MANDELA MINING PRECINCT
MINDS FOR MINES

Guideline:
Application of Electric Resistance Tomography (ERT) 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: 978-0-7988-5670-1

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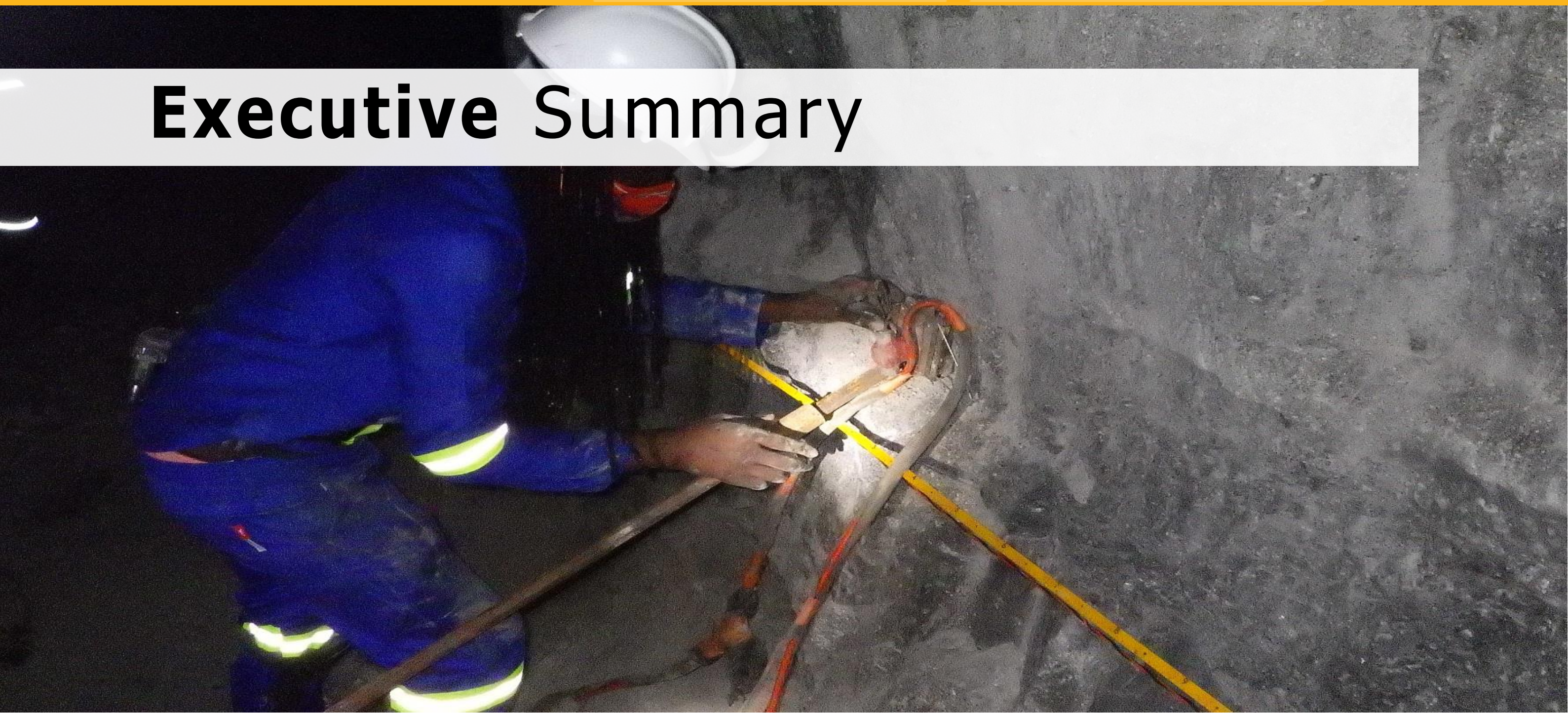
Executive Summary



In-mine electrical resistance tomography (ERT) has emerged as a promising technology for the detection and delineation of disruptive geological anomalies ahead of mining. Its niche application is to image localised anomalies such as potholes, IRUPs and faults between on-reef excavations like adjacent raise tunnels or down-dip boreholes. However, the practical application of the technology is not straightforward and has proven to be logistically challenging. For these reasons, its application has traditionally been restricted to suitably qualified and experienced specialists. Hence, the need to compile a guideline document to resolve the abovementioned obstacles was identified and this need was subsequently addressed as part of the AOK ERT research. The result was this guideline document and an associated spreadsheet-based survey planning tool. While it does not form a critical part of the guidelines, the spreadsheet can assist in determining the basic survey parameters for a given survey site.

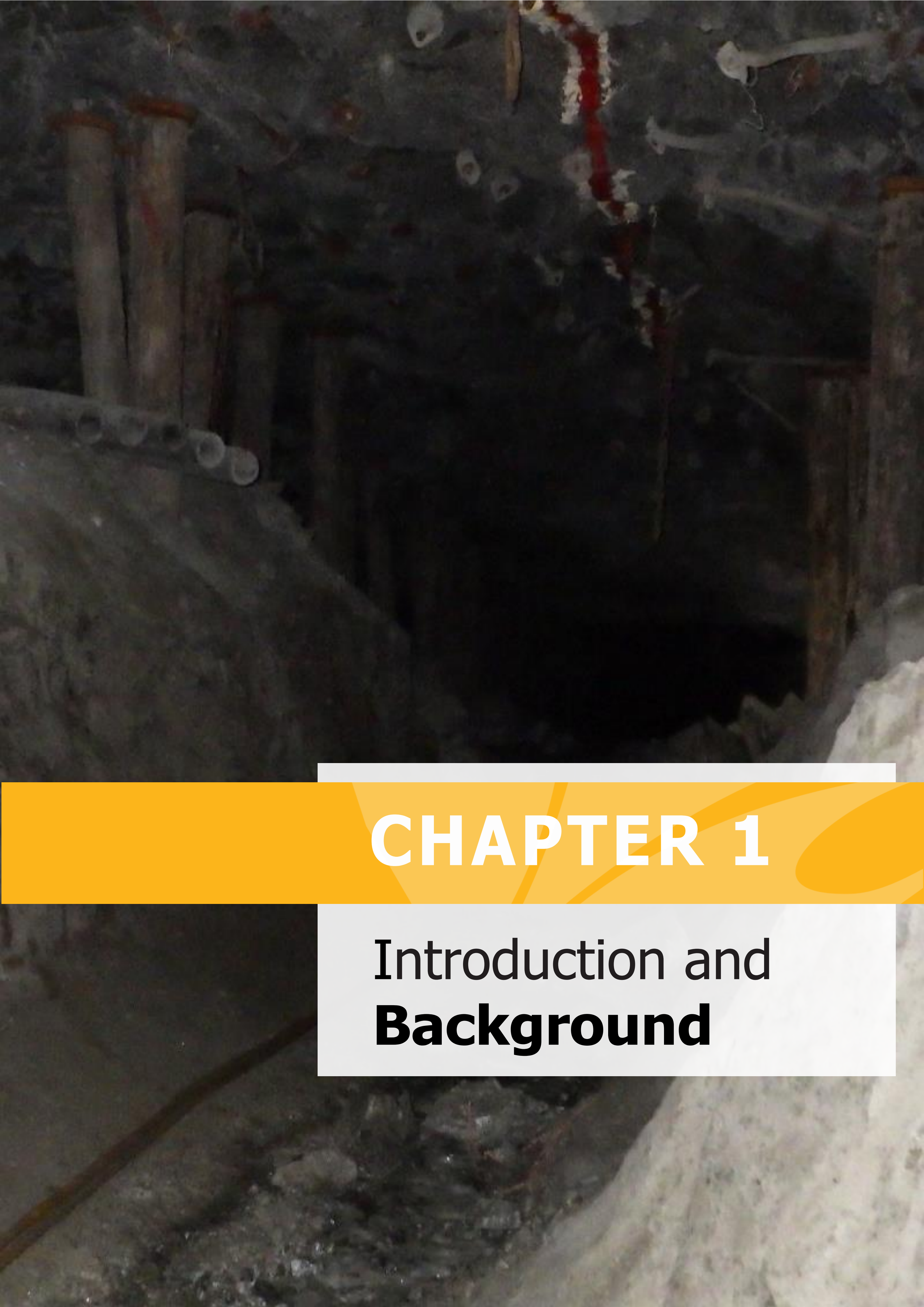
This guideline aims to provide a compact, yet comprehensive, description of the process of applying in-mine electrical resistance tomography (ERT) to detect and delineate disruptive and hazardous structures – ahead of mining – in a deep-level planar orebody environment. Key topics that are addressed include the principles of ERT, the site requirements for applying in-mine ERT, survey planning and execution, as well as data processing and visualisation. The guideline concludes with some use-case examples to illustrate the value-add that in-mine ERT offers.

Table of Contents

List of Figures

Definitions and Abbreviations

AGI	Advanced Geoscience Inc.
AOK	Advanced Orebody Knowledge
Bushveld Complex	Large layered, igneous complex in South Africa
CAD	Computer-aided design
CSV	Comma-separated values
Conductive coupling gel	A gel that helps to lower the contact resistance of a surface – to aid the injection of electrical current
Discretisation	Dividing a continuous area or volume into mathematically discrete elements to simplify make subsequent analysis
ECG	Electro-cardiogram
Electrodes	Metal stakes, bolts (or other conductive material) that provides galvanic contact with the rock
ERT	Electrical resistance tomography
Fault	planar fracture or discontinuity in rock associated with displacement of layers
FE (finite element)	A widely-used numerical method for solving solving differential equations in engineering and mathematical modeling
Hammer drill	A drill that offers rotary plus hammer action drilling
IRUP	Iron-rich ultramafic pegmatite body
LIDAR	Light detection and ranging
Merensky	Major platinum-bearing reef of the Bushveld (Igneous) Complex
Multicore cables	Electrical cable that contains multiple individual insulated conductors
Platmine	A collaborative research programme established by CSIR, Miningtek in the early 2000s and involved most of the major platinum mining houses
Pothole	depression or slump structure affecting Bushveld Complex reefs
Rawl bolt	A type of anchor bolt – similar to a sleeve anchor bolts
Resistivity	Intrinsic material property – a measure of the resistance to current flow
Supersting system	A resistivity system manufactured by the US company Advanced Geoscience Inc.
UG2	Upper Group 2 Reef – a chromitite-rich platinum-bearing reef of the Bushveld (Igneous) Complex
1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional



CHAPTER 1

Introduction and **Background**

This guideline aims to provide a compact, yet comprehensive, description of the process of applying in-mine electrical resistance tomography (ERT) to detect and delineate disruptive and hazardous structures – ahead of mining – in a deep-level planar orebody environment. Key topics that are addressed include the principles of ERT, the site requirements for applying in-mine ERT, survey planning and execution, as well as data processing and visualisation. The guideline concludes with some use-case examples to illustrate the value-add that in-mine ERT offers.

In this chapter, a brief overview of the basic principles of ERT will be provided; this will include a narrative of the historic context and evolution of ERT in general as well as its adaptation for use in deep-level mining in South Africa.

1.1 BASIC PRINCIPLES OF ERT

CSIR previously proved that the (ERT) technique can be adapted for in-mine use and that it was capable of imaging disruptions to the continuity of planar/tabular reef horizons (e.g., potholes, IRUPs and faults on the Merensky and UG2 reefs of the Bushveld Complex).

The general ERT survey method is well established and is widely used in non-mining surface applications such as groundwater studies, environmental/pollution monitoring and civil engineering applications. ERT is a tomographic technique, which implies that it involves some imaging approach. In other words, an area of interest is targeted with strategically located resistivity measurements, which are then used as input to a tomographic image reconstruction algorithm. A resistivity image of the target area is produced – showing spatial variations in electrical resistivity – and the idea is that variations in resistivity can be correlated with variations in geology such as structures that disrupt the continuity of a reef horizon.

An ERT survey typically involves several hundred measurements. Each resistivity measurement involves a unique placement of four electrodes – one pair for current injection (denoted by A and B in Figure 1) and one pair (M and N in Figure 1) for recording the resulting potential difference (voltage). Figure 1 shows a simplified representation of a single resistivity measurement. The relative placement of A, B, M and N and the value of the measured resistance (voltage/current ratio) can be used to derive an estimate of the subsurface earth resistivity in the zone close to the electrodes.

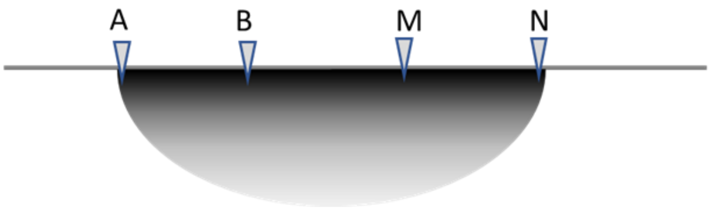
Four important concepts need to be highlighted and is schematically depicted in Figure 1:

1. The measured resistivity value is a bulk or averaged measurement, with a portion of the earth close to the electrodes contributing to the measurement.

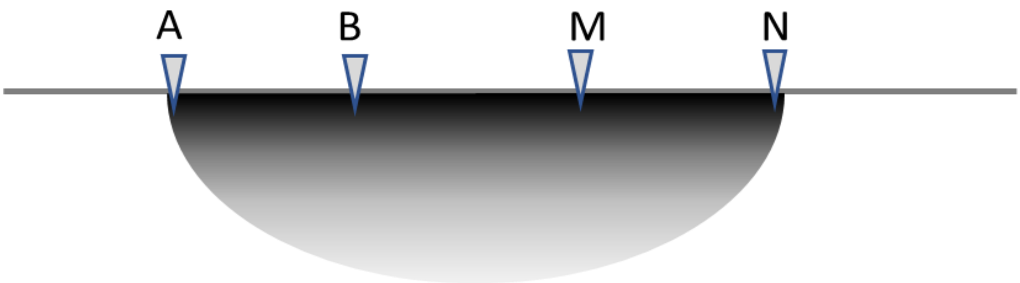
2. The contribution is greatest for shallower layers (closer to electrodes) and diminishes as depth increases – in Figure 1 the darker shades of grey imply a greater contribution to the measured resistivity,

3. The effective depth of investigation can be increased by using a greater spacing between the electrodes (e.g., the larger spacings in Figure 1b compared to 1a); and

4. For any given four-electrode measurement the depth of investigation is greatest below the central part of the electrodes.



a) Relatively small inter-electrode spacings – compared to Figure 1b



b) Relatively large inter-electrode spacings – compared to Figure 1a

Figure 1. Simplified schematic of four-electrode resistivity measurements

The above concepts play an important role in the ERT survey design and also in better understanding ERT outputs, as well as the limitations of the method. Consequently, these concepts will be referred to again in subsequent chapters.

1.2 EVOLUTION OF ERT SURVEY METHODS

ERT is essentially a modern-day version of two of the oldest geophysical methods, namely resistivity sounding and resistivity profiling. In resistivity soundings a four-electrode configuration like the one shown in Figure 1 is used to take a series of measurements, with incrementally increasing current electrode (AB) spacings. The central point of the electrode array is kept constant and the end-result is a sounding curve that provides information about the changes in resistivity with depth. Bear in mind however, that this is essentially a 1D resistivity profile at a single point. If lateral information is required, one would resort to profiling – this involves moving the four-electrode array incrementally along the surface (laterally).

Note however that moving a fixed four-electrode array along the ground would imply a very limited resolution of resistivity with depth. The key to obtaining better spatial 2D data lies in combining the principles of soundings and profiling. This implies that hundreds of measurements would be required to cover a section of earth; however, the high degree of resolution that potentially results is worth the effort. The true value of such large resistivity data sets could only be exploited relatively recently (in the last couple of decades) with advances in computing power and tomographic reconstruction (imaging) algorithms. These imaging algorithms make it possible to produce 2D cross-sectional images of subsurface resistivity changes.

While traditional resistivity and ERT applications were mostly limited to linear surface surveys (as is essentially depicted in Figure 1), many researchers have explored different geometries, such as cross-borehole, borehole-surface and then more recently, tunnel-to-tunnel geometries in underground mines.

1.3 ADAPTATION OF ERT FOR IN-MINE USE

One of the fundamental principles underlying 2D ERT surveys is the fact that all electrodes should be in the same plane. This applies, irrespective of whether a single line on surface is used, or two adjacent raise tunnels or down-dip boreholes. The objective of any ERT survey is therefore to image the resistivity distribution within the plane defined by the electrodes. In most in-mine applications the aim would be to design the survey in such a way that the image plane coincides with, for example, a planar orebody or key layer boundary associated with the orebody. The idea is that the output image will then reveal any anomalous behaviour – that is, any deviations from an undisturbed, continuous orebody horizon.

The typical in-mine ERT survey approach involves employing lines of electrodes in co-planar on-reef tunnels (i.e., raise developments); alternatively, it can also be applied in co-planar down-dip boreholes in mechanised environments. The concept of in-mine ERT is depicted in the schematic in Figure 2. The blue-shaded area represents the area if interest – a portion of the reef plane (yellow), straddled by two adjacent raise tunnels – this is the ideal in-mine ERT geometry.

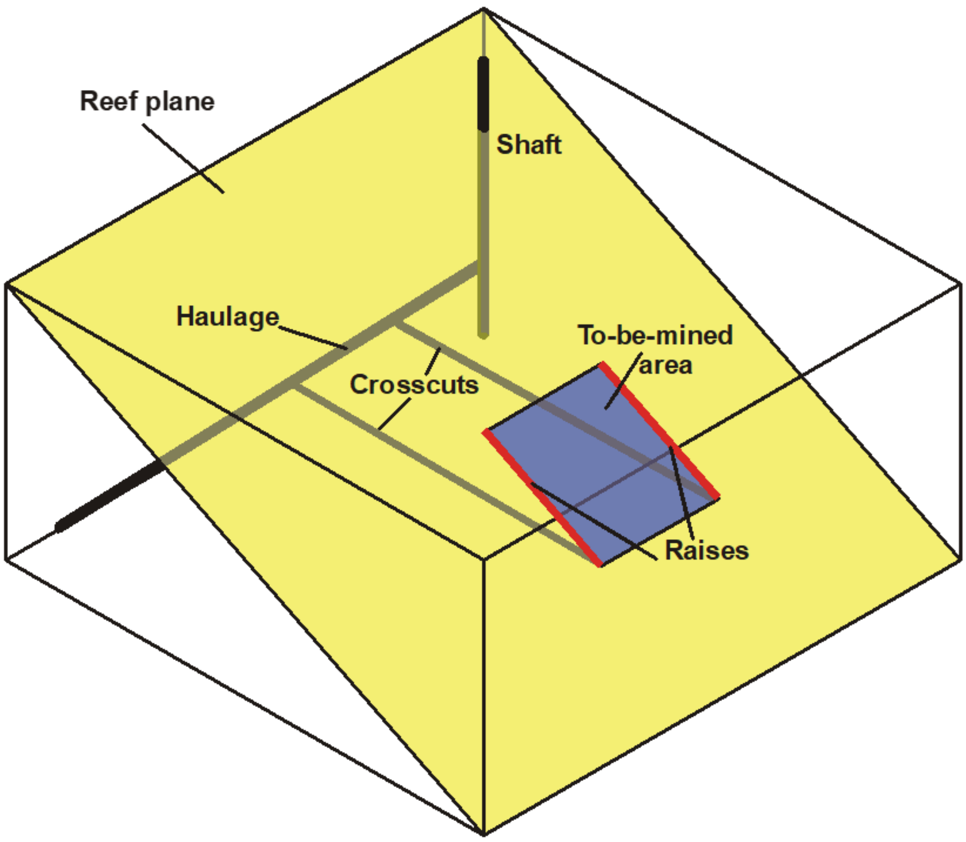
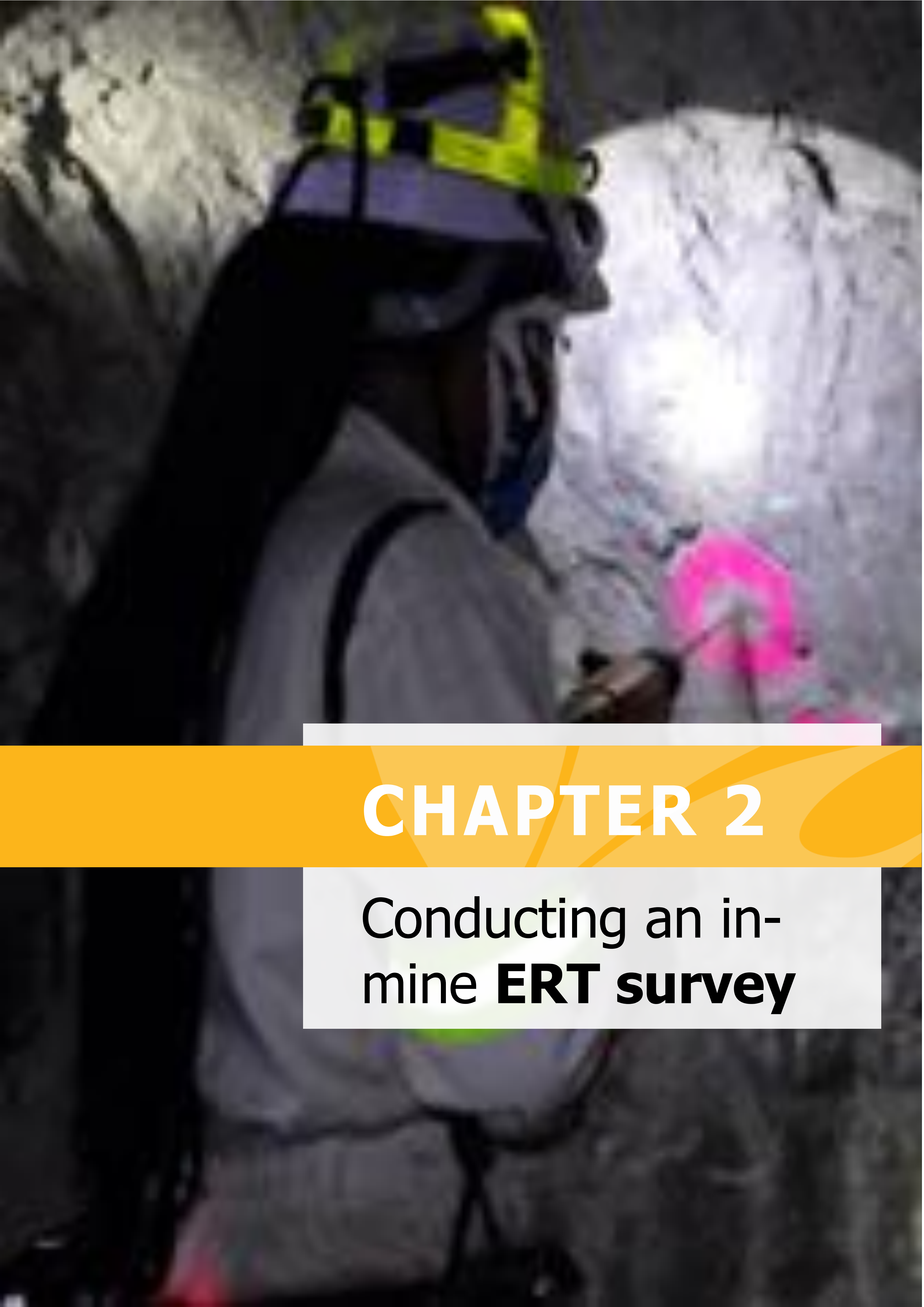


Figure 2. Schematic of the in-mine ERT concept



CHAPTER 2

Conducting an in-mine **ERT survey**

In Chapter 2 the process of planning and executing an in-mine ERT survey is described. The process comprises three distinct stages, namely survey planning, site preparation and data acquisition.

2.1 SURVEY **PLANNING**

Survey geometry requirements and determining survey parameters:

The preceding sections have provided some indication of the typical in-mine ERT scenario. In this section, the detailed survey planning will be explained. As part of the AOK ERT research a spreadsheet-based tool was created that can assist with the survey planning; however, it is important to understand the underlying principles of how the survey parameters are determined.

Consider the schematic in Figure 3. The shaded area represents an arbitrary area of interest – this could, for example represent a to-be-mined block straddled by two tunnels (or boreholes). Points A, B, C and D represent the extremities of the survey area. The locations of these points are often dictated by mining activities, extent of excavations/development etc.; however, the general rule-of-thumb is to place these points so that the effective area ABCD is slightly bigger (in the up-dip / down-dip sense) than the actual area of interest. The reason for this is depicted in Figure 4 and relates to some of the concepts highlighted in relation to Figure 1 – in particular the fourth point; that is that resolution or mapping accuracy is greatest below the central portion of the electrode spread and tapers off towards the two ends. For a survey electrode layout, this implies that there are effectively two "blind zones" at the top and bottom ends of the survey area. In these "blind zones", targets can still be detected, but not necessarily resolved properly. For this reason, it makes sense to extend the actual survey area as far as possible in the up-dip/down-dip directions.

A further very important survey parameter to consider is the spacing between the opposing tunnels or boreholes and the relationship between the up-dip/down-dip extent of the survey area and the tunnel/borehole spacing. This aspect ratio should ideally be as large as possible, preferably greater than 1. Some of the scenarios in Figure 4 reveal how a too-small effective aspect ratio implies that the "blind zones" become more pronounced, taking up a greater proportion of the total survey area.

"Blind zones" can also occur where no electrodes could be placed; for example, between points S and T in Figure 4 (v). This will result in a localized zone where detection and resolution capabilities will be compromised.

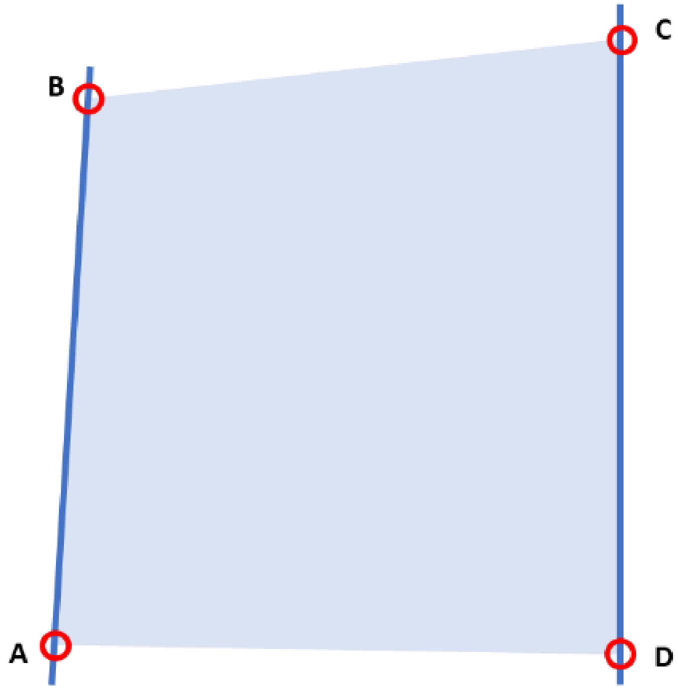


Figure 3. Schematic plan view of a prospective in-mine ERT survey area

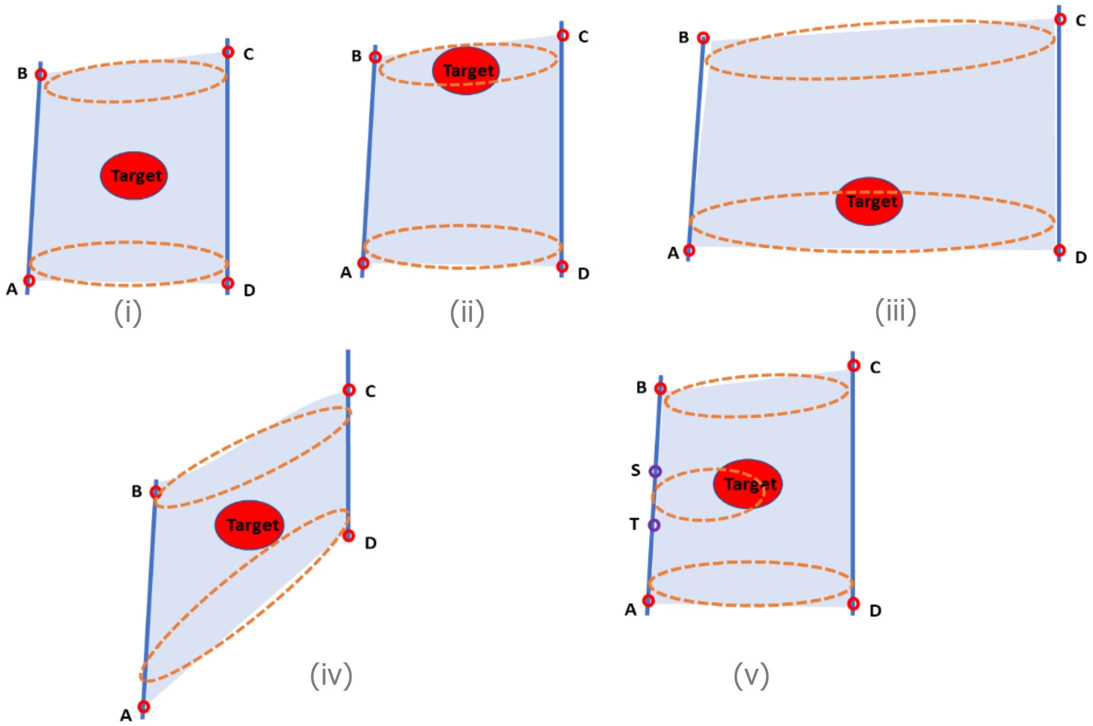


Figure 4. Schematic depictions of various ideal and non-ideal ERT survey geometries

Once the corner points of the survey area have been determined, the next step is to determine the number of electrodes to use, the inter-electrode spacing and the positioning of these electrodes. The previously mentioned spreadsheet-based survey planning tool can assist users to determine these parameters in an automated fashion; however, the basic rules-of-thumb are as follows:

- The unit electrode spacing is estimated to be approximately 6-8% of the tunnel/borehole spacing. The survey tool also considers the finite element discretization of the survey area (numerically, the survey area is sub-divided into a grid of cells and another rule of thumb is to aim for two unit cells between adjacent electrodes. To make site preparation logistics and numerical processing a bit easier, the dimensions for the FE grid cells and hence the electrode spacing are usually rounded to the nearest 0.5. For example, a tunnel spacing of 50 m equates to a unit electrode spacing of between 3 m and 4 m (3 m, 3.5 m or 4 m can be used); for an 80 m tunnel spacing, the electrode spacing will be of the order of 5 to 6.5 m (5 m, 5.5 m, 6 m or 6.5 m can be used).
- Another factor that may influence the exact choice of electrode spacing is the total number of electrodes. The above rules-of-thumb will generally result in a total number of electrodes of between 40 and 60 electrodes. Figure 5 shows a graphical representation of the calculations done by the survey planning tool for a scenario where the tunnel spacing is 90 m and the up-dip/down-dip extent of the survey areas is about 120 m. An electrode spacing of 6 m and a total number of 42 electrodes could be used; however, one could also opt for less electrodes 34 electrodes at a spacing of 7.5 m or for more – e.g., 50 electrodes at a spacing of 5 m. Less electrodes (and hence a bigger grid cell size) implies a faster/easier computational effort, but coarser resolution; a larger number of electrodes will have a smaller grid cell size, but the numerical computational effort becomes more complicated with increasing grid cell size and number. For this reason, the spreadsheet tool offers the user the option to select an appropriate parameter combination within the above prescribed range.

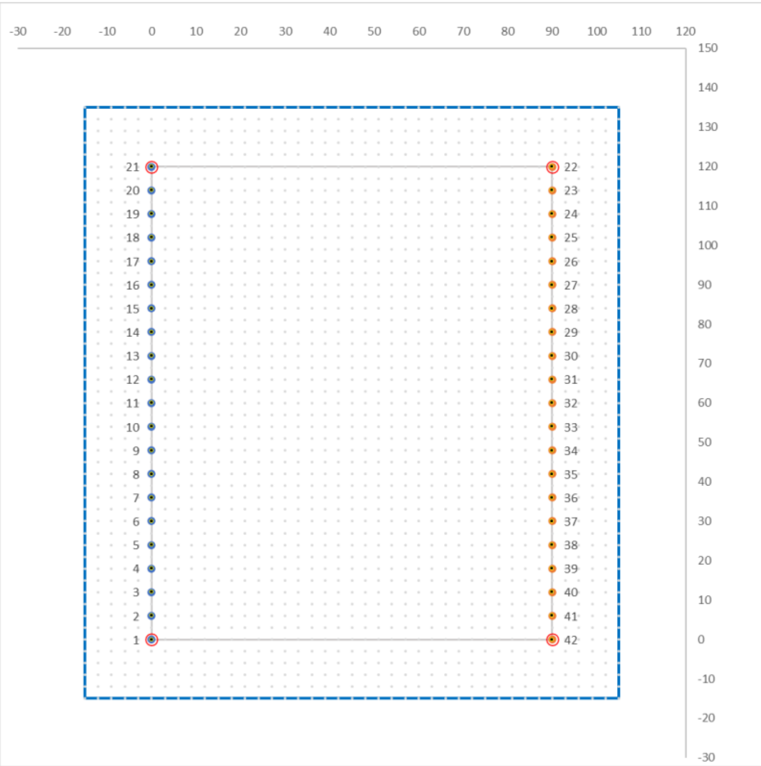


Figure 5. Screenshot of the spreadsheet-based ERT survey planning tool interface

2.2 SITE PREPARATION

This section describes the process of preparing the site for an ERT survey. If time permits, this preparation can be done a day or two before the actual data acquisition, but if properly planned and executed, it can be done in approximately 2-3 hours at the start of the same shift during which data acquisition is done. Site preparation involves the following steps:

1. Marking of electrode locations
2. Drilling electrode holes
3. Inserting electrode bolts into the holes
4. Connecting all the electrodes to multi-core resistivity cables that lead to a centrally-located control unit

Marking of electrode locations – based on the survey plan, the marking can be done using a tape measure and spray paint. Each site can be marked on the sidewall with its unique (electrode) number to help eliminate any potential errors during setup and data acquisition. The numbering typically starts at any of the corner electrodes and then follows sequentially in either a clockwise or anti-clockwise fashion.

Drilling electrode holes – a battery-powered portable hammer drill with a 10-12 mm drill bit can be used. Holes are typically drilled up to about 12-15 cm deep. Holes should be drilled near-horizontally into the sidewall, with a slight downward inclination.

Inserting electrode bolts – a steel or brass expansion or rawl bolt that match the pre-drilled hole diameter is typically used. The idea is to insert the bolt as far as possible into the hole to maximise the galvanic contact surface within the hole. A bit of conductive coupling gel – e.g. medical electrocardiogram (ECG) gel – is inserted into each electrode hole prior to inserting the bolt; this helps reduce the contact resistance and makes current injection easier. The bolts are tightened using a suitable spanner.

Connecting electrodes to multi-core cables – custom-made cables are called for – even though these can be purchased from selected suppliers of resistivity equipment, they can also be self-manufactured. Since most in-mine surveys will involve between 40 and 60 electrodes and electrode spacings ranging from about 4-8 m it would make sense to have one set of cables that can cope with this range. For example, if a 24 -core cable is used, two 200 m lengths, each with electrode take-outs, spaced about 8 m apart should enable the surveying of most scenarios (up to 48 electrodes and 8 m spacings).

Shorter 6-core cables can perhaps be used in cases where the number of required electrodes exceeds 48. Figure 6 depicts a typical electrodes/cable layout that might be used (note that all the electrodes are linked back to a single central point using two sets of multi-core cables). There is obviously some flexibility in the cable design and the deployment of cables; ultimately, the only key requirement is that all electrodes can simultaneously be connected to the control unit.

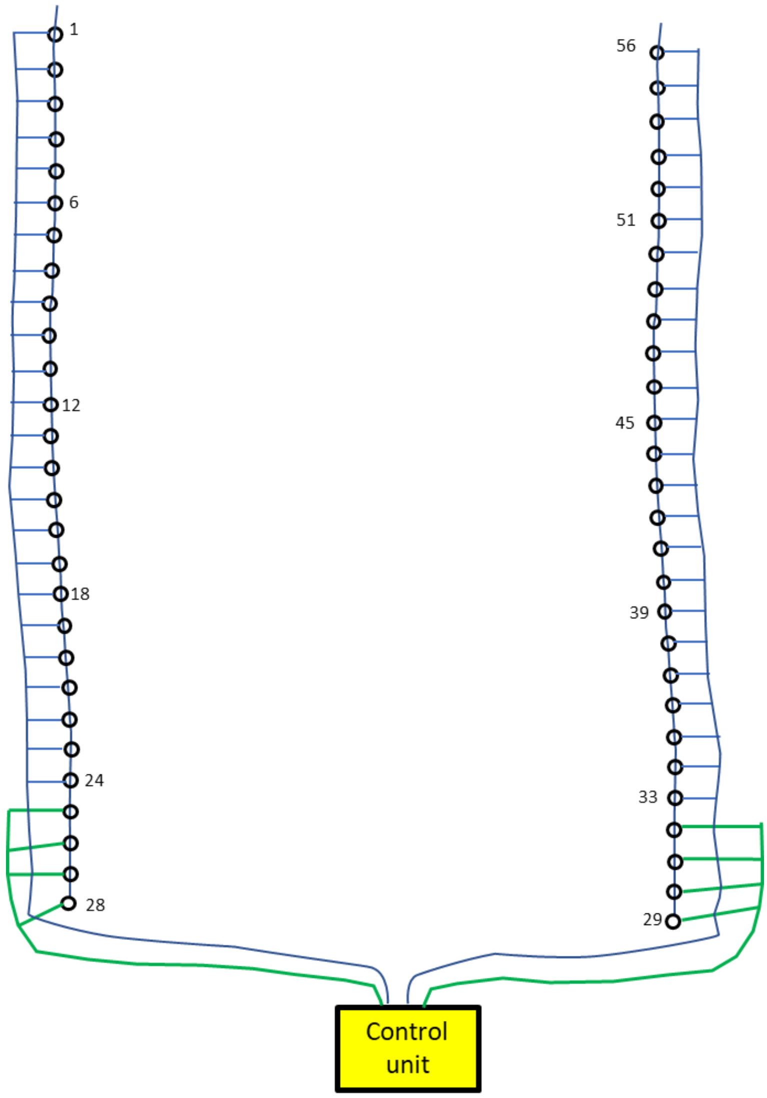


Figure 6. Illustration showing how a 56-electrode layout could be connected to the control unit

2.3 DATA **ACQUISITION**

Modern ERT equipment with automatic surveying capabilities has made data acquisition a relatively straightforward and quick exercise. The automatic capability implies that:

a) A pre-defined survey protocol file is installed on the control unit; this file dictates the number, geometry and sequence of all measurements to be taken.

b) Once data acquisition is initiated, all switching procedures to engage the pre-determined four-electrode combinations specified in the survey file, are done automatically by the system.

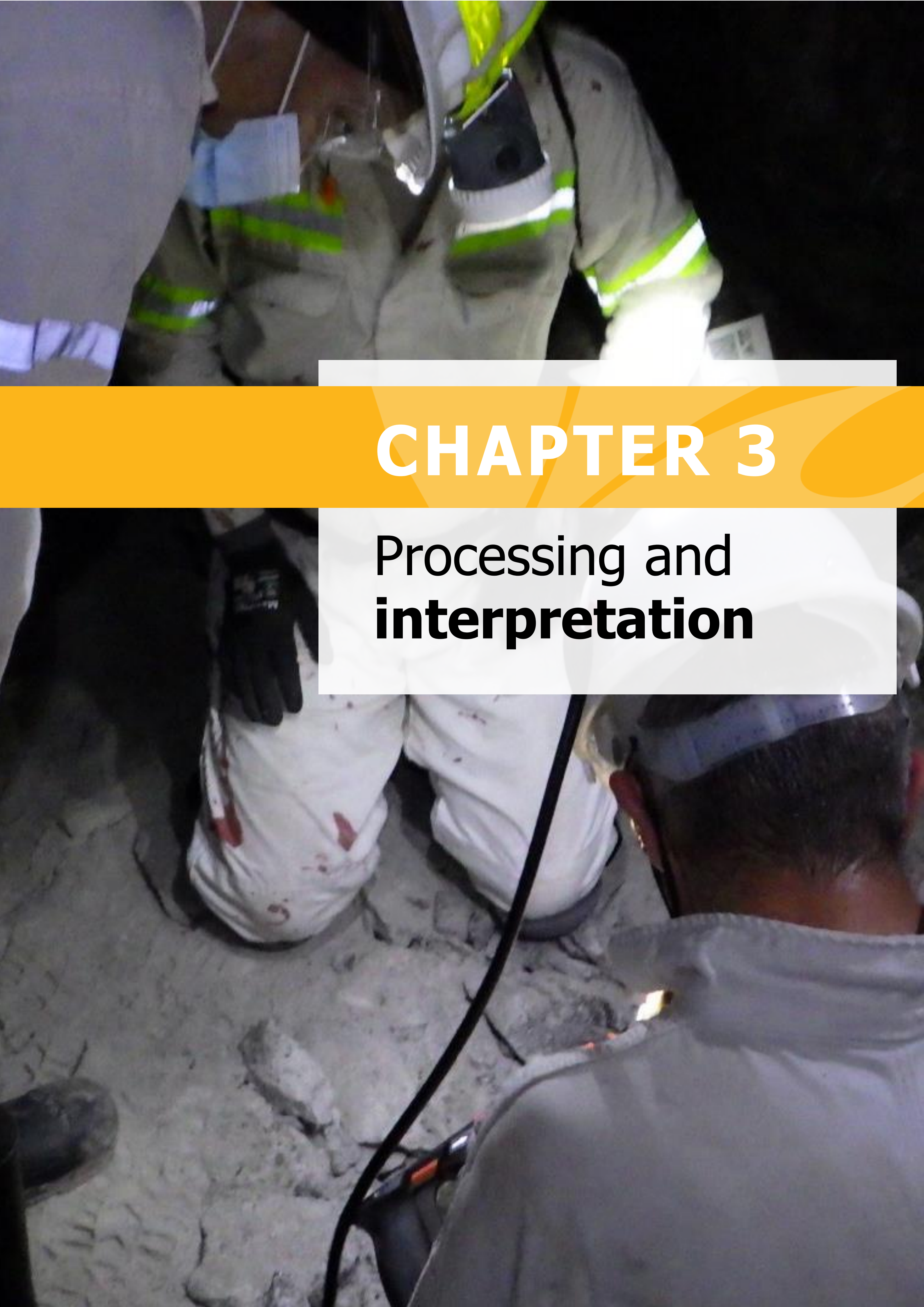
The structure and design of the survey protocol file will not be discussed in detail in these guidelines since these will vary and be specific to the commercial ERT system employed. Should a user implement an ERT system at their mine, the setting up of a few survey protocol files should be done with the assistance of a suitably qualified and experienced geophysicist. Once these survey files have been created, the appropriate ones can simply be selected and invoked for future surveys.

A few generic explanatory comments regarding the design of survey protocol files follow:

- It should be noted that the previously mentioned spreadsheet-based survey planning tool has been enhanced to automatically create the building blocks of a typical survey protocol file.
- The building blocks referred to above are essentially lines of four-electrode combinations – specifying the A, B, M and N electrode numbers for a given measurement; for example, the following two lines imply that electrodes 1 and 2 will be used for current injection, while 3 and 4 will be used for a voltage measurement for the first measurement, followed by a voltage measurement using electrodes 4 and 5:

1	**2**	**3**	**4**
1	**2**	**4**	**5**

- The exact way in which these lines are formatted in the survey file (a simple text file) will be determined by the ERT system used.
- The measurement scheme recommended for most in-mine surveys involve a combination of in-line dipole-dipole and in-line gradient array measurements.



CHAPTER 3

Processing and **interpretation**

This chapter describes the process of taking raw ERT field data and converting it into an interpretable tomographic image. A short discussion on the interpretation and visualisation of in-mine ERT data is also included.

3.1 PROCESSING OF ERT DATA

It should be noted up-front that raw ERT data sets are fairly complex and not easy to analyse in real-time and anomalies are therefore not easily identified in the field. This is because to build up a meaningful tomographic image, a large collection (several hundred) individual measurements are typically taken. While some smaller subsets of data may provide some clues in the field as to the presence of anomalies, the resistivity output image can only be constructed by combining all the measurements after the survey. For this reason, post-processing is usually recommended – this also enables a more rigorous quality control process.

Some degree of in-field data quality control is done by the resistivity system with oversight from a suitably qualified geophysicist or geophysical technician. The ERT system will typically warn the user if the contact resistance, current or voltage levels exceed certain meaningful limits; also, statistical errors are determined for individual measurements, and these can be used to exclude spurious data values from the image reconstruction process. For the tomographic image reconstruction, a specialized software tool would be required. Some manufacturers of ERT equipment offer their own software – for example Advanced Geoscience Inc. (AGI), manufacturer of the Supersting system, offers a tool called EarthImager. There are however a few commercially available software tools that are not necessarily linked to a specific system such as Res2DInv and the UBC inversion tools.

The detailed workings and underlying mathematics of the typical image reconstruction algorithm is beyond the scope of this document; however, a brief simplified description of what it entails is provided here as it will help the end-user better understand the outputs: As was alluded to in Section 2.1, the inversion software constructs a finite element model of the survey area, which comprises grid of cells. Each cell can be assigned a resistivity value and can also be perturbed by the inversion algorithm. Essentially, the algorithm mimics the same series of measurements that was used in the actual field survey and calculates a (synthetic) response of some arbitrary or random finite element resistivity model (starting model). The algorithm then compares the synthetic data to the actual field data and then perturbs and adjusts the starting model according to certain numerical/statistical rules in an effort to minimise the error (essentially the difference between the field and synthetic response); this numerical optmisation problem is of an iterative and trial-and-error nature and continuous for several iterations until some statistically acceptable error threshold is achieved. In other words, the starting model is iteratively updated until its synthetic response closely matches the observed field response. At that point the inversion process is terminated, and the updated synthetic model is assumed to be a good approximation of the actual resistivity structure.

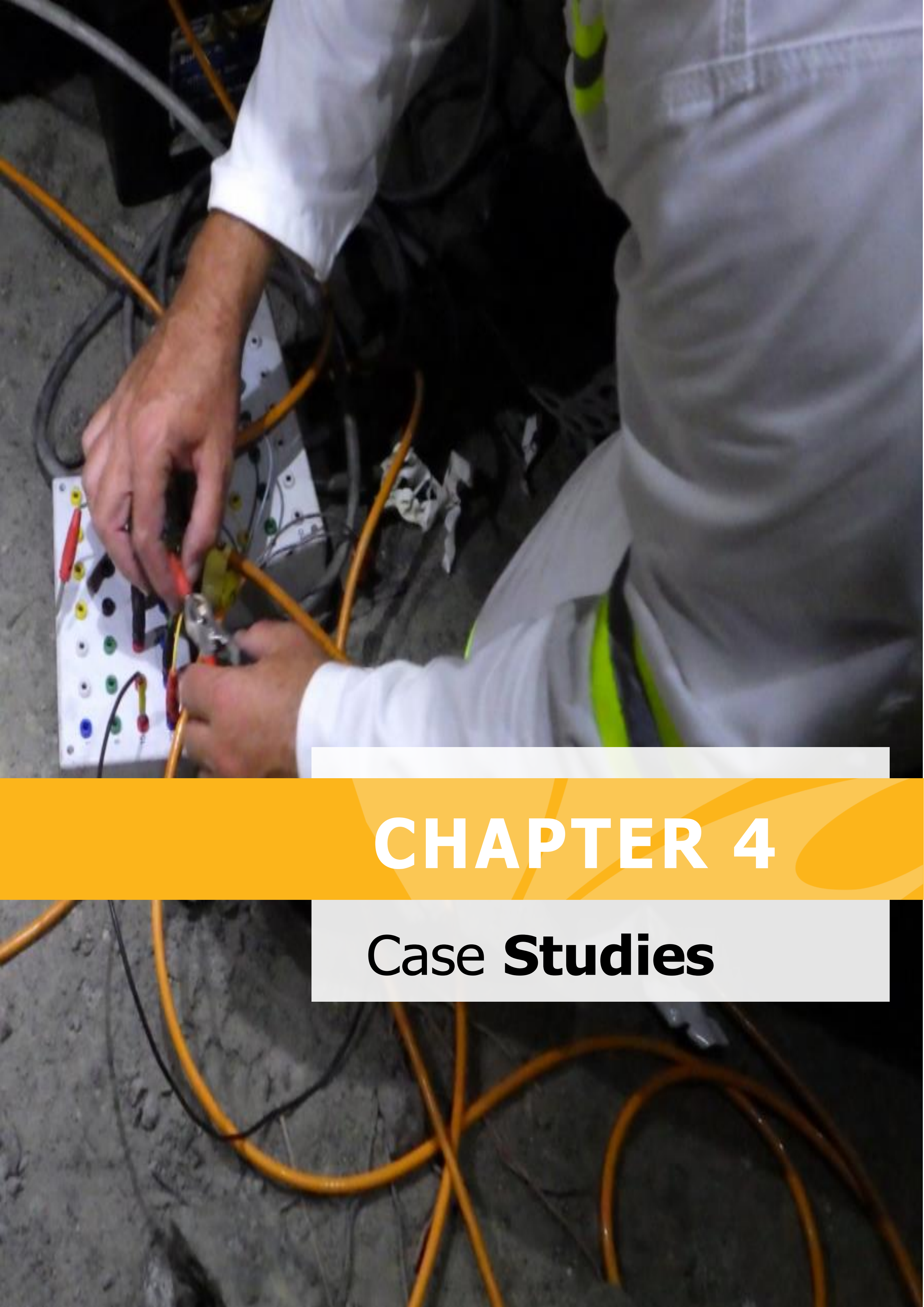
3.2 INTERPRETATION OF ERT DATA

Once an ERT tomographic image has been created it can be interpreted in terms of the subsurface geoelectric distribution, which can often be correlated with subsurface geology and/or geohydrology. A couple of important points should, however, be borne in mind when interpreting ERT images. The importance of these points cannot be stressed enough – if these points are not considered, unreasonable expectations regarding the detection and resolution capabilities of the method may result:

1) The output ERT image is not a unique solution due to the nature of the underlying optimisation problem; however, the image is considered as a statistically good estimate of the true subsurface geoelectric structure.
2) ERT does not have perfect resolution – the unit electrode spacing and associated finite element cells, as well as the limitations of geometric access around the survey block, impose a limit on the mapping accuracy – typically no better than about ½ to 1 unit electrode spacing.
3) Resolution is not uniform throughout the survey area image – therefore, targets located in certain parts of the survey area may not be as well resolved as other (refer the Section 2.1).
4) The tomographic reconstruction algorithm tends to smooth and smear anomalies to some extent.
5) Resistivity artefacts can sometimes occur due to factors such as spurious or noisy data points and very high or sudden localised resistivity contrasts.

3.3 VISUALISATION OF ERT DATA

As a final step in the ERT process, the basic ERT image derived through inversion (tomographic reconstruction) should ideally be visualised in a 3D visualisation or mine CAD software. The key to achieving this lies in proper georeferencing. Traditionally, (in-mine) ERT survey were done using an arbitrary local coordinate system; however, it is possible to transform these local coordinates to the global coordinate system employed by the mine. To do this, one needs to obtain the global coordinates for at least two points within the local coordinate grid, for example, two of the survey electrodes. This can generally be arranged through the mine’s survey department, but the global coordinates could also be extracted from a georeferenced LIDAR point cloud of the excavations surrounding the survey area. These visualisation concepts are demonstrated in one of the case studies in Chapter 4.



CHAPTER 4

Case **Studies**

In this chapter a few selected case studies are presented to illustrate the value of in-mine ERT. Even though the first two case studies date back to the PlatMine era, they represent good examples of what can be achieved when ERT is applied in an ideal environment. These surveys also present good baseline surveys for contrasting some of the advances that much of the AOK efforts focused on. The second case study is taken from the first Maseve trial survey, which was conducted as part of AOK21WP4. The case study is presented through a series of pictures that aims to illustrate the ERT survey process from site preparation through to the ultimate output (integrated with a mine plan).

4.1 HISTORIC CASE STUDIES: PLATMINE ERA

The results of two historic case studies are included here to illustrate the potential of ERT, if correctly applied in suitable environments. Both these surveys were done as controlled trail surveys. In other words, the geology of the target block where well-known and mapped and could be used for groundtruthing purposes.

The first example is of a survey done between two raise tunnels paced about 35 m apart. Several known reef disruptions (pothole A, IRUP B, as well as the minor potholes near electrodes 1-3) were successfully delineated by the ERT method (Figure 7a). Reef disruptions like potholes generally manifest as high-resistivity anomalies due to the fact that they interrupt the continuity (in a localised sense) of the otherwise continuous, flat-lying (and relatively conductive) reef horizon.

The second example is from a survey done around an abandoned stope. Access to the site comprised a strike-parallel development, the abandoned stope area as well as two raise tunnel sections. The stope was actually abandoned for mining, because of the presence of several potholes affecting the block. The ERT method was able to clearly map out these pothole structures, as can be seen in Figure 7b.

It is interesting to note that, at the time, despite the above promising results, the platinum mining industry did not embrace the technology or invest in its further development. As pointed out in the AOK close-out report. Some of the reasons for this related to the fact that the technology was perceived as logistically challenging to apply. For example, the time required to complete these surveys amounted to at least two successive days, due in part to the time-consuming site preparation and data acquisition procedures. It is these and other technical challenges that the AOK ERT research efforts aimed to eliminate or mitigate.

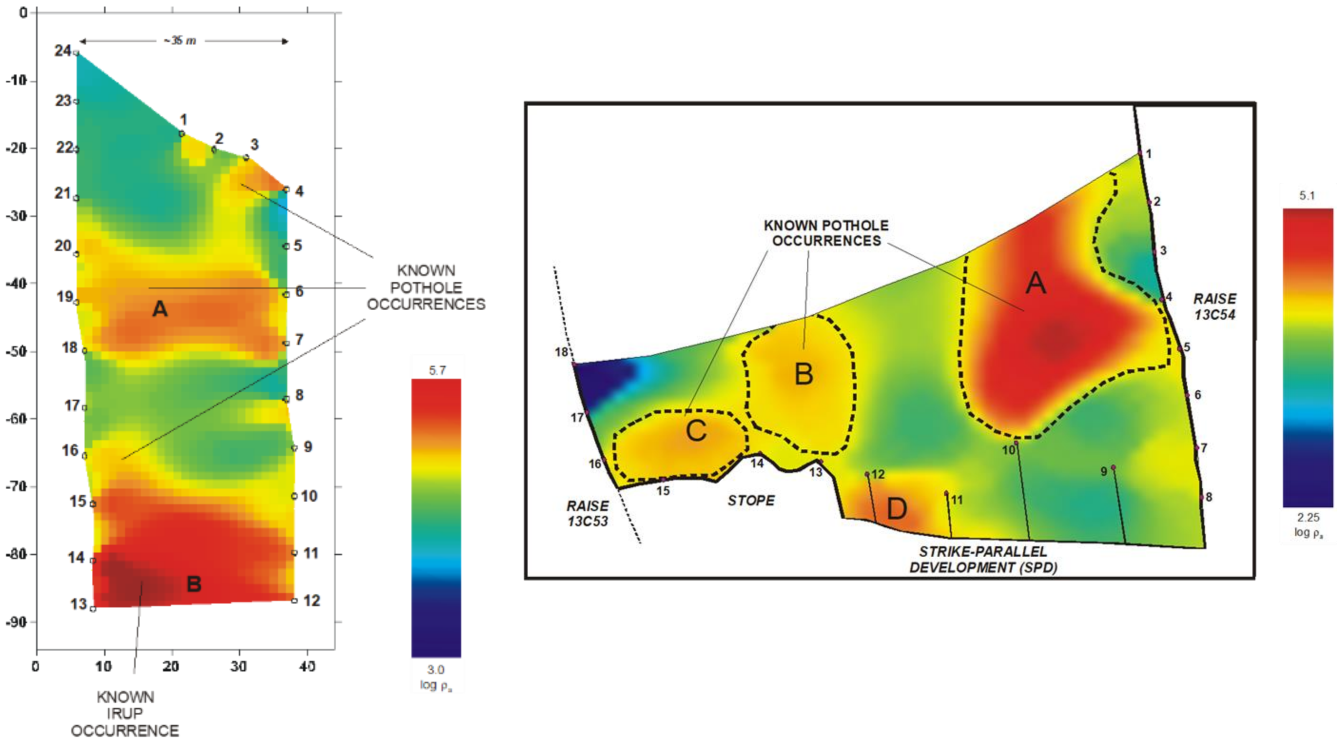
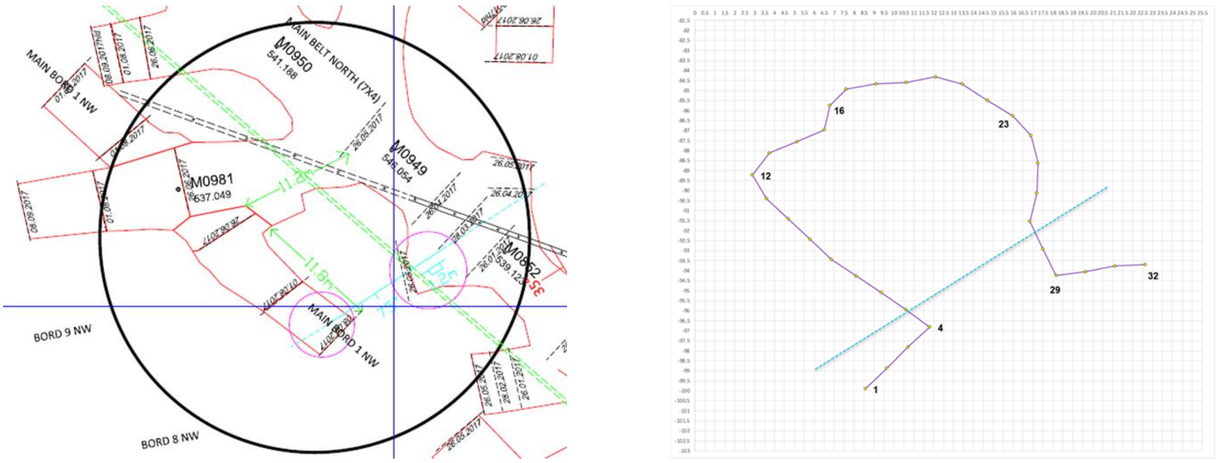


Figure 7. Historic in-mine ERT outputs

4.2 RECENT(AOK) CASE STUDY

The objective of this case study, conducted at Maseve Mine, was to image a known fault structure that affected the continuity of the Merensky Reef horizon in a small, horse-shoe-shaped pillar (Figure 8a and 8b). Most of the pillar structure was on reef, while the 'neck' and 'shoulder' part of the survey area was thrown off-reef by the inferred fault.



The area of interest (horse-shoe-shaped pillar) and the inferred fault, the finite-element discretisation of the survey area, as well as the location of the resistivity electrodes are indicated on the right

Figure 8. Maseve mine plan showing the ERT survey area location and geometry

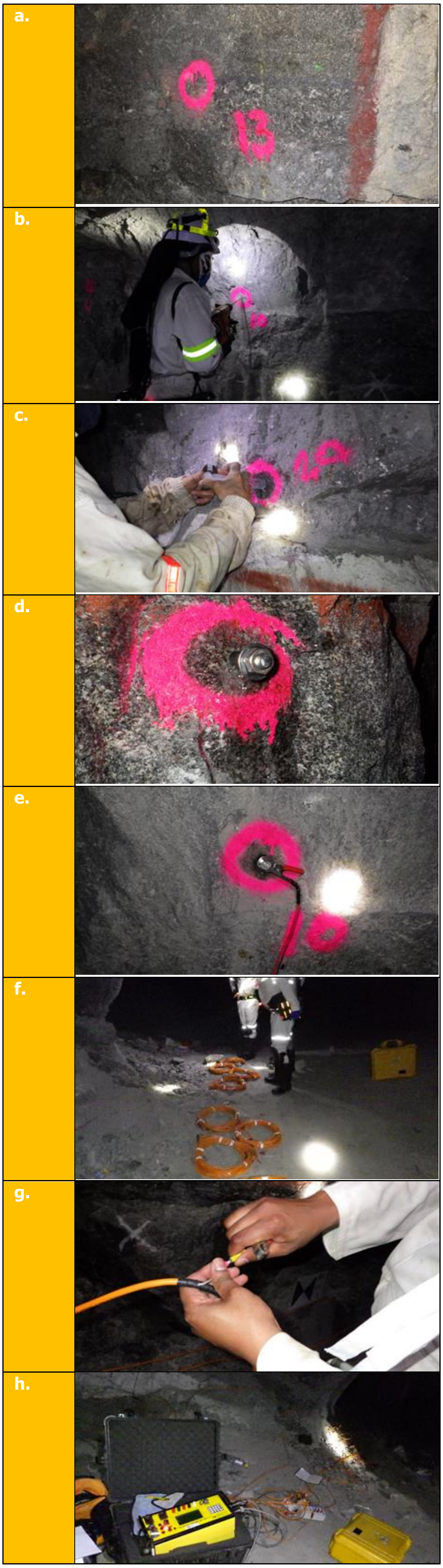


Figure 9. Steps of ERT data acquisition illustrated

The sequence of pictures in Figure 9 reflects the different steps of site preparation that was referred to in Section 3.2. Figure 9a shows an electrode location marked with spray paint; Figure 9b shows a member of the survey team drilling an electrode pilot hole; in Figure 9c, some electrode coupling gel is inserted into the pilot hole, prior to inserting the electrode bolt; Figure 9d shows a close-up view of an inserted and fastened rawl bolt; Figure 9e shows the survey team laying out the multi-core cables used to connect all the electrodes to the control unit; Figure 9f shows a short connecting or take-out cable used to electrically connect the electrode bolt to a conductor take-out on the multi-core cable; in Figure 9g the other end of the take-out cable is connected to the multi-core cable; Figure 9h shows the AGI Supersting resistivity system to which all the electrodes are connected.

Note: two significant technological advances that were implemented in the AOK ERT research deserve a mention: Firstly, with reference to Figure 9b, the portable drilling technology have improved to such an extent that the time required for drilling of electrode holes have been reduced by more than 50%, compared to the PlatMine era surveys. Secondly, with reference to Figure 9h, the modern automatic/programmable ERT system is capable of acquiring data 4-5 times faster than was possible with the equipment used during the PlatMine era.

Figure 10 shows the first-pass output image that was produced after the survey. Quantitatively, the correlation between the observed image and the inferred geological scenario is good. As was anticipated, the image shows a more conductive (on-reef) portion within the pillar and a relatively rapid transition to more resistive rock in the 'neck' and 'shoulders' of the pillar.

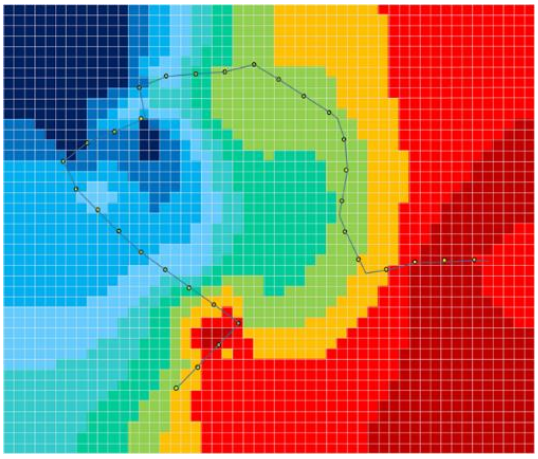


Figure 10. First-pass output for the Maseve ERT survey

The next step in the ERT process also reveals a significant advance in terms of making the output more user-friendly for the end-user. The image in Figure 10 does provide insightful information, but it would be more useful in a digital format that can be integrated with mine layout or planning information. This was achieved by exploiting an existing mine plan that was based on a LIDAR point cloud (Figure 11a). It was possible to zoom in on the ERT survey area and extract the global (mine) coordinates of selected points (electrode locations) in the ERT survey.

A coordinate transformation can then be done using standard transformation methods to transform all the ERT pixel coordinates to global coordinates. The output can then be exported in a format that can be read by the mine's CAD or planning software or any other 3D visualisation software. Figure 11b shows the ERT output image (and electrode locations) overlain on the mine plan in a 3D visualisation environment. In this example the software tool Voxler was used for this purpose. The georeferenced ERT output was in a CSV (column/text) file format for import into Voxler.

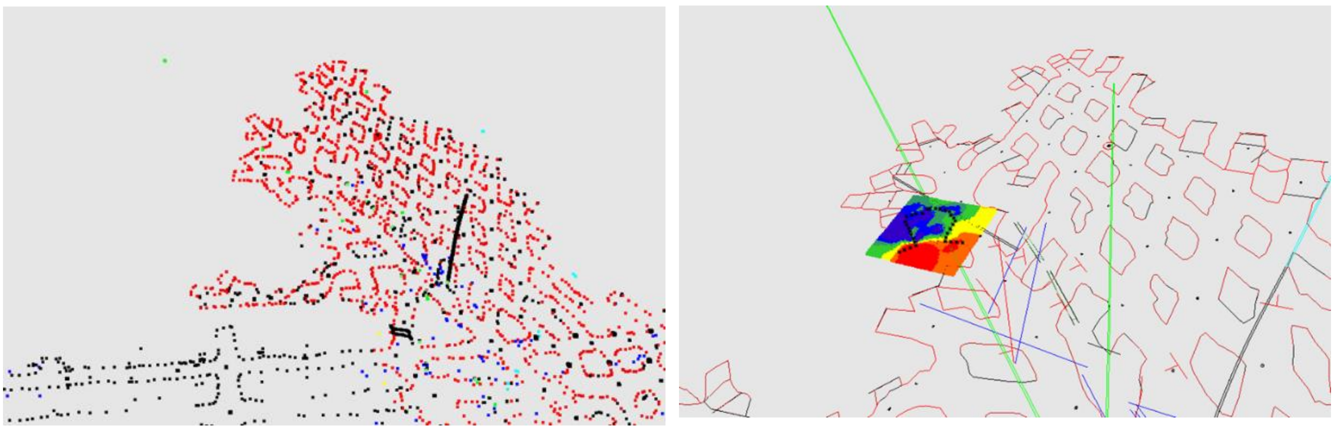


Figure 11. Point cloud version of a Maseve mine plan and ERT output integration

CONCLUSION

It has been demonstrated that in-mine electrical resistance tomography (ERT) is a promising reconnaissance tool for the niche application of detecting unseen disruptive geological structures several tens of metres ahead of mining. To be effectively applied, a tunnel-to-tunnel geometry is required; for example, two adjacent raise tunnels or on-reef, down-dip boreholes. Following the PlatMine research programme of the mid- 2000s, the local mining industry did not adopt and implement the technology, due in part to the challenging logistics of the in-mine application of ERT. The AOK research programme aimed to optimise in-mine ERT by resolving some of the key logistical challenges.

The AOK study demonstrated that technological advances in ERT hardware capabilities (including data acquisition rates), as well as improvements in battery and portable drilling technology had contributed to making the in-mine ERT application a more attractive option to the local mines. These advances alone would potentially make single-shift ERT surveys possible. Other notable optimisation-related achievements included the compilation of a spreadsheet-based survey planning tool and of this user guideline document. This guideline document provides the basic background information to enable non-specialist users to plan and execute in-mine ERT survey. The importance of designing and planning a survey is emphasized and several pitfalls of the application is highlighted in this document.

The proposed niche application for in-mine ERT is the detection and delineation of potholes or other reef disruptions in to-be-mined blocks of virgin ground.

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	AOK18WP2.7	Milestone 1. Desktop study (M. van Schoor – CSIR)
		Milestone 2. Baseline assessment based on numerical/experimental data (M. van Schoor – CSIR)
2019-2020	AOK19WP3.2	Milestone 1. Project start-up memo, including list of previous recommendations and corresponding action items (M. van Schoor – CSIR)
		Milestone 2. Memo describing/justifying selection of survey approach and hardware (M. van Schoor – CSIR)
		Milestone 3. Test site secured and authority to proceed from mining company (M. van Schoor – CSIR)
2020-2021	AOK20WP4.2	Milestone 1. Milestone report with survey results, simulation-based survey planning and groundtruthing against known geology (M. van Schoor – CSIR)
		Milestone 2. Milestone report which will include quantitative assessment of ERT survey performance in terms of implemented technological advances (M. van Schoor – CSIR)
		Milestone 3. Demonstration of ERT output incorporation into tangible and useful outputs for use by mines in a milestone report (M. van Schoor – CSIR)
		Milestone 4. Agreement reached with a mining operation to conduct field trials which will be included in a milestone report (M. van Schoor – CSIR)
		Milestone 5. Milestone report with survey results, simulation-based survey planning and groundtruthing against known geology (M. van Schoor – CSIR)
		Milestone 6. In-mine ERT technology implementation roadmap and final report (M. van Schoor – CSIR)

Year	Workpackage number	Milestone number & title
2021-2022	AOK21WP5.2	Milestone 1. Project Initiation (M. van Schoor – CSIR)
		Milestone 2. Active-tunnel seismic data activities (M. van Schoor – CSIR)
		Milestone 3. Combined passive-active seismic data activities (M. van Schoor – CSIR)
		Milestone 4. Final seismic report (M. Manzi – WITS and M. van Schoor – CSIR)
		Milestone 5. ERT – hardware/software optimisation (M. van Schoor – CSIR)
		Milestone 6. ERT – trial survey / LIDAR (M. van Schoor – CSIR)
		Milestone 7. ERT – seamless data integration ((M. van Schoor – CSIR)
		Milestone 8. Seismic/ERT data integration report (M. van Schoor – CSIR)
2022-2023	AOK22WP6.2	Milestone 1. GPR close-out report (T. Kgarume – CSIR)
		Milestone 2. ERT close-out report (M. van Schoor – CSIR)
		Milestone 3. GPR/ERT training workshop(s) (M. van Schoor – CSIR and T. Kgarume - CSIR)