MANDELA MINING PRECINCT
MINDS FOR MINES

Guideline:

The Application of Ground Penetrating Radar (GPR) technology in South African Mining

science & innovation
Department: Science and Innovation
REPUBLIC OF SOUTH AFRICA

CSIR

MINERALS COUNCIL
SOUTH AFRICA

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About the Mandela Mining Precinct

The Mandela Mining Precinct is a Public-Private Partnership between the Department of Science and Innovation and the Minerals Council South Africa. The Precinct is jointly hosted by the Council for Scientific and Industrial Research and the Minerals Council. The Mandela Mining Precinct is an initiative aimed at revilatising mining research, development and Innovation in South Africa to ensure the sustainability of the industry. This is achieved through the South African Mining Extraction, Research, Development and Innovation (SAMERDI) strategy.

The strategy comprises six research programmes:

1. Longevity of Current Mining;
2. Mechanised Mining Systems;
3. Advanced Orebody Knowledge;
4. Real-Time Information Management Systems;
5. Successful Application of Technologies Centred Around People; and
6. Test Mine.

This guideline was developed under the Advance Orebody Knowledge (AOK) research programme. The programme is aimed to create the ultimate' 'Glass Rock'' environment which includes improving geological confidence ahead of the face, reduction or identification of risk associated with geology and to have timeous information, which will contribute to the optimal extraction and ''zero harm'' objectives.

ISBN: 978-0-7988-5670-2

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Executive Summary

The guideline document is intended to be used by mine personnel to understand the application of Ground Penetrating Radar in South African mines. The guideline informs the user on the basic principles of Ground Penetrating Radar, some previous application of Ground Penetrating Radar in the South African mines, how Ground Penetrating Radar surveys are conducted, how the data is processed, interpreted, and visualized. The guideline also presents case studies of the application of Ground Penetrating Radar in mines for specific problems. A case study where GPR had limited applicability is presented where the excavation is supported by wire mesh. The wire mesh attenuated the signal and resulted in the GPR output being difficult to interpret.

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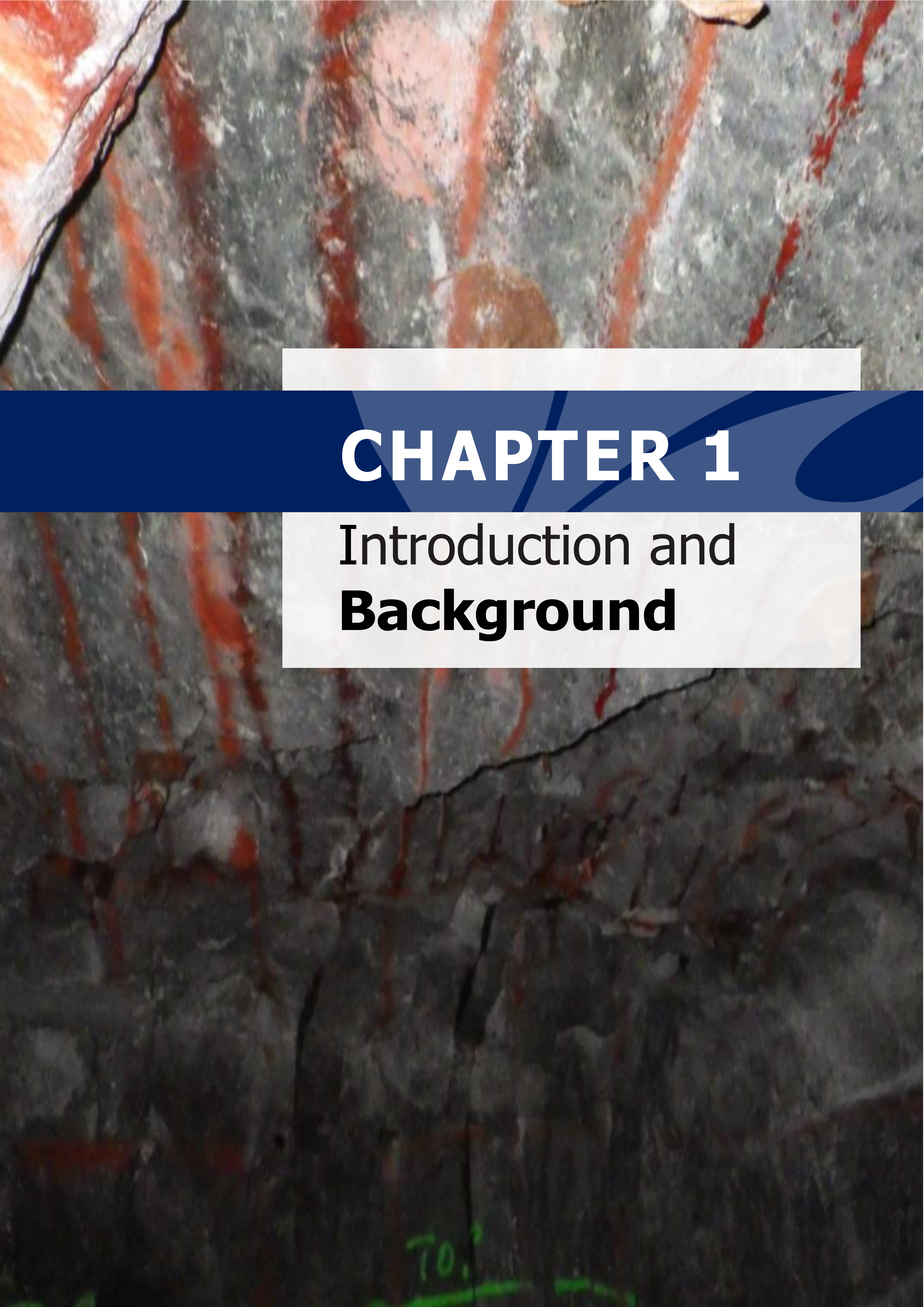
Definitions and Abbreviations

AOK	Advanced Orebody Knowledge
Band-pass filtering	The Band-Pass Filter is used to isolate or filter out certain frequencies that lie within a particular band or range of frequencies.
Background Removal	A filter used to remove the direct arrival that is caused by the signal leak from the antenna to the receive antenna.
CAD	Computer-aided design (CAD) software.
Data Editing	Data editing is aimed at arranging the data accordingly, cutting out noisy traces and corrections such as statics.
Dielectric Constant	Dielectric constant (ϵr) is defined as the ratio of the electric permeability of the material to the electric permeability of free space.
Electromagnetic Waves	Electromagnetic waves (EM waves) are waves that are created because of vibrations between an electric field and a magnetic field.
GPR	Ground Penetrating Radar
Isosurface	An isosurface is a three-dimensional analog of an isoline. It is a surface that represents points of a constant value within a volume of space
Preconditioning	Preconditioning is a method deployed in the underground mines with the aim to redistribute stresses within the rock mass during blasting.
Radar Pulse	Pulse radar emits short and powerful pulses and in the silent period receives the echo signals.
Time-varying gain	Time varied gain (TVG) is signal compensation that is applied by the receiver electronics through analog or digital signal processing. The desired result is that targets of the same size produce echoes of the same size, regardless of target range.



CHAPTER 1

Introduction and **Background**

This guideline document intends to provide mine personnel (non-Geophysicists) with the necessary basic principles of Ground Penetrating Radar (GPR), how to conduct GPR surveys and finally, how to process, interpret and visualize GPR survey results. The guideline includes the acquisition of 2-Dimensional (2-D) and 3-D surveys and visualizing the data in 3-D visualization or computer-aided design (CAD) software.

The document presents case studies on the use of GPR for identifying lithological units and the reef, fracturing within the hangingwall, and fracturing ahead of the mining face. The use of LIDAR to georeferenced GPR data and to combine the two datasets into a GPR-LIDAR 3-D model is also presented. The document ends by presenting an example where GPR has limited application due to the presence of wire mash along the skin of the excavation.

1.1 BASIC PRINCIPLES OF GPR

GPR is a non-destructive geophysical method which uses electromagnetic waves to image or map discontinuities and structures within the rock. A high-frequency radar pulse (e.g., 500 MHz) is generated by a transmit antenna and propagates through the rock until a change in the electromagnetic properties of the rock is encountered. This change in the electromagnetic properties can be due to, for example, a fracture, joint, or a target horizon within the rock. This results in some of the energy being transmitted while some are reflected and recorded by the receive antenna. A schematic representation of a GPR concept is shown in Figure 1. This type of GPR surveying mode is known as common-offset reflection profiling (Annan & Cosway, 1992).

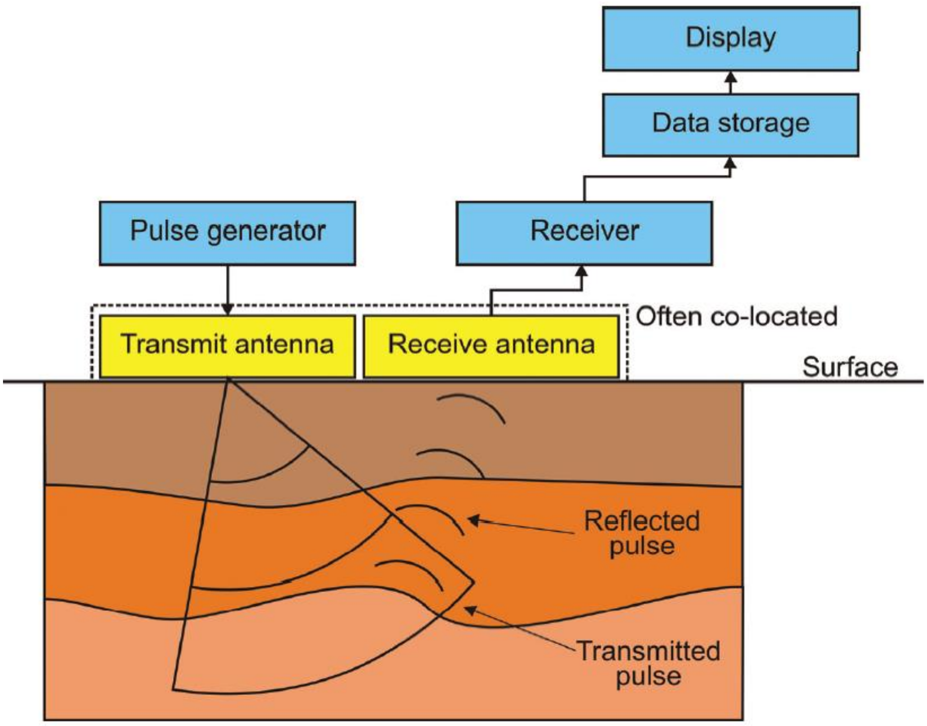


Figure 1. Schematic representation of the GPR concept (Vogt, et al., 2005).

The radar pulse recorded by the receive antenna is a recording of the signal amplitude (measured in millivolts) as a function of the signal travel time and it is called a radar trace (Figure 2).

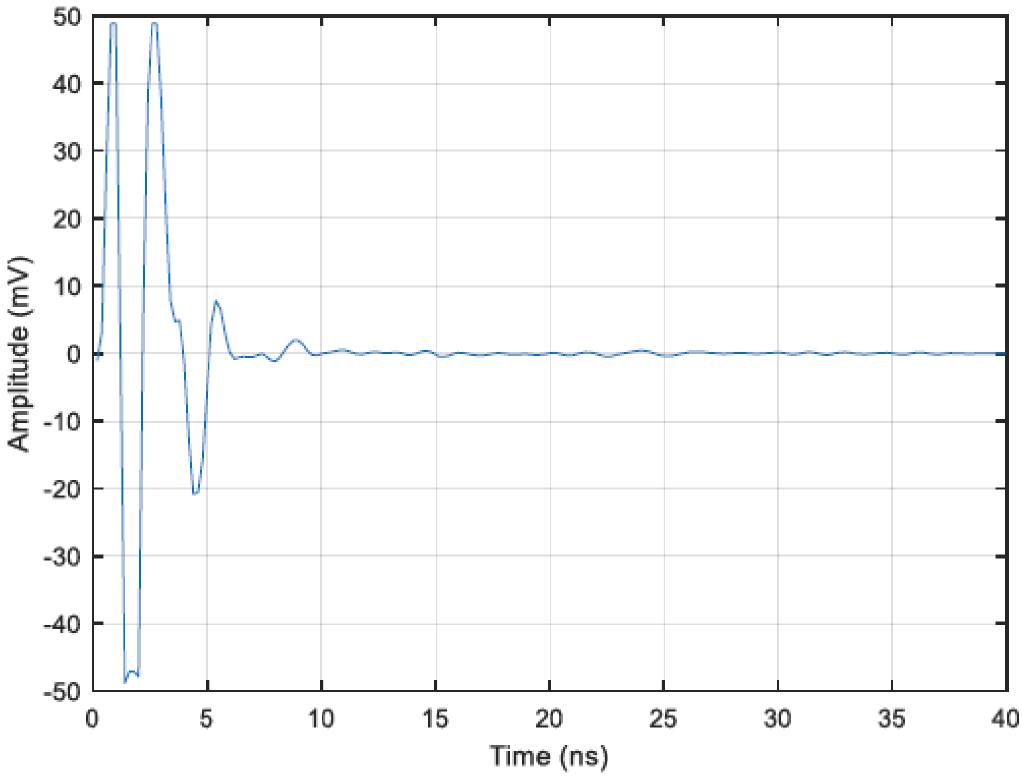


Figure 2: Radar trace

The propagation characteristics of GPR are mainly controlled by the rock conductivity and the dielectric constant (Annan, 2009). Conductivity controls the depth of penetration while the dielectric constant (permittivity) controls the propagation velocity of the radar waves (Vogt, et al., 2005). The propagation velocity of radar waves is given by:

$$v = {}^{c}/_{\sqrt{\varepsilon}} \qquad [1]$$

Where c is the speed of light (≈ 3x108 m/s) and ε is the relative permittivity of the rock. For a given radar frequency, f, the wavelength of the radar waves can be calculated by the following equation.

$$\lambda = {}^{c}/_{f\sqrt{\varepsilon}} \qquad [2]$$

The amount of the signal that is reflected at a boundary is determined by the permittivities of the two mediums (e.g., two rock types).

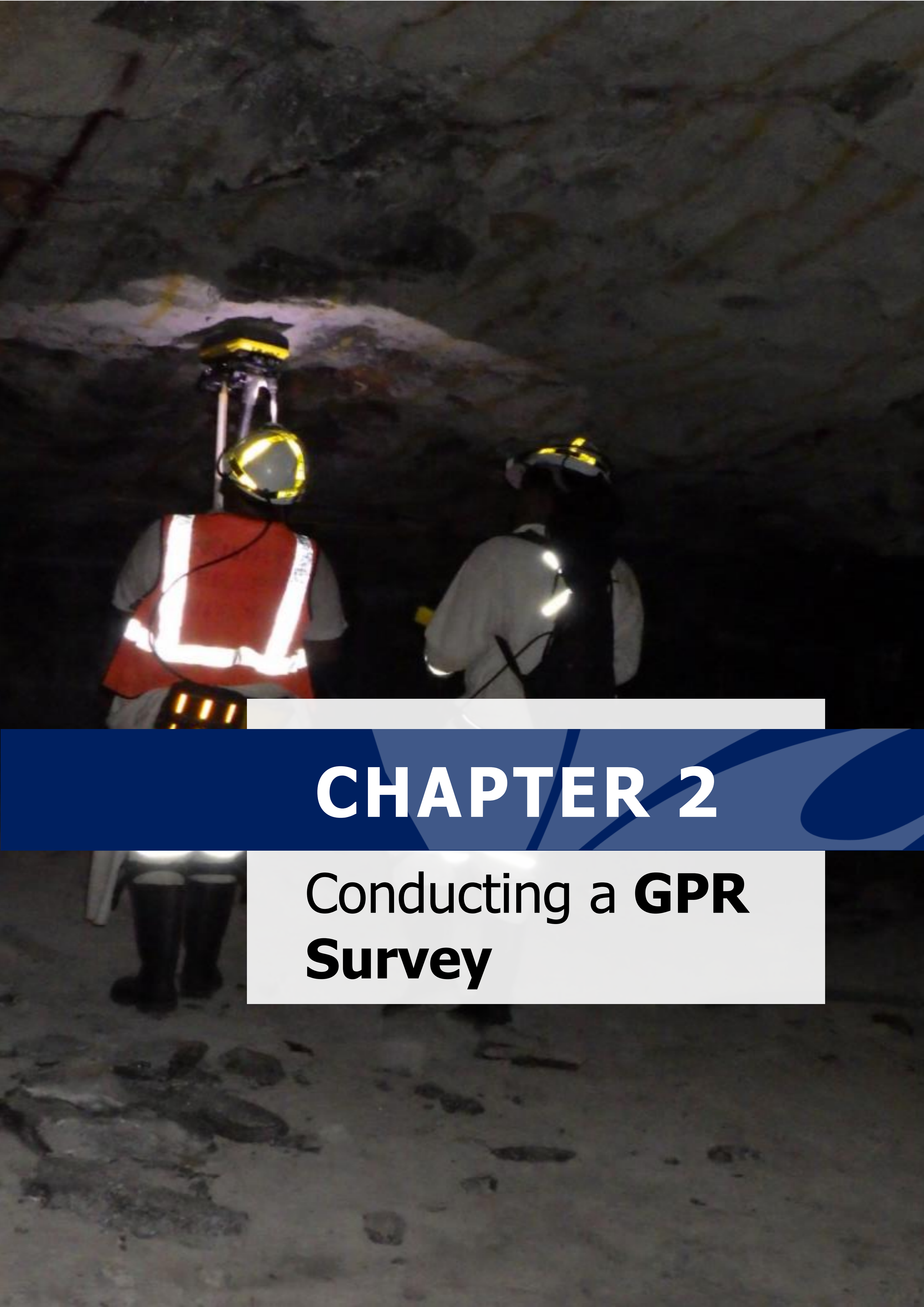
1.2 PREVIOUS APPLICATIONS OF GPR IN SOUTH-AFRICAN MINES

GPR has previously found different applications in the South African mining industry. Some of these applications include the following;

- Mapping of discontinuities (such as faults, joints, fractures etc.),
- Ore body delineation,
- Delineation of hangingwall discontinuities (such as pothole and domes), and fracture characterization ahead of the mining face.

White , et al., (1999) presented case studies where GPR was used in delineating, for example, the Ventersdorp Contact Reef in a deep-level gold mine, delineation of a fault structure ahead of the mining face in a deep-level gold mine and the delineation of pothole structures in a platinum mine. Further studies of the delineation of pothole structures in a platinum mine, the delineation of hangingwall bedding plane separation in a platinum mine and the delineation of domes in a platinum mine were discussed by White, el al., (1999).

Vogt, et al., (2005) presented results where GPR was used to map the triplets with the hangingwall of a platinum mine and used to also map the intersection of the curved joints with the Leader seam within the hangingwall of a platinum mine. Another application of GPR in mapping the hangingwall structures was discussed by Kgarume, et al., (2019) where the contact and thickness of the chromitite package and a shear zone in two platinum mines were determined. Grodner (2001) used GPR to quantify changes in fracture patterns due to preconditioning ahead of a mining face in a deep-level Witwatersrand Basin gold mine. GPR was able to determine the depth of the fracturing ahead of the mining face.



CHAPTER 2

Conducting a **GPR Survey**

A GPR survey is carried out by moving the GPR system along a survey line traversing the section of interest of the rockmass (Figure 3). As the system moves along the survey line, many radar traces are recorded at regular intervals to construct a 2-D cross-section of the rockmass.

Figure 3. GPR surveying

The 2-D GPR cross-section is known as a radargram. Figure 4 shows an example of a greyscale radargram collected using a 500 MHz GPR antenna. The x-axis represents the distance along the survey line while the y-axis represents the travel time of the radar signal. Using the travel time and an assumed radar propagation velocity, the depth of penetration of the radar signal can be determined.

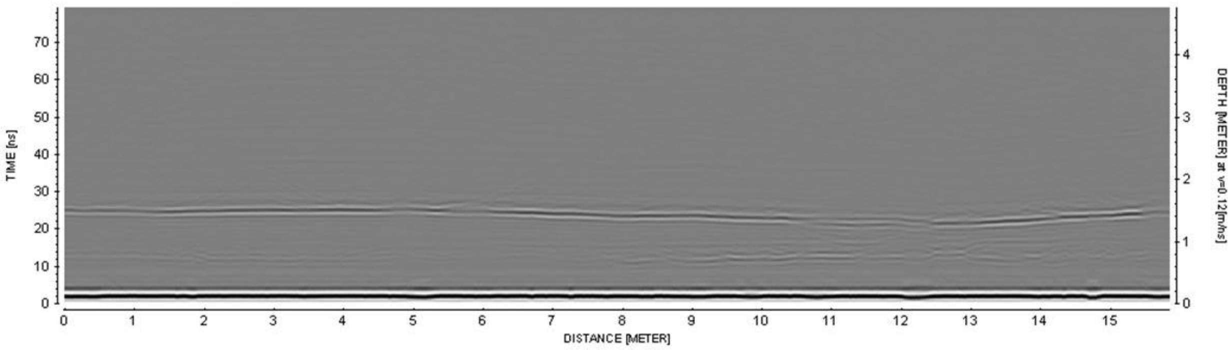


Figure 4. GPR radargram

A 3-D GPR survey is carried out by collecting several 2-D profiles using closely spaced parallel survey lines separated by some distance ΔY (like those shown in Figure 5 (a). The 2-D profiles are then processed and arranged geometrically as they were physically acquired. The adjacent 2-D profiles are then interpolated to generate a 3-D volume of the data (Figure 5 (b)). This results in a GPR model of the data volume in terms of space (x, y, z) and reflection amplitudes (A(x, y, z)). This allows for the visualization of the data in 3-D space where data can be rotated and viewed from different angles and perspectives.

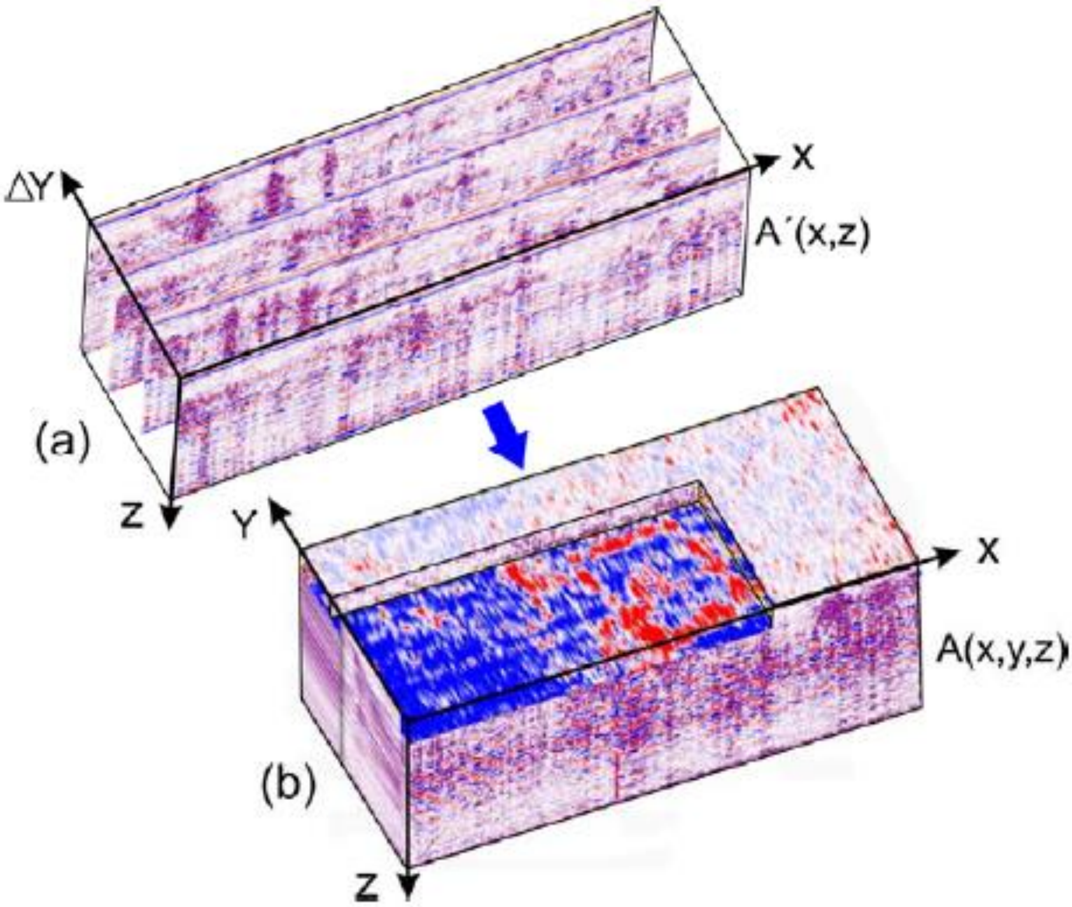
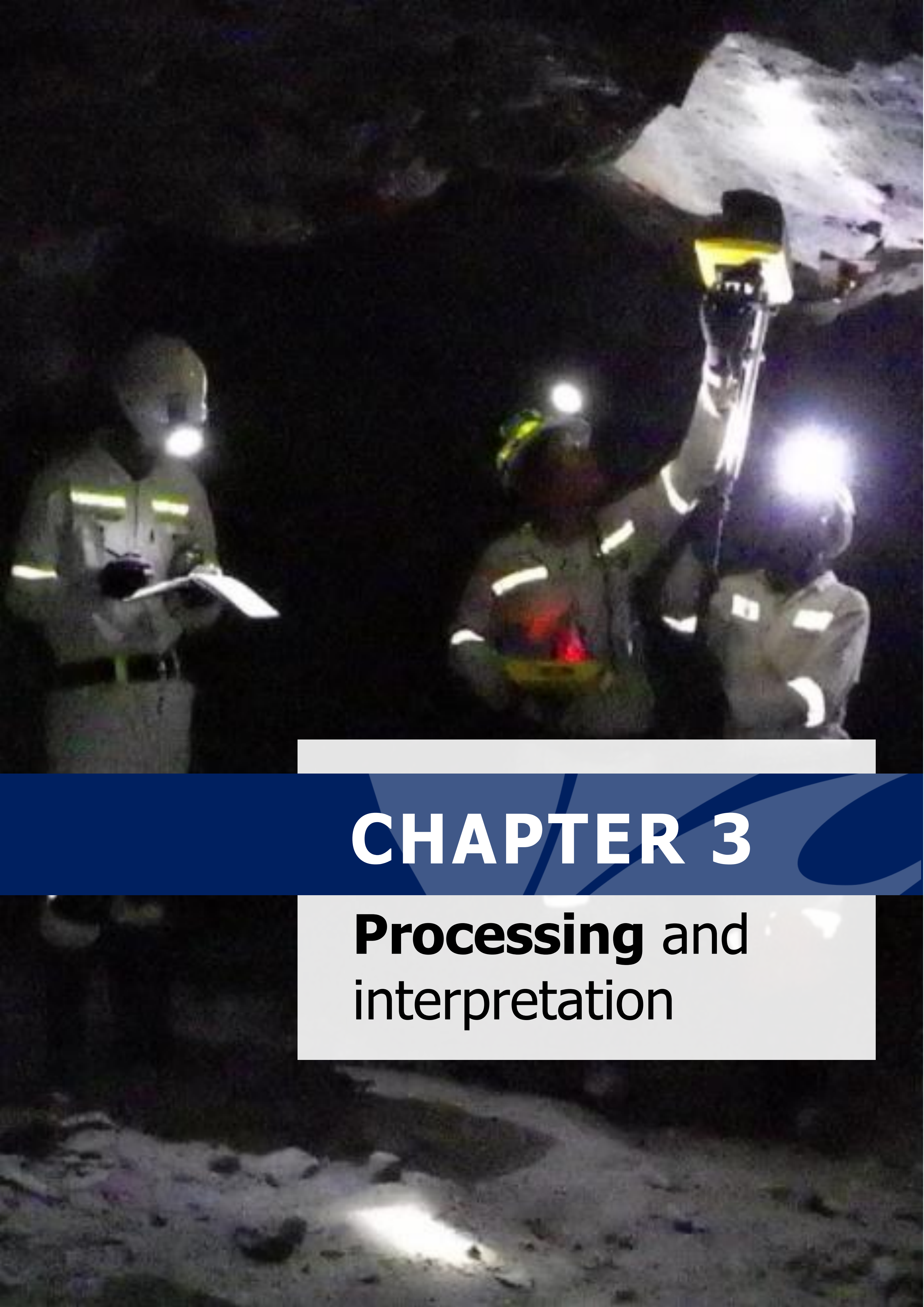


Figure 5. Individual 2-D GPR profiles collected using regularly spaced parallel survey lines. (b) Individual 2-D profiles interpolated to generate a 3-D GPR volume (Pena & Teixido, 2013).



CHAPTER 3

Processing and interpretation

3.1 PROCESSING OF GPR DATA

The processing of data is aimed at extracting reflected signal information from the raw data. The following sub-sections discuss the basic processing steps.

Data editing

Data editing is aimed at arranging the data accordingly, cutting out noisy traces and corrections such as statics. Data editing also include conversion from time to depth using appropriate velocities. Figure 6 (top) shows raw data with no processing applied and with start-time corrected to zero in Figure 6 (bottom).

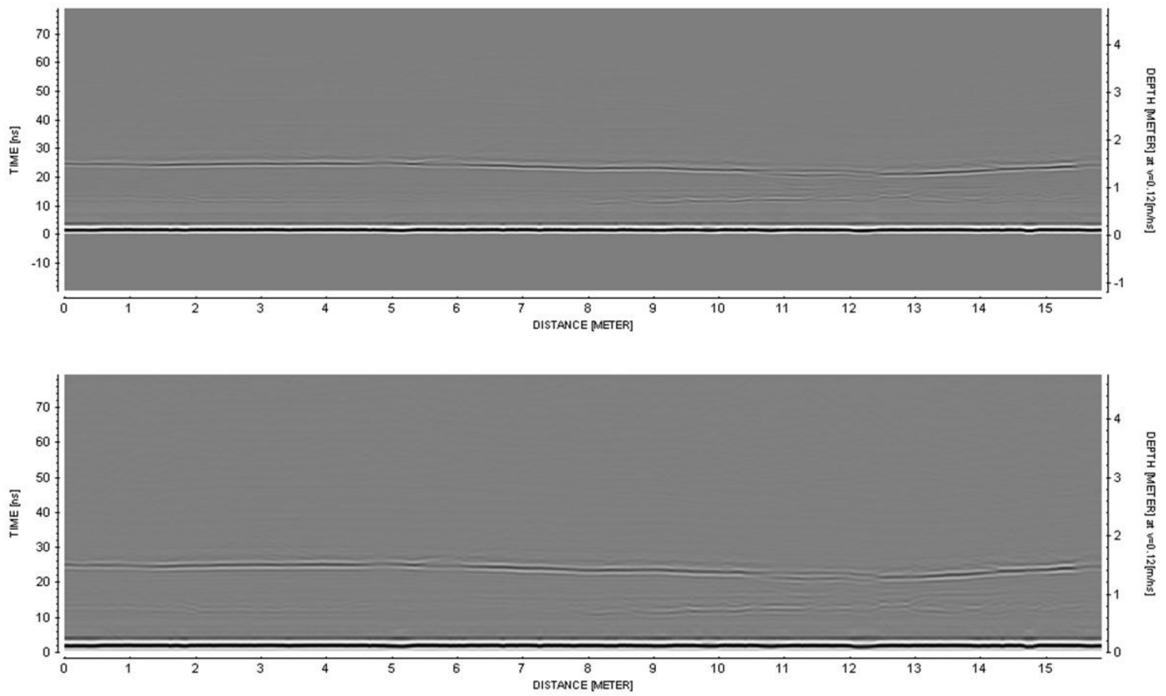


Figure 6: Raw data with no processing (top) and data with start-time corrected (bottom).

This type of correction is done because some systems acquire data before the pulse is sent into the ground. The zero of the radargram is corrected to coincide with position zero on the surface.

Band-pass filtering

The band-pass filter is used to cut out frequencies outside the antenna frequency band since they are not physical. A band-pass filter is designed by choosing four corner frequencies in the bandwidth of the antenna. For a 500 MHz antenna, the typical corner frequencies are 150, 250, 750 and 900MHz (Van Schoor, 2004). Figure 7 shows the above data set band-pass filtered with the above frequencies.

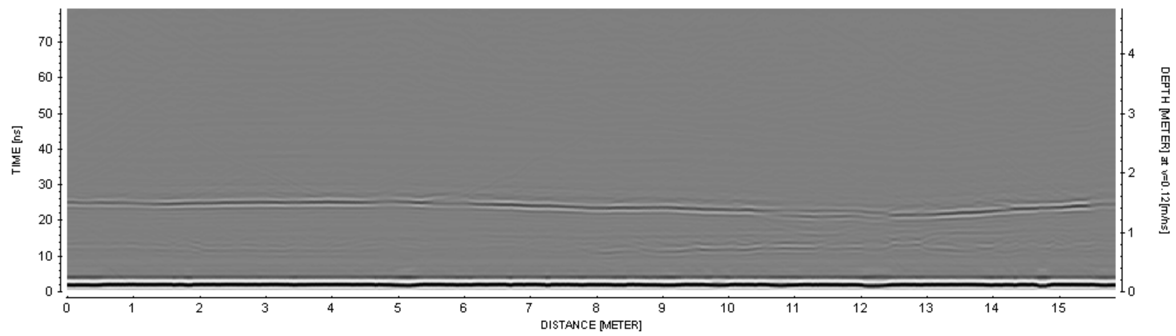


Figure 7. Above radargram band-pass filtered.

Time-varying gain

Gain is applied to bring out reflectors that occur later in time and week because of the signal attenuation. The earth has the following effects on a propagating wave; the energy of the wave decays proportionally as with r being the radius of the waveform and the frequency content changes in a time varying manner as the wave propagates in the medium (Yilmaz, 1987). The filter increases the gain of the signal with time (Figure 8).

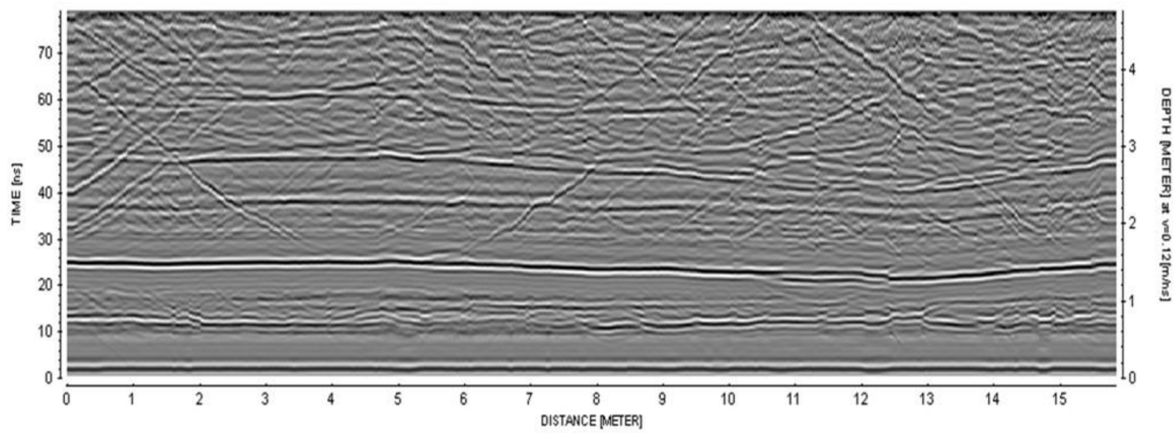


Figure 8. Signal gain applied to data.

Background removal

This filter can be used to remove the direct arrival that is caused by the signal leak from the transmit antenna to the receive antenna directly (Figure 9). This signal generally appears at zero time on the radargram (see the direct arrival in Figure 8 above).

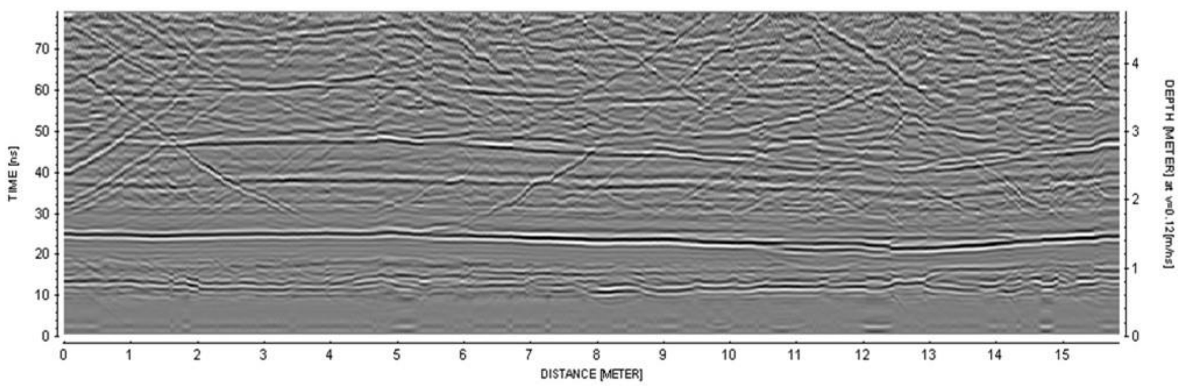


Figure 9. Background removal applied to remove the direct arrival.

3.2 INTERPRETATION OF GPR DATA

Interpretation of a GPR radargram is aimed at inspecting the radargram for reflections that could be caused by geological features of interest such as faults, joints, fractures etc. (Figure 10).

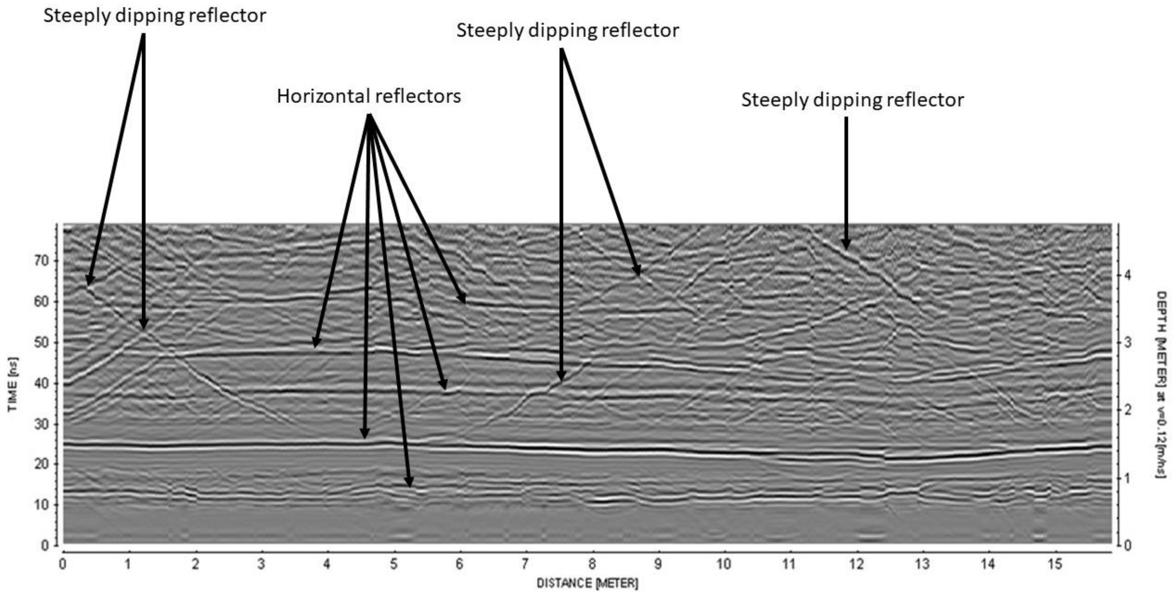


Figure 10. Interpreted radargram.

In the above radargram, the steeply dipping reflectors can be interpreted as steeply dipping fractures within the hangingwall.

3.3 VISUALIZATION OF GPR DATA

GPR data can be visualized in any of the GPR processing software which are mostly provided by the manufacturers of the GPR systems. Through the work conducted under the Advanced Orebody Knowledge (AOK) programme of the South African Mining Extraction Research, Development and Innovation (SAMERDI) strategy, ways of georeferencing and visualizing GPR data in 3-D visualization or the mine CAD software were explored. Using georeferenced underground LIDAR data, GPR survey data can thus be georeferenced based on the absolute mine coordinates of the acquired point cloud data. The condition to achieve the georeferencing is that the LIDAR data should be acquired at the same site where the GPR surveying is done. Figure 11 shows a flow diagram of how the GPR data can be georeferenced based on the LIDAR data. This makes it possible to visualize GPR data relative to the mine plan.

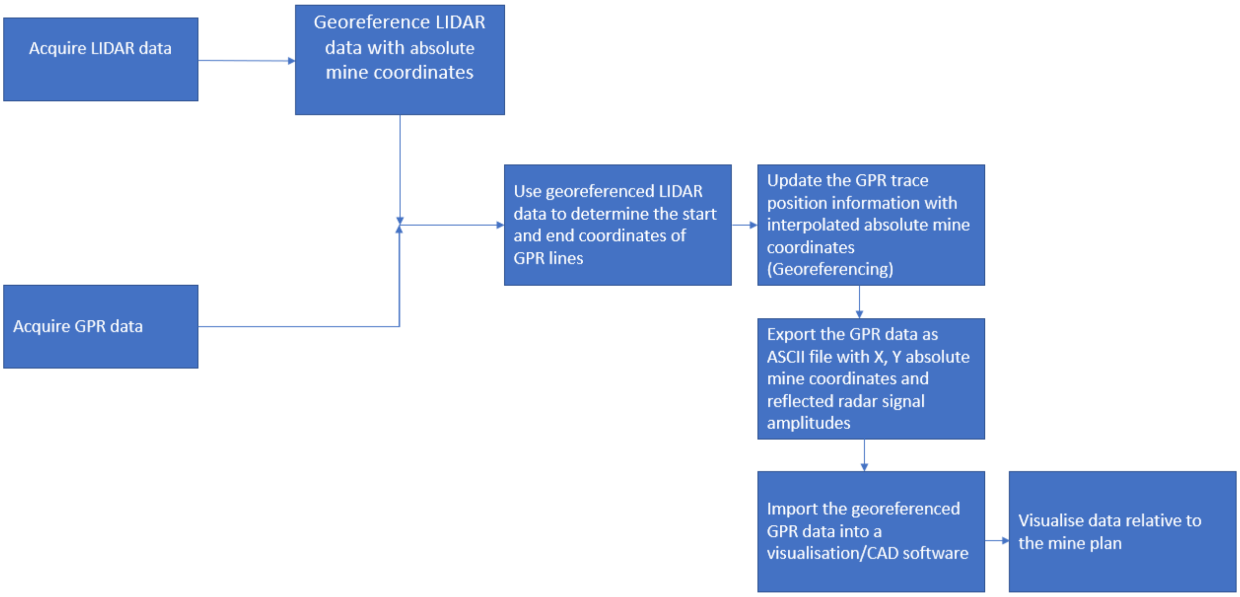


Figure 11. Georeferencing of GPR data using LIDAR data

Figure 12 shows some georeferenced GPR data of the hangingwall in a 3-D visualization software and selected GPR data visualized relative to the mine plan where the survey was conducted. The data can be rotated to be viewed from different perspectives, zoomed-in or zoomed-out for a better understanding of the data relative to the mine plan.

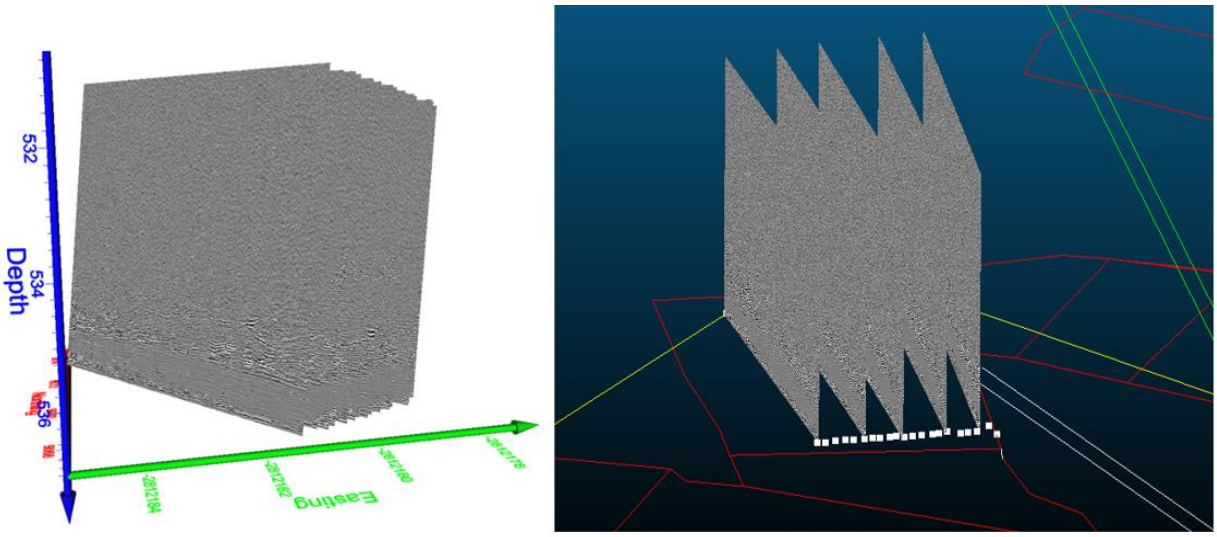
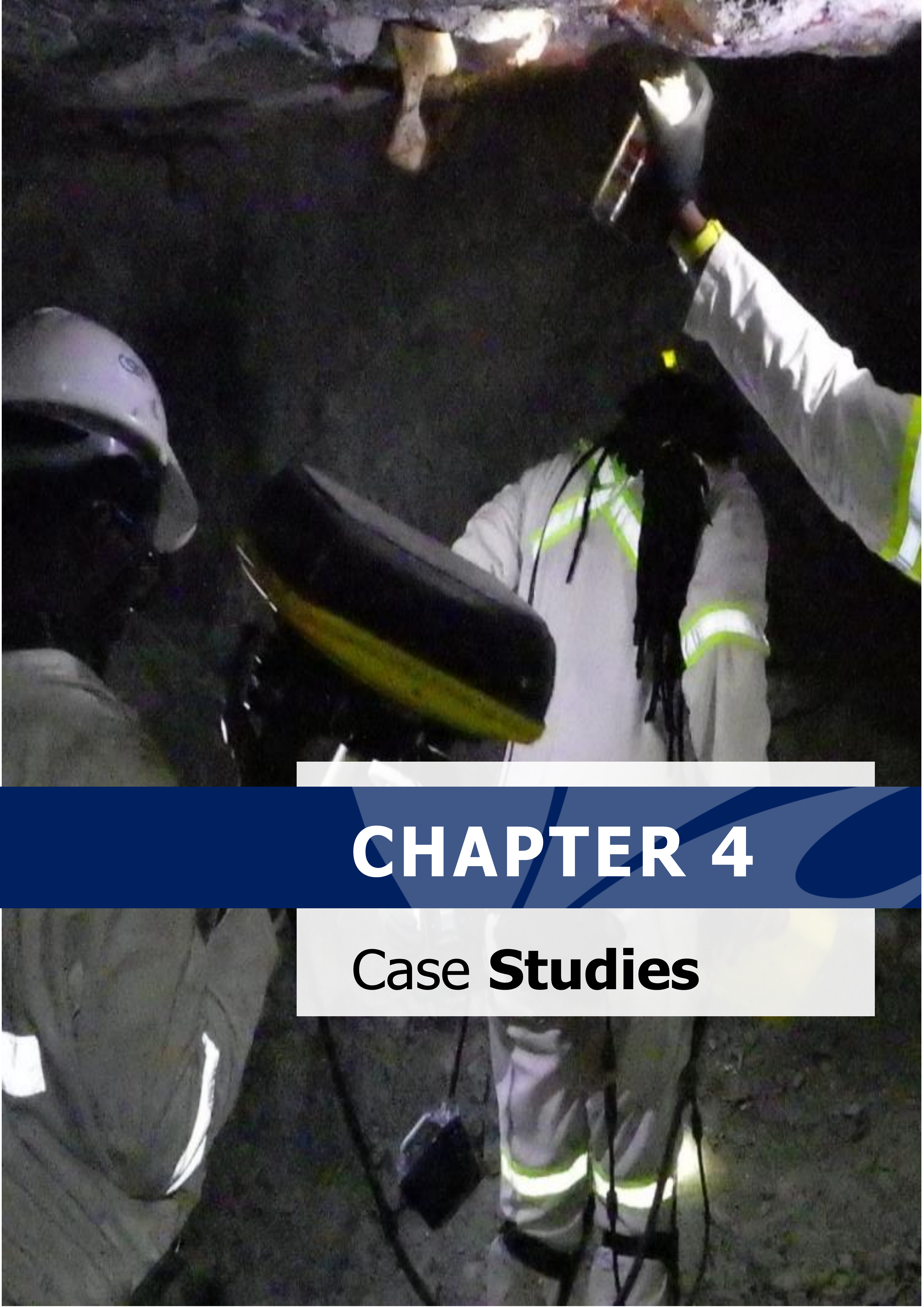


Figure 12. Georeferencing of GPR data using LIDAR data(left) and GPR data visualized relative to the mine plan(right).



CHAPTER 4

Case **Studies**

The following sections discuss some case studies of the application of GPR in mines.

4.1 IDENTIFICATION OF LITHOLOGICAL UNITS

A GPR survey was conducted in a gold mine raise line developed along the reef horizon to access a fresh block of ground for future mining. The reef being mined is the Basal reef with the reef at the site being characterized by the presence of the Basal Quartzite, the Lower Khaki Shale, and the Leader Quartzite. The distance to the contact between the Basal Quartzite and the Lower Khaki Shale needs to be known for a better understanding of the stability of the excavation. A 500 MHz antenna was used to acquire the data to determine the distance to the Basal Quartzite-Lower Khaki Shale contact (Figure 13).

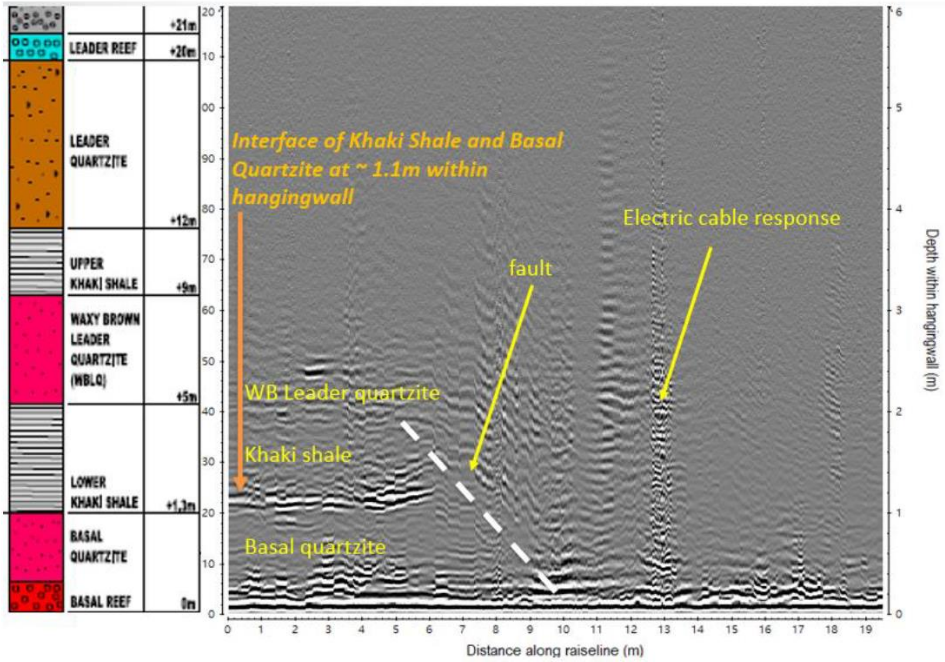


Figure 13. Using GPR to determine the distance to the Basal Quartzite-Lower Khaki Shale contact.

The Basal Quartzite-Lower Khaki Shale contact was imaged at 1.1 m within the hangingwall.

4.2 IDENTIFICATION OF THE REEF

A GPR survey was conducted at a platinum mine to identify and track the Merensky reef along the footwall of a decline. The decline is developed within the stratigraphic units above the Merensky, through the Merensky reef and ends in the stratigraphic units below the Merensky reef. A 250 MHz antenna was used to acquire the data from the Merensky hangingwall to the Merensky footwall.

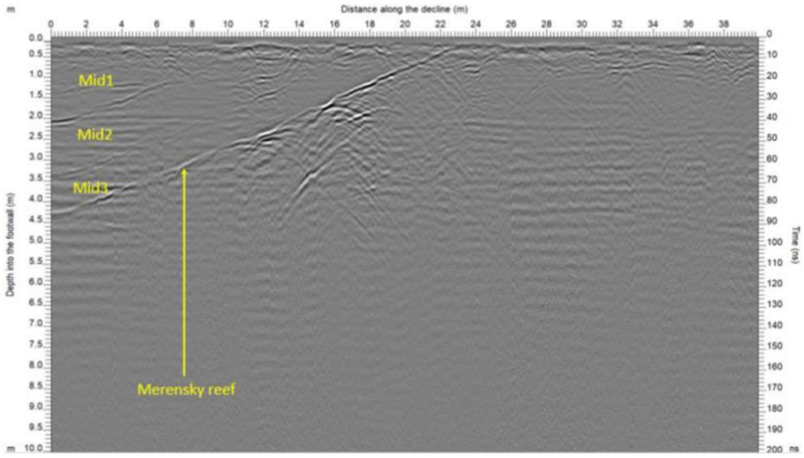


Figure 14. Using GPR to identify and track the Merensky reef.

The Merensky reef was identified and tracked from the beginning of the survey line until at about 24 m along the decline where the survey line crossed from the hangingwall into footwall of the Merensky reef (Figure 14).

4.3 IDENTIFICATION OF FRACTURING WITHIN THE HANGINGWALL

A GPR survey was conducted at a platinum mine to image the fracturing with the hangingwall. A 250 MHz antenna was used to acquire the data. Figure 15 shows the dipping fracture sets that were identified along with a shallow dipping fracture within 1 m of the hangingwall that intersects a horizontal structure at about 1 m within the hangingwall.

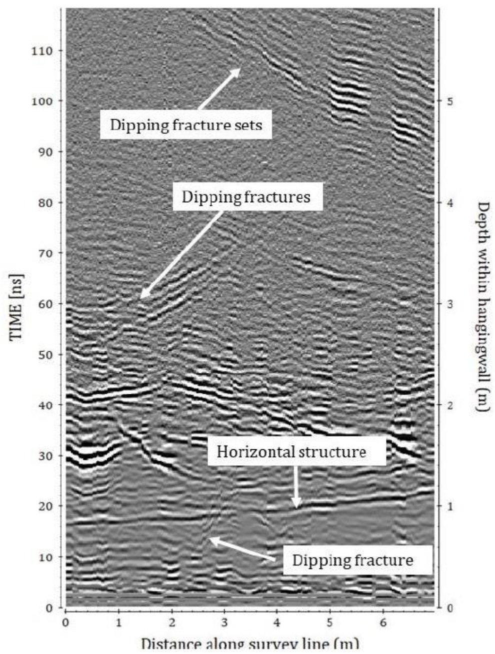


Figure 15. Using GPR to identify fracturing with the hangingwall

The interaction of dipping fractures and horizontal structures can compromise the integrity of the hangingwall by creating potentially unstable key blocks within the hangingwall.

4.4 IDENTIFICATION OF FRACTURING AHEAD OF THE MINING FACE

A mining face was scanned with a 250 MHz antenna with survey lines oriented horizontally along the mining face at 1.0 m and 1.5 m parallel to the footwall. Face parallel fractures were identified and the depth of the fracturing ahead of the mining face was determined. The depth of fracturing was shown by difference in the radargram texture (dashed yellow lines in Figure 16).

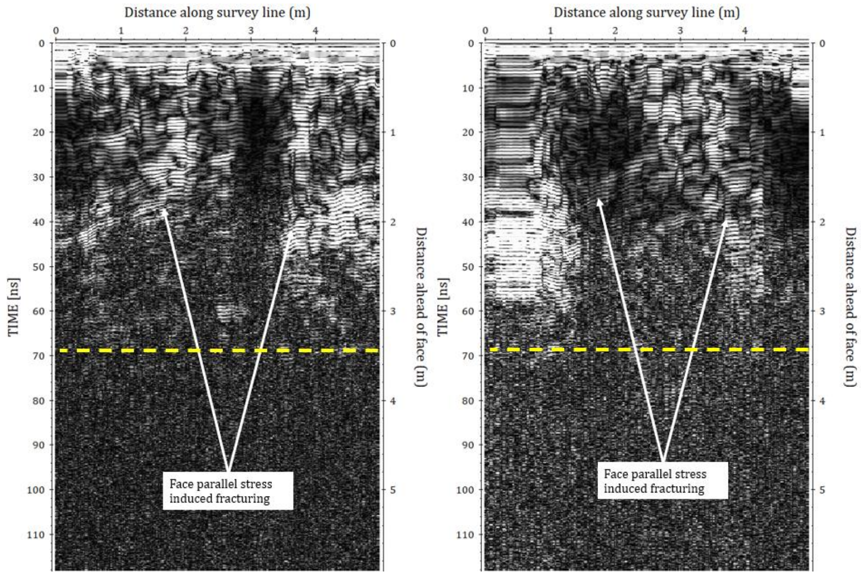


Figure 16: Using GPR to identify fracturing ahead of the mining face.

The face parallel stress induced fracturing extended to about 3.5 m ahead of the mining face.

4.5 MAPPING OF THE CHROMITITE PACKAGE

A 3-D GPR survey was conducted at a conventional platinum mine to image the top and bottom contact of the chromitite package within the immediate hangingwall and any dipping fractures that might interact with the package. A 500MHz antenna was used following closely spaced parallel lines (0.1 m in Block 1 and 0.2 m in Bock 2). Figure 17 shows a schematic of the layout used at the panel.

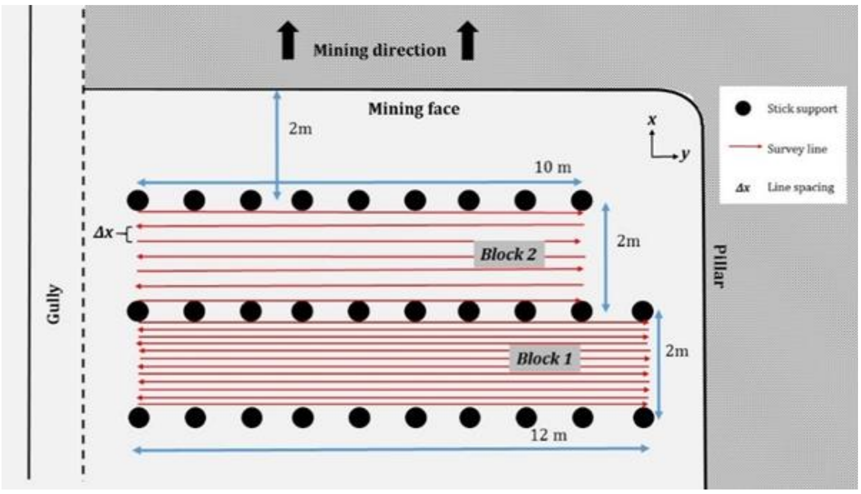


Figure 17: GPR survey layout of the hangingwall at a platinum mine panel.

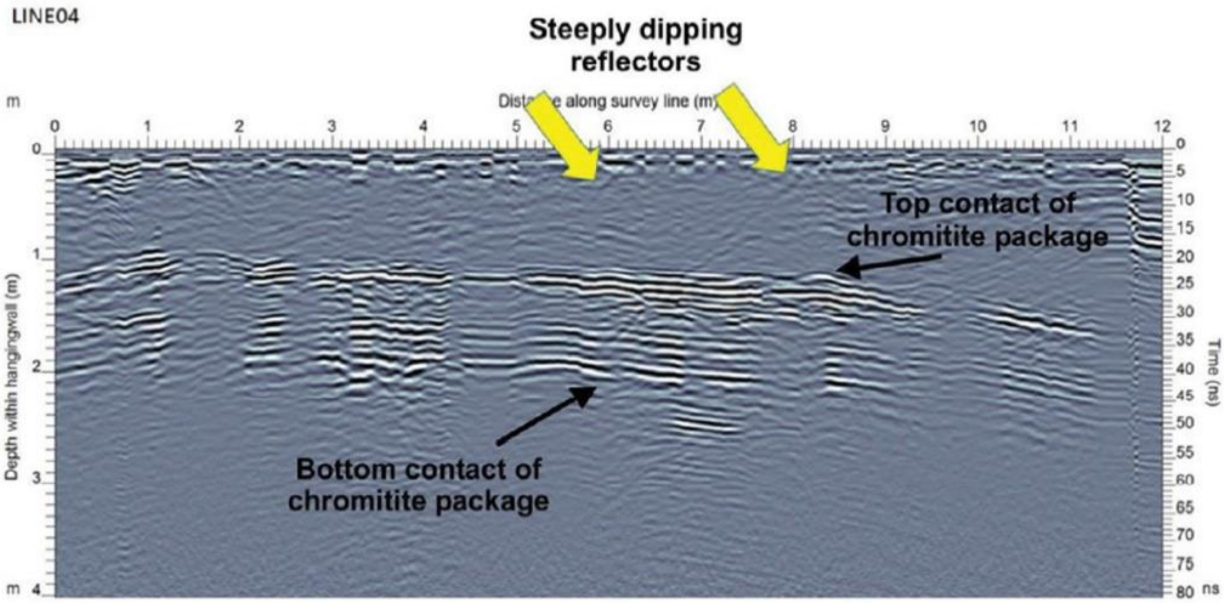


Figure 18. Radargram with chromitite package and steeply dipping fractures (Kgarume, et al., 2019).

Figure 18 shows one of the radargrams from the acquired data. Two prominent reflectors were identified and interpreted as the top and bottom contacts of the chromitite package. Two steeply dipping fractures can be identified at 6 m and 8 m along the survey line. It is the interaction of the chromitite package and the steeply dipping fractures that could result in the formation of potential loose blocks of rock within the hangingwall thus compromising the stability of the hangingwall.

Figure 19 shows the 3-D model of the hangingwall at the site.

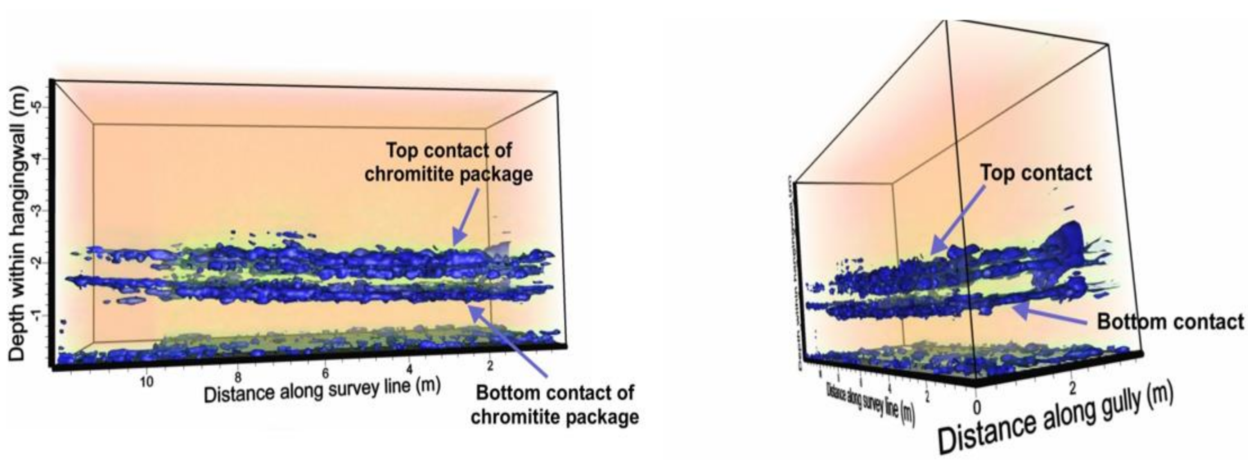


Figure 19. 3-D GPR isosurface model of the chromitite package within the hangingwall. Cross-sectional view from the face(left) and oblique view from the gully (Kgarume, et al., 2019).

4.6 MAPPING OF A **SHEAR ZONE**

A 3-D GPR survey was conducted along a roadway of a mechanised platinum mine to image the top and bottom contact of a shear zone within the immediate hangingwall. A 500MHz antenna was used for this purpose. A line spacing of 0.2 m was used to acquire the data. Figure 20 shows a schematic of the layout used along the roadway.

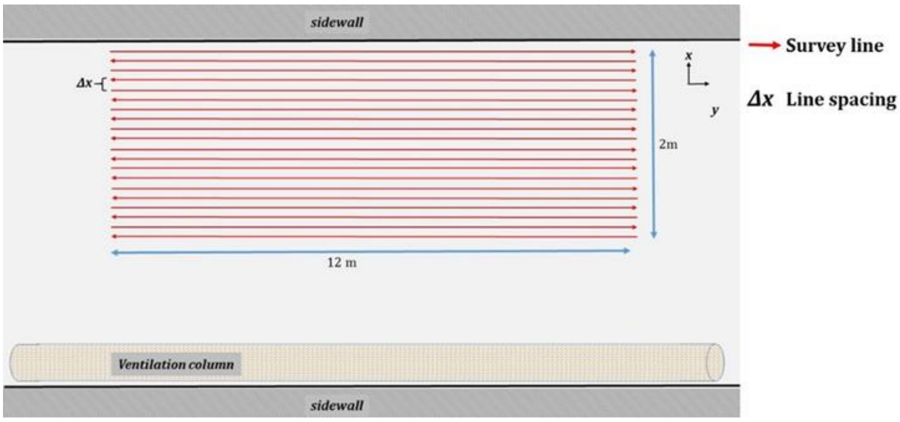


Figure 20. GPR survey layout of the hangingwall at a platinum mine roadway**.**

A radargram from the survey is shown in Figure 21. The top and bottom contacts of the shear zone can be identified on the radargram.

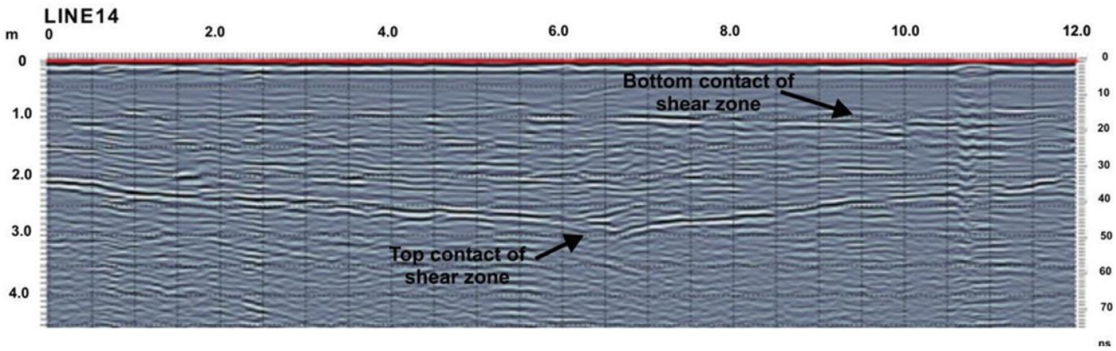


Figure 21. Radargram with the top and bottom contacts of the shear zone (Kgarume, et al., 2019)

Figure 22 shows the 3-D model of the hangingwall at the site.

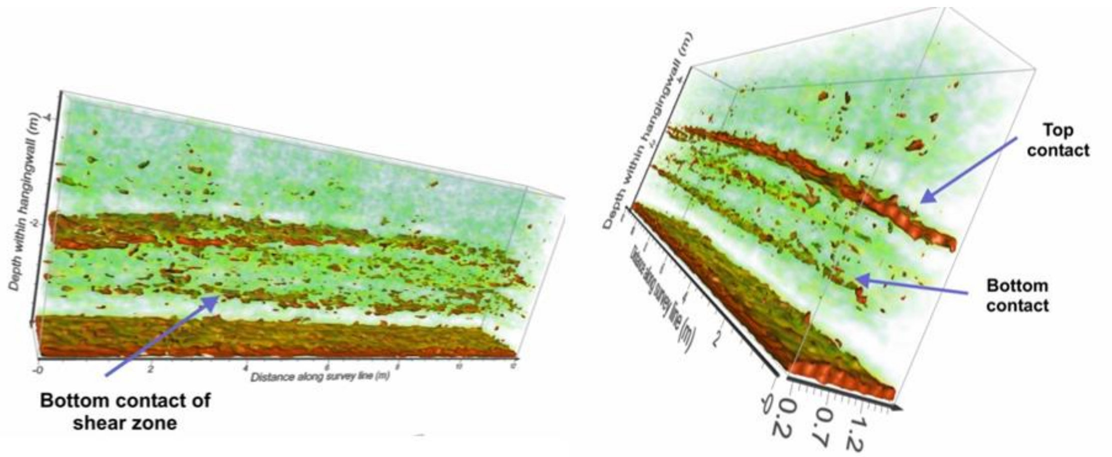


Figure 22: 3-D GPR isosurface model of the shear zone within the hangingwall. Cross-sectional view from the face(left) and oblique view from the gully (Kgarume, et al., 2019).

4.7 COMBINED **GPR-LIDAR 3D-MODEL**

GPR and LIDAR surveys were undertaken at the same underground panel at a platinum mine to create a combined GPR-LIDAR model of the excavation based on both datasets. Figure 23 shows 3-D GPR volume data and a plan view of the LIDAR data of the excavation where the GPR data was acquired.

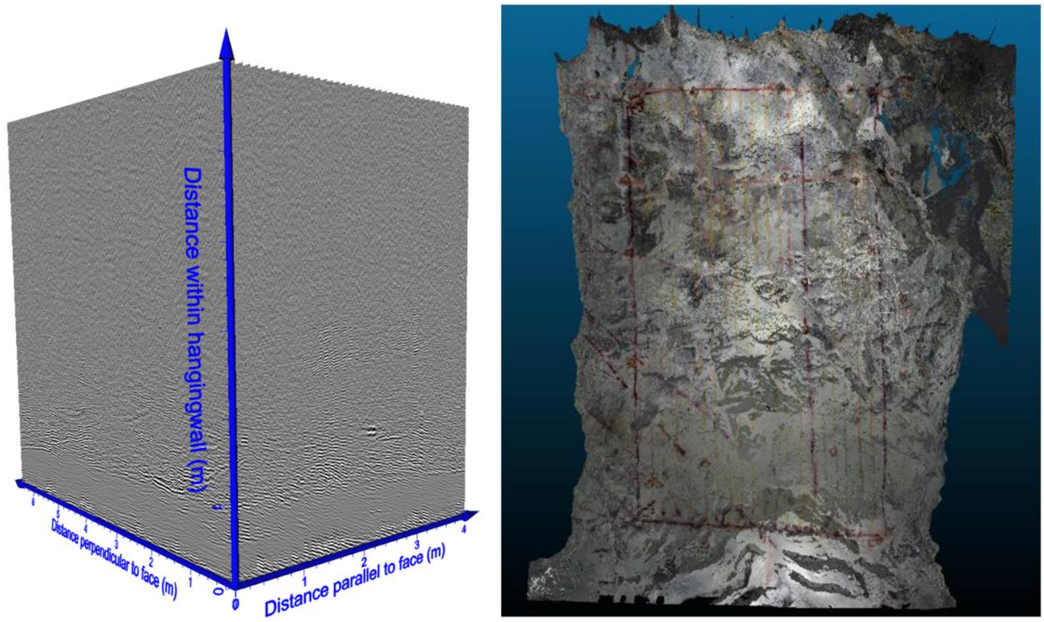


Figure 23. 3-D GPR volume (left)and plan view of LIDAR point cloud data of the excavation (right).

The two datasets in Figure are jointly plotted to create a GPR-LIDAR 3-D model of the excavation.

Figure 24 shows the two datasets jointly plotted.

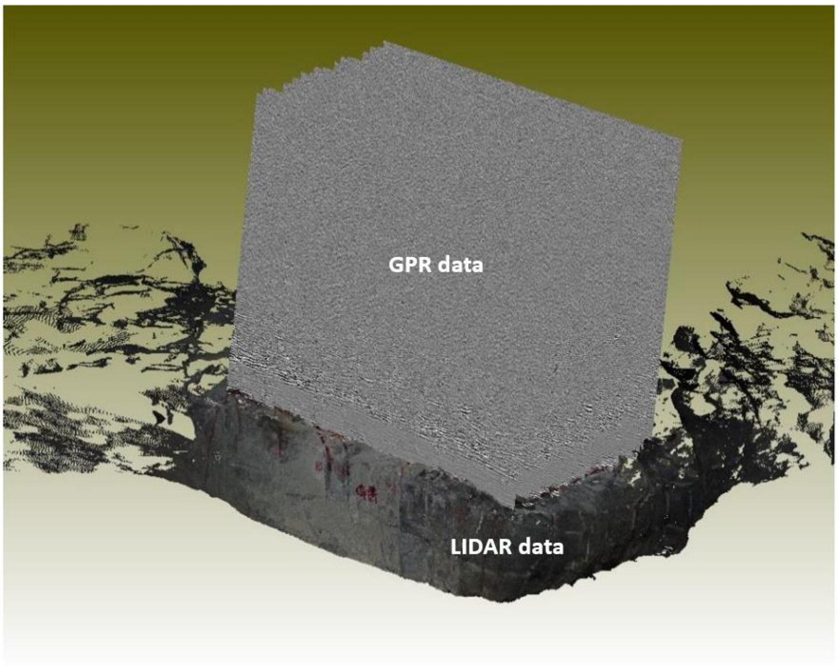


Figure 24. GPR-LIDAR 3D model viewed from the sidewall - face area.

4.8 LIMITATION OF GPR

GPR has limited application when used in an excavation that is supported using by wire mash. This is because GPR is an electromagnetic method and the presence of wire mesh tends to attenuate the signal, causing it not to penetrate the rock to the desired depths. A survey was conducted in a deep-level gold mine where the working areas are supported by roof bolts, wire mesh and shotcrete due to high stress conditions encountered at that mine.

Figure 25 shows examples of GPR data acquired along the hangingwall that is supported by wire mash.

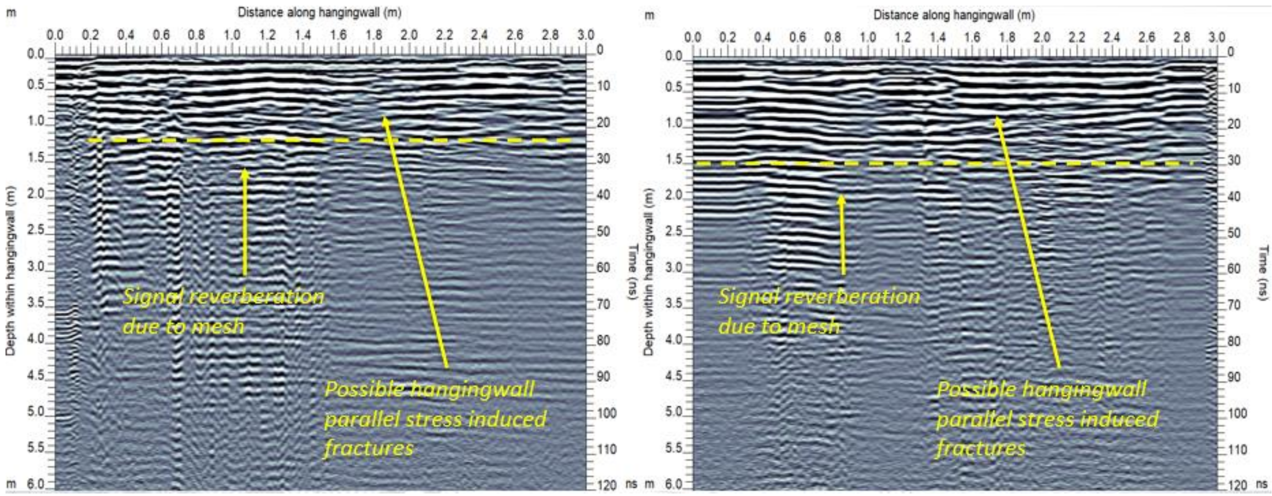
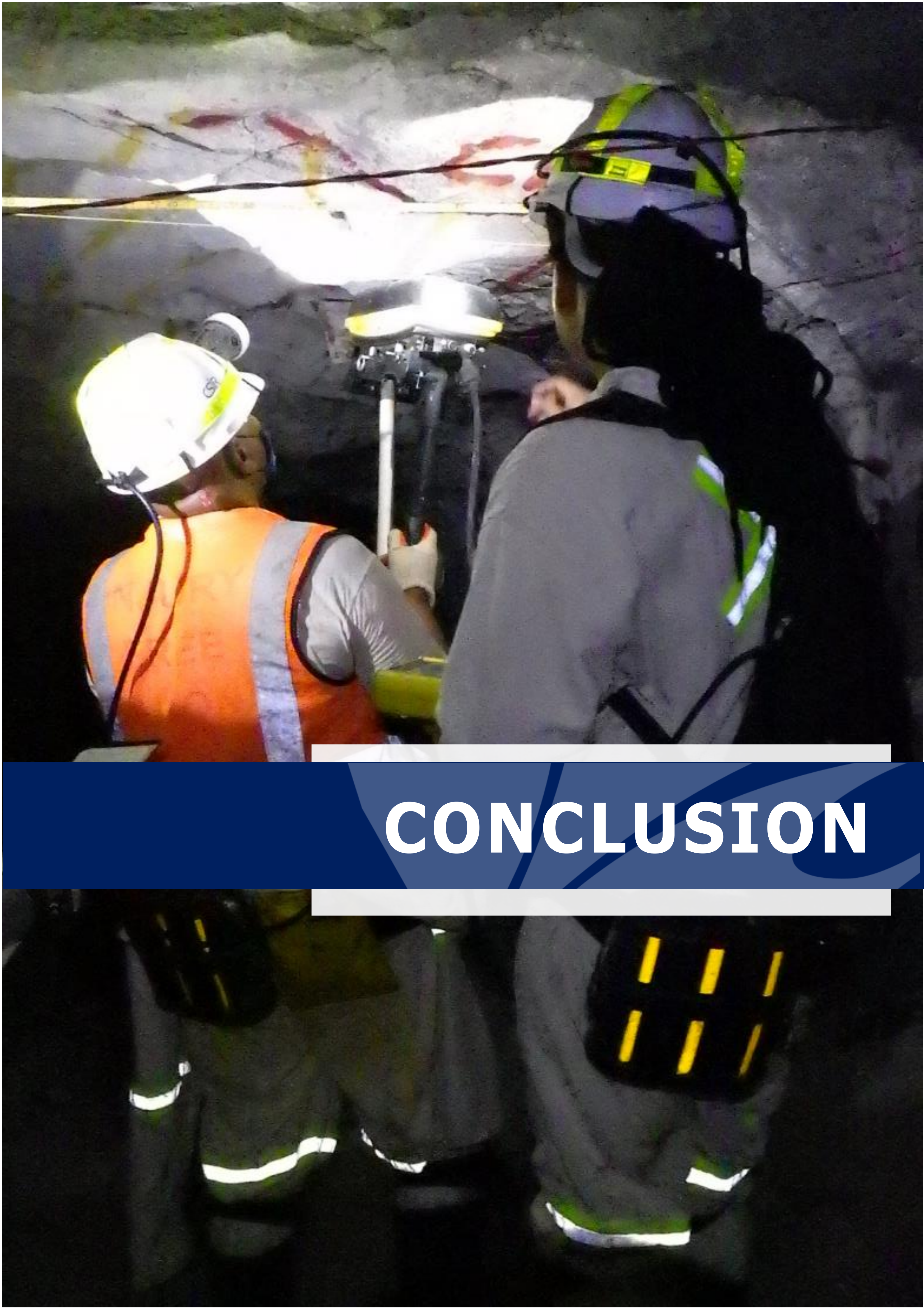


Figure 25. GPR data acquired along a wire mash supported hangingwall.

The wire mesh attenuated the signal and had an effect of reverberating the signal resulting in poor signal penetration which yields GPR outputs that are difficult to interpret. In some cases, however, fracturing within 1 m of the hangingwall was imaged. Another limitation of the GPR method is that the permittivity values of the host rock and the target must not be similar. If the permittivity values are similar, there will be weak or not signal reflection at the boundary of the two rocks.



CONCLUSION

This guideline document was compiled for the user to inform on the basic principles and the previous application of GPR in the South African mines, how GPR surveys are conducted, how the data is processed, interpreted, and visualized. Examples were given on how GPR surveys are conducted, how the data is processed, interpreted, and visualized. The case studies presented show the user the excellent application of GPR in different scenario. A limited application of GPR is when surveying the excavation which is supported by wire mash. It is found that the wire mesh attenuates the radar signal which makes the GPR outputs difficult to interpret.

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APPENDIX

LIST OF **PREVIOUS WORK**

Year	Workpackage number	Milestone number & title
2017	AOK17	Technical close-out report for period 2017/2018. Based on the following sub-activity reports: • Overview of Automated scanning electron microscope technology (B. Guy – UJ) • Review of non-conventional tools for advanced orebody knowledge (D. Vogt – Wits / Cambourne University, UK) • Technologies to characterise the rock mass ahead of mining in the Witwatersrand Basin and Bushveld Complex (R. Durrheim, M. Manzi, G. Cooper – Wits) • In-mine geophysics: Technology review and the way forward (M. van Schoor – CSIR) • Advanced Ore-body Knowledge: A Review of Platforms for Geophysical Sensor Deployment (J. Dickens – CSIR) • AOK – Review of Sensor Technologies from Meraka's Sensor Team (H. Ilgner - CSIR) including the RTIMS WP5 Report: Positioning Systems by Preis et al. • RC drilling review (Prof. D. Minnitt – Wits) Appendix G Benchmarking trial survey results
2018-2019	AOK18WP2.4	Simulate multi-sensor ground penetrating radar (GPR) trials baseline study report (T. Kgarume – CSIR)
2020-2021	AOK20WP4.4	Milestone 1. Project Start-up Memo (T. Kgarume – CSIR)
		Milestone 2. Milestone report on thermography underground results (T. Kgarume – CSIR)
		Milestone 3. Milestone report on GPR underground results (T. Kgarume – CSIR)
		Milestone 4. Milestone report on the results of a compact GPR system designed for underground mining (T. Kgarume – CSIR)
		Milestone 5. Review of seismic attributes (M. Manzi – WITS)
		Milestone 6. Report on findings of advantages and disadvantages of seismic attribute techniques (M. Manzi – WITS)
		Milestone 7. Report detailing results on the seismic attributes applied to GPR data (T. Kgarume – CSIR)
		Milestone 8. GPR/thermography model integrated into mine CAD software (T. Kgarume – CSIR)
		Milestone 9. Final report and project closure (T. Kgarume – CSIR)

Year	Workpackage number	Milestone number & title
2021-2022	AOK21WP5.4	Milestone 1. Integrated scanning technologies to identify reef identification and geological structures on the Face - inception report (T. Kgarume – CSIR)
		Milestone 2. Optimised acquisition and georeferencing methodology of both 3D GPR and LIDAR data (H. Grobbelaar – UJ)
		Milestone 3. Improved rockmass structural characterisation model using LIDAR point cloud and 3D GPR data (T. Kgarume – CSIR)
		Milestone 5. Visualisation of the enhanced GPR-Lidar 3D model in CAD software (T. Kgarume – CSIR)
2020-2021	AOK20WP4.4	Milestone 1. ERT close-out report (M. van Schoor – CSIR)
		Milestone 2. ERT Guideline report (M. van Schoor – CSIR)
		Milestone 3. GPR close-out report (T. Kgarume – CSIR)
		Milestone 4. GPR Guideline report (T. Kgarume – CSIR)
		Milestone 5. GPR/ERT training workshop(s) (M. van Schoor – CSIR and T. Kgarume - CSIR)