

**Physical property studies, tunnel numerical simulations and in-mine seismic
experiments to image the gold orebody at South Deep Gold Mine**

By

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A thesis submitted in fulfilment of the requirements for the degree of

Master of Science

In the

Faculty of Science,

School of Geosciences

University of the Witwatersrand, Johannesburg



September 2024

DECLARATION

I declare that this dissertation is my own work, unaided work. It is being submitted for the degree of Master of Science at the University of the Witwatersrand, Johannesburg, South Africa. It has not been submitted before for any degree or examination at any other university.

Melendy

Signed on 09/09/2024 at the University of the Witwatersrand, Johannesburg.

ABSTRACT

The investigation endeavors to assess the physical characteristics of deep borehole cores within the Upper Elsburg Reefs (UER) of the South Deep gold mine of the West Rand goldfield. Specifically, these cores are sourced from three boreholes situated approximately 2.6 km beneath the surface within the confines of the South Deep gold mine. The focal point of this study lies in non-destructive testing methods aimed at elucidating the intrinsic attributes of these rocks, with particular attention directed towards seismic velocities and densities. These measurements hold paramount importance in conducting numerical simulations to designing the in-mine (or tunnel) seismic reflection surveys acquired at South Deep gold mine, as part of the ERA-Min3 FUTURE (Fiber-optic sensing and UAV-platform techniques for innovative mineral exploration) project.

Cultivating a profound comprehension of the seismic velocities and densities across diverse rock formations can significantly augment the interpretation of seismic reflections, thereby facilitating more refined assessments of subsurface geology and structural configurations. In pursuit of this goal, our study endeavors to delve into the fundamental acoustic properties of the gold-rich UER, with the overarching aim of deepening our understanding of its seismic reflectivity. To realize this objective, a comprehensive array of physical measurements, encompassing ultrasonic velocities and bulk densities, were conducted on drill-core specimens.

To accurately portray the physical attributes of the lithological units under scrutiny, a total of twenty-four samples were subjected to exhaustive analysis for density and seismic velocity utilizing a spectrum of methodologies. Density determinations were procured through a diverse set of techniques, including dimensional assessments, employment of the KT20 MagSus tool, and utilization of the SNOWREX AHW-3 Professional Weighing Scale boasting a heightened sensitivity of 0.01 g. Ultrasonic measurements were undertaken employing the Proceq Pundit PL 2000 ultrasonic pulser velocity tester, equipped with two pairs of transducers boasting a center frequency of 54 kHz. The in-mine seismic survey was acquired to delineate geological structures that crosscut and displace the orebody

The study locale encompasses three distinct rock formations: the UER, gold-bearing conglomerate units (termed reefs), basaltic lava, and dyke specimens. The UER primarily comprises quartzites, exhibiting a P-wave velocity range of 5202-5802 m/s, an S-wave range of 3037-4768 m/s, and bulk densities spanning from 2.66-2.71 g/cm³. Conglomerate reefs exhibit a P-wave velocity range of 4467-5970 m/s, an S-wave range of 4040-4854 m/s, and bulk densities ranging from 2.67-2.94 g/cm³. Lava samples extracted from the boreholes showcase a P-wave velocity range of 5916-6711 m/s, an S-wave range of 3275-5659 m/s, and bulk densities spanning from 2.75-2.90 g/cm³. Singular dyke samples were encountered, exhibiting a P-wave velocity of 5921.5 m/s, an S-wave velocity of 5385 m/s, and a density of 2.85 g/cm³.

The study employed the synth-seis code to simulate 1D seismic responses based on borehole data collected from the mine, aiming to validate findings from velocity and density measurements. Analysis of the seismograms indicated notable contrasts between conglomerates and quartzites, particularly evident in density and S-wave measurements, suggesting potential for improved rock discrimination with alternative seismic sources. Additionally, 2D numerical simulations were conducted to model wave propagation in the Upper Elsburg Reef (UER), revealing discrepancies between simulated and synthetic seismogram results, indicating potential limitations in seismic imaging. Furthermore, ray tracing was used to design a seismic survey inside the mine along the tunnel floor to image VCR (Ventersdorp Contact Reef) orebody and other geological structures.

The real seismic survey was finally conducted inside the tunnel (SDT1), demonstrated the value of in-mine reflection seismic surveys for mapping geological structures at significant depths, which would otherwise be costly and logistically challenging. Despite noise interference from mine operations, processing algorithms enabled extraction of reflections and structural mapping from the dataset, underscoring the importance of such surveys in mining exploration and planning.

DEDICATION

To my beloved late parents, Mr SD and Mrs TI Mulanduli who instilled in me the values of love, resilience, and determination, this thesis is a tribute to your enduring influence on my life. Though you are no longer here to witness this moment, your unwavering support and encouragement remain etched in my heart, driving me to pursue knowledge and excellence.

To my cherished adoptive parents, Mr TC and Mrs MM Munenyiwa whose boundless love and unwavering commitment have shaped my journey, I dedicate this thesis as an expression of my profound gratitude. Your decision to embrace me into your lives not only changed my destiny but also enriched it with love, wisdom, and a sense of belonging that I will forever hold dear.

ACKNOWLEDGMENTS

I am deeply grateful to the many people who have assisted me throughout my MSc journey. I would like to express my wholehearted appreciation to my supervisor, Professor Musa Manzi, for his unwavering support, guidance, and motivation in my scientific career. Without his invaluable assistance, completing this Master's thesis would not have been possible. Apart from being a supervisor, Musa became a friend and a brother at times but still managed to be professional at the same time. Apart from just the work on this thesis, Musa made sure that he exposed me to the various mines in South Africa and often he would give me an opportunity to lead projects, the skills acquired in my journey with him through this MSc will forever be remembered as the very few blocks that were necessary to establish me as a Geophysicist.

I would like to express my deepest gratitude to the Geology Department of South Deep Gold Mine, with special recognition to Jones, Mothipa, and Annah. The team, led by Mr. Jones Manamela, went above and beyond to ensure that we could conduct experiments in the mine smoothly. I appreciate their contributions as geologists, which have illuminated my understanding of the mine geology. Andrew from the rock mechanics lab at Wits in the school of mining. Salizwa and Mpofana also contributed significantly to this work.

I would like to acknowledge further, the support from my family, particularly my brother Ndwamato who always makes sure I am well in all aspects of my life so I can only worry about my studies. Lawulani, Khathutshelo 'Rama', Malaika, Ms. Denge, S'lindile, Azwianzi, Phekolazi, Ayesha, Lutho, Rabelani Singo, Phumudzo, Ntsako, Tariro, Obonabulumko, and Dakalo my friends, who I now cherish as my community made sure that, on days when I felt overwhelmed, they reminded me of why I started. Throughout my MSc journey, my buddy and business partner Kenneth provided me with technical assistance.

I would like to express my gratitude to Boart Longyear and the National Research Fund (NRF) for providing me with the financial support that made this work possible

and my stay at Wits University very comfortable. Special thanks to the Wits Seismic Crew of the Wits Seismic Research Centre who supported me throughout all stages of my research. I also want to acknowledge the school of Geosciences, led by Prof Gillian Drennan, for providing a secure environment for research and learning within the university. I appreciate the entire staff for their help and support.

I would like to extend my heartfelt acknowledgments to the following groups and individuals for their invaluable assistance throughout this project. Wits University, Polito University, University of Venda and Uppsala University played pivotal roles in the acquisition of the data in South Africa as part of the Future Project. Ian James's expertise was indispensable in processing the acquired data. Additionally, I express my sincere gratitude to Petrel and Globe Claritas for their consistent provision of academic licenses to the Wits Seismic Research Centre. Their unwavering support has been instrumental in advancing our research endeavors.

We would like to extend our sincere gratitude to the Department of Science and Innovation (DSI) for their invaluable support in sponsoring South African partners in the EU Future project. Additionally, we express our heartfelt appreciation to the Advanced Orebody Knowledge Programme for their generous sponsorship of the project. Special thanks go to Michelle Pienaar for her relentless support and guidance throughout this endeavor.

Last but not least, I would like to acknowledge Eternal Glory Church (EGC) and Pastor Martin Mgiba for creating a warm and welcoming community. Their openness allowed us to live out Hebrews 10:24-25.

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LIST OF ABBREVIATIONS AND ACRONYMS

m	meters
km	kilometers
2D	Two dimensional
3D	Three dimensional
e.g.	For example
V_p	Primary wave velocity
V_s	Secondary wave velocity
Pb	Lead
Sr	Strontium
UER	Upper Elsburg Reef
Ga	Billions of years ago
SDT1	South Deep Tunnel Seismic Line1
LVL	Low Velocity Layer
FD	Finite Difference
VCR	Ventersdorp Contact Reef
DAS	Distributed Acoustic Sensing
DGPS	Differential Global Positioning System
FUTURE	FIBER-OPTIC SENSING AND UAV- PLATFORM TECHNIQUES FOR INNOVATIVE MINERAL EXPLORATION
MEMS	Micro-Electro-Mechanical Systems
P-wave	Primary wave
S-wave	Secondary wave

1. INTRODUCTION

For more than a half-century, geophysical technologies have been utilized effectively for mineral exploration and prospecting on mining camps and regional sizes, both in green and/or brownfield sites ([Malehmir et al., 2017](#); [Brodic et al., 2021](#); [Donoso et al., 2021](#)). Although the combination of field geology, geochemistry, drilling, and various geophysical approaches (ground or airborne) has resulted in several discoveries, there is still a huge need for innovation and enhancement of current exploration methodologies, particularly for in-mine applications. This demand is mostly driven by a rise in total metal consumption, as well as growing requirements for the sustainability of the raw materials chain in order to maintain developing economies and a trend toward green technology ([Eaton et al., 2003](#); [Valero et al., 2018](#); [Brodic et al., 2021](#)).

It is necessary to redirect exploration efforts below 800 m depth to investigate and exploit deeper mineral resources, as shallow seated ones have already been explored and exploited ([Donoso et al., 2021](#)). In the past ten years, the usage of seismic technologies has increased due to their ability to retain a high vertical resolution with depth. Given that a substantial portion of the mineral riches on the globe is found in crystalline or hardrock environments with frequently complicated geological and tectonic settings, seismic exploration in such regions is a difficult undertaking. Exploration targets are commonly located in dipping, or even steeply dipping, structures in these types of terrains where low impedance contrasts with the nearby rocks are widespread ([Tertyshnikov, 2014](#); [Nkosi, 2016](#); [Riedel et al., 2018](#); [Liu et al., 2021](#)).

It is estimated that over 40% of the world's gold has been mined from the Witwatersrand Basin, making it a major powerhouse in the global gold industry. The region has a rich history of gold mining and continues to be a top contributor to the world's gold supply ([Frimmel et al., 2005](#)). However, gold mining operations continuously face various challenges. Most economically viable gold resources are located between 3 km to 5 km below the surface, after the shallow resources were exhausted. Using standard exploration methods including drilling, gravity, magnetic, and surface 2D reflection seismic techniques, as well as surface and subterranean geological mapping, it is challenging to comprehend the subsurface geology and structural framework at such depths ([Nkosi, 2016](#)).

Seismic techniques retain strong vertical resolution with depth and, as a result, have become more common in the recent decade for localizing mineral resources and mine-design. Modern mineral exploration is increasingly turning to the use of geophysical methods, particularly reflection seismic, which is frequently used for hydrocarbon exploration, in order to improve our understanding of existing deposits and find new mineralization at depth for the future ([Schodde, 2017](#); [Bellefleur et al., 2019](#); [Donoso et al., 2021](#)). Given that a large portion of the world's mineral riches is found in crystalline or hardrock environments with sometimes complicated geological and tectonic settings, seismic exploration in such locations is a difficult task ([Eaton et al., 2010](#); [Brodic et al., 2021](#)).

Around the world, various examples demonstrate the effectiveness of seismic methods in mineral exploration. In Canada, the Sudbury Basin has seen successful application of seismic techniques to map complex nickel-copper sulfide deposits ([Eaton et al., 2003](#)). Similarly, in Australia, seismic surveys have been instrumental in delineating mineral deposits in the Broken Hill region, known for its lead-zinc-silver ore bodies ([Dentith, 2003](#)). In Scandinavia, seismic reflection methods have been employed to explore the depth extensions of massive sulfide deposits in the Skellefte district, Sweden ([Malehmir et al., 2012](#)).

Seismic methods for exploration and monitoring pose a challenge in mining environments due to several factors. Safety protocols, obtaining adequate authorization, logistical obstacles, and restricted space and time for data collection are all crucial considerations. However, the most significant obstacle is the high level of noise emitted by mining equipment, such as trucks, shovels, drills, explosives, and rock crushers. Incorporating seismic methods in such an environment requires careful planning and adherence to established protocols to ensure that the data collected is accurate and reliable ([Malehmir et al., 2017](#)).

The cost of production would go down and the return on capital infrastructure investments would go up if it were feasible to see clearly under a mining site and map the position or extent of the resources at great depths. Yet only the seismic reflection technique has the necessary depth of penetration and can deliver high-definition pictures of the subsurface ([Zheng and Wang, 2023](#)). The overall performance of seismic

approaches is very site- and geology-dependent. Seismic techniques may be used to directly find mineral deposits at depths more than 1 km and to provide high-resolution images of the geologic structures supporting such deposits ([Eaton et al., 2010](#); [Malehmir et al., 2012](#)).

Although numerous 3D reflection seismic surveys have been carried out over the Witwatersrand Basin Goldfields to map gold-bearing horizons (known as reefs, [Manzi et al., 2012](#)), direct measurements of physical rock properties (such as seismic velocities, bulk density, and porosity) of the Upper Elsburg Reef (UER) Package and its hanging wall and footwall rocks have not been made in order to more thoroughly understand the lateral extent and depth of the orebody being mined. Thus, it is crucial to comprehend the physical rock characteristics of ore-bearing horizons and the rocks that serve as their hosts in order to more accurately interpret seismic data collected for mineral exploration. Mineralized zones, their host rocks, and neighboring lithological units can all be better understood by laboratory studies of physical rock properties ([Nkosi, 2016](#)).

Many variables affect the likelihood that prospective reflectors can be imaged seismically, such as the geometry and structural complexity of rock horizons, their depth of burial, and the difference in acoustic impedance between the horizon and its host rocks ([Chaubey, 2007](#)). Velocity analysis is essential for high-resolution reflection seismic imaging, but it is difficult in settings with crystalline structures and complexity due to the fact that seismically detected horizons are primarily interpreted from seismic travel time data that have been depth-corrected using sophisticated velocity analysis ([Chen, 2018](#)). The velocities obtained from seismic data are inherently uncertain, making it difficult to make judgments solely on a single set of velocity data ([Nkosi, 2016](#)).

Current computer efficiency has evolved to the point where we can begin to perform wave-field simulations for realistic 3D models at frequencies of relevance to both seismologists and engineers. [Graves \(1996\)](#) provided detailed formulations that describe the incorporation of moment-tensor sources, the implementation of a stable and accurate representation of a planar free-surface boundary for 3D models, and the derivation and implementation of an approximate technique to model spatially variable anelastic attenuation with a staggered grid.

A combination of physical properties studies and numerical simulations of wave propagation through rocks in three dimensions seeks to improve the way seismic surveys are conducted both on surface and in-mine tunnels. The information from the physical properties can be fed into the numerical model as input data and calculate both the P- and S-wave responses that would be recorded for specified source type, geometry, and receiver spacing ([Bazargan, 2022](#)).

Aims and objectives.

This project aims to provide insight into the physical properties of the rocks within the Witwatersrand Supergroup with particular emphasis on the Upper Elsburg Reef (UER), measure the bulk densities and seismic velocities of the various rock samples from the South Deep gold mine, calculate the acoustic impedance and reflection coefficients of the reefs and host rocks. Using these measurements, the study aims to investigate the seismic reflectivity of the individual reefs within the UER package and that of the Ventersdorp Contact Reef (VCR) at the top of the UER.

This work aims to provide a comprehensive understanding of the physical properties of the Upper Elsburg Reef (UER) package that are crucial for the understanding of seismic wave propagation to help with planning of in-mine reflection surveys to ensure efficiency and optimum results. The in-mine seismic surveys are then acquired, and results are compared with the legacy surface seismic data and physical properties.

Research questions:

- Is there any significant physical properties contrast between members of the Upper Elsburg Reef package?
- Can the endmembers of the Upper Elsburg Reef package be imaged by the in-mine seismic method?
- Would it be possible to use S-waves as opposed to P-waves to map the UER package?
- Can in-mine or tunnel seismic surveys be acquired successfully in an operating or active mine?
- Can tunnel seismics be used to map structures (faults and dykes) in mine tunnels ahead of the mine face?

2. STUDY AREA AND GEOLOGICAL BACKGROUND

2.1. A brief overview of the geology of the Witwatersrand Basin

The Witwatersrand Basin is an Archean sedimentary basin that hosts the world's largest gold deposit and served as the primary source of gold for several years. The renowned basin supplied over a third (approximately 52,000 tons from 1886 to present time) of all the gold produced in the world and is thus responsible for the emergence of the South African gold mining sector, specifically in the city of Johannesburg and its surrounding metropolis ([Makiese, 2012](#)).

The 350 km long basin, composed mainly of metamorphosed conglomerates extends over four provinces of South Africa with a width of 200 km and approximate thickness of 10 km ([Jones, 1998](#)). To date, an approximation of 3.6 km has been explored for gold production in the minerals and resources industry. This deposit is a classic clastic sedimentary deposit, mainly composed of sediments that originated from the granitic greenstone basement through erosion and transportation. It is an important resource for studying the geological history of the area and understanding the processes that shaped its formation. The stratigraphic succession generally depicts an upward-coarsening depositional history with marine sedimentary rocks dominating near the base and clastic continental sedimentary rocks predominant toward the top ([Phillips and Law, 2000](#)).

2.2. Regional geological context

The basin is located on the Kaapvaal Craton, an ancient stretch of continental Southern African origin developed between 3.7 and 2.7 Ga. ([Robb and Meyer, 1995](#)). The craton is thought to have formed as a result of the fusion of an enormous granitoid basement with arc-like oceanic terranes indicated by mafic/ultramafic volcanoes and accompanying deposits ([De Wit et al., 1992](#)). The basin formed as a result of further magmatic activity, primarily the Cordilleran-style accretion of the composite terranes along the proto-margin, continent's which resulted in sediment deposition, specifically arenaceous and argillaceous lithologies, into a fluvio-deltaic environment in the center of the Kaapval Craton ([Robb and Meyer, 1995](#)). The basin is said to be of the early Proterozoic age, deposited between 2.6 and 2.3 Ga, overlying either the Archean granite-greenstone basement or the volcano-

sedimentary Dominion Group. However, there are age constraints due to the limited availability of whole rock Rb-Sr and Pb-Pb isotope determinants ([Allsopp and Welke, 1986](#)). The lowermost stratigraphic unit of the basin is formed by a white quartzite ridge named the Orange Grove Quartzite, forming the northern scarp edge of the Witwatersrand plateau in the Johannesburg area. This unit forms part of the West Rand Group which comprises mainly, iron rich shales and quartzite. The gold bearing conglomerates are found in the arenaceous upper stratigraphic units known as the Central Rand Group ([Tucker et al., 2016](#)). The layers of this basin are underlain by Dominion Group metamorphosed volcanics and minor clastic deposits, which in turn overlie an earlier granitic greenstone basement. The large volcanic sedimentary Ventersdorp Supergroup, the dolomitic and quartzitic Transvaal Supergroup, and Karoo Supergroup sediments cover much of the Witwatersrand.

2.3. Proposed models for the gold provenance

Since its discovery, the origin of the Witwatersrand gold has been a hot topic of discussion and has been referred to as "the most controversial question in the history of economic geology." The spectrum of suggested genetic models are described by three end members based on the interactions between gold and sedimentary processes and post-burial events ([Phillips and Law, 2000](#)). The three proposed genetic models are referred to as the unmodified placer model, modified placer model and the hydrothermal replacement model ([Law and Phillips, 2006](#)). The unmodified placer model indicates a detrital origin for the gold (syngenetic formation) ([Frimmel, 2005](#)). The modified placer model indicates that the gold had concentrated in the host conglomerates initially through detrital processes and subsequently hot metasomatic fluids resulted in the re-precipitation of gold. In contrast the hydrothermal replacement model (epigenetic formation) indicates that gold concentrated by metasomatic fluids after the lithification of the host conglomerates ([Frimmel, 2005](#)).

2.4. Goldfields in the Witwatersrand Basin

In what is referred to as the Golden Arc, almost 400 km of the Witwatersrand Basin's gold-bearing conglomerate units (reefs) are mined over seven main goldfields and a few minor occurrences ([Figure 2.1](#)). The Witwatersrand Basin's Vredefort Dome, a significant meteorite impact site, serves as the arc's focal point ([Therriault et al., 1997](#)). According to estimates, the original asteroid's width was 15 km. Steeply sloping upturned layers of the underlying Witwatersrand Supergroup strata surround a central core of up-domed granitic basement.

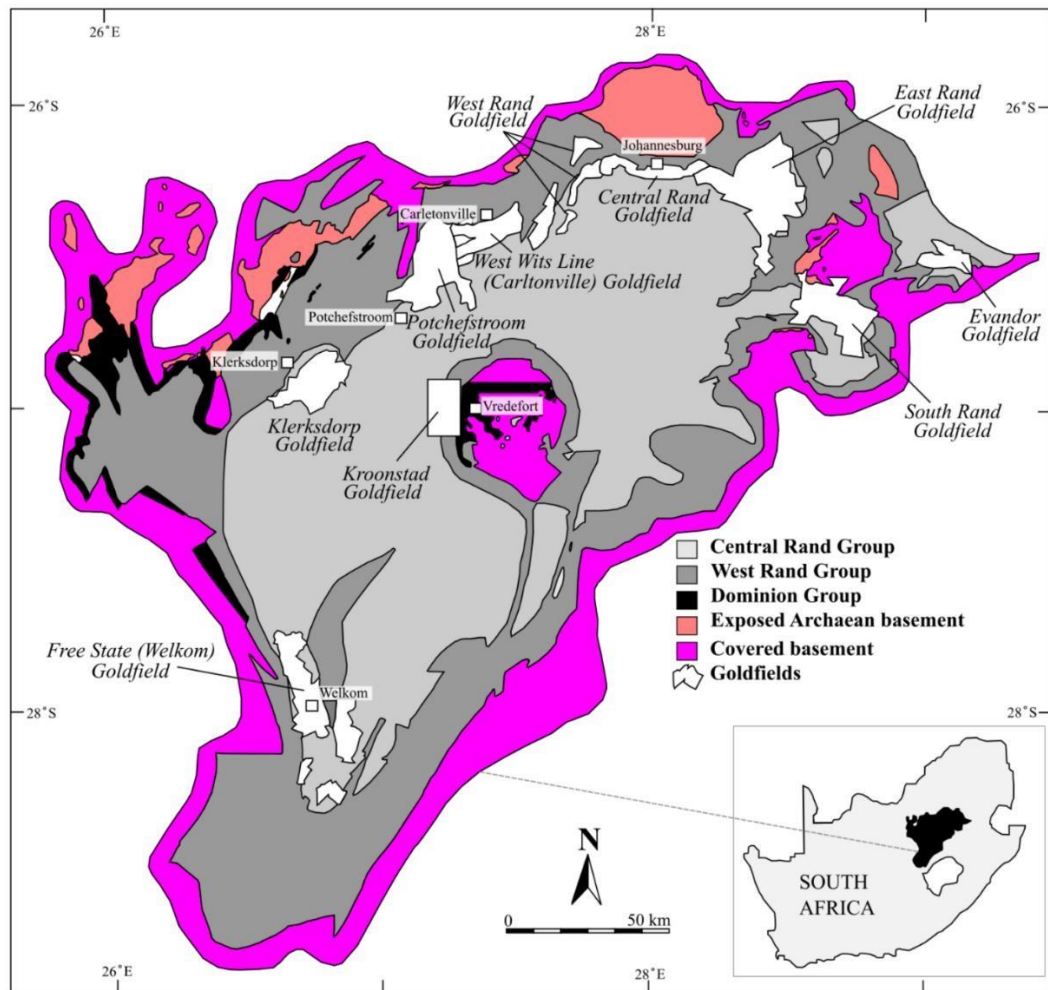


Figure 2.1: A geological Map elucidating the regional geological characteristics of the Witwatersrand Basin. This representation has undergone refinements in accordance with the revisions proposed by [Pretorius et al. \(1986\)](#). Furthermore, the depiction encapsulates the distribution of the Archaean basement across both surface and subsurface realms, along with the delineation of Goldfields, modified [after Rance et al. \(2006\)](#).

The gold bearing reefs, namely the Langlaagte, are found to the east and the west of the Central Rand goldfield (Figure 2.1). The gold-bearing reef of Boksburg Gap is situated further to the east, across a gap in the continuity of the reef horizons. These reefs are found in the East Rand Goldfield, which is a sizable basin located nearby (Macgregor and Zealley, 1915). The Witpoortjie Break, a significant horst formation, marks the western boundary of the Central Rand Goldfield. Northwest to the break is where exploration on several conglomerate reefs belonging to the West Rand Goldfield has been active for over a century (Myers et al., 1990).

The Transvaal and Karoo Supergroups' heavier, more recent sediments gradually cover the Witwatersrand Basin strata as they extend southwest to the West Rand Goldfield. It has required lengthy investigation to determine the precise location of gold-bearing reefs because of the thickness of these sediments, which has led to the discovery of the West Wits Goldfield (Howarth, 2012). This goldfield is divided into an Eastern and a Carletonville section by the Bank fault. The Eastern sector includes the Venterspost, Libanon, and Kloof mines.

Further exploration of the Central Rand led to the discovery of gold in the Klerksdorp area, however this gold was found in lower grade conglomeritic reefs of the West Rand group. This became the main gold reef of the Klerksdorp Goldfield. The Welkom Goldfield, which is situated on the southwestern side of the Potchefstroom Gap, was discovered after the West Wits Goldfield, located to the southwest (Scott, 1953; Tucker et al., 2016). The Welkom Goldfield, which is situated on the southwestern side of the Potchefstroom Gap, was discovered after the West Wits Goldfield, located to the southwest. Younger cover sequences cover this goldfield (Pretorius and Wolf, 2012). The Evander Goldfield northeast of the basin (Figure 2.1), which is likewise covered by younger rock layers, is the most recent of the main Goldfields, having been found in the 1950s (Tucker et al., 2016).

A distinctive feature across all the Witwatersrand Goldfields are the records of metamorphic conditions and pelitic assemblages indicative of greenschist metamorphism, with minimal regional-grade changes over a strike of approximately 200km strike-length. The higher grades are recorded locally in close proximity to

granitoid domes and intrusions related to the Bushveld Igneous Complex ([Phillips, 1986](#)). This becomes a notable feature as the recorded temperatures during peak metamorphism and the abundance of pyrite are responsible for the provision of ideal conditions for the (re)mobilization of gold and provide an explanation for the abundance of gold in the fields as well as many of the textural variations and the development of secondary textural features ([Phillips, 1986](#); [Kirk et al., 2003](#); [Safonov and Prokof'ev, 2006](#)).

2.5. Geology and stratigraphy of the Witwatersrand Supergroup

The Witwatersrand Supergroup is a 7.5 km thick geological sequence of siliciclastic sedimentary rocks that has now been divided into the lower West Rand Group and an upper Central Rand Group (SACS, 1980), and further sub-divided into the Lower Hospital Hill, Middle Government and Upper Jeppestown subgroups and the Johannesburg and Turffontein Subgroups, respectively (Mason, 2005; Netshilongolwe, 2018). Overall, the supergroup comprises mainly arenaceous meta- sediments, argillaceous meta-sediments, and meta-conglomerates that are extensively mineralized with gold (Phillips, 1986). The supergroup overlies the granitoid-greenstone terranes of the Kaapvaal Craton and in some places the Dominion Group. It is overlain by the Ventersdorp Supergroup and Transvaal Supergroup (Eriksson et al., 2011; Gumsley et al., 2020).

The current age estimate of the supergroup is constrained to be 2.7 Ga obtained by ion- microbe on zircon from the Makwassie Quartz Porphyry of the Ventersdorp Supergroup. However, many current models suggest that Ventersdorp volcanism occurred after the sedimentation of the Witwatersrand within a negligible time break, implying an age of the Witwatersrand to be close to 2.8 Ga (Phillips, 1986; Walraven et al., 1991; Cornell et al., 2021).

The defining feature of the Witwatersrand Supergroup is exemplified by the major stratigraphic units of the Central Rand Group which are the marker horizons, individual conglomerate reefs around the auriferous northern and western basin edges. The strata of the Central Rand Group can be correlated with the strata of the Goldfields with minor variations besides the Welkom, Klerksdorp, and Evander Goldfields (Tucker et al., 2016).

According to Mellor (1915), the nomenclature of the Witwatersrand Supergroup has undergone several revisions and therefore the proposed stratigraphic reports may contain variations. It is for this reason that they proposed the use of a chronostratigraphic scheme, which divided the Witwatersrand into a “Lower” and “Upper Witwatersrand System” using Formation as the essential unit, for the suitability of a Lithostratigraphic scheme (SACS, 1980).

These divisions outline the two major forming Goldfields of the Witwatersrand Supergroup which are the West Rand and Central Rand Groups, respectively, with the latter typically forming the Upper Witwatersrand System and the former, the Lower Witwatersrand System. However, there are constraints to this division as well, as the dividing horizon is completely unrepresented in some districts thus making it difficult to maintain a reliable lithostratigraphic scheme ([Tucker et al., 2016](#); [Handley, 2023](#)).

[Mellor \(1915\)](#) suggests that a preferable/recommended lithostratigraphic scheme is to distinguish the two systems by using the base quartzite series of the Main Reef as the dividend feature. This becomes inclusive of the Jeppestown Series which comprise a large proportion of large salty rocks that will then form part of the Lower Witwatersrand System. This division is much more practical as it is argued to be natural and recognizable to field-geologists and engineers conducting classification in the remote districts of the Rands. This then implies that the lower system is dominated by argillaceous beds and the upper by coarse quartzite beds and conglomerates, with only a single notable group of argillaceous type – the Kimberly shales ([Nwaila et al., 2017](#); [Gumsley et al., 2020](#)).

Lower Witwatersrand System

The Main Reef is directly underlain by a series of quartzite, grits and conglomerate beds which essentially form the definitive rock units of the Lower Witwatersrand System; however, these are very much similar to the rock units overlying the Main Reef ([Cousins, 1965](#)). This is mainly because the considerable bodies of quartzites, grits and pebble leaders underlying the Main Reef tend to progressively diminish in thickness and textural coarseness and thus ultimately disappear or become similar to the upper portions of the underlying Jeppestown Series ([Mellor, 1915](#)). These beds extend to a thickness of 1.8 km over a great portion of the Rand, progressively thinning to the east and west.

2.5.1. West Rand Group

The Dominion Group, also known as the granitoid-greenstone basement, is the base for the West Rand Group, a sedimentary sequence that is about 5 km thick. Sandstone, siltstone, shale, and mudstone that were formed during a phase of thermal subsidence make up the majority of the sediments, which are shallow marine to offshore shelf sediments ([Agangi et al., 2014](#)). Goldfields, known to form the Lower Witwatersrand System, comprises mainly the Witpoortjie and Panvlakte Horst block structures which are superimposed over broad folding associated with the south-east plunging syncline ([Harmony, 2010](#)). The Witpoortjie Horst Block forms the southern edge of the Roodepoort Fault that strikes north-easterly. It is comprised of stratigraphically older sediments of the West Rand Group, underlying the Central Rand Group sediments, which have now been removed by erosion ([Carrick, 1986](#)). The goldfield comprises unevenly distributed pelitic rock types, rich in iron that are approximately 4500 m in the Lower Witwatersrand System ([Phillips, 1986](#)).

At the base of the goldfield is a shale bed known as the Parktown Shale, which forms a 1 km thick, mostly argillaceous formation. The pelites are red in surface exposure, magnetic due to the presence of magnetite and locally calcareous or Fe-rich shales. They exude a dominant mineralogy of quartz, chlorite, with white mica, tourmaline and scattered fine magnetite. The bedding is defined by alternating micaceous and siliceous layers and is attenuated by weathering ([Wang et al., 2014](#); [Nwaila et al., 2017](#)).

Overlying the Parktown Shales are the Coronation Shales which are a black, magnetic formation of a thickness of 150 m, surrounded by thick, arenaceous lithologies. These are defined by a mineralogy of fine magnetite, chlorite, and quartz grains. The Jeppeshtown Shale is the uppermost layer of the pelites in the lower Witwatersrand System ([Borhcers, 1961](#); [Safonov and Prokof'ev, 2006](#)). These are significantly dark green pelites, slaty rocks, exuding a red colour on the surface as a result of weathering. These occur a few meters into the footwall of the main

conglomerate reef dividing the upper and lower systems of the Witwatersrand. The Jeppestown Shales are approximately 150 m thick, and are persistent throughout the Witwatersrand Basin, with a mineralogy of chlorite, minor quartz, and white mica (Phillips, 1986).

The aforementioned shales overlie the Orange Grove schists and Orange Grove conglomerates still at the basement of the goldfield and are overlain by thick beds of white quartzites (Carrick, 1986). Above the quartzite bed is a continuous belt of highly ferruginous, brown, red shale, with lenticular bodies of quartzite. This is followed by a distinctive feature of the West Rand Golfield, the Government Reef or better known as the 'Red' group shales, which are highly ferruginous shales exhibiting a conchoidal fracture containing a fairly large number of large magnetite crystals (Nwaila et al., 2017).

Upper Witwatersrand System

The Upper Witwatersrand System mainly refers to the upper division of the system at a horizon defined by the 'Main Reef'. This division has been established by geologists and engineers alike for the purposes of gold mineral exploration in the Witwatersrand Supergroup. According to Mellor (1915), the Witwatersrand Upper System is a continuous succession of course- grained sedimentary beds that reach an approximate thickness of 2.7 km overlying the conglomerate reef and interrupted only by the Kimberly shales, which occur in two sub- divisions. At several horizons this succession of coarse sedimentary deposits contains groups of conglomerates, in which mining activity occurs. Amongst these sedimentary beds and conglomerates, are intermediate quartzite units which form a larger portion of the system (Mellor, 1915).

The Kimberly shales of the Upper Witwatersrand System show a considerable variation in character from being distinctively coarse in texture to being fitly and much

finer grained as quartzites or sandstones. Overlying this shale bed is a series of undisturbed series of coarse sediments comprising mainly grits and conglomerates (Tweedie, 1968; Nwaila et al., 2017).

2.5.2. Central Rand Group

The Central Rand Group, deposited between 2.9 to 2.7 Ga, is composed largely of alluvial sandstones and auriferous conglomerates, which form major depositional packages with significant sequence boundaries that resulted from tectonic activity in the north and western parts of the basin, has the most well defined structural and sedimentological boundaries (Pretorius, 1963). It is therefore used as a geographical and geological entry. Furthermore, its stratigraphy is used as a marker stratigraphic profile for the Goldfields in the Witwatersrand Basin, with minor variations besides the Welkom, Evander, and Klerksdorp Goldfields (Tucker et al., 2016).

2.5.3. South-Deep gold mine orebody

The South Deep gold mine is served by two complexes - the Twin Shaft Complex and South Shaft Complex. Each complex comprises a main shaft and two subvertical shafts (as shown in Figure 2.2a). The mining region is divided into two phases, namely Phase I and Phase II. These phases are located to the north and south of the Wrench Fault system, respectively (Manzi et al., 2013). The Upper Elsburg Reef accounts for roughly 93% of the South Deep gold mine's resource, while the VCR (1.5 m thick conglomerate unit) accounts for 7%. The orebody is composed of Witwatersrand conglomerates, varies in thickness from 1 m to more than 100 m, and runs for many kilometers (Wesseloo and Joughin, 2007). The Upper Elsburg region is characterized by distinct conglomerate units, namely EA, EB, EC, and ED, which are interspersed with quartz wackes. Conversely, the Upper Elsburg Massives are comprised of conglomerate packages known as MA, MI, and MB units (Figure 2.2.b). Interestingly, the Upper Elsburg Massives are entirely seismically transparent (Manzi et al., 2013) due to a lack of significant acoustic impedance contrast between the conglomerates and quartzite within the UER package.

However, these reefs are overlain by the basaltic lavas of the Ventersdorp Supergroup. At the base of the Ventersdorp Supergroup is the Ventersdorp Contact Reef (VCR, gold-bearing conglomerate), which can be imaged by the seismic method because of a significant acoustic impedance contrast between the overlying basaltic lavas and underlying quartzites and conglomerates of the Central Rand Group. It is thus this seismic marker that is targeted for seismic surveys at South Deep gold mine (Manzi et al., 2013).

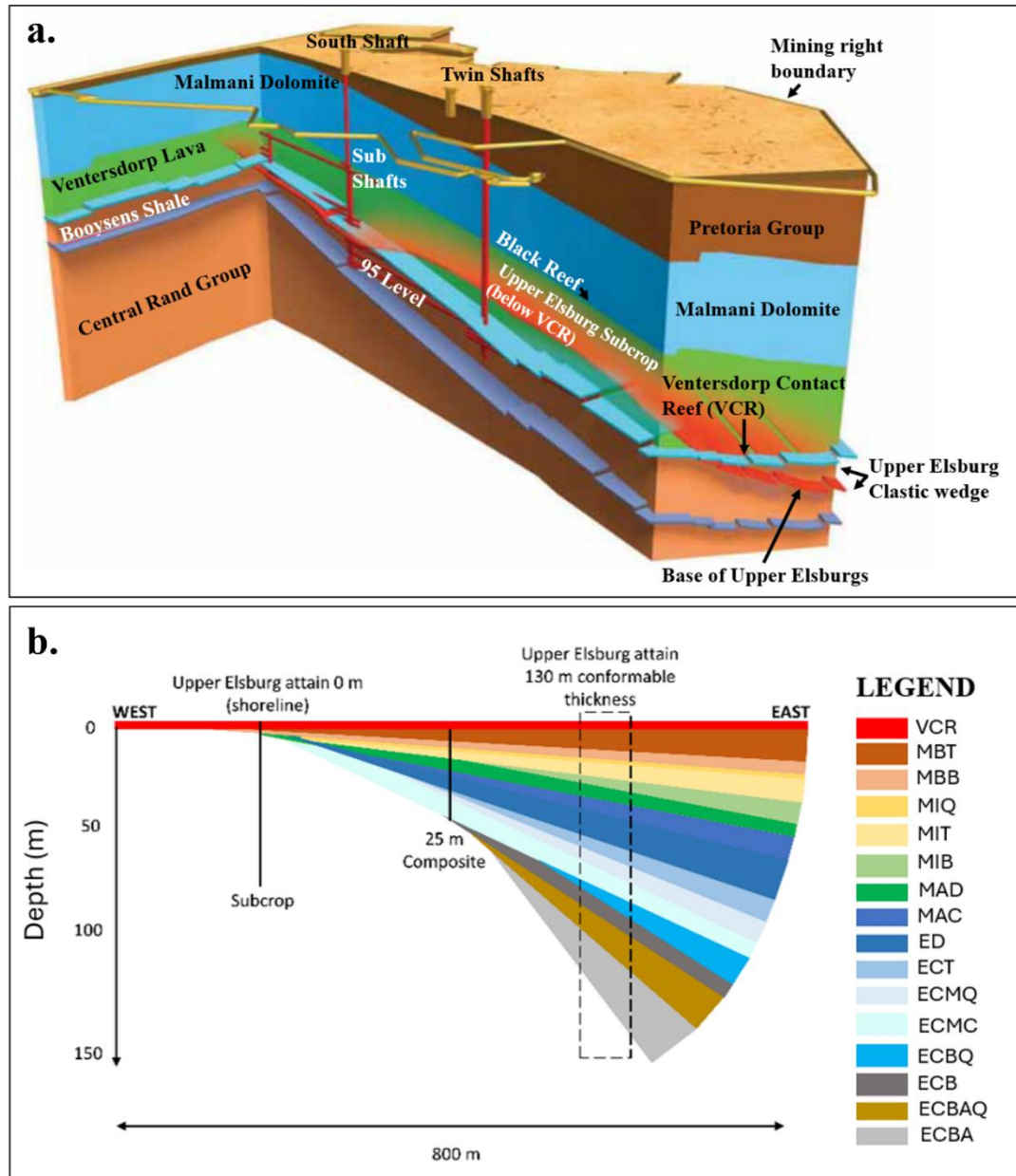


Figure 2.2: A modified 3D schematic illustration of the South Deep Gold mine (a), and a section through the orebody indicating the targeted mining zones (b). Modified after (South Deep Internal Technical Report, 2012).

[Table 2.1](#) further breaks down the different end-members of the UER and gives a geological description of each member. This table further confirms that the package is entirely composed of the quartzites and conglomerates, making them difficult to resolve with the seismic methods since quartzites and conglomerates exhibit similar densities and velocities ([Manzi et al., 2012a,b](#)). Because of its high gold quality, the Upper Elsburg Individuals' EC reef is a prominent exploration target in the South Deep gold mine. The EC conglomerate is highly sorted and clast supported, with an oligomictic base. It is overlain with ED quartzwacke and hence has a very poor reflective interface.

According to research by [Osburn et al. \(2014\)](#), the Ventersdorp Contact Reef (VCR) of the Ventersdorp Supergroup sits on top of the UER at an angle of approximately 5°. The VCR is a strong and continuous seismic reflective interface that is used as a ghost reflector for seismically transparent reefs below it at South Deep gold mine. At the shoreline, the gold-bearing EC conglomerate can be found where it meets the VCR, and the Upper Elsburg reefs converge and merge. The shoreline composites, located just east of the shoreline, consist of densely packed conglomerate and quartzites from the Upper Elsburg package.

Due to the Elsburg reefs' eastward divergence and their position next to the VCR's base, a unique package of metasedimentary rocks has formed, creating a wedge shape that affects the amount of ore available. The thickness of the wedge has a direct correlation with decreasing gold grades, which can be attributed to a decrease in the proportion of conglomerate pebbles as one moves further away from the coast. At the eastern limit of the mining permit, the clastic wedge reaches a thickness of 120 m ([South Deep Internal Technical Report, 2012](#)).

Table 2.1: A stratigraphic breakdown of the different members of the Upper Elsburg Reef, modified after ([Wesseloo and Joughin, 2007](#)).

Stratigraphy		Geological description
Lava-W2b		Jointed lava
VCR		Tuffaceous quartzite
MB	MBT	Siliceous quartzite and conglomerate (50/50) with phyllonite on bedding
	MBB	Siliceous quartzite and conglomerate (50/50) with phyllonite on bedding
	MBQ	Siliceous quartzite and conglomerate (50/50) with phyllonite on bedding
MI	MIT	Siliceous conglomerate
	MIB	A combination of MIT and MBT characteristics
MA	MAD	Slightly argil. Quartzite, quartzite, and conglomerate, phyllonite on bedding
	MAC	Siliceous quartzite, conglomerate, rough surfaces
ED		Argillaceous quartzite, phyllonite abundant on bedding planes
EC	ECT	2 cycles, sub argillaceous & siliceous split by phyllonite, rough surfaces
	ECMQ	Argillaceous quartzite, abundant phyllonite on bedding
	ECMC	Conglomerate generally siliceous, rough tight bedding no infill
	ECBD	Quartzite and conglomerate
	ECB	Siliceous conglomerate, rough tight bedding, no infill
	EC9Q	Argillaceous quartzite, phyllonite abundant on bedding planes
	EC9C	Conglomerate, multiple cycles separated by argil. Quartzite or phyllonites

3. LITERATURE REVIEW

3.1. The reflection seismic method

3.1.1. 3D reflection seismics

The seismic reflection method was initially developed in the 1920s and has since evolved from 2D to 3D, with the first large 3D datasets being acquired in the late 1970s and the method becoming routine in the early 1990s ([Robinson and Treitel, 2008](#); [Talagapu, 2005](#)). In the early 1980s, the limitations of 2D seismic data in terms of structural imaging led to the development and widespread adoption of 3D reflection seismic method. The evolution of the 3D reflection seismic method has been significant in the field of geophysics. The fine sampling in the inline and crossline directions in 3D seismic surveys provides accurate 3D higher geometrical resolution and sharpened detail on the spatial distribution of lithologies, porosities, and fluids. High-resolution 3D seismic data can be used to generate vertical geologic sections in any direction, enhancing both structural visualization and stratigraphic interpretation ([Chopra and Marfurt, 2012](#)).

Legacy seismic data in the Witwatersrand Basin

The year 1987 marked a significant milestone in the South African mining industry, as a hard rock 3D seismic survey was conducted to facilitate mine planning and exploration at the South Deep project area. Over a decade later, in 2003, Gold Fields Ltd. carried out a high-resolution 3D seismic reflection survey, with a specific focus on the auriferous VCR in the Kloof and South Deep gold mines. This survey was meticulously planned to coincide with the 1987 3D South Deep seismic survey, reflecting the company's strategic approach to mining exploration and planning ([Manzi et al., 2019](#)).

In their work, [Manzi et al. \(2012a, b\)](#) merged legacy 3D seismic data, reprocessed them using advanced processing algorithms, and enhanced the signal-to-noise ratio (SNR) of the data for improved structural interpretation. Utilizing the prestack time migration technique, in particular, they achieved superior stratigraphic and structural imaging in faulted areas. The incorporation of seismic attributes proved valuable in identifying subtle geological structures crucial for ore resource

evaluation. This, coupled with improved mapping of seismic horizons and reefs, provided a more comprehensive understanding of the interplay between fault activity, reef distribution, and tectonic events. The integration of underground mapping and borehole data further refined the imaging and modelling of major fault systems, ultimately leading to the discovery of resources in faulted areas.

The work conducted by [Manzi et al. \(2012b\)](#) employed 3D reflection seismics to address safety concerns for mine workers related to water intrusions and the ignition of flammable gases. To enhance the resolution of the seismic data, the researchers manually picked horizons and faults and applied edge detection attributes. Specifically, they focused on identifying structures that displace the VCR and BLR (Black Reef Formation at the base of the Transvaal Supergroup) horizons, as these are most likely connected to overlying dolomitic aquifers. The researchers then correlated occurrences of water and methane with faults mapped through geological and seismic methods, characterizing the strikes and dips of these structures and assessing their continuity and connectivity.

[Figure 3.1 a-c](#) shows a topographic view from the South Deep mining area with the surface legacy 3D reflection seismic grid shown in purple. The two shafts are also shown in relation to the pre-existing boreholes that were used in the physical properties study for this work. The 3D seismic data shown is from the improved processing work by [Manzi et al. \(2012a\)](#) covering the South Deep gold mine. [Figure 3.1a](#) shows the location of the boreholes (yellow and blue circles) used for the study, the tailing dams, and the shaft position (red square). [Figure 3.1b](#) shows the 3D view of the seismic data and mine infrastructure (shaft position and mine tunnels). The mine tunnels shown in [Figures 3.1a,b](#) were used for in-mine seismic survey (green line in [Figure 3.1b](#)) in this study, especially level 100 tunnel (shown in yellow). The underground boreholes used for physical property studies are shown in blue and yellow in [Figure 3.1c](#).

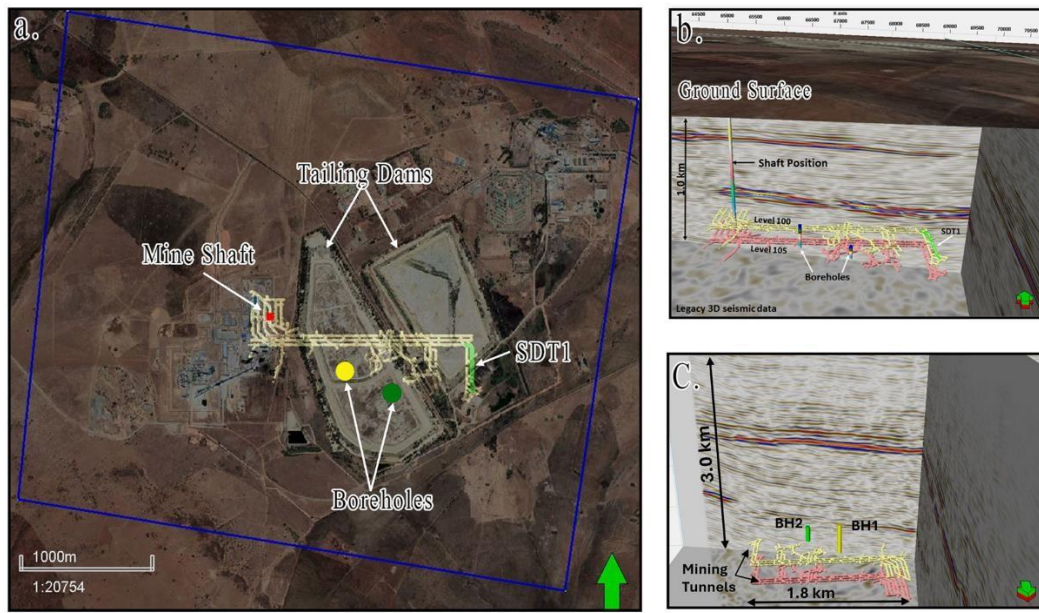


Figure 3.1: (a). Topographic view of the South Deep gold mine area, with the blue box representing the previous seismic 3D cube. (b) A topographic view of the mine area with the legacy seismic data displayed in relation to the mine tunnels (yellow and brown coloured infrastructure) and shaft. (c) A portion of the legacy seismic data (Manzi et al., 2012a,b) with the two boreholes (yellow and red) used for the physical properties study. The yellow tunnel represents the level 100 tunnel, and brown tunnel represents the level 105 tunnel. Green line along the 100 level tunnel in (b) is the seismic profile acquired in this study. Yellow circle: BH1 borehole, Green circle: BH2 borehole.

3.1.2. In-mine seismic experiments

There are several methods for researching subsurface geology. Direct techniques involve drilling boreholes, both horizontally and vertically from the stope. Seismology, resistivity, gravity, and borehole/downhole geophysical methods are examples of indirect, or geophysical, approaches. Seismology, as done from the Earth's surface, provides the most information about the underlying structure of any of them. Large faults could be found, while minor faults that are crucially significant might go unnoticed. Consequently, this has given room for in-mine/ underground seismic surveys to be explored (Buchanan et al., 1981). To be successful and socially acceptable, exploration methods must be cost-effective, sensitive to deep target characteristics and capable of greater depth penetration, while having minimum impact on the environment. Manzi et al. (2019) provide a summary of how the active surface reflection seismic method has been used to explore for the

deep-seated (> 2 km) gold-bearing quartz pebble conglomerates in the Witwatersrand Goldfields in South Africa. These surface surveys, however, could not characterize subtle and complex geological structures in sufficient detail to support in-mine exploration, mine planning and contribute to safety. In recent years, in-mine seismic surveys are increasingly gaining popularity in geophysics as novel and cost-effective exploration tool ([Brodic et al., 2021](#); [Rapetsoa et al., 2022](#)). One advantage of in-mine seismic surveys over traditional surface methods is that seismic sensors and energy sources are closer to the geological targets, hence higher resolution. The main disadvantage is that the in-mine seismic surveys suffer more noise from mine-related noise than surface seismic methods. The usage of equipment underground is, however, subject to highly strict safety standards in the mining sector. The underground field approach must be as straightforward and feasible in order to create a workable production system ([Buchanan et al., 1981](#)). On the positive side, the frequencies of the recorded seismic waves are significantly greater than in surveys on the ground surface since the shot sites are also set in the hard rock. Consequently, the wavelengths are proportionately shorter, and the resolving power, or the ability to detect thin strata, is more advantageous than in soft rock locations ([Schmidt, 1959](#)).

[Reid et al. \(1979\)](#) made the initial effort at Peak Mine in the late 1970s when they conducted in-mine seismic reflection studies between 1977 and 1979. The study served as the basis for the high-resolution reflection seismic technique's application. In order to help with the mining and development of nickel sulfide orebodies, Western Mining Corporation at Kambalda, Western Australia, launched a significant research program in the 1990s. The goal was to evaluate the effectiveness of underground (in mine) mapping techniques for identifying stope geometry and hard rock geological structure ([Greenhalgh et al., 2000](#)).

In-mine seismic measurements were carried out at the Hunt Underground mine by [Greenhalgh et al. \(2000\)](#), and it was shown that high frequency (>1 kHz) waves may travel across lengths of tens of meters. They also showed that reflection imaging could be used to define stope geometry and that tomographic imaging

could map velocity inhomogeneities. A strong link between the seismic maps and the known geology was visible. Over the next several years, it is probable that the use of in-mine seismics will rise.

An in-seam seismic reflection test was carried out by [Carneiro and Gendzwill \(1996\)](#) at the Kloof gold mine in South Africa. The target was the Ventersdorp Contact Reef (VCR). Prior to mining, the project's objective was to evaluate the use of seismic techniques for locating stratigraphic boundaries and identifying ore layer discontinuities. The extensive cracking around the mine entrances, which led to poor coupling between sources and receivers as well as energy dispersion and absorption, made the task more difficult. Weak and sporadic reflections were seen, which may be related to the target beds. And it was found that more work is needed to improve the quality of the data and confirm the geological correlation.

In an underground potash mine in Canada, [Gendzwill and Brehm \(1993\)](#) conducted high resolution in-mine seismic reflection studies. They made use of 50 Hz geophones, a hammer as the seismic source, and a digital stacking seismograph with a sample rate of 0.1 ms. Between 20 and 80 ms, prominent frequency reflections up to 1100 Hz were seen. The geophones' erroneous high-frequency resonance was eliminated using deconvolution filters. Seismic data were used to depict the usual stratification of the flat-bed sedimentary rocks and a small structure, verifying the extent of the geological abnormalities seen at the mining level. Astonishingly, the outcomes revealed almost-vertical reflected waves that moved in both directions at the speed of the shear wave which could not be interpreted geologically, leaving room for more studies to aid interpretation.

Challenges in South Africa

Although the combination of field geology, geochemistry, drilling and different geophysical methods (ground or airborne) has led to numerous discoveries, there is still a great need for innovation and improvement of the present exploration strategies, especially for in-mine purposes. This need, particularly in South Africa,

is largely driven by an overall increasing demand to provide the mining industry with accurate geological information and knowledge that will contribute to optimal ore extraction and mine safety, i.e., achieving ‘zero harm objectives’. This goal is likely to be achieved using in-mine seismic surveys in combination with drilling and underground geological mapping. Surface seismic methods maintain a good vertical resolution with depth and, therefore, have been used more routinely for localizing mineral deposits and mine planning in the last decades in South Africa. However seismic methods, like most exploration technologies, have their challenges. For example, seismic data conducted in brownfield areas can suffer from mining and anthropogenic noise. In some cases, some mines can no longer acquire seismic data on the surface due to a lack of access to the mining sites because of mine infrastructure and environmental issues. In such cases, in-mine seismic surveys are considered a solution. However, further complications and restrictions are introduced if underground spaces (e.g., developmental tunnels, mining stopes, exploration holes, etc.) are used for seismic or other exploration purposes. The nature of these spaces imposes numerous limitations, resulting in conventional active-source seismic imaging being rather difficult, size limited (small scale) or even an impossible task. Logistical challenges related to active mining operations, and strong vibrational noise, combined with the GPS-denied nature of underground spaces preventing accurate time synchronization, are just some factors that have restricted in-mine exploration primarily to drilling.

Most in-mine seismic exploration has been connected to physical property studies or vertical seismic profiling (VSP) surveys inside or in the near-vicinity of boreholes (seismic side-scans). The issue with such surveys is that they don’t provide a 3D picture of the geology ahead of the mining face as the obtained information is only limited within the vicinity of the holes.

In addressing deep South African mining challenges, SAMERDI’s (South African Mining Extraction Research, Development and Innovation) Advanced Orebody Knowledge (AOK) was launched in 2018 by Mandela Mining Precinct (MMP) with the promise of shaking up mineral exploration in South Africa through a partnership with academia/industry and high-tech companies as well as with public

communities to cover social acceptance aspects. This project is part of the AOK project titled, “Developing technologies that will be used to obtain information ahead of the mine face such Tunnel Seismic Prediction” and also part of the EUSA international collaborative project ERA-MIN3 FUTURE (Fiber-optic sensing and UAV-platform techniques for innovative mineral exploration) project. At South Deep gold mine, the existing active surface 2D and 3D seismic data ([Manzi et al., 2013](#)) provide a unique opportunity to compare the results from in-mine seismic approach to evaluate the reliability and accuracy of the final results.

3.2. Elastic properties of rocks

A variety of physical properties that may not be easily determined in boreholes can be estimated using laboratory measurements on hand samples or samples taken from drill holes. The properties acquired from the laboratory measurements are not in situ (may not be representative) and frequently exhibit a scale dependency, which pose the most issues with the laboratory measurements (frequency, grain size, etc.). Due to the fact that samples from hardrock environment often have extremely low porosities (less than 2%) and have been compacted through numerous phases of deformation and metamorphism, this appears to be less of an issue in the crystalline environment ([Malehmir et al., 2013](#); [Nkosi et al., 2023](#)).

In reflection seismology, the study of the physical properties of rocks is crucial for interpreting seismic data and understanding the subsurface geology. Seismic reflections depend on the contrast of the compressional and shear wave velocity and density in the subsurface, which in turn depend on the rock's structure, elasticity, porosity, pore fluid, and pressure ([Dvorkin, 2004](#)). By analyzing these properties, geoscientists can infer information about the composition, porosity, and fluid content of the rocks, which is essential for various applications such as hydrocarbon exploration, geothermal energy, and underground waste disposal ([Dvorkin et al., 2014](#)).

Understanding the seismic properties of rocks is a critical aspect of identifying potential reservoirs, seals, and structural traps lying beneath the surface. This knowledge facilitates the exploration and extraction of natural resources, which is crucial in the energy and environmental domains ([Dvorkin, 2004](#)). Consequently, the study of physical properties of rocks in reflection seismology is essential in deducing subsurface geological features and making informed decisions in various industries ([Arora et al., 2011](#)).

Majority of rocks are heterogeneous composites; only monomineralic rocks have a single mineral type. When holes and cracks filled with fluids exist, heterogeneity becomes more pronounced. Physical rock qualities are therefore influenced by mineral content, porosity/fracturing, and internal rock structure ([Schön, 2015](#)). In order to properly plan, anticipate, and interpret surface seismic data gathered for the purpose of mineral exploration, it is crucial to comprehend the seismic velocities associated with ore deposits and their host rocks ([Malehmir et al., 2013](#)).

3.2.1. Types of seismic waves

According to the study of stress and strain, shear strain and cubic dilatation are the two main forms of elastic disturbance that make up strain. Each of these forms of deformation moves through the medium at its own velocity, according to the solution of the equation of motion. Moving "volume" strain is the first sort of disturbance, while "shape" strain is the second type ([Aziz, 2020](#)). Due to its second arrival after the P-wave, the shear wave (S-wave) is also known as the secondary wave. P- and S-waves are also referred to as body waves due to their independent propagation in an unbounded medium ([Wu and Wu, 2008](#)).

An energy or mechanical disturbance called a seismic wave can move from one place on Earth to another. Seismic waves can be produced by a sudden release of energy, such as a volcanic eruption, chemical explosion, or earthquake. Seismic waves may be divided into two categories: body waves, which flow through the interior of the Earth, and surface waves, which cross the surface of the planet. Compressional and shear waves make up body waves, whilst Rayleigh and Love

waves make up surface waves. Seismic waves carry detailed information about both the seismic source and the physical characteristics of the rock they penetrate (Ghaychi Afrouz, 2020).

By assuming that the Earth has the elastic qualities of a solid, it is possible to explain how energy is transmitted into the ground. Since the whole Earth's crust is thought to be elastic (apart from the local area of the shot), this sort of acoustic wave transmission is known as elastic wave propagation. In an elastic solid, several wave phenomena can take place. They are categorized based on how the solid's constituent particles behave when a wave passes through them (Talagapu, 2005).

3.2.1.1. Body waves

Upon arrival, body waves are categorized as either main (P-wave) or secondary (S-wave). The first and fastest waves are P-waves. Along longitude, they are compressed (Figure 3.2). S-waves, which are shear waves that shake the ground perpendicular to the direction of transmission, arrive second (Ghaychi Afrouz, 2020).

Longitudinal Wave (P-waves)

When a plane P-wave passes through a medium, the particles move around in their neutral locations in the direction of the wave's propagation. The pathway is made up of a series of alternating compression and rarefaction zones (Figure 3.2a). This kind of wave is frequently used in seismic exploration operations such as reflection and refraction.

The P-wave arrives at a certain observation site first among the seismic wave types because it travels at the quickest speed for the medium in consideration. This is a typical finding of seismologists who analyse earthquake seismograms (Alsadi, 2017). The formula for the P-wave propagation velocity is:

$$V_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} \quad (3.1)$$

Where, ρ is the medium density, μ is the rigidity modulus and λ is the shear modulus . From this equation, the P-wave velocity depends on the medium density (ρ) and elastic characteristics (λ and μ).

Transverse Waves (S-Waves)

The shear strain or "shape" deformation is the traveling disturbance in this scenario. There are no volume changes in the medium that this sort of wave travels through. The transverse displacement of the path particles with respect to the propagation direction is a result of the shear strain (rotation of a portion of the medium). Shear waves and secondary waves, or simply S-waves, are other names for them. The term "SV-wave" refers to an S-wave that is flowing horizontally ([Figure 3.2b](#)) but is so polarized that the particle motion is constrained to the vertical plane ([Alsadi, 2017](#)). It is referred to as an SH-wave ([Figure 3.2c](#)) when the polarization plane is horizontal. S-wave velocities are calculated using the formula:

$$V_s = \sqrt{\frac{\mu}{\rho}} \quad (3.2)$$

Where ($l = 0$), S-waves cannot propagate in liquid mediums.

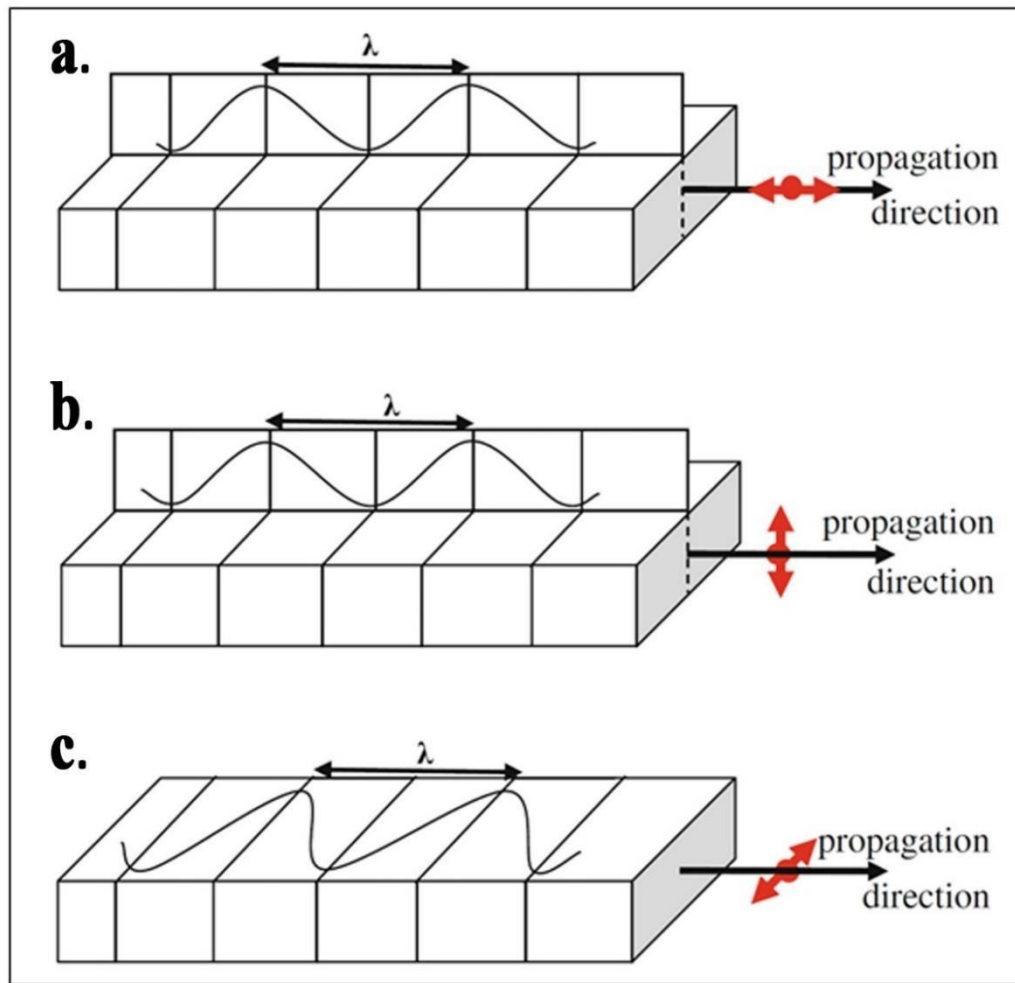


Figure 3.2: : A plane body wave's propagation through a medium causing particle to move about in it. (a). P-wave, (b), SV-wave, and c. SH-wave, where λ denotes the wavelength (*modified After Alsadi, 2017*).

3.2.1.2. Surface waves

Surface waves are waves that move on the Earth's free surface, as suggested by their name. The primary characteristics shared by all surface waves, as shown on earthquake seismograms, are their low frequency in comparison to the body waves and generally large amplitudes (high energy content) (Foti, 2000). They also move at a velocity that is typically slower than body waves flowing through the same medium. It is a well-known fact that surface waves exhibit more pronounced dispersion phenomena because their velocity depends on the frequency of each harmonic component. Rayleigh and Love waves are the two primary subtypes of surface waves (Alsadi, 2017).

Rayleigh Waves

Lord Rayleigh discovered Rayleigh waves in 1885. Rayleigh waves typically form at the free surface of a semi-infinite solid medium. With deeper water, the wave's amplitude rapidly decreases. In this case, the traveling disturbance consists mostly of a combination of particle movements associated with both P- and SV-waves. [Figure 3.3a](#) shows the particle motion, which is on a vertical plane parallel to the propagation direction and has a retrograde elliptical orbit ([Alsadi, 2017](#)).

It is a type of seismic surface wave that moves freely across a semi-infinite material. This medium is known as the low-velocity layer (LVL) or the weathering layer. Apart from the energy source, Rayleigh waves travel horizontally in a retrograde elliptical motion. With increasing depth, this wave's particle velocity reduces (amplitude) until finally reversing. This area is towards the bottom of the weathering layer ([Talagapu, 2005](#)).

When a low-velocity surface layer covers the semi-infinite medium, Rayleigh waves display a phenomena called 'dispersion'. In the subsurface material, wavelength components that are excessively long (when compared to the thickness of the surface layer) penetrate further and move at a speed that is around 0.9 times that of the S-wave. Ground roll is the term for surface waves that are characterized as Rayleigh waves and are often observed on shot recordings collected from seismic reflection surveys. Since ground-roll waves are regarded as unwanted noise, attempts are often undertaken to eliminate them or at the very least reduce the masking impact they have on the seismic reflection signal ([Alsadi, 2017](#)).

Love waves

[Love \(1911\)](#) identified the second subtype of surface waves. Similar to SH-wave vibration mode, transverse particle movement is limited to the horizontal plane. Between the top and bottom boundary-planes of the surface layer, there are several reflections that allow love waves to propagate ([Figure 3.3b](#)). For extremely long wavelengths, the propagation velocity in the subsurface medium approaches the S-

wave velocity, but for short wavelengths, it is closer to the surface layer's velocity. Similar to Rayleigh waves, the period of the harmonic component affects how quickly Love waves propagate (Alsadi, 2017).

The Love wave is a surface wave that propagates within the LVL and has horizontal motion perpendicular to the direction of propagation but no vertical motion. In crustal research, such waves are also known as the horizontal SH-wave, Q-wave, Lq-wave, or G-wave, and they usually move through many reflections inside the LVL. The seismic record is filled with several noise trains when such waves are converted into another mode, further masking the amount of reflected energy (Talagapu, 2005).

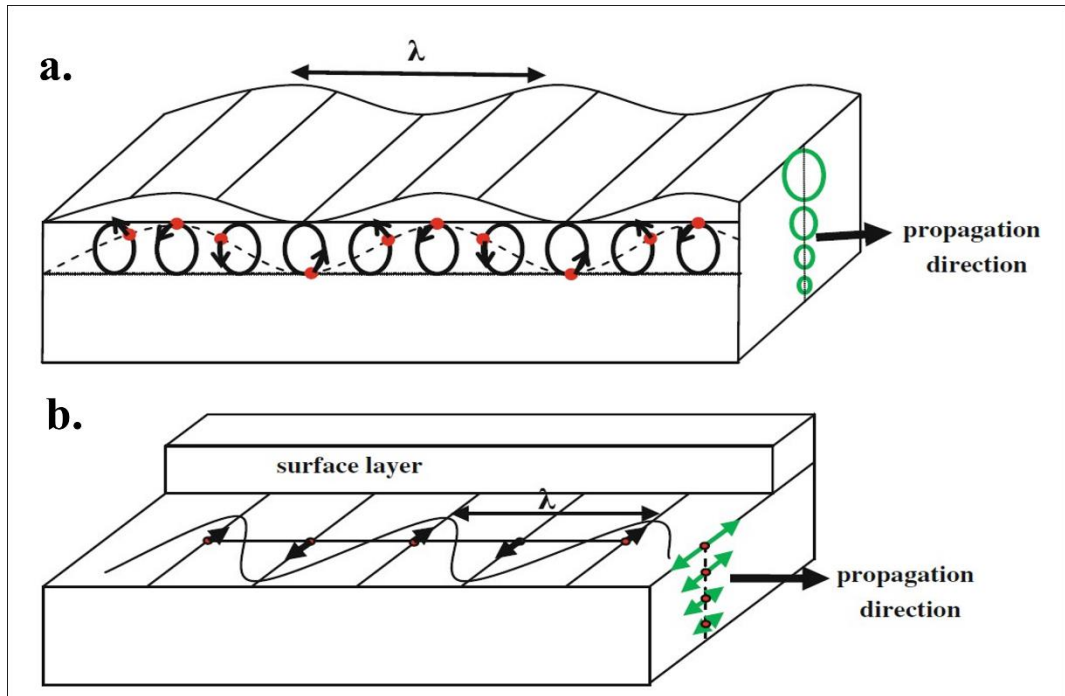


Figure 3.3: Movement of planar surface waves as they travel through a medium, (a) Rayleigh wave, (b) Love wave, with the wavelength represented by λ (modified after Alsadi, 2017).

3.2.2. Propagation of seismic waves

All attributes (waveform, speed, and travel-path geometry) of a seismic wave may change as it is propagating. The physical characteristics of the host material dictate the extent and nature of these modifications. Whether caused by a natural or artificial event, a sudden pressure pulse launches a seismic field. From the source zone, the generated seismic energy spreads outward as a wave motion. Under these circumstances, the seismic wave propagates out from the source zone in all practicable directions (seismic energy source within an elastic medium). A travel ray-path is established after the source-point and detector-point coordinates are provided in a certain medium ([Alsadi, 2017](#)).

Rocks differ in their elastic moduli and densities, and as a result, in their seismic velocities, due to their varied compositions, textures (such as grain size and degree of sorting), porosities, and included pore fluids. Seismic wave travel times must be converted into depths, so knowledge of the compressional wave (P-wave or V_p) and shear wave (S-wave or V_s) velocities of rock layers encountered during seismic surveys is crucial. In addition, this knowledge can be used to determine the lithology of a rock, or, in some cases, the type of pore fluid contained within it. The presumption that rocks are homogeneous and isotropic in structure has to be addressed in order to connect rock velocities to lithology ([Kearey and Hill, 2002](#)).

In situ or laboratory measurements using properly prepared rock samples are both options for determining the rock velocity. Seismic surveys provide velocity estimates for rock strata that are separated by reflecting or refracting surfaces in the field. It would be feasible to connect velocity values so obtained with specific rock units encountered within drilling sequences if boreholes are close to a seismic survey. By tracking the passage of high-frequency (1 MHz) acoustic pulses through cylindrical rock specimens, velocities are calculated in the lab. This allows for the quantitative evaluation of the impact of changing temperature, confining pressure, pore fluid pressure, or composition on velocity. It is significant to emphasize that the validity of laboratory measurements at low confining pressures is questionable. Under typical laboratory conditions, a rock's intrinsic velocity cannot be reached below a confining pressure of roughly 100 MPa (megapascals), or 1 kbar, at which

point the solid contact between the rock's grains that characterizes pure rock is restored (Kearey and Hill, 2002).

In hardrock environment like the Witwatersrand Basin, laboratory studies of physical rock qualities do offer certain benefits over geophysical logging (for example, Vertical Seismic Profile (VSP) surveys). The fact that measuring individual samples is less expensive than measuring complete holes is one of these advantages. Another is that a lab environment allows for a greater variety of measurements than vertical holes do. The precise monitoring of testing circumstances, such as increasing levels of stress and temperature, is a third advantage. This is critical for determining the correlations between different physical properties, such as for assessing the impacts of temperature, porosity, density, and confining stress. (Nkosi, 2016).

3.3. Numerical simulations

A seismic wave field generated at the tunnel face is already propagating ahead of the construction, transporting a significant amount of energy in the preferred direction. Seismic sensors installed on the working front may readily record reflection signals. Due to the comparable measurement geometry, seismic processing procedures typical in surface seismic measurements can also be used. Unfortunately, because of the presence of the tunnel boring machine's cutting wheel, access to the tunnel face is typically quite limited (Jetschny, 2010).

It is essential to be able to visualize how complex structures would impact seismic wavefields in order to derive knowledge about the structure and composition of the crust from seismic data. Since most subsurface configurations do not have accurate analytical solutions to the wave equations, numerical approaches are the only way to acquire the solutions. Seismic modelling has evolved into a crucial technique for the analysis of seismic measurements as more precise information from seismic data is required. data capture parameters It is beneficial at all stages of seismic research. It can assist in choosing the best recording parameters for seismic data acquisition (Bohlen, 2002).

In order to obtain fine features from seismic field recordings, it is necessary to compare synthetic and field seismograms in order to better interpret seismic measurements. The key component of seismic inversion processes is modelling. Due to its capability to precisely describe seismic waves in any heterogeneous medium, explicit finite difference techniques have been frequently employed to simulate seismic wave propagation in 2D elastic media. These elastic finite difference simulators compute synthetic seismograms for 2D elastic models of the earth crust, but they are unable to simulate the Earth's anelastic behavior, which includes seismic wave attenuation and dispersion ([Bohlen, 2002](#)).

To represent the propagation of P-SV waves in 2D viscoelastic media, [Robertsson et al. \(1994b\)](#) presented a staggered grid, velocity-stress finite difference approach that is also based on the generalized standard linear solid (GSLs). The 3D scenario was also later added to their algorithm. The biggest disadvantage of the FD approach is the enormous amount of processing resources needed to construct accurate 3D models. Such computing demands are typically beyond the capabilities of sequential systems, including single-processor workstations and supercomputers with shared memory setups ([Bohlen, 2002](#)).

The simulation of seismic wave propagation in realistic computational models, which can include anisotropic media, nonplanar interfaces between layers and blocks, velocity/density/quality-factor gradients inside layers, and frequently with free-surface topography, is necessary for accurately synthesizing observed seismic data ([Klin et al., 2010](#); [Maeda et al., 2017](#); [Bliyeva et al., 2022](#)). Anisotropy is crucial for many applications in seismic exploration and is becoming more and more relevant, especially in structural research. Approximate approaches are required because analytical methods cannot solve realistic (structurally complicated) models.

The finite-difference (FD) approach is still widely used to simulate earthquake motion, and its significance in the seismic sector and structural modelling is rising. This is due to the FD method's ability to handle somewhat complicated models, produce a full solution when waves interact with the model, be comparatively

accurate, and be computationally efficient (Moczo et al., 2007; Preston et al., 2008; Liu et al., 2009; Li et al., 2019).

A space-time grid, or a collection of discrete grid points in space and time, covers a computing domain in the FD technique. By their values at the grid points, the functions defining a wavefield and those characterizing the physical characteristics of the medium are represented (Salon and Chari, 1999; Liu et al., 2009). The spacetime grid is theoretically arbitrary, and the values of the functions connecting the grid points are often not assumed. The so-called FD equations are used to estimate the spatial and time derivatives of a function at a specific grid location. The derivative is expressed using the values of the function at a certain set of grid points that are close to the given position (Moczo et al., 2007).

Due to the complicated geological, geometrical, and stressful conditions in underground mines, both analytical and experimental approaches have a limited use in resolving seismic wave propagation issues. Fortunately, the development of sophisticated numerical techniques and the rapid expansion of computer technology have made numerical modelling an essential and indispensable tool for studying seismic wave propagation (Wang, 2016).

Wave 3D software

To simulate wave propagation in a two- or three-dimensional elastic media, the WAVE software was developed. This wave's propagation may be tracked from its point of origin via buildings nearby to the stope, where it is reflected and refracted. This software was originally developed for mining studies but has since been applied to a variety of other tasks, such as the removal of radioactive waste, measuring pile-driving vibrations, and finding wave-guide fractures. The wave equation is solved as a system of first-order equations using finite differences on a staggered grid in the three dimensions of WAVE3D, a method that has been extensively used in seismological applications. Cundall (1992) created the program's initial version, which comprised the mesh system and a cutting-edge

implementation of a discontinuity that was used to represent both free surfaces and fractures. Then, [Hildyard \(1995\)](#) improved it by incorporating elements such as higher-order grid accuracy, tabular mining layouts, and more complicated fracture behavior with contact logic and intersections ([Linzer et al., 2021](#)).

As wave models generate full seismic waveforms, it is possible to compare them to the extensive whole seismic dataset. To better understand seismic behavior, wave models have long been utilized. Wave models may now, however, be applied directly to the inversion of seismic data due to advancements in processing power ([Hildyard et al., 2022](#)).

4. METHODOLOGY

This project aims to make use of the advanced computer powers, geology, and geophysics. The following workflow was adopted to ensure completion of the aims and objectives of this project, including (1) sampling and core-logging, (2) core cutting and polishing, (3) physical property measurements (seismic wave velocities and bulk densities), and (4) 1D, 2D and 3D numerical simulations.

4.1. Core sampling and preparations

For this study, the method that was used for the recovery of the core is diamond drilling. Diamond drilling gives far more precise cutting possibilities than more traditional drilling techniques. This not only ensures that any drilling work is done to an even higher degree, but it also lowers the possibility of accidentally damaging surrounding structures. By so doing, this preserves the rock sample to allow for detailed analysis.

Few exploration boreholes (see [Figure 3.1](#)) have been drilled upward ($+90^\circ$) such that they intersect the end-members of the Elsburg package all the way up to the VCR. These boreholes were selected as they allow us to measure the properties of the reefs within the Upper Elsburg Reefs (UER) package which is the main focus of the numerical simulations. The specimens composed of basaltic lavas, quartzconglomerate (locally termed ‘reefs’) and quartzites from boreholes drilled from the hangingwalls of mine tunnels (see [Figure 3.1](#)) located at depths down to 3 km below ground surface. Core samples were prepared at the Wits Rock Mechanics preparation laboratory, and all the samples were cut to an average length of 10.46 cm using the saw shown in [Figure 4.1a](#). A few samples had a smaller length due to their conditions before preparation. All the samples had the same diameter with some of the samples having a half diameter. All the samples were polished in the same lab, to ensure proper coupling on the samples when physical properties (mainly seismic velocities) were conducted.

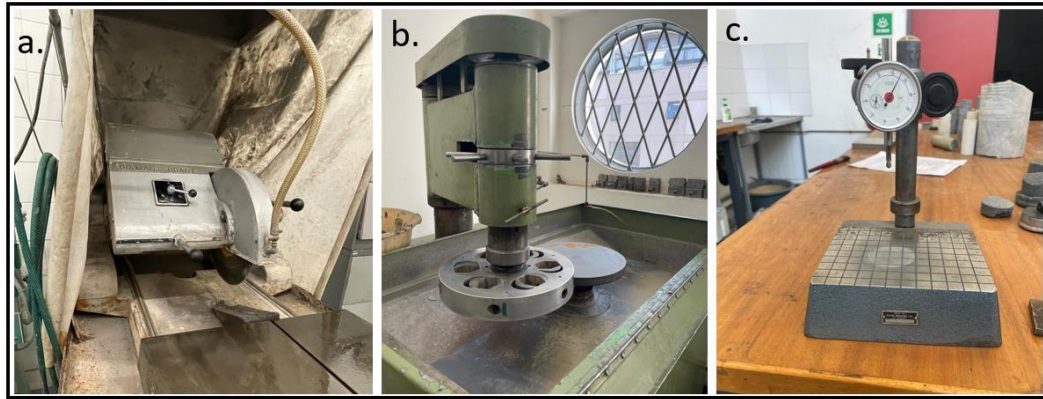


Figure 4.1: A summary of the three main tools used to prepare the rock samples at the Wits Rock Mechanics laboratory. (a) Diamant Boart Cut off saw, (b) Lapping Machine, and (c) Dial-Gauge.

4.2. Physical property measurements

4.2.1. Bulk density

All the measurements of the bulk density were obtained using the mathematical relationship between volume and the mass of the core samples, $\rho = \frac{m}{V}$. The samples

were all cylindrical in shape and the volume was calculated using the relation $V = \pi^2 h$. The mass of each sample was weighed using the AFP 3100L analytical balance with a capacity of 3100g/6.8lb and a readability of 0.01g and the length/ height was obtained using a Kanon flat head vernier calliper.

KT-20 Instrument

The first density measurements were conducted using the KT-20 instrument, this instrument can measure the density of a tiny sample using water displacement by using the integrated external tensiometer and sample container. The density measurement sequence used for these measurements consists of four steps as illustrated in [Figure 4.2](#): (1) Zero calibration; (2) measure sample in air; (3) measure the water-submerged sample; and (4) measurement results.

Step 1: The tensiometer was attached to the KT-20. We lifted the KT-20 in the air and select ‘measure’ by hitting the ‘OK’ button. Following the completion of the

zero-calibration measurement, we proceeded to the next step by pressing the ‘OK’ button.

Step 2: The sample holder wire was wrapped around the sample and then you link it to the tensiometer with the system's hooked. We held the KT-20 in the air and hit the ‘OK’ button to choose ‘measured’. When the sample measurement finished, we clicked ‘next’ to proceed.

Step 3: Using a water bucket as shown in [Figure 4.2](#), we placed the sample in water and ensured it was fully submerged. Once the sample was submerged, we selected ‘measure’ by pressing the ‘OK’ button. Once the measurement of the sample was complete, we selected ‘next’ to continue to the results.

Step 4: Results of the density measurement were then displayed in g/cm^3 . We then saved the results by pressing the ‘OK’ button to store the density measurement under the specified record ID.

Density measurements were also collected at the Wits Integrated Physical Property Laboratory (WIPPL) to compare the results with those which we collected at the Council for Geoscience (CGS) physical properties lab using different machines. The same twenty-four samples were used for the measurements. The instrument used for this was the SNOWREX AHW-3 Professional Weighing Scale with a maximum load capacity of 3 kg, readability of 0.1 g, repeatability of 0.1 and an accuracy of 1/15000. [Figure 4.3](#) summarises the different steps followed in the measurement of the bulk density in the WIPPL. [Figure 4.3a](#) shows the samples and the setup of the balance on the stand. The stand used for these measurements allows the balance to measure the samples from the bottom through the attachment of a basket that holds the samples. [Figure 4.3b](#) shows measurement of the sample mass in air (W_a) and [Figure 4.3c](#) shows the measurement of the sample mass in water (W_w).

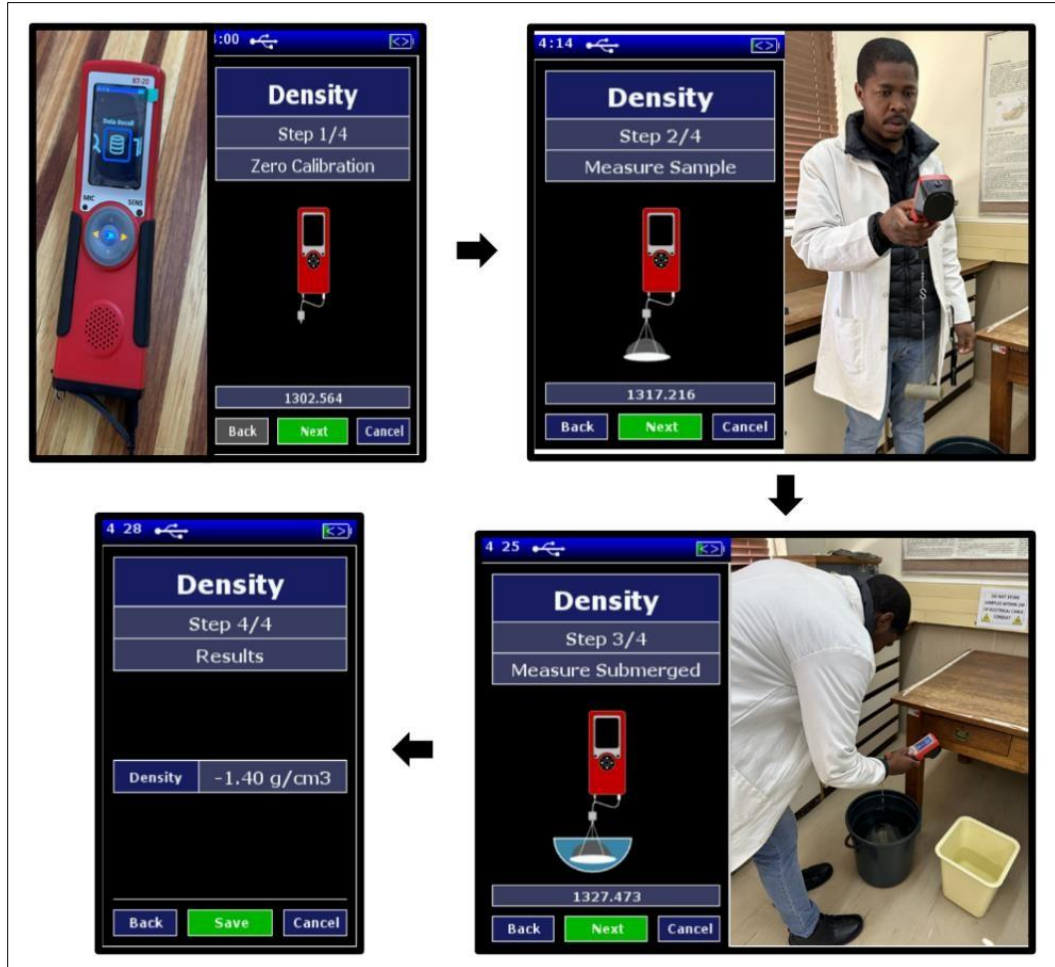


Figure 4.2: KT20 Density measurement tool, summarising the four steps followed to measure Density at the Physical property lab at the Council for Geosciences (CGS).

The density was then calculated using the formula as described by Archimedes buoyancy principle ([Agrawal, 2021](#)): Density of the specimen = $\frac{SG}{\rho_L W^a}$ where $SG = \frac{W_a - W_w}{W_a}$, and ρ_L is the density of the liquid used to submerge the samples in the density of the liquid used (water) was 1g/cm^3 and therefore, the density of the samples is equal to the specific gravity.

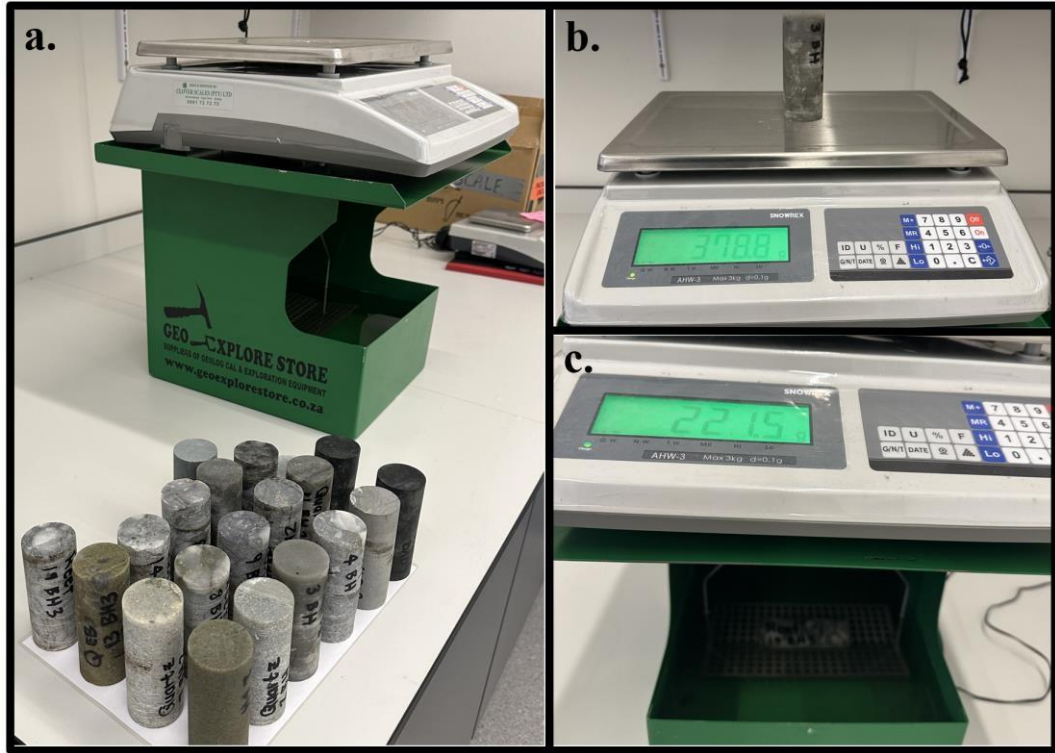


Figure 4.3: (a) Samples from South Deep gold mine, and (b) the setup of the balance, weighing a sample on top, and (c) weighing a sample submerged in water.

4.2.2. Seismic velocities

The seismic velocities (P- and S-wave) were measured using 250 kHz transducers at ambient room temperature and atmospheric pressure. In order to investigate the source of seismic reflectivity, we computed synthetic seismograms from the measured petrophysical data and compared them with real seismic profiles from the study area. The following flow was followed using the PUNDIT PL200 oscilloscope for both P-wave and S-wave velocity measurements as summarised in [Figure 4.4a-d](#).

1. The 'measurement' option was selected in the main menu after powering the instrument on, to commence measurements ([Figure 4.4a](#)).
2. The system then allowed us to input the length of the sample (in meters) and the name of the sample for us to be able to differentiate the different samples after saving them.

3. A couplant was then applied to the parallel sample edges then firmly pressed and held the transducers against the sample (Figure 4.4b,c).
4. The sensor automatically discovers and notes the initial arrival and determines the velocity for P-wave velocities. Then we clicked the save icon to record the value on the data sheet, along with the sample name and length of the sample axis being measured (Figure 4.4d).
5. Measuring the S-wave velocities necessitated human determination of the commencement of the shear wave echo, as it is always preceded by a small P-wave component identified by the auto triggering. The S-wave travels in a one-dimensional plane, thus it was critical that the transducers were properly aligned and a specific shear wave couplant paste (Sanotech Shear Gel in this case) was used to obtain the strongest signal.

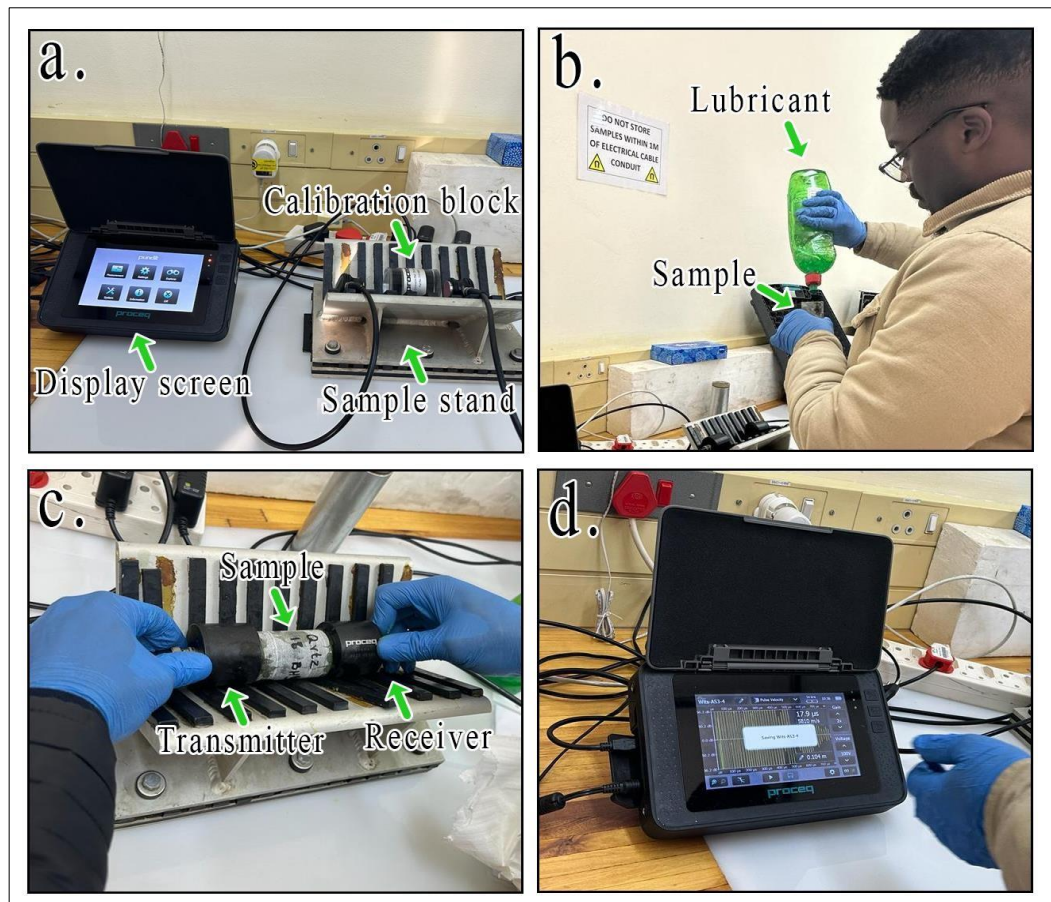


Figure 4.4: Pundit measurement tool (a), sample measurement setup (b). A lubricant applied to a sample before P-wave measurements. (c) Two transducers measuring the seismic velocity through the sample. (d) The pundit user interface saving results (measurements).

4.3. Numerical simulations

4.3.1. 3D numerical simulations

For 3D modelling, two software packages were used; WAVE3D used in conjunction with mXrap. The program WAVE was employed to model the propagation of waves in a 3D elastic medium. Furthermore, the wave propagation was followed from its initiation at a source, through its reflection and refraction from structures in the tunnel vicinity. mXrap was used for model building and to view the model and the propagation of the wave in the vicinity of the model.

The WAVE application's command driven interface was used to define the grid, define the properties, layout of the geology, point and line history positions, initial boundary stresses and source representation. South Deep gold mine provided the infrastructure files (tunnels, shaft, etc.) and a geological model with all the lithologies associated with UER package (in dm. or dxf. formats) to be used for simulations and seismic survey design planning. Three applications from the mXrap software were used namely: Mine Geometry Model (MGM), Common Model Builder (CMB), and Wave Results Viewer.

Several steps were followed to calculate wave-field simulations of three dimensional models (this case the orebody) and the peak-particle velocities (Figure 4.5).

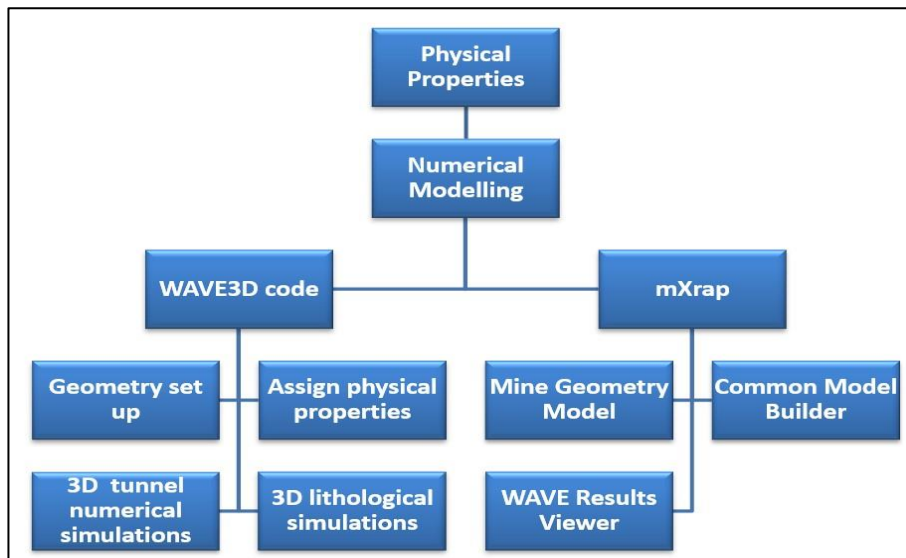


Figure 4.5: Overview of the numerical simulations workflow, outlining the steps from WAVE3D model construction to the final product.

Once the physical property measurements were completed, the next phase involves conducting simulations to elucidate the behavior of seismic waves within 3D framework. By inputting relevant parameters (including physical properties) and geological data, the Wave3D code generates simulated wavefield responses, providing insights into how seismic waves propagation through the mine infrastructure, orebody and host rocks. Additionally, the mXrap software (developed by the Australian Centre for Geomechanics) was used to enable the calculation of peak-particle velocities, crucial metrics for evaluating the structural integrity of the orebody. Through meticulous execution of these steps, one can produce accurate and reliable simulations that contribute to a deeper understanding of the seismic characteristics associated with the tunnel, orebody, and host rocks, ultimately providing a guide for future seismic survey designs.

The Mine Geometry Model application was used to quickly produce predefined fixed geometries on a consistent grid pattern. The South Deep gold mine survey files (dxf, dtm) were utilized as the app's input geometry. A specified volume was discretized into a cubic cell grid in a predictable pattern. The algorithm determines which cells are within and outside excavations, as well as which cells are being divided by excavation borders. For usage in mXrap applications or other programs, such as packages for numerical modelling, the models may be immediately exported in a variety of formats. The Common Model Builder was used to assign physical properties of the different lithologies that are present on the model (Figure 4.6)

	Step ID	Volume	↓ Date	Type	Material	Comment	Export Step Order
1	39	3,732,000	2017-Jan-01	Rock	Lithology	ECBA2021	2
2	40	1,286,000	2017-Jan-01	Rock	Lithology	ECBAQ2021	3
3	41	2,441,000	2017-Jan-01	Rock	Lithology	ECBQ2021	4
4	42	1,014,000	2017-Jan-01	Rock	Lithology	ECMC2021	5
5	43	286,000	2017-Jan-01	Rock	Lithology	ECMQ2021	8
6	44	731,000	2017-Jan-01	Rock	Lithology	ECT2021	7
7	45	3,082,000	2017-Jan-01	Rock	Lithology	MAC2021	6
8	46	5,424,000	2017-Jan-01	Rock	Lithology	MBT2021	12
9	47	1,733,000	2017-Jan-01	Rock	Lithology	MIB2021	10
10	48	252,000	2017-Jan-01	Rock	Lithology	MIQ2021	11
11	49	27,000	2017-Jan-01	Rock	Lithology	MIT2021	9
12	50	248,000	2017-Jan-01	Rock	Lithology	VCR2021	13
13	51	320,000	2017-Jan-01	Development	Void	TUNNEL2021	1

Figure 4.6: mXrap software Common Model Builder interface showing the different material types.

After the physical properties have been assigned to the model, the Common Model Builder exports meta data with material properties and the grid geometry as a wave file. Wave Results Viewer was then used to view the model snapshots and histories from the Wave3D model.

3D Finite-Difference modelling

The lithology data were received from South Deep mine as datamine (.dm) format files, of which included, the points (pt) and triangles (tr) for each reef on each section. The lithology files were converted to .dxf files using Datamine software.

Model Building on mXrap

The Mine Geometry Models Application was used for building and exporting mining geometry models that we received from the mine. Most geotechnical analyses include a stope, cave, and development geometry. Mine geometry evolves over time, and it is vital to include these changes in any back analysis or numerical modelling that explores stability or monitoring parameters over time, which is why the model had to be updated by the mine based on the information the mine had.

The model and the mine tunnel are displayed in [Figure 4.7](#).

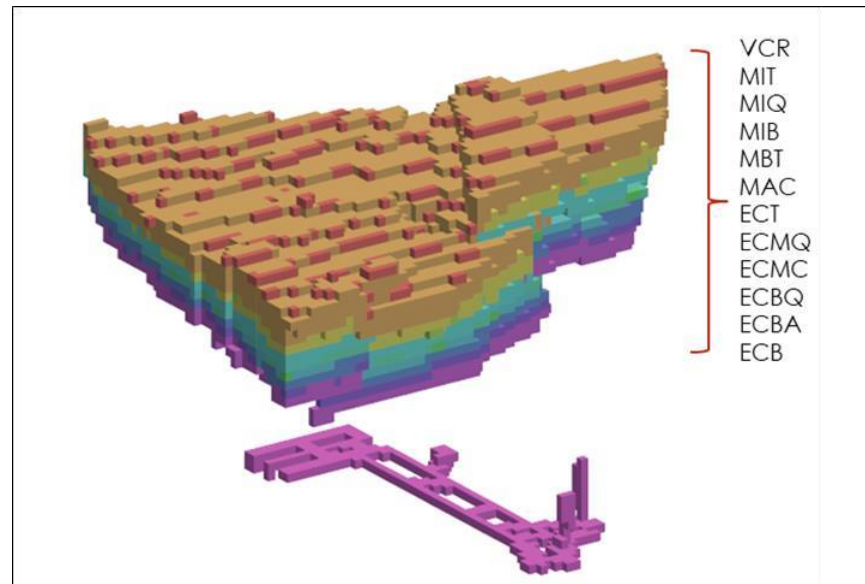


Figure 4.7: A model containing 12 of the South Deep Gold mine reefs constructed using Mine Geometry model on mXrap together with the mine tunnel. The mine surfaces, namely VCR, MIT, MIQ, MIB, MBT, MAC, ECT, ECMQ, ECMC, ECBQ, ECBA, and EC, consist of alternating quartzites and conglomerates (reefs) mined at South Deep gold mine.

Common Model Builder (CMB) application was used to allocate physical properties to the model. The application extracts the volume of each of the steps (reef in this case), and then allows the user to specify the material, type and add a comment, of which we used to specify the different reefs (see [Figure 4.6](#)). For assigning physical properties of materials (surfaces) used in the model, the physical properties used were those measure at the CGS lab and the density measurements from the Wits University Lab. The Export Step Order was used to set the colour scheme of the different reefs.

Model building on Wave 3D

After specifying the physical properties on the CMB application, the application was then used to export the model as a readable WAVE file and generated metadata based on the specified model. This was to ensure that the model can be run on WAVE3D. The export contained the following files in .txt format:

1. **Rock properties file** – which specifies the physical properties of the different reefs.
2. **Base file** – which is a file that specifies the grid and location of the materials.

The histories and source file were specified independently with WAVE3D syntax using a text editor. The following source properties were used: Source type – dilatational, amplitude = $10e6$, period = $4e-3$ and wave type – cosine form. The geophones were defined initially spaced 10 grids apart in 100 x 100 x 100 grid space and as a test run, we used 41 geophones.

4.3.2. 2D modelling

In order to predict the seismic response of the orebody, we utilized Tesseral 2D seismic finite difference modelling software to simulate seismic wave propagation through a subsurface environment housing an orebody composed of sixteen distinct units representing members/units of the Upper Elsburg Reefs. The graphical user interface was used to construct a geological model of the orebody and the tunnel

(Figure 4.8). Essential geological parameters such as P-wave velocity, S-wave velocity, and bulk density, were used for each unit to accurately characterize the subsurface structures. The tunnel floor served as the zero-depth reference point, with both receivers and shot points positioned at this level to ensure uniformity in spatial distribution. A total of seventy-two receivers and forty-one shot points were strategically configured for seismic acquisition. The Ricker wavelet was employed as the seismic wave type for generating synthetic seismic data. This comprehensive methodology allowed for the generation of realistic seismic simulations, enabling detailed analysis of the orebody's seismic response and facilitating comparison with actual seismic survey data upon completion. The model as seen in Figure 4.9 has a horizontal span of 360 m and a depth of 140 m, with a grid cell of 1 m in both vertical and horizontal directions. The top of the model shows the tunnel floor, and the bottom of the model shows the shales at the base of the UER package. Figure 4.9 shows examples of synthetic shot gathers from the 2D model. Both shot gathers show evidence of clear P-wave first breaks as shown in green arrows.

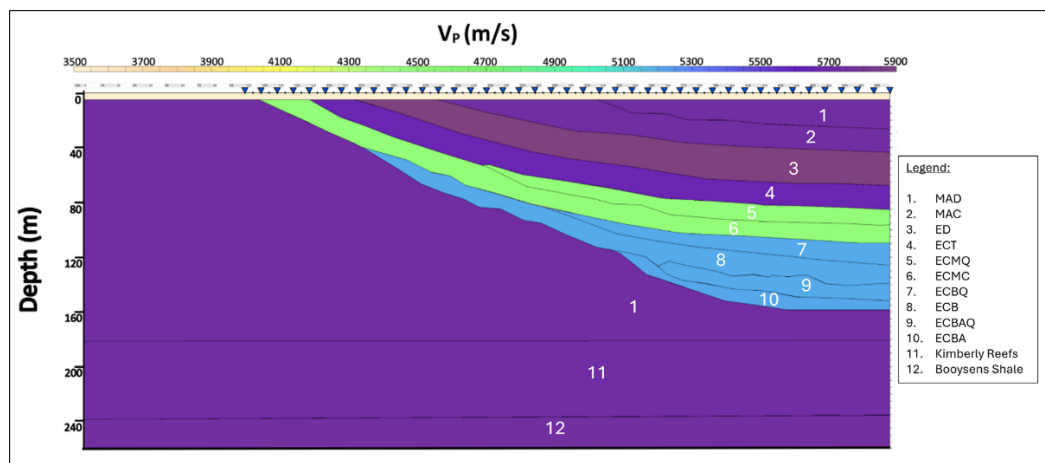


Figure 4.8: Geological model of the orebodies at south deep from the tunnel floor to the shales at the bottom, the model was built on Tesseral model based on physical property measurements and the geological model is based previous geology studies by Kwangwari (2014) and South Deep Internal Technical Report (2012) on the South Deep orebody model.

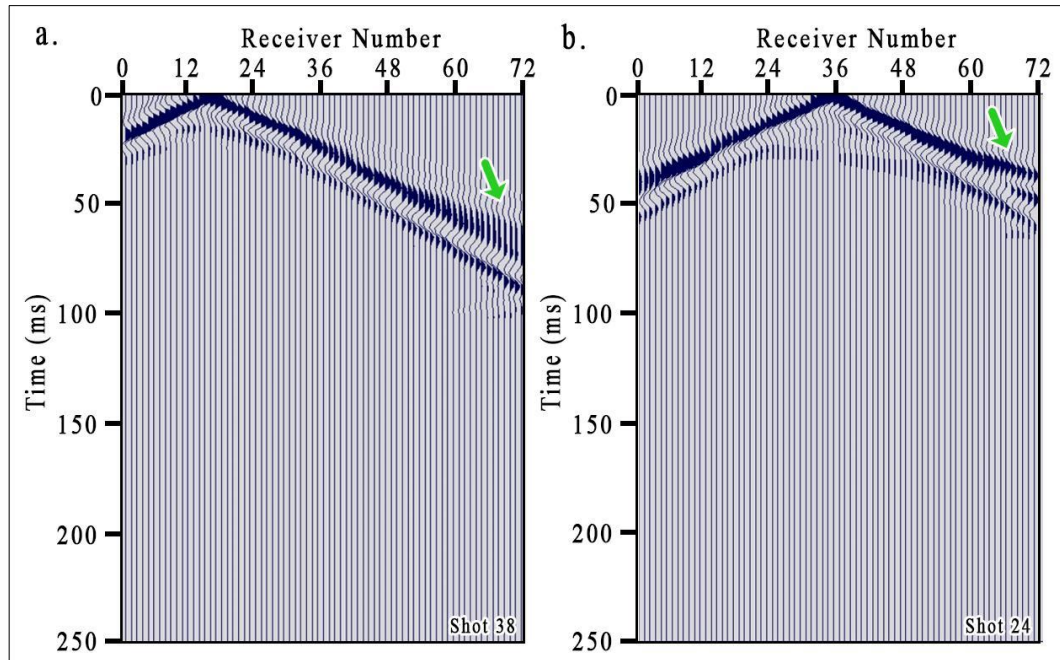


Figure 4.9: Synthetic shot gathers generated from Tesseral 2D modelling. Shot 38 (a) and shot 24 (b), with the green arrows showing evidence of clear P-wave first arrivals.

4.3.3. 1D synthetic seismogram

The SynthSeis Program (Figure 4.10), developed by Westgate (2020), was utilized to create 1D synthetic seismograms from data collected from five borehole logs from the mine. The program's primary objective was to produce synthetic seismograms using velocity and density data. To achieve this, all borehole logs were digitized into excel files and imported into the program. With the density and seismic velocities of each formation logged, the program generated a synthetic seismogram, which can be exported as either a.png image or as a time series in another spreadsheet for further manipulation or display options.

To replicate seismic data collection environments, reflection coefficients were convolved with a seismic wavelet to create synthetic seismic traces. A Ricker wavelet with frequencies ranging between 10 Hz and 100 Hz and a sampling rate of 1 ms to 4 ms were used. In this study, a 50 Hz frequency and a 2 ms sampling rate were utilized.

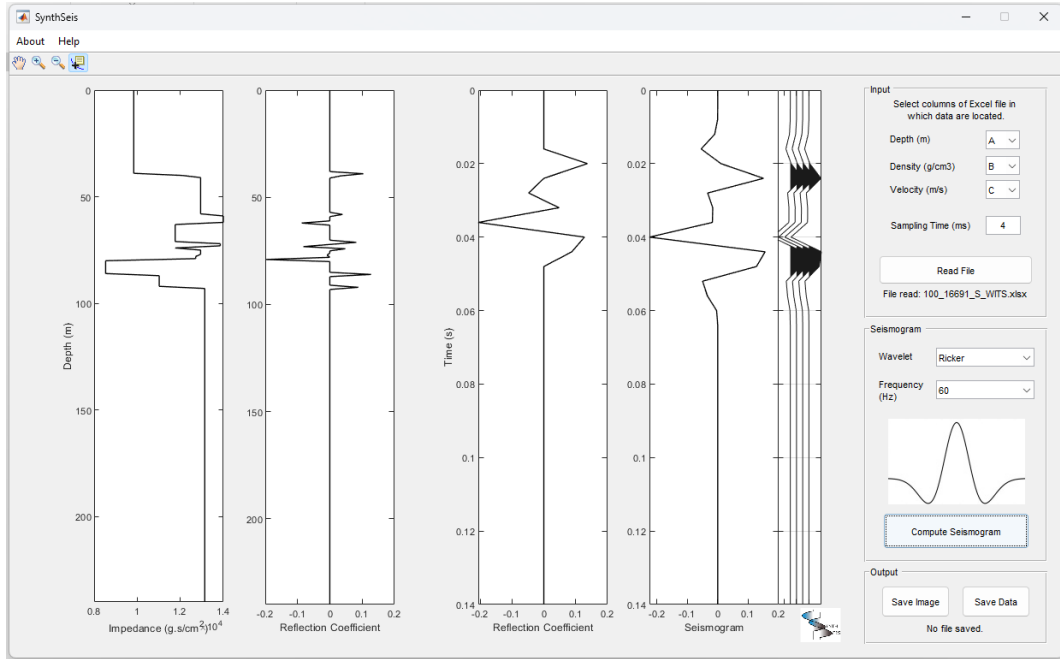


Figure 4.10: User interface of the synthesis program utilized for generating synthetic seismograms, providing a visual representation of the tools and parameters employed in the process.

4.3.4. 3D seismic modelling and survey designs

In modern-day exploration endeavours, it is crucial to perform subsurface illumination investigations to ensure that seismic surveys designed to acquire 2D/3D seismic data are cost-effective and operationally efficient. Subsurface illumination modelling is an invaluable resource for evaluating the impact of survey parameters on subsurface imaging and amplitude analysis. It provides valuable insights into optimal geometric configurations, shooting directions, and subsurface imaging, while also helping to refine data processing and interpretation strategies in geologically complex areas (Misra et al., 2008). In order to properly design the

survey, assess the fold coverage of reflected rays along the tunnel, a 3D ray tracing method was utilized. This technique was applied by designing a seismic profile at South Deep Gold mine, which is illustrated in [Figure 4.11](#). The Ventersdorp Contact Reef (VCR) located at the top of the Upper Elsburg Reef package was utilized to calculate and investigate the propagation of rays from sources and receivers positioned at 5-meter intervals along the planned profile along the mine tunnel floor. The VCR was chosen due to its seismic reflective nature compared to the underlying UER package ([Manzi et al., 2012a,b](#)). The resulting ray counts and paths for the entire planned profile are presented in [Figures 4.12](#) and [4.13](#), respectively.

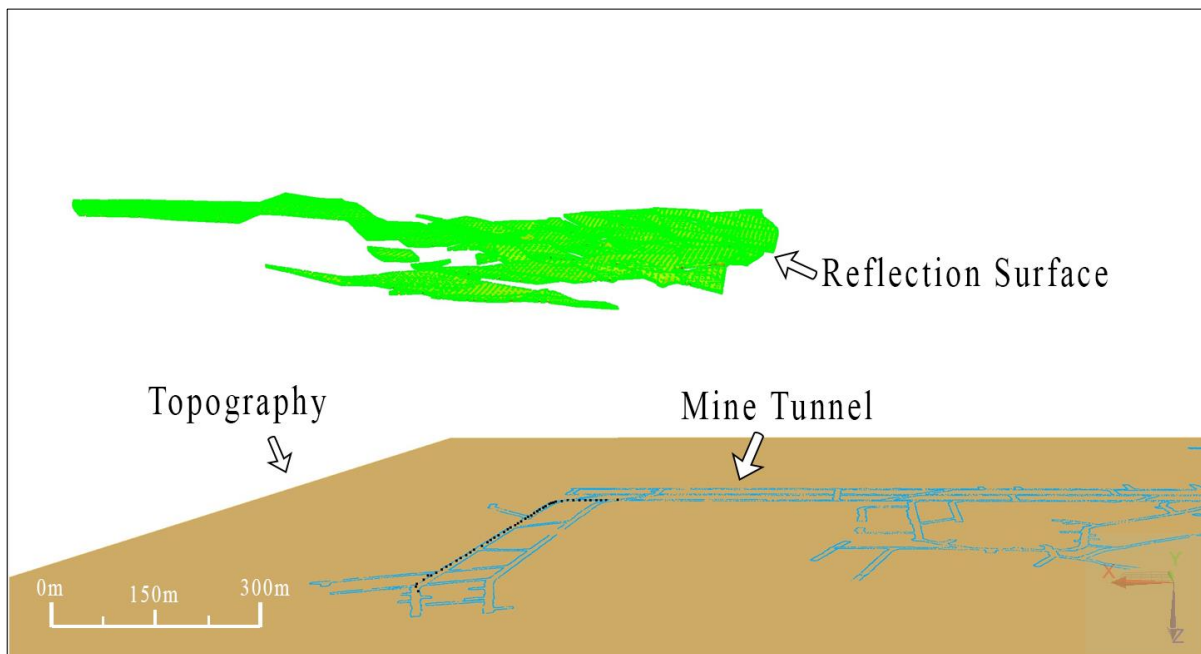


Figure 4.11: Model setup showing the reflection surface in this case the Ventersdorp Contact Reef (VCR - green), the mine tunnel (in blue) and the topography of the model.

The reflected rays from the VCR with respect to the host roc was useful in determining the positions of receivers and shooting direction, which helped in optimising the acquisition geometry. The results were also used for quality control during data processing and interpretation, especially in complex geological environments such as hard rock formations as the one at South Deep gold mine.

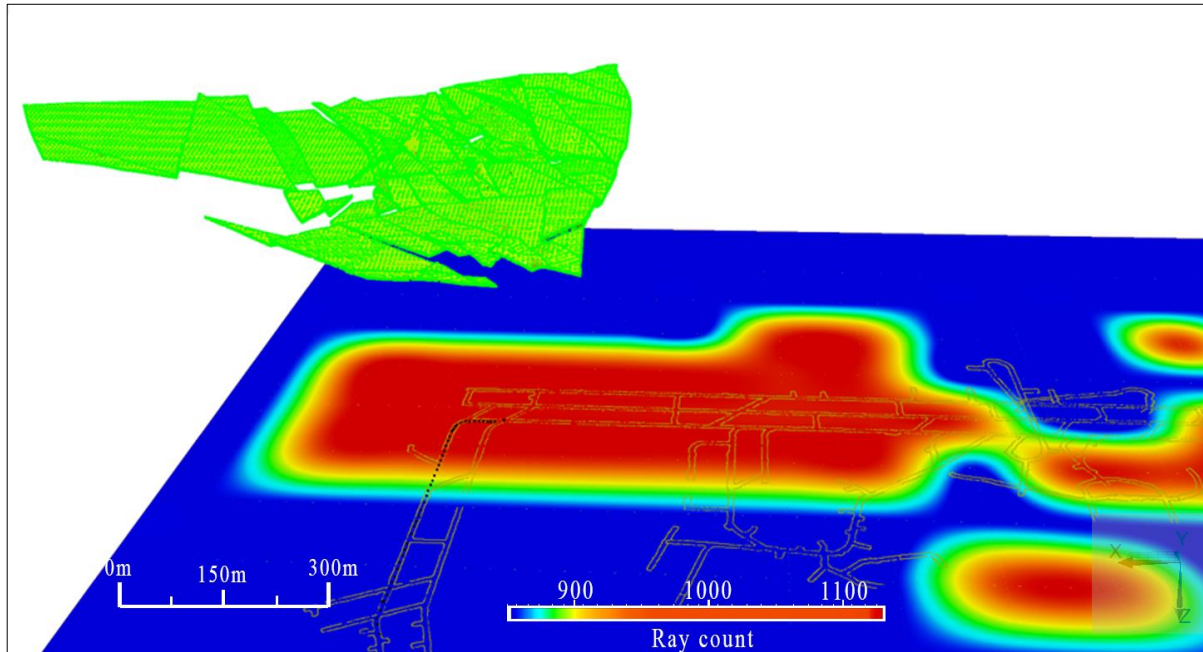


Figure 4.12: A diagram showing the different ray counts on the topography where the geophones/receivers were positioned. This shows the density of the reflections that come from the Venterdorp Contact Reef (VCR-green).

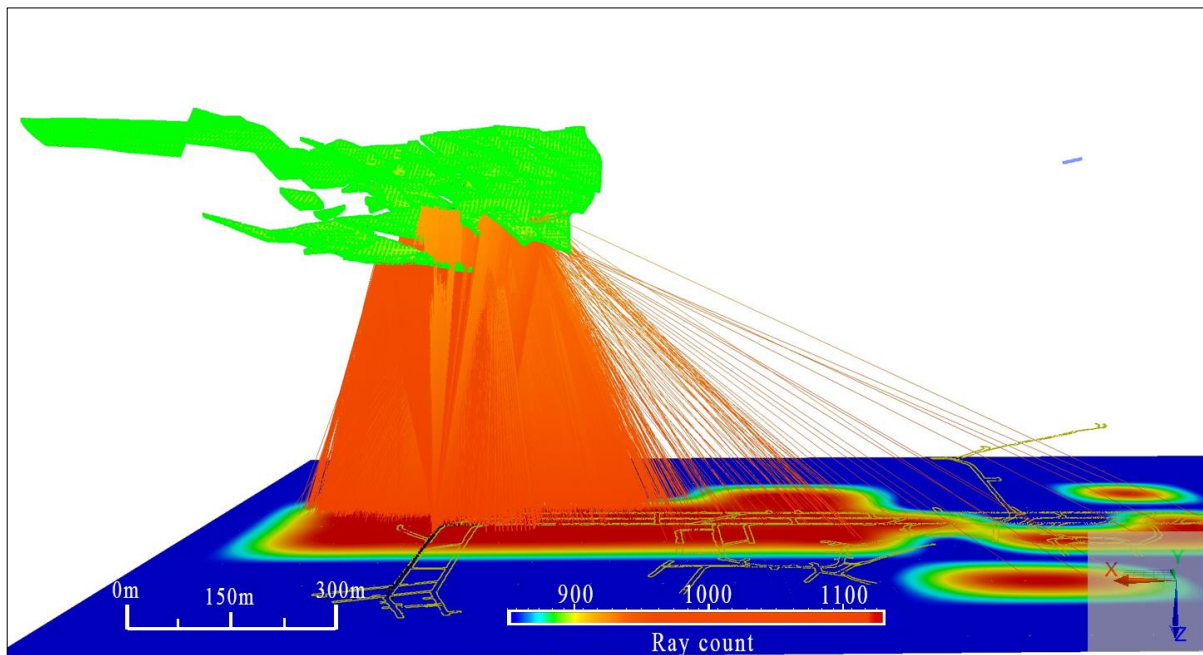


Figure 4.13: A diagram showing the ray traces from the VCR to the topography.

Upon examination of [Figures 4.12 and 4.13](#), it became apparent that the concentration of rays is heightened on a singular side of the tunnel. The reason for this occurrence is due to the reflective surface being positioned solely on one edge rather than directly above the tunnel, causing most of the traces to not be reflected

throughout other areas of the topography. We executed various configurations to ascertain the receiver's distribution with relation to the shooting direction and to chart reflection shadow areas. This was particularly vital for the planning and design of the real seismic survey along the tunnel.

5. IN-MINE SEISMIC SURVEY

5.1. Data acquisition

Before conducting the seismic surveys, a team inspected the mine site for several days to assess the tunnel's condition and determine the best locations for shots and receivers (Figure 5.1a-d). In-mine seismic experiments involved the use of a cabled system and Distributed Acoustic Sensing (DAS) fiber optic cables. The survey was a continuation of the pilot study by Rapetsoa et al. (2022) who conducted surveys at Maseve mine between 2020 and 2022 to test the feasibility of using seismic surveys in underground mine tunnels. The first week of the experiments involved testing the GPS time system (developed under EU-funded Smart Exploration Project, Malemir et al., 2019) underground, by first locking it on the surface with the satellite before transporting it underground to provide GPS time signal to the source and receivers (DAS array). Upon arrival underground, the GPS time system was tested by connecting it to a mobile device to check for GPS connection, moreover, and also deployed the nodal sensors and tested their functionality in underground spaces. The DAS system was deployed for both active and passive acquisition and the signals were recorded using the DAS interrogator in a continuous mode. Active acquisition deployed the GPS time system that was placed beside the interrogator. DAS array was collocated with the cabled seismic system, which deployed one-component 5 Hz geophones for comparison purposes. The sensors were drilled into the ground for good ground coupling at every 5 m, with a total of three geodes connected. The tunnel seismic acquisition utilized the 500 kg drop-hammer with a shot spacing of 10 m and a time tagging system was used to synchronize the underground DAS and surface nodal array 3 km above the mine tunnel (using broadband micro-electromechanical sensors (MEMS), Sercel WINGs, one-component). However, the time tagging system required a GPS connection to operate. To solve this, the GPS time tagging system was mounted on the Bobcat and moved along with it for every shot. In the end, the surface-tunnel seismic recording was successfully achieved. However, this MSc study focuses only on the seismic data acquired along the tunnel with the cabled (Geode) system as shown in Figure 5.1. Other researchers within the ERA-MIN3 Future project are processing on the other datasets

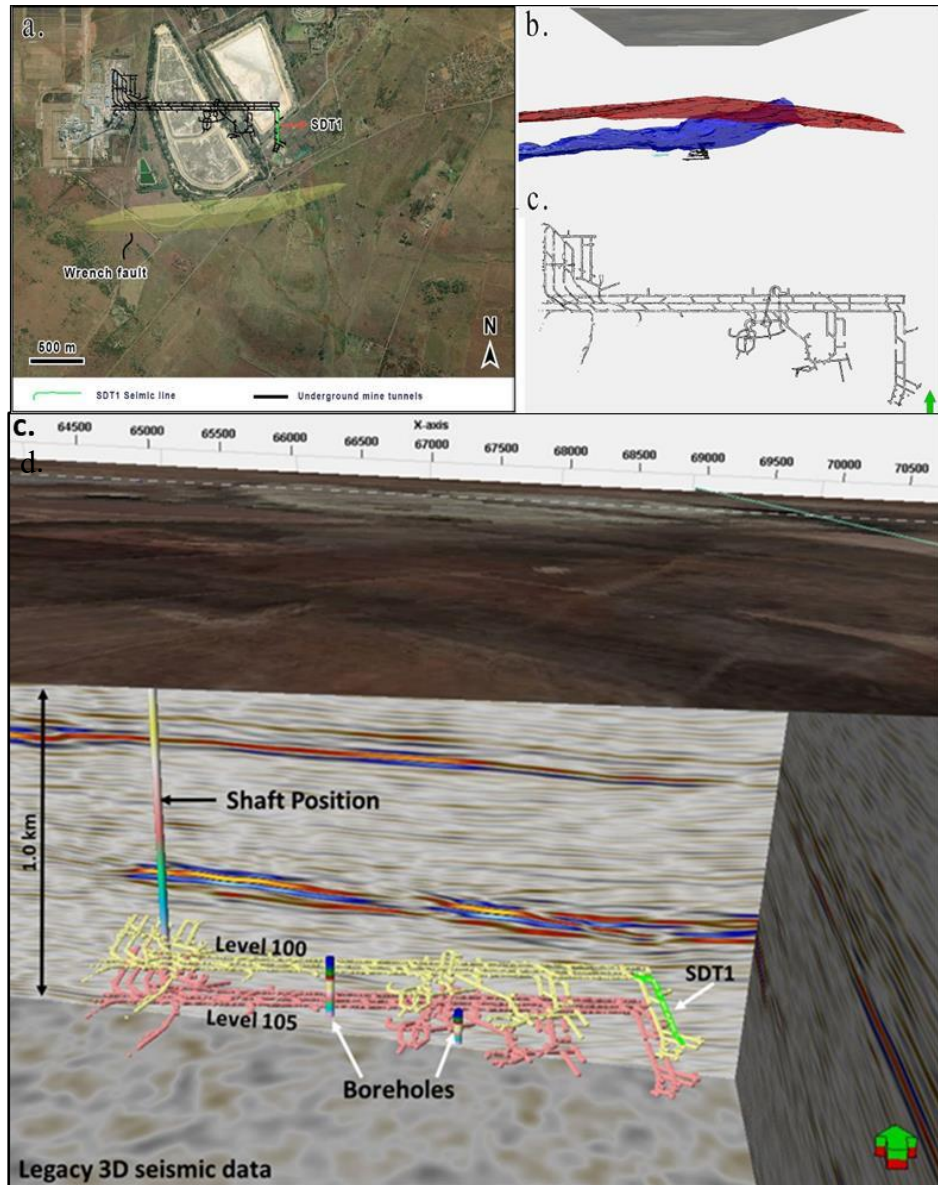


Figure 5.1: Map of the South Deep Gold Mine's surface and underground .1: Map of the South Deep Gold Mine's surface and underground workings. (a). South Deep Tunnel. (a). South Deep Tunnel-1 (SDT1) seismic profile (green). (b) A -1 (SDT1) seismic profile simplified 3D (green). (b) A simplified 3D overview of the mine overview of the mine showing only the Ventersdorp Contact Reef (VCR – blue surface) and the Black Reef (BLR – blue surface – black surface) and the Black Reef (BLR). (c) A close-up image of an underground mining tunnel.– black surface). (c) A close-up image of an underground mining tunnel. (d) 3D view of the mine tunnels, boreholes, legacy seismic data, and location of the seismic profile (SDT1).(d) 3D view of the mine tunnels, boreholes, legacy seismic data, and location of the seismic profile (SDT1).

Tunnel seismic survey using a cabled system

One in-mine 2D seismic profile was conducted in July 2023 with a total length of 360 m (SDT1 in [Figures 5.1a-d; 5.2a-d](#)) within the known members of the Upper Elsburg Reef package. [Table 5.1](#) summarises the acquisition parameters. The data were collected using 72 14 Hz cabled geophones/receivers ([Figure 5.2b](#)) connected to the powered geode system ([Figure 5.2d](#)), with a spacing of 5 m and a N-S orientation. We drilled holes along the tunnel floor to plant all the cabled geophones and increase the coupling; although, this process proved time-consuming as it took two days to drill and plant geophones along the profile, but this was anticipated considering the hardrock environment in the tunnel. The seismic source used for this survey was the GPEG 500 kg, mounted on a bobcat and the setup for the survey is displayed in [Figure 5.2a](#).

The equipment used for recording consisted of 1C cabled seismic receivers. Singlecomponent geophones were placed on the tunnel floor, with only a few of them vertically planted in drilled holes on the side walls. The seismic profile was obtained by spacing the cabled geophones 5 m apart. We stacked four shot recordings vertically at each position to enhance the signal-to-noise ratio (S/N). To prevent noise interference from sources like mines or directed waves, we experimented with various sample rate options. After analysing the shot collections at different sampling rates, we selected a rate of 2 ms, which produced the best results considering the limitations of the survey's sensors' resonant and bogus frequencies.

Table 5.1: The acquisition parameters for tunnel seismic profile (SDT1).

Survey Parameters	
Profile Name	SDT1
Profile length	360 m
Recording length	4 s

Sampling rate	2 ms
Direction	N - S
No of Receivers	72
Receiver spacing	5 m
Geophone	5 Hz
No of shots	41
Shot spacing	10
Source type	GPEG-500 kg
Vertical stacks	4



Figure 5.2: A summary of the South Deep Tunnel-1 (SDT1) acquisition setup. (a) The type of source used for the survey with the blue lines showing where the cabled system was, (b) the type of sensor/geophone used, (c) the recording unit setup, and (d) the geode system and the power supply.

5.2. Data processing

Globe Claritas seismic processing software was used for the processing of the seismic data. The software was preferred as it allows users to create workflows that allow the automation of seismic data processing through pre-defined steps. By establishing a list of processing modules and defining the conditions necessary for each of the individual modules, the desired processing flow is established. The different processing steps that were followed when processing SDT1 dataset are summarised in [Table 5.2](#). In general, the dataset was passed through a conventional processing workflow.

Reflection seismic processing focused on cleaning the top 200 ms from ambient and coherent noise to enhance target reflections. Generally, the data were collected in a

noisy and active mine environment and on the fractured, muddy and flooded tunnel floor at depth of ~ 3 km below the ground surface, which resulted in the introduction of noise in the dataset. Figures 5.3a-c and 5.4a-c show examples of the raw and processed field data. The data exhibit clear P-wave first breaks as observed in Figures 5.3a and 5.4a indicated in green arrows. The secondary events/sources were also observed in raw shot gathers as a result of moving vehicles, rock crushing and drilling activities. Also notable in the data was the bobcat-generated noise and double impacts (Figures 5.3a and 5.4a, indicated in red arrows) made by the impulse source bouncing on the hard tunnel floor, however, these were easy to remove during the processing stage (Figures 5.4b-c). Processing steps were taken to suppress noise and enhance target reflections (Figures 5.3b and 5.4b, shown in yellow arrows) associated with geological structures. The proximity of electrical noise to the seismic profile introduced constant 50 Hz noise in the dataset, which was easily removed by applying a notch filter.

In general, the overall processing strategy (Table 5.2) as demonstrated in Figures 5.2a-c and 5.3a-c involved: (1) evaluation of data bandwidth via different frequency panels, focusing on those panels that show the presence of direct/refracted/reflected arrivals; (2) removal of frequencies above 130 Hz (5.3a-c); (3) suppress ground roll using fk filtering; (4) enhance reflected arrivals via deconvolution (Figure 5.3b, c), spectral balancing and fx deconvolution, and (5) velocity analysis and normal moveout correction, and (6) CMP stacking (Figure 5.4).

Table 5.2: Summary of the processing steps followed to process seismic line (SDT1).

Step	Process	Parameters
1	Data input	Read SEG2 data
2	Geometry setup	2.5 m CMP spacing, crooked line binning
3	Trace editing	Remove noisy, dead, and unbinned traces
4	First break picking	All available offsets
5	Elevation statics	Datum: 1130 m, replacement velocity: 3500 m/s

6	Radial trace filter	Vrange: -5500:5500 m/s and Lowpass filter: 8 – 28 Hz
7	Airwave filter	Velocity: 350 m/s
8	Fast FK filter	Dip: 10
9	Horizontal median filter	LMO: 3500 m/s
10	Wiener deconvolution	Gap: 0 ms and length: 20 ms
11	Bandpass filter	10 – 30 – 130 – 175 Hz
12	NMO and stacking	Velocity: 4000 m/s – 5500 m/s
13	Depth conversion	Velocity: 5500 m/s

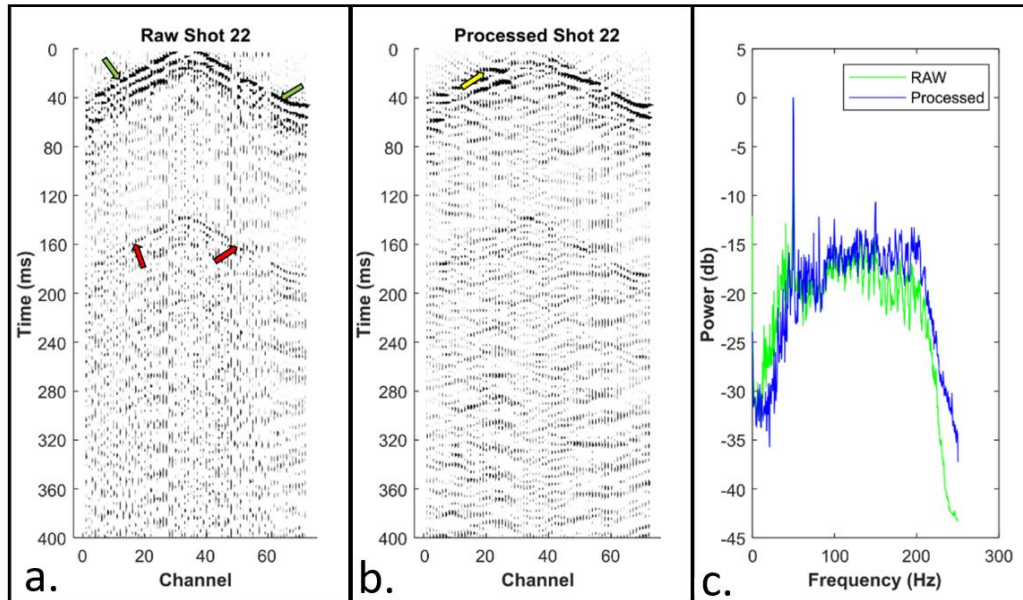


Figure 5.3: (a) Raw shot gather with arrows indicating first breaks (green) and secondary source from the plate rebound (red). (b) Processed data without deconvolution (with a reflection shown in yellow). (c) Amplitude spectrum.

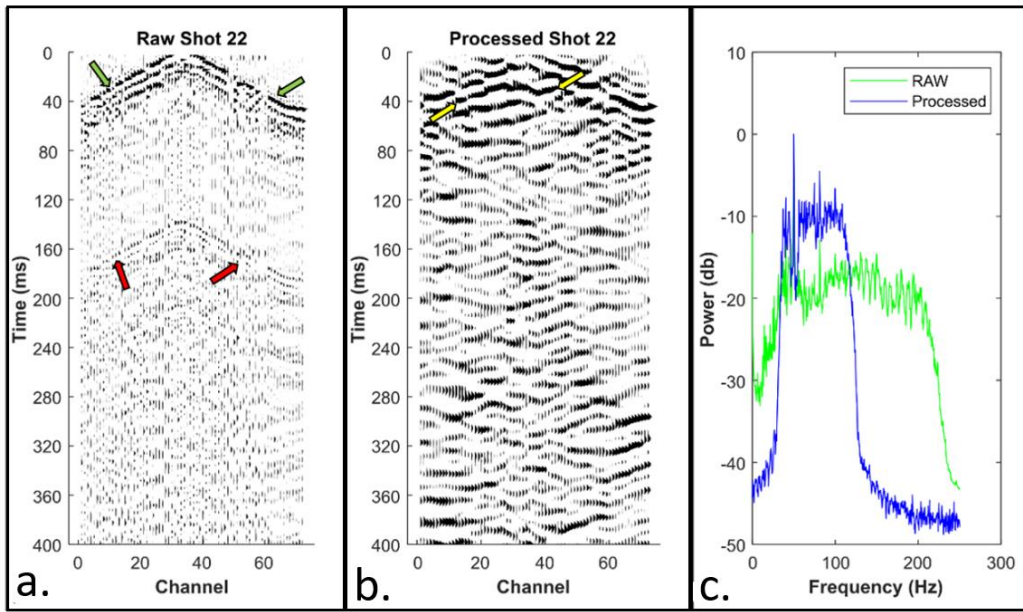


Figure 5.4: (a) Raw shot gather with arrows indicating first breaks (green) and secondary source from the plate rebound (red). (b) Processed data with deconvolution applied (with a reflection shown in yellow). (c) Amplitude spectrum.

Although detailed description of processing is beyond the scope of this project, the following pre-stack processing steps were relevant to the study and are briefly described:

Creating geometry from SPS files

From the data collected in the field, the only information we have a record of is, the channel numbers and the shot ID. There is still a need to correlate this information with the actual earth surface locations in order to understand the subsurface conditions and the constraints thereof. From the DGPS system, we recorded the position of the receivers the shots (Northing, Easting and Elevation). This information was then used to create what is known as SPS files, which basically describes three ASCII files namely; shots file (.s), receivers (.r), which gives the X,Y, and Z locations of the shots and the receivers respectively, and the relations (.x) file which associates the shot and receiver positions with the file (SHOTID) and channel numbers.

CDPs (Common Depth Midpoints) – crooked line binning

We added automatic hit points and defined a wiggly line. The picks were reduced from the default 40 to 10 picks, this mainly because the software struggled to resolve a short line that has a lot of picks. For the purposes of improving the signal to noise ratio (SNR), established a set of CDP "bins" along the line and collect traces into a CDP bin if the midway between the shot and receiver locations falls within the bin boundaries.

Merging seismic data and geometry

The output from creating geometry using SPS is a geometry file (.geom), and it is the one that is merged with the data. The raw input data was combined with the geometry information incorporated into the trace headers. This was accomplished by adding the geometry database information into the trace headers using the 'merge geometry' job and saves the shots with geometry.

Trace editing.

Because geophones might act erratically in the field or get polluted with noise, it is critical that the data undergo general quality control. Loosely attached geophones, weakly coupled geophones, and geophones with too sensitive leaf springs are common examples. Traces with reverse polarity are not rare and can be attributable to a variety of factors such as setup, demultiplexing operations, reversely coupled or reverse polarity geophones. Trace editing is a quality control procedure that may be conducted during fieldwork or data processing. We deleted faulty traces and noisy shots, as well as mute (zero) initial break, air waves, and stretching effects in trace editing. Bad traces were destroyed, which might have been caused by dead geophones or poor geophone-ground/surface coupling.

FB (First Break) picking

After the initial processing of the data (mainly trace editing and geometry set-up), the first break (FB) picking on almost all traces was carried out automatically, followed by a careful inspection and manual correction where required. Data preprocessing and FB picking were the most time-consuming parts due to the noisy nature of the data. However, FB picks of good quality were of main importance for the success of the method applied. Some tests were carried out to match the frequency content of the geophone. The FBs at far offsets show typically a dominant frequency greater than 130 Hz. The FB quality varied from trace to trace, which was considered in the interpretation. Based on the reciprocal times, we estimated an average error of almost 2 ms for the FB picks. First, a two-layered generalized linear inversion 2D ray tracing method (e.g., [Sheriff, 1991](#)) was carried out. The inversion is based on the reciprocal time differences using identically travel times for both directions of a ray path. The inversion was carried out for the profile. To solve problems due to the nonlinear profile geometries, refraction tomography was carried out using the 3D approach. This algorithm uses a starting model (1D or 2D) and a built-in forward modelling, a first-order finite-difference (FD) approximation to the eikonal equation, and an algorithm to compute the travel times to all cells in the model. Subsequently, the ray tracing from the receiver locations is performed by backward propagation perpendicular to the isochrones. The inversion is iterative with a least-squares conjugate gradient solver and regularization for faster convergence, and to reduce the number of unknowns. We tested different inversion parameters, and generated the 2D ray path coverage and associated P-wave refraction tomogram as shown in [Figures 5.6a,b](#).

The subsequent steps in processing are summarized in [Table 5.1](#), which includes the appropriate static corrections, filtering of the noise, deconvolution to compress the wavelet and improve the spatial resolution of the data, normal moveout correction, stacking, final datum shift. Finally, the time domain stack was depth converted and correlated with the geological information for interpretation.

A general assessment of the tunnel seismic results (stacked section) shows that the data, although acquired in a noisy mine environment, are of good quality from which structural interpretation can be drawn. The stacked section is shown in [Figure 5.5](#).

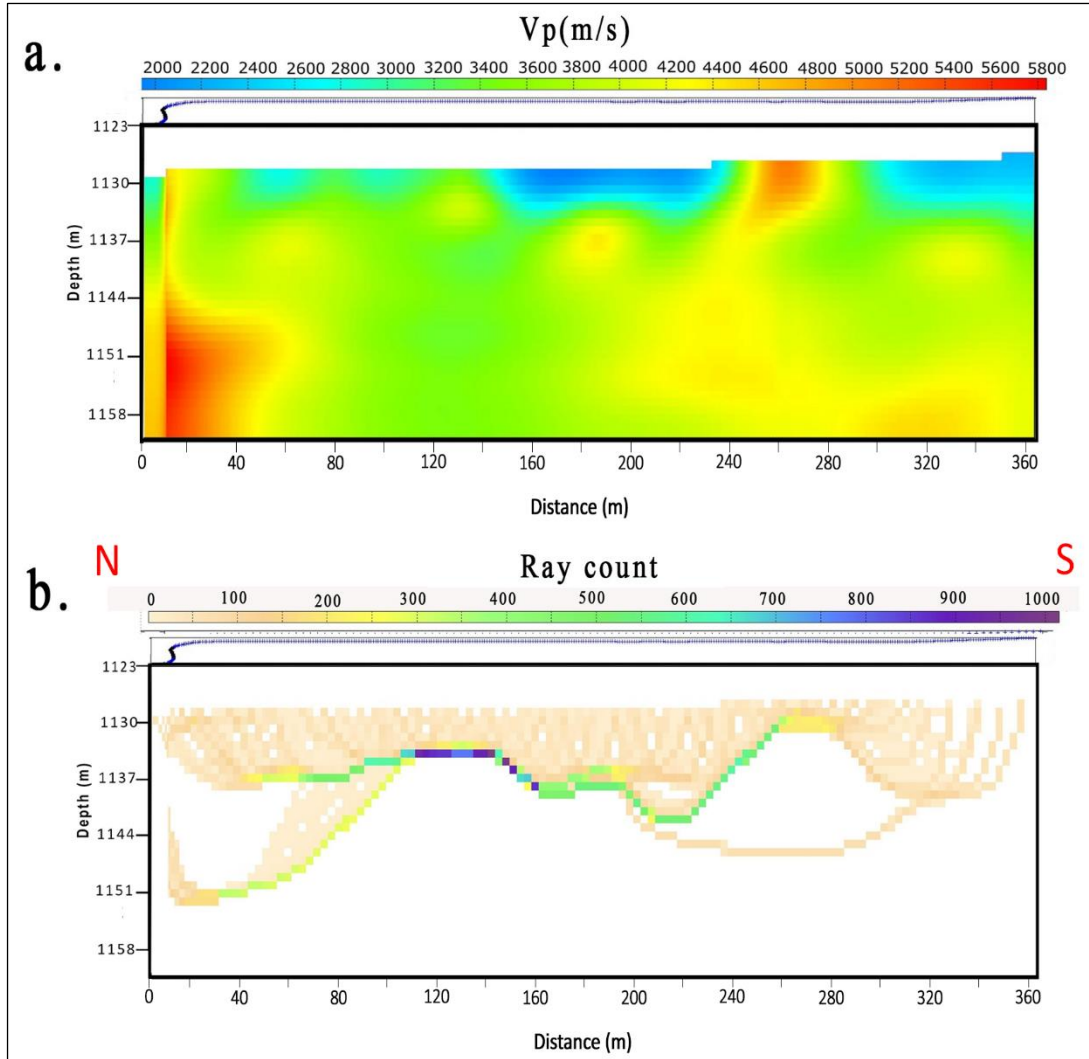


Figure 5.5: (a) 2D travel time tomography results from seismic profile SDT1 (South Deep Tunnel 1) that was acquired in the mine tunnels at depth of ~3 km, together with the (b) ray path coverage of approximately 16 m depth of penetration.

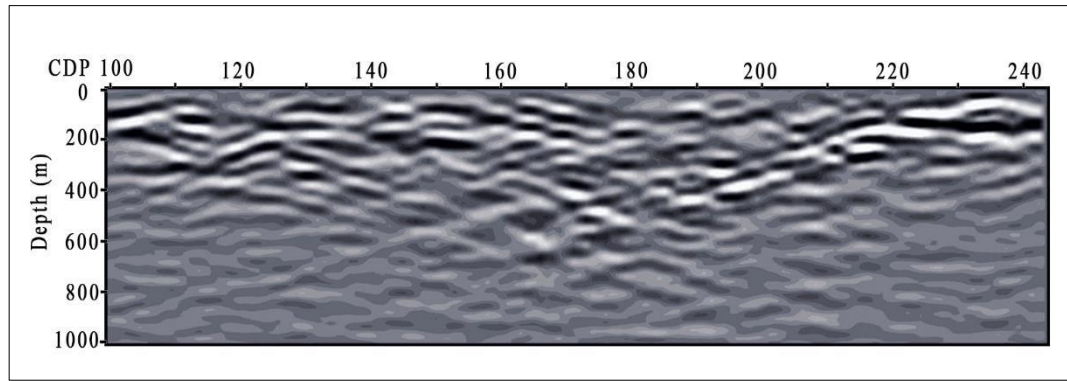


Figure 5.6: *A depth converted Stacked seismic section from the SDT1 seismic data.*

6. RESULTS AND INTEPRETATIONS

6.1. Rock samples and description

Twenty-four samples were obtained from three of the grade control boreholes (Figure 6.1) at South Deep gold mine for this research. These boreholes were drilled upwards within development stopes and are utilized to assist present mining activities by giving grade information and logging data for reef identification; as a result, they give a comprehensive understanding of the Upper Elsburg Reef package.

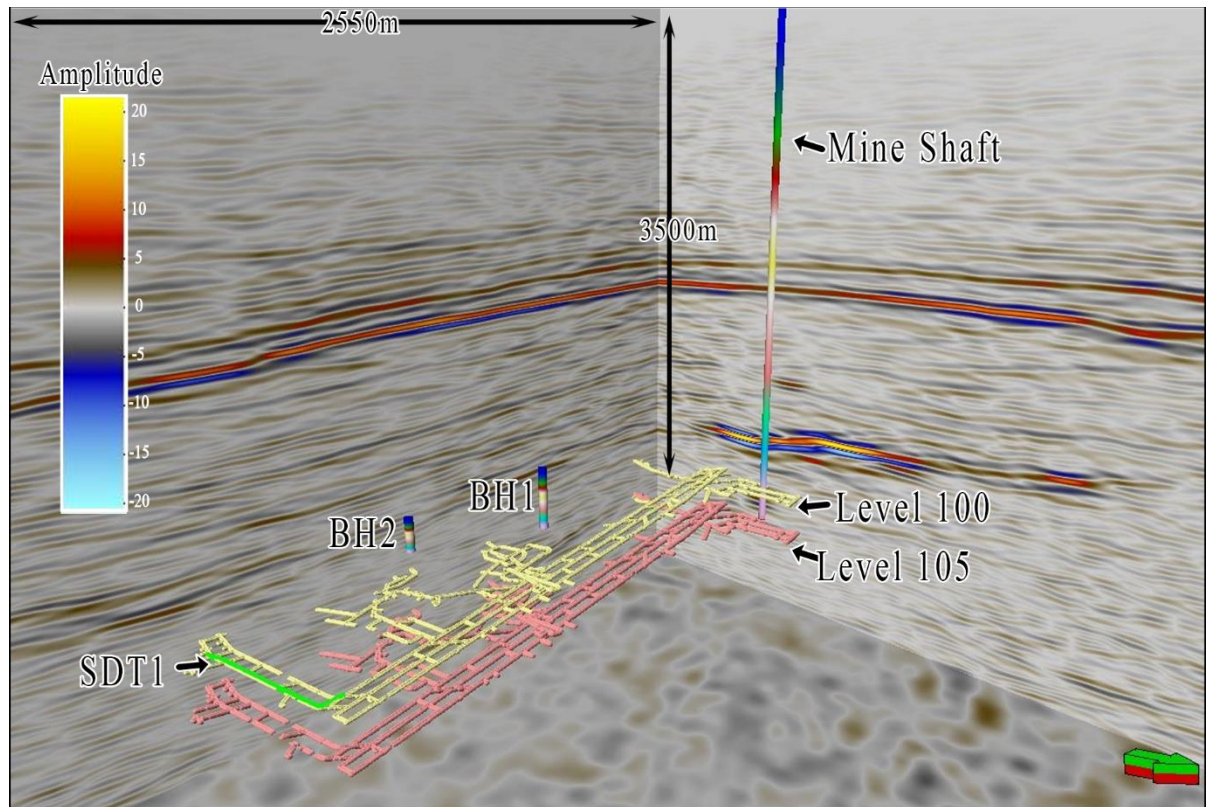


Figure 6.1: Visualization of historical 3D seismic data alongside the two boreholes (BH2 and BH1 together with its deflection (BH1-D1)) utilized for assessing physical properties, as well as the depiction of mining tunnels and shaft at the South Deep gold mine.

The samples contain the various alternating bands of quartzites and conglomerates (reef) from the base of the Upper Elsburg Reef up until the Ventersdorp Contact Reef (VCR). Then samples have a length of 10 cm and an average diameter of 4.2 cm, except for three samples of lengths less than 7 cm and two of the samples being half-diameter core samples. Table 6.1 summarises the different samples collected from the boreholes.

Table 6.1: List of the twenty-four samples with descriptions and dimensions.

Sample Number	Sample Description	Length (cm)	Diameter (cm)
1	Quartzite EB	10,37	4,18
2	Quartzite EB	10,33	4,18
3	Quartzite (internal)	10,46	4,17
4	Reef	10,39	4,18
5	Dyke	10,19	4,13
6	Lava	10,17	4,15
7	Quartzite EB	10,37	4,20
8	Reef	10,05	4,16
9	Reef	10,17	4,17
10	Reef	10,48	4,17
11	Quartzite MBT	10,47	4,18
12	Lava	10,46	4,16
13	Quartzite EB	10,48	4,13
14	Quartzite ECB	10,03	4,16
15	Reef ECT	10,46	4,16
16	Quartzite ED	10,18	4,15
17	Reef	10,18	4,18
18	Quartzite MIQ	6,25	4,17
19	Reef MBT	10,05	4,18
20	Reef (VCR)	3,93	4,12
21	VCR contact lava	3,02	4,16
22	Lava	10,16	4,15
23	Reef MAC	12,29	half-core

24	Reef ECMC	12,76	
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6.2. Bulk density and ultrasonic measurements

The findings of the bulk density tests by rock type are shown in [Table 6.2](#). For the purpose of this study, density measurements were conducted in three different ways, firstly the dimensions of the samples, KT20 magnetic susceptibility tool and also using the SNOWREX AHW-3 Professional Weighing Scale. Both the KT20 and the SNOWREX tools use the principle of instantaneous water immersion.

Table 6.2: Bulk density tests by rock type from the South Deep gold mine.

Sample No	Sample Description	KT20 Tool (g/cm ³); Dimensions (g/cm ³); SNOWREX AHW-3 (g/cm ³)		
1	Quartzite EB	2,69	2,71	2,71
2	Quartzite EB	2,69	2,98	2,70
3	Quartzite (internal)	2,65	3,01	2,66
4	Reef	2,65	2,99	2,67
5	Dyke	2,83	3,16	2,85
6	Lava	2,78	3,22	2,80
7	Quartzite EB	2,67	3,16	2,68
8	Reef	2,68	2,88	2,70
9	Reef	2,94	3,22	2,94
10	Reef	2,74	3,05	2,75
11	Quartzite MBT	2,66	2,81	2,66
12	Lava	2,83	3,16	2,84
13	Quartzite EB	2,69	2,90	2,70
14	Quartzite ECB	2,69	2,86	2,71
15	Reef ECT	2,73	2,81	2,74
16	Quartzite ED	2,67	2,74	2,67

17	Reef	2,76	3,16	2,76
18	Quartzite MIQ	2,64	2,80	2,66
19	Reef MBT	2,56	2,91	2,69
20	Reef (VCR)	2,69	3,86	2,71
21	VCR contact lava	2,68	4,65	2,75
22	Lava	2,89	3,21	2,90
23	Reef MAC	n/a	3,49	2,67
24	Reef ECMC	n/a	3,25	2,81

The density results from the density measurements showed varying values for the different tools used, which can primarily be attributed to the type of tools used to measure the samples and the size of the samples. The values were compared with existing literature (Nkosi, 2016) to make a conclusive decision on what tool to use, and in Nkosi (2016) the SNOWREX tool was preferred. The samples have a density range between (2,66 – 2,71 g/cm³), similar to the values reported for the quartzites along the Carbon Leader Reef (CLR) of ~2.66 -2.68 g/cm³ (Nkosi et al., 2017).

The results presented are based on measurements taken using Proceq PUNDIT equipment and are rounded to two decimal places. An average was calculated from the four ultrasonic measurements taken for each sample. Because the Proceq system supplied findings in excel format, a standard mathematical average procedure was utilized.

Based on ultrasonic measurements (Table 6.3), the P-wave velocity range for the Elsburg Reef package falls within the range of 5124-5914 m/s, which correlate with quartzite and conglomerate values published by Nkosi et al. (2016). The Upper Elsburg Reef package is primarily composed of quartzites and conglomerates, and all the quartzites in our sample fall within this range. Out of the twenty-four samples we took, 11 were reefs, 9 were quartzites, 3 were lavas, and one was a dyke. The Pwave values for the samples had a mean value of 5757.08 m/s, with a range of

4467.26-6711 m/s. Only sample twenty-four was an outlier, which could be attributed to challenges with coupling on the half-core sample. The S-wave velocities for the same samples had a mean value of 4538.98 m/s, with a range of 3037.25-5659.00 m/s.

[Nkosi et al. \(2017\)](#) observed a direct proportionality between the P-wave velocity and the quartzites of the Witwatersrand Basin. The observed P-wave velocities from that study were within the range of ~5070–5468 m/s along the Carbon Leader Reef (CLR). Results from this study focus primarily on the quartzites within the Upper Elsburg Reef package and based on [Table 6.3](#), the P-wave velocities of the quartzites are ranging between 5202 and 5802 m/s. The corresponding S-wave velocities for quartzites to compare with this study could not be found as yet. The quartzite samples from these studies have a range between 4070.00 and 4853.75 m/s

According to a study by [Nkosi et al. \(2017\)](#), the P-wave velocities of conglomerates from the Upper Elsburg Reefs range from approximately 4467.25 to 5970 m/s, while those of the Carbon Leader Reef (CLR, conglomerate unit) range from approximately 5070 to 5468 m/s. The density range of the conglomerates was measured to be approximately 2.67 - 2.94 g/cm³, and for CLR, it was found to be approximately 2.89 - 3.15 g/cm³. The lavas studied had a P-wave velocity range of approximately 5915.5 - 6711.00 m/s, which is close to the values estimated by [Malehmir et al. \(2014\)](#) for basaltic lavas from the Witwatersrand Basin at approximately 6500 m/s. The basaltic lavas have a density range of approximately 2.75 - 2.90 g/cm³. According to [Nkosi et al. \(2017\)](#), lavas from the Ventersdorp Supergroup of the Witwatersrand Goldfields are expected to have higher densities and seismic velocities compared to the quartzites.

In the list of samples, there was only one dyke sample available. This particular dyke has a P-wave velocity of 5921.5 m/s, an S-wave velocity of 5385 m/s, and a density of 2.85 g/cm³. It is worth noting that the Witwatersrand Basin is metasedimentary, whereas the lavas are igneous intrusions. Consequently, the lavas should have considerably higher density and seismic velocities when compared to the metasedimentary rocks found within the basin.

The experimental physical property data (bulk density, P-wave, and S-wave velocities) acquired in this investigation are summarized in [Table 6.4](#). Boreholes BH1, BH1-D1, and BH2 were sampled for bulk density, P-, and S-wave velocity measurements. The bulk densities of the reef samples (conglomerates) range from 2.67 g/cm³ to 2.94 g/cm³ (mean = 2.74 g/cm³, standard deviation = 0.077). Quartzite samples have bulk densities ranging from 2.66 g/cm³ to 2.71 g/cm³ (mean = 2.68 g/cm³, standard deviation = 0.020), while lava samples have densities ranging from 2.75 g/cm³ to 2.90 g/cm³ (mean = 2.82 g/cm³, standard deviation = 0.054). The data demonstrate that quartzites have the lowest mean density compared to lavas and reefs, whereas lavas have the highest mean density. Amongst the samples used, there was only one dyke and as such, statistical analysis could not be conducted.

Table 6.3: Seismic wave velocity measurements for all the twenty-four samples collected from the two boreholes drilled underground at South Deep gold mine.

Sample No	Sample Description	Average P-wave (m/s)	Average S-wave (m/s)
1	Quartzite EB	5730	4589
2	Quartzite EB	5754	4578
3	Quartzite (internal)	5802	4823
4	Reef	5630	4527
5	Dyke	5922	4869
6	Lava	6071	5013
7	Quartzite EB	5569	4597
8	Reef ECT	5658	4555
9	Reef MIT	5913	4768
10	Reef	5769	4556
11	Quartzite MBT	5715	4720
12	Lava	5916	5385
13	Quartzite EB	5676	4779
14	Quartzite ECB	5202	4070
15	Reef ECT	5730	4715

16	Quartzite ED	5896	4854
17	Reef	5829	4695
18	Quartzite MIQ	5637	4276
19	Reef MBT	5635	4555
20	Reef VCR	5970	3633
21	VCR contact lava	6711	3275
22	Lava	6239	5659
23	Reef MAC	5731	4411
24	Reef ECMC	4467	3037

Table 6.4: Summary of physical measurements on 4 different types of rocks amongst the 24 samples from the boreholes at South Deep.

	Rock Type			
Physical property measurements	Reef	Quartzites	Lavas	Dyke
Density (g/cm³)				
Range	2,67 – 2,94	2,66 – 2,71	2,75 – 2,90	2,85
Mean	2,74	2,68	2,82	2,85
Std. Dev	0,077	0,020	0,054	0
P-wave velocity (m/s)				
Range	4470 - 5970	5202 – 5802	5920 – 6711	5920
Mean	5630	5660	6230	5920
Std. Dev	400	190	300	0
S-wave velocity (m/s)				
Range	3037 - 4768	4070 – 4850	3275 - 5659	5385
Mean	4350	4530	4833	5385
Std. Dev	530	250	930	0

6.3. Numerical simulations

6.3.1. 1D synthetics derived from density and P-wave velocities

To investigate and study any potential source of seismic reflectivity within the alternating quartzite and conglomerate units of the UER package measured along BH1, BH1-D1, and BH2, 1D synthetic modelling was conducted. In [Manzi et al. \(2013\)](#), it was stated that the units within the UER package are seismically transparent because of the quartzites and conglomerates have similar densities and velocities. They further stated that the VCR above the package is a strong seismic reflector due to a significant acoustic impedance contrast between the hangingwall basaltic lavas of the Ventersdorp Supergroup and footwall quartzites and conglomerates of the Central Rand Group. The observations made by [Manzi et al. \(2013\)](#) were derived from analysing the surface seismic data, not on physical property measurements. To the author's knowledge, this is the first study to conduct detail physical property measurements from core samples from South Deep gold mine. Therefore, the secondary objective of the study was to conduct laboratory physical property measurements to study the seismic reflectivity of the South Deep gold mine UER orebody. The seismic reflectivity studies were conducted for both P-wave and S-wave velocities, and bulk densities. This was done to provide a guide for seismic processing of the tunnel seismic datasets on whether to focus on S-wave or P-wave reflections.

When there is a difference in acoustic impedance between the two geological boundaries, a seismic reflection can be produced. The acoustic impedance, which results from the product of velocity and density, affects the reflection coefficient (RC). When the RC is larger than or equal to 0.06 in hardrock settings, reflections can be produced ([Mahlatji, 2021](#)).

The 1D seismograms along all boreholes were computed using a Ricker wavelet with a dominant frequency of 60 Hz and no attenuation effect, with the temporal sampling rate set to match that of the conventional seismic data (2 ms). The results are presented in [Figures 6.2, 6.3 and 6.4](#) for BH1-D1, BH1, and BH2, respectively. [Tables 6.5, 6.6 and 6.7](#) show the summary of the results acoustic impedance and reflection coefficients (Rc) for BH1-D1, BH1, and BH2, respectively.

Table 6.5: *Physical properties of samples from borehole (BH1-D1), where Z is the acoustic impedance, and Rc is the reflection coefficient.*

Borehole	Depth (m)	Sample	Z (Pa.s/m ³)	R _c
BH1-D1	0	LAVA	16178,7	-0,038
BH1-D1	40,12	VCR	14988,435	
BH1-D1	41,12	MBT	16088,73	
BH1-D1	59,14	MBB	17384,955	
BH1-D1	63,42	MIT	15300,435	-0,064
BH1-D1	72,37	MAC	16876,275	0,049
BH1-D1	73,67	DYKE	15300,435	-0,049
BH1-D1	75,19	MAC	15742,32	0,014
BH1-D1	78,08	ED	15277,275	-0,015
BH1-D1	80,32	ECT	12552,9725	-0,098
BH1-D1	87,08	ECMC	14097,42	0,058
BH1-D1	92,77	ECB	15535,8	0,049
BH1-D1	240	EB		

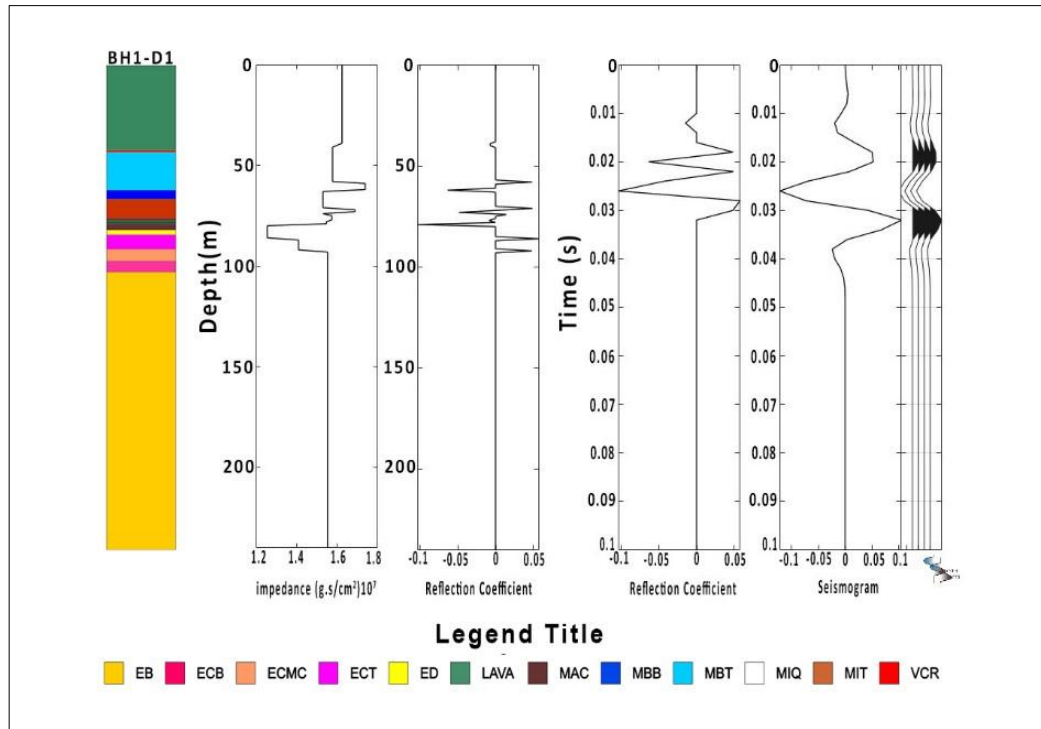


Figure 6.2: Geological log derived from borehole BH1-D1 at South Deep gold mine. Reflection coefficients were derived from the acoustic impedance calculated from P-wave velocities and densities, and synthetic seismograms were generated using the reflection coefficient and a Ricker wavelet (60 Hz).

The difference in acoustic impedance between the Upper Elsburg Reef (UER) package hangingwall (lavas) and footwall (quartzites and conglomerates) across all the boreholes shows that the interface is linked to a strong reflection, which can be used as a ghost reflector for the UER mineralization. These results confirmed observations by [Manzi et al \(2012a,b; 2013\)](#). Surprisingly, there is a notable reflection at the interface between the VCR and MBT in [Figure 6.2](#). This was not expected since both VCR and MBT consist of conglomerates and quartzites. Furthermore, the results in [Figure 6.2](#) suggests that the endmembers between the VCR and reef ECMC do not have much of a contrast due to minor differences in density and seismic velocities between the endmembers which, again, in agreement by the P-wave reflection seismic studies conducted by [Manzi et al. \(2012a,b\)](#).

The R_C of 0.039 ([Table 6.5](#)) between MBT (quartzite) and MBB (quartzite) interface implies that no strong reflection will be generated at this boundary, implying that it cannot be easily imaged by a surface seismic reflection method. Similar conclusion may be drawn regarding the interface between the same endmembers on [Tables 6.5](#)

and 6.6 with reflection coefficients of -0.035 and 0.039 consecutively. However, the interface between MBB and MIT, ED and ECT, and ECT and ECMC endmembers resulted in a R_C greater than 0.06 which suggests that strong reflections will be generated, at least with P-wave reflection analysis.

The data in Table 6.5 show reflection coefficients between different lithologies ranging between -0.098 and 0.058. Evidently, a reflection coefficient of -0.098 was observed at the interface between ED (quartzite) and ECT (reef). This is probably attributed to the change in the density between the two endmembers; for example, the density of the reef is much greater than that of the quartzite and thus affecting the acoustic impedance which then translates to the observed acoustic impedance. This also explains why the contact between the two endmembers could be imaged seismically. The seismograms in Figure 6.2, shows that there are two potential major reflectors in this borehole (BH1-D1), which can be generated at the MBBMIT and ED-ECT interfaces. There is a correlation between the value of the reflection coefficient and the amplitude of the reflector as seen in Figure 6.2.

Table 6.6 and Figure 6.3 represent data from borehole BH1. It is clear from Table 6.6 that there are more synthetic reflections seen across the boreholes when compared to the borehole BH1-D1. The interfaces between the following endmembers: MBB-MIQ, MIQ -MIT, MIT-MAC, ECT-ECMC and, ECMC-ECB all have a reflection coefficient greater than 0.06 (Figure 6.3 and Table 6.6). As seen in Figure 6.2., only two reflectors were visible on the seismogram from BH1D1, which are attributed to the interfaces between MBB and MIQ and between ECT (reef) and ECMC (reef). However, the reflections observed in Figure 6.3 for borehole BH1 are not as strong as compared to the VCR-generated reflector observed across all the boreholes.

Table 6.6: Physical properties of borehole BH1, where Z is the acoustic impedance (calculated from the P-wave velocities and densities), and Rc is the reflection coefficient.

BHID	Depth (m)	REEF	Z (Pa.s/m ³)	Rc
BH1	0	LAVA	16178,7	-0,033
BH1	14,9	VCR	15157,4775	0,030 -
BH1	17,37	MBT	16088,73	0,035
BH1	31,83	MBB	14993,09	0,074 -
BH1	46,25	MIQ	17384,955	0,064
BH1	47,28	MIT	15300,435	0,064 -
BH1	55,22	MAC	17384,955	0,064
BH1	60,49	MIT	15300,435	0,014
BH1	73,14	MAC	15742,32	-0,015
BH1	77,69	ED	15277,275	-
BH1	79,62	ECT	12552,9725	0,098
BH1	84,59	ECMC	14097,42	0,058
BH1	87,86	ECB	15535,8	0,049
BH1	379,04	EB		

As seen with borehole BH1-D1, the seismograms in [Figure 6.3](#), also show that there are two major reflectors in this borehole and from [Table 6.5](#), it can be seen that the two reflections can be attributed to the interfaces between ECT (reef) and ECMC (reef) and ECMC and ECB.

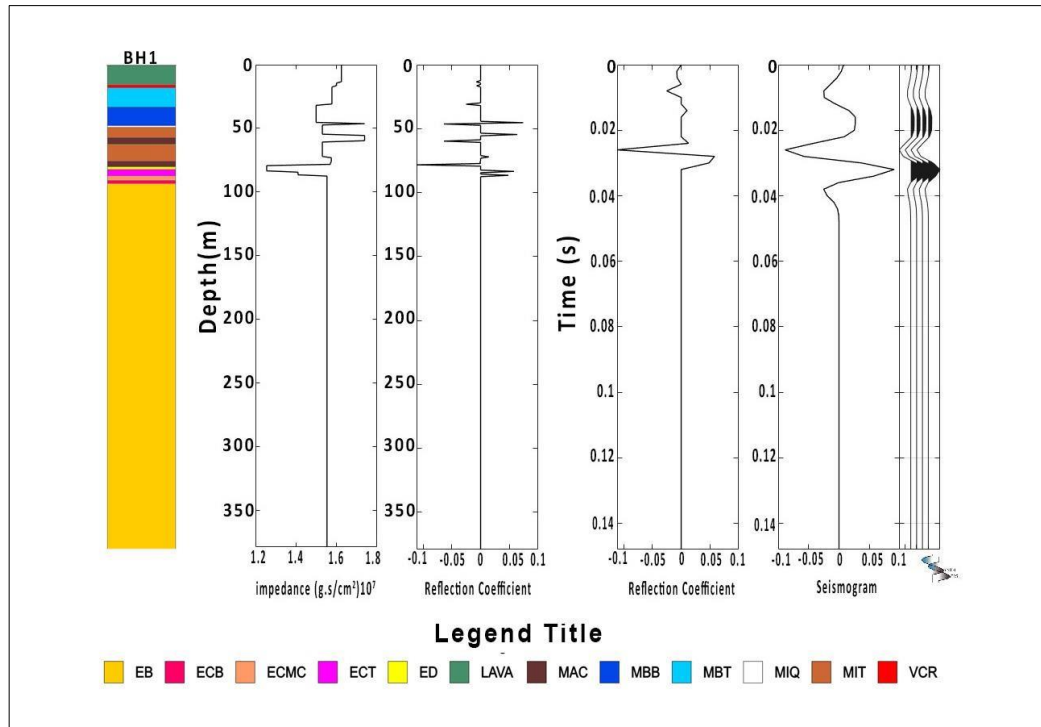


Figure 6.3: Geological log derived from borehole BH1 at South Deep gold mine. Reflection coefficients were derived from the acoustic impedance (calculated from P-wave velocities and densities), and synthetic seismograms were generated using the reflection coefficient and a Ricker wavelet (60 Hz).

Table 6.7 and Figure 6.4 show results from borehole BH2. The borehole was the shortest of all three, and the frequency used for the seismograms was also 60Hz. This could also be attributed to the length of the borehole as the physical properties of the rocks in all three boreholes are the same. The reflection coefficients in these borehole range between 0.057 to 0.039. only two interfaces in this borehole had a value greater of equal to 0.06. The interface between MBB and reef MIT.

Table 6.7: Physical properties of samples from Borehole BH2, where Z is the acoustic impedance (calculated from P-wave velocities and densities), and Rc is the reflection coefficient.

BHID	Depth (m)	Reef	Z (Pa.s/m ³)	R _c
BH2	0	LAVA	16178,7	-0,023
BH2	18,6	VCR	15445,3075	
BH2	19,44	MBT	16088,73	0,020
BH2	21,97	MBB	17384,955	0,039
BH2	24,56	MIT	15503,605	-0,057
BH2	26,6	ECT	15535,8	0,001
BH2	30,89	EB		

The seismograms in [Figure 6.4](#) show that there are two major reflectors in BH2 and from [Table 6.7](#) it can be seen that the two reflections can be attributed to the interfaces between the VCR and MBT (MBT) and also ECT (reef) and EB (quartzites). It is worth noting the strong reflection observed between the VCR and MBT is caused by the strong reflection between the MBT quartzites and basaltic lavas above the VCR, which is consistent with observations from previous studies ([Manzi et al., 2012a,b](#); [Nkosi et al., 2016](#)).

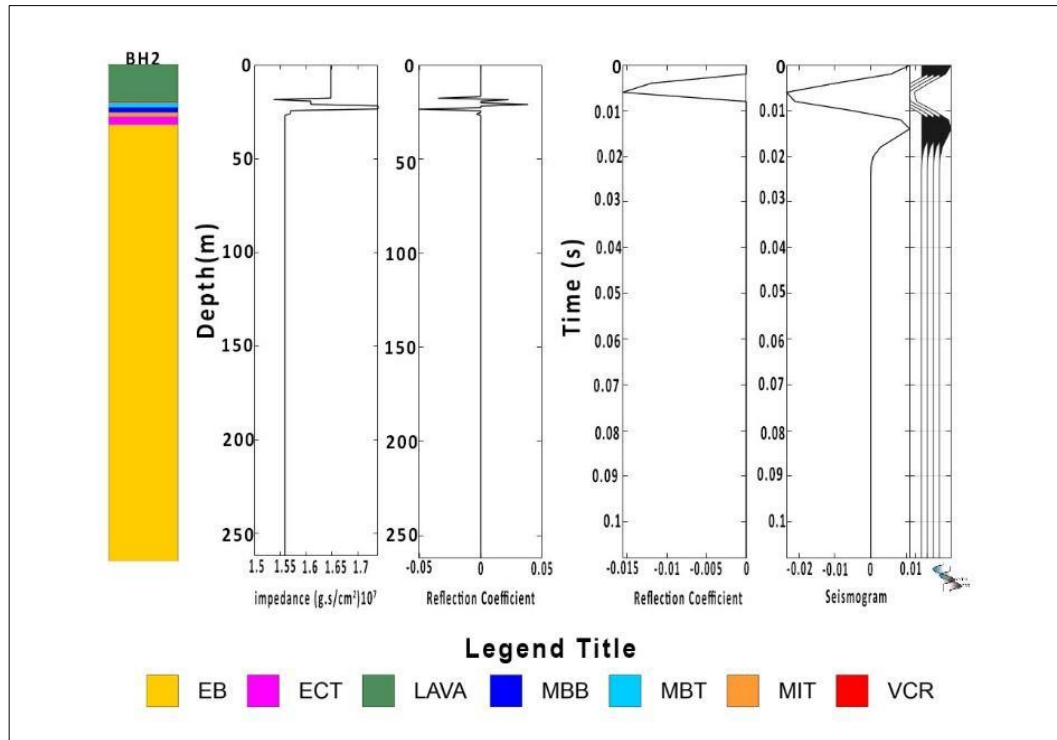


Figure 6.4: Geological log derived from borehole BH2 at South Deep gold mine. Reflection coefficients were derived from the acoustic impedance (calculated from Pwave velocities and densities), and synthetic seismograms were generated using the reflection coefficient and a Ricker wavelet (60 Hz).

6.3.2. 1D synthetics derived from density and S-wave velocities

In order to further examine the reflectivity of the interfaces between members of the Upper Elsburg Reefs, synthetic seismograms were computed using secondary wave (S-wave) velocities and bulk densities instead of the P-wave velocities and bulk densities used in the initial synthetic seismograms.

Table 6.8 shows that the reflection coefficients between the endmembers on four occasions exhibit a reflection coefficient greater than 6%, which then infers notable reflections along the boundaries of those rocks. There are two notably high reflection coefficients that can be observed in the following interfaces: Lava and VCR and ECMC and ECT.

Table 6.8: Physical properties of borehole BH1-D1, where Z is the acoustic impedance (calculated from the S-wave velocities), and Rc is the reflection coefficient.

BHID	Depth (m)	Reef	Z (Pa.s/m ³)	Rc
BH1-D1	0	LAVA	9844,075	
BH1-D1	40,12	VCR	12115,64	0,103
BH1-D1	41,12	MBT	12958,2	0,034
BH1-D1	59,14	MBB	14017,92	0,039
BH1-D1	63,42	MIT	11776,04	-0,087
BH1-D1	72,37	MAC	13876,65	0,082
BH1-D1	73,67	DYKE	11776,04	-0,082
BH1-D1	75,19	MAC	12959,51	0,048
BH1-D1	78,08	ED	12729,83	-0,009
BH1-D1	80,32	ECT	8534,673	-0,197
BH1-D1	87,08	ECMC	11029,7	0,128
BH1-D1	92,77	ECB	13105,13	0,086
BH1-D1	240	EB		

In Figure 6.5, two significant reflectors in the borehole are revealed by the seismograms. Table 6.8 confirms that these reflections are attributed to the interfaces between the lava & VCR and between ECMC and ECT. The seismogram in Figure 6.5 reveals two noteworthy reflectors in the borehole, which stem from the interfaces: Lava and VCR and between ECMC and ECT.

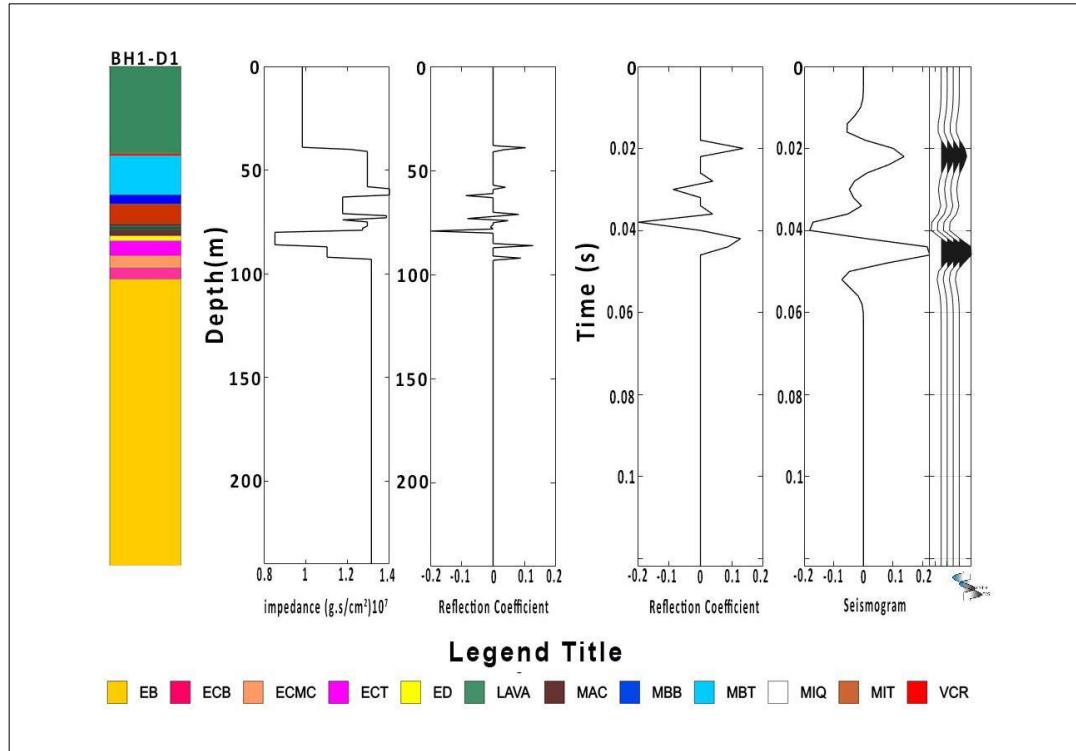


Figure 6.5: Geological log derived from borehole BH1-D1 at South Deep gold mine. Swave reflection coefficients were derived from the acoustic impedance, and synthetic seismograms were generated using the reflection coefficient and a Ricker wavelet (60 Hz).

Table 6.9 and Figure 6.6 both represent data from borehole BH1. It is clear from Table 6.9 that the borehole exhibits some strong reflections between the lithological contacts such as: Lava and MBT, MBT and MBB, MBB and MIQ, ECT and ECMC. All these contacts have a reflection coefficients greater than 0.06. These reflections were not as evident in the seismogram produced by the P-wave velocities (e.g., Figure 6.3)

Table 6.9: Physical properties of borehole BH1, where Z is the acoustic impedance (calculated from the S-wave velocities), and Rc is the reflection coefficient.

BHID	Depth (m)	REEF	Z (Pa.s/m ³)	Rc
BH1	0	LAVA	9844,075	0,109
BH1	14,9	VCR	12252,28	0,028
BH1	17,37	MBT	12958,2	-0,065
BH1	31,83	MBB	11374,16	0,104
BH1	46,25	MIQ	14017,92	-0,087
BH1	47,28	MIT	11776,04	0,087
BH1	55,22	MAC	14017,92	-0,087
BH1	60,49	MIT	11776,04	0,048
BH1	73,14	MAC	12959,51	-0,009
BH1	77,69	ED	12729,83	-0,197
BH1	79,62	ECT	8534,673	0,128
BH1	84,59	ECMC	11029,7	0,086
BH1	87,86	ECB	13105,13	
BH1	379,04	EB		

Based on the analysis of borehole BH1, it can be seen from the seismogram in [Figure 6.6](#) that there are three major reflectors present. Referring to [Table 6.8](#), it can be concluded that these reflections correspond to the interfaces between reefs: MBB and MIQ, ECT and ECMC, and ECMC and ECB.

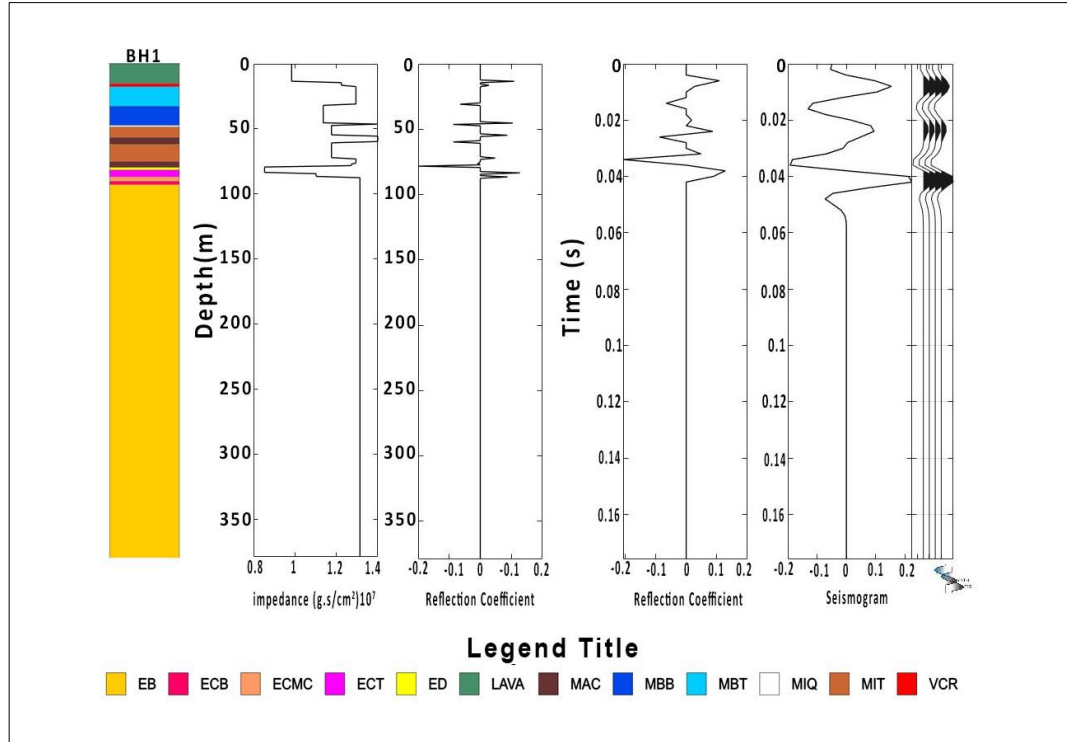


Figure 6.6: Geological log derived from borehole BH1 at South Deep gold mine. S-wave reflection coefficients were derived from the acoustic impedance, and synthetic seismograms were generated using the reflection coefficient and a Ricker wavelet (60 Hz).

Table 6.10 and Figure 6.7 show results from borehole BH2. The borehole was the shortest of all three. The reflection coefficients in these borehole range between 0.057 and 0.039. only two interfaces in this borehole had a value greater of equal to 0.06, i.e., the interface between MBB and MIT (reef). The seismogram in Figure 6.7 also shows that there are two major reflectors in BH2, which are generated by the interface between the lava and MBT (reef). This reflection coincides with the VCR, which is consistent with all the results from other boreholes.

Table 6.10: Physical properties of Borehole BH2, where Z is the acoustic impedance (calculated from the S-wave velocities), and Rc is the reflection coefficient.

BHID	Depth (m)	REEF	Z (Pa.s/m ³)	R _c
BH2	0	LAVA	16178,7	-0,023
BH2	18,6	VCR	15445,31	
BH2	19,44	MBT	16088,73	0,039
BH2	21,97	MBB	17384,9	0,020
BH2	24,56	MIT	15503,605	-0,057
BH2	26,6	ECT	15535,8	0,001
BH2	30,89	EB		

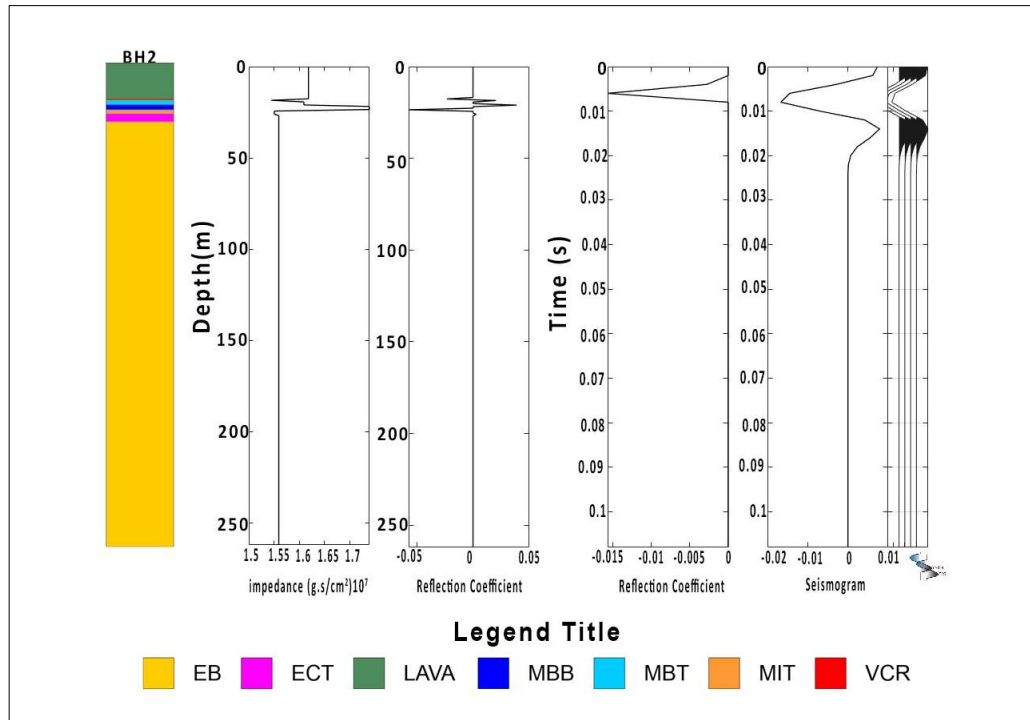


Figure 6.7: Geological log derived from borehole BH2 at South Deep gold mine. S-wave reflection coefficients were derived from the acoustic impedance, and synthetic seismograms were generated using the reflection coefficient and a Ricker wavelet (60 Hz).

6.3.3. 2D modelling

A finite-difference model built on Tesseral software package was used to investigate the source of seismic reflectivity using the physical property measurements and the geological model for the Upper Elsberg Reef (UER) package from South Dee gold mine. The model is presented in Figure 6.8 has a horizontal span of 360 m and a depth of 240 m, with a grid cell of 1 m in both vertical and horizontal directions. The top of the model shows the tunnel floor, and layers below represent the fractured rock and UER orebody, which is made-up of multi-stacks of reefs (conglomerates) interbedded by quartzites. In this case, the VCR and lava are not present because they occur at the hangingwall of the tunnel. Furthermore, the model assumes that the orebody is not faulted and that the reflection during the seismic acquisition will come from below. The model also doesn't account for several wavefields that will be generated from the hangingwall rocks, fractures, tunnel

sidewalls and mode conversions. This modelling allowed for the generation of realistic seismic simulations, enabling detailed analysis of the orebody's seismic response and facilitating comparison with actual seismic survey data upon completion. Figure 6.9 shows an example of a shot gather retrieved from the 2D modelling. The reflection (green arrow) on the modelled shot gather manifests above the first break (black arrow), and this can be attributed to the dipping nature of the lithology, which is expected. From the model, it was clear that multiple reflections were not expected within the conglomerates and quartzites of the package as predicted by 1D model. This assisted in the design and interpretation of the acquired seismic data, which is discussed later.

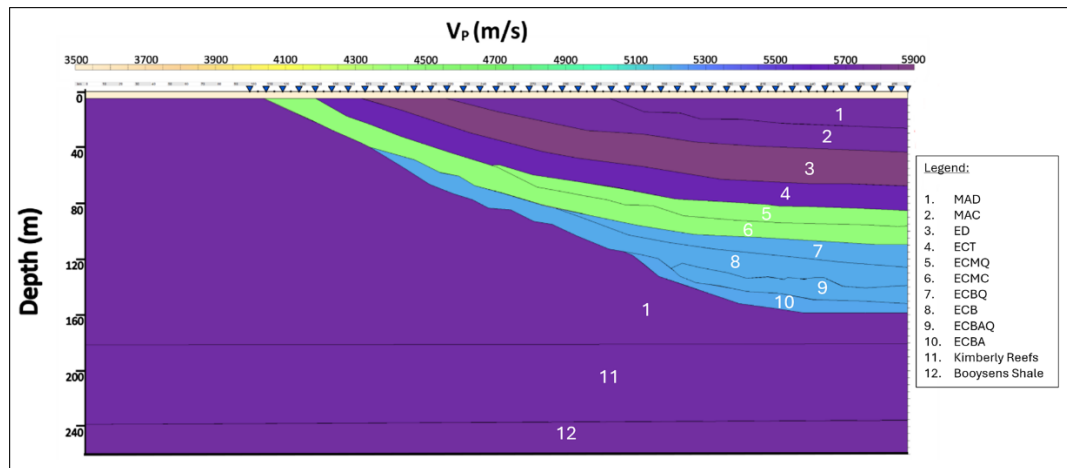


Figure 6.8: A 2-Dimensional view of the Upper Elsburg Reef (UER) package below the South Deep GOLD mine tunnel and the 42 receivers located on the tunnel floor. The top (0m) indicates the tunnel floor and below that are alternating conglomerate reefs and quartzites of the Upper Elsburg Reef package.

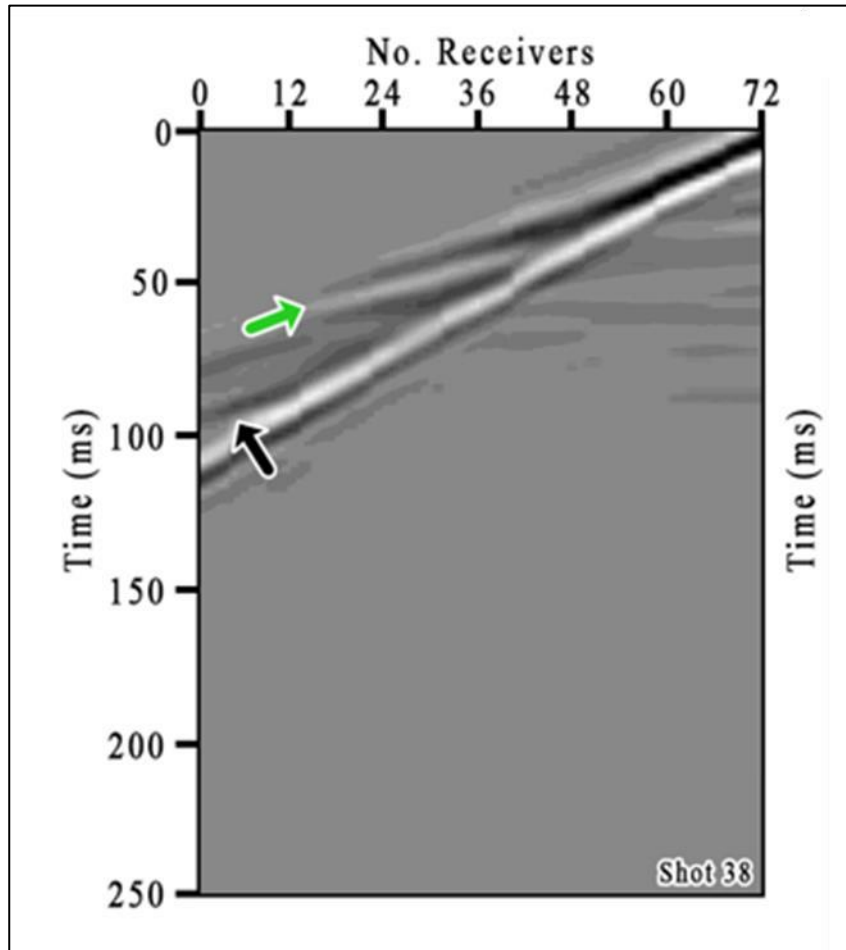


Figure 6.9: Synthetic shot gather. Black arrow denotes *P*-wave first arrivals, while green arrows indicate reflections.

6.3.4. 3D modelling

The results from Wave3D modelling currently have not been concluded as yet as there were not the main priority for this MSc thesis, however Salizwa Plaatjie (a PhD student at Wits) is currently working on improving the model and running more iterations which will further aid the model to understand the wavefield propagation within the tunnel and rockmass at the South Deep gold mine. This section summarises some of the early findings of the work on Wave-3D numerical simulations.

In a previous study by [Linzer et al. \(2020\)](#), they delved into the impact of stopes on seismic inversions concerning scalar moment, corner frequency, source radius, and stress drop. This investigation was carried out through numerical modelling

utilizing WAVE3D. The primary goal was to ascertain whether the source parameters, as derived from the observed waveforms, were a result of a combination of stoperelated and shearing sources, rather than solely attributed to shear sources within the host rock. The outcomes of the work indicated that stopes exerted a notable influence on seismic inversions. Specifically, it was observed that the seismic moment and source radius of the shear source within the stope were greater in comparison to the model without a stope.

In this study, the tool was used to study the wavefield propagation through the mine tunnel, infrastructure, orebody and rockmass as shown in [Figure 6.10](#).

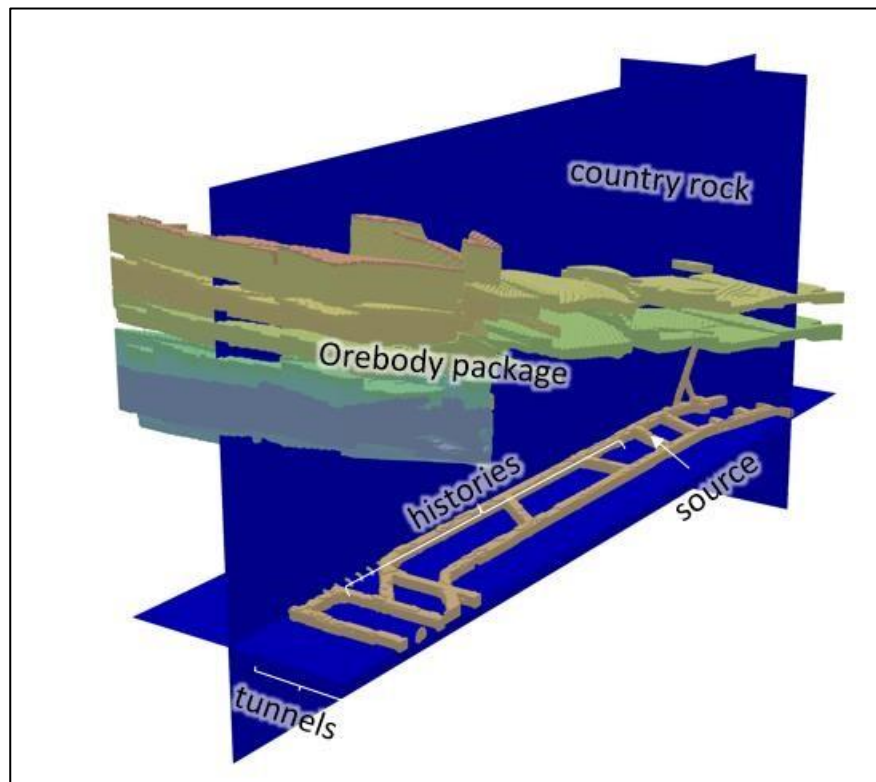


Figure 6.10: Design of the seismic survey inside the tunnel incorporating the mine tunnel, UER (Upper Elsburg Reef) package, country rock (quartzite), geophones locations and source. Source: dilatational, waveform: cosine, frequency: 200 Hz, period: 0.005 s.

These wavefield characteristics could then taken into account when processing and interpreting the data. However, it is worth noting that our model used the dilatational source, not an impulse source which is suitable for active seismic

surveys. The model is being improved to allow for the incorporation of the impulse sources and other typical active seismic sources like the vibroseis sources with long sweeps. The snapshots of a slice through the tunnel are presented in [Figure 6.11](#). These snapshots show the propagation of the dilatational source from [Figures 6.11a to 6.11d](#). As time passes, the wavefield spreads out in each snapshot. At time 0,01107s ([Figure 6.11b](#)), the wavefield experiences interference from the mine tunnel. This could be due to the proximity of the source to the tunnel, the speed of propagation of the wave before it interacts with the tunnel, and the impedance contrast between the country rock (modelled with density = 2.7 g/cm³, P-wave velocity of 6100 m/s and a S-wave velocity of 3500) and the tunnel (modelled with density of 1, P-wave velocity of 330 m/s and a S-wave velocity of 0 m/s).

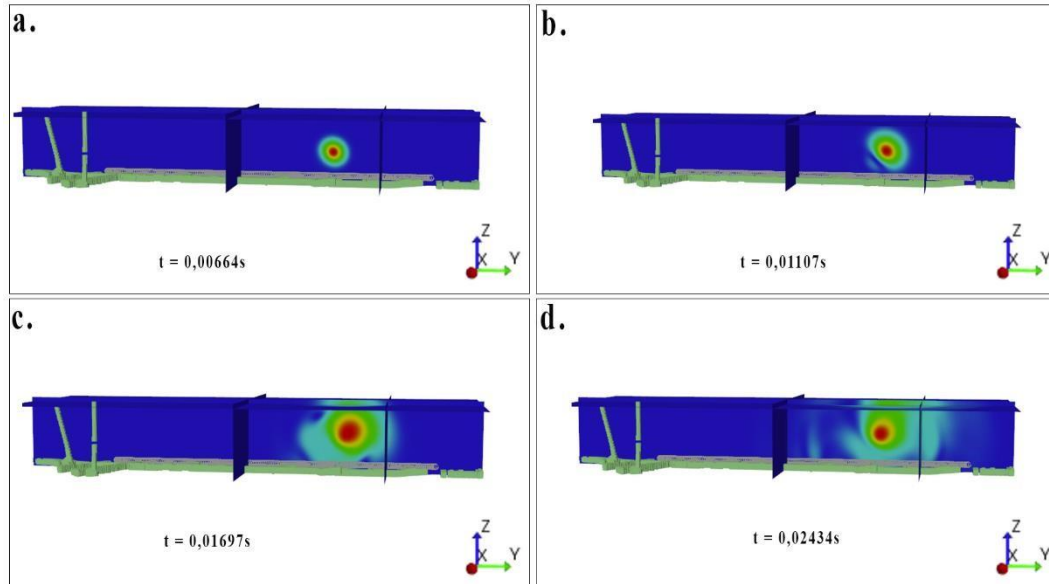


Figure 6.11:(a-d) Snapshots of the 3-D wave propagation in the vicinity of the South Deep Gold mine tunnel as observed on mXrap wave results viewer. Periods: (a) 0.00664 s, (b) 0.01107 s, (c) 0.01697 s, and (d) 0.02434 s.

The interaction of the wavefield with the mine geology is summarised in the snapshots shown in [Figure 6.12a-d](#). The same dilatational source was used for this demonstration. It is observed that the interaction between the wavefield and the orebody from the mine is marked by a sharp distortion in the observed wavefield, compared to that observed from the interaction between the tunnel and the wavefield. The 3-dimensionality of the wavefield propagation is also seen in these

snapshots, Although the source was modelled from inside the mine tunnel, as it propagates outside the tunnel, it experiences some interference which is shown on [Figure 5.16.b](#). Also, more importantly the reflections are observed at the wavefield reaches the contact between the VCR and basaltic lavas, which was predicted by the physical properties and 1D synthetic modelling (see [Figure 6.12d](#))

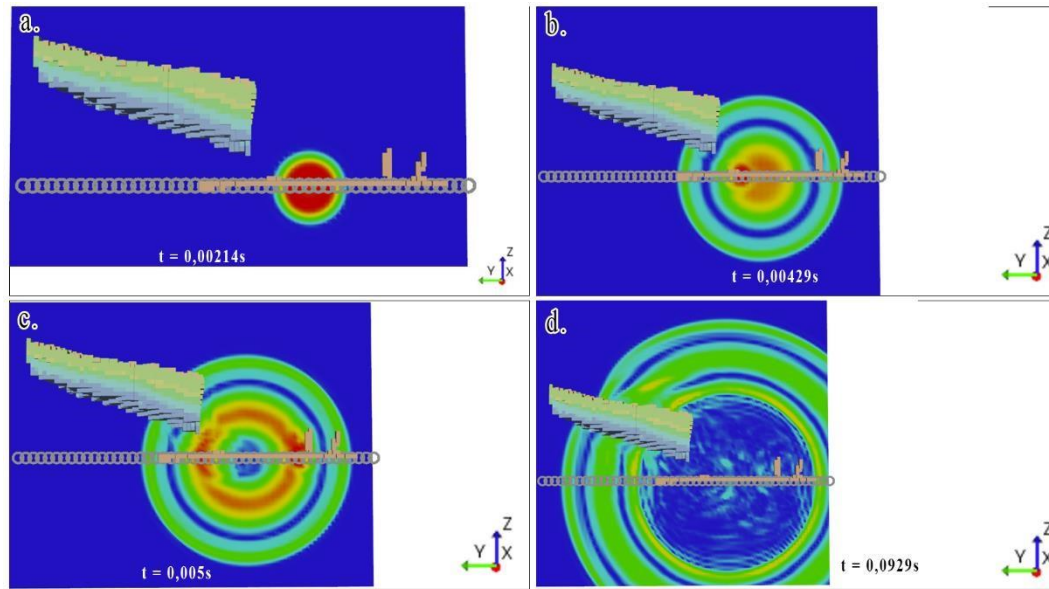


Figure 6.12: Snapshots from *mXrap* wave results viewer showing the interaction of the mine geology with the Seismic wavefield from a source located in the mine tunnel. Periods: (a) 0.00214 s, (b) 0.00429 s, (c) 0.005 s, and (d) 0.0929s.

[Figure 6.13a,b](#) shows showgathers from the receivers comparing two different cases that have been modelled in [Figures 6.11 and 6.12](#). Observations from the two shot gathers show that the data observed from the tunnel alone without any geology ([Figure 6.13a](#)), the gathers observed when there is geology in the model ([Figure 6.13b](#)). This then guides where we position the receivers in the model. What is also important from these results is that the presence of the mine tunnel does affect the propagation of the wavefield, but this is governed by the distance between the source and the receiver as seen in the two cases. In both models, the P-wave first arrivals were clear on the synthetic shot gathers. This model demonstrates that when generating energy along the tunnel floor, one should also expect energy reflected from both below and above the tunnel floor. This was not easy to observe in the 2D modelling case.

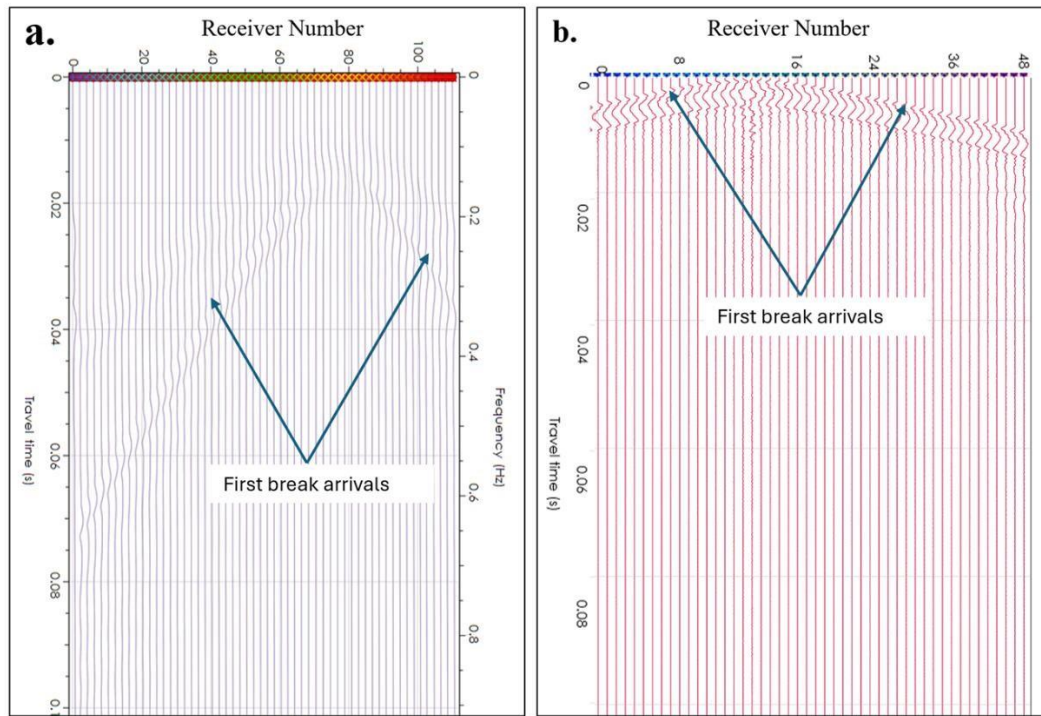


Figure 6.13: First break picks from the interaction of the propagating wave in two different setups: (a) Tunnel with lithologies, and (b) propagation of waves in the vicinity of a tunnel without lithology.

6.4. Tunnel seismic data

6.4.1. Refraction tomography

TomoPlus was used to extract the 9312 first break arrival times from the seismic field data. The algorithm calculated the distribution of subsurface velocities that resulted in the best fit to the arrival timings by starting with a simple 1D gradient velocity model. The type of tomographic inversion applied to the dataset was a nonlinear first-arrival travel time inversion and this was applied until convergence was reached. This algorithm ray traces synthetic travel times for each shot, minimizing the disparity between the input and synthetic first break picks. The model misfit was examined on a shot-by-shot basis in the first examination of the synthetic and picked first arrival models.

Figure 6.14 shows the un-interpreted (Figure 6.14a) and interpreted (Figure 6.15a) velocity tomogram for the entire 72 geophone spread after 20 iterations. Most of the rays are localized above a depth of 20 m (see Figure 5.4b). P-wave velocity is increasing as a function of depth, which is expected for the P-wave refraction

tomogram. The uppermost section exhibits consistently low velocities, a phenomenon often associated with fracturing induced by the operational presence of moving machinery, specifically the mine underground trains and vehicles. Concurrently, a persistent low-velocity region spans the middle portion of the section, extending vertically from the base to the apex, indicative of highly fractured and faulted zones. Notably, the northern aspect of the section, shown in [Figure 6.14](#), manifests a distinct low-velocity feature exhibiting a discernible dip towards the right, suggesting localized geological complexities in that specific direction.

It is worth noting that the seismic tomograms show the presence of three distinct velocity zones. The near surface P-wave velocities (blue zone) exhibit velocities between ~ 2000 and 3000 m/s at varying depths of $\sim 0 - 7$ m. The major yellow-to-green zone with relatively higher velocities of $3100 - 4400$ m/s. The thickness of this zone can be observed from surface to the maximum depth of penetration across different area of the profile. The third P-wave velocity zone (orange to red) is characterized by velocities between ~ 4500 and 5800 m/s ([Figure 6.14a,b](#)). This zone is observed at the surface and deep level of the profile. Interpretation of the deep P-wave velocities was carried out with care, as we observe a maximum ray coverage (see [Figure 5.4b](#)) penetration down to 20 m in the velocity model.

In addition, and important for the mine, the refraction tomogram shows that the tunnel floor and the rocks below are characterised by some faulting and fracturing. Low velocities on the first layer might be due to a fractured and flooded tunnel floor. The top 20 m of the model is characterised by the alternating quartzites and conglomerates ([Figures 6.14 and 6.15](#)). The intact rock with high velocities could be interpreted as intact quartzite or a dyke ([Figures 6.14 and 6.15](#)).

The P-wave velocity model was also integrated with the legacy 3D reflection seismic data to investigate the structural architecture around the suspected faulted zones. The legacy reflection seismic data show a good correlation with the 2D tomogram. For example, a low velocity zone on the P-wave tomogram correlates very well with the fault mapped on reflection seismic data (see [Figure 6.16 a,b](#)).

The information regarding the details about the legacy profile is given by [Manzi et al. \(2012a, b\)](#).

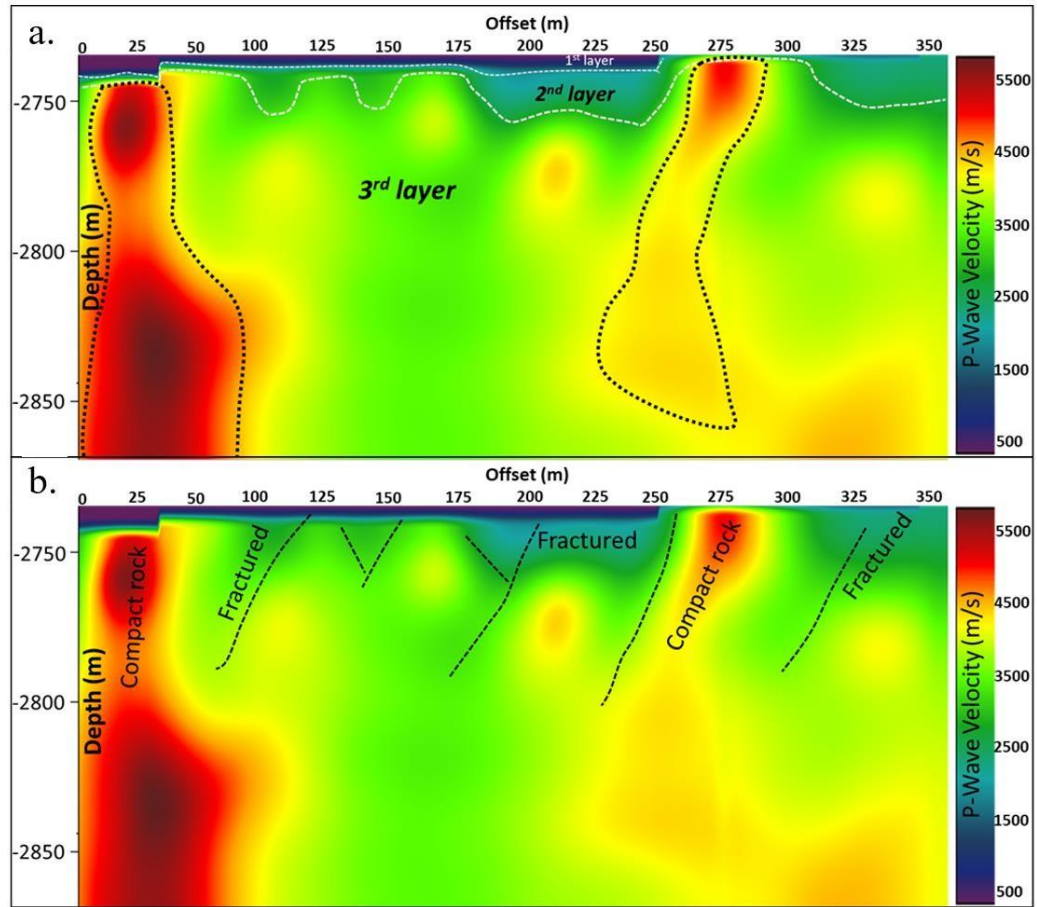


Figure 6.14: Interpretation of the P-wave refraction for profile SDT1. (a) layers within the tomogram and (b) the fracturing and faults observed within the tomogram.

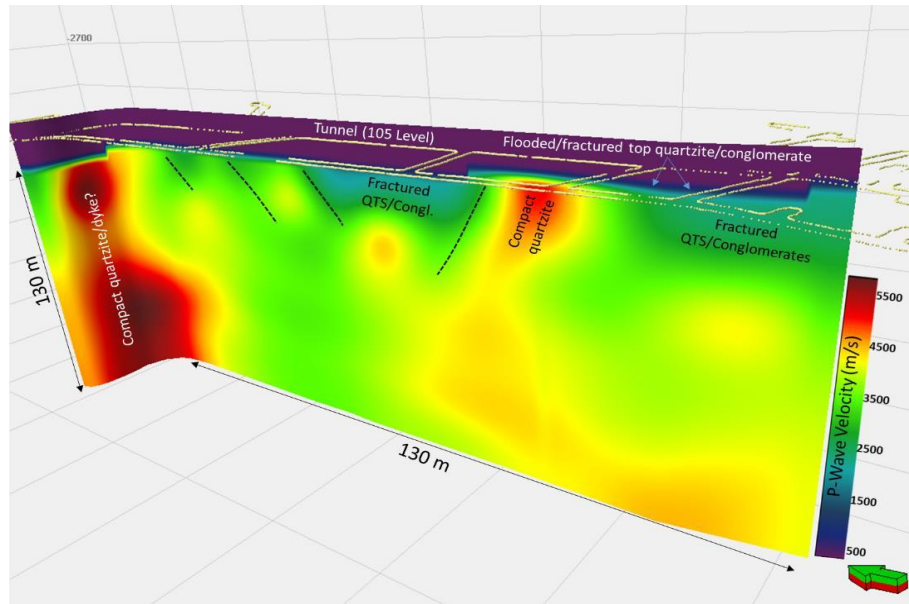


Figure 6.15: Interpretation of the P-wave refraction for profile SDT1, showing fracturing and faulting of the rock layers.

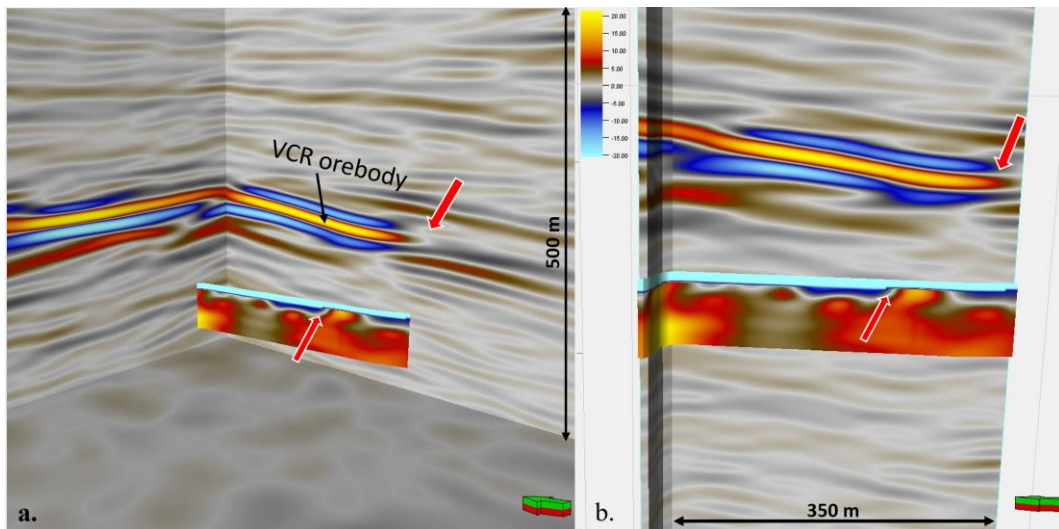


Figure 6.16: Interpretation of the P-wave refraction for profile SDT1 and legacy seismic data, showing the low-velocity zone correlating with faulting. (a) Inline, crossline and depth slice integrated with the P-wave refraction tomogram. (b) Inline section integrated with the P-wave refraction tomogram. VCR: Ventersdorp Contact Reef.

6.4.2. 2D reflection seismic section

Figure 6.17 shows a depth-converted seismic section obtained from the SDT1 seismic profile. Interpretation of the faults and fractures was of particular interest in the tunnel study because the UER is seismically transparent and our profile was too short to image the shale below the tunnel floor. A careful inspection of the reflected energy on the seismic sections suggests that they originate from faulting and fracturing as estimated by P-wave tomograms. The central segment of this seismic profile displays reflections that have a high level of coherence, thanks to the increased fold-of-coverage. However, it is important to exercise caution at the distal ends of the profiles, as the reflections observed there may be artifacts related to the low fold-of-coverage. Upon careful examination of the reflections near the surface, a consistent pattern can be observed. However, this pattern is interrupted by noticeable disruptions along the reflections, particularly in the top 0-200 m of the subsurface. It is crucial to take these observed disruptions into account when interpreting subsurface structures. Additional investigation may be required to ascertain whether these disruptions are caused by geological features or artifacts in the seismic data processing.

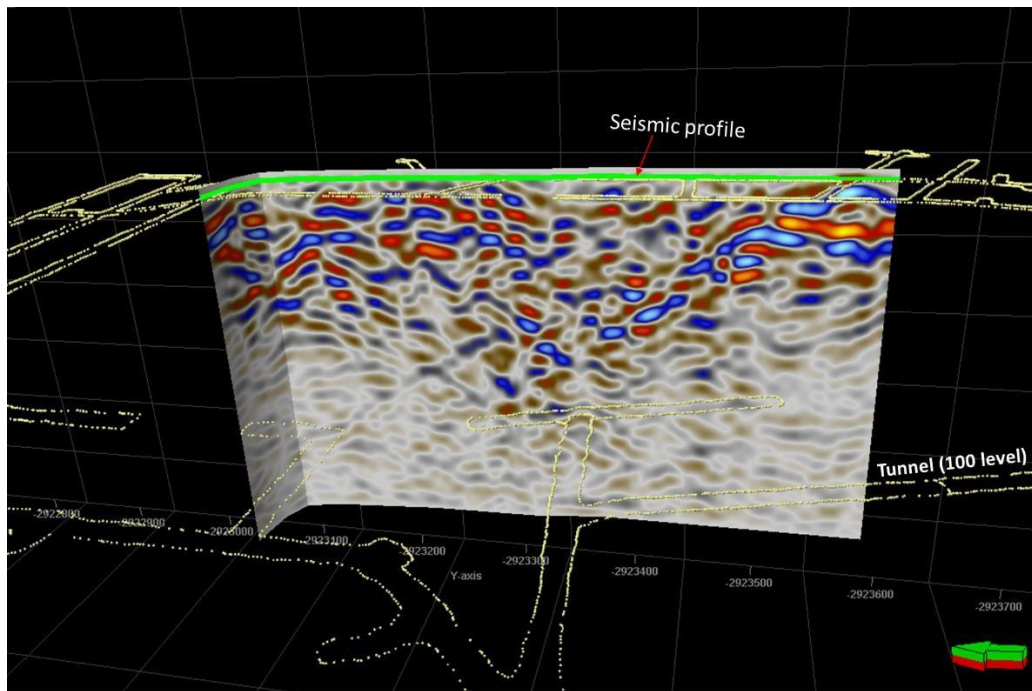


Figure 6.17: A depth converted stacked seismic section from the SDT1 seismic data.

Within certain depth ranges and Common Depth Point (CDP) intervals, the seismic dataset reveals a distinct dipping reflection. Notably, this reflection can be observed between CDPs 195 and 253, at depths ranging from 1-400m. This usually suggests a geological feature displaying a uniform dip and offers valuable insights into subsurface structural properties. Moreover, a consistent reflection with a similar dip can be observed within a specific depth range of 210-450m, which corresponds to a broader CDP range of 128 to 155. The fact that this dipping reflection is present across different depth intervals and CDP spans highlights its geological importance and persistence.

To enhance the detection of the geological structures, complex-trace attributes (The phase and cosine of phase) (Manzi et al., 2013b; Manzi et al., 2019) were extracted along the profile and the interpretation was constrained to the boreholes closest to the profile (Figure 6.17). The complex-trace seismic attributes computed for the profile included amplitude (Figure 6.18a,b), phase (Figure 6.18c), and paraphrase (cosine of phase) (Figure 6.18d). Before the computation of the seismic attributes, the data were preconditioned through structural smoothing filters (combination of median and mean filters (eqn 6.1 & 6.2)) (Figure 6.18b) to enhance the signal-to-noise ratio of the data.

$$f(x, y) = \frac{1}{|S_{xy}|} \sum_{(s,t) \in S_{xy}} g(s, t) \quad (6.1)$$

Where, $f(x, y)$ represents a seismic attribute value at a specific location (x, y) in a seismic dataset.

S_{xy} : This set includes neighboring seismic trace points or seismic data samples surrounding the point (x, y) .

$|S_{xy}|$: The number of seismic traces or data points in the set S_{xy} .

$\sum_{(s,t) \in S_{xy}} g(s, t)$: The sum of the seismic attribute values (e.g., amplitudes, velocities) from all the points in the set S_{xy} .

$g(s, t)$: The value of the seismic attribute at the point (s, t) .

$$f(x, y) = \text{median}\{g(s, t) | (s, t) \in S_{xy}\} \quad (6.2)$$

Where, $f(x, y)$ Represents a seismic attribute value at a specific location (x, y) in a seismic dataset.

S_{xy} : This is the set of neighboring seismic traces or data points around point (x, y) , used to analyze the attribute's variability.

$g(s, t)$: The value of the seismic attribute at the point (s, t) , such as amplitude or velocity.

$\text{median}\{g(s, t) | (s, t) \in S_{xy}\}$: The median value of the seismic attribute over the set of neighboring points.

It is clear that the filtered section (Figure 6.18b) is much better than the original section (Figure 6.18a). When displayed with suitable color bars, phase (Figure 6.18c) and paraphase (Figure 6.18d) made strong seismic events easy to distinguish from weak seismic events, in terms of amplitude or frequency in relation to peaks and troughs. In general, the seismic section shows a delineation of the weaker zone along the strata, which is indicated by white arrows in Figure 6.18d. White arrows in Figure 6.18c and green arrows in Figure 6.18d show the continuity of a strong reflection. The instantaneous phase (Figure 6.18c) and cosine of phase (paraphase) are independent of the amplitude and are therefore less sensitive to noise and best detectors of lateral continuities of reflections. Figure 6.19 shows the 3D visualisation of the depth converted original seismic section (Figure 6.19a) and paraphase display (Figure 6.19b). The continuity of the horizon (green arrows) and faulting are well defined by the paraphrase attribute. The horizon indicated in green arrows may be associated with one of the top gold-bearing conglomerate units with the UER package. Finally, the tunnel seismic profile was integrated with the legacy seismic data to investigate if there were any structural correlations between the two datasets. Figure 6.20 shows the integrated 2D tunnel-3D seismic datasets. It is very clear that the two datasets show the imaging of the similar structures, especially the NNE trending structure. The structure is one of the most dominant geological structures in that region and it is tracked between the 2D tunnel and 3D seismic datasets as indicated by red arrows. Most importantly, the structure crosscuts and displaces the VCR orebody and the underlying UER package. This information is critical for mine planning and development in this region.

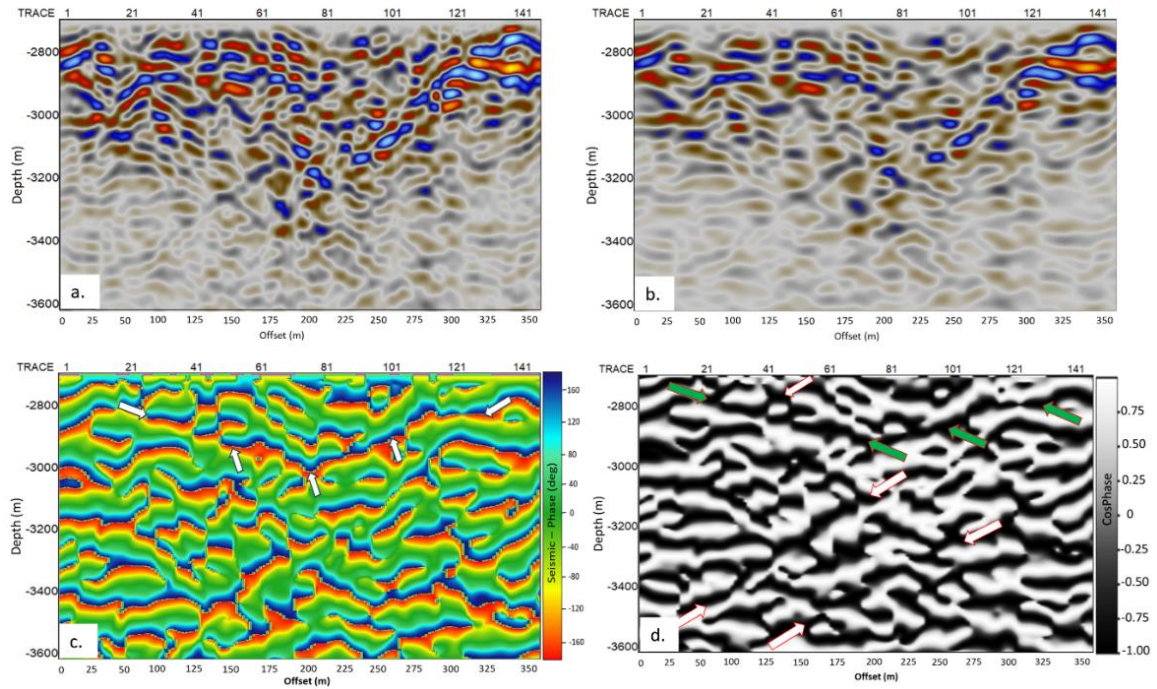


Figure 6.18: (a) Original amplitude display showing strong seismic amplitude related to the faulting in the region. (b) Structurally smoothed amplitude display showing improved quality of the data. (c) Instantaneous phase and (d) Paraphase display highlighting lateral continuity of the reflections. The color overlays exhibit more information than is visible on traditional black and white seismic sections. White and green arrows show continuous reflections associated faulting and fracturing.

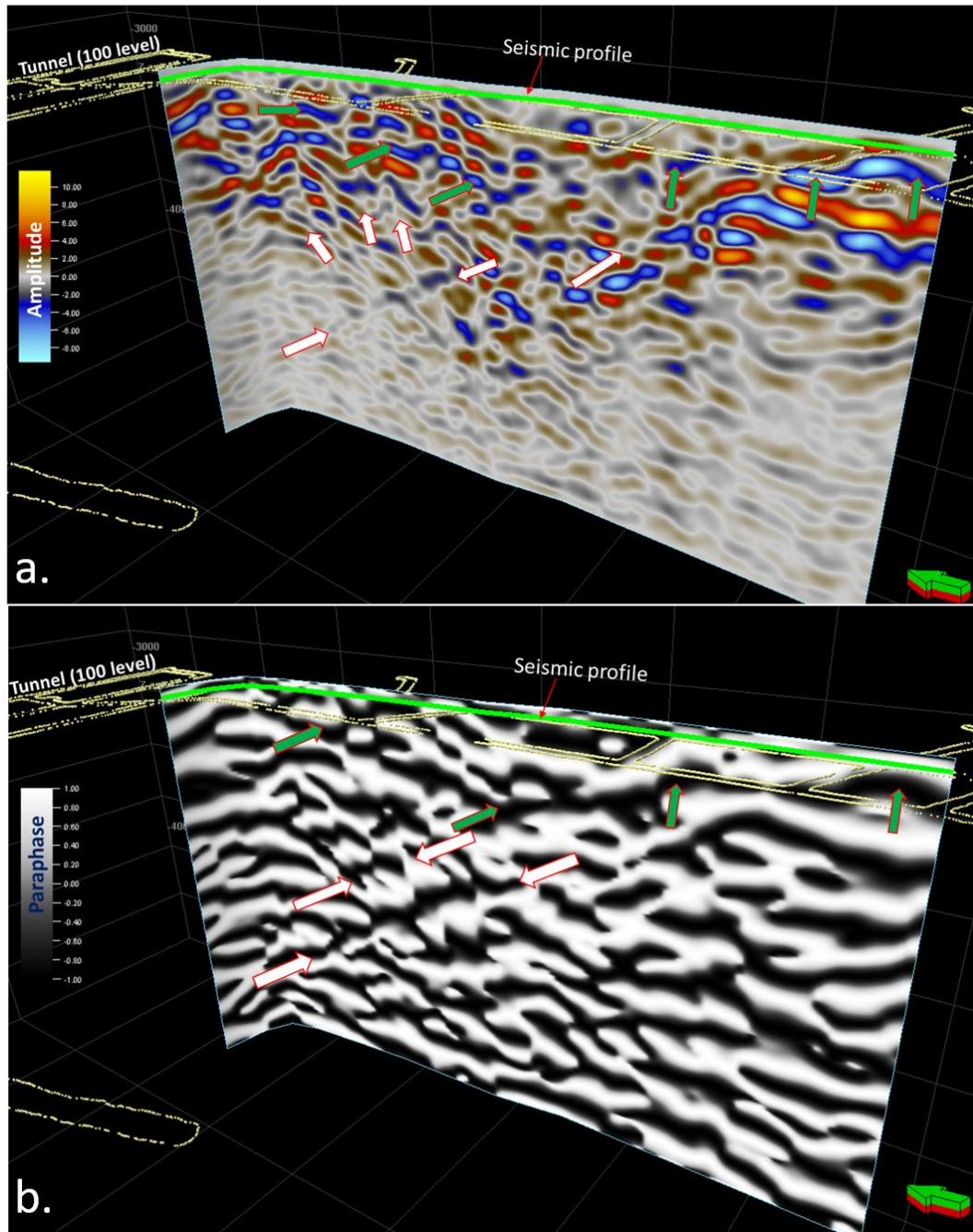


Figure 6.19: (a) Original amplitude display showing strong seismic amplitude related to the faulting in the region. (b) Paraphase display highlighting lateral continuity of the reflections. White arrows show faults and dykes, while green arrows show continuous reflection.

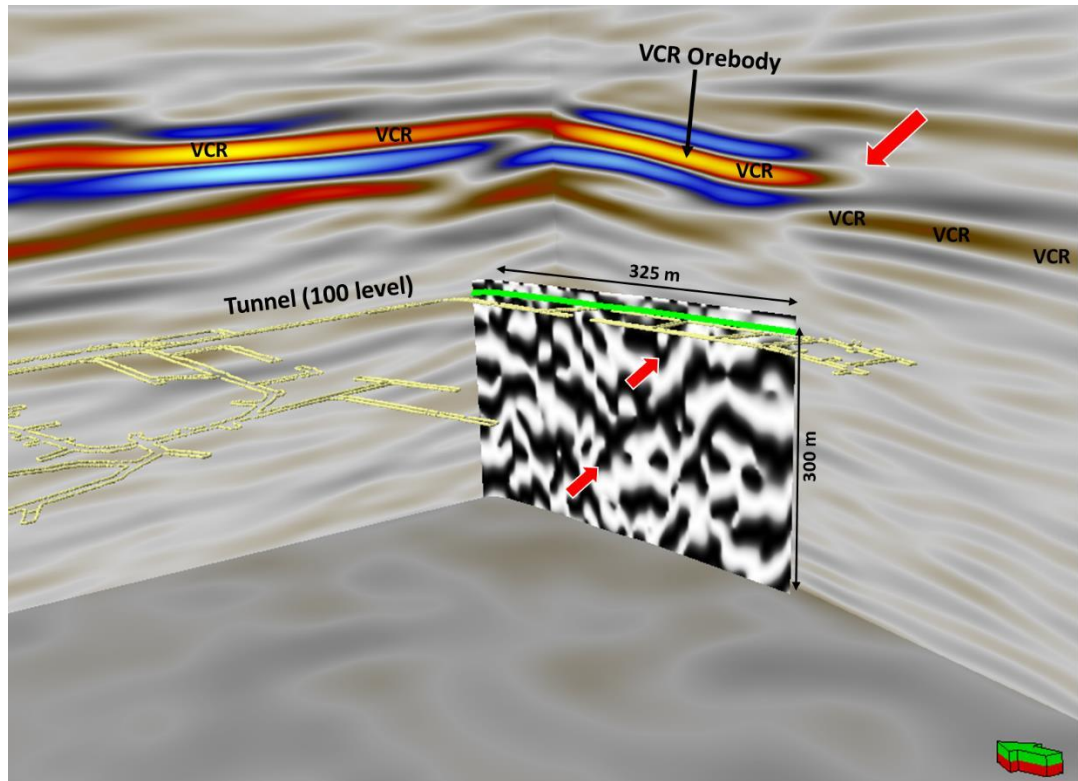


Figure 6.20: Paraphrase display highlighting lateral continuity of the reflections. Red arrows show the faults that are visible in both the legacy seismic data and the 325m seismic line conducted in the mine tunnel.

7. DISCUSSIONS

7.1. Bulk density and seismic velocities

The samples analysed in this study consist of conglomerates, quartzites, and basaltic lavas. Conglomerates reefs and quartzites of the Upper Elsburg Reef orebody are part of the Central Rand Group of the Witwatersrand Supergroup. While the basaltic lavas are part of the Ventersdorp Supergroup, which unconformably overlies the Central Rand Group. The dyke sample analysed in this study may be associated with one of the four different tectonic events: Karoo Supergroup (150 Ma), Pilanesberg (1.30 Ga), Transvaal Supergroup (2.20 Ga), and Ventersdorp Supergroup (2.60 Ga).

In general, our results show that seismic velocities increase as function of bulk density. The results presented display a direct linear association between seismic velocities and densities for most lithologies from the Upper Elsburg Reef package.

Acoustic impedance between the basaltic lavas and underlying quartzites and conglomerates dominates the strong seismic reflectivity observed across all the three analysed boreholes (BH1, BH1-D1, and BH2). The BH1 was initially drilled vertically but, at depths, was deviated by a few degrees towards east. BH1, on the other hand, was a vertical hole. The acoustic impedance and reflection coefficients were calculated using the bulk density and seismic velocity values measured for each sample across the entire boreholes. No downhole geophysical measurements were conducted in these holes, hence the motivation for laboratory ultrasonic measurements and bulk densities. The twenty-four samples collected comprised of four different rock samples namely, 10 reefs, 9 quartzites, 4 lavas and 1 dyke. [Table 7.1](#) shows the summary of seismic velocity for different rock types.

Table 7.1: Different ranges of seismic velocities for the various rock types

Rock Type	Average Density (g/cm ³)	Average P-wave (m/s)	Average S-wave (m/s)	Range (P-wave) (m/s)	Range (S-wave) (m/s)
Reefs	2,74	5630	4345	4467 – 5970	3037 – 4768
Quartzites	2,68	5660	4526	5202 – 5802	4070 – 4854
Lavas	2,82	6230	4833	5916 – 6711	3275 – 5659

Dyke (1)	2,85	5922	5385	5922	5385
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A study conducted by [Manzi et al. \(2015\)](#) analysed the quartzites from Mponeng gold mine of the West Wits line goldfield. The study revealed that the P-wave velocities of quartzites ranged from 4920 to 5870 m/s while their densities varied from 2.7 to 3.01 g/cm³. This research at South Deep gold deep mine also reveals that the quartzites had an average P-wave velocity of 5664.44 m/s and an average density of 2.68 g/cm³, which fall in the range of those reported in studies by [Manzi et al. \(2015\)](#) and [Nkosi et al \(2017\)](#).

Density versus seismic velocities

[Figure 7.1](#) shows the variation of seismic velocities as a function of the bulk density of rocks. From [Figure 7.1](#), it can be noted that the quartzites and the conglomerates cluster around the same P-wave velocity ranges, although they sparse out along the density ranges. From the results presented in [Figure 7.2](#), the cluster observed between quartzites, and conglomerate reefs is better spread apart towards the lowdensity samples, this means that there is much of a better contrast between the shear wave velocities of the conglomerate reefs and that of the quartzites irrespective of the similarities in the mineralogical composition. The lavas in the dataset still maintained a high velocity even when we conducted shear wave velocity measurements, which is expected for igneous rocks.

According to [Table 2.1](#), the conglomerates and the quartzites consist of quartz mineral, which slows down the seismic velocities. However, relatively higher density values associated with some of the conglomerates (reefs, e.g., [Figure 7.1](#)) may be attributed to gold mineralisation, i.e., the type of pyrite grains that are not present in the mineralised quartzite samples. The lava and dyke samples also exhibit relatively high densities and seismic velocities ([Figure 7.1](#)) than quartzite and conglomerate samples, which is expected for igneous rocks and intrusives ([Zama et al., 2017](#)). In general, the seismic velocity and density results suggest that observed contrasts in these samples are due to different mineral compositions. However, it is worth noting that other factors that affect the densities and velocities include the

presence of fractures, fracture orientation, stress or pressure, and mineral alignments. These detail investigations were not part of this study, however future studies are encouraged to look into these.

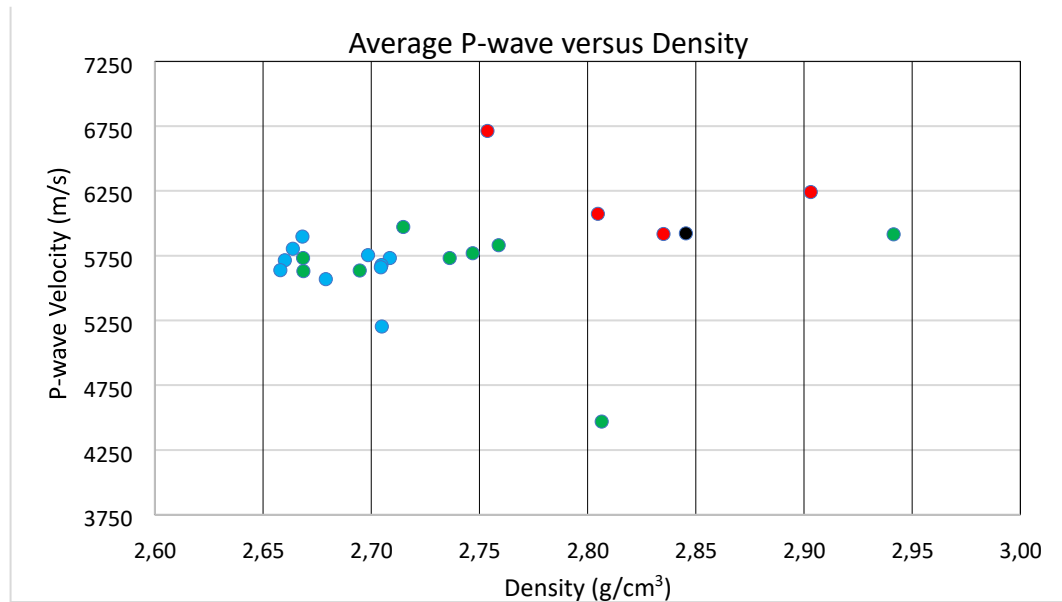


Figure 7.1: Different P-wave velocities from samples; quartzites (blue), Lavas (Red), Conglomerate reefs (green) and the dyke (Black) from South Deep Gold mine plotted as a function of density.

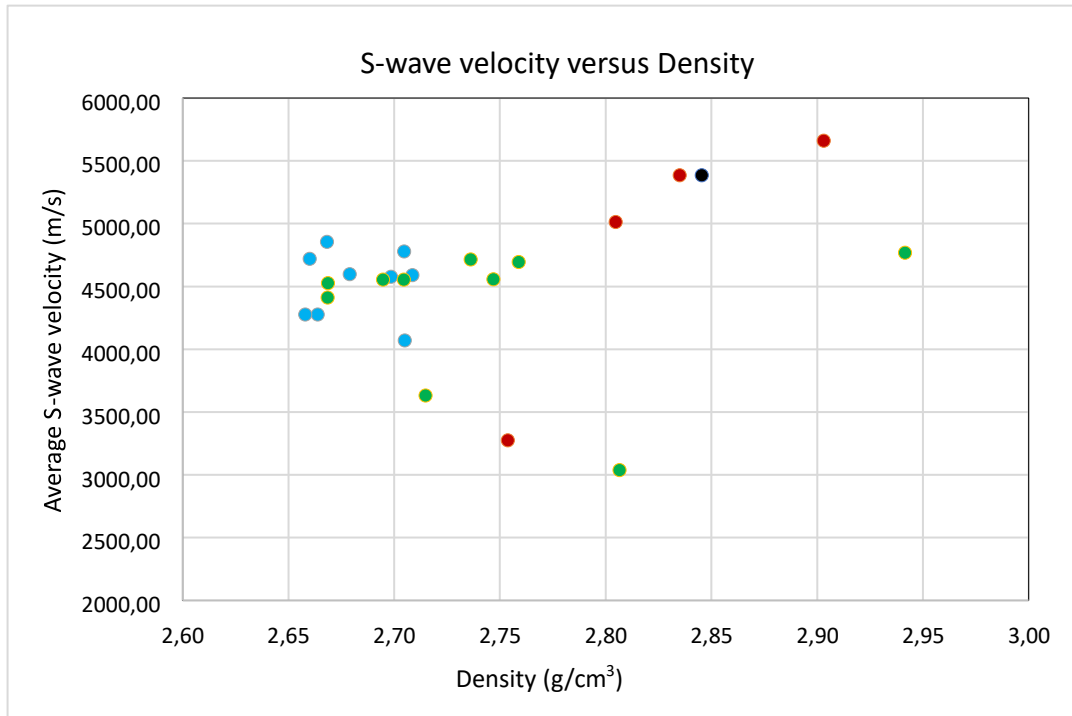


Figure 7.2: Different S-wave velocities from samples; quartzites (blue), Lavas (Red), Conglomerate reefs (green) and the dyke (Black) from South Deep Gold mine plotted as a function of density.

Error analysis

In statistics, error bars are used to indicate the uncertainty or volatility of a data point on a graph. They convey information about the dispersion of data around the mean value and provide a rough indication of how accurate a measurement is (Pang et al., 1997). Error bars were calculated for the data, and the data were grouped into four different rock types and the standard deviations were calculated as per the different categories of rock types.

Figure 7.3 shows the error bars calculated for the P-wave velocities and densities of the four different classes of rocks present. The distribution of the data around the mean value was plotted in Figure 7.3 using error bars. Quartzites and conglomerate reefs are plotted as small error bars which show that the data is clumped around the mean, whereas the lava samples show wider error bars which suggest that the data deviates from the mean more.

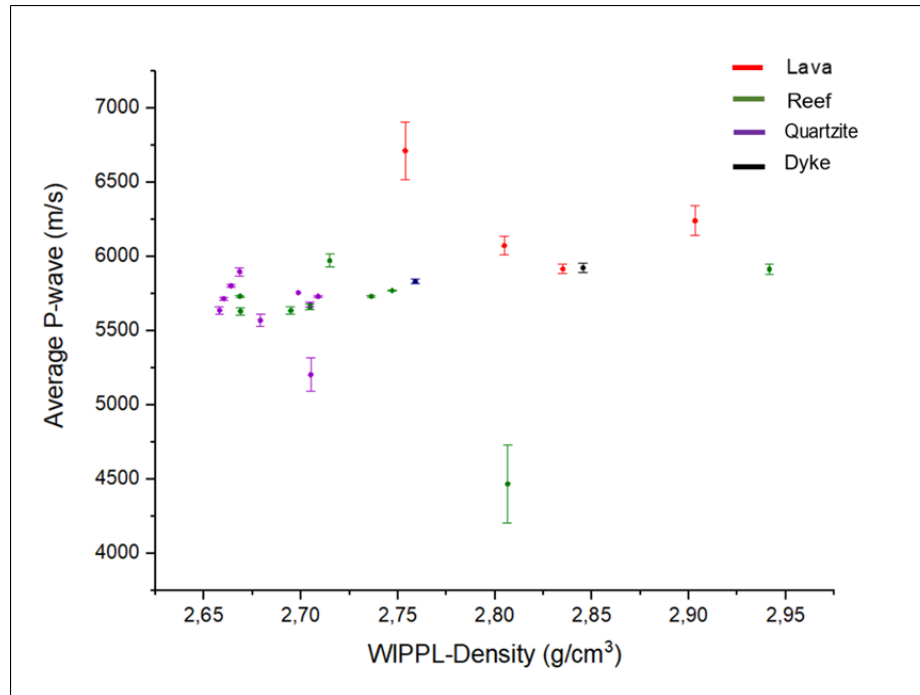


Figure 7.3: Error bars graph depicting the relationship between Density (x-axis) and Average P-wave (y-axis), showcasing the variability in P-wave measurements with corresponding error bars for each density value. value measured in the Wits integrated Physical Properties Lab (WIPPL).

Error bars for the S-wave measurements and density measurements were also calculated and plotted in [Figure 7.4](#) to understand how accurate the measurements were. As per with the P-waves, S-waves also show that the quartzites and conglomerates are characterised by smaller error bars, which means the values do not deviate from the mean. It also important to note that, S-waves exhibit much longer error bars for different rock types. The dyke and the lava samples in [Figure 7.4](#) show a much greater deviation from the mean. This was not observed with the P-waves for the same rocks, and this can be attributed to the coupling effect on the samples, or the difficulty in picking the S-waves. This is because during the measurements of S-waves, a different couplant was used which is not the same as the one used for the measurement of P-waves. It is worth noting that the quartzites show the smallest error bars, which translates as a reliability tool for these measurements.

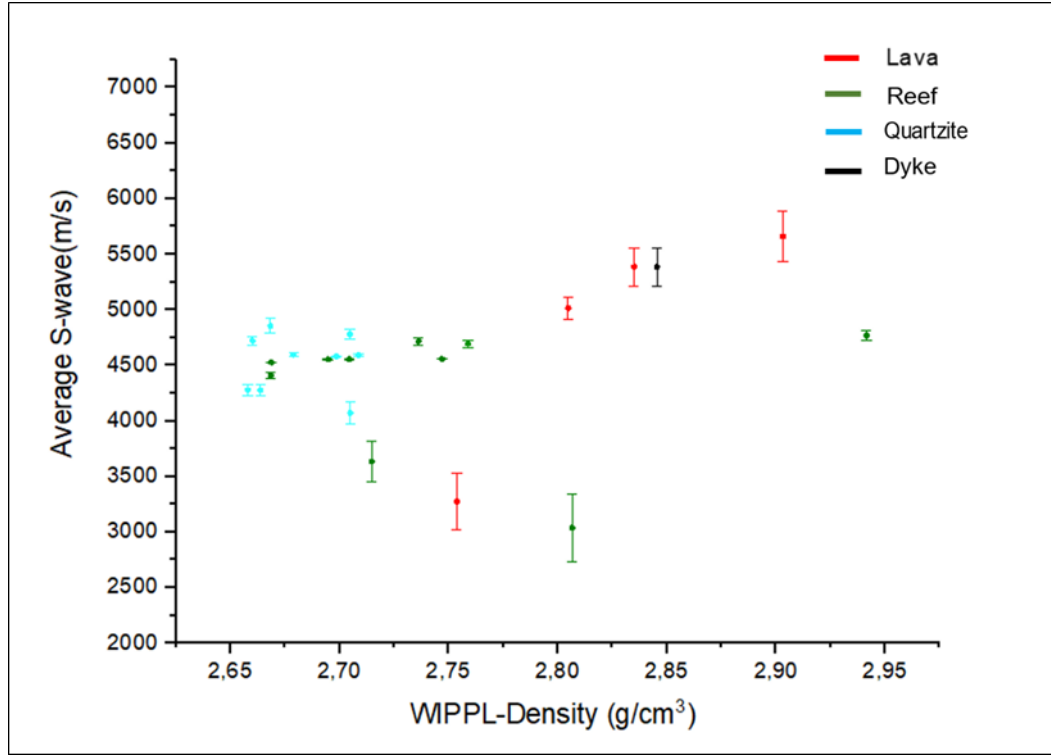


Figure 7.4: Error bars graph depicting the relationship between Density (x-axis) and Average P-wave (y-axis), showcasing the variability in S-wave measurements with corresponding error bars for each density value measured in the Wits integrated Physical Properties Lab (WIPPL).

In general, the error analysis that were considered during this study was the identification and picking of P- and S- arrival times. Other potential sources of errors in the measurements are laboratory conditions (e.g., vibrations) and smoothness of the sample surfaces, which can contribute to nonlinearity in the measurements.

7.2. Synthetic seismograms derived from P-wave velocities

The synthetic models were computed from three different boreholes with the aim of analyzing the reflectivity of the Upper Elsburg Reefs (EUR) package at different positions in the tunnel as the orebody thins towards the west and thickens towards the east. Previous studies have shown that the VCR is a seismic marker because it occurs at the interface between overlying basaltic lavas and underlying quartzite and conglomerates and has been used in several studies as ghost reflector seismically transparent gold orebodies such as UER orebody (Manzi et al., 2012; Manzi et al., 2013; Osburn et al., 2014). However, in addition to the VCR strong

reflector, the results from this work suggest that there might be enough acoustic impedance some conglomerates and quartzite members of the UER package to make make them seismically detectable. However, this might still be difficult due to the thickness (< 1 m) of individual reef of the UER package.

[Figure 7.5a](#) shows a seismogram from borehole BH1-D1 and the contact (i.e., VCR) between the lavas and the MBT quartzites is marked with a strong reflection on the seismogram, which demonstrates that the VCR is associated with the strong reflectivity. The strong reflection observed between MBB and MIT (red dots) is due to a strong contrast between the two end members. [Wesseloo and Joughin \(2007\)](#) confirm that the MBB contains 50% conglomerates and 50% quartzites, meanwhile MIT is entirely a conglomerate reef. So the observed contrast is mainly due to the increase in density caused by the mineralised MIT reef.

In [Figure 7.5b](#), two interfaces are displayed which exhibit a high reflection coefficient between ECT and ECMC (red dots) and MBB and MIT (blue dots). MIT is a conglomerate reef and MBB is a quartzite with 50% conglomerates. This suggests that the other members of the UER also have reflectivity, indicating that the UER may not be entirely seismically transparent. Therefore, the interface between MIT and MBB could be used as evidence to support this claim. Furthermore, the same interface shows a strong reflection even on the borehole in [Figure 7.5a](#). These results suggest that any of these reflections could be used as a ghost reflector for seismically transparent reefs within UER package.

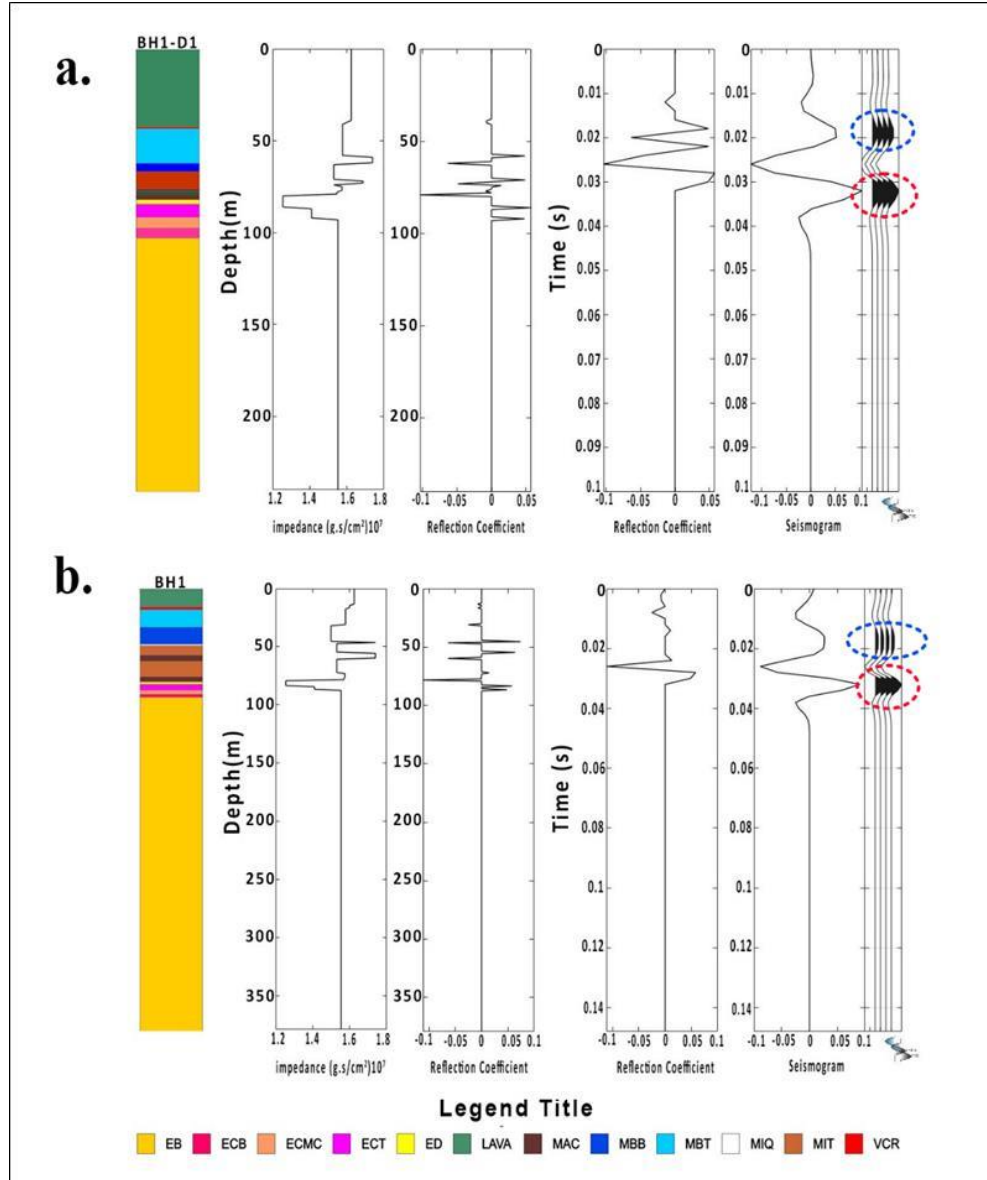


Figure 7.5: Seismogram from borehole BH1-D1 (a) and borehole BH1 (b). The red and the blue dots show reflections of interest.

7.3. P-wave versus S-wave 1D synthetics

Previous studies on synthetics have always traditionally been conducted using Pwave velocities (Nkosi et al., 2013; Mahlatji, 2021). The fundamental reason for the choice of the type of velocity to use is that P-wave velocities can be used to calculate the density and elastic properties of the materials through which they travel, which in turn can provide information about the composition and temperature of the Earth's interior. In some instances, where shear sources are not

available, S-wave reflections can be extracted from P-wave data for processing. Several studies have use S-wave reflection from P-wave data for mineral explorations and very few studies have used S-wave laboratory measurements to compute the synthetic models for survey planning and designs (Schulte-Pelkum and Blackman, 2003).

For this specific study, S-wave measurements were collected on different samples with the aim of computing seismograms which will then be compared with those from the P-wave measurements. Figure 7.6 shows a comparison between two seismograms computed from the same borehole, one with P-wave velocities (Figure 7.6a) and the other with S-wave velocities (Figure 7.6b). It is important to note that, the same endmembers of the UER that were responsible for the observed reflections from the seismogram generated using P-wave velocities, are also the same endmembers that are responsible for the observed reflections from the seismograms generated using S-wave velocities. The reflection from the contact between the lavas and MBT quartzite is clear in Figure 7.6a, b. However, it is important to note that the reflection observed from the P-wave velocity is subtle than the one observed from the S-wave velocities.

The wavelet next to the seismogram seen in Figure 7.6a is not as sharp as the one in Figure 7.6b. The sharp wavelet observed in the reflection coefficient in Figure 7.6b brings somewhat a level of ambiguity with regards to the depth to the reflective interface. This can be seen after comparing Figure 7.6a, b. The wavelets in Figure 7.6b are smoothed and the depth to the reflective interface matches that observed in the geological log on the far left of Figure 7.6b. It can be inferred from these observations that; the S-wave measurements are more detailed to map the UER than the P-wave velocity measurements.

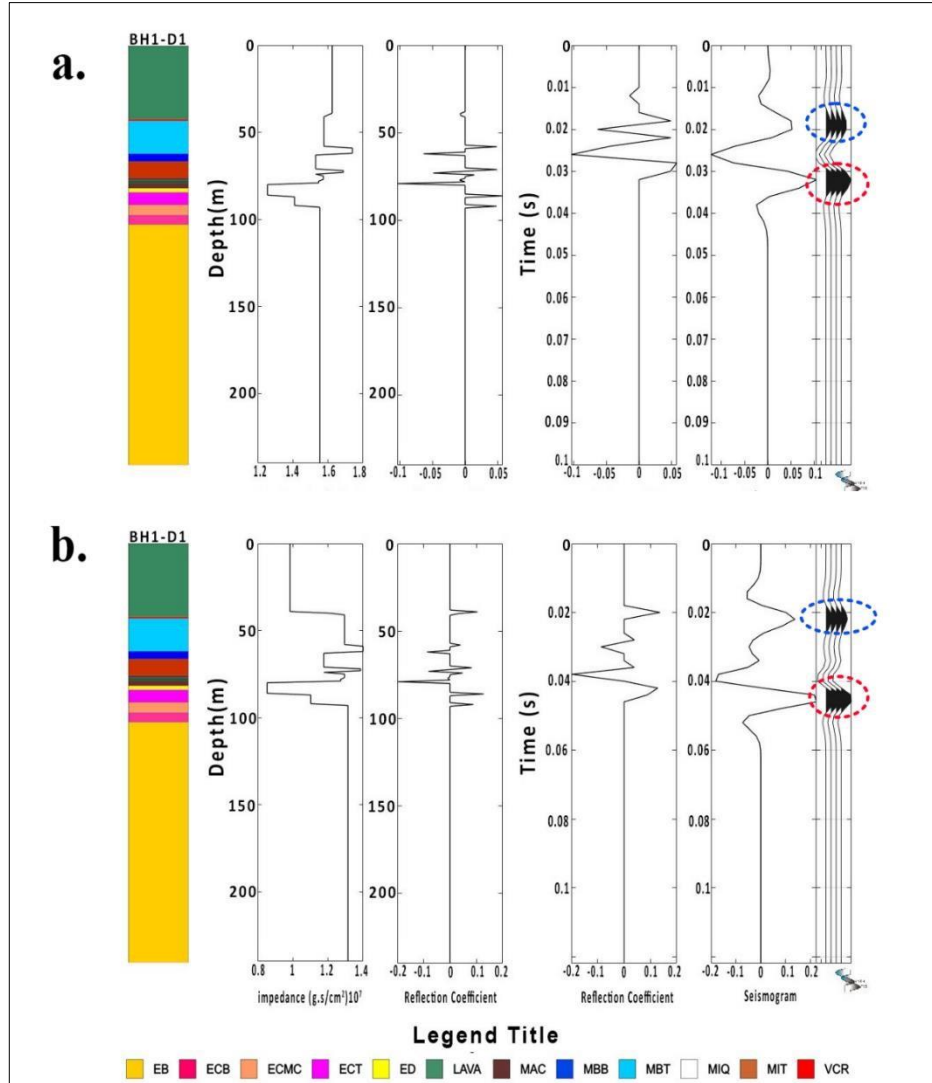


Figure 7.6: Synthetic seismograms of borehole BH1-D1 (a) computed from P-wave velocities and (b) computed from S-wave velocities. The blue and red circles show significant reflections from the seismograms.

The seismograms shown in Figure 7.7a,b summarize both P- and S- wave velocity derived seismograms from borehole BH1. The first notable difference between the S-wave and the P-wave synthetic seismograms is that, there are three strong reflections observed in Figure 7.7b, and meanwhile Figure 7.7a shows only two

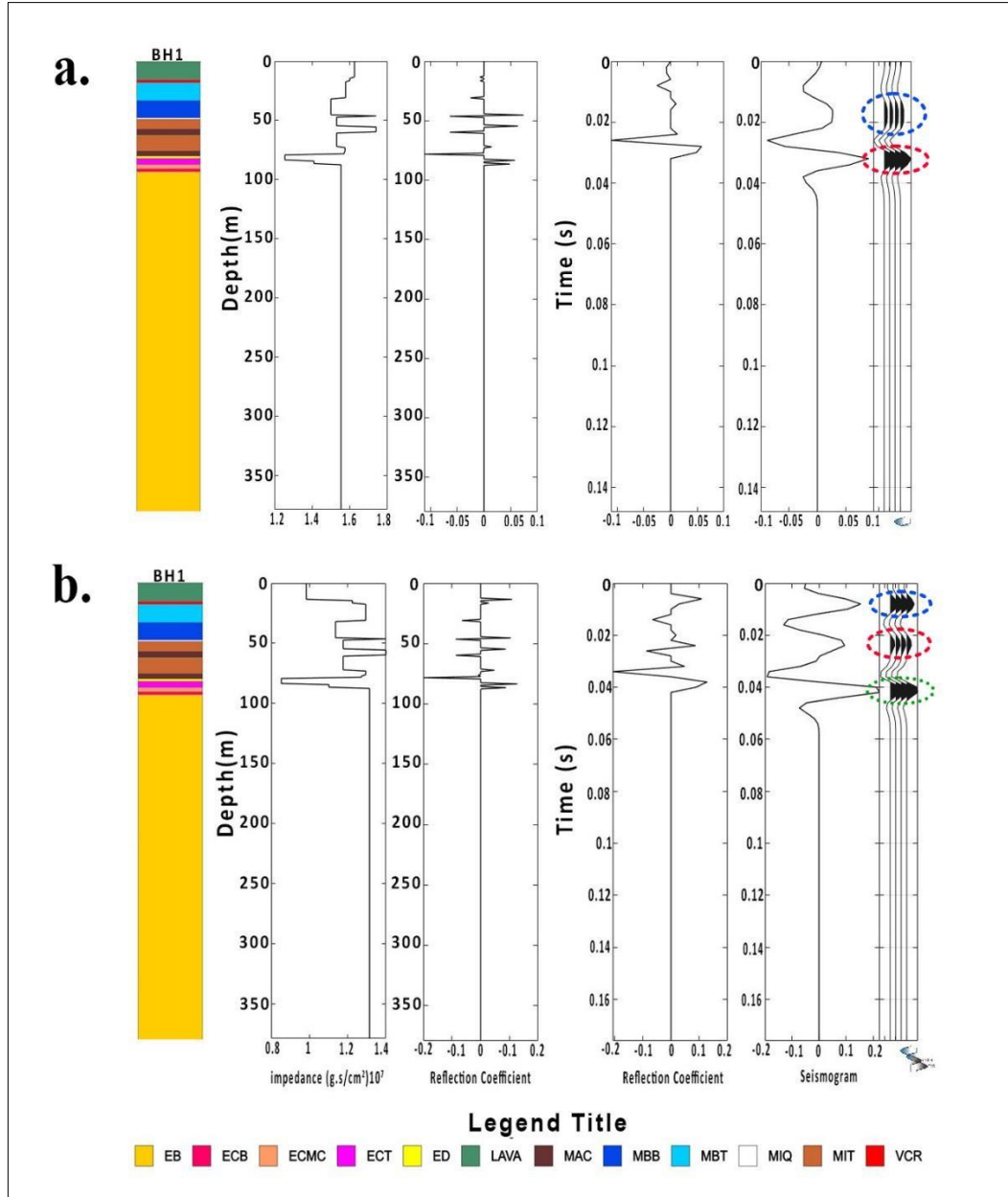


Figure 7.7: Synthetic diagrams from borehole BH1. (a) P-wave velocities, and (b) S-wave velocities.

strong reflections on the seismograms.

There is an additional reflection that is visible from the S-wave synthetic seismogram which is not visible from the P-wave synthetic seismogram. This could possibly suggest that there is a contrast in the S-wave velocity that was not observed on the P-wave synthetic seismogram. The reflection that is visible in the S-wave synthetic seismogram, is observed between quartzite MIQ and the conglomerate MIT.

Synthetic seismograms from BH2 did not accurately depict the lithology responsible for the observed reflection, as shown in Figure 7.8a. In order to determine the cause of this discrepancy, we ran the same synthetic seismograms with the same lithologies but reduced the length of the bottom lithology (EB). The results, shown in Figure 7.8, indicate that the length of the top or bottom layer can impact our ability to map the lithologies responsible for reflections, but this also depends on the mineral composition of the specific rock.

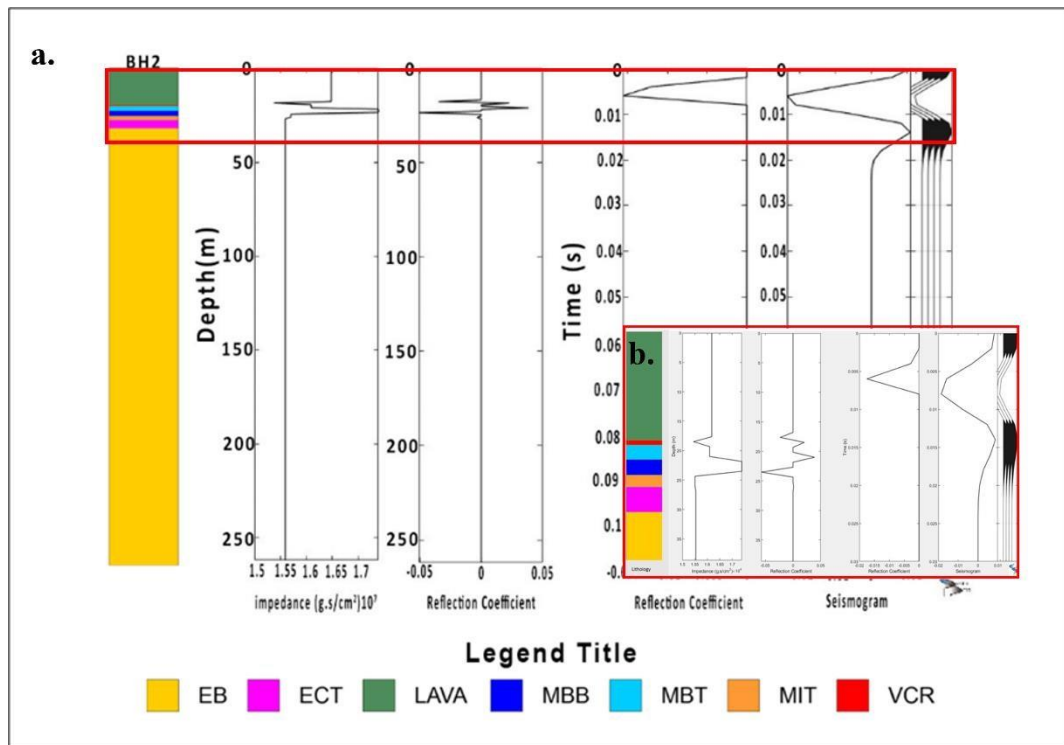


Figure 7.8: (a). P-wave synthetic seismogram for BH2, (b) Demacaded by a red rectangle, shows a closeup synthetic model computed with information from the top 80m of BH2.

7.4. Seismic reflectivity as observed in legacy seismic data.

Data from borehole BH2 was plotted against an arbitrary line extracted from the legacy 3D seismic data to investigate the source of reflections observed on 1D synthetics as shown in Figure 7.9. From the physical properties measured from

BH2, the contact lava-VCR and MBT-ECT were the two notable reflections corresponding with those seen on the synthetic data. This correlation provides evidence that VCR is not the only major reflection that can be interpreted from the seismic data, implying that future surveys should consider looking at the S-wave reflection processing approaches in addition to P-wave reflection processing approaches.

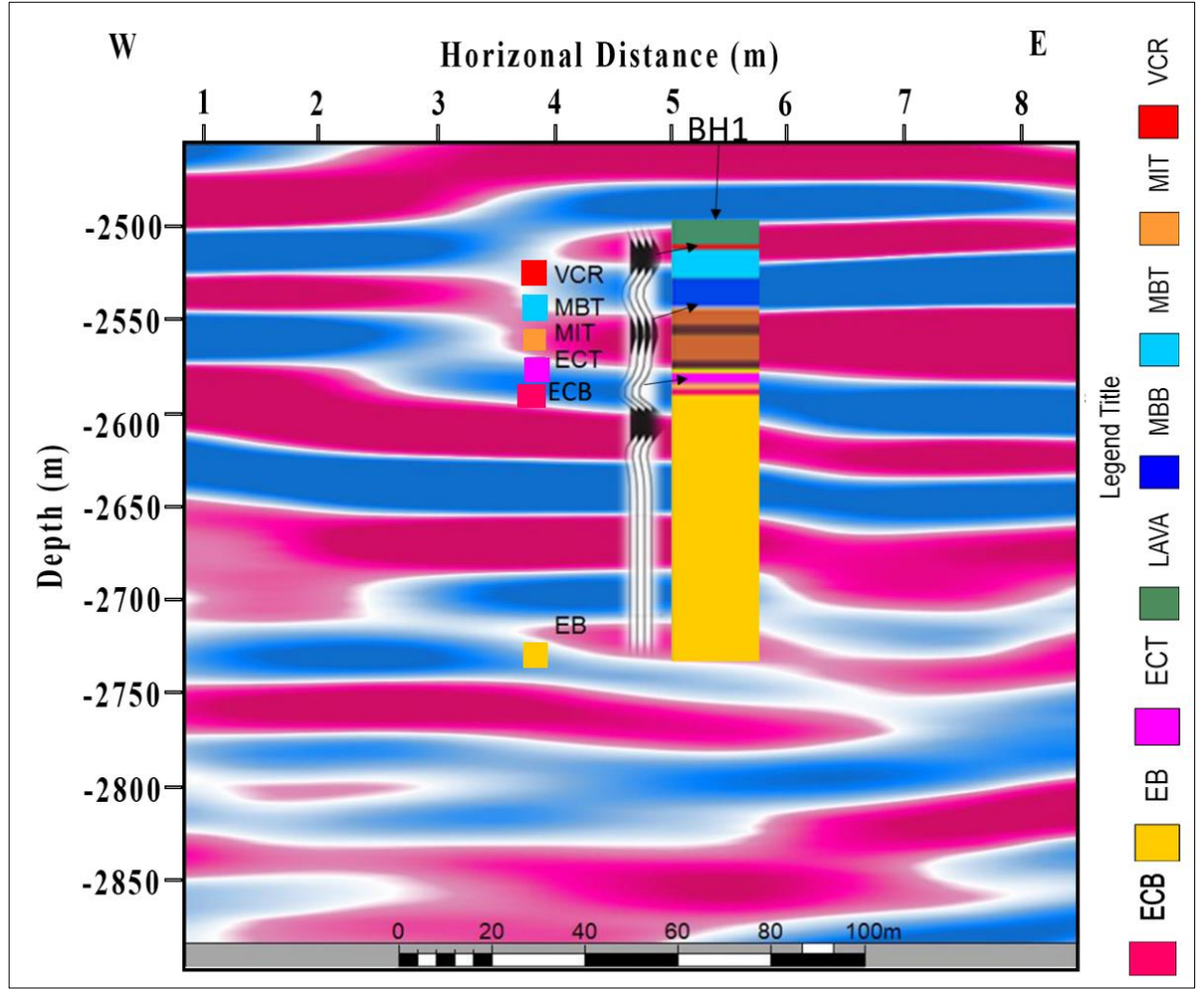


Figure 7.9: Correlation between 1D synthetic (from S-wave velocities) data and legacy 3D seismic data. An arbitrary profile was extracted across BH1 for comparison purposes.

7.5. 2D synthetic shotgathers versus real shot gathers

The synthetic model from Tesseral was merged with the receiver coordinates used for the experiment in the mine tunnel (SDT1). This allows us to make meaningful observations regarding the reflections seen on the dataset. Figure 7.10a represents a shotgather from the synthetic model, and Figure 7.10b. represents a shot gather from the in-mine/tunnel survey. It is worth noting that the shotgather from the synthetic model is entirely free of noise, whilst that from the survey is noisy and this was considered when doing the comparisons. The noise in the real shotgather is attributed to the machinery, vehicles, drilling, groundroll and all the different sources of noise that exist in an operational underground mine. Clear P-wave first

breaks (black arrow) can be observed together with reflections (green arrow). The reflection on the modelled shot gather manifest above the first break, and this can be attributed to the dipping nature of the lithology (Figures 7.10a,b-7.12a,b). This is because the reflection point is not directly beneath the source, but rather offset to the side, causing the reflection to arrive later than the direct wave or first break. As a result, the reflection appears to be coming from a deeper layer than it actually is, causing it to plot above the first break as observed by Zelt et al. (2003).

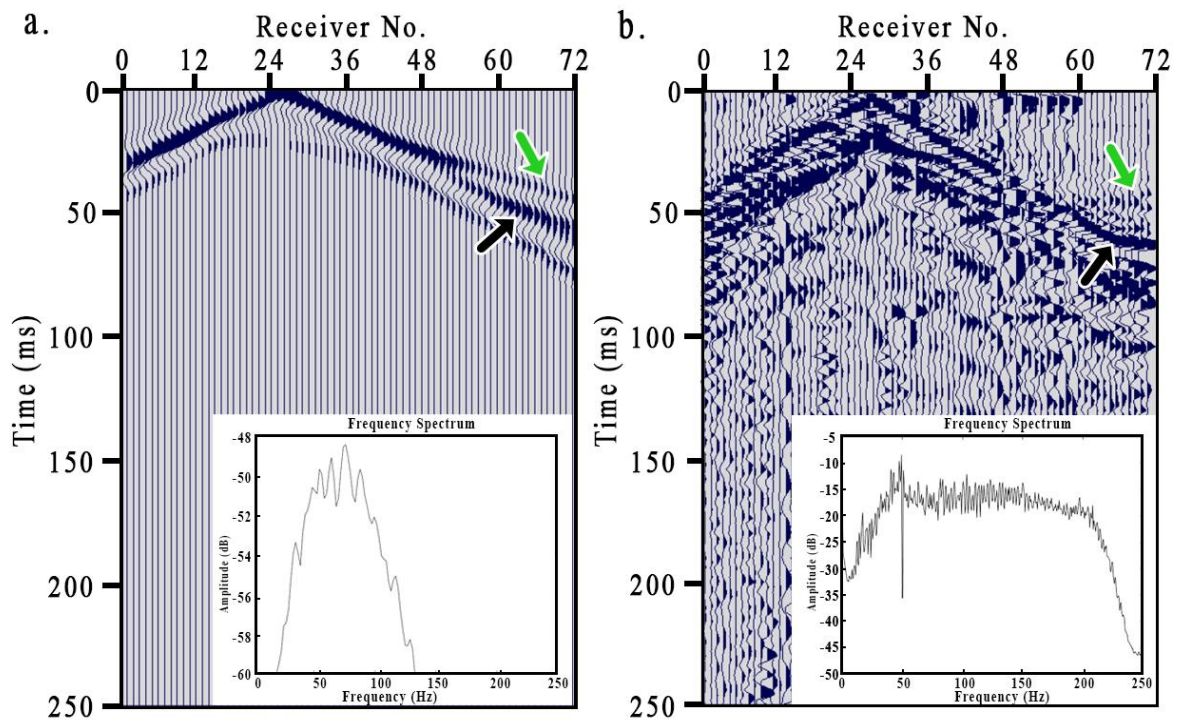


Figure 7.10: Comparison of shot19 (a) Synthetic shotgather of the model from Tesseral and (b) a raw shotgather from SDT1 seismic line. The black lines show the first arrivals, and the green arrows show reflections.

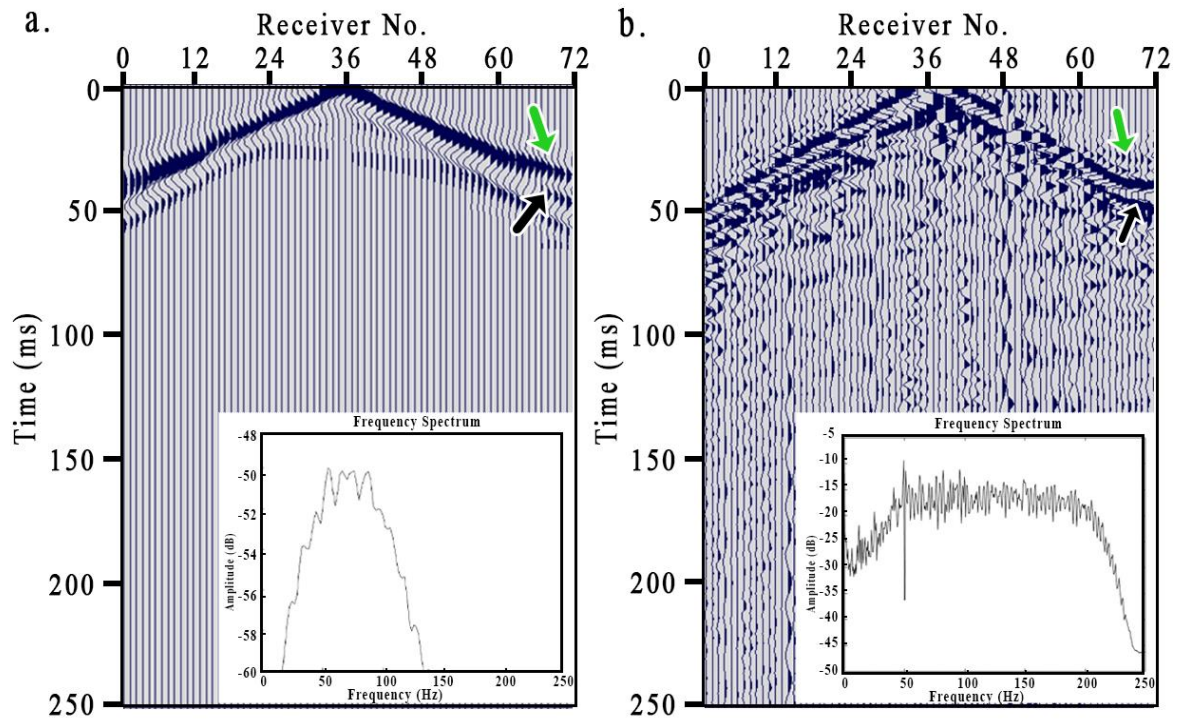


Figure 7.11: Comparison of shot24(a) Synthetic shotgather of the model from Tesseral and (b) a raw shotgather from SDT1 seismic line. The black lines show the first arrivals, and the green arrows show reflections.

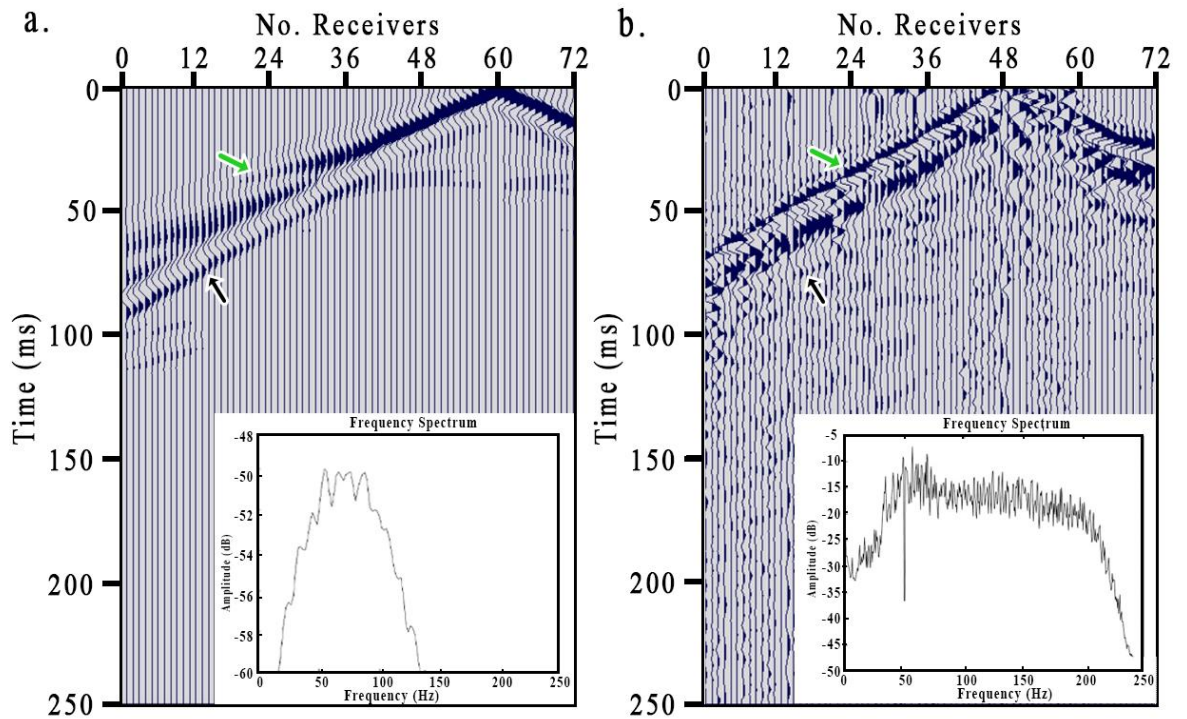


Figure 7.12: Comparison of shot30(a) Synthetic shotgather of the model from Tesseral and (b) a raw shotgather from SDT1. The black lines show the first arrivals, and the green arrows show reflections.

7.6. Structural interpretation from 2D reflection seismic data

To fully understand the quality of the data and enhance the structural interpretation, it is essential to determine the resolution limits of the seismic data with the survey design parameters. The resolution limits determine whether or not one can detect subtle geological features. Two standard theoretical criteria are often used to determine the vertical resolving power of P-wave reflection seismic data. These are Rayleigh's and Widess's criteria. The vertical resolution using Rayleigh's criterion is given by:

$$VR_R = \frac{\lambda}{4} \quad (7.1)$$

However, according to the Widess criterion, the vertical resolution limit for the data with a sufficiently high signal-to-noise ratio (S/N) is given by:

$$VR_w = \frac{\lambda}{32} \quad (7.2)$$

Based on the frequency analysis of our data, the dominant frequency (f) of 65 Hz and interval velocity (v) of 6000 m/s were observed, which provided a 92 m dominant wavelength. Therefore, for $\lambda/4$ (since the data exhibit low SNR) Widess's criterion, the achievable resolution limit is 23 m. However, smaller features can still be detected through advanced seismic attribute analysis, especially if the SNR of the data is high (Manzi et al., 2015; Nkosi et al., 2017). It is worth noting that the detection of a geological layer presupposes a sufficiently strong density and velocity contrast across the geological interfaces. The detectable limit is much higher than the resolvability limit and is defined as the minimum layer thickness required to produce an observable seismic reflection (Sheriff, 1991; Malehmir et al., 2012).

The final depth-converted seismic section was integrated with borehole information and mine mapping data to derive the final structural interpretation. Figures 7.12 and 7.13 show the 3D visualisation of the seismic profile below the tunnel. Since the individual reefs within the UER package could be imaged with confidence because the majority of them occur above the tunnel floor, the primary focus of interpretation

was to identify faults and dykes that crosscut the strata below and above the tunnel floor. The structures below the tunnel floor were well defined by the tunnel seismic data because most of the seismic energy reflected from structures the tunnel floor, while the continuity of the structures above the tunnel floor was confirmed and constrained by legacy 3D seismic data. It is also worth noting that the out-of-plane reflectivity caused by 2D seismic imaging was considered during the interpretation. The data were also not migrated to avoid artifacts related to migrating short profiles. However, the effects of interpreting un-migrated sections was also considered.

The depth converted stacked seismic section suggests that the area is characterized by several north–northeast and north–northwest-trending faults and dykes, particularly towards the south of the profile where major faulting is observed. In general, the majority of these faults and dykes are large enough to be visible on seismic sections as observed through the while arrows in [Figures 7.13 and 7.14](#). The cosine of phase attribute ([Figure 7.14](#)) exhibits a more detail structural architecture (shown by white arrows) that was not readily seen on the amplitude display in [Figure 7.13](#). This attribute shows subtle complex architectural character such as cross-cutting relationships, continuity, and connectivity.

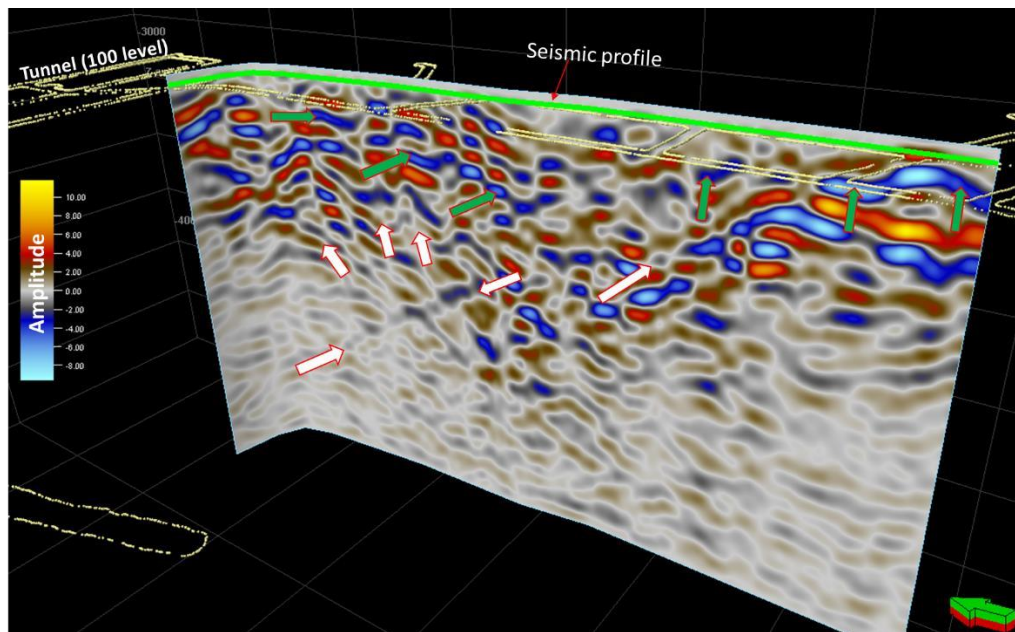


Figure 7.13: 3D visualization of the amplitude display showing the imaging of faults below the tunnel floor. Green arrows show a continuous reflection associated with the lithological boundary or fault. White arrows show the imaging of dykes and faults.

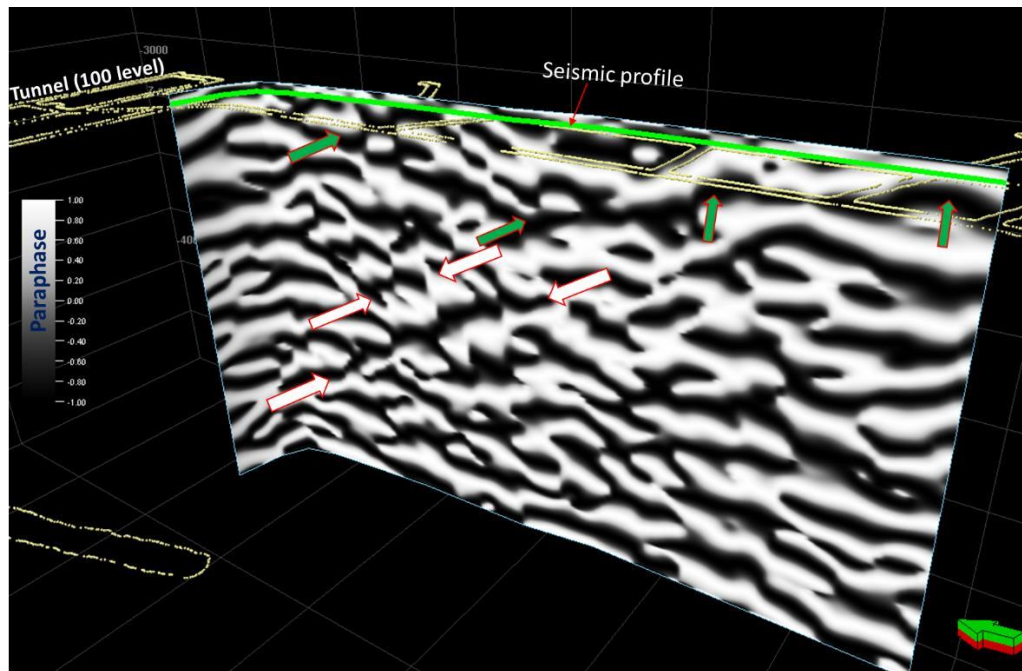


Figure 7.14: 3D visualization of the paraseismic display showing the imaging of faults below the tunnel floor. Green arrows show a continuous reflection associated with the lithological boundary or fault. White arrows show the imaging of dykes and faults.

To constrain the interpretation of the structures observed on seismic data, the mine mapped structures were integrated with the tunnel seismic interpretation into 3D space. The most dominant structure that was mapped by both seismic and mine data is the Moose Dyke. 2D seismics shows that the Moose Dyke is north-northeast trending (Figure 7.15). The Moose Dyke was first described and defined through drilling and underground mapping and its presence is confirmed by the tunnel seismic data. The seismic section shows that the Moose Dyke crosscuts and offsets the VCR orebody above the tunnel, meaning that the dyke is associated with faulting. Importantly, the geometric nature of this dyke suggests that it was active (intruded) after the deposition of the orebody. Most importantly, the cosine of phase attribute shows the continuity of the dyke below the known depth from mine mapping as indicated by the white arrow in Figure 7.15. The identification of this structure and associated faulting is critical for the mine as it may represent losses of mineable ground and potential safety hazards.

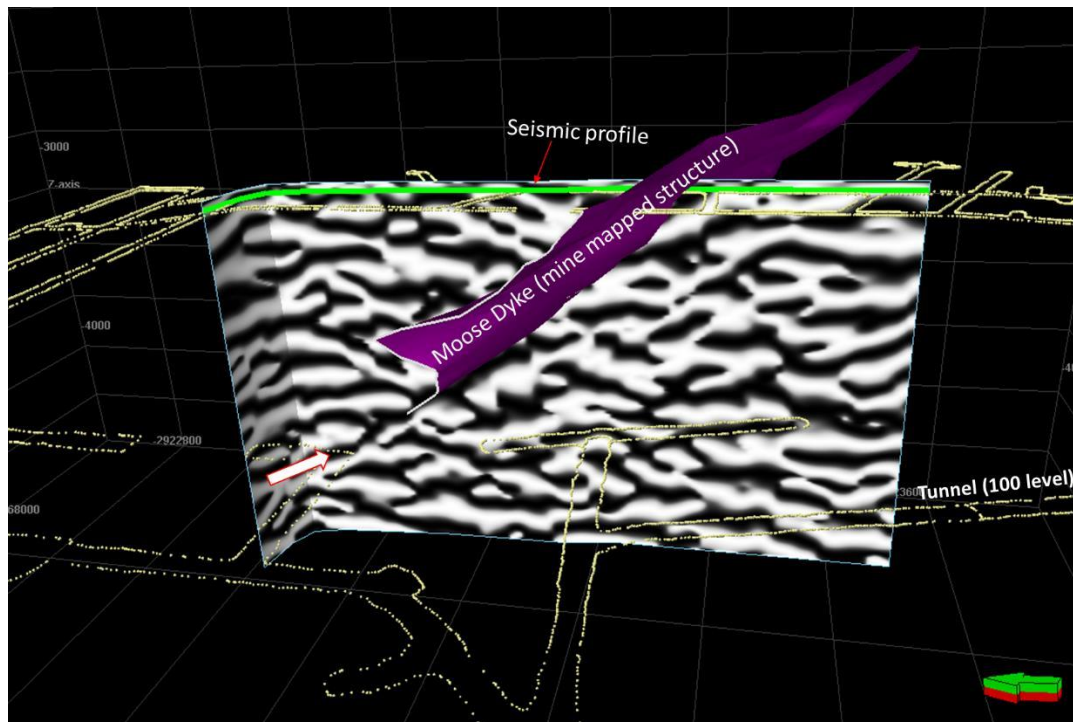


Figure 7.15: Mine structure (Moose Dyke) integrated with the seismic interpretation.

Figure 7.16 shows the integration of structures mapped by seismics and those defined by underground mapping. There were only two structures interpreted by the mine in this region (Figure 7.16a), while seismic data show the imaging of at least 5 major structures that are associated with other small ones (Figure 7.16b). Most importantly, paraphrase attribute has imaged the clustering of fractures around the major faults, which cannot be achieved through drilling. Overall, the seismic structural mapping and sampling density is estimated to be greater than the surface and underground borehole coverage. Thus, the risk of spatial aliasing of the structures, particularly subtle ones, is hugely minimized. This information may greatly increase the confidence towards cost estimation for the extracting of the ore resources, particularly with regard to quantifying geological loss factors (e.g., in the Moose Dyke zone and along the fault-crosscutting zones) (Figure 7.16).

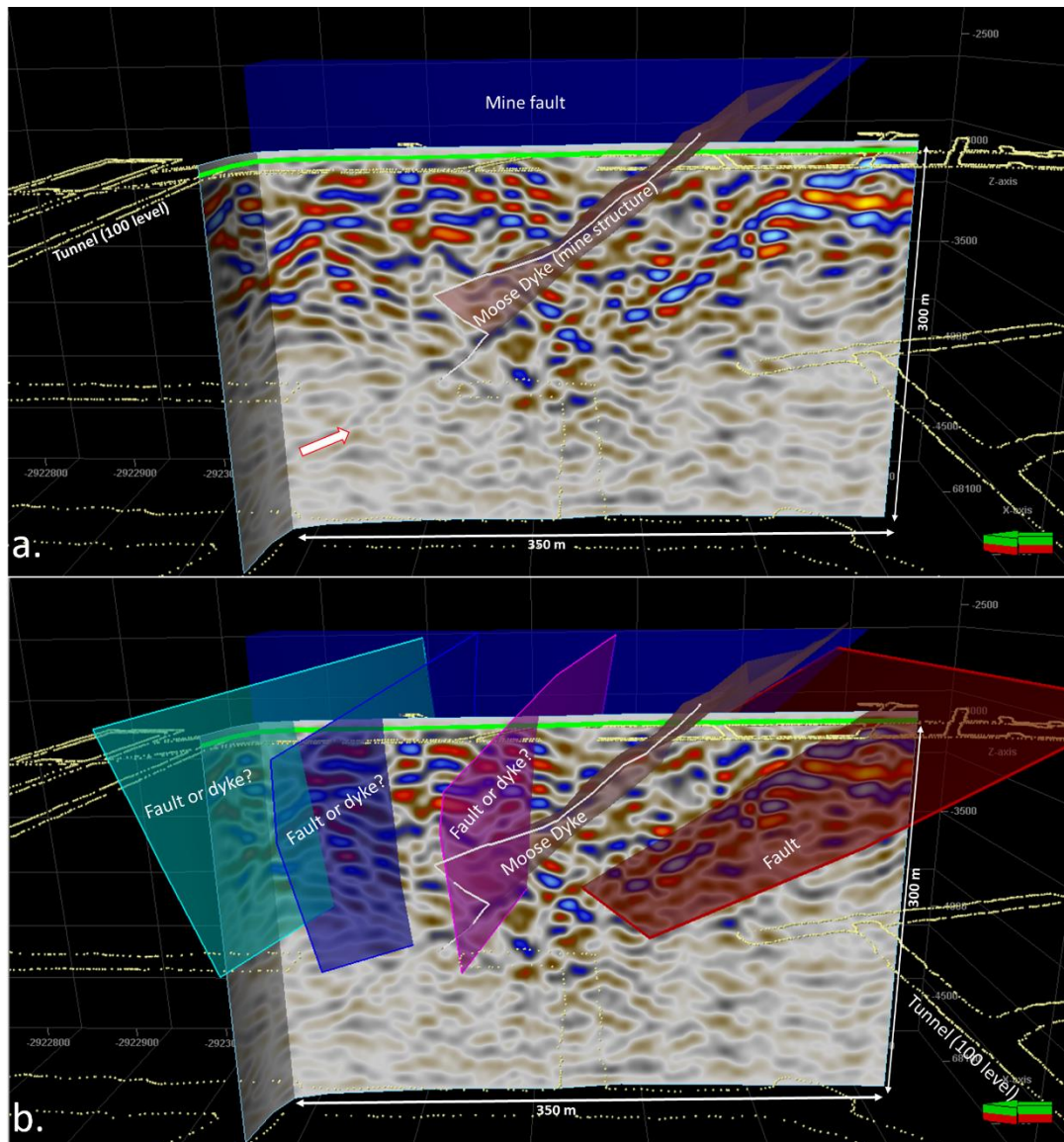


Figure 7.16: Structural interpretation of the tunnel seismic profile. (a) Mine mapped faults integrated with tunnel seismic profile. (b) Integration between seismic and mine mapped faults.

The integration of legacy 3D seismic data with the 2D tunnel seismic data further provided constraint on the interpretation of the structures (Figure 7.17). For example, it very clear that the Moose Dyke extends, crosscuts and displaces the VCR orebody above the tunnel as show in red arrows in Figure 7.17, which is not observed on the mine mapped data since the mine mapping was only focused on the structures below the VCR. The legacy seismic data also provide further evidence that the dyke is associated with faulting as observed on the inline and crossline of the 3D seismic data (Figure 7.17).

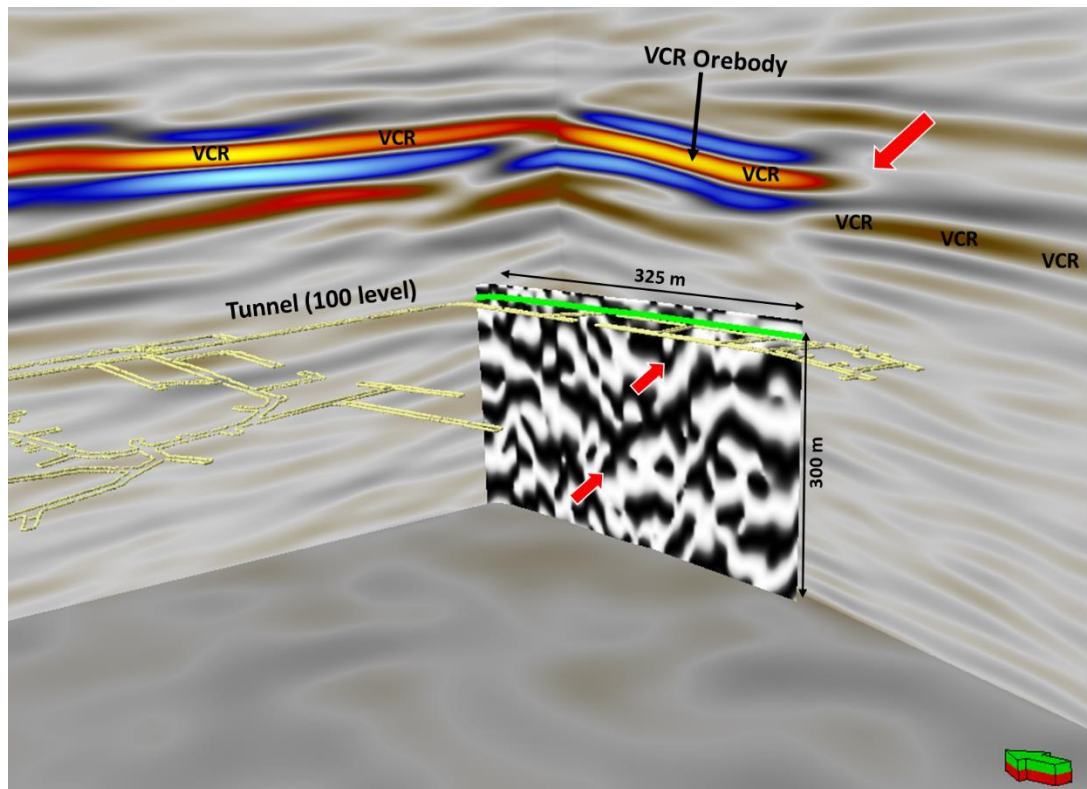


Figure 7.17: Structural interpretation of the tunnel seismic profile, showing the location of the Moose Dyke with respect to the orebody.

Finally, the final seismic structural interpretation (Figure 7.18) was integrated with the VCR orebody model as shown in Figure 7.19. The VCR orebody model, derived from the interpretation of the legacy seismic data, shows substantial variations in strike and dip throughout the seismic survey area. Based on the model, the interpretation of the data has revealed complex normal faulting in the vicinity of the mine. The new seismic interpretation shows some degree of structural complexity that would not have been identified using drilling (e.g., only two faults were mapped in the area through drilling and underground mapping). The structures are predominantly north–northeast and north–northwest trending faults with throws less than 25 m but greater than 5 m. The detection of the continuity of Moose Dyke and its depth position has been greatly improved by the seismic results. The imaging of additional faults to the two faults already identified by the mine, variations of their throws and dips, and the presence of the detected small numerous fractures are significant and should be factored into mine planning and development. The confidence in the structural model and mine plan can be

significantly improved as South Deep Gold Mine plans to extend their current mining to the south, and the new infrastructure to exploit the deeper orebody can be optimally designed in relatively structurally complex areas.

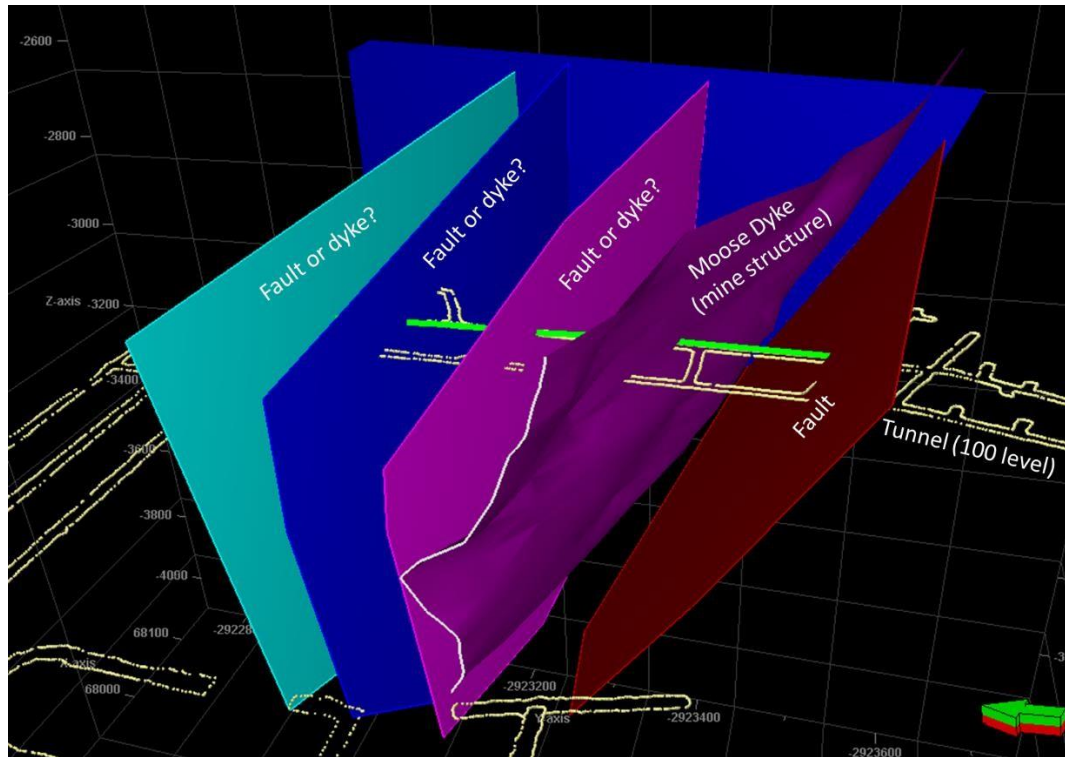


Figure 7.18: The structural framework of the region, showing a series of faults detected by seismics and derived from the borehole data.

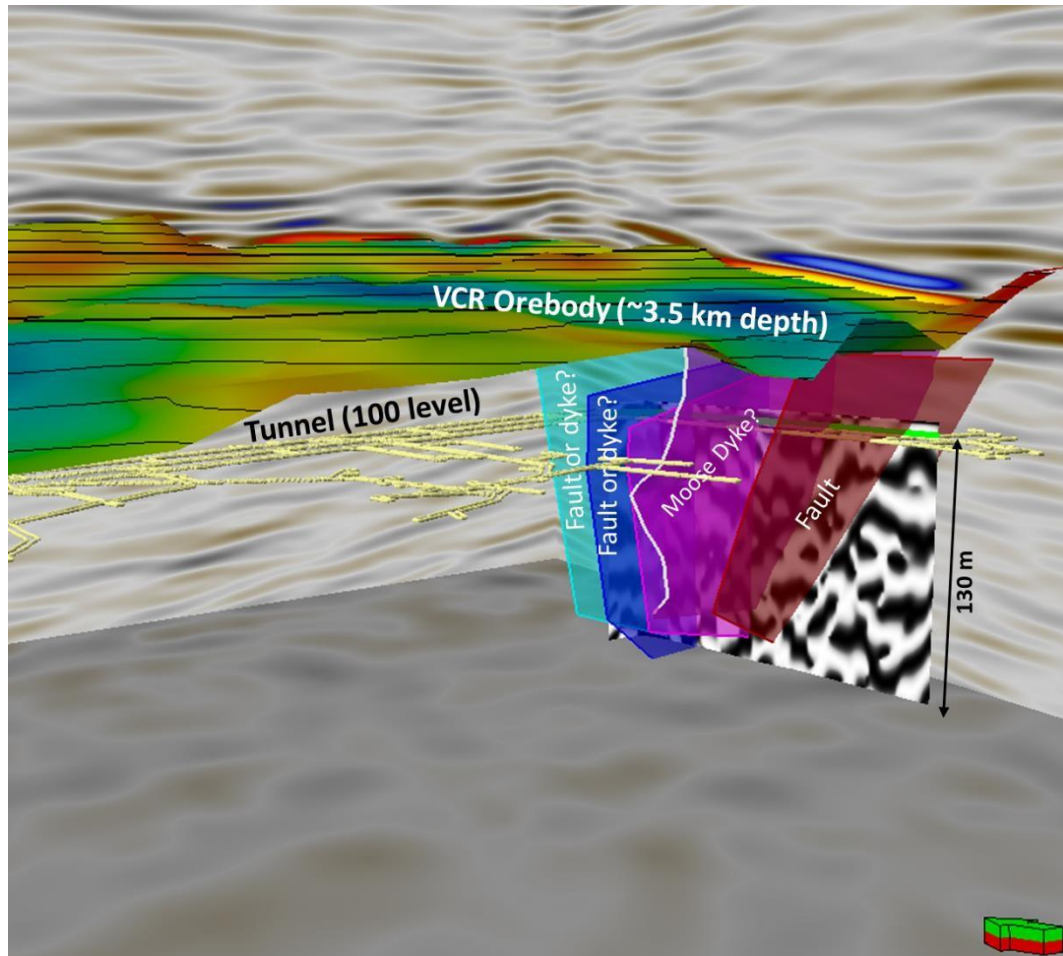


Figure 7.19: Integration seismic-defined structures and mine structures (VCR orebody and Moose Dyke).

8. CONCLUSIONS AND RECOMMENDATIONS

The main focus of this work was to measure the physical properties of rocks that constitute the Upper Elsburg Reef (EUR) package. The package includes 16 different endmembers, but the main objective was to understand the differences in the properties of each member. It is known that this package is seismically transparent due to the thickness of these layers and the types of rock within this package. During the study, four distinct types of rocks were observed, namely reef (conglomerate), quartzites, dyke, and lava.

Three different methods were tested to measure the bulk density and the preferred method was chosen based on previous literature and quality of data on previous studies. The methods used included sample dimensions, KT20 MagSus tool, and SNOWREX AHW-3 Professional Weighing Scale. Out of the three, the last method proved to be the most reliable and accurate. The intention was not to impose a specific density measurement method for all samples, but rather to provide guidance on what worked best for these types of samples with specific sizes and porosity levels.

During the experiments, we conducted laboratory seismic velocity measurements of P-wave and S-waves under atmospheric pressure and temperature. This method was chosen in order to preserve the rocks for further measurements. The Pundit instrument was used to measure both primary (V_p) and secondary wave velocities (V_s) of the samples. Interestingly, we found a considerable variation amongst quartzites from the same formation, which confirms previous research in the area that outlines the mineral composition of the rocks. While most of the rock types fall within the same range, some of them display significant differences, which could potentially make them seismically transparent. Further analysis of the mineralogy of the quartzites found in the Upper Elsburg Reef (UER) package through thin sectioning would be ideal. This would help us to understand how they differ and allow us to infer how that could account for the differences in seismic velocities as well as the density.

We utilized the synth-seis code to conduct simulations based on borehole data obtained from the mine. The purpose of this was to further corroborate our findings from velocity and density measurements. Our analysis of the seismograms revealed that the physical property contrast between the conglomerates and the quartzites was significant enough to cause a reflection in the seismograms when P-wave measurements and density were used. However, we also found that the density and S-wave measurements of the seismograms demonstrated a more pronounced contrast between the rocks, which allowed us to better discern them during a seismic survey. This suggests that testing a different type of source may yield even better results in distinguishing the different endmembers.

Numerical simulations were conducted in 2D to model the wavefield propagation and reflections that could be observed from the different layers of the UER package. The results from these simulations were compared to the synthetic seismogram results. Both models used the same physical properties, which further validates the synthetic measurements. These results suggest that the UER package may not be seismically transparent when seismic surveys are conducted in the mine tunnel, as the simulations assume that the receivers are in the vicinity of the orebody. Wave3D provides us with valuable information that can be exported as SEG-Y and compared to data obtained from the seismic survey. The 3D analysis conducted during the survey indicates that waves propagate in all directions and that reflections detected by the sensors on the tunnel floor originate from the hanging wall, sidewalls, and directly beneath the sensors. The ongoing 'FUTURE Project' will delve thoroughly into this and investigate how the different reflections differ and how they can best be identified.

The seismic line conducted in the tunnel (SDT1) did show the importance in-mine reflection seismic surveys because this allowed us to map geological structures at depths that would generally cost significantly large amounts of money given the logistical factors that would need to be deployed in order to image structures at that depth and resolution. The tunnel seismic surveys did prove to be noisy, given the activity in an operational mine, but processing algorithms did allow us to still get reflections and map structures from that dataset.

This study emphasizes the significance of merging older 3D seismic data with contemporary active data to verify and constrict interpretations of seismic velocity tomograms and stacked reflection sections within the study area. By blending 3D seismic data with traditional 2D seismic techniques, a more comprehensive and continuous representation of the subsurface was achieved. This, in turn, improves the accuracy of identifying structural and stratigraphic features. The integration of 3D seismic data is a significant step forward in subsurface analysis, as conventional 2D seismic methods often fall short in providing precise and detailed information. Ultimately, this validates the accuracy of the 2D tunnel seismic approach to mapping.

Due to the economic significance of the conglomerate-reefs found in the study area and their associated rocks, the number of samples that we could collect from the mine is limited. Additionally, the type of tests we could carry out with the available samples is restricted. Ideally, we would like to conduct destructive tests on these samples and simulate their behaviour at depths of less than 2.5 km. Measuring the seismic velocities of these rocks under pressure would help us assess the accuracy of the velocities obtained from the samples under uniaxial stress.

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