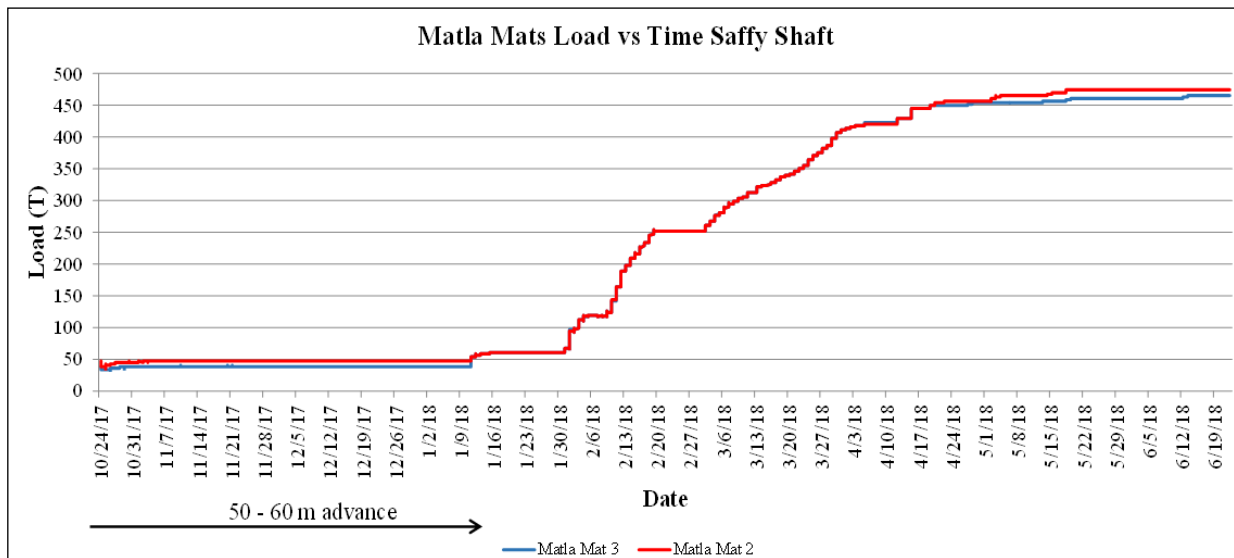
Figure 3.20: Load data obtained from a MatlaMat (load cell) installed on two new generation packs. Note the pre-load (approximately 40 tonnes) achieved by using the packs. The instrumented packs experienced an increase in load when the panel advanced approximately 50 m as a result of the surrounding hangingwall instability. The panel was only supported with old generation grout packs (no pre-load) on a 3 m square grid pattern (Liebenberg and Du Plessis, 2018).

Marikana structures were identified in this area (Figure 3.12). These structures dip towards the south and cut across the hangingwall layers. Consequently, the hangingwall beam is cut-off at the one end, creating a highly discontinuous hangingwall (Figure 3.11). The delineated blocks can detach from the potential parting planes (UG2A markers or hangingwall 1A/hangingwall 2 contact). The instability typically only occurs when the in-stope timber elongates show signs of buckling due to their loading capabilities being exceeded when a critical mining span is reached. In some instances, anomalous stress fracturing conditions are visible along the edges of the pillars.

In the case where a breast mining method is used and the Marikana structures are encountered, the best option is to mine in an eastern direction, limiting the inter-pillar span to 27 m (Figure 3.11). The mining face will incrementally increase the span as the Marikana structure is exposed at the advancing face position. As the structure obliquely cross-cuts the mining direction, only a portion of the structure is exposed at a time (after each blast). The structure and associated behaviour can therefore be controlled by the appropriate support. The span will only reach its maximum if the structure is fully exposed by the mining span.

The alternative strategy as shown in Figure 3.10 is to mine using a split down-dip configuration with the western face leading. Other orientations have shown to be problematic and result in instabilities (e.g. breast mining towards the west, up-dip mining and long panel down-dip).

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3.2.3. Eastern Platinum Limited 2 Shaft

Instabilities were reported at 10 Chrome West 33 and 34 Raise lines (Figure 3.21). Figure 3.22 shows the geologic structures exposed in the panel, including NNW-SSE striking, near-vertical joints and faults, WNW-ESE striking, low-angle joints and faults Marikana structures) as well as interlinking joints and faults which alternate in strike direction from E-W to NE-SW.

The anomalous conditions reported included unstable hangingwall behaviour with separation occurring along low-angle geologic structures, pillar slabbing experienced along the in-stope dip pillars (Figure 3.23) and buckling of the timber elongates (Figure 3.24).
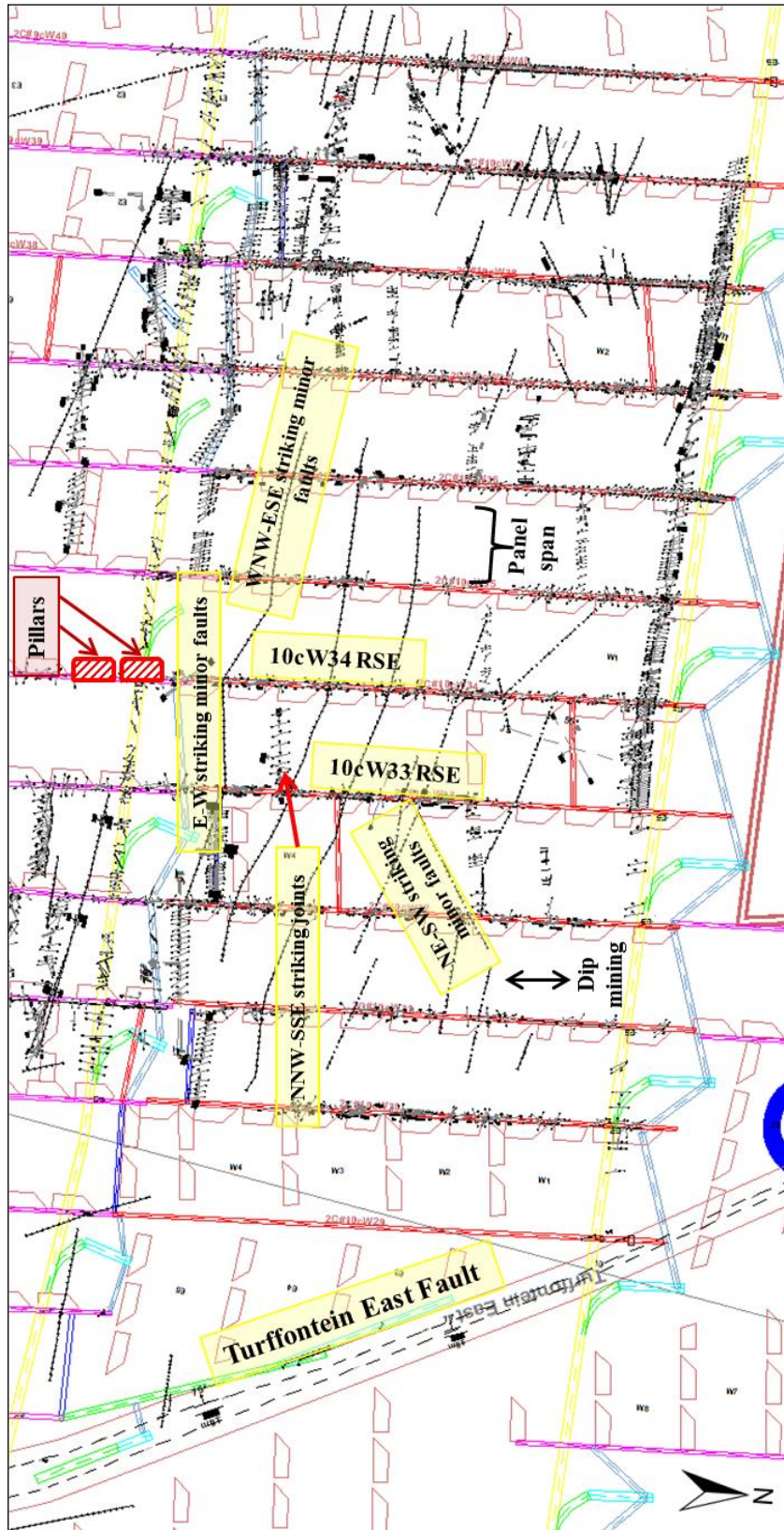
Figure 3.21: Mining layout and geologic structures at Eastern Platinum Limited 2 Shaft.

From the investigation conducted by the author, the slabbing of the non-yield pillars was found to be a result of both the joint orientation and an alteration zone present along the reef top and/or bottom contacts. Site 1 in Figure 3.22 shows the orientation of the NNW-SSE striking joints in relation to the dip pillars. The joints intersect the pillars at oblique angles (Figure 3.23). These slabs defined by the joint planes are mobilised where an alteration zone is present along the pillar top- or bottom contacts of the UG2 Reef. This results in the observed 'pillar slabbing' experienced.

Similar to the Saffy site where these Marikana structures are intersected, the hangingwall is of a discontinuous nature (Figure 3.24). A breast mining configuration (Figure 3.11) in an eastern direction or a split down-dip configuration with the western face leading (Figure 3.10) are the most suitable layouts and mining directions when the Marikana structures are exposed.
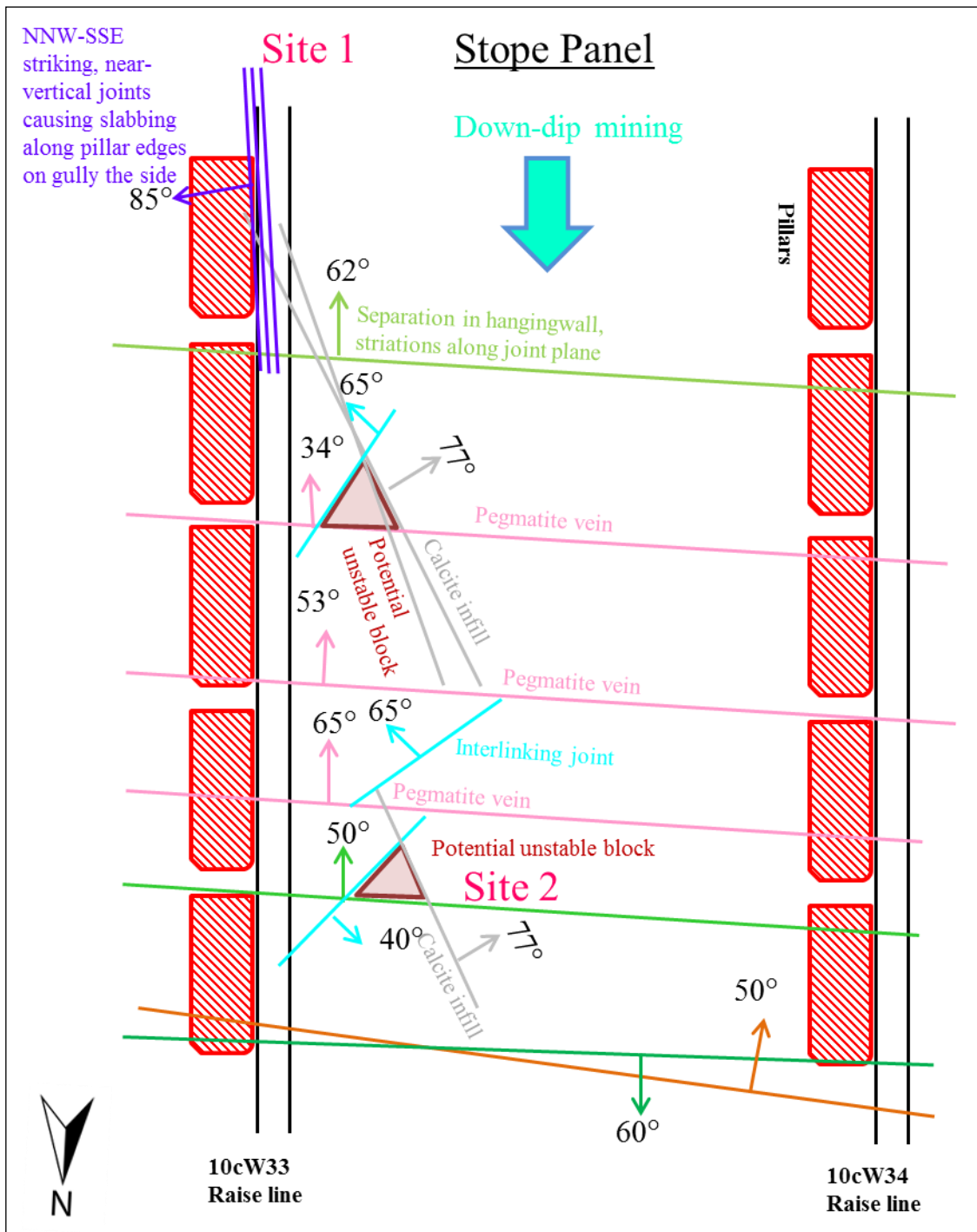
Figure 3.22: Geotechnical mapping of the down-dip panel at Eastern Platinum Limited 2 Shaft where two sites with anomalous rock mass conditions have been identified along 10 Chrome West 33 Raise line.
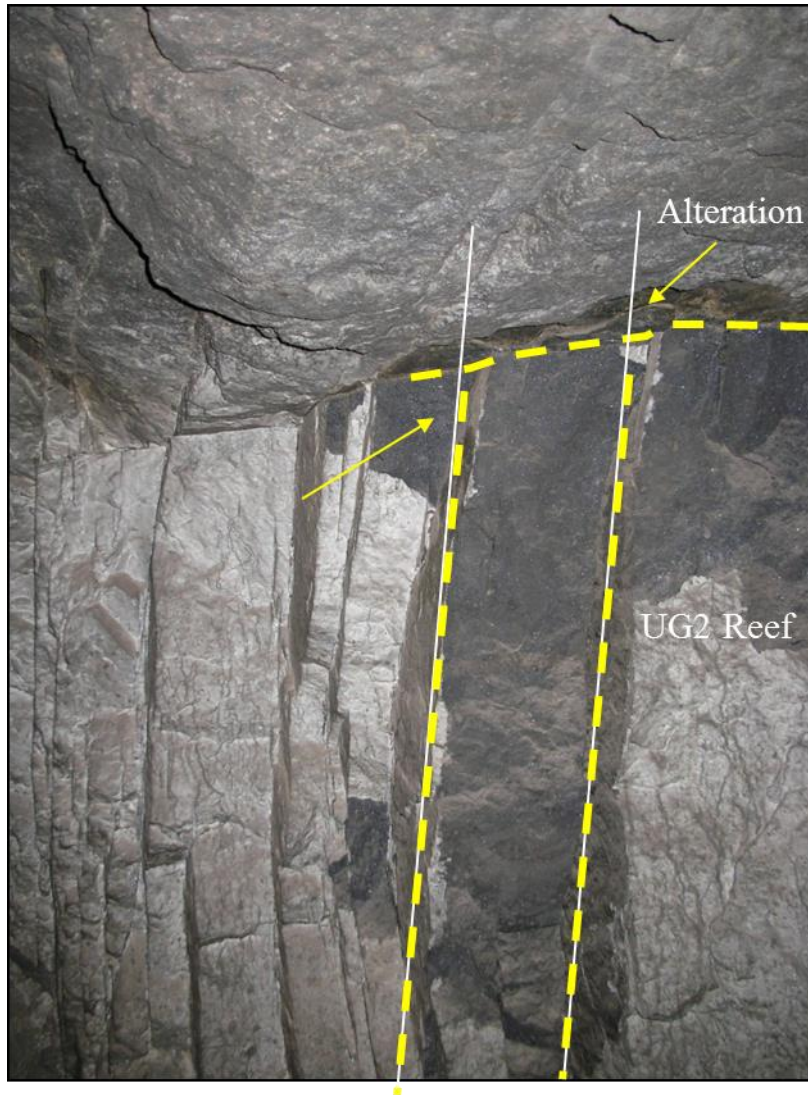
Figure 3.23: Slabs defined by joint planes at 10 Chrome West 33 Raise line. Joint planes intersecting pillars at oblique angles resulting in the observed slabbing of pillar material along joint planes.

At site 2 (Figure 3.22), timber elongate failure was observed (Figure 3.24) as a result of the intersection of a Marikana structure. The critical span seems to be reached when the panel has advanced for approximately twice the panel span (e.g. 60 m). The dislocated block causes overloading of the support units and ultimately support units fail. This behaviour results in large-scale back breaks and the hypothesis of a critical span of 60 m has been confirmed by the instrumentation results obtained from Saffy Shaft (Figure 3.20).
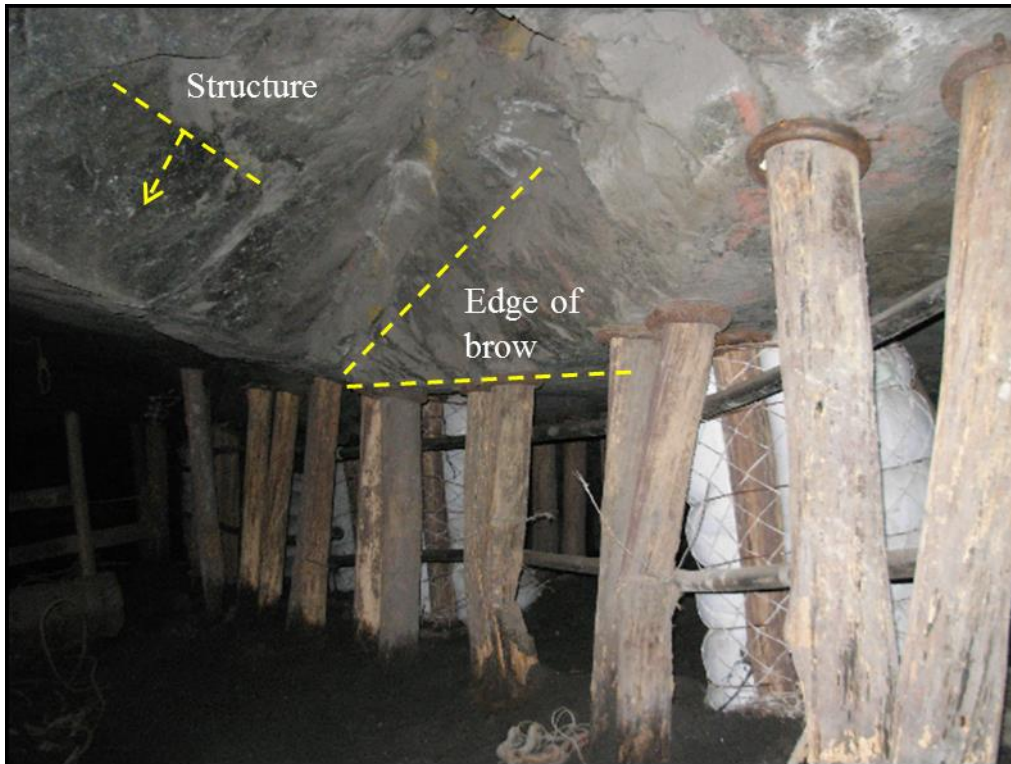
Figure 3.24: Unstable hangingwall condition in the back area with the buckling of timber elongates located on the down-dip side of the Marikana structure.

3.2.4. Hossy Shaft

Hossy Shaft is currently operating as a hybrid mining operation. Conventional mining and mechanized cleaning is conducted using strike and dip belt drives. Figure 3.25 illustrates that the main geologic structures exposed along the western levels strike NNW-SSE, NW-SE and WNW-ESE (Marikana structures). Ore reserves have been abandoned in the vicinity of these structures (red hatching in Figure 3.25) due to the associated hangingwall instabilities experienced. Some critical belt drives, the main arteries of the shaft have collapsed, as shown in Figures 3.26 and 3.27. The excavation widths of the belt drives are 5 m. Although it is a relatively small span, the geologic structures exposed in the belt drives contributed to the instabilities and large-scale hangingwall unravelling. Pillar slabbing (Figure 3.28) has also been identified in the belt drives where alteration is present along the top reef contact. The joint planes are mobilized, especially when intersecting the pillar at oblique angles. This results in the observed slabbing.
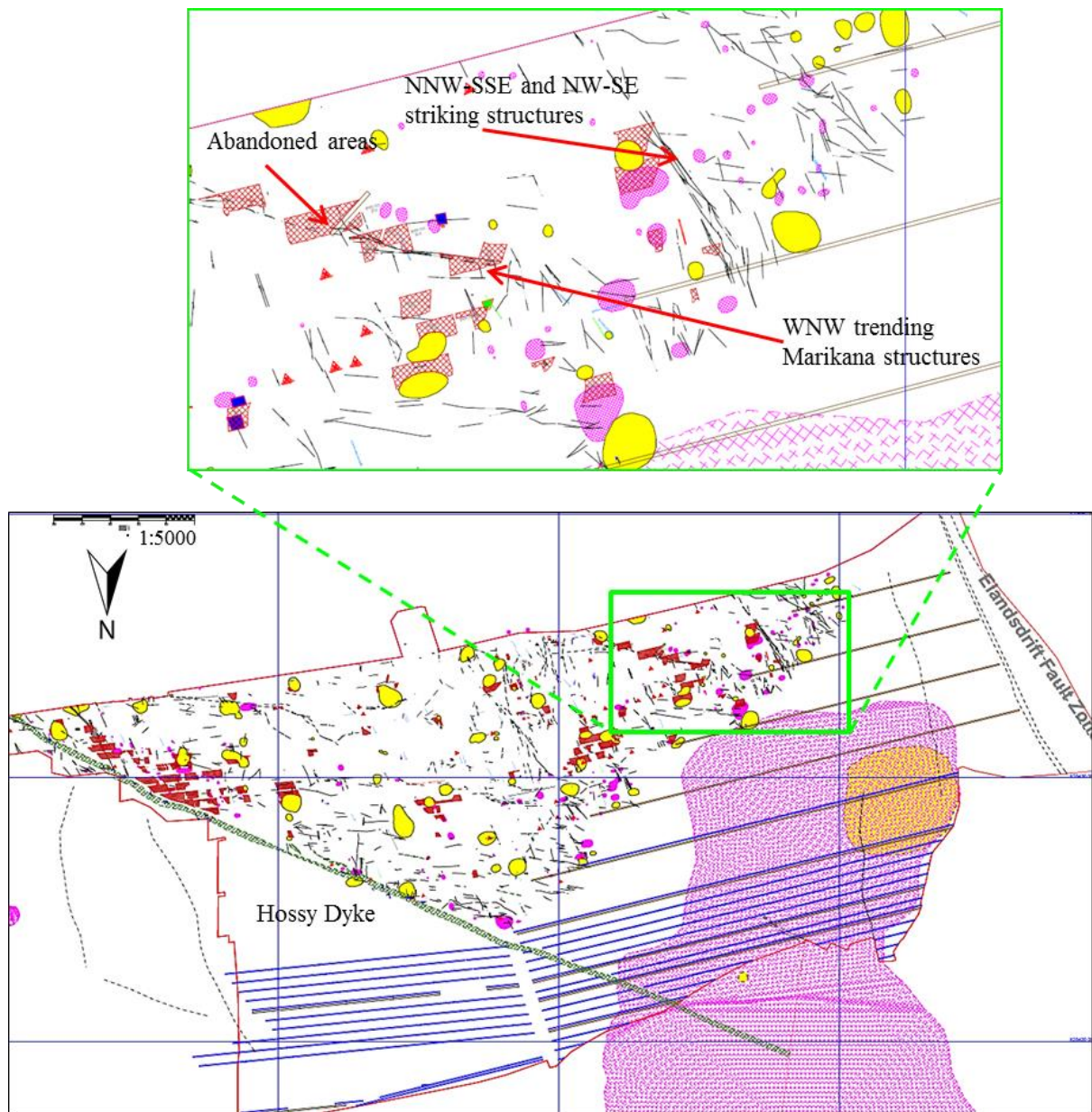
Figure 3.25: A 1:5000 plan of Hossy Shaft, showing the Hossy Dyke along the eastern boundary and the Elandsdrift Fault Zone forming the western boundary of this shaft. The green block is zoomed in on the western, upper levels of this shaft. The geologic structures exposed in this area was indicated and the abandoned ground (red hatched areas) shown, caused by falls of ground and adverse hangingwall conditions.
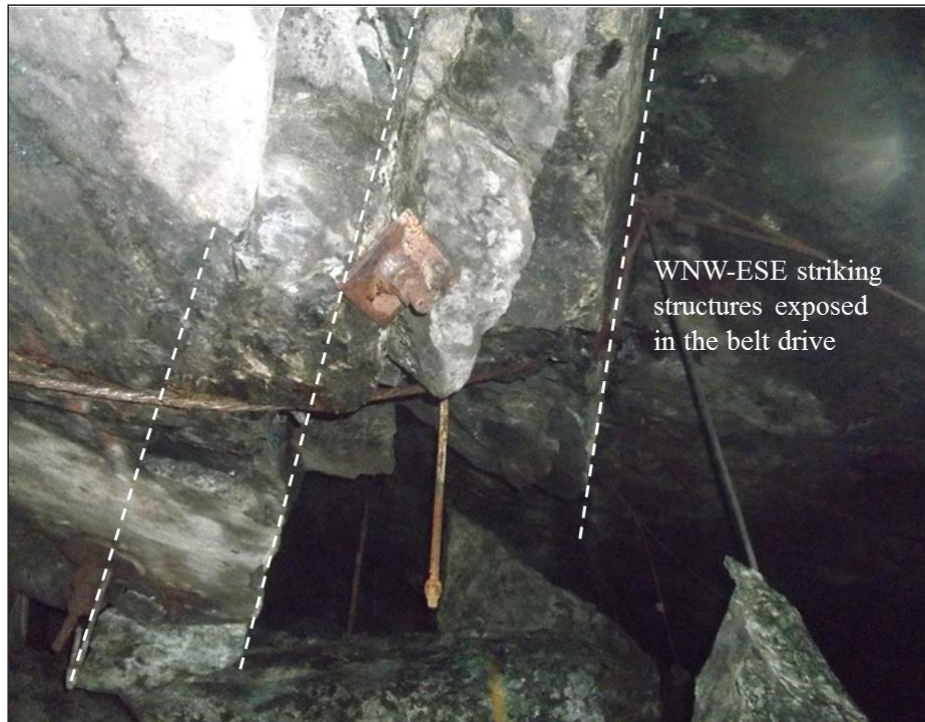
Figure 3.26: Hangingwall and support failure in the belt drive where Marikana structures were intersected. This area was supported by 1.8 m long resin bolts and 4 m long cable anchors and trusses. The support was clearly not adequate in this area.

Figure 3.27: Collapse in a belt drive. It is suspected that the poor quality of cable anchor installation contributed to the collapse.
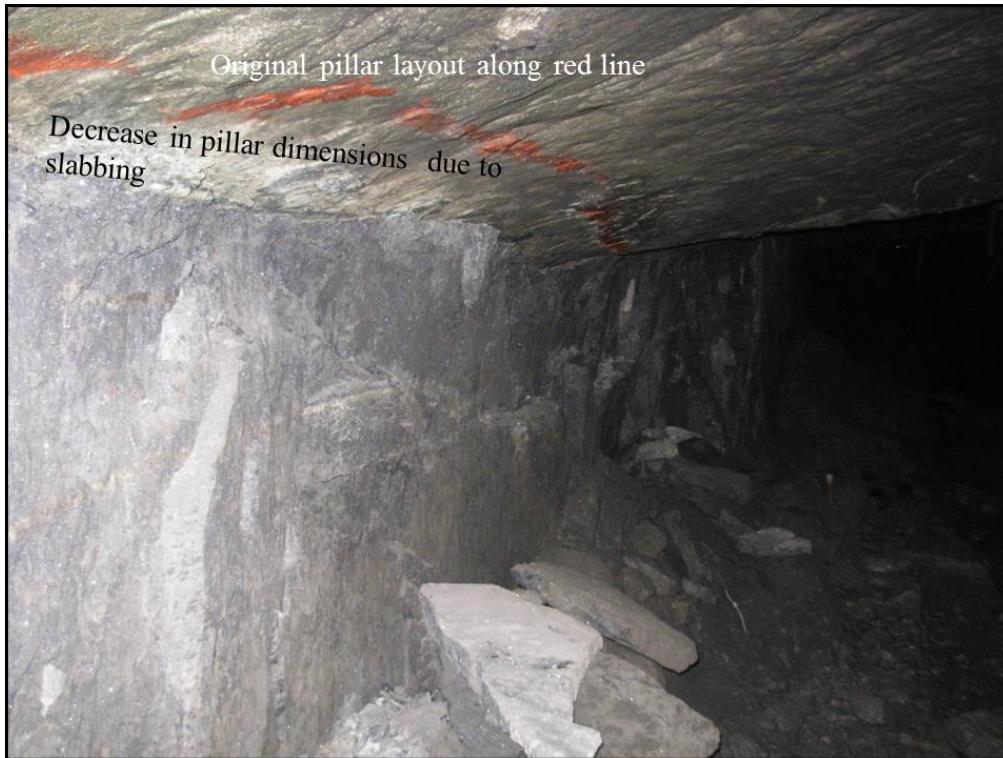
Figure 3.28: Time-dependent pillar slabbing along a belt drive. The red line on the hangingwall indicates the original size of the pillar.

Joint mapping conducted by the author along the western levels were captured in the Dips software package. The 227 entries are summarised in Figure 3.29. The results show that the majority of structures strike NNW-SSE and WNW-ESE, which corresponds with the major structural orientations. The Marikana structures are exposed throughout Hossy Shaft. These structures are continuous over long distances (more than 5 m). The combination of these structures with the deformation event 1 and deformation event 2 (ramp structures) and alteration can cause adverse hangingwall conditions and a fall of ground risk (Figures 3.30 and 3.31). Deformation events 1 and 2 have been discussed in Section 2.4.1. Figure 3.32 shows the Marikana structure with pegmatite infill.
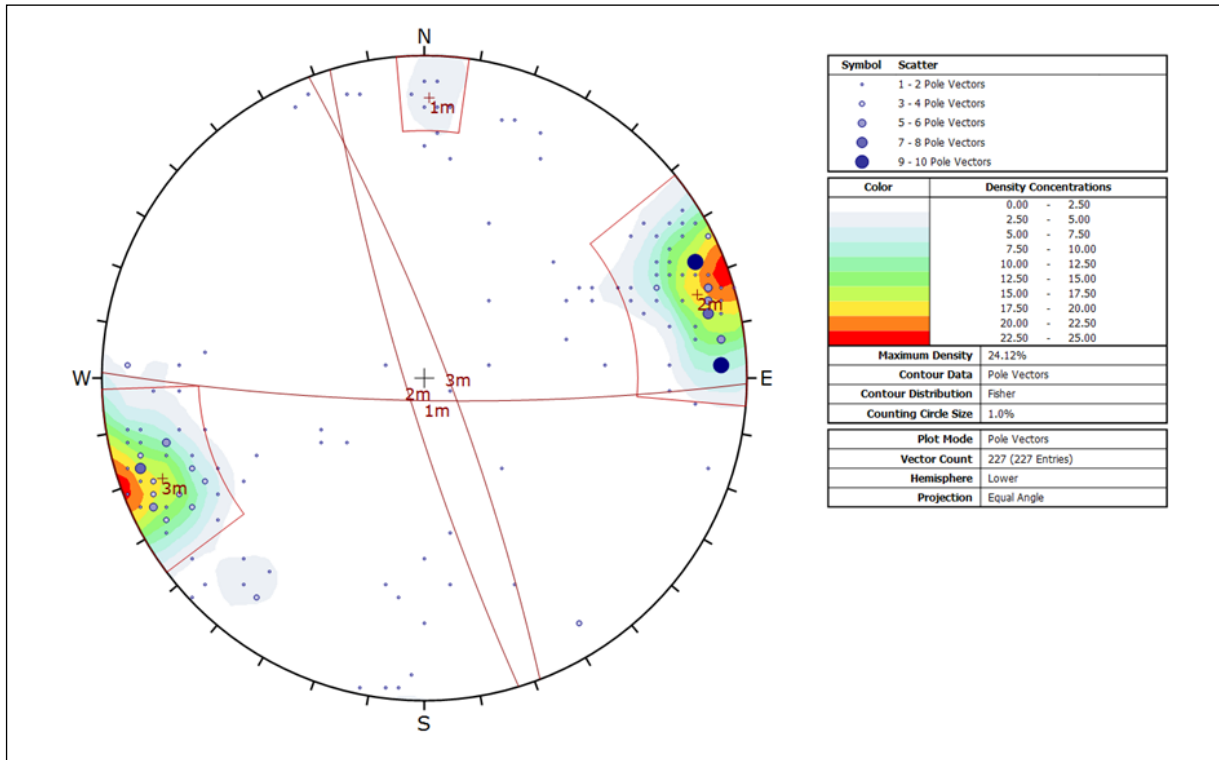
Figure 3.29: Representation of the joint mapping conducted by the author along the western levels at Hossy Shaft. The trends of these structures are similar to the structures exposed at Saffy Shaft, shown in Figure 2.21.

Figure 3.30: Intersection of deformation event 1 (ramp structure) and a Marikana structure. Alteration has also been exposed along the hangingwall pyroxenite units. This represents the worst case scenario and unfavourable conditions. Rock bolt support failure is also visible in the vicinity of the fall of ground.
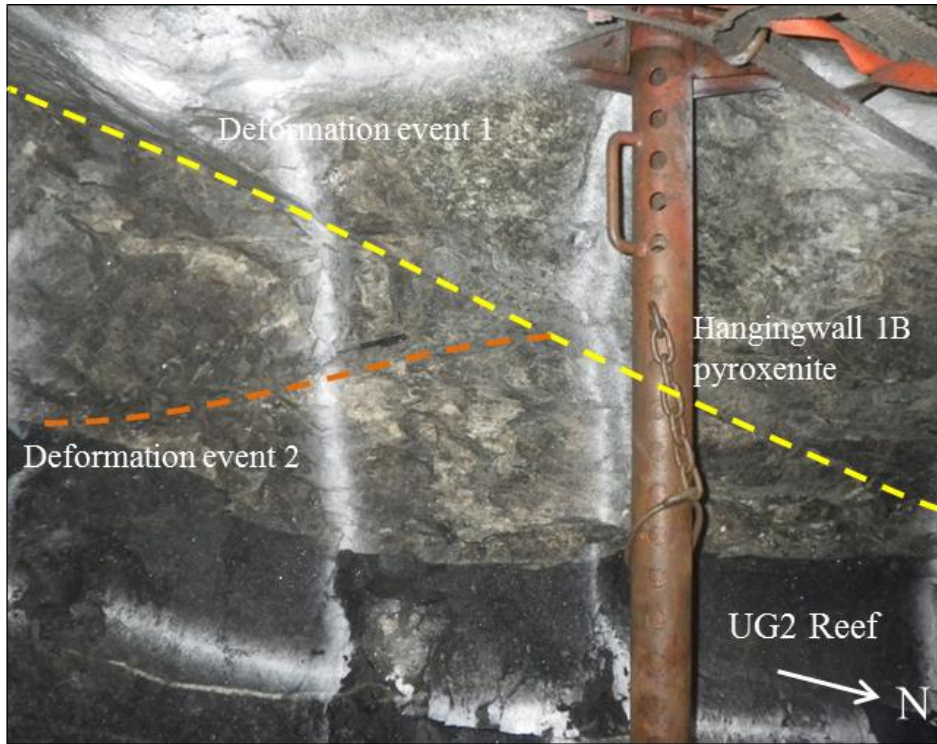
Figures 3.31: Deformation event 1 and 2 (ramp structures) together with alteration exposed along the stope face as discussed in Section 2.4.1.
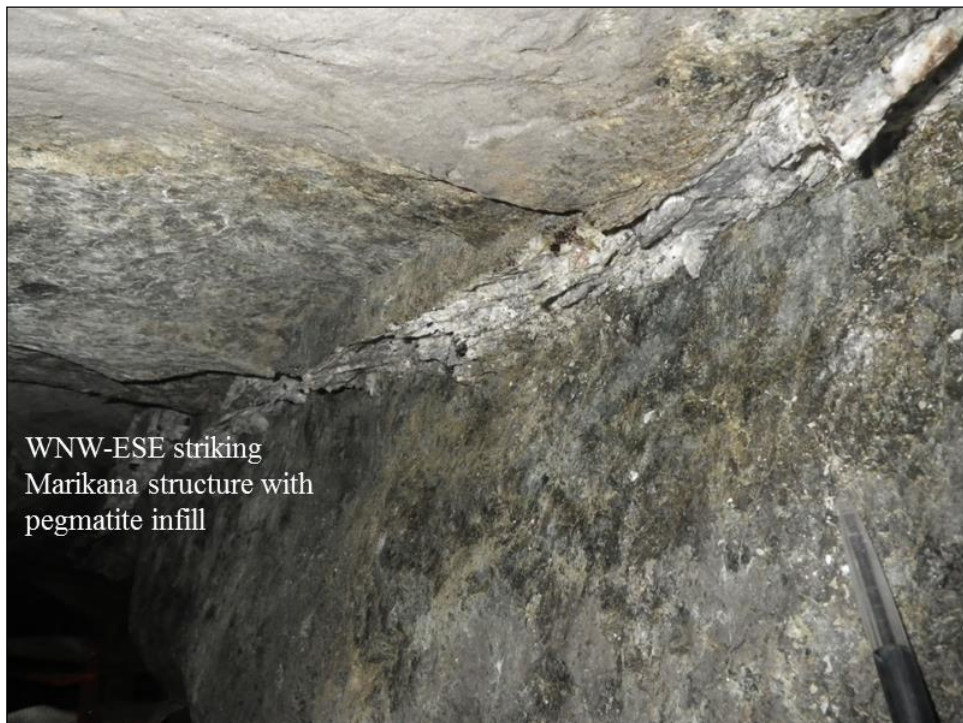
Figure 3.32: Marikana structure with pegmatite infill exposed in a development where a fall of ground occurred.

In an attempt to identify and confirm the occurrence and extent of the geologic structures in the hangingwall, a sub-surface profiler (ground penetrating radar system) was used by the author to scan up to 10 m into the hangingwall. This ground penetrating radar (GPR) system is designed specifically for the challenges faced by underground mining operations. The scanner is rolled along the hangingwall and the data collected is wirelessly transmitted and processed in real time. This gives instant feedback on the geologic structures present in the area (Figure 3.33).
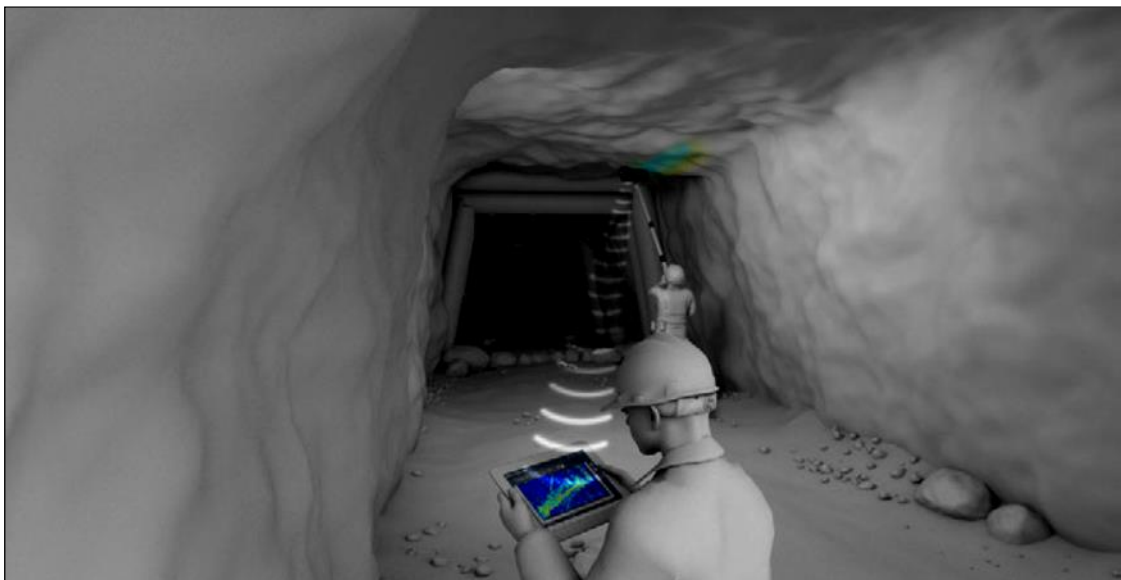
Figure 3.33: Illustration of how to operate the sub-surface profiler in an underground environment to detect the geologic structures in the hangingwall. The results and interpretation of the geologic structures (Figure 3.34) is shown in Figure 3.35.

A scan was done in a down-dip direction in a panel for a distance of 34 m. The ground conditions in the panel appeared to be competent from observations in the stope (Figure 3.34). The scan in Figure 3.35, however, shows that the area is structurally complex. Ramp structures (deformation events 1 and 2) as well as Marikana structures are present in the hangingwall of the panel. The results from the scanner indicated that some of the structures ramp up to the position of the UG2A markers (3 – 4 m in the hangingwall) where others ramp up to the hangingwall 1A/hangingwall 2 contact (8 m in the hangingwall). Also, the Marikana structures cut into the hangingwall beyond the 10 m depth that the profiler can detect. The scan confirmed the findings at Saffy, Eastern Platinum Limited 2 and Hossy Shafts that the ramp structures 'ramp up' to the prominent weakness planes (UG2A markers and/or the hangingwall 1A/hangingwall 2 contact). With this new technology, it was the first time that the presence of these structures could be confirmed in the hangingwall in areas where the hangingwall still appeared competent. This contributes to an improvement in the spatial understanding of these structures and what should be considered in terms of mining strategies and support design.
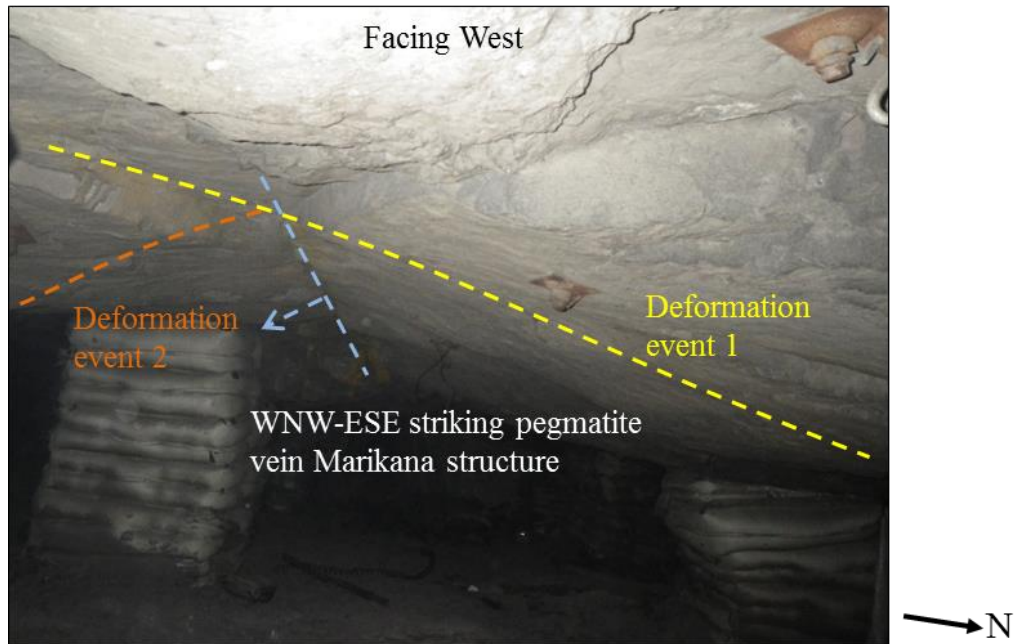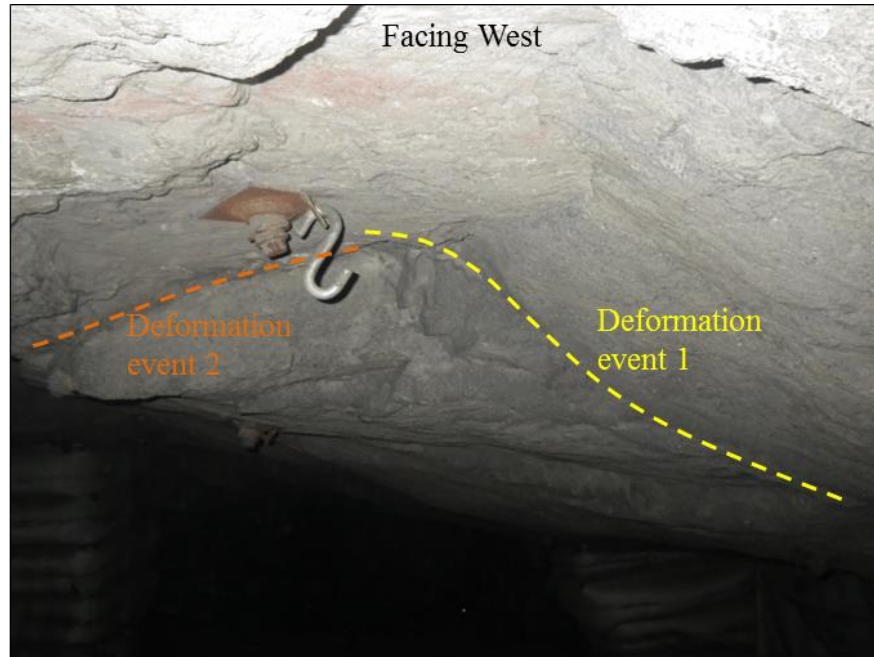
Figure 3.34: A mining panel with geologic structures exposed. The hangingwall appears to be competent.
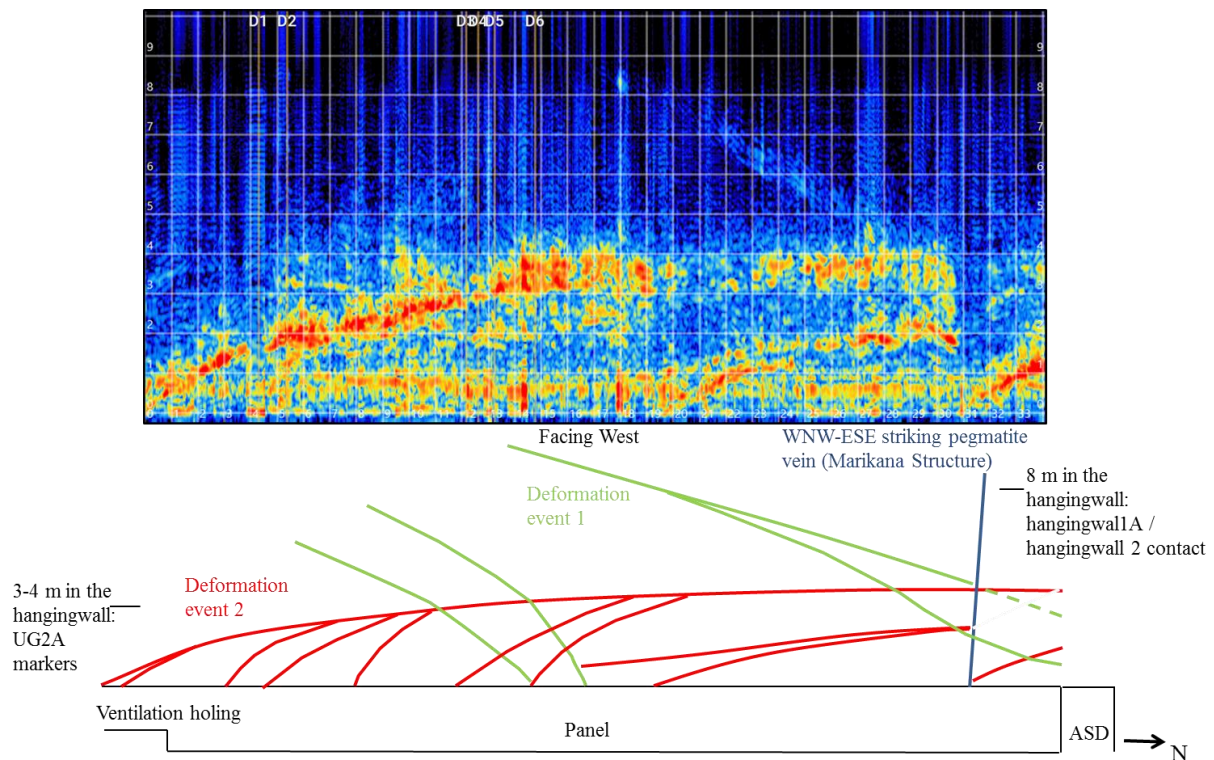
Figure 3.35: Scan along dip for 34 m with a sub-surface profiler showing the geologic structures exposed up to 10 m in the hangingwall. The bottom diagram shows the interpretation of the data captured in the scan.

3.3.   Findings and Remedial Actions

The chapter discusses the observation made by the author regarding the presence and occurrence of major geologic structures namely, WNW-ESE striking Marikana structures, NNW-SSE striking clusters as well as deformation events 1 and 2 (ramp structures). In these areas and under these geotechnical conditions, the support strategy must be able to provide the required support resistance to the known potential instability plane. Boreholes drilled vertically into the hangingwall of the UG2 Reef in areas of instability identified and confirmed separation along various positions along the borehole length. However, it was most prevalent at prominent weakness planes (UG2A markers and / or the hangingwall 1A/hangingwall 2 contact).

The pro-active identification of the geologic structures and this understanding of the potential failure mechanisms will assist in implementing the most suitable mining and support strategy. From the case studies and learnings, remedial strategies have been proposed by the author to prevent these associated instabilities. These strategies are summarised in the table below.

Table 3.1: Remedial strategies proposed in areas where regional and secondary geologic structures are present, as a result of the work conducted in this study.

Conditions	Remedial strategies proposed
Anomalous ground conditions suspected. Support failure observed.	• Use the ground penetrating radar technology (sub-surface profiler) to detect the structures present in the hangingwall. • Drill vertical boreholes into the hangingwall to determine if separation (along geologic structures and/or alteration zones) has occurred.
Back breaks when the mining span exceeds 27 m.	• A maximum inter-pillar span of 27 m should be maintained to prevent instability once a critical mining span is reached. • The critical span is reached when the panel has advanced for approximately twice the panel span.
Instabilities observed when mining in a particular direction.	• Apply a split-dip layout with the western face leading. • Breast mining towards the east.
Uncharacteristic pillar behaviour: • Pillar slabbing as a result of unfavourable joint plane intersection.	To circumvent the risk of slabbing pillars injuring people: • A split-dip layout can be considered. This will move the development end (travelling way) away for the edges of the pillar. • If the development end is, however, located adjacent to a pillar, pinning and strapping of pillars can be considered. • When slabbing pillars are encountered as a result of alteration, increase the factor of safety to cater for the pillar slabbing which will impact on the long term pillar stability.
Support not appropriate for certain ground conditions.	• Mine with either high strength active cementitious grout packs (new generation) only. • Integrate both, high strength active

	cementitious grout packs (new generation) with alternating lines of timber elongates.
Risk of unexpected collapses.	• Installation of 'fit for purpose' monitoring devices to warn of instability.

3.4. References

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THE IMPACT OF ALTERATION ZONES IN THE PYROXENITE LAYERS OF THE UG2 REEF

4. THE IMPACT OF ALTERATION ZONES IN THE PYROXENITE LAYERS OF THE UG2 REEF

Davis and Reynolds (1996) describe a shear zone as a strained, sheet like and planar or curviplanar, discontinuous zone when compared to the adjacent rocks. These zones can form a network consisting of individual shears that can be subparallel sets, deflect towards one another and link up in an anastomosing pattern. It can also cross-cut or displace one another. Knipe (2016) studied aquifers (Figure 2.20) and indicated that it may be associated with layer-parallel shears in the hangingwall 1 pyroxenite. Layer-parallel shears may form areas of secondary porosity and permeability which could host water. Ground water inflow along these structures and inter-linking structures may promote the formation and existence of alteration zones along the pyroxenite units in the vicinity of the UG2 Reef. The case studies referred to in this chapter investigate the impact of alteration zones on mine stability. The hangingwall pyroxenite, which has been exposed to hydrothermal fluid flow, serpentinization, and layer-parallel shearing, is the source of this material (Figure 3.2).

Site investigations were conducted by the author at Newman, Rowland, Hossy and Saffy Shafts at Lonmin (Figure 1.2) as well as Everest Mine (Figure 1.1) situated in the Eastern Limb of the Bushveld Complex. The formation of the alteration zones have been described in Chapter 2. The presence of the alteration zones and its location relative to the position of the mining cut (UG2 Reef) may result in potential instability and needs to be considered in the mining strategy. Areas where both the alteration zones and large-scale geologic structures (Figure 1.12) are exposed are the worst case scenario. This chapter describes the findings of the various case studies, the impact of the structures present on mine stability as well as key learnings and remedial strategies that can be applied at the different sites.

4.1. Introduction

The problematic alteration zones are associated with the hangingwall, footwall and internal waste pyroxenite units of the UG2 Reef. The alteration zones have a 'clay-like' nature (Figures 2.28 and 2.29), reducing the rock mass strength and the cohesion along natural parting planes. The friction angle also decreases between the alteration zones and other contacts. This in turn may lead to hangingwall instability, unravelling of the hangingwall units (Figures 4.1, 4.2 and 4.3) and could affect the pillar strength and integrity (Figure 4.4).

The alteration zones have been identified as a main contributor to the unstable conditions experienced at the sites investigated. Similarities exist between the sites that will be discussed in this chapter; therefore similar remedial strategies may be appropriate and can be applied. These strategies will be expanded on and will be referred to at other sites where applicable.

The following topics are discussed in this chapter:

- The impact of the alteration zones on ground condition and pillar behaviour. This include:
  - Sites where the alteration zone is located along the top reef contact. The investigations by the author include:
    - Unravelling around installed support units and ore reserved write-offs at Newman Shaft.
    - Anomalous hangingwall and pillar behaviour experienced at Rowland Shaft.
    - Unravelling around installed support units and anomalous pillar behaviour at Hossy and Saffy Shafts and also at Everest Mine, where the unexpected behaviour resulted in mine closure.
  - Sites where the alteration zone is situated in the hangingwall of the UG2 Reef:
    - Instability initiated within/from the altered hangingwall layers at Newman, Saffy and Hossy Shafts.
- The formation of the alteration zones:
  - Neotectonic activity could also play a role in the formation of these zones. This may promote the inflow of ground water and the formation of alteration zones. Site investigations were predominantly conducted at Saffy Shaft where large footwall excavations expose these geologic structures. A regional view of the structures, possible formation and potential failure mechanisms was formulated by the author. Geologic mapping was also done at Saffy and Hossy Shafts to determine the similarities of the structures and prevailing ground conditions.

The findings are intended to contribute towards the understanding of the formation and occurrence of these alteration zones. Pro-active identification of these alteration zones should be promoted to ensure the most suitable support strategies and layouts are implemented.

Figure 4.1: An alteration zone along the top contact of the UG2 Reef, causing fallout around an installed grout pack. This results in ineffective support being provided to the hangingwall which could result in large-scale unravelling, especially when intersected by prominent regional geologic structures as described in Chapter 3.
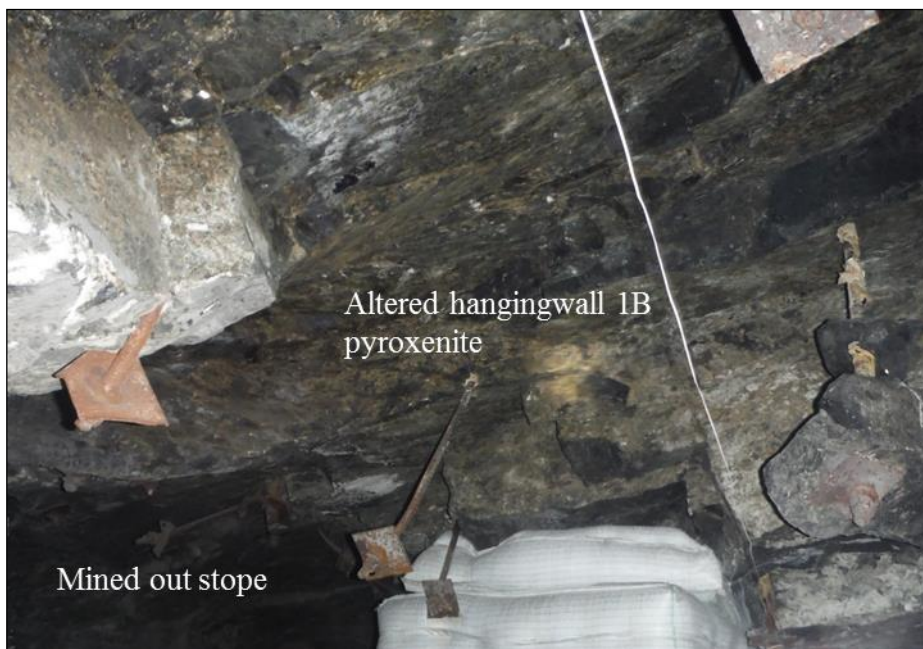
Figure 4.2: Alteration zone along the top contact of the UG2 Reef resulting in the unravelling of the immediate hangingwall around the installed rock bolts. This impacts the overall hangingwall stability.

Figure 4.3: The effect of an alteration zone exposed along the top reef contact in a development end. This resulted in unravelling of the hangingwall in the excavation. This figure also shows the failure of secondary support due to the unravelling of this 'clay-like' alteration zone (approximately 10 cm up to 1 m in thickness) that is present along the top reef contact.

Figure 4.4: An alteration zone along the top reef contact affect the pillar strength and integrity.

4.1.1. Site Investigations

From the various site investigations conducted, the following were found. Newman Shaft has an alteration zone along the hangingwall and footwall units which contributed to significant mining losses due to the poor hangingwall conditions experienced. Rowland Shaft experienced a fall of ground where altered hangingwall conditions were present in the stope area. Unstable pillar and ineffective support behaviour were also identified. Hossy and Saffy Shafts have regional alteration zones present along the hangingwall units which affect the hangingwall stability as well as pillar and support behaviour. Everest Mine was closed due to large-scale collapses caused by a prominent alteration zone present along the hangingwall contact of the in-stope pillars.

The mining layouts at the Lonmin sites consist of breast and dip mining panels with 27 – 30 m inter-pillar spans. The panel strike spans have been selected based on the expected behaviour of the hangingwall layers. A non-yield pillar layout is used on the stoping horizon and pillar widths vary with depth. The hangingwall beam thickness is the vertical distance between the top reef contact and the top contact of the UG2A markers (Figure 1.3), which is a known natural parting plane. To provide sufficient support resistance for this beam of up to 10 m, alternating rows of pre-stressed timber elongates and grout packs (or grout packs only at reduced spacing) are used as the primary in-stope support system. The principal purpose of the in-stope support system at Lonmin is to maintain the integrity of the hangingwall 1B pyroxenite, including the

UG2A markers. The installed support elements must meet the following requirements as described in Chapter 3.

Identification of the presence of alteration zones and an understanding of the deformation events that contributed to their formation can assist in the planning and mine design processes. It will assist that appropriate strategies are implemented prior to mining and could guide whether mining blocks are mineable or not. If the presence and impact of the alteration zones are ignored and the resulting rock mass behaviour is not understood, it can cause large-scale instabilities and have a significant effect on the viability of a mine.

4.2. The impact of alteration zones on rock mass conditions and pillar behaviour

4.2.1. Newman Shaft

The western areas of Newman Shaft (Figure 4.5) are mining towards the Elandsdrift Fault Zone. The structural geology of Newman Shaft is complex and contributes to the instability of the excavations as mining approaches this fault zone. Mining at 6 Chrome West Level exposed an alteration zone along the top contact of the UG2 Reef. On-reef development (raise lines) indicated that the position of the alteration zone is not restricted to the top contact of the UG2 Reef only, but can extend to the pyroxenite hangingwall and/or footwall units. This zone created challenges for mining operations as it contributed to adverse ground conditions and falls of ground. The area affected by this alteration zone extends across six raise lines (refer to the black hatched area in Figure 4.5).
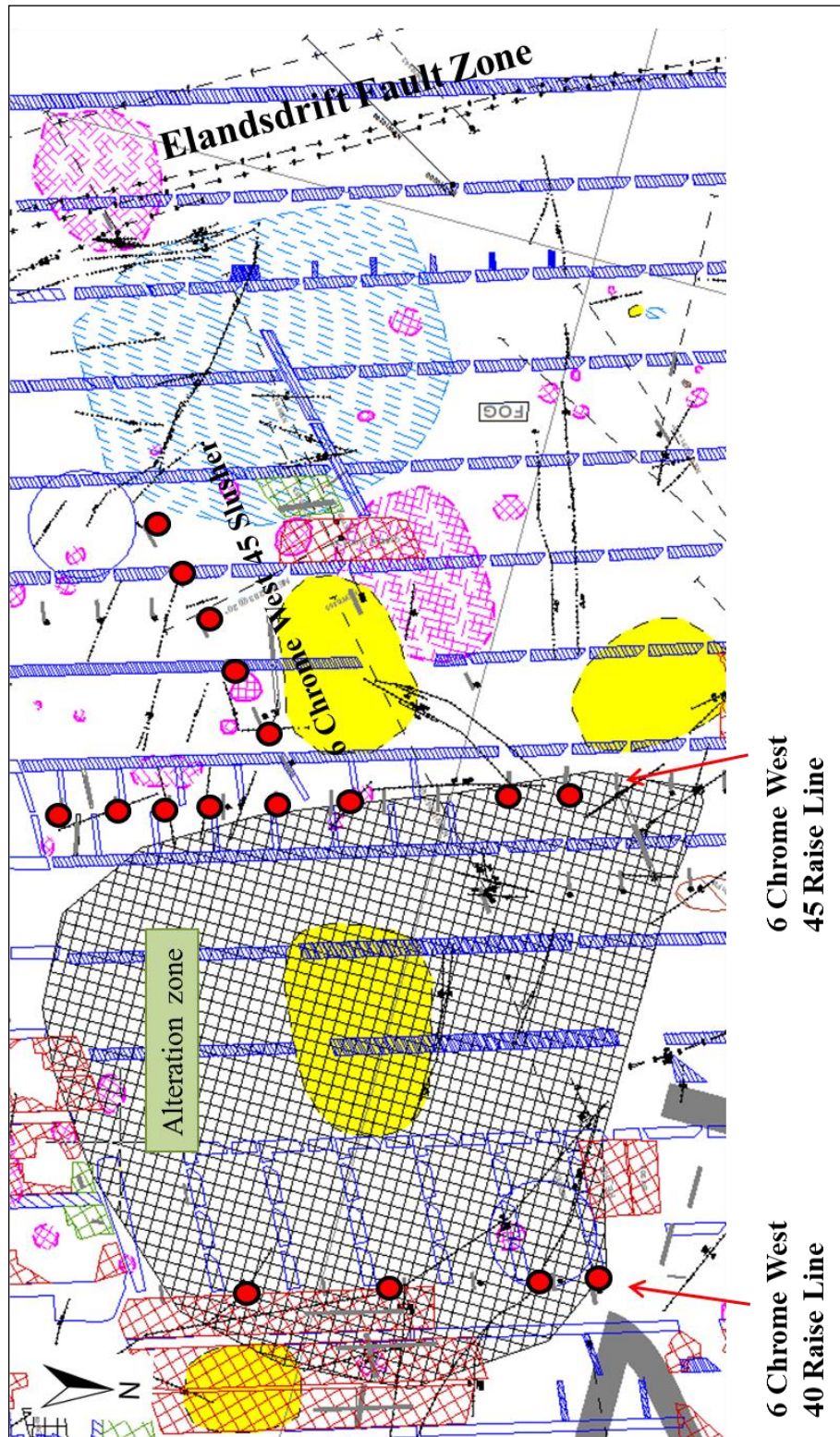
Figure 4.5: Mine plan of 6 Chrome West Level at Newman Shaft, indicating areas affected by the alteration zone. The boreholes that were drilled vertically into the hangingwall are indicated by the red ellipses. Six raise lines of ore reserves were abandoned due to the anomalous hangingwall conditions encountered as a result of the alteration zone.

The resulting conditions are difficult to support and secondary support seemed to be ineffective (Figure 4.3). Furthermore, as a result of the weak nature of the 'clay-like' pyroxenite material, the immediate hangingwall layer will be extracted with the reef and this will impact on stoping width and grade. Where the alteration zone is located deeper into the hangingwall, it is very difficult to detect and it poses a risk in terms of large-scale instabilities (Figure 4.6). It can also occur along the bottom contact of the UG2 Reef (Figures 4.7 and 4.8). In these areas, the footwall is less competent and does not provide a solid foundation for the installation of timber elongates or grout packs (Figure 4.8). The location of the alteration zone relative to the UG2 Reef therefore provides challenges in terms of the mining as well as the support strategy.

Figure 4.6: An alteration zone in the hangingwall can cause the unravelling of key blocks due to separation along joints or parting planes.
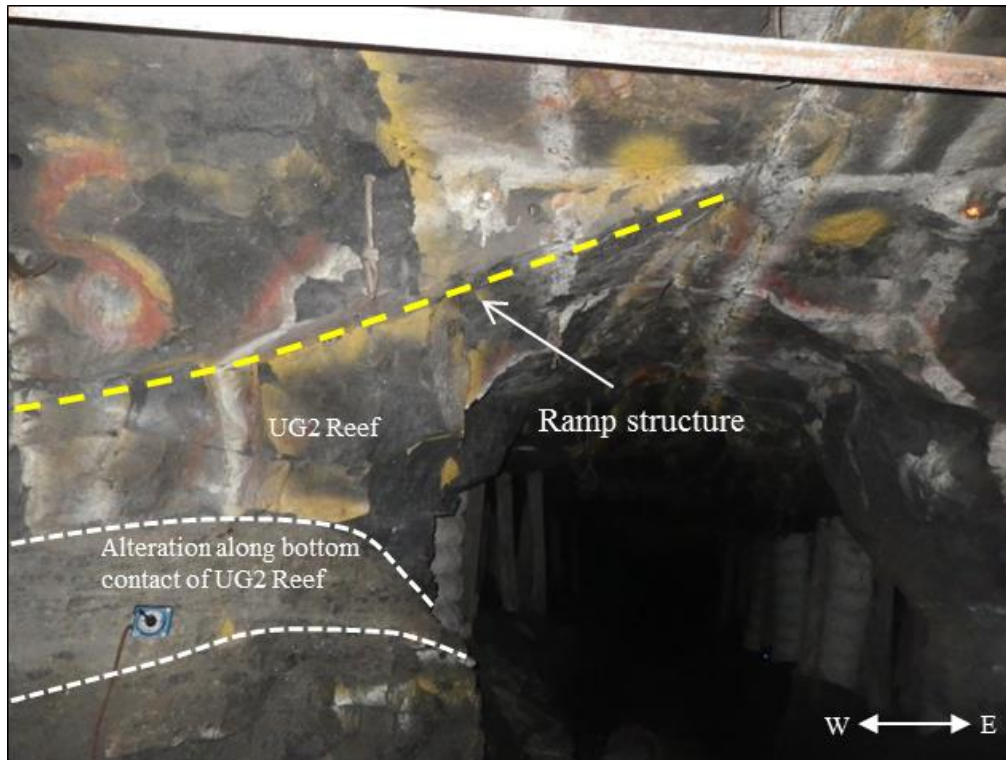
Figure 4.7: The presence of an alteration zone along the bottom contact of the UG2 Reef. Also note the ramp structure present along the hangingwall.

Figure 4.8: An alteration zone along the footwall contact of the UG2 Reef causing footwall heave and premature failure of the installed timber elongates. This can result in large-scale hangingwall failure.

A drilling campaign was initiated by the author on Newman Shaft to determine the position of the altered hangingwall material with reference to the UG2 Reef in the areas affected (Figure 4.5). The information obtained from the drilling campaign identified two scenarios which will be discussed in terms of the associated risks:

- Position of alteration zone.
- Fallout height and support strategies.
- Economic impact in terms of dilution.

Scenario 1: Alteration zone located along the top contact of the UG2 Reef

The core was logged in order to determine the position of the altered hangingwall material relative to the UG2 Reef. The first four boreholes were drilled vertically into the hangingwall along dip in 6 West 40 Raise line (Figure 4.5). Figures 4.9 and 4.10 illustrate that the alteration zone is present directly above the top contact of the UG2 Reef, as can be seen in the underground exposure and borehole logs. The underground observations showed that the alteration zone had a thickness of 0.3 m where it was exposed in this area. Although the rock bolt support caters for the expected fallout thickness (1.2 m), it will be a challenge to support this material as it unravels between and around the installed support units (Figure 4.2). The

unravelling of this altered material also causes dilution and impact on the grade. If the mining grade is too low it will not be economically viable to mine the affected area. A remedial support strategy could be mining with permanent blast resistant mesh in an attempt to provide additional areal support and prevent the possible unravelling.
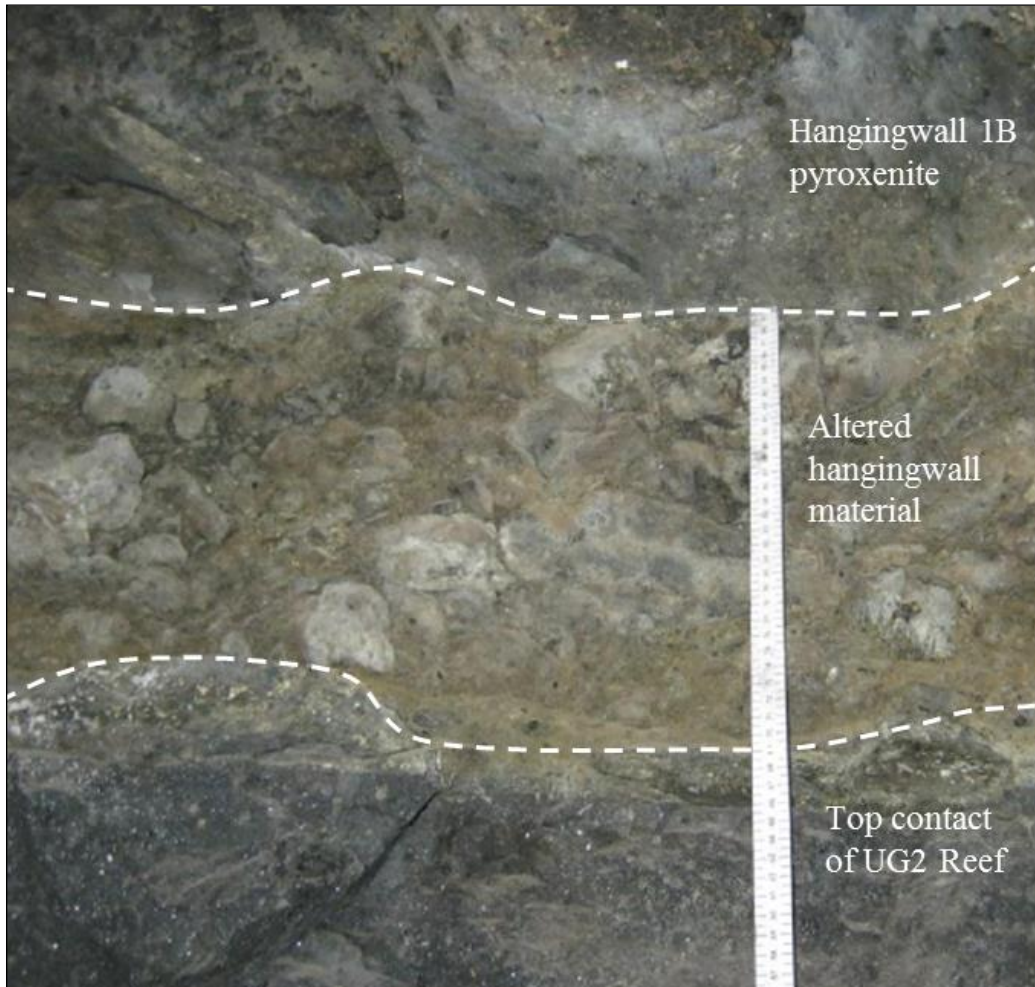
Figure 4.9: Photograph of the alteration zone along the top contact of the UG2 Reef (approximately 0.3 m thick).
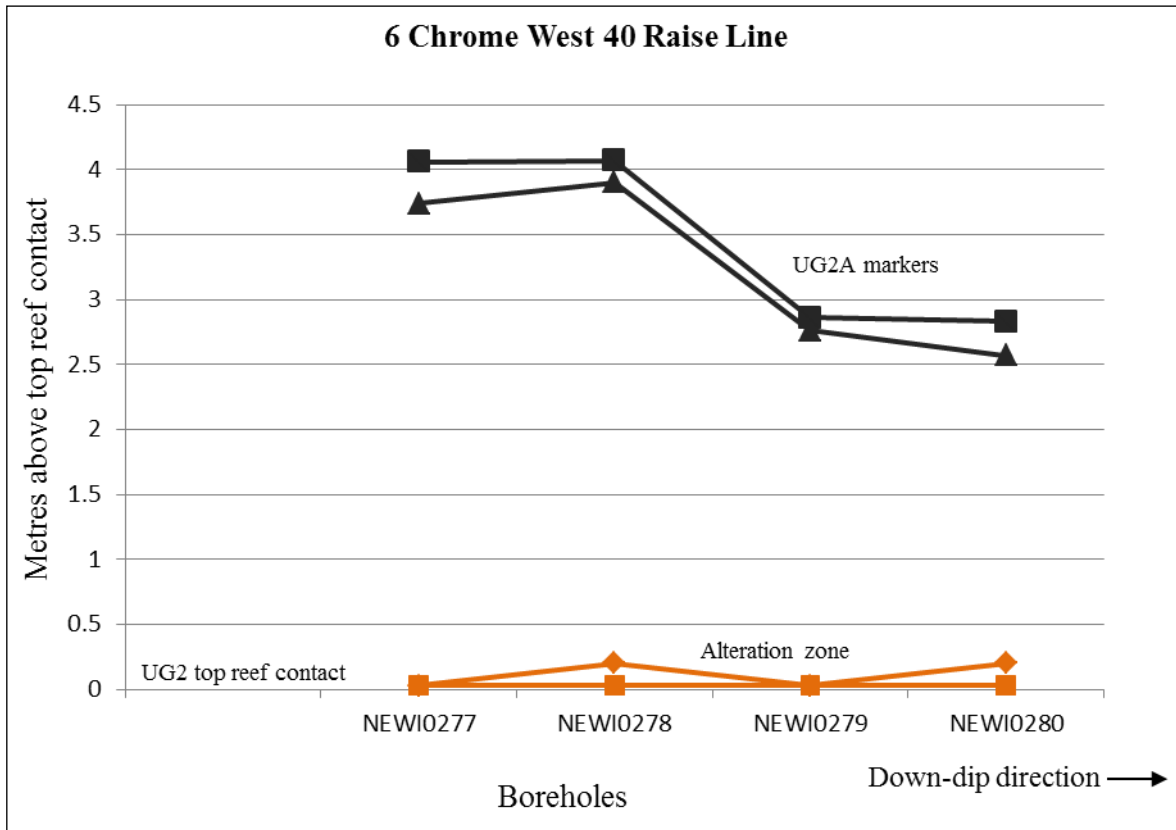
Figure 4.10: Location of alteration zone with reference to the UG2 Reef and UG2A markers along the 6 West 40 Raise line. The orange lines are the position of the alteration zone contacts and the black lines are the position of the UG2A markers contacts.

Scenario 2: Alteration zone located in the hangingwall units, in the vicinity of the UG2A markers

Another eight boreholes were drilled vertically into the hangingwall along 6cW 45 Raise line (Figure 4.5). Figure 4.11 shows that the alteration zone is situated in the vicinity of the UG2A markers in seven of the eight boreholes drilled. As can be seen from Figure 4.11, the UG2A markers are situated at 1.5 m to a maximum of 3.25 m above the UG2 top reef contact. The support strategy implemented at Newman Shaft ensures that the timber elongates support up to this natural parting plane. With the UG2A markers being a known parting plane, the presence of the alteration zone at this location contributes to a decrease in the friction angle and cohesion of the alteration zones and other contacts. On Newman Shaft, grout packs are also installed as supplementary back area support to prevent large-scale hangingwall instabilities and back breaks. However, the alteration zone can also be present at the hangingwall 1A/hangingwall 2 contact (at 7 m), exacerbating the problem (Figure 4.12). This scenario does not have a dilution risk, but rather a large-scale instability risk. The effectiveness of the support (timber elongates and grout packs) in these conditions is questionable. High strength, stiff active support will be required to support to the highest possible partible plane. An example of a suitable product is the recently developed, new generation modular grout pack. Figures 3.19 and 3.20 show the support characteristics of these grout packs.

Figure 4.6 show the separation along joints at 6 West 45 Raise line. The raise line was developed 1.4 m wide supported with rock bolts and no stoping was done at this panel. The instability might be due to the presence of the alteration zone in the vicinity of the UG2A markers or the hangingwall 1A / hangingwall 2 contact. The alteration zones in the hangingwall are already creating unstable conditions during the development phase (span of 1.4 m), stoping in these areas may be challenging, if at all possible.
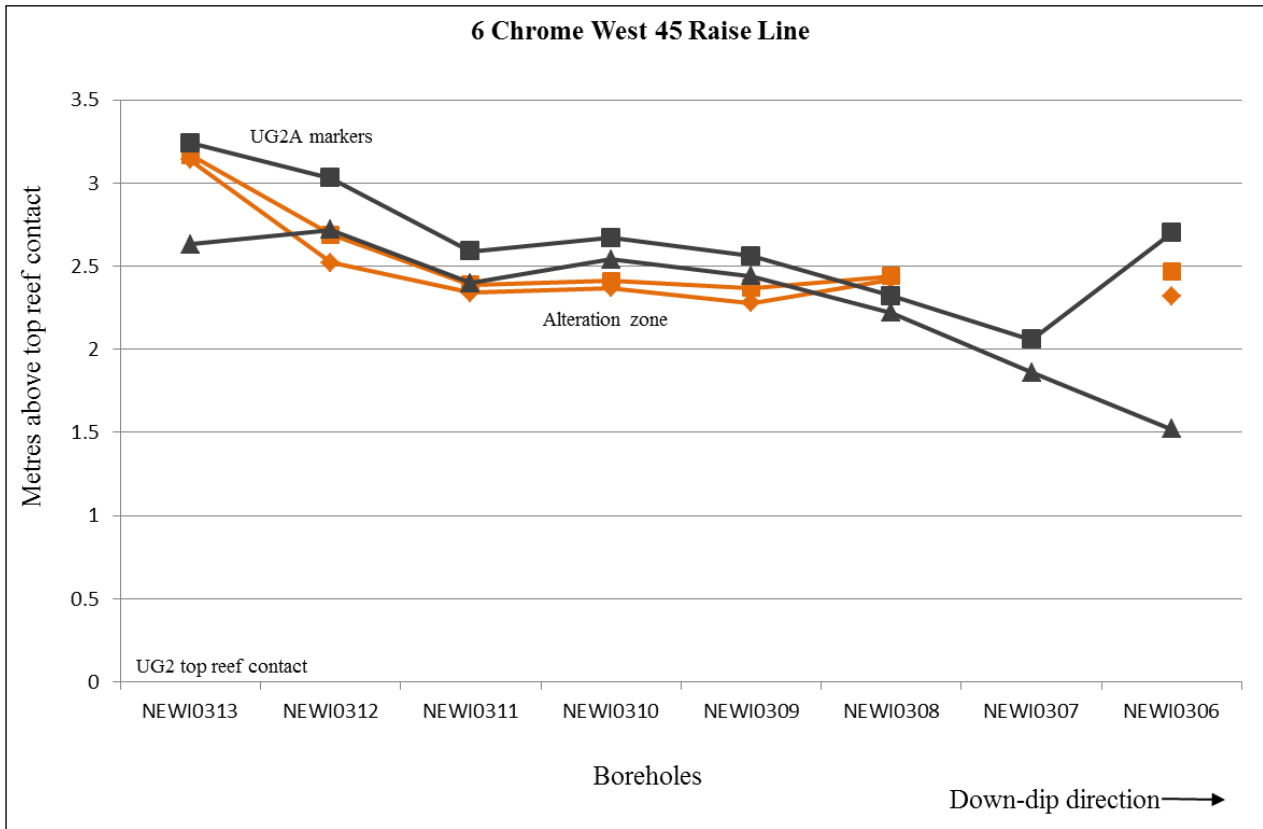
Figure 4.11: Location of alteration zone with reference to the UG2 Reef and UG2A markers along 6 West 45 Raise line. The orange lines are the position of the alteration zone contacts and the black lines are the position of the UG2A markers contacts.

Figure 4.12 is an illustration of the five boreholes that were drilled vertically into the hangingwall along 6 West 45 middle slusher (see Figure 4.5), that was developed on strike from east (NEWI0318) to west (NEWI0322). Two alteration zones can be identified in Figure 4.12. It is hypothesised that *alteration zone one* migrates from the top UG2A marker to the top contact of the UG2 Reef and again towards the bottom UG2A marker. *Alteration zone two* is only present in the first two boreholes, NEWI0318 and NEWI0319. The alteration zone migrates from the hangingwall 1A/hangingwall 2 contact (7 m) towards the lower UG2A marker. Figure 4.12 show that the alteration zones possibly follow ramp structures (Figure 3.2), as discussed in Chapter 3. Hangingwall separation can therefore occur at various positions. This contributes to the

unpredictability and scale of potential instabilities and will have an effect on the installed support. Stiff, active support units will be required to support to the highest possible parting plane.

Geotechnical logging of the boreholes was conducted by the author and Q-ratings ranging from 0.001 to 0.5 were calculated. This indicates exceptionally poor to extremely poor ground conditions.
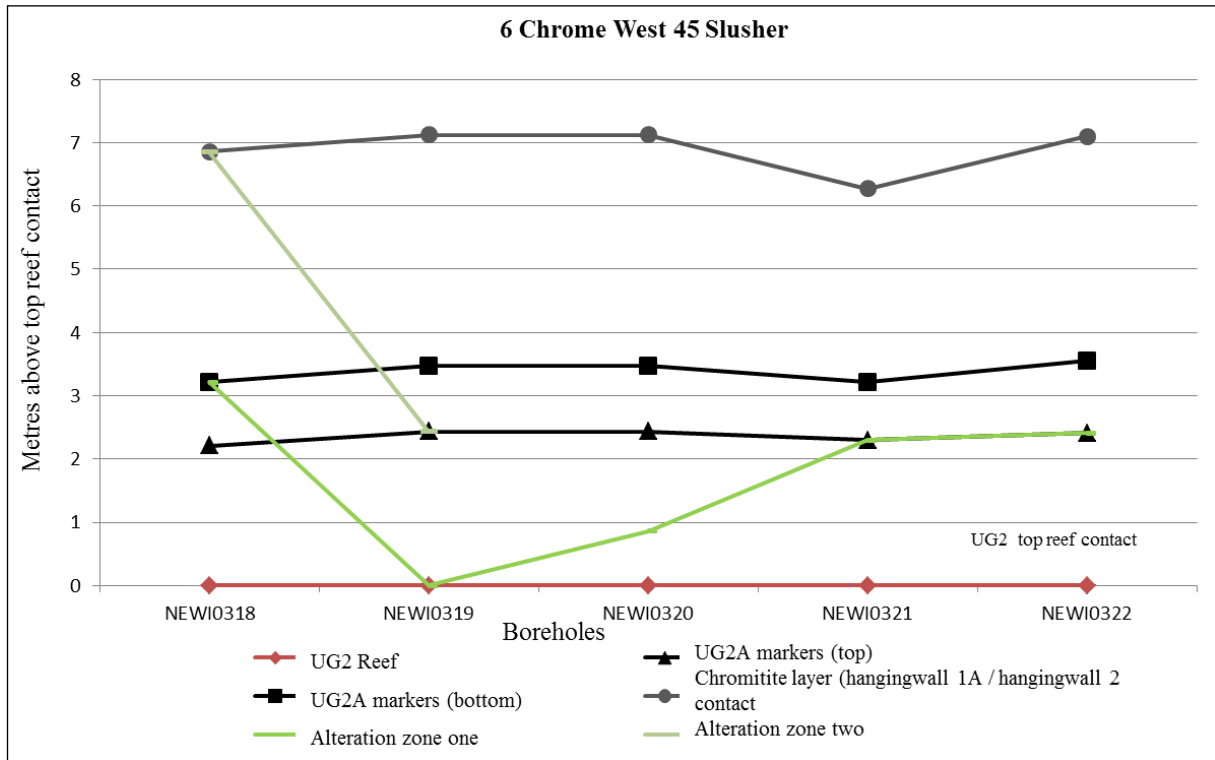
Figure 4.12: Location of alteration zones with reference to the UG2 Reef and UG2A markers along 6 West 45 Slusher. The alteration zones possibly follow ramp structures (Figure 3.2) and may also 'ramp up' from the UG2A markers, as can be seen in borehole NEWI0318 and NEWI0319 (alteration zone two).

4.2.2. Rowland Shaft

A structurally related fall of ground (13.5 m x 3.75 m) occurred at Rowland Shaft during the period of this study. At this site, the alteration zone is present along the top reef contact and the UG2A markers (Figure 4.13). The fall of ground parted from one of the chromitite layers of the UG2A markers situated approximately 1.25 m above the reef. Mining occurred at a depth of approximately 1000 mbs. The fall of ground consisted of a solid block of hangingwall pyroxenite (Figure 4.13). The fall of ground occurred due to the intersection of an E-W striking low-angle joint (dipping at 22° towards the south) and a NNW-SSE striking, sub-vertical joint. The upper boundary of the fall of ground was defined by one of the chromitite layers of the UG2A markers. As mentioned, these chromitite layers are known instability planes with little or no cohesive strength.
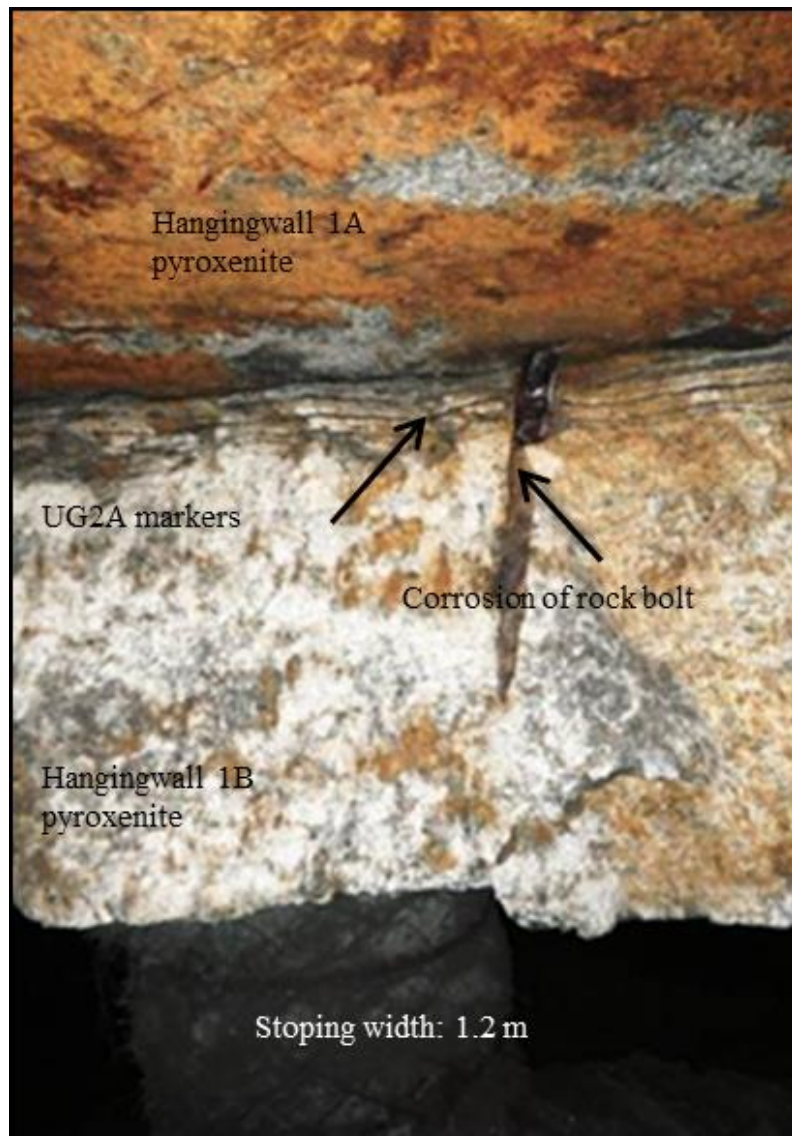
Figure 4.13: Fall of ground caused by ineffective support and corrosion of rock bolts.

The support in the panel consisted of rock bolts (primary support) and grout packs (back area support). Investigations conducted by the author after the fall of ground, highlighted the following issues:

- The thin chromitite layers in the hangingwall 1B pyroxenite form natural parting planes. An alteration zone was exposed along the top contact of the UG2 Reef (Figure 4.13) and/or along thin UG2A markers. This contributes to a decrease in the friction angle of the alteration zones and other contacts. As a result, the potential for parting and consequently hangingwall separation of the strata can occur.
- Corrosion of in-stope rock bolts (Figure 4.13).
- Scaling along the in-stope pillars (Figure 4.14).
- The intersection of secondary geologic structures led to the formation of low-angled, unstable blocks. The interpretation of the geologic structures was important as these influence the

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mechanisms driving the rock mass failure. Geologic structures exposed in the study area at Rowland Shaft include minor faults and joints (Figure 4.15) striking predominantly NNW-SSE and WNW-ESE as well as NE-SW, which coincides with the strike orientation of regional and secondary structures.

- Premature loading of the grout pack support.

Figure 4.14: Anomalous pillar behaviour (illustrated in Figure 4.19) where stress fracturing was identified in the vicinity of the fall of ground where an alteration zone occurred along the top reef contact.

Abnormal hangingwall conditions and pillar behaviour

In a non-yield pillar environment, hangingwall convergence and scaling pillars are not anticipated. The study site on 31 East Level at Rowland Shaft, including the split up-dip mining configuration and layout parameters are illustrated in Figure 4.15. The fall of ground occurred in East 10 East Panel as shown in Figure 4.15.

The grout pack support showed signs of loading (grout cracking) indicating that convergence was occurring in the panel. The underground investigation identified an alteration zone exposed along the top contact of the UG2 Reef. To investigate the extent of the alteration zones and to confirm the position and condition of the prominent parting planes, a borehole was drilled vertically into the hangingwall at East 11 Panel (Figure 4.15). A borehole camera was used to assess the condition of the hangingwall strata and to determine if separation occurred anywhere along the length of the borehole. This borehole intersected the top contact of the UG2A markers at 1.6 m and confirmed separation at the hangingwall 1A/hangingwall 2 contact, at 6.5 m above the top reef contact (Figure 4.16).

Convergence measurements were conducted in East 11, Western Panel using continuous closure loggers. The objective of the monitoring was to give early warning of any potential instability and to understand the convergence behaviour. Figure 4.17 shows that 3 mm of additional convergence were recorded over a period of approximately 6 weeks. Once mining activities stopped, the convergence also stopped. Restricting the mining span also controls convergence.
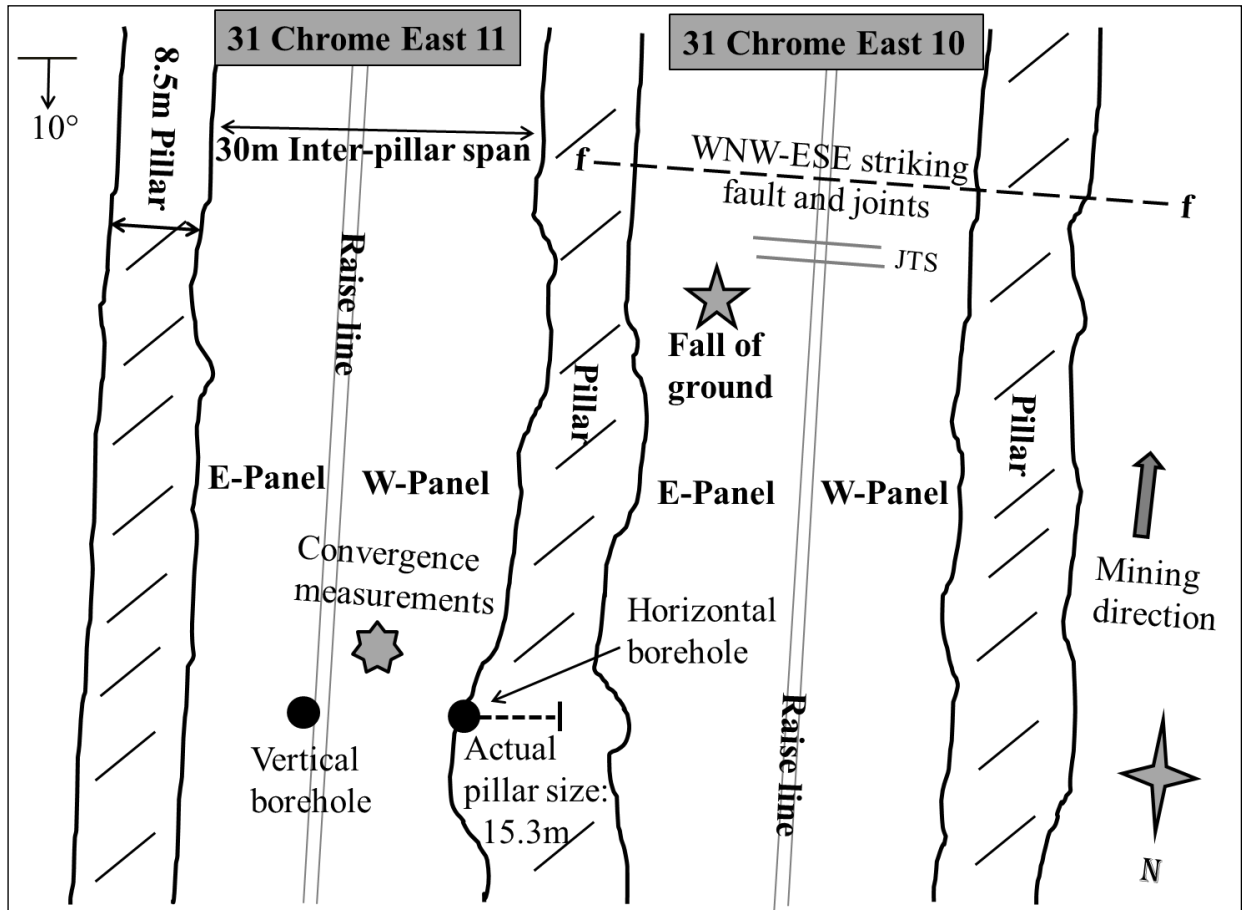
Figure 4.15: Split up-dip mining layout at 31 Chrome East Level, showing the fall of ground and where the vertical and horizontal boreholes were drilled as well as where the convergence measurements were taken.
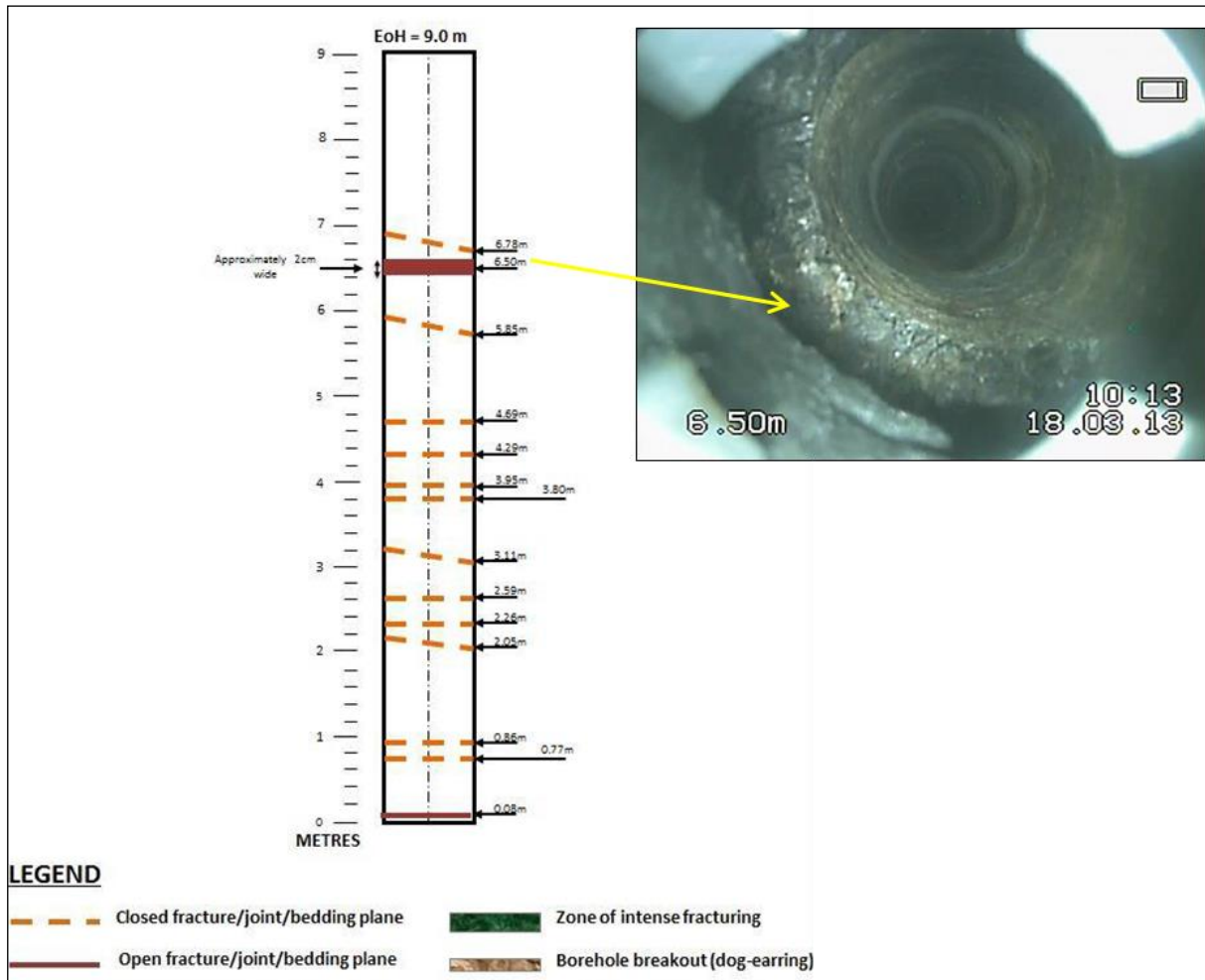
Figure 4.16: Vertical borehole log indicating an open discontinuity in the hangingwall at 6.5 m (possible hangingwall 1A/hangingwall 2 contact).
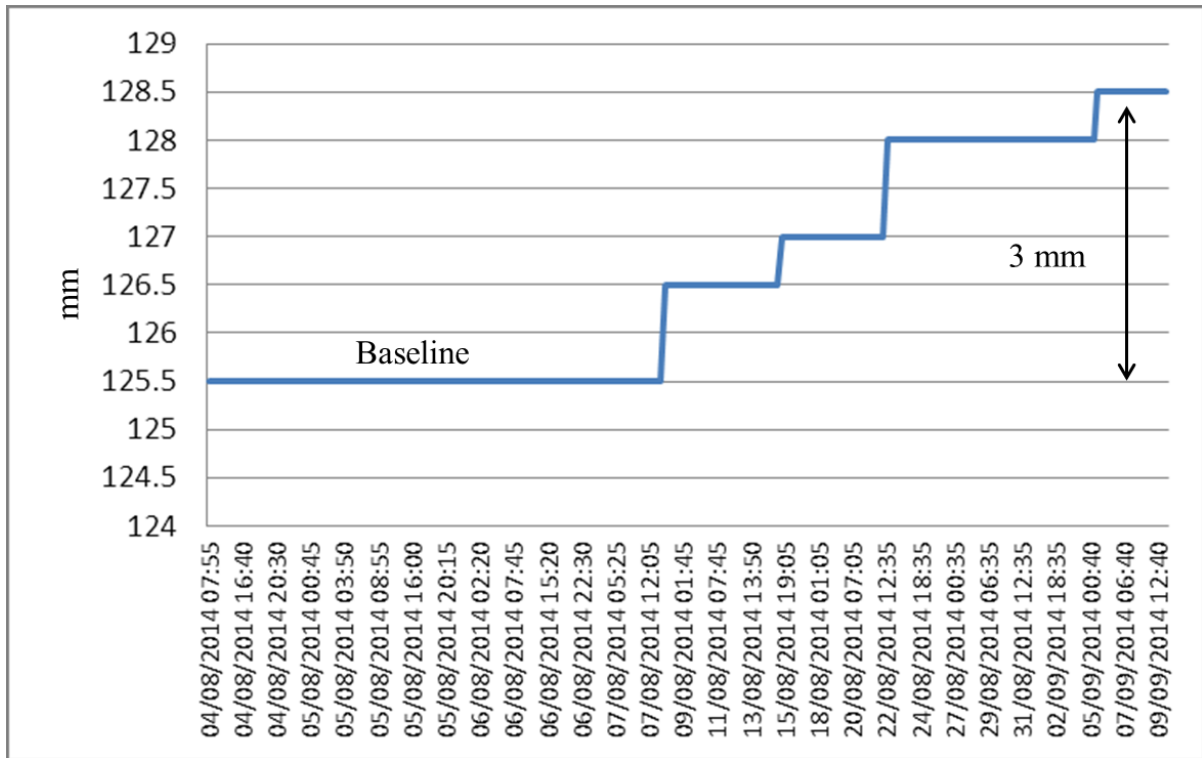
Figure 4.17: Convergence measurements conducted at East 11, Western Panel.

The scaling experienced along the exposed surface of the pillar (Figure 4.14) indicated high pillar stress. The pillar design incorporated a factor of safety of 1.6 resulting in a pillar width of 8.5 m to ensure the stability of the entire hangingwall 1 pyroxenite layer, as well as support the overburden rock mass to surface. Additional regional support is provided by mining and geologic losses present in the mined area.

Figure 4.15 illustrates that the pillar between East 11 Panel and East 10 Panel had an actual width of 15.3 m (exceeding the required width). Also, the pillars were continuous with no pillar holings along the entire level. Therefore, it seems unlikely that the mechanism causing the observed scaling should be as a result of the pillar exceeding its peak strength.

A borehole was drilled horizontally into the pillar from East 11 to East 10 Panel (refer to the position in Figure 4.15). The objective was to determine the extent and depth of fracturing in the pillar. A borehole camera was used to examine the borehole. The borehole fracture log is shown in Figure 4.18. A disruption in the UG2 Reef was identified where reef is present up to 2.5 m into the pillar. For the remaining 3.5 m, hangingwall pyroxenite is exposed. The panel width of the eastern side of East 10 Panel was reduced in the vicinity of the borehole (Figure 4.15). This may have been due to the exposure of potential rolling reef, explaining the off-reef portion identified in the borehole log, increasing the pillar width.

Dog-earring along the borehole was observed to a depth of 1.72 m into the pillar (Figure 4.18). A pillar of this size should not be crushing. The behaviour identified in other areas (east of the Elandsdrift Fault Zone) where an alteration zone is present along the top contact of the UG2 Reef, causes pillars to fail by axial splitting (i.e. Hossy and Saffy Shafts).
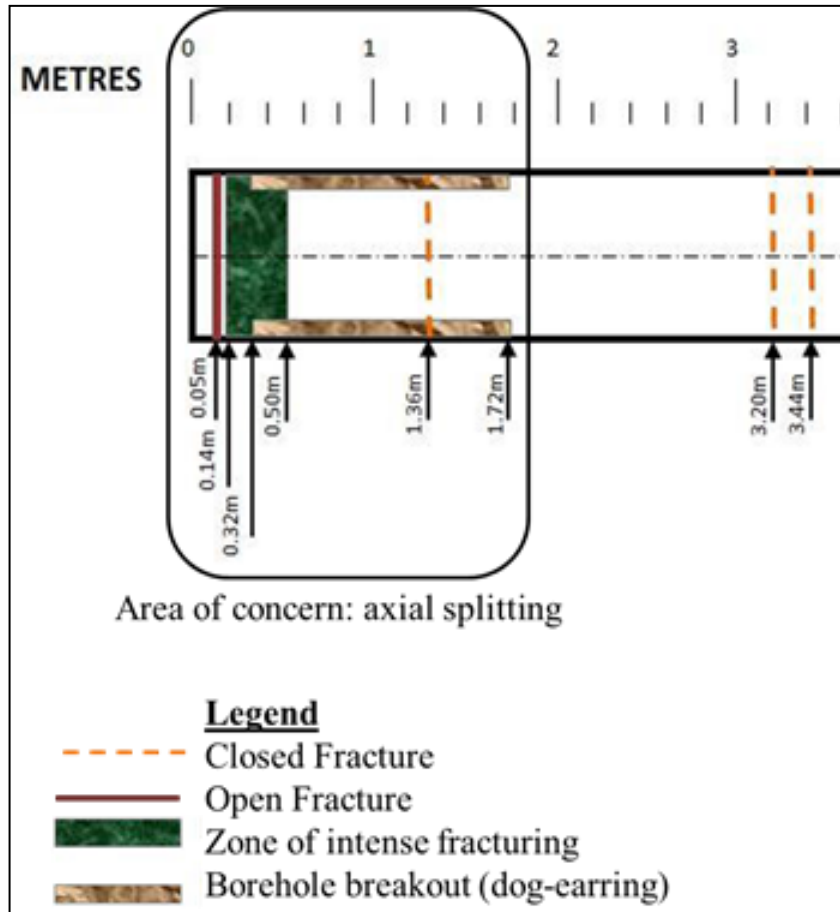
Figure 4.18: Horizontal borehole fracture log that was recorded in the pillar borehole (Figure 4.15) to determine the depth of fracturing. Visible from the log is that the zone of intense fracturing extends for a distance of 0.5 m. Dog-earring along the pillar was observed to a depth of 1.72 m.

Figure 4.16 show that instability was also experienced as a result of possible separation along the hangingwall 1A/hangingwall 2 contact (Figure 1.3).

Figure 4.19 illustrates the proposed failure mechanism that was identified at the fall of ground site. The alteration zone will contribute to the formation and migration of the failed pillar material observed.

A remedial strategy proposed was to implement stiff, active support in order to support to the height of potential parting planes. High strength active (new generation) grout packs should be considered to provide high early strength close to the face and prevent back breaks.
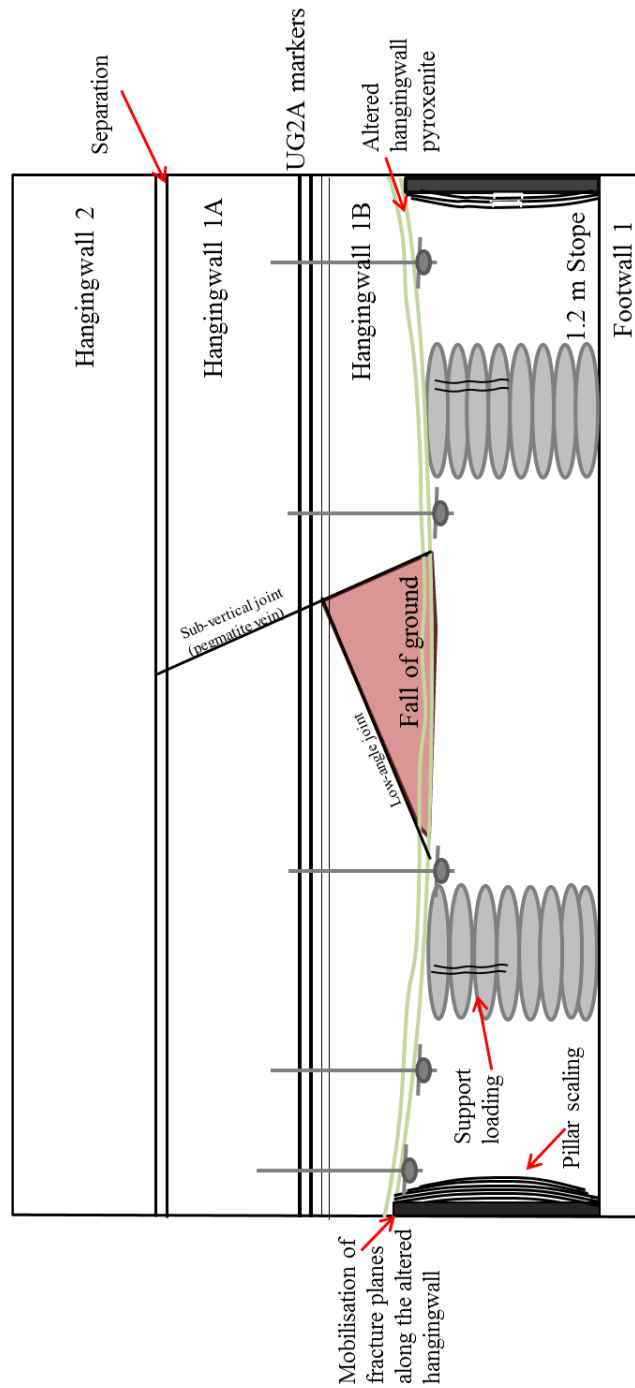
Figure 4.19: Illustration of the proposed failure mechanism when separation occurs in the hangingwall and mobilization along altered material along the top reef contact.

4.2.3. Saffy Shaft

The alteration zones are not well understood in terms of their formation and location. The formation and reactivation of the associated geologic structures is explained in this section. These structures are water bearing that might have triggered the formation and presence of alteration zones along the pyroxenite layers, as explained by Gebrekristos and Cheshire (2012) in Chapter 2.

Hartzenberg and Du Plessis (2017) described the structural complexities of Saffy Shaft (Figure 4.20) at the 'Bermuda Triangle' (Figure 4.21). It represents a portion of ground along the Eastern levels of Saffy Shaft which is bounded by the Saffy East Fault to the west and the Turffontein West Fault to the east. The WNW-ESE and E-W striking, layer (sub)-parallel shearing and alteration zones exposed in the 'Bermuda Triangle' form part of the author's site investigations. The alteration zones cover approximately 57 000 m^2 in this area. Figures 2.20 and 4.20 show the water intersections associated with the geologic structures. Low water intersections are associated with layer parallel structures in the hangingwall 1 pyroxenite and variable water intersections are associated with sub-vertical structures (maximum water intersection measured to be more than 80 000 litres per hour).
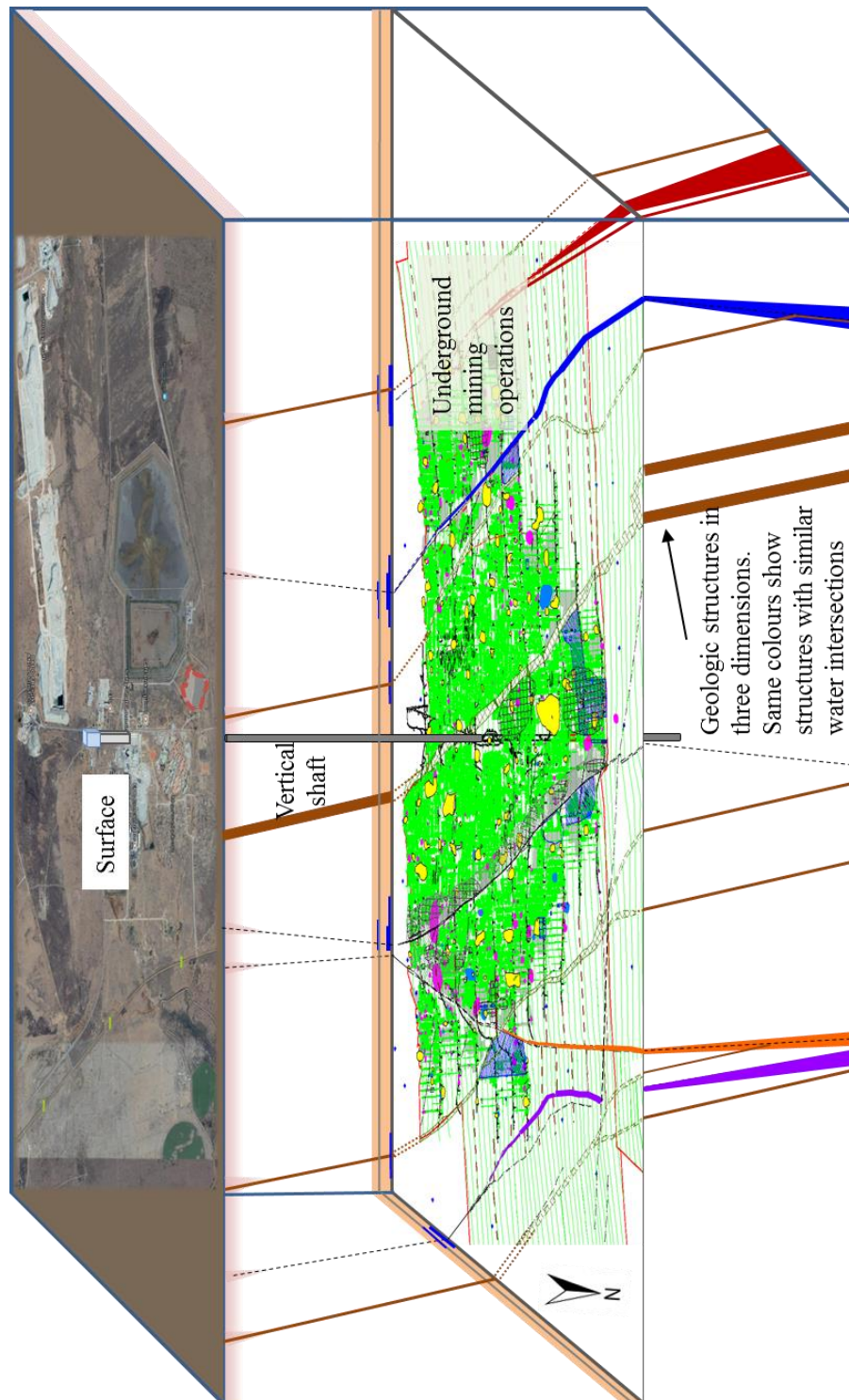
Figure 4.20: Three-dimensional illustration of Saffy Shaft (Figure 2.20), showing the major faults and dykes exposed in the underground mining operations. Similar colours (i.e. red) show structures with similar water intersections, age and composition. Figure 2.20 show the geologic structures and water intersections exposed along the underground excavations (Knipe, 2018). Common practice is to seal the boreholes that intersect water, which divert the water within the rock mass.
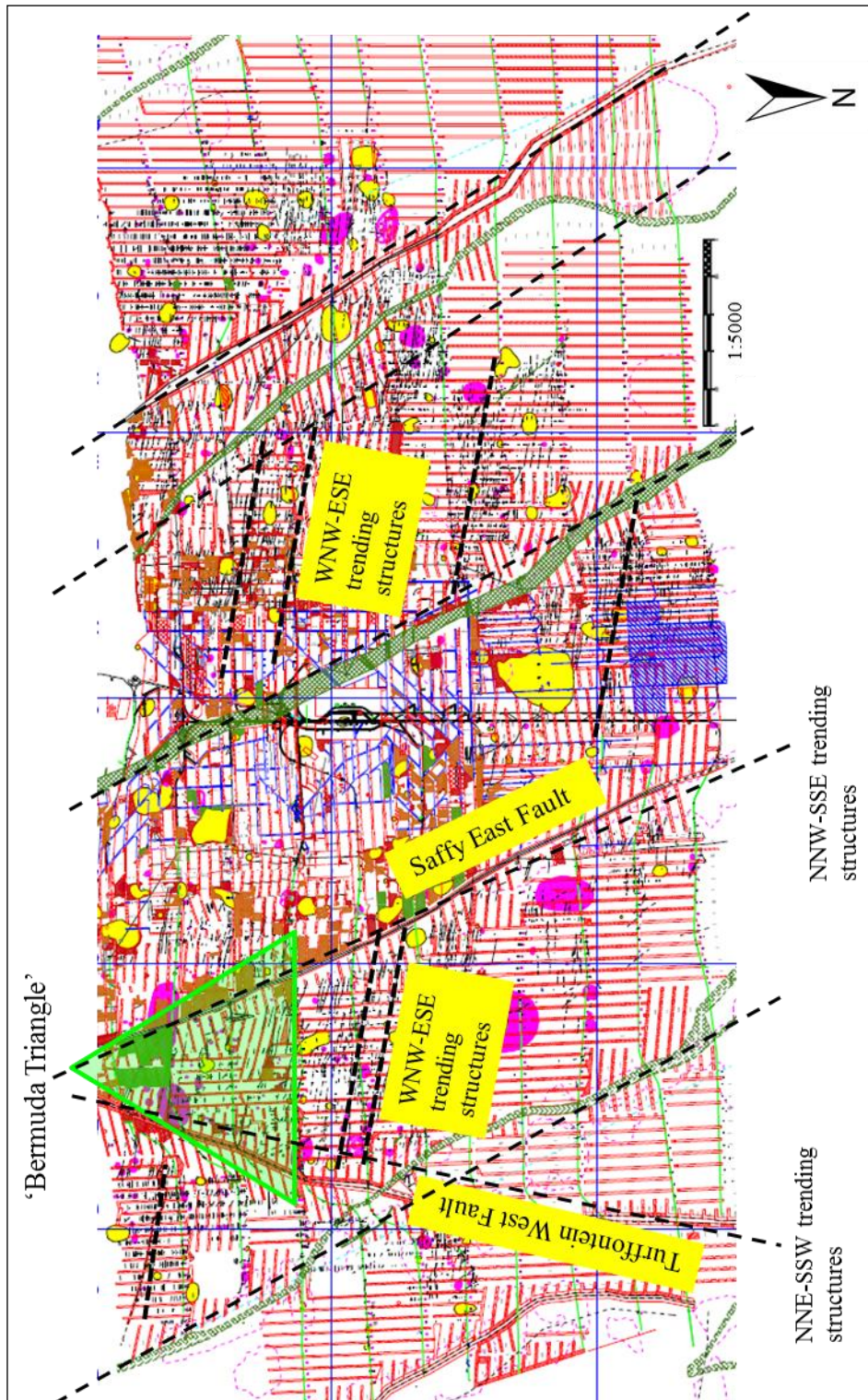
Figure 4.21: Structural plan (as extracted from the Mine Information System) of the Saffy Shaft block, showing the location of the 'Bermuda Triangle'. The UG2 Reef dips at approximately 10˚ towards the north. The affected area is located at 500 mbs. Note that the major trends of the geologic structures are NNW-SSE, NNE-SSW and WNW-ESE.

Saffy Shaft, being a conventional mine with footwall infrastructure, provided an opportunity to investigate the major structures (Saffy East- and Turffontein West Faults) where it was intersected by the footwall haulages (Figure 1.3).

The Saffy East Fault

The Saffy East Fault forms the western boundary of the graben defining the 'Bermuda Triangle'. The structure strikes NNW – SSE, dips eastwards at an angle of 75 – 80˚, and displaces the reef by 10 – 15 m down to the east. The main fault plane exhibits a generation of sub-vertical extensional serpentine slickenfibres (mineral fibres showing the direction of relative displacement), which are overprinted and partially obliterated by a younger generation of horizontal slickensides (striations indicating the direction of movement) and calcite-chlorite slickenfibres. These indicate that the Saffy East Fault initially formed as a normal dip-slip fault, which subsequently underwent a phase of sinistral strike-slip reactivation. The secondary faults were formed together with the Saffy East Fault during the initial extensional phase of normal dip-slip movements. Minor ground water flow can be observed along the Saffy East Fault.

A series of NNW-SSE to NW-SE striking, 10 – 65˚ dipping, WSW- to SW-dipping, listric-shaped minor faults, splay from the latter on its eastern side. They merge with sub-horizontal layering; thereby forming layer-parallel extensions of variable dimensions (Figure 4.22). All these structures form part of a shear joint envelope that developed when the Saffy East Fault underwent a later reactivation phase of sinistral strike-slip. Figure 4.22 indicates that the intersection of closely spaced faults and joints can result in adverse ground conditions. The intersection of steeply dipping faults and listric faulting might lead to falls of ground. These structures strike parallel to the Wegener Stress Anomaly.
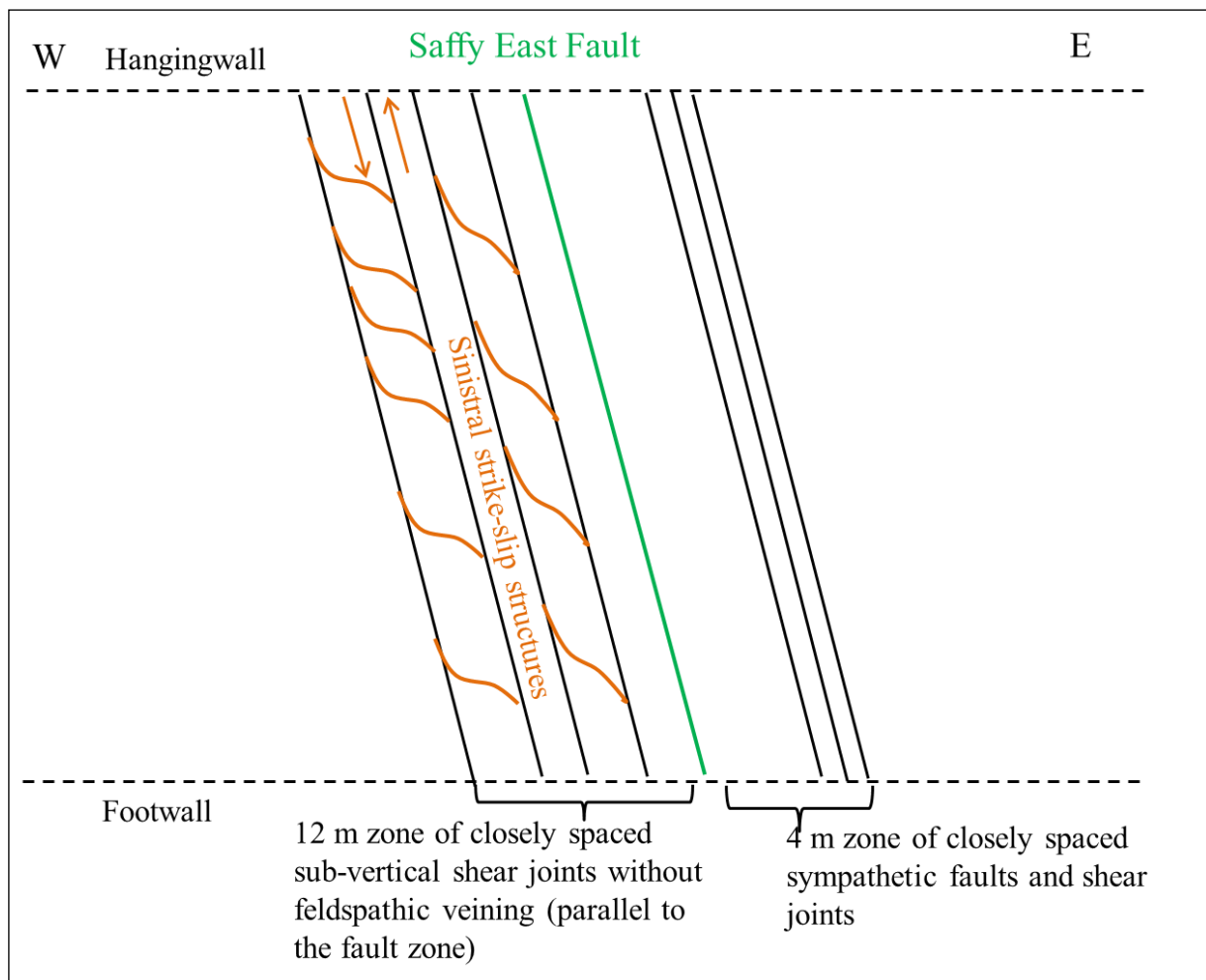
Figure 4.22: Schematic representation of the section view with the secondary structures associated with the Saffy East Fault as observed in the sidewall of a haulage. The fault is dipping at 85˚ with a throw of 10 m.

The Turffontein West Fault

This fault (Figure 4.23) forms the eastern boundary of the graben 'Bermuda Triangle'. This fault strikes NNE-SSW, dipping at of 70˚ towards the west displacing the reef by 30 – 42 m down to the west. This fault is characterized by an 40 cm wide zone which comprises of a 2 – 5 cm wide semi-ductile fault rock with a mylonitic fabric (proto-mylonite) developed around massive plagioclase-quartz pegmatite veining (25 - 35 cm wide), and exhibiting intense hydrothermal alteration (infill of serpentine, chlorite or calcite).

The secondary faulting (Figure 4.23) comprises of both sub-vertical shears and shear joints sympathetic to the Turffontein West Fault, as well as extensional, listric-shaped, westerly inclined splays merging with the layering. The listric extensional faults contain thin (a few centimetres wide) plagioclase-quartz veins. Furthermore, subsidiary extensional normal dip-slip faults (with 40 – 50 cm offsets) antithetic to the Turffontein West Fault are developed in its immediate hangingwall. When these structures are exposed by mining operations, adverse ground conditions might occur. These exhibit normal dip-slip movements and

contemporaneous serpentinization, but no evidence of a later phase of strike-slip reactivation along their planes. Minor ground water flow is present along the Turffontein West Fault itself, but not along the subsidiary fault-fracture system in its hangingwall blocks. These structures do not strike parallel to the Wegener Stress Anomaly. Neotectonic activity is characterized by reactivation of ancient faults, dykes and creation of new fractures. It could also play a role in the exploration of groundwater. Figure 2.20 show that there isn't a continuous alteration zone along the NNE- strike length of this major structure.
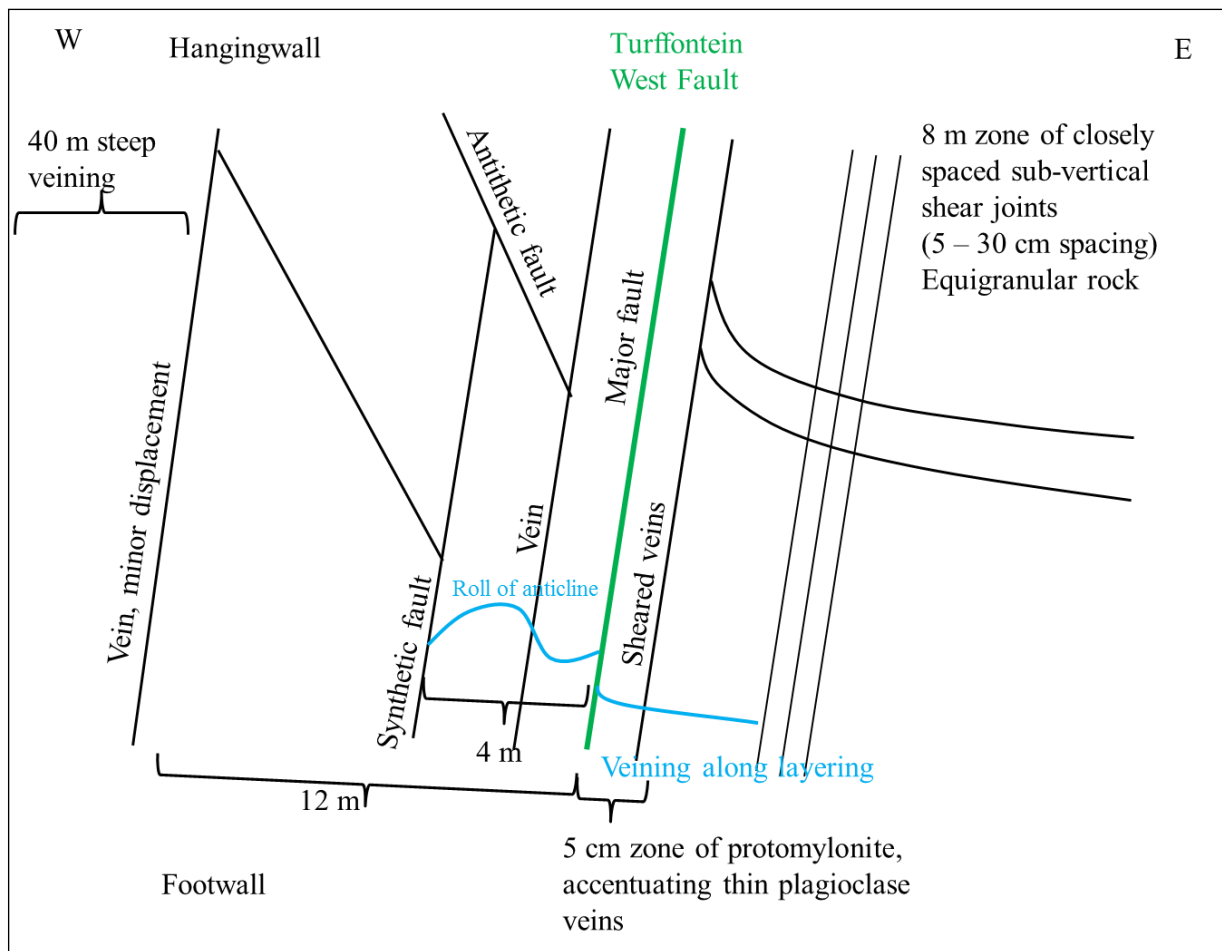
Figure 4.23: Schematic representation of the section view of structural elements associated with the Turffontein West Fault exposed in the sidewall of a haulage.

WNW-ESE and E-W striking fault systems

Apart from the subsidiary fault and shear joint system of the 'Bermuda Triangle' developed immediately adjacent to both the Saffy East- and Turffontein West Faults, the interior of this graben is traversed by a system of closely spaced faults and joints. These are WNW-ESE striking, dipping at 60 – 80˚ to the north- and south-dipping structures and displace the UG2 Reef between 0.3 m and 1.8 m. These faults and joints exhibit signs of hydrothermal fluid flow and associated alteration (serpentinization, chloritization, and/or

calcitization) and plagioclase-quartz pegmatite veining. These structures have been termed the Marikana structures (Figure 4.24). It was confirmed by sub-surface profiling (Figure 3.33) that these structures cut through the hangingwall up to or beyond the hangingwall 1A/hangingwall 2 contact and contributes towards large-scale instabilities from the findings at the various site investigations.

Layer (sub)-parallel shearing and alteration zones

Figure 4.24 show the scanned image along dip in a panel for 19 m, as well as an interpretation from a sub-surface profiler. Notice how the deformation events 1 and 2 (ramp structures) 'ramp up' to the potential weakness planes. These are also possible sources/locations of the alteration zones. The red zone from the scanned image confirms that a significant alteration zone is present along the UG2A markers, at the scanned location.
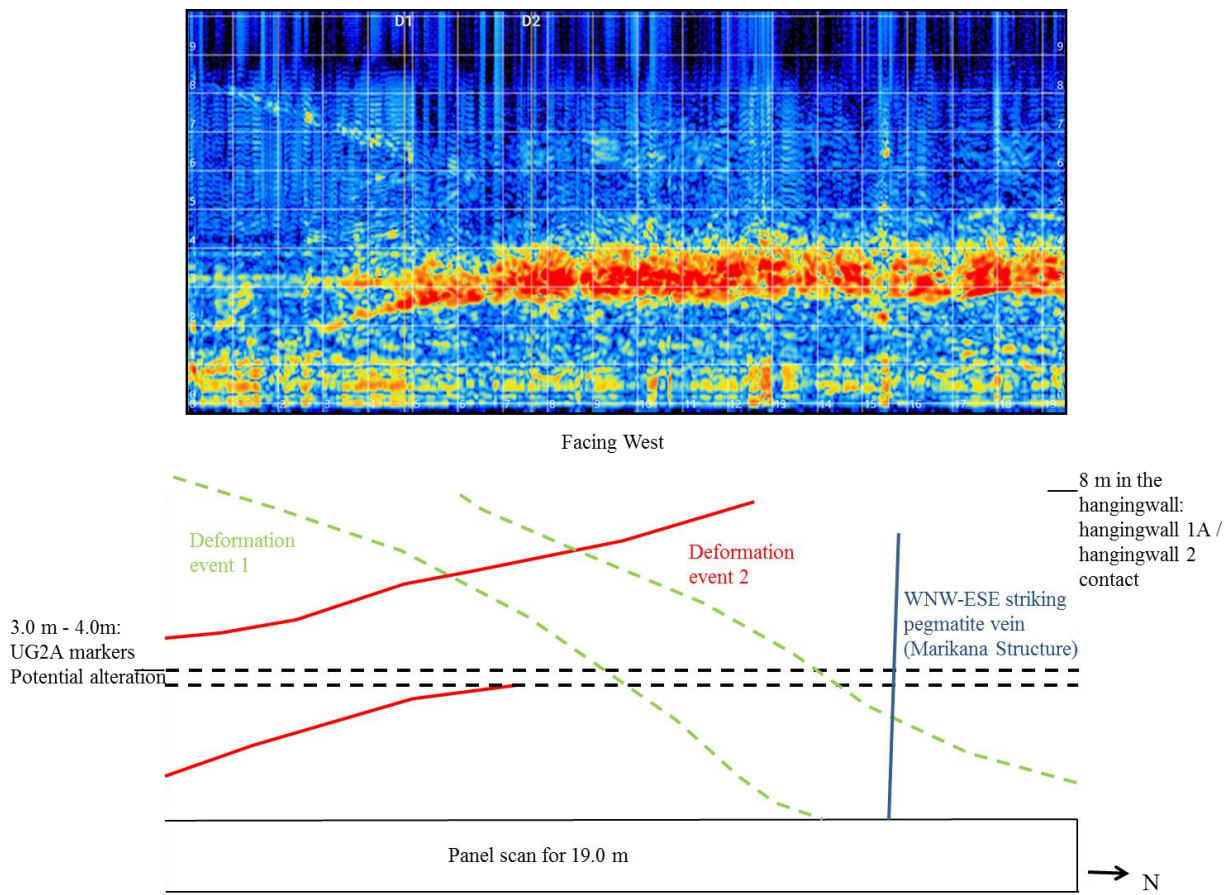
Figure 4.24: Sub-surface scan and interpretation of the hangingwall, showing a Marikana structure, deformation events 1 and 2 as well as an alteration zone along the UG2A markers.

Layer (sub)-parallel shears or shear zones (Figure 4.25) with associated ductile and semi-brittle fault rocks and hydrothermal alteration zones (serpentinization and chloritization) are developed in the vicinity of the UG2 Reef. These alteration zones occur along the top contact of the UG2 Reef (Figure 4.9), and/or along the

UG2A markers (Figure 4.24) in the hangingwall of the UG2 Reef, as well as at the footwall 5/footwall 6 shear (Figure 1.3).

Compressional and extensional interlinking ramps splay from individual alteration zones and can merge with others at various stratigraphic levels, i.e. forming an interlinking compressional and extensional system between layer-parallel alteration zones (Figure 4.25). These proto-mylonite-bearing ductile shear zones formed as flexural-slip thrusts in late-Bushveld Complex time during cooling and bending/flexing of the layered complex as shown in Figure 4.26.

On-reef pillars often exhibit fracturing at an angle of 45˚ (Figure 4.25) to the layer-parallel shear zone developed along the UG2 top reef contact. Pillar failure in the form of slabbing usually occurs along this fracture system in the vicinity of the altered hangingwall 1B pyroxenite. This fracture system is interpreted preliminarily to be part of an extensional shear fracture system, which formed between the layer-parallel footwall 5/footwall 6 and the UG2 top reef contact shear zones. It is hypothesized that this occurred during a phase of post-Bushveld Complex extensional reactivation of late-Bushveld flexural-slip thrusts, referred to as alteration zones (Figure 4.25). As more ground water is introduced into the rock mass it will contribute towards deterioration in the ground conditions which will promote large-scale instabilities.
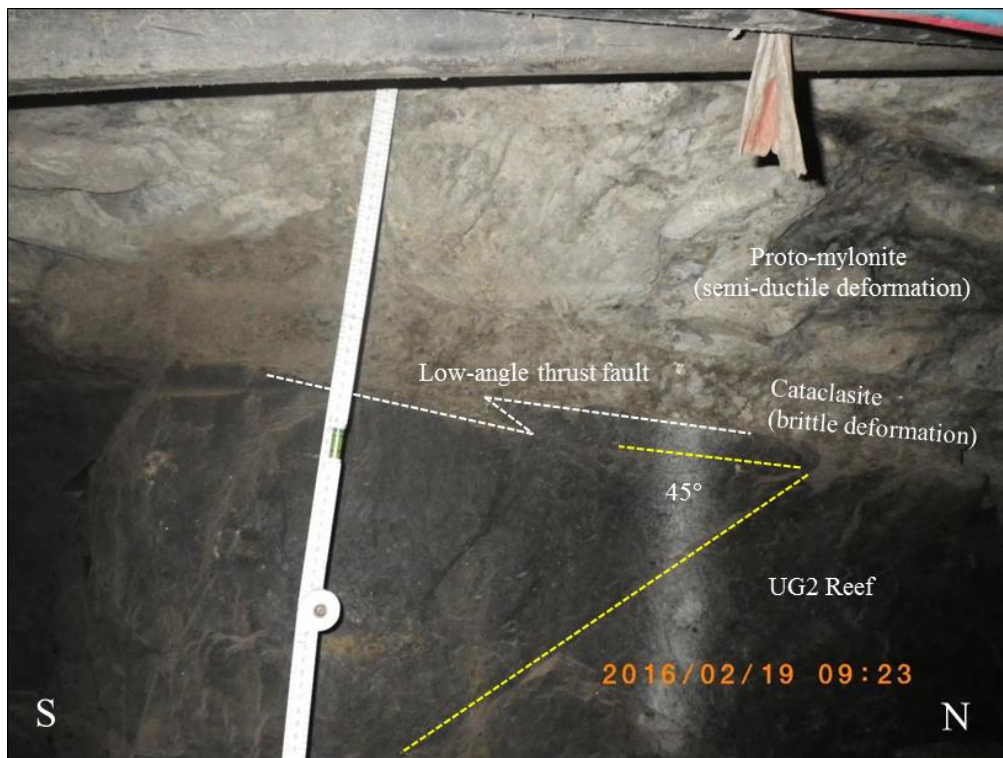
Figure 4.25: Late-Bushveld Complex layer-parallel flexural-slip thrusting towards the south (out of the Bushveld Complex at Lonmin) along the UG2 top reef contact.

Layer (sub)-parallel deformation zones was identified by the author during underground investigations. It is hypothesized by the author that the deformation zones exhibit a developmental history comprising at least two stages, namely (Figure 4.26):

- Deformation event 1: southerly-directed (out of the Bushveld Complex at Lonmin), reverse dip-slip movements (flexural-slip thrusting) along prominent lithological contacts under ductile conditions, accompanied by proto-mylonite formation and intense hydrothermal alteration (serpentinization) within the shear zones.

- Deformation event 2: northerly-directed (into the Bushveld Complex at Lonmin) extensional (normal dip-slip) movements under brittle conditions, reactivating flexural-slip thrusts and developing a new extensional shear fracture system around them. These result in cataclastic overprinting of older proto-mylonites and are accompanied by intense hydrothermal alteration (calcitization) and calcite veining. It is important to note that the effects of deformation event 2 are not always present (Figure 4.26).

Interlinking ramp structures have also been identified between the major structures that trend NNW-SSE and WNW-ESE as illustrated in Figures 3.2 and 3.4. The illustrations shown in Figures 3.35 and 4.24 confirm that these structures 'ramp up' to the weakness planes. This is the first time that the location of these structures could be confirmed by means of sub-surface profiling and contributes to the understanding of the structures in three-dimensional space (Figure 3.2).

Although the descriptions discussed above appear complex, the associated behaviour can be identified from the structures exposed (Figure 4.26). The inflow and presence of water will impact on the degree of alteration along these deformation zones. It is hypothesized that the discontinuities (top reef contact, UG2A markers and hangingwall 1A/hangingwall 2 contact) are water bearing structures. The water is mobilized along the geologic structures when mining starts and this may possibly have a destabilizing effect. It has been noted during the site investigations that the alteration zones are dry in old mined out areas, as opposed to the current mining operations where it has a 'clay-like' nature (wet) that promotes unravelling and instability.
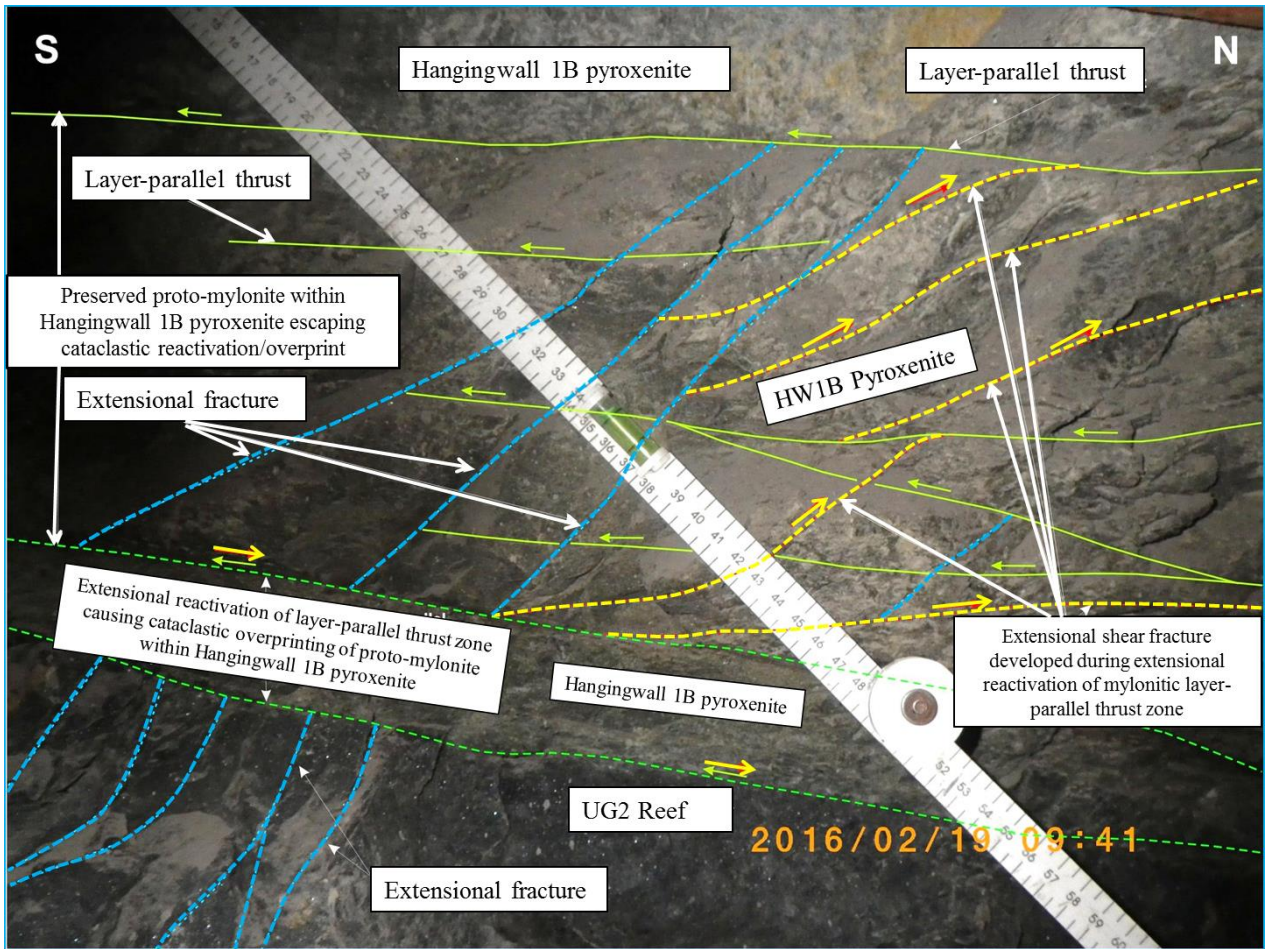
Figure 4.26: Alteration and ramp structures exposed in the hangingwall 1 B pyroxenite.

Figure 4.27 is a section view of a borehole that was drilled into the hangingwall, beyond the hangingwall 1A/hangingwall 2 contact in an area which experienced instability. From this borehole it is clear that multiple structures, including possible ramp structures, joints and alteration zones are present in the hangingwall. Separation is identified along some of these structures by means of a borehole camera. The storage of the ground water is predominantly along the UG2A markers and hangingwall 1A/hangingwall 2 contact as shown in Figure 4.27. The first phase of instability is anticipated to occur up to the UG2A markers which will be followed by subsequent instability up to the hangingwall 1A/hangingwall 2 contact. This information coincides with the sub-surface profile scan (Figure 4.24) that confirmed the occurrence of multiple geologic structures and how these combinations contribute to large-scale instabilities.
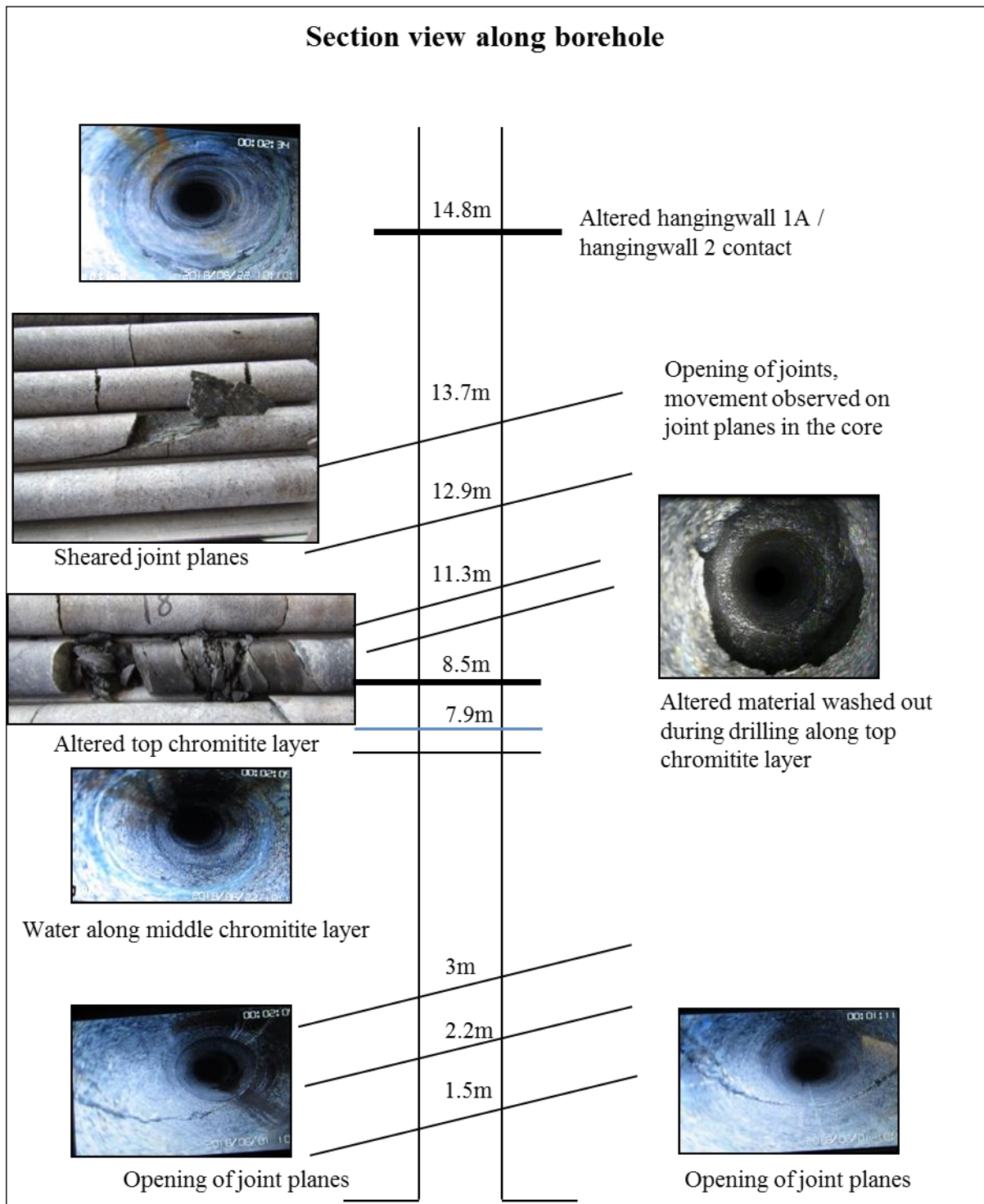
Figure 4.27: Section view of borehole log with images illustrating multiple geologic structures exposed in the hangingwall, in an area where large-scale hangingwall instability was experienced (Liebenberg and Du Plessis, 2018). All of the structures shown in the log experienced minor movement on the alteration.

The geologic structures and alteration zones that have been studied in detail at Saffy Shaft has also been exposed along the Eastern levels on Hossy Shaft (Figure 3.25). Unstable hangingwall conditions related to the occurrence of complex geologic structures and alteration zones were experienced, similar to Saffy Shaft.

Approximately 20 000 m^2 of ore reserves had to be abandoned along the Eastern levels on Hossy Shaft, mining towards the Hossy Dyke (Figure 3.25). This was due to the exposure of persistent alteration along the top reef contact, resulting in unravelling around installed support units and falls of ground (Figures 4.1 and 4.2). Figure 4.28 is a stereographic projection of the main joint sets exposed in the vicinity of the Hossy Dyke. The stereo net plot shows that three of the joint sets strike approximately NNW-SSE, NW-SE and WNW-ESE. These orientations are similar to the structures exposed along Hossy's western levels (Figure 3.29) as well as Saffy Shaft (Figure 2.21). Also, falls of ground occur within 5 m from the current face positions in the stoping panels. Along the western level belt drives, significant pillar slabbing has been experienced. Here a persistent alteration layer is present. The excavation span is only 5 m with 7 m belt protection pillars on either side. The pillar slabbing is related to the mobilization of pillar material along the joint planes, as experienced at Eastern Platinum Limited 2 and Saffy Shafts.
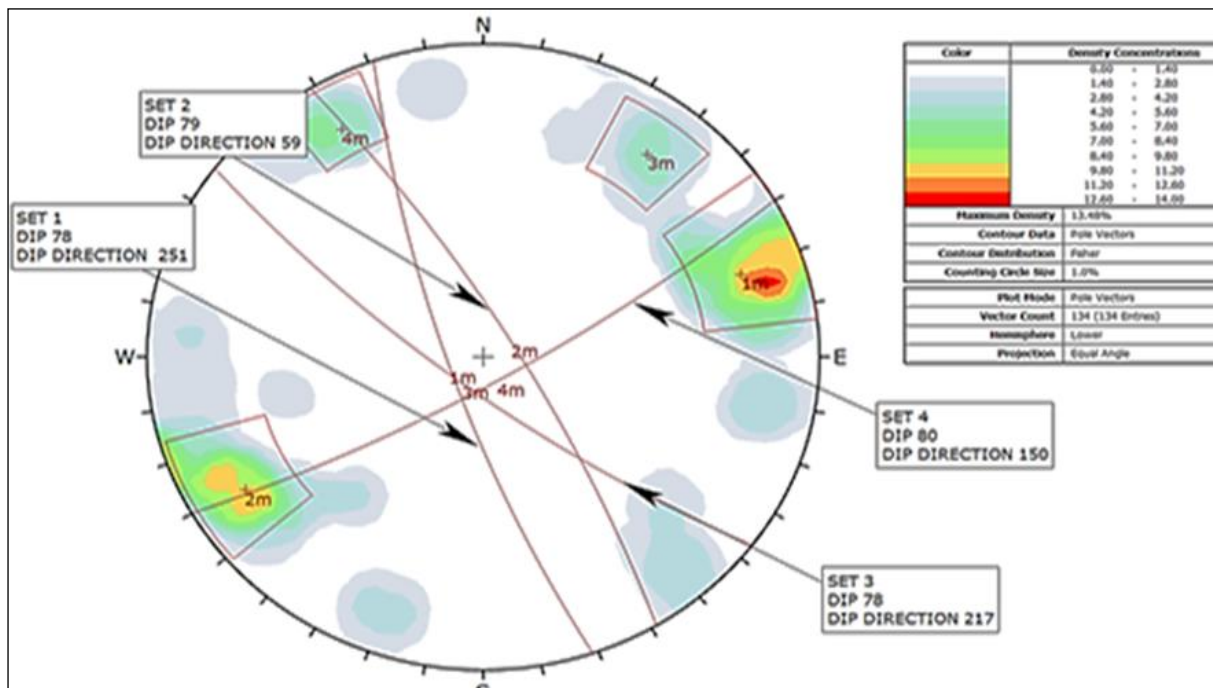
Figure 4.28: DIPS stereo net projection indicating the grouped joint sets. Predominant strike direction of the structures is NW-SE, which may promote ground water inflow.

4.2.4. Everest Mine

Similarly on Everest Mine (Figure 4.29), situated along the Eastern Limb of the Bushveld Complex, anomalous pillar behaviour was observed by the author as a result of a significant alteration zone present along the top of the pillars (Figure 4.30). The pillars deteriorated to such an extent that the mine stability was jeopardised. From the underground investigations, the failure of pillars was caused by the presence of the alteration zone and is not due to excessive stress.
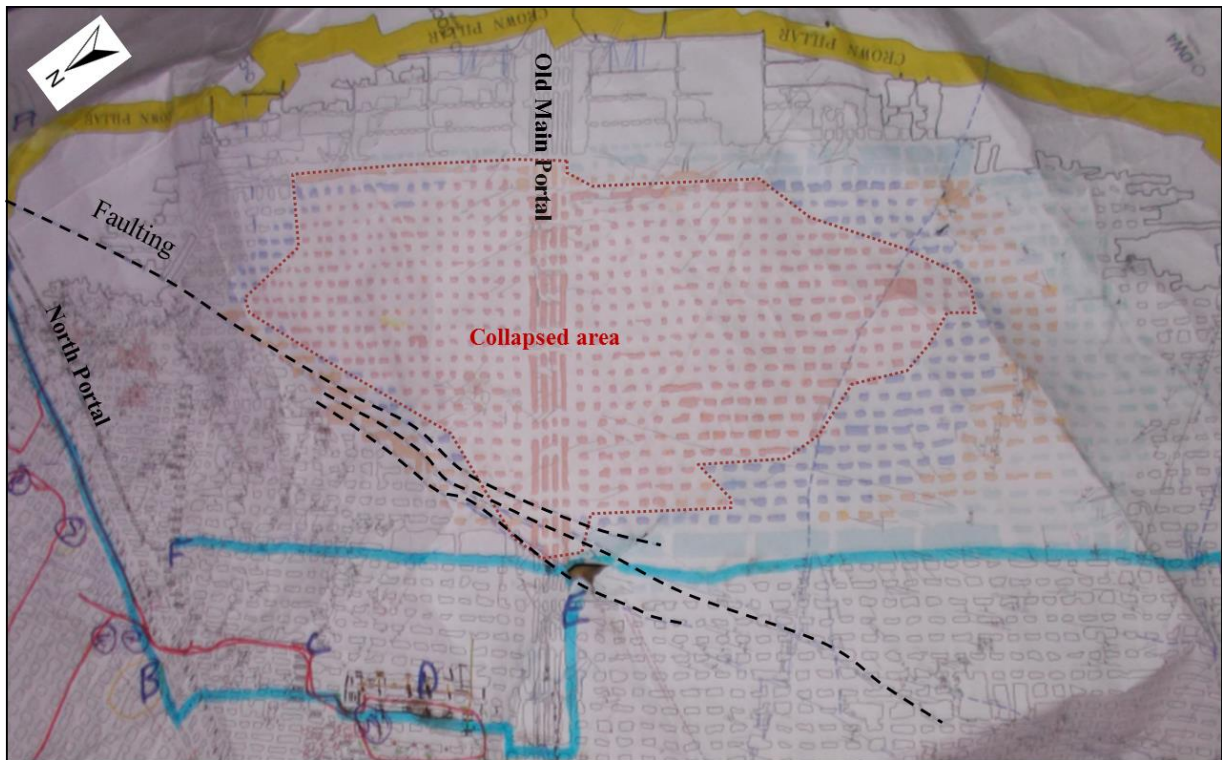
Figure 4.29: Everest Mine where the red hatched area show the collapsed area.
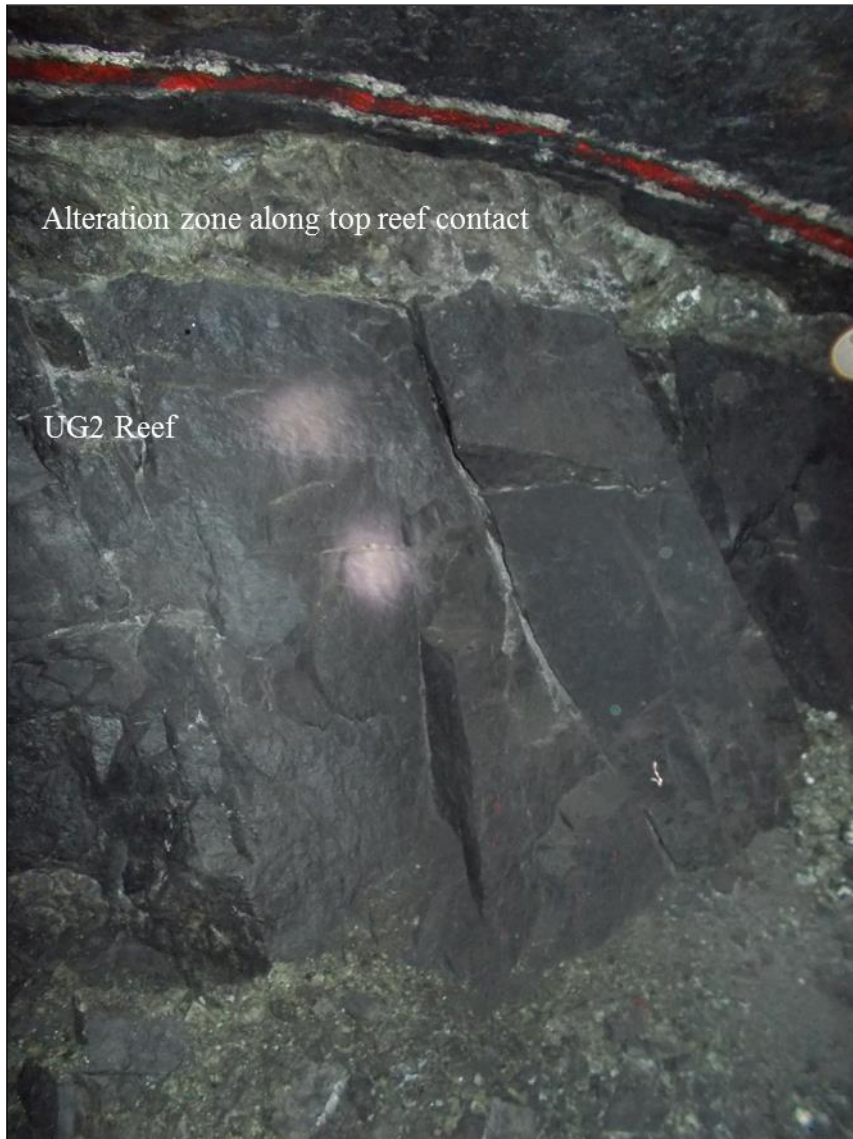
Figure 4.30: Alteration zone exposed along the top reef contact.

Figure 4.31 shows the modes of failure along the in-stope pillars where alteration is present. Mobilisation can be identified along the alteration zone, causing the joints to dilate. The slabs of rock defined by the joint planes are mobilised, resulting in the external pillar slabbing observed. As with the Bimha instability at the Great Dyke, tension cracks were visible on surface as a result of the pillar failure. It is therefore very important to understand this change in pillar behaviour where alteration zones are present to ensure that it is anticipated in the pillar and mine design. Further work is required to understand this pillar behaviour.
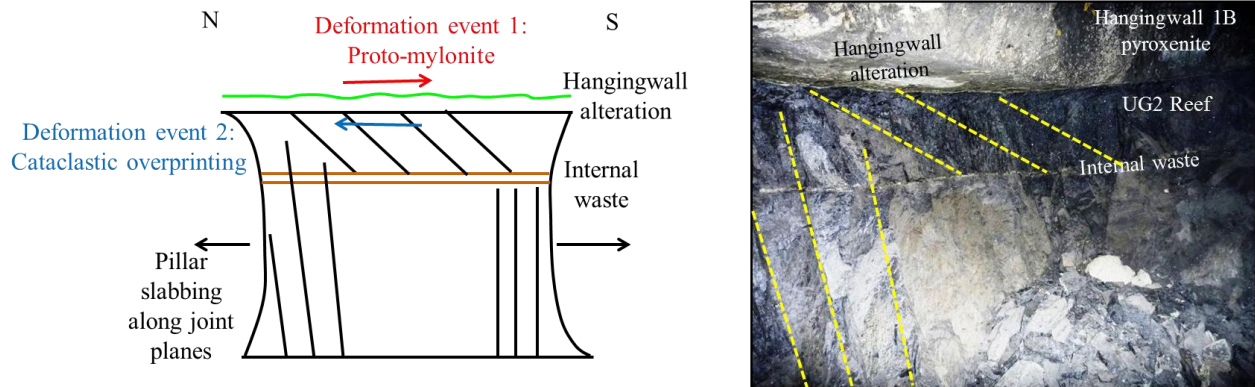
Figure 4.31: Pillar behaviour when an alteration zone and jointing is present.

4.3. Findings and Remedial Actions

Drilling campaigns should be launched in areas where alteration zones are expected. The location (relative to the UG2 Reef) and extend of the alteration zones should be determined prior to developing areas to be mined. This is to determine if it is economically viable to mine or not and will impact on the appropriate mining and support strategy.

Effective identification of the structures and alteration zones can assist in the planning and design processes to ensure appropriate design and layout strategies. The main risks of the presence of alteration zones along the top reef contact include:

- Unravelling of the hangingwall between installed support units.
- Excessive loading of support units.
- Premature failing of the pillars along joint planes.
- The mobilization of joint planes along the hangingwall alteration zone.
- Large-scale instabilities where the alteration zones are located in the hangingwall units (UG2A markers and / or the hangingwall 1A/hangingwall 2 contact).

The challenges of mining these areas include the unpredictability of the position of the alteration zones, increasing the risk to persons as a result of the potential increase or occurrence of small- to large-scale falls of ground. The risks include ore reserve write-offs, low extraction ratios, increased support resistance requirements, costly support and increased mining costs. This also includes increased stope volume and hence increased grade tonnage to be transported and processed with a potential decrease in recovery. Pre-development of the orebody is expensive and there is no guarantee of mining. Instability of the hangingwall resulting from the poor ground conditions remains an unknown risk. As improvements in support and mining technology occur, it may enable the reserves to be extracted by applying alternative layouts, mining

methods and support strategies. From the case studies, the remedial strategies that have been proposed by the author to prevent these occurrences are described in the table below.

Table 4.1: Remedial strategies proposed in areas where alteration zones are present, as a result of the work conducted in this study.

Conditions	Remedial strategies proposed
Alteration zone is located at the top contact of the UG2 Reef.	• Apply permanent blast resistant mesh (Figure 4.32) in an attempt to contain the possible unravelling between support. • Use flexible mining cycles to ensure daily blasting is not required. This will allow time for support installation. • If the grade is too low (dilution), abandon the problematic areas. • Use ground penetrating radar technology (sub-surface profiler) to identify the structures. • Pinning and strapping of the pillars to prevent pillar slabbing. • Increase the factor of safety of the pillars to ensure that the unravelling pillars (slabbing phenomena) are accommodated. • Further work is required on the design of pillars where alteration zones are present.
Alteration zone is located in the hangingwall or footwall units of the UG2 Reef.	• Implement stiff, active rock bolt support to reinforce the hangingwall up to the UG2A markers. • Implement the stiff, active (new generation) modular grout pack to prevent separation in the hangingwall. • Limit the mining spans to 27 m.
Presence of water in conjunction of the alteration zone.	• Sealing of boreholes that intersect water is common practice. The mobilisation of this water in the rock mass structures contribute to poor ground conditions.

	• Drain the water from the boreholes to promote 'dry' and not 'wet' conditions along the alteration zones. 'Wet' conditions promote unravelling as well as instability and should be prevented.

Figure 4.32: Permanent, blast resistant mesh to prevent the unravelling of the alteration zone.

4.4.   References

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CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

5. CONCLUSIONS

The case studies conducted by the author at various shafts at the Marikana Operations and in the Bushveld Complex confirmed, and in some instances challenged, the findings in literature regarding the mechanisms controlling the UG2 hangingwall and in-stope pillar behaviour. Unstable behaviour is mostly caused by the exposure of numerous low-angle structures of various scales, commonly referred to as 'doming'. On most operations, these low-angle structures are treated simplistically or are simply ignored. Also, the presence of pegmatite veins, that is a common joint characteristic, is generally ignored as the potential for instability is not well understood. Furthermore, the presence of alteration zones is typically overlooked as it is not common. The exposure of these prominent structures or a combination of these structures can create circumstances that impact on the exposed hangingwall conditions, stable mining span, support- and pillar behaviour. In some instances the impact have resulted in loss of life, ore reserve write-offs and even mine closure.

This study focused on the following key areas:
- Investigate the formation and occurrence of the prominent geologic structures exposed in the underground mine workings which contribute to the large-scale instabilities.
- Develop an improved understanding of the potential failure mechanisms associated with these structures.
- Develop remedial strategies and leading practices to minimise the impact associated with these structures.
- Identify gaps in knowledge and make suggestions for further work.

During the study, the following failure modes have been identified by the author:
- Structure:
  - Marikana structures: The WNW-ESE striking, pegmatite veins that dip towards the south cut the hangingwall strata. Separation along these structures has a direct impact on the hangingwall behaviour. The presence and orientation of these structures should be considered when determining the mining span and direction.
  - NNW-SSE striking joint clusters: These structures run parallel to the major fault orientation and contribute to hangingwall instability. Where an alteration zone is present in a pillar, these structures contribute to the pillar slabbing observed.
  - Ramp structures: These low-angled curved structures 'ramp up' to significant stratigraphic weakness planes. This results in unstable block and low-angle wedge formation when it terminates against prominent geologic structures.
  - Dykes: These vertical igneous intrusions may increase the horizontal compression in the hangingwall. It also disrupts the continuity of the hangingwall with weak near-vertical

planes at the dyke contacts. Both of these conditions will impact on the hangingwall behaviour and should be considered in the support design methodology.

- Alteration:
  - When present along the top reef contact; this may result in the unravelling around installed support units. It can also cause anomalous pillar behaviour by mobilizing the joint planes, impacting on the pillar strength.
  - When present along the bottom reef contact situated within the immediate footwall; this may result in footwall heave causing the failure of support units.
  - When present in the hangingwall units (UG2A markers and/or the hangingwall 1A/hangingwall 2 contact), it may cause instability, impacting on both the hangingwall and support behaviour.
- A combination of Marikana structures, NNW-SSE striking clusters, ramp structures and alteration zones could result in large-scale instabilities which are considered the worst case scenario.

5.1. Overview of the formation and occurrence of prominent geologic structures

The underground failures and sites that were investigated by the author provided evidence of specific key characteristics of the dominant geologic structures. The investigations and information collected from literature by the author provided the background and context for an improved understanding of the key contributors to the anomalous behaviour on the UG2 Reef horizon.

From the study, it was found that the regional stress field influenced the hangingwall rock mass behaviour. Neotectonic activity in Southern Africa has been analysed in terms of known stress fields. Most of South Africa is dominated by a NW- to WNW- trending horizontal compressive stress field. This is also described as the Wegener Stress Anomaly. Neotectonic activity is characterized by reactivation of ancient faults, dykes and creation of new fractures. It could also play a role in the exploration of groundwater.

Where alteration is present along the stratigraphic layers, specifically at the interfaces (UG2A markers and/or the hangingwall 1A/hangingwall 2 contact), it promotes separation along stratigraphic layers which contribute to structurally-related instabilities. Also, the inflow of ground water is promoted along these structures, contributing to the presence of alteration zones.

5.1.1. Impact of the prominent geologic structures and alteration zones on the hangingwall stability

Regional structures

Investigations conducted by the author confirmed that the predominant strike direction of the major geologic structures across the Marikana Operations is NNW-SSE, NNE-SSW and WNW-ESE. The NNW-SSE

striking Pongola rift faults were activated 50 Ma ago and continued for 10 Ma during the cooling of the Bushveld Complex. The faults acted as feeder systems for the magma that formed the Bushveld Complex. Two of these major structures, the Saffy East- and Turffontein West Faults, have been exposed at Saffy Shaft and was studied by the author. The Saffy East Fault, striking NNW-SSE, initially formed as a normal dip-slip fault, which subsequently underwent a phase of sinistral strike-slip reactivation. The secondary faults were formed together with the Saffy East Fault during the initial extensional phase of normal dip-slip movements. Where alteration is present along the stratigraphic layers, specifically at the parting planes (UG2A markers and/or the hangingwall 1A/hangingwall 2 contact), it promotes separation and contribute to structurally-related instabilities. This was confirmed by the evidence from the water study conducted at Saffy Shaft. The affected area was 57 000 m^2 in size with the alteration zone located parallel to the major faults on Saffy Shaft. The Saffy East Fault and secondary structures strike parallel to the Wegener Stress Anomaly. Neotectonic activity is characterized by reactivation of ancient faults, dykes and creation of new fractures. It could also play a role in the exploration of groundwater. A large-area is covered by the alteration zone adjacent to the NNW- strike direction of this major fault. The site investigations by the author confirmed that minor ground water flow was present along the NNE-SSW striking Turffontein West Fault. However, no water was present along its subsidiary fault system situated in the hangingwall blocks. These structures do not strike parallel to the Wegener Stress Anomaly. There is not a continuous alteration zone along the NNE- strike length of this major structure.

Most of the large-scale collapses investigated by the author at the Lonmin sites were associated with the intersection of WNW-ESE striking structures. At Eastern Platinum Limited 2 and 3 Shafts, approximately 47 000 m^2 of ground were abandoned due to falls of ground. The studies conducted at these sites illustrated the presence of lineament structures on aeromagnetic images of the affected areas. It is believed that these structures contributed to the instabilities experienced. Underground investigations identified these lineaments as WNW-ESE striking structures, dipping at approximately 60˚ towards the south with a pegmatite infill. These structures were classified as regional structures as it cross cuts the stratigraphic layering. In this study, these structures are referred to as Marikana structures as they are present on all the Marikana Operations and even at operations adjacent to the Marikana Operations. In all instances it was found that these structures contribute to major structurally-related, large-scale instabilities.

Marikana structures

Large-scale instabilities associated with the Marikana structures have been identified by the author at Rowland, Eastern Platinum 2, Eastern Platinum 3, Hossy and Saffy Shafts. It was confirmed that these feldspathic veins and calcite veining formed during the time period of approximately 1.15 – 1.1 Ga. These structures (lineaments) cause adverse hangingwall conditions and terminate against NNW- and NNE trending, near-vertical structures. The various site investigations conducted for this study showed that this is

not the case in all instances. The application of ground penetrating radar technology (the so-called sub-surface profiler) by the author confirmed that the Marikana structures cut into the hangingwall beyond the 10 m that the profiler could detect. This confirmed earlier findings from that these structures are regional structures and impact on the stability of stratigraphic layers.

Similar to earlier studies, it was confirmed that the critical panel spans were reached at approximately 27 m as a result of the intersection of the Marikana structures. These structures, dipping towards the south, created unstable hangingwall conditions once the critical span was exceeded. This typically occurred once mining advanced for approximately twice the panel span which is approximately 50 m. Instrumentation installed at Saffy Shaft confirmed observations made from various site investigations conducted by the author (Rowland, Saffy, Eastern Platinum 2 and Eastern Platinum 3 Shafts). Findings from the investigations and an assessment of the prevailing structures showed that the preferential mining direction will impact on the behaviour of the structure and the hangingwall stability. Mining should approach these structures from the stable side. The results concluded that the least risk mining option for the typical conventional layouts was a split down-dip layout with the western face leading. Breast mining towards the east was also classified as a low risk option to control stable spans where Marikana structures would be intersected. These findings are an illustration of how geologic understanding of the UG2 and rock engineering knowledge was combined in this study.

Ramp structures

At several of the investigation sites, the large-scale instabilities were also associated with the intersection of low-angled, curved ramp structures. Low-angle joints were always believed to contribute to instabilities on the UG2 Reef horizon; however, it has not been well understood. Findings from the author's investigations indicates that the ramp structures together with the intersection of Marikana structures create unstable blocks, resulting in large-scale unravelling and instabilities of the hangingwall. Ramp deformation events 1 and 2 (ramps with different dip directions) that contribute towards the formation of these structures have been identified by the author at the various sites studied at the Marikana Operations.

The application of the ground penetrating radar technology (sub-surface profiler), in affected areas identified the ramp structures and confirmed that these structures 'ramp up' to the prominent weakness planes (UG2A markers and/or the hangingwall 1A/hangingwall 2 contact). This confirmed the observations made at various associated instability sites where the source of instabilities was believed to initiate at weakness contacts situated significantly high above the reef horizon. With this new technology, the location of these structures, which is located deep in the hangingwall, could be confirmed for the first time. This contributes to an improvement in the spatial understanding of these structures and confirmed that it should be considered in the mining strategy and support design processes.

Alteration zones

The intersection of alteration zones creates various forms of instability in the rock mass. This included hangingwall unravelling, large-scale instability from affected parting planes as well as pillar instability. This study found that the alteration zone may follow the ramp structures and ramp to interfaces situated below, directly above the reef or within the hangingwall units at Newman Shaft. This also showed that the alteration could ramp to various stratigraphic positions. At most impacted sites, alteration zones are unnoticed until anomalous hangingwall, support or pillar behaviour is reported. Careful inspection of core or underground site investigations, however, confirmed its presence. The lack of awareness and understanding of the impact of these alteration zones contribute to the significant rock mass instabilities experienced.

The studies indicate that the storage of ground water is mainly restricted to the UG2A markers and/or the hangingwall 1A/hangingwall 2 contact situated above the UG2 Reef. Weathering in the hangingwall pyroxenite of the UG2 Reef can be pronounced by the unique aquifer properties of the UG2 pyroxenite. It may have contributed to the formation of alteration zones ('clay-like' material). Similarly the deformation event 1 and deformation event 2 associated alteration zones have been identified by the author as contributors to anomalous pillar behaviour. The amount of weathering and tendency to form aquifers varies for different pyroxenites as the weathering is dependent on the composition of the constituting pyroxene minerals.

Investigations at Saffy Shaft confirmed that a larger area is covered by alteration along the Saffy East Fault (NNW-trending) versus a smaller area covered by an alteration in the vicinity of the Turffontein West Fault (NNE-trending). In most instances, the common practice on mines is to seal the boreholes or areas (haulages) that intersect water. This may divert the water within the rock mass. It has been noted during this study that the alteration zones are dry in old mined out areas, as opposed to the current mining operations where it has a wet (clay-like) nature that promotes unravelling as well as instability. It is believed that should the boreholes be drained, dry on reef conditions could result. This may prevent unravelling as well as instability along alteration zones. Further work is required to substantiate this observation.

The alteration zone can be located in the footwall, along the top reef contact, within the reef or along the hangingwall units of the UG2 Reef. The interpretation by the author from the sub-surface profiler scan in an impacted area where alteration was present, confirmed that the deformation event 1 and deformation event 2 (ramp structures) 'ramp up' to the potential weakness planes. These are also possible sources or locations of the alteration zones defining interfaces. Figure 5.1 illustrates the findings of a borehole camera survey and underground observations in an area which experienced panel-scale instability at Saffy Shaft. This site investigation confirmed the presence and interaction of the Marikana structures, ramp structures and alteration zones along potential weakness planes. This may cause large-scale instabilities and should be

considered in the layout and support design strategies. This is a further example of how this study focussed on the integration of geologic understanding and rock engineering design and possible solutions are given below.

The remedial strategies in affected areas where the alteration zone is located in the hangingwall include mining with either new generation, high strength active cementitious grout packs only, or integrating these packs with alternating lines of timber elongates. In the case where the alteration zone is located along the top reef contact, mine with permanent blast resistant mesh in an attempt to contain the potential unravelling between support. Flexible mining cycles should be considered that daily blasting is not required. This will allow time for support installation. However, if the grade is too low as a result of the added dilution, abandon the problematic areas. If the alteration zone is located in the footwall, the potential exist that the support units will fail prematurely. The support resistance could be impacted, resulting in falls of ground. Alternative support systems should be considered where instability is anticipated. The installation of 'fit for purpose' monitoring devices is recommended to provide early warning of potential related instabilities.
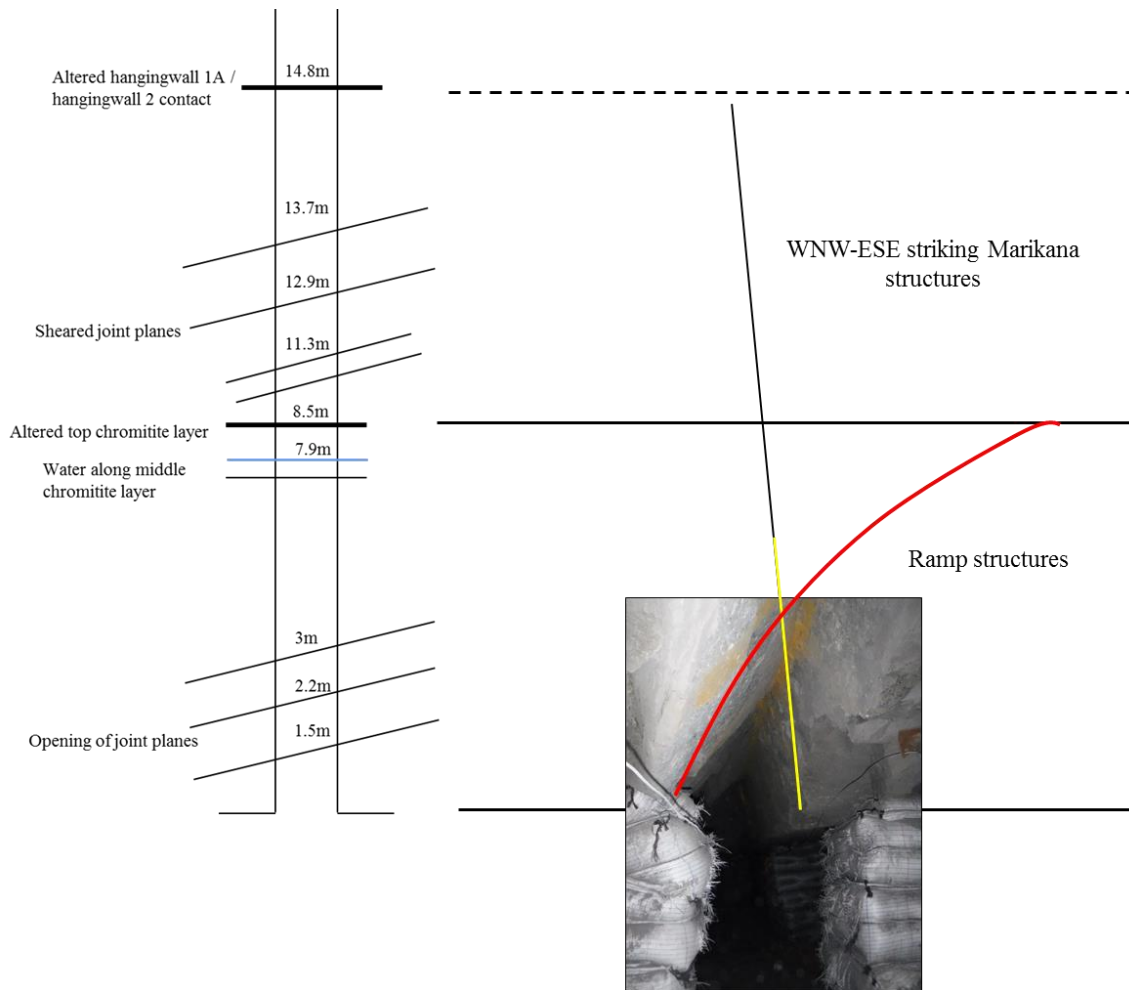
Figure 5.1: Structural interpretation of a borehole drilled into the hangingwall units. Alteration zones could be identified at the UG2A markers and the hangingwall 1A/hangingwall 2 contacts. The ramp structures were identified with separation along some of the structures, causing instability of the hangingwall. The exposure of the ramp structures, Marikana structures and alteration zones may cause large-scale collapses.

5.1.2. Impact of alteration zones on pillar behaviour

Unstable pillar behaviour was investigated by the author where NNW-SSE striking clusters and/or an alteration zone is present. Previous investigators believed that associated pillar instabilities occurred due to the fault gouge material (alteration) in the pillars being compressed, deforming the pillars and failing the pillars in tension. The pillars were therefore effectively pulled apart. Consequently, when pillar failure occurred, hangingwall unravelling was initiated and differential movement of the hangingwall became widespread resulting in subsequent mine wide instability, e.g. at Everest Mine. The pillar behaviour investigated at the Lonmin Marikana Operations for this study provided an alternative mechanism.

From the investigations conducted, the slabbing experienced in the non-yield pillars was as a result of both the joint orientation and an alteration zone being present. Where joints intersect the pillars at oblique angles,

these slabs defined by the joint planes are mobilised. This results in the observed 'pillar slabbing'. Rock engineering literature indicates that the presence of these alteration zones in pillars could reduce the pillar strength significantly and that traditional pillar strength formulae are probably not applicable in these cases. Unstable pillar behaviour and pillar slabbing experienced on Hossy and Saffy Shafts was studied by previous workers. It was initially thought that the pillar slabbing only occurred on pillars that were cut smaller than the specified size. It was, however, hypothesized that the major contributing factor to the pillar slabbing was the very weak contact present along the hangingwall and pillar interface. As a result, the pillar strength could be significantly reduced. The findings from this latest study confirmed this hypothesis.

5.2.   Suggestions for further work

The following additional work has been identified from this study and should be considered:

1. **Pillar design criteria for areas with alteration zones.** Large-scale, pillar instabilities and collapses have been experienced in many of the UG2 mines. The unstable behaviour of the UG2 pillars could be related to the presence of an alteration zone. The 'clay-like' nature of the altered material results in ongoing pillar deformation over time. Axial splitting of the pillars is experienced as opposed to the more typical 'hour-glassing' mode of failure where more competent rock is present. Numerical modelling, could be considered to investigate the effect of the weak alteration layer at different positions within the pillar. A comparison with traditional analytical pillar strength calculations, based on empirical formulae, may be considered to illustrate the value of numerical modelling for these cases.

2. **Stable span design in UG2 mines.** Significant collapses have been reported in both conventional and mechanised UG2 mines in the Bushveld Complex. Mechanised bord and pillar operations use tendons as support to reinforce the hangingwall. The support cannot prevent collapses from prominent partings situated significantly above the reef. Collapses of small spans have been reported where prominent stuctures were exposed. Consequently, in 2010, there were attempts by the industry to determine stable spans for UG2 bord and pillar mines. In most cases bord spans were reduced to 6 m and extraction ratios limited to 75%. However, the prominent geologic structures contributing to unstable spans, are not well understood. This resulted in ongoing instabilies in both conventional and mechanised operations. Various support and design strategies, including the application of numerical modelling have been suggested to verify the beam theories. Additional research is required to determine the most appropriate design methodology for stable span design in the UG2.

3. **Improved ore body knowledge.** Detailed mapping and plotting of geologic structures is required to gain an improved understanding of the structural geology of a resource block. The presence and

significance of the prominent structures as highlighted in this study can be verified by applying technologies such as ground penetrating radar, seismic surveys, borehole camera surveys and stress measurements. This information may be used to create improved geotechnical risk plans to provide information and strategies for short- and long term mine planning.

4. **The presence of water in combination with alteration zones.** The intersection of ground water in the underground mine workings contribute to the deterioration of ground conditions. It is believed that there may be a link between water intersected in the haulages and what may be exposed on the reef horizon. Investigations have showed wet (current mining areas) versus dry (previouly mined areas) conditions to exist along exposed alteration. The studies have shown that the wet alteration conditions have a more significant impact on the pillar behaviour and hangingwall stability. The impact of dry versus wet alteration conditions should be investigated.

The common practice, where high water yields are intersected by haulages, is to seal boreholes or water intersections. However, this practice diverts water into the rock mass. It is believed that this may contribute to the wet alteration conditions experienced on reef. Further work is required to understand if there is a relationship between the sources of water impacting on the on-reef conditions experienced.

Although water sealing is a common practice on most mines where significant water is intersected, it should be considered to drain the water and use the drainage water in the water reticulation systems to optimize the water usage which may result in a possible cost saving. This in turn may also promote stable ground conditions on reef. The practicality of this should be investigated.

5. **Optimisation of ground penetrating radar technology.** The sub-surface profiler is currently only used for line scans (two dimensional) to locate geologic structures, specifically the prominent structures in the hangingwall. This system may be optimised by scanning a grid format to create three-dimensional images of structures exposed in the hangingwall. Underground observations, together with mapping, information from the scans and isopach plans may be utilized to create a better spatial understanding of the geologic structures. This information will improve the understanding regarding the occurrence and potential failure mechanisms of the structures exposed.

6. **Laser scanners utilized at the excavation face.** The excavation face presents the highest risk area for falls of ground. Laser scanning technology is available and may be utilized as a tool for early entry examination. It is anticipated that the technology may be used to detect geologic structures and installed support in order to highlight 'hotspots' where falls of ground can potentially occur. The

information from the scanner can possibly be used to decide whether to conduct barring, install additional support or to abandon areas.

7. **Optimise and simplify monitoring instrumentation.** The highest risk of falls of ground is in the unsupported face area. Current rock mass monitoring devices are not blast resistant and can therefore not be installed in this high risk zone. This equipment should be designed to be blast resistant and to give early warning of possible collapses. The ideal scenario would be to install the instrumentation as part of the already installed support units. Consequently an entire monitoring grid will be generated which could give early warning of potential collapses.

8. **Transfer of knowledge regarding problematic ground conditions associated with prominent geologic structures.** Currently the prominent structures as discussed in this study are not identified due to a lack of knowledge and understanding from mining personnel. When an area of instability is identified, the area is typically barricaded off and the development or stoping panel is re-established. Training should be done on the identification, structural interpretation and the impact on mining strategies in order to implement the most suitable, least risk mining layout.