

**REAPPRAISAL OF LEGACY REFLECTION SEISMIC DATA USING
ADVANCED PROCESSING TECHNIQUES AND SEISMIC ATTRIBUTES**

MICHAEL CLIFFORD WESTGATE

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DECLARATION

I declare that this thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.



Michael Clifford Westgate

Student Number: 720646

Signed on the

28th day of July 2020 at Morningside Village Estate, Johannesburg

ABSTRACT

Reflection seismic data, once processed and interpreted, are typically archived and sometimes even discarded. This may happen especially when the data are initially acquired with specific goals in mind (such as mineral exploration) and are deemed as no longer useful after those goals have been realized. It is tempting to regard used data as useless, however in this thesis, I show how legacy seismic data can sometimes hold more value than they are credited and that, by repurposing them, they can provide insight into further areas of study. This is done via three investigations. First, I reprocess a legacy seismic profile originally intended for gold exploration in the southwestern margin of the Archaean (3.7 – 2.6 Ga) Kaapvaal Craton (South Africa) and repurpose it for iron-oxide prospection. By integrating borehole data and seismic attributes, I quantify the subsurface geometry of haematite-hosting metasediments of the 2.64 – 2.43 Ga Griqualand West Supergroup to reveal some degree of folding that locates these metasediments (~ 500 m thick) at a mineable depth of 900 m. This profile, located near Sishen iron mine, thus enhances our understanding of the strato-structural architecture and ore resource evaluation within the area. Second, I show how reprocessing a legacy seismic profile also intended for gold exploration can provide insight into the tectonically rich setting of the western margin of the Kaapvaal Craton, where the 1.2 Ga Kheis Province, 145 Ma Morokweng impact crater, and the associated first-order scale structures contribute in constraining the complex tectonic history of the region. Integrating the profile with borehole data suggests a significantly different interpretation of the supracrustals and their interaction with first-order scale faults to already-published interpretations. Furthermore, the reprocessed data exhibit strikingly improved imaging of the overlying Phanerozoic cover, revealing the 250 Ma Dwyka and 1.2 – 1 Ma Kalahari Group sediments to show significant disruptions as a result of neotectonic activity. Third, I demonstrate how application of novel complex seismic attributes to legacy seismic cubes from both the onshore hard rock Witwatersrand Basin and the offshore Bredasdorp Basin can better improve the detection of thin (~ 2 m thick) gold-bearing horizons and hydrocarbon reservoirs, respectively. Before detailing these investigations, I lay the theoretical foundation thereof by providing sufficient geological background of each setting, a comprehensive review of the seismic processing sequence as applied to the two legacy profiles, a motivation for the value of legacy data as well as the challenges of its reappraisal, and an expository description of the composite seismic attributes used in my investigations.

DEDICATION

This thesis is dedicated to my God and Saviour, Jesus Christ, whose beautifully complex and intricate creation will never cease to fascinate and captivate me. Not only this, but the gift of rational thought and rigorous inquisition that allows us to discover such beautiful complexity which points to the grand designer is one of my biggest appreciations in life.

“Great are the works of the LORD, studied by all who delight in them.”

Psalm 111:2

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LIST OF PAPERS

This thesis is based on the following manuscripts, which are referred to in the text by their Roman numerals:

- I. **Westgate, M.C.**, Manzi, M.S.D., James, I., Harrison, W. (2020). New insights from legacy seismic data: reprocessing of legacy 2D seismic data for imaging of iron-oxide mineralisation near Sishen mine, South Africa. *Geophysical Prospecting*.
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Additionally, I have made the following contributions during my PhD studies that do not form part of this thesis:

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- V. **Westgate, M.C.**, Manzi, M., Malehmir, A. (2019). Reassessment of Legacy 2D Seismic Reflection Data from the Kaapvaal Craton using Unconventional Methods. 16th SAGA Biennial Conference & Exhibition 2019.
- VI. **Westgate, M.C.**, Manzi, M., Cooper, G., Durrheim, R. (2019). An alternative reflection seismic interpretation approach based on symmetry: Case studies from oilfield and goldfield data in South Africa. 8th International Geosciences Student Conference 2019.
- VII. **Westgate, M.C.**, Manzi, M., Cooper, G., Durrheim, R. (2018). Symmetry as an Alternative Seismic Attribute: Case Studies from the Hard Rock and Soft Rock Environments, South Africa. 80th EAGE Conference and Exhibition 2018.
- VIII. **Westgate, M.C.**, Manzi, M., Cooper, G., Durrheim, R. (2017). Theoretical Overview of Complex Seismic Attributes and Applications to Soft and Hard Rock Environments in South Africa. 15th SAGA Biennial Conference & Exhibition 2017.
- IX. **Westgate, M.C.**, Manzi, M. Theoretical overview of complex seismic attributes: Applications to soft and hard rock environments in South Africa. International Geophysical Conference, Qingdao, China 2017.

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LIST OF ABBREVIATIONS

AGC	Automatic gain control
AVO	Amplitude versus offset
CDP	Common depth point
CVS	Constant velocity stack
CMP	Common midpoint
DMO	Dip moveout
FFT	Fast Fourier transform
FT	Fourier transform
IFFT	Inverse Fast Fourier transform
NMO	Normal moveout
PreSTM	Prestack time migration
PSTM	Poststack time migration
RMS	Root mean square
SEG	Society of Exploration Geophysicists
SNR	Signal-to-noise ratio
SPS	Shell processing support
TAR	True Amplitude Recovery
TWT	Two-Way-Time
WFT	Windowed Fourier transform

1 INTRODUCTION

Reflection seismics is well-known for its unprecedented ability to accurately quantify the geometry and extent of subsurface bodies, making it a useful tool in multiple areas of applicability. For example, it has been used extensively in the hard rock settings by the mineral exploration industry for targeting deeply buried metals such as gold and iron for mining potential (e.g. [Manzi et al., 2013](#); [Malehmir et al., 2017](#); [Markovic et al., 2019](#)), as well as for deep crustal and tectonic investigations (e.g. [Tinker et al., 2002](#); [Dehghannejad et al., 2012](#); [Tankard et al., 2012](#); [Buntin et al., 2019](#)). Further applications of reflection seismics can be found, for example, in soft rock settings for hydrocarbon exploration (e.g. [Bouvier et al., 1989](#); [Boyd et al., 2011](#); [Isiaka et al., 2017](#)), geotechnical characterisation of urban environments (e.g. [Brodic et al., 2017](#); [Salas-Romero et al., 2019](#)), and carbon sequestration (e.g. [Popik et al., 2020](#)). As such, it has been an active and rapidly developing field of research since its inception in the early 20th century. The power of reflection seismics lies in its accuracy and typically strong signal component compared to noise, quantified by the signal-to-noise ratio (SNR). This is due to the large data redundancy that results from the great fold multiplicity found in a typical reflection seismic survey.

The terms “hard rock” and “soft rock” are defined primarily by the type of rock being described and hence its depositional environment. In general, “hard rock” is associated with igneous and metamorphic rocks that generally have a complex and irregular subsurface structure, and “soft rock” is associated with sedimentary rocks that typically have a simple and uniform structure (i.e. regular dip, thickness, etc.) ([Hall, 1988](#)). The geology of South Africa is predominantly characterised by hard rock settings, as detailed in Chapter 2, and these are frequently accompanied by mineral deposits such as volcanogenic massive sulfide deposits and banded iron formations ([Allen et al., 2008](#); [Ahmadi, 2015](#))

In South Africa, reflection seismics has been used historically to investigate the deep crustal structure and tectonics of the lithosphere, with specific attention to the ca. 3.7 – 2.6 Ga Kaapvaal Craton (Figure 1.1), the stable core of the southern African crust. On the western margin of the craton, for example, the relatively unconstrained boundary between the Kaapvaal Craton and the Namaqua-Natal fold belt (Figure 1.1) was investigated by [Stettler et al. \(1998; 1999\)](#) using a deep (16 s two-way-time), 226 km long reflection seismic profile that was acquired in 1991, along with supporting magnetotelluric, gravity and magnetic data to examine and characterise the Kheis Province that overlies this boundary. The Kheis Province was proposed to be the consuming margin of a tectonic plate collision ([Stettler et al., 1998; Stettler et al., 1999](#)). Further reflection seismic data were collected between 1983 and 1994 across the Kaapvaal Craton by the (Anglo) Gold Division of Anglo American Corporation (now AngloGold Ashanti Ltd.) in the search for deep-seated gold hosted by possible outlying units of the Witwatersrand Supergroup. Over 36 000 km of 2D reflection seismic data were collected over the eastern, central and western margins of the craton, most of which were made available for research (e.g. [Tinker, 2001](#); [Tinker et al., 2002](#)). Two particular 6 s TWT profiles from these data were also located near the Kheis

Province on the western edge of the Kaapvaal Craton. These profiles, named KBF01 and KBF03A, were interpreted by [Tinker et al. \(2002\)](#) and are structurally complex, comprising geological contributions from multiple stratigraphic packages and are constrained by multitudes of faults and folds, as well as crosscutting intrusives. The importance of these two lines is that they are featured as the primary data sources for [Paper I and Paper II](#), as detailed in later sections of the thesis, for their imaging potential of mineral and tectonic features, respectively.

The reflection seismic method has been used to investigate not only the tectonic structure of the Kaapvaal Craton in South Africa, but also its great mineral wealth of gold, platinum, oil and coal (e.g. [Durrheim, 1986](#); [Stevenson et al., 2003](#); [Malehmir and Bellefleur, 2010](#); [Manzi et al., 2015](#); [Mkhabela and Manzi, 2017](#); [Scheiber-Enslin and Manzi, 2018](#)).

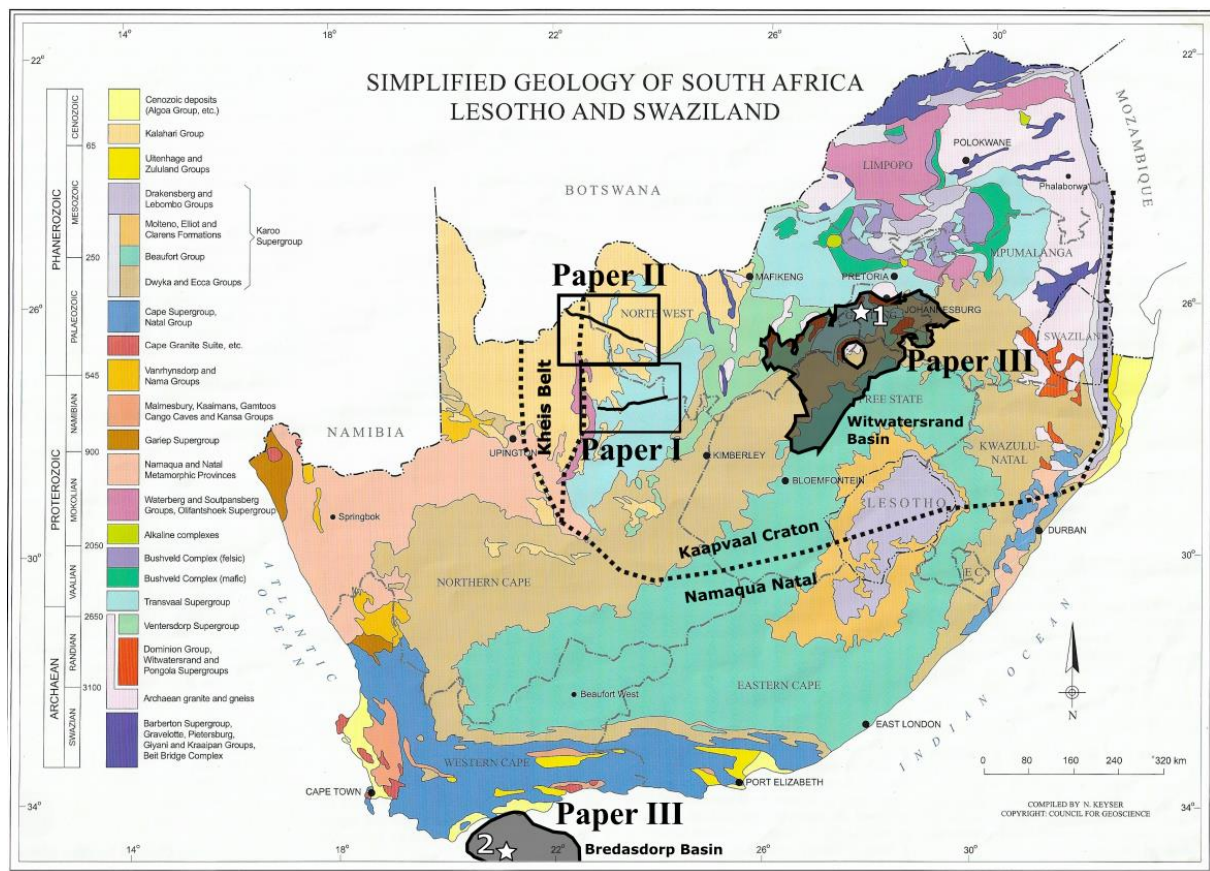


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Of the various mineral prospection projects conducted across the Kaapvaal Craton, one of the most notable are the gold-bearing rocks found throughout the Witwatersrand Basin in the centre of the craton (Figure 1.1). These gold deposits, from which over 30% of the world's total historically mined gold originates ([Kirk et al., 2003](#); [Norman and Whitfield, 2006](#)), occur predominantly within quartz pebble

conglomerates known as reefs. The origin of the Witwatersrand gold has been highly debated, with three main hypothesis being proposed to explain its genesis: (1) placer model suggesting that gold was introduced into the basin as clastic particles by sedimentary processes (e.g. [Minter, 1978](#)); (2) hydrothermal model suggesting that gold precipitated from hydrothermal aqueous solutions during post-depositional alteration ([Phillips and Law, 2000](#); [Phillips and Powell, 2011](#)); (3) modified placer model which suggests that gold was introduced as detrital clastic particles, which were remobilized after burial, causing compositional changes within the ore ([Frimmel and Hennigh, 2015](#); [Heinrich, 2015](#)). The discovery of the Witwatersrand's extensive gold deposits led to a surge in the 1980s in reflection seismics activity for gold prospecting (e.g. [Durrheim, 1986](#); [Pretorius, 1989](#); [Campbell, 1990](#); [Pretorius, 2003](#)) and subsequently resulted in the first 3D seismic survey of hard rock hosted minerals in 1987 ([Campbell and Crotty, 1990](#)). Since 1987, the gold mines in South Africa have used the 3D seismic reflection surveys to facilitate accurate mine planning and design. For example, in 2003 Gold Fields Ltd. conducted a 3D seismic survey in the West Rand goldfield of the Witwatersrand Basin covering Kloof and South Deep gold mines ([Manzi et al., 2012](#)). These datasets are used as one of the case studies in [Paper III](#) for application of modern seismic attributes to enhance the detection of two gold-bearing reefs, as detailed in this thesis.

In addition to the gold deposits in the Witwatersrand Basin, other mineral deposits of significance have been discovered across the Kaapvaal Craton, such as the platinum-group elements in the Bushveld Igneous Complex, as well as chromium and uranium deposits across the craton ([Stevenson and Durrheim, 1997](#); [Stevenson et al., 2003](#); [Cawthorn, 2010](#)). Not least of these mineral deposits is the high-grade, haematite-rich banded ironstones found along the western margin of the Kaapvaal Craton (e.g. [Bau and Dulski, 1996](#); [Stoch et al., 2017](#); [Basson et al., 2018](#)). One of the world's largest open-pit iron mines, Sishen mine, is located within this region near Kathu town in the Northern Cape province of South Africa. The 14 km long mine targets a 400 m deep 986-Mt haematite orebody ([Stoch et al., 2017](#)). Investigation of the iron-oxide, addressing primarily the ore mineralogy, has been limited to observations within the Sishen open pit and prior drill core data ([Van Schalkwyk, 1984](#); [Van Schalkwyk and Beukes, 1986](#); [Alchin and Botha, 2005](#); [Smith and Beukes, 2016](#); [Basson et al., 2017](#)). No reflection seismic surveys have been used to characterise the iron mineralisation found at or near Sishen mine and the only surveys within the region are coincidental, including the previously mentioned 2D seismic profile KBF01, which is reappropriated in [Paper I](#) for iron-oxide prospecting southeast of Sishen mine (Figure 1.1), as detailed in later sections of the thesis.

South Africa also exhibits a considerable presence of hydrocarbons; not only is coal mining prevalent in South Africa, evidenced by the fact of being among the world's top six coal producers, there has also been a plethora of offshore gas and oil field discoveries along the southern continental shelf of South Africa. [Wood \(2015\)](#) describes the history of South Africa's offshore hydrocarbon prospecting using reflection seismics and other geophysical methods. Two of these discoveries, the Oribi and Sable oil

fields located within the Bredasdorp Basin (Figure 1.1), were of notable significance. The Oribi oil field, discovered in 1990 by Soekor (now PetroSA upon mergence with Moss gas Pty Ltd in 2002), was the first oil field development in South Africa, and the Sable oil and gas field, discovered in 1989, produced between 20 and 25 million barrels during its production period from 2003 to 2008 (Wood, 2015). The latter of these two, the Sable field, consists of two reservoirs (the E-BD oil reservoir and E-CE gas reservoir) that have been imaged by 3D reflection seismics and form one of the case studies of Paper III, as detailed in later sections, in which modern seismic attributes are utilized to improve the interpretation of these legacy seismic data.

With the rapid advancement of technology, the reflection seismic method is constantly being re-evaluated and updated (e.g. Khaidukov et al., 2004; Araya-Polo et al., 2017; Wang et al., 2018). In general, since the inception of the reflection seismic method, the acquisition systems and available processing and interpretation algorithms have been modified and improved as technological abilities have increased (e.g. Karsli, 2006; Buzlukov et al., 2013; ten Kroode et al., 2013; Chen et al., 2015; Peng et al., 2018).

However, seismic designs and acquisition developments in the reflection seismic method do not imply that old or legacy seismic data are rendered useless. On the contrary, multiple studies in the literature have shown that outdated, or legacy, data can be reprocessed or reinterpreted using updated processing and interpretation tools. The results have proven remarkably fruitful; imaging resolution is improved, the signal-to-noise ratio is enhanced, and overall geological models are refined (e.g. Malajczuk et al., 2016; Manzi et al., 2018; Ketelhodt et al., 2019; Manzi et al., 2019; Malehmir et al., 2019; Manzi et al., 2020). Not only are the legacy data improved, but are done so in an efficient and cost-effective way, since the data do not need to be collected. This bypasses the cost of data acquisition but at the expense of being limited by the original acquisition parameters and location. This idea of legacy data reappraisal is central throughout this thesis; all of the seismic data used throughout Papers I to III are legacy data and are either reprocessed and interpreted (Paper I and II) or reinterpreted (Paper III) to provide further insight into their geological locations as outlined in the Thesis Structure below.

1.1 Aims and Objectives

In this thesis, I show how legacy reflection seismic data can be reprocessed and reinterpreted with substantial improvement, with the aim of denying the commonly accepted belief that legacy data have “run their course” and are of no further use. I demonstrate this through three different case studies, featured in Papers I to III.

- **Paper I:** The aim of this paper is to demonstrate how legacy seismic data can be reprocessed and reappraised for alternate mineral prospecting. In particular, 2D legacy seismic data that were originally acquired for gold exploration in 1994 conveniently overlie iron-oxide

mineralisation near the Sishen iron mine in southwestern of the Kaapvaal Craton (South Africa), and are reprocessed with the aim of better imaging the iron-oxides and characterising their structure for future resource evaluation and future mining endeavours.

- **Paper II:** This paper seeks to demonstrate how legacy seismic data from 1994 can be reprocessed for improved imaging of tectonostratigraphic sequences. More specifically, the goal of this paper is to reprocess and interpret a legacy 2D seismic profile located on the north-western margin of the Kaapvaal Craton in South Africa, where it interfaces with the Kheis Province, to provide insight into strato-structural architecture of this region. The reprocessed seismic data are supported by instantaneous seismic attributes for interpretation.
- **Paper III:** In this paper, modern and novel seismic attributes are applied to high-resolution legacy seismic data from both hard rock and soft rock settings with the aim of better constraining the structure of subsurface targets. This is done via two case studies. Firstly, seismic attributes are applied to legacy 3D seismic legacy data from Kloof gold mine in the West Rand goldfields of the Witwatersrand Basin that were acquired in 2003 to enhance the detection of thin gold-bearing reefs that exhibit faulting and folding, thus testing the applicability of novel attributes on the hard rock seismic data. Secondly, these attributes are applied to merged 1996 and 2000 legacy 3D seismic data from the offshore Bredasdorp Basin with the goal of enhancing the interpretation of the hydrocarbon reservoir of the Sable oil and gas fields, thus testing the application of novel attributes on soft rock seismic data.

1.2 Thesis Structure

This thesis is based primarily on three papers and is characterised by three underpinning topics: legacy reflection seismic data, seismic reprocessing, and seismic attributes. These three topics and the three manuscripts to which they are applied are organised in this thesis. Chapters 2 to 6 are dedicated to the relevant geophysical theory and the manuscripts are presented in chapters 8 to 10.

Chapter 2 gives an integrated overview of the geological settings of each of the three papers. Firstly, the western margin of the Kaapvaal Craton and its interface with the Kheis Province is expounded upon, giving an overview of the strato-structural architecture of this area, the location of the legacy profile KBF03A in [Paper II](#). Secondly, an overview of the iron mineralisation found within the western margin of the Kaapvaal Craton is given, as well as its origin and historic mining activities at Sishen mine, some 140 km south of the location of the study area of [Paper I](#). The legacy profile KBF01 that is discussed in this paper is located ~ 15 km south of Sishen mine. Thirdly, the stratigraphy at Kloof gold mine in the Witwatersrand Basin, and its place in the basin's general stratigraphy, is given, as well as the origin and structure of the gold-bearing horizons pertinent to the first case study of [Paper III](#). Finally, an overview of the Sable E-BD and E-CE oil and gas fields within the Bredasdorp Basin is given, where the second case study of [Paper III](#) is located.

Chapter 3 gives a detailed theoretical overview of the seismic processing steps that were used to reprocess seismic profiles KBF01 and KBF03A, discussed in [Papers I and II](#), respectively. The processing steps and associated parameters used for each profile are first summarized, after which each processing step is treated theoretically with a real data example accompanying most of the steps. These general steps include: pre-processing and quality control; refraction statics correction; 1D and 2D frequency filtering; deconvolution; velocity analysis and stacking; and migration. The aim of this chapter is to provide sufficient background material of seismic processing steps as applied in [Papers I and II](#), without overly deviating into related topics.

Chapter 4 is an expository of legacy seismic data reappraisal. Firstly, the value of reassessing legacy data is motivated with a brief literature review as well as an example taken from [Paper II](#), in which reprocessing the seismic profile significantly improved the stratigraphic imaging. Secondly, some of the reprocessing challenges concerning the two seismic profiles discussed in [Papers I and II](#) are reviewed.

Chapter 5 is a brief overview of the theory underpinning seismic attributes. The topic of seismic attributes is itself colossal and thus this chapter is restricted to the theory of instantaneous seismic attributes, as well as the theory behind the novel seismic attributes based on symmetry and attribute composites, both of which are used in [Paper III](#) to enhance the interpretation of the legacy seismic data from the Witwatersrand and Bredasdorp basins.

Chapter 6 is a list of the references used in Chapters 1-5.

Chapter 7 presents summaries of each of the papers in sequential order.

Chapter 8, Paper I, demonstrates how reprocessed legacy seismic data can be used for iron-oxide (and in general, mineral) prospecting, despite being originally collected for gold exploration at an expected depth (> 3 km) much deeper than the iron mineralisation (< 3 km depth). The reprocessed seismic profile images the iron-oxide mineralisation, located at depths between 200 m and 900 m, with greater clarity and allows for more confident interpretation. The seismic data are integrated with magnetotelluric, magnetic, borehole, and outcrop data to further constrain the structural interpretation. The investigation reveals the iron mineralisation to be located at mineable depths and provides useful information for potential future mining projects in the area.

As primary author, I fully prepared, reprocessed and generated displays of the reflection seismic data using Globe Claritas software, from raw shot gathers to final migrated section. This process is detailed in Chapters 3 and 4, as well as the papers. I also coded the program used to compute the synthetic seismogram using MATLAB software (see [Appendix A](#)). Additionally, I interpreted the seismic profile and integrated it with the other geophysical datasets, generated all the figures used in the manuscript, and prepared the manuscript of the paper, with guidance from second author Musa Manzi (my

supervisor). Third author Ian James assisted me with the computation of the first break traveltimes tomograms and assisted with manipulation of raw legacy data. Fourth author Wesley Harrison assisted with the processing and interpretation the magnetotelluric data.

Chapter 9, Paper II, deals with using today's standard seismic processing algorithms with particular attention to the strato-structural architecture of the western Kaapvaal Craton margin. In this paper, we show that by reprocessing the legacy data, we are able to image the Phanerozoic and Archaean to Palaeoproterozoic metasediments found in the subsurface of the area, as well as their interface with the Archaean basement up to 7 km depth with notably greater clarity. In particular, reflections associated with the Mesozoic Karoo sediments and Cenozoic Kalahari sediments are significantly improved. Subsequent application of modern seismic attributes improves interpretability further and reveals that these sediments have likely undergone neotectonic events, possibilities of which are postulated. Furthermore, the improvement in imaging of the underlying Palaeoproterozoic metasediments provides a good basis on which a revised tectonic history is constructed. As the paper has developed, two major discussion topics have evolved. The first is around the Phanerozoic neotectonics and what mechanism may have caused the evident disruptions within the Mesozoic and Cenozoic sediments. The second topic is the general and complex tectonic history of the region that involves a reinterpretation of the metasediments and a major fault that runs through the entire metasedimentary package and into the basement within the seismic profile, originally interpreted as a normal fault but now suggested to have a more complex nature with a polyphasal tectonic history.

As the primary author of this paper, I fully prepared, reprocessed and generated displays of the reflection seismic data using Globe Claritas software, with the guidance of secondary authors Musa Manzi and Alireza Malehmir. Further to this, I coded and computed all seismic attributes presented in the paper, as well as the synthetic seismograms using MATLAB software and authored most of the text pertaining to the geophysics. Musa Manzi assisted with the preparation of the manuscript and compiled all the images for the paper. Musa Manzi, Roger Gibson (my co-supervisor) and Marco Andreoli assisted with the structural interpretation of the profile and boreholes as well as with valuable discussion points regarding the tectonic history of the profile. Adam Bumby assisted with the neotectonic interpretations.

Chapter 10, Paper III, comprises two case studies in which novel seismic attributes are applied to legacy seismic data from both hard rock and soft rock settings to improve the interpretability of the legacy 3D reflection seismic data and to provide high-quality and high-resolution deep-targeting solutions for mineral and hydrocarbon exploration. These attributes are computed by taking two existing instantaneous attributes (from a selection of instantaneous amplitude, cosine of instantaneous phase, and symmetry, the last of which is a new approach I developed) and hybridising them into a single instantaneous attribute that takes the form of a hue-saturation-intensity image and exhibits characteristics of both input attributes. The hard rock case study utilises 3D legacy seismic data from

Kloof gold mine in the Witwatersrand basin and enhances the seismic imaging of two gold-bearing reefs. The soft rock case study utilises 3D legacy seismic data from the offshore Bredasorp Basin, in which the subsurface characteristics and geometry of the Sable gas and oil fields are delineated more accurately.

My contribution to this paper as primary author involved conceptualising the novel symmetry attribute based on Hermitian symmetry in the Fourier transform, which I then coded using MATLAB (see [Appendix A](#)). I also scripted code that computes instantaneous attributes and compiles them into the novel “composite attributes”, as described in Chapter 10, and applied these attributes to the 3D seismic data from both case studies. I compiled most of the text in the paper and all of the images, with the assistance of Musa Manzi, Glen Nwaila and Sbonele Ngcongo.

Chapter 11 provides concluding remarks and an outlook for potential future research.

Appendix A contains all code, verbatim, that was developed during the period of my PhD research. This comprises three collections of code that were all scripted using MATLAB. The first code was used to compute the synthetic seismograms presented in Chapters 8 and 9 ([Papers I and II](#)). This code is unique in that it was compiled into a standalone program and distributed throughout the Seismic Research Centre at the University of the Witwatersrand, Johannesburg, where it has been used by a number of honours and masters students for their research projects. The code reads in velocity and density logs and allows the user, via a graphical user interface, to calculate an acoustic impedance log in the depth domain, convert it into the time domain and subsequently compute a synthetic seismogram with a selection of optional wavelets and a user-defined dominant frequency and sampling rate. The second code was used for the computation of the symmetry attribute, as well as the instantaneous amplitude and cosine of instantaneous phase. Also included is the code that incorporates two input attributes into a hue-saturation-intensity image to create the composite attributes that are detailed in Chapter 10. Third, and last, is the code used to assign unique identifiers to receiver and source pegs with unique locations. This code was used when preparing legacy data for reprocessing and is detailed in Chapter 4.

Appendix B contains copies of peer-reviewed extended abstracts that were submitted to various geophysical conferences and gatherings at which I presented talks over the extent of my PhD studies.

2 GEOLOGICAL BACKGROUND

This section provides a brief summary of the geological settings of each of the study areas presented in this thesis, which consist of the western margin of the Kaapvaal Craton (3.7 – 2.6 Ga), the Witwatersrand Basin and the Bredasdorp offshore Basin, all of which are in South Africa (see Figure 1.1). A more comprehensive description is given in the papers (Chapters 8-10).

[Papers I and II](#) use 6 s 2D legacy data collected near the western margin of the Kaapvaal Craton, where it interfaces with the Kheis Belt. [Paper I](#) investigates seismic imaging of the iron-oxide mineralisation hosted by metasediments within the Griqualand-West Supergroup (2.64 – 2.43 Ga) located at the south western margin of the craton and [Paper II](#) is concerned with the tectonic setting of the western margin of the craton. [Paper III](#) consists of two case studies, one associated with the gold-bearing horizons (reefs) of the Witwatersrand Basin at the centre of the Kaapvaal Craton and the other with the Sable oil and gas fields within the offshore Bredasdorp Basin, both of which involve 2D arbitrary lines extracted from the high-resolution 3D legacy seismic data.

2.1 Western Margin of the Kaapvaal Craton

The Kaapvaal Craton (Figure 1.1) covers an area of $\sim 1.6 \text{ Mkm}^2$, spanning over multiple countries in southern Africa. It formed between ~ 3.7 and 2.6 Ga by major granitic batholiths that intruded into and stabilised the continental crust. It served as the centre of major amalgamation of southern African crust ([Nguuri et al., 2001](#); [Fouch et al., 2004](#)), and has experienced multiple deformation events (e.g. [Walraven et al., 1990](#); [Van der Westhuizen et al., 1991](#); [Zhao et al., 1999](#); [Beach and Smith, 2007](#); [Dankert and Hein, 2010](#)), including a multitude of both extensional and compressional events, with both positive and negative tectonic inversions, as well as notable meteorite impacts, such as the ~ 2 Ga Vredefort and ~ 145 Ma Morokweng impact events (e.g. [Gibson et al., 1998](#); [Hart et al., 1997](#), respectively). To the south of the Kaapvaal Craton is the 1.2 – 1 Ga Namaqua-Natal Province (or fold belt) (Figure 1.1), and the boundary between these terranes is well exposed in the KwaZulu-Natal Province and southern part of the Northern Cape Province of South Africa ([Moen, 1998](#)). However, towards central Northern Cape, this boundary is much more elusive due to the Kheis Belt (Figure 1.1), a predominantly arenitic tectono-metamorphic transition zone between the Kaapvaal Craton and the Namaqua-Natal Province ([Vajner, 1974](#); [Moen, 1998](#)) that was thought to be 1.83 – 1.73 Ga until [Van Niekerk and Beukes \(2019\)](#) proposed a much younger ~ 1.2 Ga age. The boundary is further obscured due to the thick sand and calcrete cover of the Quaternary Kalahari Group, which before [Matmon et al. \(2015\)](#) was considered to be Tertiary. The Kheis Belt is considered by [Vajner \(1974\)](#) to be disturbed and reworked Archean crust during the ~ 1.8 Ga Kheis Orogeny, however it has been found that the Kheisian fabric of the belt is aged at <1.3 Ga, leading to the suggestion of the Kheis Belt to have been formed mainly during the Namaqua Orogeny (e.g. [Eglington, 2006](#)). It is near this transition zone that the seismic data presented in both [Papers I and II](#) have been acquired (see Figure 1.1, Figure 2.1, and

Figure 2.2), and thus particular focus is given to the geology of this region. The lithostratigraphies of the study areas of [Papers I and II](#) are discussed here and later summarised in Figure 2.3, which was adapted from [Papers I and II](#).

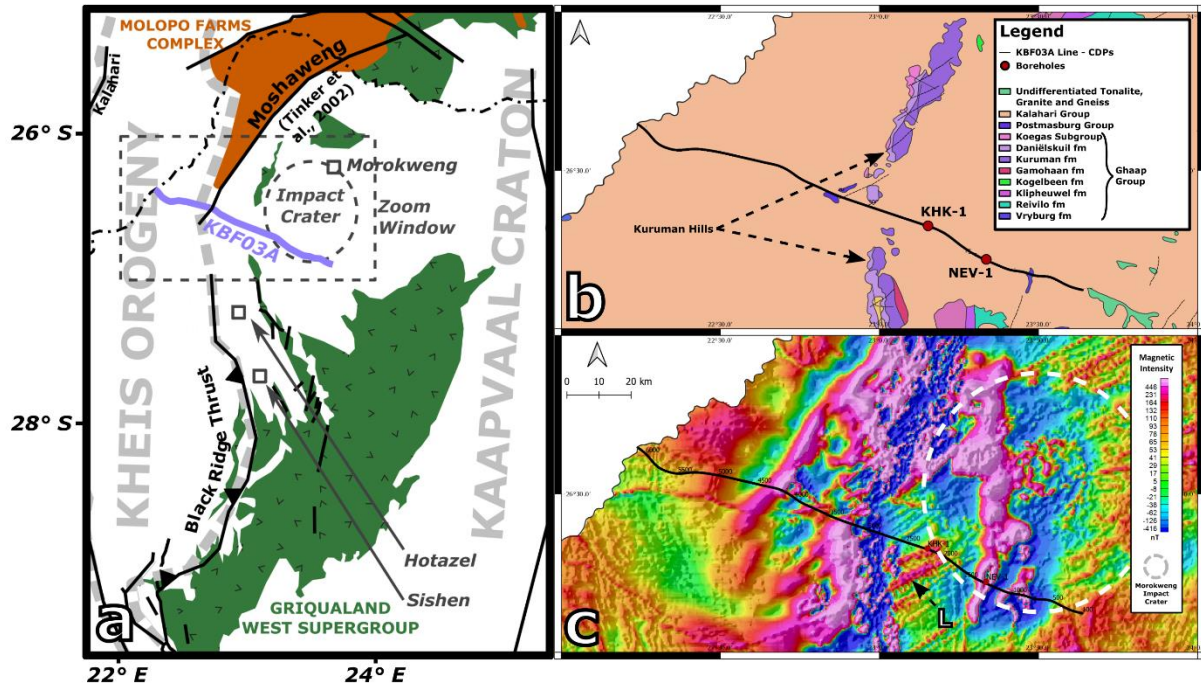


Figure 2.1: Overview of geological context for Paper II, showing the general tectonostratigraphy in the region (a), as well as the surface stratigraphy near the seismic profile KBF03A (b) and the corresponding magnetic map (c). The “Zoom Window” in (a) corresponds to the limits of (b) and (c), as well as that of the box in Figure 1.1. Figure adapted from [Paper II](#). Maps (b) and (c) adapted from [Council of Geoscience \(2019\)](#).

In terms of tectonics, the Kaapvaal Craton within the regions of study has been affected by several deformation events, including notably the Kheis Orogeny (~ 1.2 Ga), Pan-African Orogeny ($\sim 650 - 500$ Ma), the Cape Orogeny ($\sim 310 - 240$ Ma), the Gondwana breakup ($\sim 204 - 120$ Ma), and the Morokweng meteorite impact (~ 145 Ma). Evidence of these events, as proposed in [Paper II](#), is found in the stratigraphic structure of the rock units found within the area, contributions of which are from the Ventersdorp (2.78 – 2.64 Ga), Griqualand-West (2.64 – 2.43 Ga), Olifantshoek (1.93 – 1.85 Ga) and Karoo Supergroups (~ 250 Ma), all overlain by the expansive sediments of the Kalahari Group, as shown in Figure 1.1 and Figure 2.1b. Of particular interest, and a primary focus of [Paper II](#), is a major fault that intersects the seismic profile KBF03A discussed in [Paper II](#), and its effect on the units found within the profile. This fault has been interpreted as a normal fault by [Tinker et al. \(2002\)](#), who made use of the same legacy profile KBF03A from 1994. According to their interpretations, the fault has a downthrow of ~ 6.5 km and is an extension of the Moshaweng Fault. [Beukes et al. \(2019\)](#) interpreted the same fault as a thrust fault about 35 km north of the study area of [Paper II](#), leading to the proposition of a scissor fault. However, our findings in [Paper II](#) suggest that this fault experienced multiple episodes

of deformation involving reactivations. This proposition is supported by the reprocessed legacy seismic profile of [Paper II](#), which is reinterpreted using novel composite attribute analysis, as described in Chapter 9. Additionally, [Paper II](#) shows that the younger (< 300 Ma) sediment cover is also notably disturbed, which is only evident in the reprocessed profile, and provides possible explanations for the surprising neotectonics (see Chapter 9 for more detail).

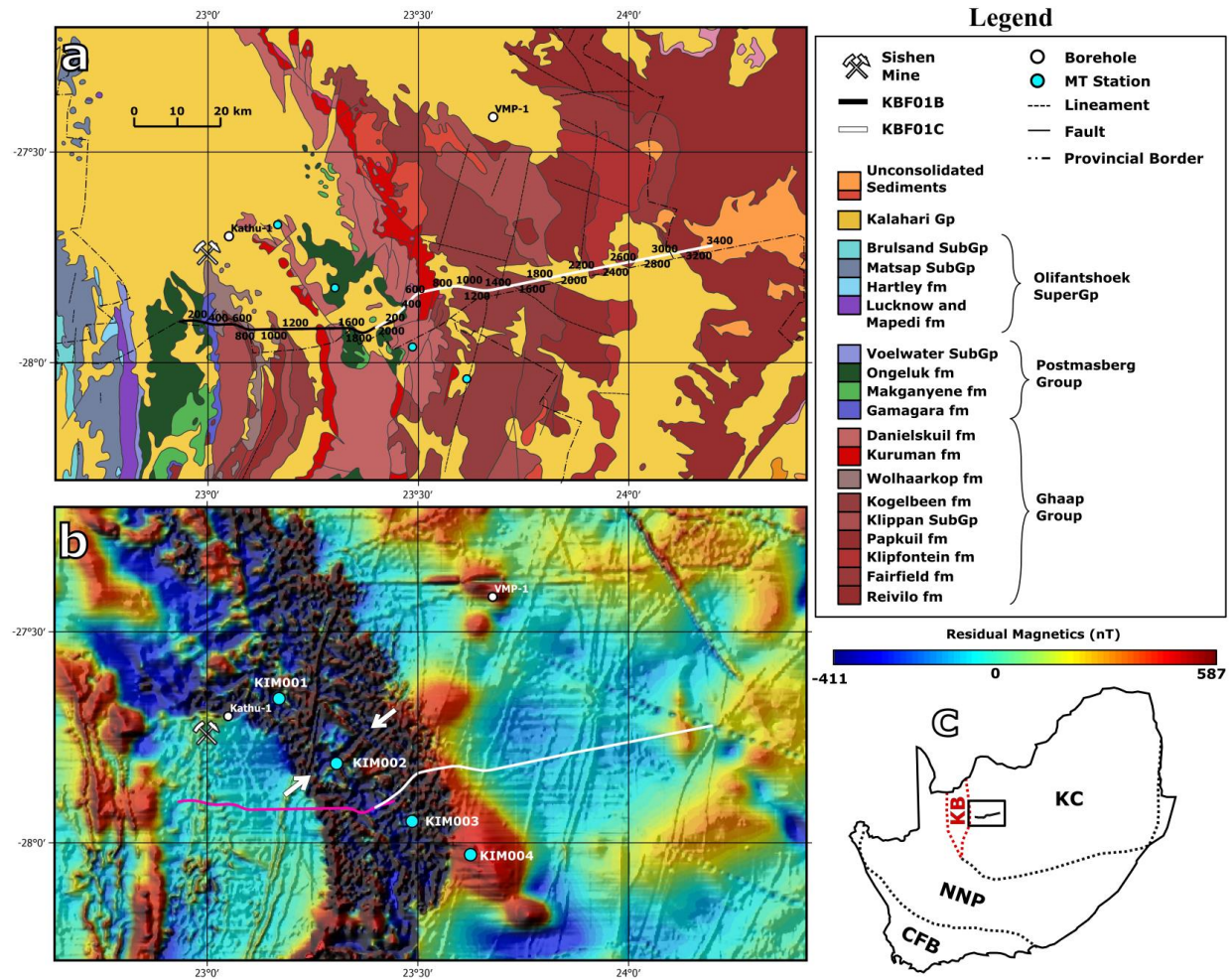


Figure 2.2: Overview of geological context for [Paper I](#), showing the surface stratigraphy near the seismic profile (a) and the corresponding magnetic map (b). The limits of (a) and (b) correspond to the box in Figure 1.1. The seismic profile KBF01 shown here constitutes two parts, as detailed in Chapter 8, which are coloured black and white in (a) and pink and white in (b). Figure adapted from [Paper I](#). Geological and Magnetic data obtained from [Council of Geoscience \(2019\)](#).

Also found along the western margin of the craton is an extensive occurrence of banded iron formations (BIFs) within the Griqualand-West Supergroup (GWS), made evident by the significant magnetic anomaly of the area (Figure 2.2b) ([Bau and Dulski, 1996](#); [Stoch et al., 2017](#); [Basson et al., 2018](#)). Haematite and conglomeritic iron ore are concentrated within the 2.5 Ga Ghaap Group, especially within the Kuruman Formation (Figure 2.2 and Figure 2.3), which hosts the ore being mined at Sishen mine (Figure 2.2) and is the target mineralisation for seismic imaging in [Paper I](#). Sishen mine is an

open-cast mine that targets a 986 Mt haematite reserve within the Kuruman Formation. The mineralisation has a significant acoustic impedance contrast with its host rock, enough for seismic detection, as determined by borehole log data and synthetic seismogram modelling (more detail can be found in Chapter 8).

The origin of the iron-oxides is uncertain, with multiple competing models proposed (see Chapter 8 for details), and the banded iron formations present are Lake Superior-type (Bailey and Tyler, 1960; Basson et al., 2017). Studies conducted on the mineralisation within the region are restricted to structural and geochemical analyses done in and around Sishen mine (e.g. van Schalkwyk and Beukes, 1986; Mortimer, 1995; Carney and Mienie, 2003; Basson et al., 2017; Stock et al., 2017), with no seismic data collected within the area for targeting the deep-seated iron-oxide mineralisation. Hence the seismic profile KBF01, located just 15 km south of Sishen mine and conveniently located on outcrop of the Kuruman iron-hosting metasediments, is a prime candidate for imaging untouched iron-oxide deposits extending beyond the mine and the structures that may have played a role in the mineralisation process, thus contributing to future mining prospects, as well as providing insight into how these deposits were formed.

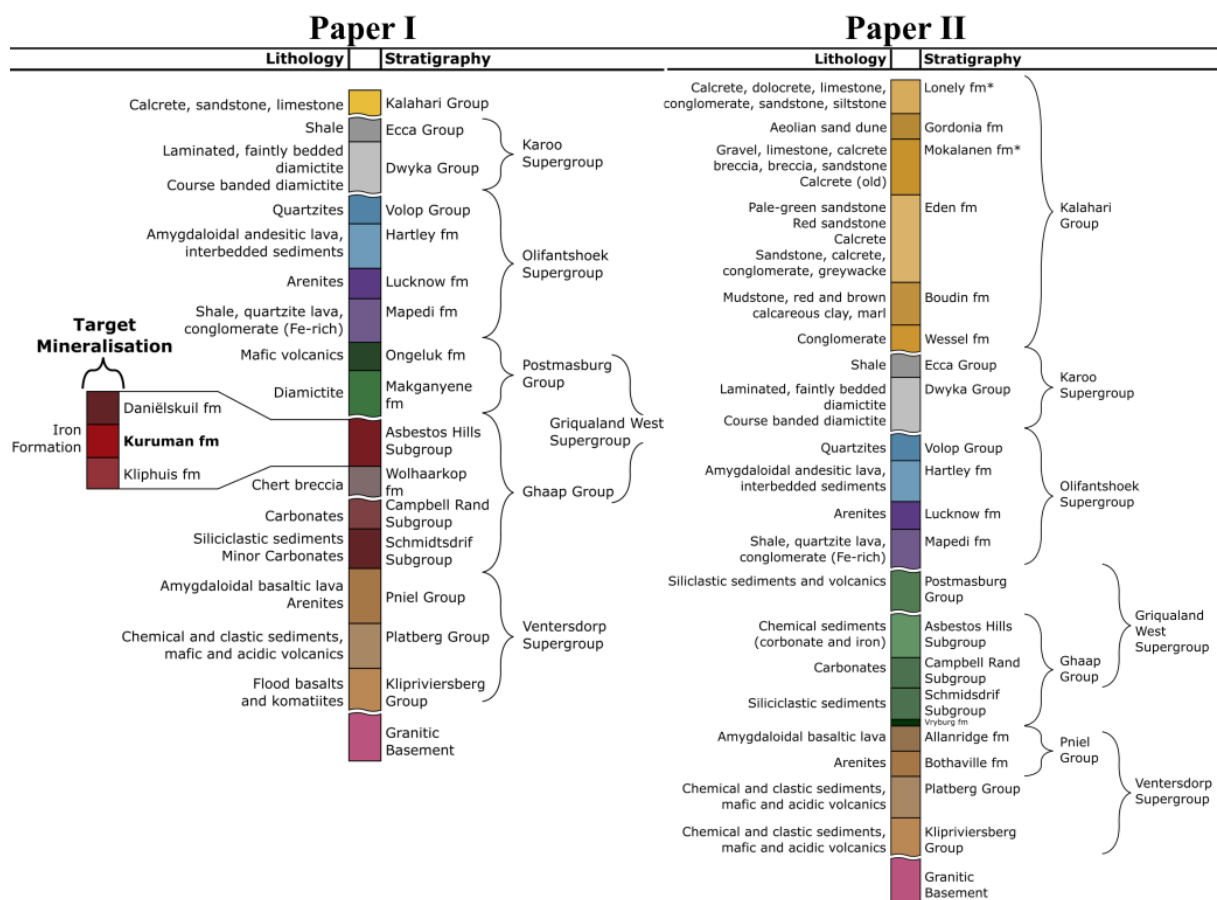


Figure 2.3: Summary of the lithostratigraphies for Papers I and II. Images sourced from Papers I and II. Colours are unique to each stratigraphy and do not correlate. Figures are taken from Papers I and II. (after Beukes, 1986; Tinker et al., 2002; Basson et al., 2017; Stoch et al., 2017)

2.2 Central Margin of the Kaapvaal Craton: Witwatersrand Goldfields

Paper III consists of two case studies, one hard rock and one soft rock, in which advanced seismic attributes are applied to legacy processed 3D seismic data with the goal of enhancing subsurface structures hosting mineral and hydrocarbon targets, respectively, for better geometrical delineation.

The first case study utilises 3D seismic data from Kloof gold mine within the West Wits Line goldfields of the Witwatersrand Basin, located between Johannesburg and Bloemfontein in South Africa (Figure 2.4). Prior to mine establishment, preliminary orebody models were based on exploration boreholes, surface mapping, and potential field data, after which 3D reflection seismic data were collected to accurately constrain the orebody geometry at depth (Durrheim, 1986; Manzi et al., 2013). The 3D seismic survey was conducted in 2003 over Kloof extension areas, subsurface regions of suspected orebody extensions beyond established shaft development. In total, a region of 12 x 16 km area was covered with a depth extent of 11 km, with the primary aim of mapping the target orebodies between 3 km and 4.2 km (Manzi et al., 2013).

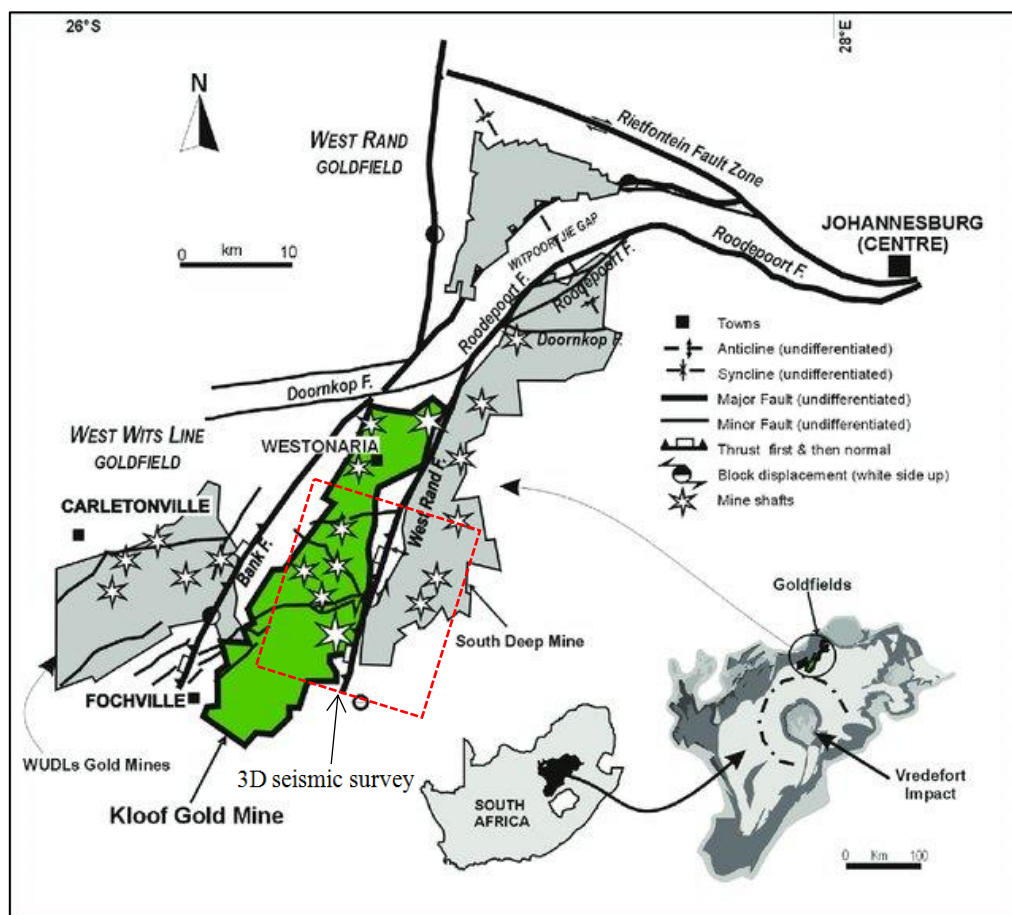


Figure 2.4: Geological map showing the location of Kloof gold mine and the 3D seismic survey in the West Wits Line goldfield. The map also shows a series of major structures that affect the Witwatersrand goldfields (modified from Dankert and Hein, 2010).

Extensive research pertaining to the geology around the Kloof gold mine, as well as the Witwatersrand Basin at large, has been conducted (e.g. Pretorius, 1989; Beach et al., 2007; Jolley et al., 2007; Dankert and Hein, 2010; Basson et al., 2017; Stoch et al., 2017), as well as numerous reflection seismic studies (e.g. Durrheim, 1986; Gibson et al., 2000; Pretorius et al., 2003; Stevenson et al., 2003; Manzi et al., 2013; Malehmir et al., 2014). The regional lithostratigraphy, shown in Figure 2.5, comprises predominantly arenitic units and shales, with occurrences of conglomeratic gold deposits, from the 2.97 – 2.71 Ga Witwatersrand Supergroup, mafic lavas from the 2.78 – 2.64 Ga Ventersdorp Supergroup, dolomites and BIFs of the 2.64 – 2.05 Ga Transvaal Supergroup, and mudstone and conglomerates from the 500 – 182 Ma Karoo Supergroup (Manzi et al., 2013).

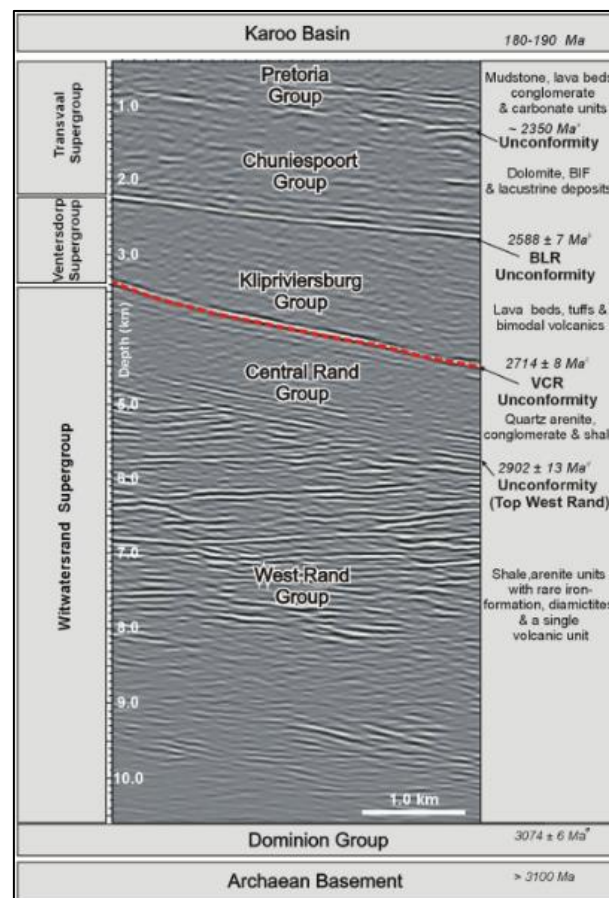


Figure 2.5: Seismic stratigraphy of Kloof gold mine, showing the target ore body (the Ventersdorp Contact Reef, or VCR) and stratigraphic units interpreted from the 3D seismic data, along with their lithologies and ages. Figure adapted from Manzi et al. (2013). BLR: Black Reef.

The target is a gold-hosting conglomerate (reef) at the base of the Ventersdorp Supergroup (Figure 2.5), where the lower Ventersdorp Supergroup overlies the upper Witwatersrand Supergroup. This boundary is a ~ 1.5 m thick reef known as the Ventersdorp Contact Reef (VCR) and is the target gold deposit at the Kloof gold mine and across the West Wits Line goldfield (Manzi et al., 2013).

The geological cross section through the mine itself is shown in Figure 2.6. The gold within the ~ 2.71 Ga VCR is attributed to recycling of underlying gold-rich sediments and has highly variable reef characteristics due to a depositional environment consisting of slopes and terraces within a fluvial system (Frimmel, 2018). The intersection point of the VCR and the Black Reef (BLR), another reef at the base of the Transvaal Supergroup, is of particular interest in Paper III (Figure 2.5 and Figure 2.6). The ~ 2.64 Ga BLR is ~ 1.5 m thick and exhibits localised concentrations of gold deposits and is found within the Black Reef Formation, a formation consisting of arenitic quartz and quartz pebble conglomerates at its base (the horizon of which is the BLR), with upward fining to siltstone and shale. The junction of the BLR and VCR, the subcrop position, is a real example of a typical wedge feature (Figure 2.6; Widess, 1973) and is thus a good candidate for seismic attribute investigation for resource evaluation.

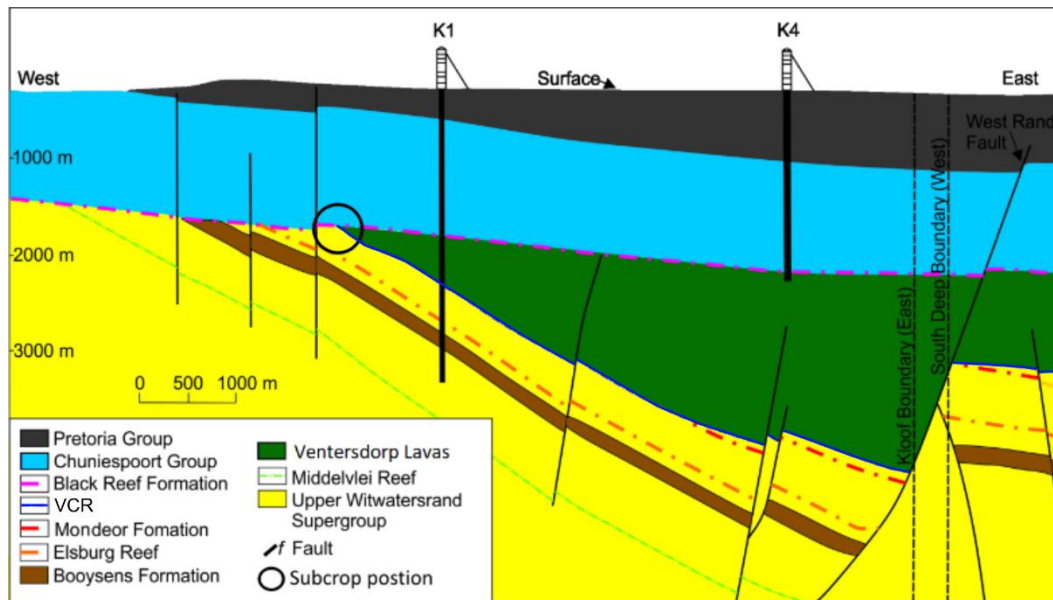


Figure 2.6: Stratigraphy of the first study area for Paper III, showing the subcrop position of the Ventersdorp Contact Reef (VCR) against the Black Reef Formation (BLR) (Sibanye Gold Limited, 2014).

2.3 Bredasdorp Basin

The other case study in Paper III is within the Bredasdorp Basin, off the coast of South Africa (Figure 1.1). The hydrocarbon potential of this basin is significant, with one particular reservoir, known as E-BD, serving as the target of investigation for Paper III. This reservoir is not extensively documented in the literature and most of the information thereof is constrained to internal Soekor reports such as Barton and Grobber (1997), in which they state that E-BD is an oil reservoir that was discovered by Soekor in 1990 by a well that penetrated a 30 m thick sandstone that contained a 17 m oil column. The sandstone has average porosity and permeability of 18% and 380 mD, respectively, confirming a reservoir of good quality. The depositional environment of the ~ 112 Ma deposit was likely deep-marine channels with trubidite systems of three stages. The lateral edges of this reservoir serve as good candidates for seismic

attribute enhancement as they fall below the tuning thickness of the seismic data ([Barton and Grobblers, 1997](#)).

The 3D seismic data were acquired in 2000 as part of the E2000 survey, as a follow up of the 1996 MEGA1997 survey by Soekor Ltd. The details of the survey and its comparison to the 1996 survey has been presented in [Barton \(2001\)](#). The aim of this survey was to assess the extension of the E-BD oil reservoir further up-dip as well as to address issues from the previous MEGA1997 survey. Such issues included: (1) the tuning thickness was greater than the thickness of E-BD; (2) the internal flow boundaries, as determined by the seismic data, were poorly understood; and (3) ambiguity existed in matching reflection amplitudes in the seismic data to the E-BD reservoir characteristics.

3 REFLECTION SEISMIC PROCESSING

The fundamental principles of the reflection seismic method are summarised in Figure 3.1. A seismic wavefield is induced in the earth's subsurface via a seismic source and the wavefield undergoes various phenomena that depend on the elastic properties of the geology through which the wavefield permeates, the mathematical theory of which is well described by wave theory and continuum mechanics (e.g. Mase, 1970; Krebs, 2019). The wavefield is then sampled on the earth's surface by geophones that conform to a predesigned survey geometry, and the recorded signals are manipulated, or processed, based on the underlying theory of wave propagation to ultimately produce an image that represents the subsurface boundaries that reflect seismic energy, with the goal of imaging targeted subsurface bodies and delineating the geometry thereof (e.g. Yilmaz, 1987; Telford et al., 1990). The phenomena that alter the initial wavefield manifest in the geophone signals in several ways as illustrated in Figure 3.1. The geophone retrieved signals are collectively called a gather and when grouped with the corresponding source/shot are termed "a shot gather". The reflections manifest as characteristic hyperbolic features in the shot gather (Heiland, 1946; Kearey, 2009), indicated in blue in Figure 3.1, while the direct waves and critically refracted waves manifest as linear features that comprise the start of the target signal, indicated in green and orange in Figure 3.1, respectively. Reflected waves occur due to a change in acoustic impedance (given by the product of rock density and seismic velocity) and refracted waves occur due to a change in velocity between rock types in the subsurface (e.g. Yilmaz, 1987; Dentith and Mudge, 2014). The surface waves, or ground roll, have low velocity and high amplitude, and manifest as such in a linear manner within the shot gather, as indicated in red in Figure 3.1. There are other and more subtle or situational features such as diffractions, phase changes and multiples, and some of these are discussed further in this thesis but the primary aim of this chapter is to give a summarised review of the processing steps that were applied to the case studies in question.

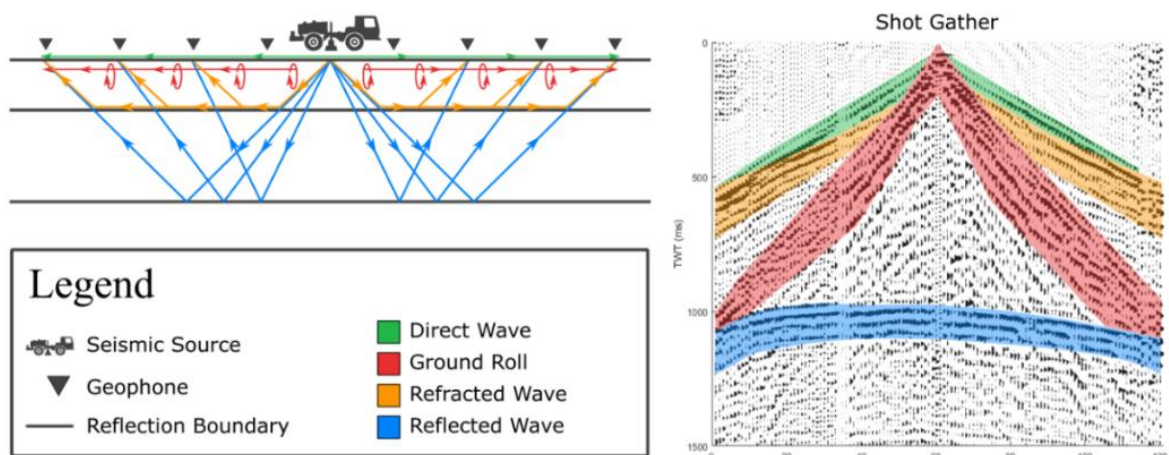


Figure 3.1: An illustration of the basic principles of the reflection seismic method. Main wavefield events are coloured in the shot gather so as to correspond with those illustrated in the diagram. The primary phenomenon exploited are the reflected waves, which are colour coded in blue.

The usual goal of a reflection seismic survey is to exploit the reflected waves as these provide information of the deeper geology. As such, the other signals are either completely removed (such as the ground roll), or used to assist in enhancing the reflections and then removed (such as the direct and refracted waves being used for refraction static corrections).

[Papers I and II](#) involve reprocessing of two 2D reflection seismic data from two seismic surveys conducted in the western region of the Kaapvaal Craton in South Africa, namely KBF01 and KBF03A, respectively. The sprocessing steps used are first shown here, followed by a brief theoretical review of the steps used in the sections of this chapter. For a more comprehensive discussion on the processing steps and associated parameters for each survey, the reader is referred to the papers in which they are implemented (Chapters 8 and 9).

The reprocessing sequence of these two profiles is given in Table 3.1, which follows today's standard processing sequence. The aim of this chapter is to provide a sufficiently comprehensive overview of each of the steps used in the reprocessing sequences of profiles KBF01 and KBF03A. Real data examples are shown for selected processing steps. More detailed descriptions of the processing steps and parameters in Table 3.1 can be found in the papers (Chapters 8 and 9).

Processing Step	KBF01 Parameters	KBF03A Parameters
1. Geometry and CDP binning	✓	✓
2. First break picking	✓	✓
3. Trace editing	✓	✓
4. Amplitude Recovery	AGC window length: 250 ms	AGC window length: 500 ms
5. Floating datum statics correction	Average datum elevation: 1690 m Replacement velocity: 6000 m/s	Average datum elevation: 1140 m Replacement velocity: 6000 m/s
6. Refraction statics correction (Inversion of weathered layer and bedrock velocities and geometry)	RMS error < 5 ms	RMS error < 8 ms
7. Frequency filtering	Notch filter: 50 Hz Bandpass: 5-15-70-80 Hz	Notch filter: 50 Hz Bandpass: 5-15-75-100 Hz
8. F-K filtering	F-K mute below 3600 m/s	F-K mute below 3100 m/s
9. Predictive deconvolution	Average prediction gap: 40 ms (range of 20-65 ms) Average operator length: 100 ms (range of 80-130 ms)	Average prediction gap: 30 ms (range of 26-40 ms) Average operator length: 100 ms (range of 80-130 ms)
10. Velocity Analysis	CVS	CVS
11. NMO correction	Stretch mute: 60%	Stretch mute: 60%
12. Residual statics	Repeat NMO corrections and residual statics (2 iterations)	Repeat NMO corrections and residual statics (3 iterations)
13. DMO	✓	✓
14. Stack	✓	✓
15. F-X deconvolution	✓	✓
16. Kirchhoff Migration	Migration velocity: 6000 m/s Maximum allowed stretch: 50%	Migration velocity: 5500 m/s Maximum allowed stretch: 50%

Table 3.1: Processing steps used for seismic profiles KBF01 and KBF03A from [Papers I and II](#), respectively.

3.1 Preprocessing and Quality Control

Prior to processing of reflection data, the data need to be checked and edited, if necessary, so as to conform to standard. Conventionally, the data are recorded in a multiplexed state, which are demultiplexed before processing. However, this is mostly outdated by modern standards. The resulting format, which is typically stored as a SEG-Y file (the Society of Exploration Geophysicists standard file format for storing geophysical data) or other typical format for seismic data, is an array of time series that correspond to all the traces within the survey, each trace has a number of headers that categorise the trace, for example the ID of its corresponding shot, or the coordinates of the corresponding receiver location, typically referred to as a receiver peg. The rest of the pre-processing sequence typically involves Vibroseis correlation, if the survey was conducted using a Vibroseis source, trace editing, setting of geometry, and amplitude recovery. These steps are described in more detail below.

Vibroseis Correlation

The Vibroseis method is a widely used and invaluable tool for seismic data acquisition as a seismic source. The acquisition equipment typically involves a weight that is vibrated against the ground at an initial frequency. The frequency is then altered to sweep through a range of predetermined frequencies and the resulting signal is thus termed a sweep. The signal subsequently detected by the geophones is computationally manipulated to produce traces akin to those detected with an impulse source, but with the benefit of a greater frequency content. For a more detailed overview of the method, the reader is referred to [Meunier \(2011\)](#). The purpose of this section is to provide a review of the preprocessing steps that is necessary for data acquired using the Vibroseis method, as is the case for the data in [Papers I and II](#).

The simplified convolutional earth model, which is given in more detail in Chapter 3.4, that is associated with the Vibroseis method states that the recorded signal, $s(t)$, is given by the convolution of the sweep signal, $sw(t)$, and the earth reflectivity function, $e(t)$ ([Heiland, 1946](#); [Yilmaz, 1987, 140-141pp](#)):

$$s(t) = sw(t) * e(t) \quad (3.1)$$

where $*$ denotes convolution. This is illustrated in Figure 3.2. The sweep signal $sw(t)$ typically runs linearly from a lower frequency to a higher frequency in a finite time known as the sweep length, also illustrated in Figure 3.2. This is known as a chirp signal. There are other frequency sweeps, such as downsweep or logarithmic sweeps, but these are not discussed here as the data presented in this thesis were obtained using chirp signals. The recorded signal is then cross-correlated with the sweep signal, resulting in

$$s'(t) = s(t) \otimes sw(t) = k(t) * e(t) \quad (3.2)$$

where $s'(t)$ is the new trace, $\otimes$ denotes the cross-correlation operator and $k(t)$ is the Klauder wavelet, given by the autocorrelation of the sweep signal (Baeten, 1989). The purpose of moving from Equation 3.1 to Equation 3.2, as detailed in Yilmaz (1987, 140-141pp), is to reduce the time-expanded earth response of the sweep signal to a localised wavelet, given by the Klauder wavelet, while reattaining the broadband information content. The cross-correlation process is illustrated in Figure 3.2.

As per the Vibroseis method, if $sw(t)$ is recorded during acquisition, it can be correlated with $s(t)$ to produce the signals needed for processing. This is done computationally before other processing steps.

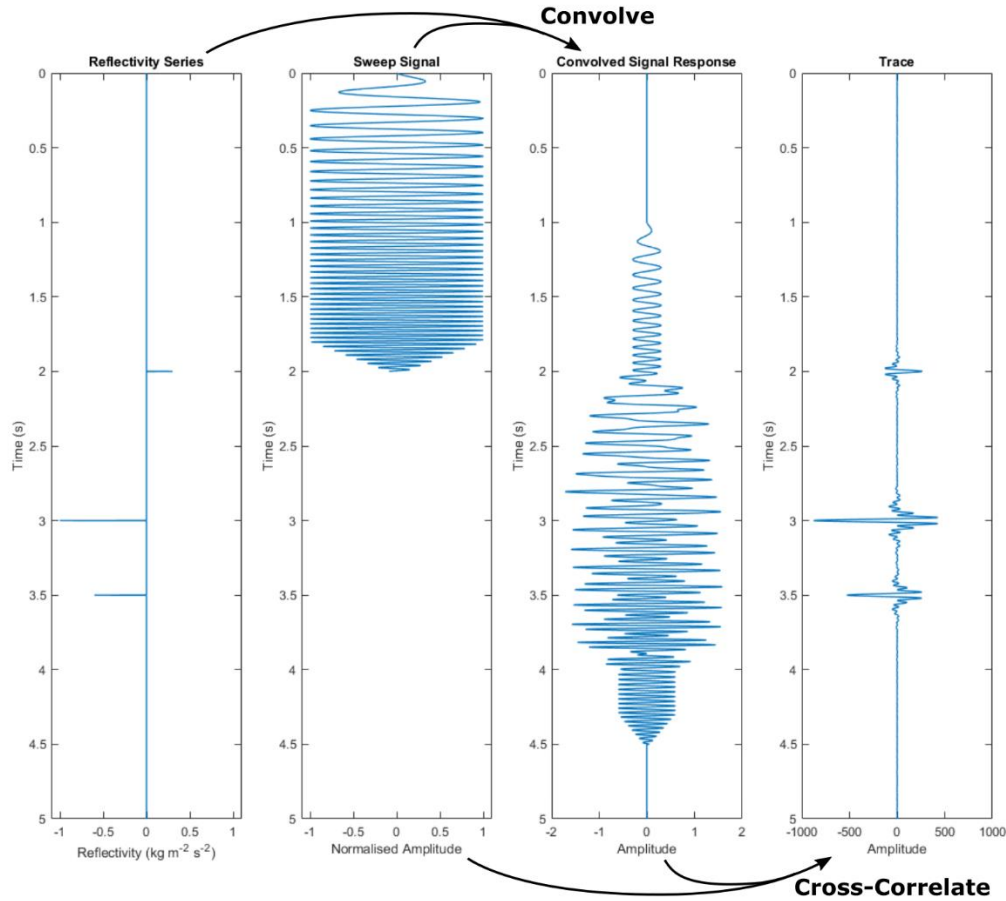


Figure 3.2: Illustration of the Vibroseis method earth model: A trace is given by the cross-correlation of the sweep signal and the signal response, the latter of which is a convolution of the sweep signal and the reflectivity series.

Amplitude Recovery

The energy that is injected into the subsurface during a seismic survey is attenuated in a variety of ways before it is detected by the geophones. The three primary causes of this attenuation or partial loss are:

1. **Spherical Divergence:** Over time, vibrational energy from a point source radiates spherically away from the source. As such, the input energy is spread over a spherical surface of area $4\pi r^2$ upon reaching a distance r from the point source (with the assumption of a uniform, isotropic medium) (Yilmaz, 1987; Telford et al., 1990). With the source located on top of a uniform half-

space, as is typically modelled for surface seismic surveys, the energy is distributed over a hemisphere and so the energy sampled at distance r away from the point source will have decreased by a factor of $2\pi r^2$.

2. **Absorption:** Mechanical energy of the seismic wave is lost due to anelastic attenuation. For example, the energy is partially converted into heat energy through friction as the wave travels through the subsurface. This attenuation follows an exponential trend with distance travelled from the source and is quantified by the well-known quality factor, Q , which is defined as the factor of energy loss of the seismic wave over one wave cycle (Dentith and Mudge, 2014; Telford et al., 1990).
3. **Elastic Scattering:** Heterogeneities in the subsurface potentially cause the seismic wave to reflect, refract, or diffract. With a typical reflection seismic survey, the targeted energy is the reflected energy and energy that is diffracted beyond the receiver spread or refracted below the critical angle is not fully recorded by the receivers (Yilmaz, 1987; Dentith and Mudge, 2014). This does not lead to energy attenuation, but simply a loss of energy that is not recovered during the survey.

There are numerous ways to recover the amplitude that is lost via the above mechanisms (e.g. Yilmaz, 1987, 49-62pp; Wu and McMechan, 2018) and the choice thereof is based on the desired seismic analysis used in the seismic survey design. For example, if an amplitude-versus-offset (AVO) analysis is desired, the amplitudes must be recovered in a way that is consistent with the attenuation model (i.e. the effects of spherical divergence and absorption must be reversed by inverting the mathematical model and applying corrections), this is known as true amplitude recovery (TAR) (Luh, 1992).

However, for most reflection seismic surveys, the geometry of subsurface features is the primary investigation and so the nature of the amplitude recovery is inconsequential, with the simple requirement that amplitudes from deeper events are recovered so as not to be dominated by shallow events. This is typically done by applying a time-dependent gain function, $g(t)$, to each trace in the record (Yilmaz, 1987).

The gain function can have an explicit dependence on time, such as $g(t) \sim t^n$, or $g(t) \sim \exp(\alpha t)$, where n is an integer and α is a constant, or it can implicitly depend on time such as the automatic gain control (AGC) method (Yilmaz, 1987; Eaton et al., 2003). The gain function can also be dependent on the velocity field but discussion here is restricted to time-dependent gain functions as these were used in the field studies. This method utilises a moving window of predefined length that slides down the traces, one sample at a time. For each point at the centre of the window, the root-mean-square (RMS) of the amplitudes in the window is calculated and the ratio of a desired RMS and the window RMS is assigned to $g(t)$ at the centre of the window (Yilmaz, 1987). The smaller the window is, the more localised the events are that are enhanced, and therefore so is the noise in the data.

Figure 3.3 shows a shot gather (a) taken from the seismic profile KBF03A with different types of gain applied to it, including the AGC method (b), the $g(t) \sim t^n$ gain (c), and the $g(t) \sim \exp(at)$ (d) gain. The AGC is demonstrated to be the best candidate and was used in the processing sequences of both KBF01 and KBF03A.

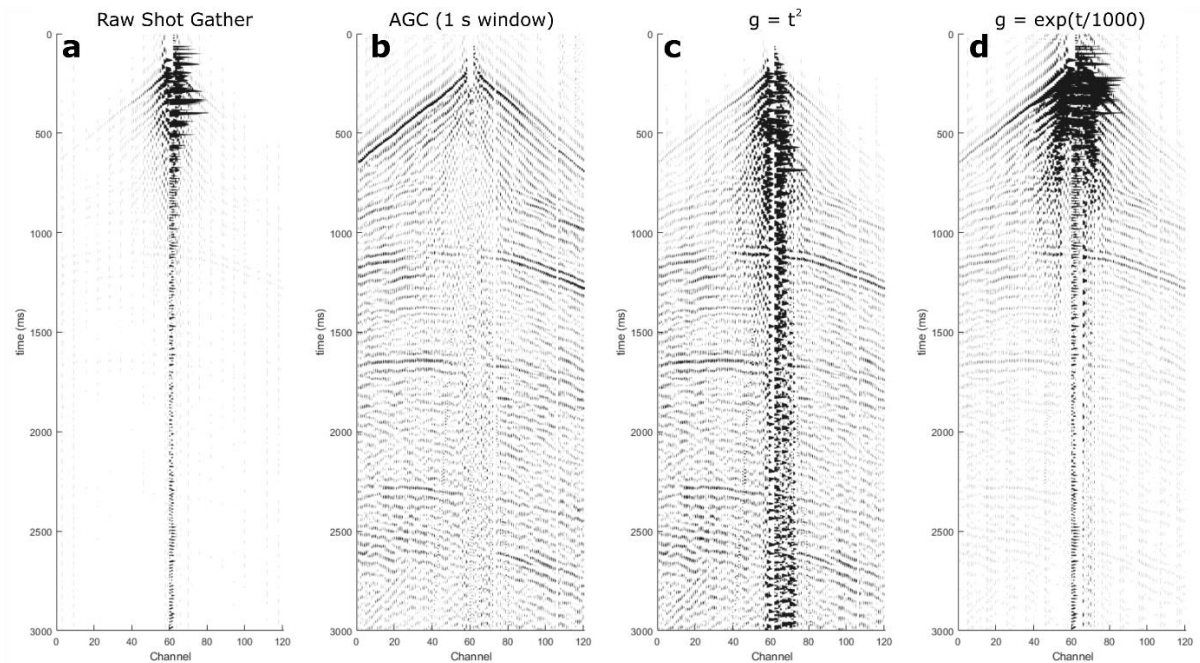


Figure 3.3: Comparison between various gain functions used in amplitude recovery for pre-processing. The raw shot gather is shown (a), as well as the AGC (b), quadratic (c), and exponential (c) amplitude gains.

Geometry

A seismic profile can be designed in a variety of ways. One of the primary objectives when designing the geometry of a survey is to oversample the target area. In doing so, coherent desired signals such as reflected or refracted waves can be boosted and unwanted signals, such as ambient noise or scattered waves, can be attenuated. In general, this oversampling is referred to as redundancy. A typical geometry setup that achieves this is seen in Figure 3.4, where multiple source-receiver pairs are used with varying offsets. By having multiple source-receiver pairs whose midpoints coincide, a single subsurface point is sampled multiple times. The resulting traces are then manipulated and added, as detailed in Chapter 3.5, to boost the signal-to-noise ratio (SNR), enhancing the desired signals and attenuating the undesired signals. The result is a single trace located at the common midpoint (CMP) of the source-receiver pairs that emulates a single source and single receiver both coinciding on the CMP. This is repeated for multiple sampling points to produce an image of the subsurface.

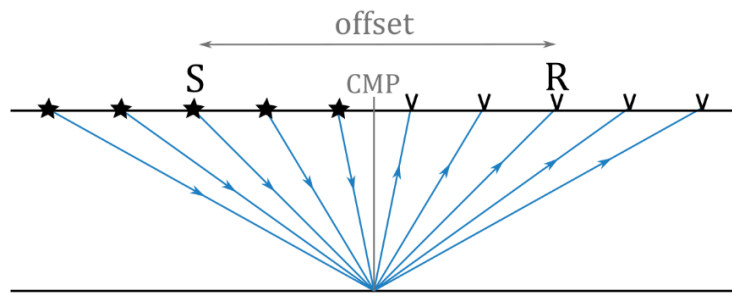


Figure 3.4: Diagram illustrating a seismic profile geometry that allows for multiple sampling of one subsurface location.

The survey geometry is typically recorded and stored separately from the field seismic data and the two are merged by storing the geometry information in the trace headers during pre-processing. The SEG-Y trace headers usually contain only shot IDs and a range of channel IDs for each shot. Shot IDs are unique identification numbers for each shot in the survey and channel IDs are the unique identification numbers associated with the individual traces within each shot. This is not enough information for a full reflection processing sequence as most of the important processing steps such as refraction statics, CMP binning and stacking, and migration require the relative locations of sources and receivers. As such, the survey geometry information, consisting of locations of sources and receivers and ties between the two, needs to be added to the headers.

Multiple binning methods can be used for 2D seismic data. A common approach, and the one used in Papers I and II, is by crooked CMP line (Nedimović and West, 2003). This involves fitting a crooked line to the seismic profile upon which CMP bins are placed and are evenly spaced. The crooked line is designed to maximise the number of traces that sample the same CDPs in each of the CMP bins. This is done by plotting a cloud of midpoints between every shot-receiver pair and fitting a line along the locations where this cloud is most dense.

Implementing the geometry information is particularly important when dealing with legacy data as the geometry data is likely separated from the seismic data and needs careful implementation. This is discussed in detail in Chapter 4 and the aim of this section is to provide a brief overview of conventional practices around implementing geometry data that are pertinent to legacy data reappraisal.

The global standard of storing seismic geometry data, as stated by the [SEG Technical Standards Committee \(1995\)](#) revision 1 data exchange format, is a set of format files collectively termed the Shell Processing Support format, or SPS. The SPS format comprises three filetypes, *.s*, *.r*, and *.x*, that jointly contain all the necessary information to fully describe the survey geometry of a given dataset. Table 3.2 below summarises the structure of these filetypes. The *.s* file contains the shot information; each shot has an associated easting, northing and elevation and is given a unique identifier, typically “shotpoint number” or “SHOT_PEG” or “Peg ID” for Globe Claritas, to identify unique shot locations. The *.r* file has the same structure as the *.s* file but is used for the receiver locations and has identifiers labelled

“REC_PEG” or “Peg ID”. Finally, the .x file ties the shot file and receiver file together and associates the geometries thereof with the shot IDs and channel IDs that are stored in the trace headers, thus completing the geometry relations. The data stored in the .x file comprises the shot IDs, the associated SHOT_PEGs, the channel IDs associated therewith, and the REC_PEGs corresponding to the associated channels. Before the abovementioned data are listed, each SPS file has a series of header lines that contain general information of the geometry, such as description of survey area, coordinate information, time, map projection, etc. An optional comment file is occasionally included in the package.

Filetype	Line	Content
All	1	H00 SPS format version number SPS 2.1;
	⋮	⋮
	n	HXX Description of grid units metres;
Receiver (.r)	n+1	HYY Peg ID (REC_PEG) Cols 12:21
	n+2	HYY Map grid easting Cols 47:55
	n+3	HYY Map grid northing Cols 56:65
	n+4	HYY Surface elevation Cols 66:71
	n+5	HYY 1 2 3 4 5 6 7 8
	n+6	HY 567890123456789012345678901234567890123456789012345678901234567890
	n+7	R 100 -43660 3087259 1455
	⋮	⋮
	⋮	⋮
	LAST	R 1149 6630 3087356 1229
Shot (.s)	n+1	HYY Peg ID (SHOT_PEG) Cols 12:21
	n+2	HYY Map grid easting Cols 47:55
	n+3	HYY Map grid northing Cols 56:65
	n+4	HYY Surface elevation Cols 66:71
	n+5	HYY 1 2 3 4 5 6 7 8
	n+6	HY 567890123456789012345678901234567890123456789012345678901234567890
	n+7	S 100 -43660 3087259 1455
	⋮	⋮
	⋮	⋮
	LAST	S 1146 6654 3087362 1229
Cross Reference (.x)	n+1	HYY Field record number (SHOTID) Cols 8:15
	n+2	HY Field point number (SHOT_PEG) Cols 28:37
	n+3	HYY From channel Cols 39:43
	n+4	HYY To channel Cols 44:48
	n+5	HYY Channel increment Cols 49:49
	n+6	HYY From receiver Cols 60:69
	n+7	HYY To receiver Cols 70:79
	n+8	HYY 1 2 3 4 5 6 7 8
	n+9	HY 567890123456789012345678901234567890123456789012345678901234567890
	n+10	X 176 100 60 1201 100 160

Table 3.2: Example of Shell Processing Support (SPS) file structures. There are n+9 file headers in the .s and .r files and n+10 headers in the .x file. HYY represents “H(n+1)”; i.e. the (n+1)th header in the file.

After the geometry of the survey is sorted, common depth point (CDP) bins can be created by defining the locations and sizes of the bins based on the survey design. For 2D seismic surveys, the bins usually follow the trend of the line and, more specifically, the trend of the highest shot-receiver midpoint fold.

Trace Editing

It is important for the data to undergo general quality control as geophones may behave unpredictably in the field or are contaminated with noise. Common examples include loosely connected geophones, poorly coupled geophones, or geophones with overly sensitive leaf springs. Figure 3.5 illustrates a shot

gather with examples of noise-contaminated traces, as well as traces whose polarity needs reversing. It is not uncommon to have traces with reverse polarity, which may be attributed to, for example, the setup, demultiplexing processes, reversely connected or reverse polarity geophones.

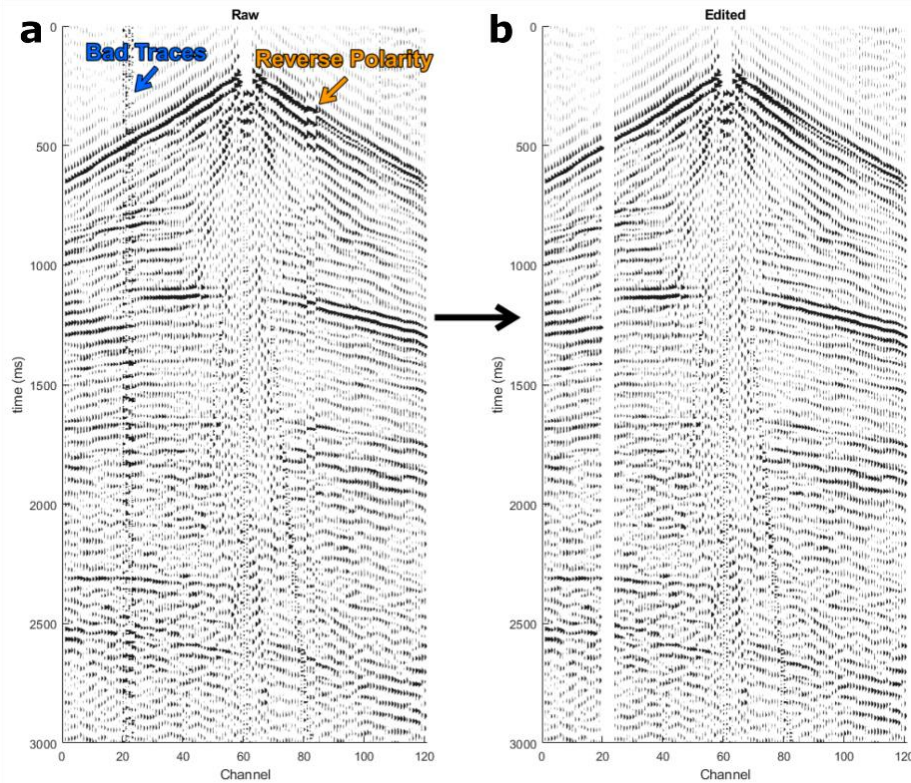


Figure 3.5: Example of pre-processing quality control. Bad traces seen in the raw gather (a) reduce the signal-to-noise ratio and are removed, and traces with reverse polarity show up as anomalies in the continuity of first breaks and reflections and are subsequently reversed, as seen in (b).

During this step, contaminated traces are either fully or partially muted or killed/removed and polarity is corrected where necessary, as shown in Figure 3.5. This step also ensures the data are correctly sorted and confirms the geometry is correct.

Floating Datum Statics

When land surveys are conducted over areas of significantly varied topography, which is typically the case for expansive surveys, such as the seismic profiles KBF01 and KBF03A, the CDP gathers exhibit misalignment of traces due to the differences in travel times caused by the relative changes in topography. The result is a decrease in coherency along reflection hyperbola trajectories. This results in a decrease of the signal-to-noise-ratio (SNR) because amplitudes are summed along hyperbolae defined by the velocity field and if a trace's reflection is not aligned with the hyperbola, it can lower the summed amplitude of the reflection signal.

To remedy this, traces are shifted in time to a datum level that replaces the topography of the survey, as illustrated in Figure 3.6. This is done by selecting a replacement velocity, usually equal to the bedrock

seismic velocity, for the virtual layer between the datum and the sources and receivers (collectively survey pegs), and by calculating the time shift for each trace using the replacement velocity and the difference between the survey peg elevations and the datum elevation. For a surface survey with substantially rugged topography, as illustrated in Figure 3.6a, the average elevation of the datum is shifted to lie above the highest survey elevation. This ensures that no reflections lie above the elevation, avoiding data loss. The time shift in this case, for each source-receiver pair is given by:

$$\tau_D = \frac{E_D - E_S}{v_r} + \frac{E_D - E_R}{v_r} \quad (3.3)$$

where τ_D is the datum shift, E_S and E_R are the shot and receiver elevations, respectively, E_D is the datum elevation, and v_r is the replacement velocity (Heiland, 1946; Telford et al., 1990). The time shifts for the data example are shown in Figure 3.6b. Equation 3.3 is based on the assumption that ray paths at the surface are vertical, which is a reasonable approximation if the weathered layer has a low velocity (and therefore strong refraction) and the receiver offsets are small compared to depth of investigation (Yilmaz, 1987, 220-229pp).

For surveys that are relatively flat, a flat, or fixed, datum can be used (E_D is constant). However, for surveys with rugged topography, like lines KBF01 and KBF03A that traverse the hills of the Kheis Belt, the shifts become large, and the datum can no longer be fixed. Instead, a floating datum is used that is essentially a smoothed version of the topography, as shown in Figure 3.6. In profiles KBF01 and KBF03A, a floating datum is used with a constant velocity.

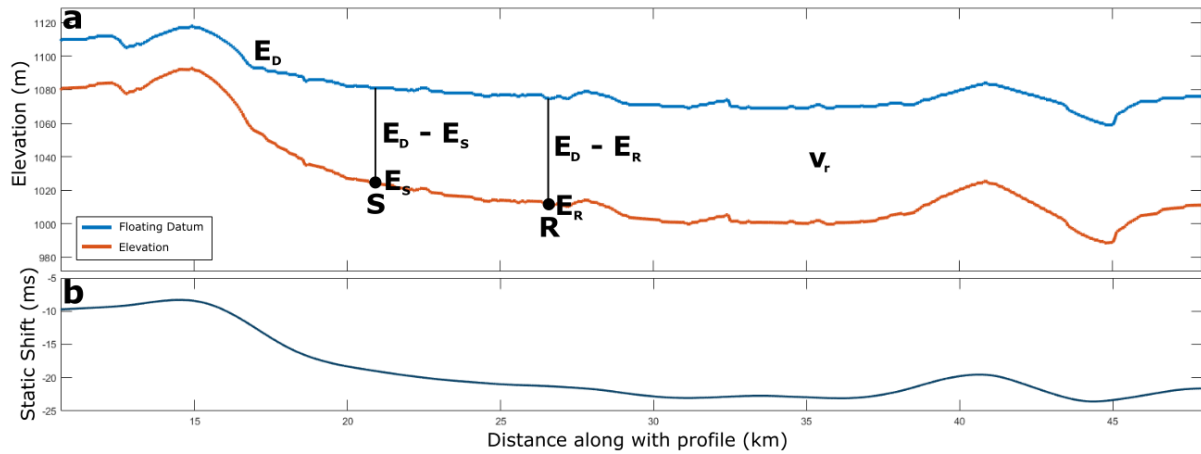


Figure 3.6: Illustration of how floating datum statics are calculated using Equation 3.3. The elevation profile is from profile KBF03A in Paper II. The top (a) shows the elevation as well as the new datum and the bottom (b) shows the static shifts.

3.2 Refraction Static Corrections

Land seismic surveys are hindered by the uppermost layer that has undergone substantial weathering and is comprised of loosely consolidated sediments. This weathered layer will have a significantly lower seismic velocity profile compared to the underlying target layers and will often exhibit strong lateral velocity variations. The overall effect is that each trace in the survey experiences a constant, “static”, shift in time, thus disrupting the coherency in hyperbolic trajectories of reflections within CDP-sorted traces, reducing the overall SNR (Telford et al., 1990).

To counteract this, the velocity and geometry of the weathered layer are modelled and static corrections are calculated to compensate for the travel time delays resulting from the weathered layer. The traces are reduced to a new datum level, similar to the floating datum statics described in Chapter 3.1. The statics are comprised of two corrections; one that compensates for the long-wavelength component and one that compensates for the short-wavelength component. (Yilmaz, 1987; Telford et al., 1990). The former is computed using either an uphole seismic survey (known as “field statics”) or by performing refraction modelling (known as “refraction statics”), which is treated in this section, and the latter is computed using the velocity model and reflection travel times (known as “residual statics” or “surface-consistent statics”), which is treated in Chapter 3.5. The refraction statics can yield the short-wavelength component but this is commonly not implemented and left until residual statics are computed.

Field statics, the first method that deals with the long-wavelength correction, is thusly named as it requires extra in-field preparation. Uphole surveys are conducted in which sources are placed inside a drill hole that extends beneath the weathered layer and the signal is recorded on the surface, allowing a velocity-depth profile of the weathered layer to be modelled throughout the survey. However, not all seismic surveys can be handled this way due to the thickness of the weathered layer being too large to drill through or due to the nature of the survey. The two profiles KBF01 and KBF03A, for example, utilised vibrator trucks as sources, forcing the sources to be on the surface. It is in these cases that refraction statics are often used to model the weathered layer and provide the long-wavelength correction. Other methods, such as the Plus-Minus method (Yilmaz, 1987) and uphole drillings can be used but the refraction method was used in this thesis and hence discussion will be restricted thereto.

Basic Refraction Theory

The theory of refraction seismics is well established in the literature (e.g. Dobrin, 1960; Yilmaz, 1987; Telford et al., 1990). The method used in both Papers I and II was the least squares method (Yilmaz, 1987) and this method is treated in this section. Other methods, such as the Plus-Minus method or the general reciprocal method are outside the scope of the thesis and are not discussed here.

For a simplified horizontal earth model, as illustrated in Figure 3.7, the raypath that is incident on the base of the weathered layer at the critical angle is refracted along the weathering boundary and departs

refracted energy back to the receivers along its path, starting with the receiver that is at the crossover distance x_c and ending at the furthest receiver in the spread. The travel time τ_{ab} of these refracted signals between the a^{th} receiver and b^{th} shot is given by (Farrell and Euwena, 1984):

$$\tau_{ab} = s_b + r_a + \frac{x_{ab}}{v_b} \quad (3.4a)$$

where x_{ab} is the distance between the a^{th} receiver and b^{th} shot, v_w and v_b are the weathering layer and bedrock velocities, respectively, and

$$s_b = \frac{z_{sb}(v_b^2 - v_w^2)^{1/2}}{v_b v_w} \quad (3.4b)$$

$$r_a = \frac{z_{ra}(v_b^2 - v_w^2)^{1/2}}{v_b v_w} \quad (3.4c)$$

Are the the traveltimes beneath the source and receiver, respectively, and collectively comprise the intercept time $t_0 = s_b + r_a$. Here, z_{sb} and z_{ra} are the depths to bedrock beneath the b^{th} shot and a^{th} receiver, respectively, as illustrated in Figure 3.7 (for generality, it is assumed that these depths are not equal).

By picking the first arrivals in the data, τ_{ab} is obtained and the unknowns in the suite of Equations 3.4 are z_s , z_r , v_b and v_w . Because of the redundancy typically found in seismic data, there are vastly more source-receiver pairs than the unknowns presented above. Hence, Equation 3.4a becomes a collection of n linear equations in m unknowns where $n > m$. This is a typical least-squares inverse problem that is commonly found in geophysics (Yilmaz, 1987).

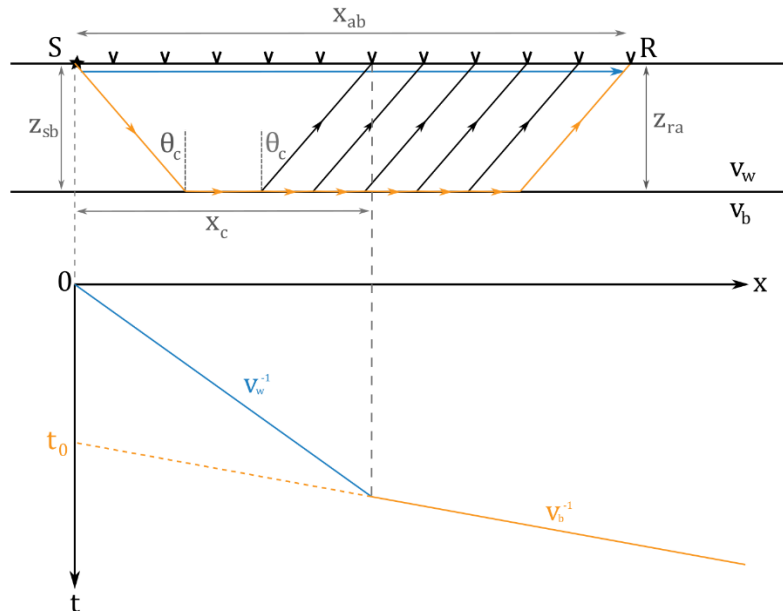


Figure 3.7: Concepts of critically refracted waves along the boundary between the weathered layer with velocity v_w and bedrock with velocity v_b from source S to receiver R. S and R are separated by a distance x_{ab} and the (generally unequal)

depths beneath S and R are z_{sb} and z_{ra} , respectively. Direct waves are plotted in blue and an example refracted wave is plotted in orange. Redrawn from [Yilmaz \(1987\)](#).

Inversion theory is a well-established and complex subject of specialisation in many fields, not only geophysics. As such, the basic concepts of inverse theory are treated here along with their relation to refraction statics, as described above. For more detail on the subject, see [Ellis and Oldenburg \(1994\)](#), [Scales et al. \(2001\)](#), and [Zhdanov \(2015\)](#).

Inversion of Refracted Waves

In the case of refraction statics, the measured observations are the picked first arrivals, the modelled observations are the travel times of the critically refracted waves between the weathered layer and the bedrock layer, the model used to calculate the travel times is given by [Equation 3.4a](#), and the scenario parameters that are varied are the velocities and geometry of the weathered layer and bedrock layer. The error in modelled observations is quantified by the RMS time variation between the picked arrivals and the modelled arrivals.

Figure 3.8 showcases a real example of the refraction statics correction. This example is a single shot taken from profile KBF01. The picked first arrivals are plotted in Figure 3.8a along with the modelled arrivals based off the final model (shown in Figure 3.8b). Note that the model parameters being inverted are the lateral velocity profiles of the weathered layer and the bedrock layer as well as the geometry nodes that can be seen along the boundary of the two layers as blue dots (Figure 3.8b). The method implemented here is based on the Generalised Linear Inversion method by [Woodward \(1992\)](#). This model had an RMS residual of 4.94 ms, just over the sampling period of the data (4 ms). The static corrections for the receivers of the shot are plotted in blue in Figure 3.8c, along with the static corrections for the shot in Figure 3.8a as well as the neighbouring 300 shots. The statics for both receivers and shots follow a similar trend, this long-wavelength component is due to the general effect of the topography of the surface and the weathering layer. The value of applying static corrections is evident in the comparison between the pre-corrected and post-corrected shot gathers, given by Figure 3.8d and e, respectively. Two observations can be made; firstly, the first breaks are more linear in the corrected shot, as is expected from [Equation 3.4a](#), highlighted by the orange arrows. Secondly, the reflected signals exhibit much clearer and coherent hyperbolic trajectories, as illustrated by the blue arrows. For more details on the data seen in Figure 3.8, including the acquisition and processing parameters, the reader is referred to [Paper I](#) (Chapter 8).

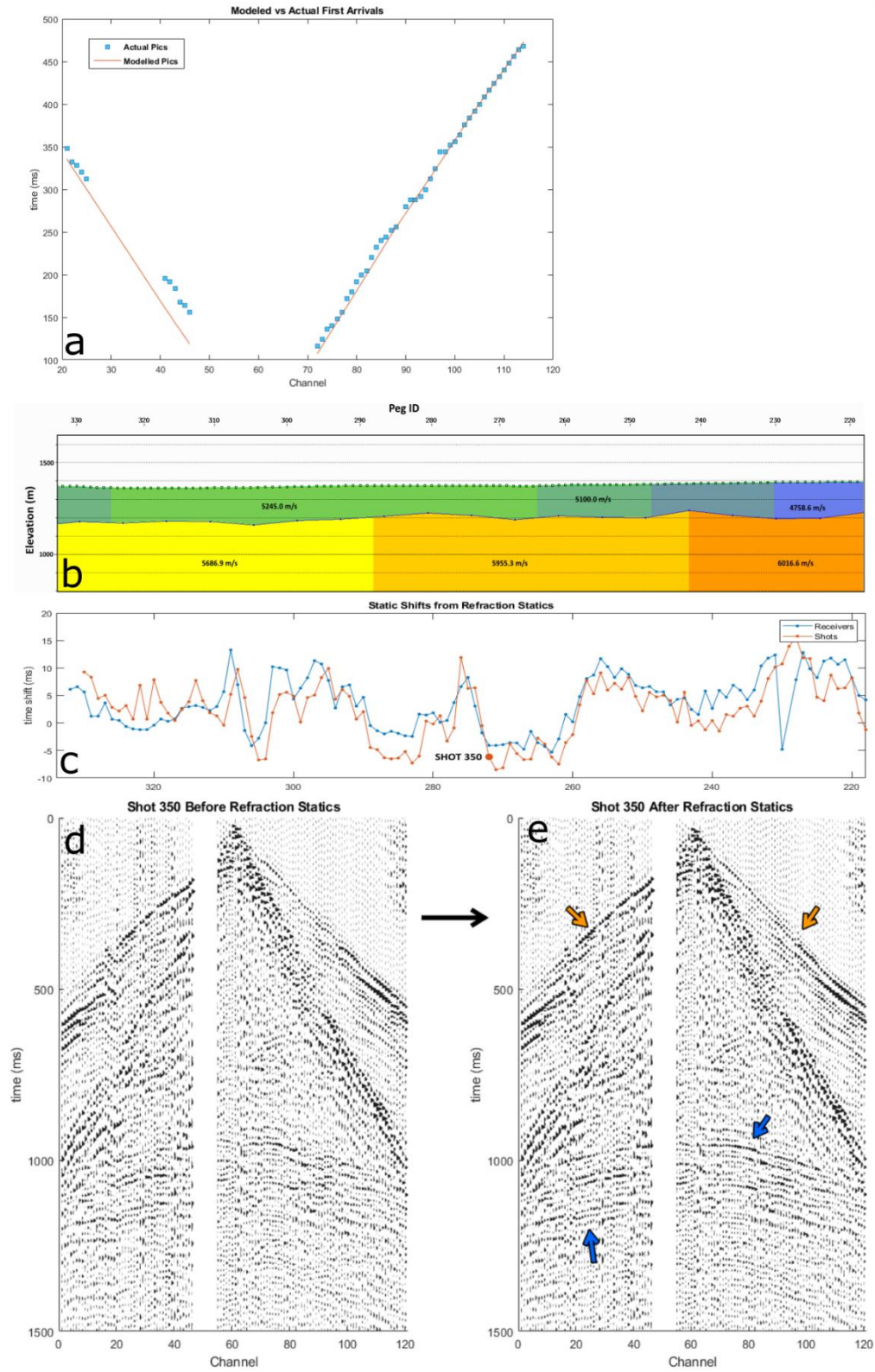


Figure 3.8: Example of refraction statics applied to a shot taken from profile KBF01 (Paper I). The picked first break arrivals with the modelled first arrivals are shown (a), as well as the modelled scenario of the weathered and bedrock layers (b). The static shifts are shown for the receivers as well as the shots in the vicinity of shot 350 (c), where the selected shot is emphasised as a large dot. Finally, the effects of applying the static correction are shown in (d). Orange arrows show areas where first breaks are now linear, and blue arrows indicate reflection hyperbolae with better coherency post refraction statics.

3.3 Fourier Transform and Frequency Filtering

Computational filters comprise a vital part of signal processing, and therefore trace processing in reflection seismics. One of the fundamental building blocks of signal processing is the Fourier transform (FT) (Bracewell, 1986; Yilmaz, 1987, 9-20pp; Chatfield, 2004). This integral operator decomposes a signal of arbitrary dimension into a series of sinusoids with characteristic frequencies and phases. The amplitudes of these sinusoids quantifies the intensity of contribution of the corresponding sinusoids to the signal. Plotting the sinusoid amplitudes against the sinusoid frequencies gives the signal's amplitude spectrum, and plotting the phases against the frequencies gives the signal's phase spectrum.

In the real world, observed signals are frequently contaminated by noise and undesired signals. That is, a given signal is a superposition of the desired signal and undesired signals. These undesired signals will often be characterised by a specific frequency or frequency range that is distinct from that of the desired signal. The FT is exceptionally useful for removing these signals and thus enhancing the targeted signals. The basic process by which this is done, as illustrated in Figure 3.9, is as follows: the signal is converted into the frequency domain via the FT, unwanted frequencies are removed from the spectrum, and the signal is transformed back into the time domain via the inverse FT, yielding the filtered signal.



Figure 3.9: Illustration of the flow of frequency filtering. A signal is transformed, filtered, and then transformed back to give the filtered signal.

In reflection seismics, the FT can be used to filter the traces in both one and two dimensions. One-dimensional filtering is performed on each individual trace (either prestack or poststack) along the time dimension and is known as f - x filtering, and two-dimensional filtering is performed on each shot gather, along both the time and offset dimensions and is known as f - k filtering. Both of these methods were used in processing the profiles KBF01 and KBF03A and are described here in further detail.

Frequency-Offset (f - x) Filtering

The Fourier transform $Y(f)$ of a one-dimensional signal $y(t)$ is given by (Gibbs, 1898; Bracewell, 1986):

$$Y(f) = \int y(t)e^{-i2\pi ft} dt \quad (3.5a)$$

where f is the frequency and the limits of integration span the domain of $y(t)$. The inverse transform is given by:

$$y(t) = \int Y(f)e^{i2\pi ft} df \quad (3.5b)$$

For computational processing, these equations have numerical equivalents (Chatfield, 2004), but the theory remains the same. The necessity for these numerical equivalents results from the seismic signal being digitalised and hence discretely sampled typically at a fixed sampling rate. The most common numerical adaptation is the Fast Fourier Transform (FFT) algorithm. By computing the FFT for each trace in a prestack gather, a frequency function is given for each offset at which a receiver is located, thus this filtering technique is referred to as f - x filtering.

In reflection seismics, the geophysicist may encounter different phenomena that will require frequency filtering of the traces. For example, a portion of the survey may be located near an AC-carrying power cable that affects the coils in the geophones and manifests as a monofrequency signal in the recorded gathers. Another example is if a Vibroseis source is being used as a source in the survey, and frequencies outside the sweep range are being detected by the geophones from external sources that need to be filtered out.

The process of filtering in the frequency domain is by multiplying the amplitude spectrum by 1 where the signal is desired and by 0 where undesired signal is located. Different filter types exist for different scenarios as those explained above. These filter types are illustrated in Figure 3.10, and are listed below. In each case, the filtering is carried out by multiplying the signal spectrum with the filters in Figure 3.10.

1. **High-pass (Figure 3.10a):** This filter is chosen in the case that unwanted frequencies occur below a specific frequency known as the cutoff frequency, f_c . Frequencies below f_c are multiplied by 0 and frequencies above by 1, the filter “passes” high frequencies. This filter is used if there is a strong presence of long wavelengths or a high DC (zero frequency) component.
2. **Low-pass (Figure 3.10b):** This filter is similar to the high-pass filter but inverted; frequencies below f_c are preserved and the rest are attenuated. This is a common filter as noise frequently manifests in frequencies higher than the desired signal.
3. **Band-pass (Figure 3.10c):** This filter preserves frequencies between a lower threshold and an upper threshold frequency, f_l and f_u , respectively. This is useful in reflection seismics, for example, when the Vibroseis method is being utilised and frequencies outside the sweep, such as external low-frequency undulations, need to be attenuated.
4. **Band-stop (Figure 3.10d):** This filter is the inverse of the band-pass filter, it zeros frequencies lying between f_l and f_u . This is useful in seismics if noise is spread over a range of frequencies or if an external source has its own characteristic sweep.
5. **Notch (Figure 3.10e):** This filter removes a single frequency, f_N , from the spectrum, which is useful if undesired signal is reduced to a narrow band. For example, in South Africa, AC current is carried through power cables with an average frequency of 50 Hz. This frequency can be

picked up by geophones lying close to a pylon and can easily contaminate the signal especially at large offsets where the signal is weak.

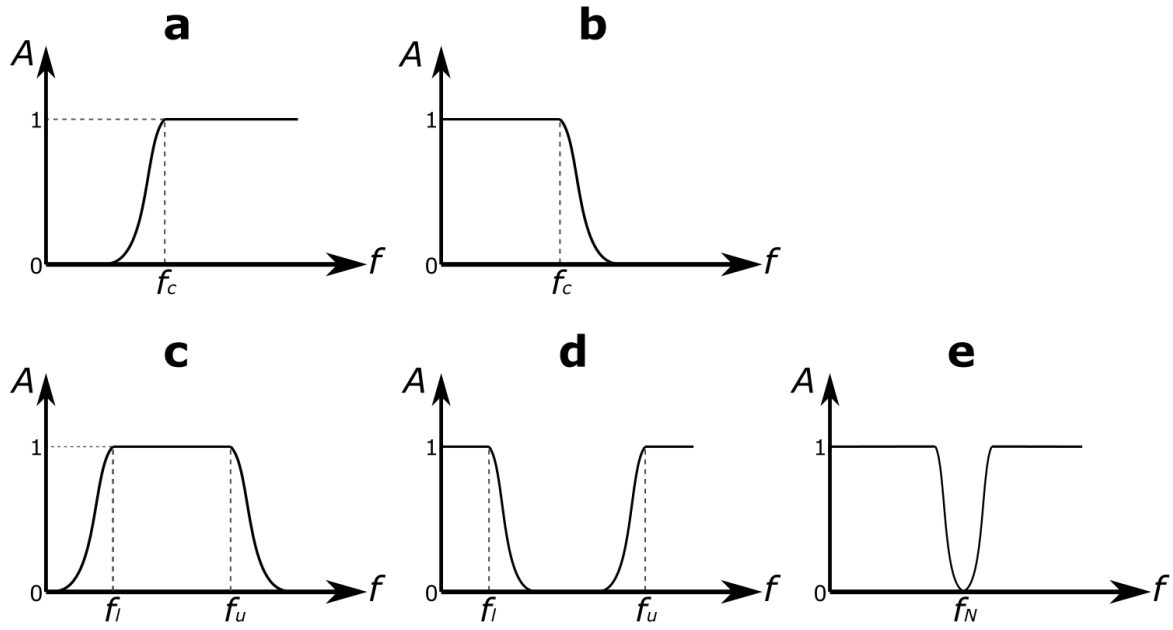


Figure 3.10: Different common frequency filters used for f - x filtering: High-pass (a), low-pass (b), band-pass (c), band-stop (d), and notch (e). Each filter has a taper applied to the edges to reduce Gibbs ringing. Where relevant, f_c denotes cutoff frequency, f_l denotes lower-bound frequency, f_u denotes upper-bound frequency, and f_N denotes notch frequency.

As also shown in Figure 3.10, these filters should not discontinuously jump from zero to one or visa versa, but they taper off. This is because if tapers are not used, ringing known as the Gibbs phenomenon (Gibbs, 1898) will be caused in the data. Different types of tapers can be used depending on the data, some of the most common are the Butterworth, Hamming, or Cosine Bell filters. In the frequency domain, the different types of filters control the way in which the filters taper off, such as those seen in Figure 3.10. In the time domain, these filters look like general amplitude-controlled sinusoids akin to the sinc function.

Figure 3.11 demonstrates how f - x filtering works. The shot gather was taken from profile KBF01. This gather, which has had an AGC applied, is a prime example of the issue described above regarding AC current; a power line is located very near the shot and is evidently contaminating the gather with 50 Hz noise, as seen in channels 86 to 108 as well as in the f - x spectrum. The filter used to clear this noise is a notch filter (Figure 3.10e) with $f_N = 50$ Hz. The result is a much cleaner gather, with clearer reflections and p-wave and s-wave arrivals.

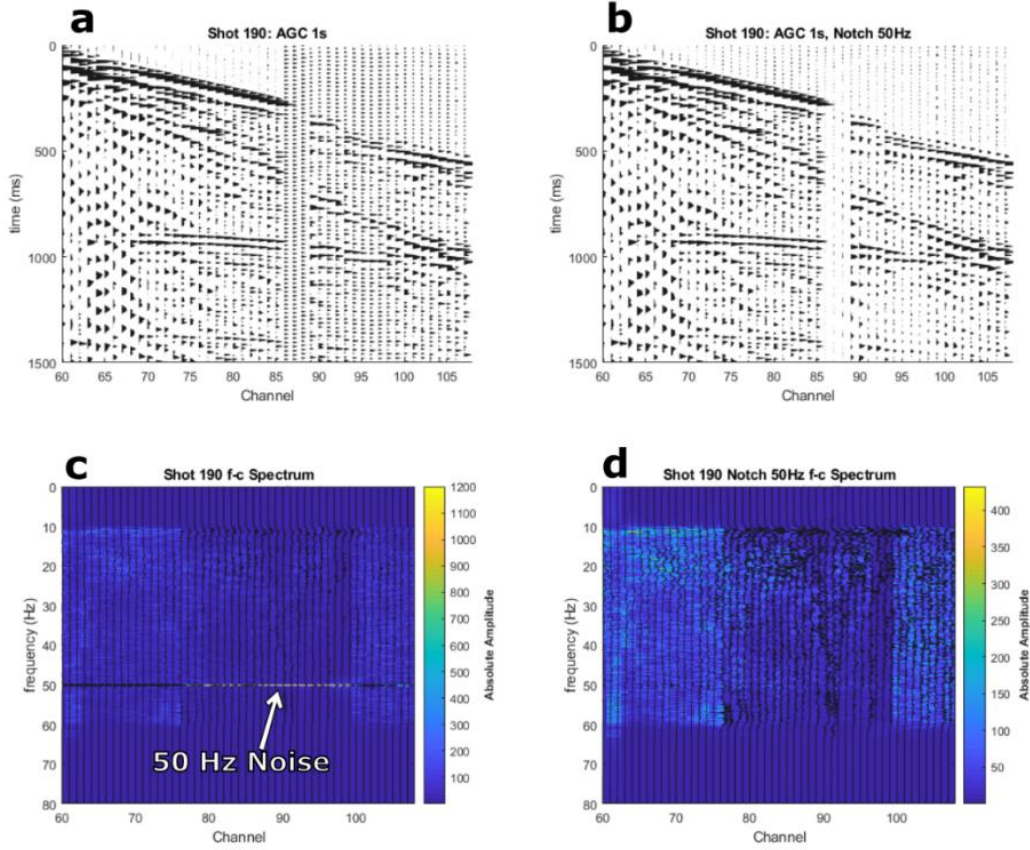


Figure 3.11: Example application of 50 Hz notch filter to shot gather 190 from profile KBF01 (Paper I). The prefiltered gather is shown in (a), the filtered gather in (b), and the corresponding f - x transforms (here termed f - c for “frequency-channel”) in (c) and (d), respectively.

Frequency-Wavenumber (f - k) Filtering

The FT and its inverse (Equations 3.5a and b) easily extend into two dimensions:

$$Y(k, f) = \int y(x, t) e^{-i2\pi(kx+ft)} dx dt \quad (3.6a)$$

$$y(x, t) = \int Y(k, f) e^{i2\pi(kx+ft)} dk df \quad (3.6b)$$

where k is the spatial frequency, or wavenumber and other terms are identical to those in Equations 3.5a and b.

With application to reflection seismics, the 2D FT is useful in that it identifies signals that propagate at a specific velocity. Basic wave theory states that a wave function whose FT is given by $F(k, f)$ propagates with a velocity v proportional to the ratio of its frequency to its wavenumber:

$$v = \frac{\omega}{k} \quad (3.7)$$

Here, $\omega = 2\pi f$ is the angular frequency.

Following [Equations 3.6a and 3.7](#), and illustrated in Figure 3.12, any signal that has a characteristic velocity will manifest as a strongly coherent linear feature in the f - k domain. In seismics, these linear signals are specifically attributed to refracted p- and s-waves as well as surface waves. This is particularly useful in reflection seismics because shot gathers will almost always be dominated by high-amplitude, low-velocity surface waves comprised of Rayleigh waves, whose particle motions are elliptical, and Love waves, whose particle motions are transverse ([Telford et al., 1990](#)). These waves, along with the s-wave, serve no use in vertical-component surveys that target p-waves, and are thus filtered out. The s-wave will generally have a higher velocity than the surface waves (about 110%) and so the typical filter used is one that zeros all signals with velocities lower than the s-wave, as illustrated in Figure 3.12. This velocity depends on the characteristics of the rocks through which the wave is travelling but is roughly half the velocity of the p-wave arrival. As is the case with the 1D filters, 2D filters have a taper applied to the edges to avoid ringing in the data.

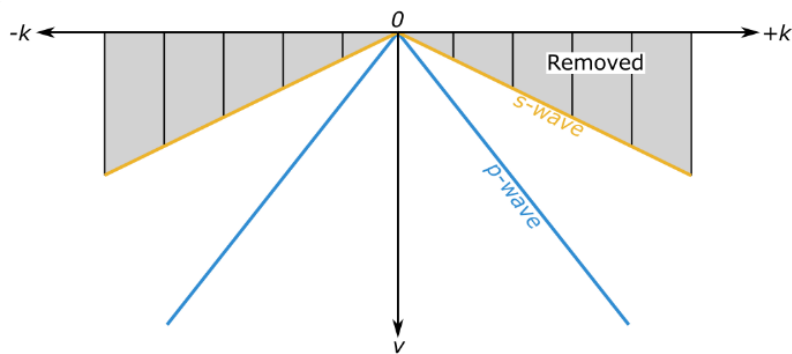


Figure 3.12: Illustration of f - k filter design for prestack data. The s-wave arrival, whose velocity is roughly half that of the p-wave arrival, is usually undesired, as well as any signal with a lower velocity. Hence, these signals are removed, as shown by the greyed out area. Other linear signals, such as refracted waves, have been excluded for simplicity.

An example of f - k filtering applied to real data is shown in Figure 3.13. This shot gather has a strong presence of ground roll as seen in both the t - x (Figure 3.13a) and f - k domain (Figure 3.13c). Analysis of the shot gather reveals the s-wave velocity to be 3536 m/s. After muting all the velocities lower than this, the gather appears much cleaner (Figure 3.13b); the reflections near 1 s are more clearer as they are not being contaminated by the ground roll and shallower reflections are emerging where the ground roll was.

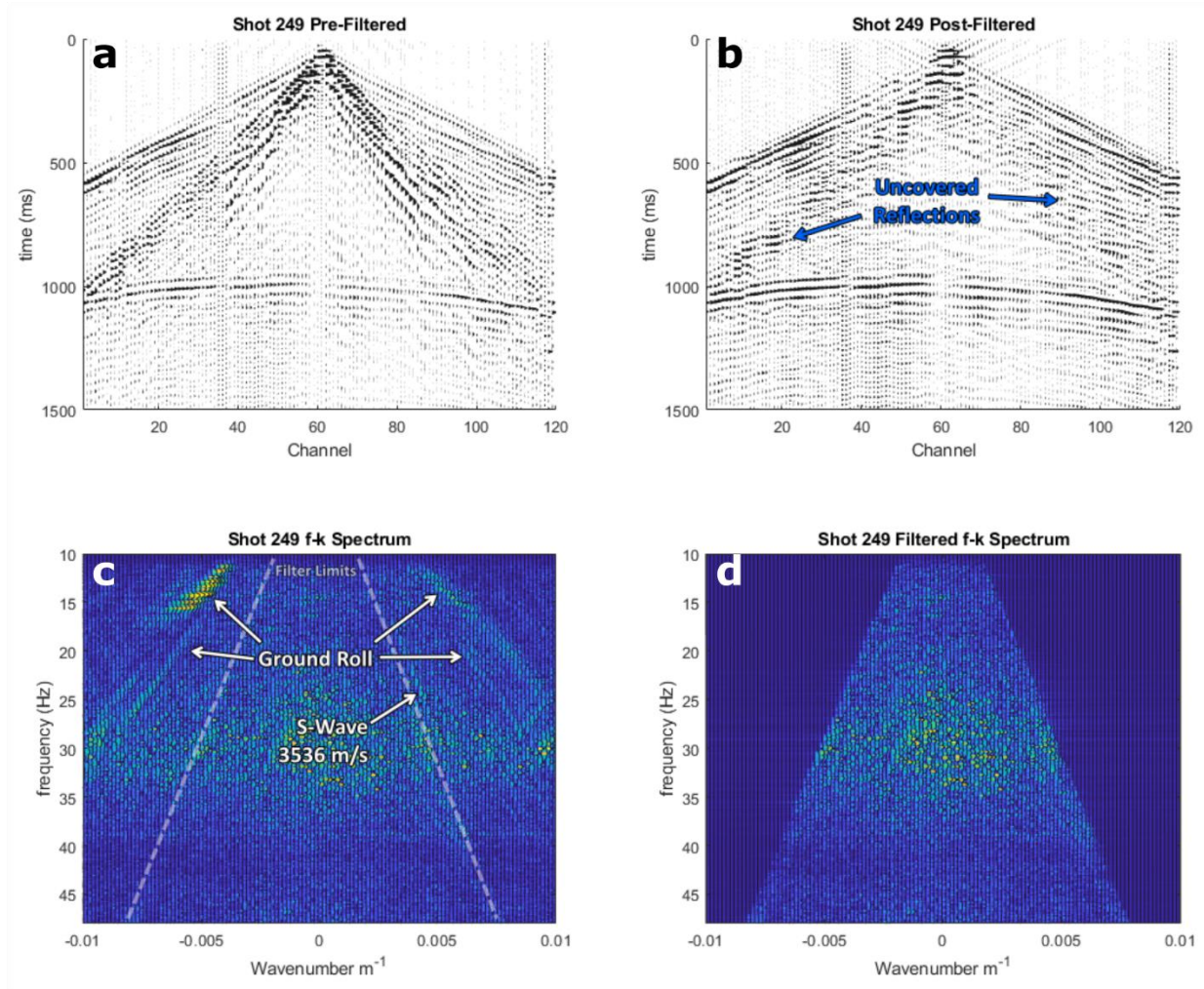


Figure 3.13: Real example of f - k filter taken from profile KBF01 (Paper I). (a) and (b) show the shot gather before and after filtering, respectively, and (c) and (d) display the respective f - k spectra. The removal of ground roll leads to notable low-amplitude reflections and a clearer shot gather.

3.4 Deconvolution

The aim of deconvolution is to increase the temporal resolution (and therefore depth resolution in final stacked and migrated section) of reflections as well as to suppress reflection multiples. This is done by computing either deterministically or statistically the convolutional inverse of the characteristic wavelet of a survey and convolving the inverse with the entire dataset. This results in compressing the wavelet in the data and increasing temporal resolution. Typically, deconvolution computes the best inverse filter of the inherent wavelet using a leased-squares solution known as the Wiener-Hopf method (Linton and McIver, 2001). The two most common derivatives of this approach are spiking deconvolution and predictive (or gap) deconvolution, the latter of which is used for profiles KBF01 and KBF03A. These principles are explained in greater detail in the section.

Convolutional Earth Model

Typical seismic surveys sample subsurface points repeatedly to provide an excess of data and thus provide more accurate imaging of the subsurface. This is known as data redundancy and is achieved by conducting surveys that have multiple source-receiver pairs sampling the same point with varying offsets (offset is the surface distance from a given source to a corresponding receiver). Prior to migration, the goal of processing is to manipulate the reflection data that has non-zero offsets in a way that simulates a zero offset survey, while exploiting the redundancy of seismic data to maximise the SNR.

The zero-offset section can be modelled using the convolutional model (Yilmaz, 1987, 85-92pp). This model states that a zero offset trace, $s(t)$, is given by the convolution of the input wavelet, $w(t)$, with the earth's impulse response, $e(t)$:

$$s(t) = w(t) * e(t) \quad (3.8)$$

The earth's impulse response (also known as the reflectivity series) is calculated, as illustrated in Figure 3.14, as follows: at a reflection boundary, located at depth z , the reflection coefficient is given by:

$$R(z) = \frac{I_+(z) - I_-(z)}{I_+(z) + I_-(z)} \quad (3.9)$$

Where I_+ is the acoustic impedance of the deeper layer (given by the velocity of that layer multiplied by the density of that layer), and I_- is the acoustic impedance of the overlying layer. This is illustrated in Figure 3.14a,b. The function $R(z)$ can be carried into the time domain using the velocity function, $v(z)$, of the model; by multiplying z by $2/v$, the reflection coefficients in Figure 3.14b are relocated to their two-way-time (TWT) locations, thus giving $R(t)$ (Figure 3.14c). $R(z)$ is then convolved with a model wavelet, $w(t)$, to produce a synthetic seismogram $s(t)$ of the section (Figure 3.14d,e).

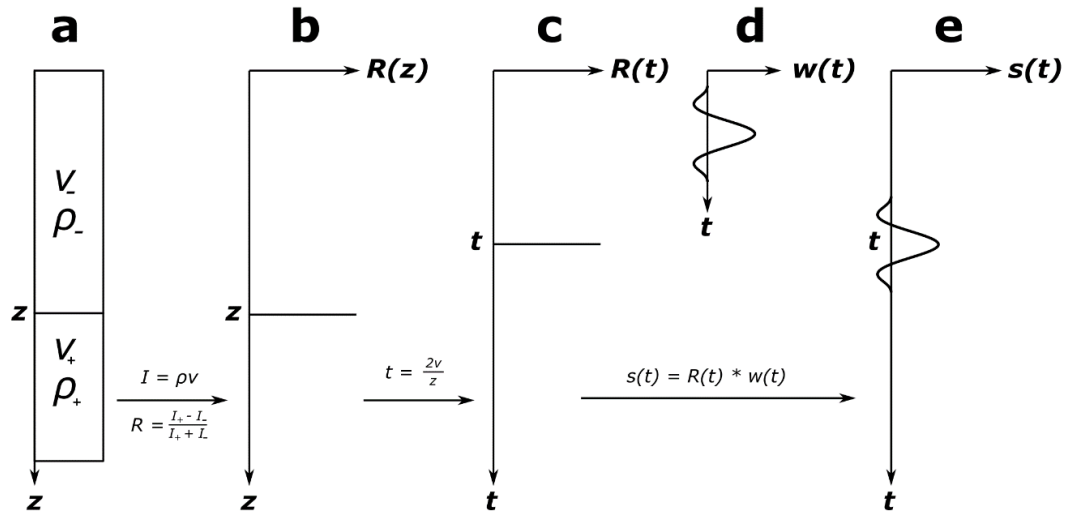


Figure 3.14: Illustration of the deconvolutional model and how it is used to calculate a synthetic seismogram, $s(t)$, using a modelled wavelet $w(t)$, given the velocity v and density ρ logs.

This process is particularly useful in modelling seismic data from borehole logs, as seen in the real example of borehole modelling from [Paper II](#) in Figure 3.15. If a downhole survey records the density and sonic velocity as functions of depth in a borehole, the acoustic impedance contrasts can be calculated at each sample point, as described above, and the reflectivity series can be constructed. A wavelet is then chosen to represent the survey wavelet and is convolved with the reflectivity series to give the modelled seismogram, as illustrated in Figure 3.14 and Figure 3.15.

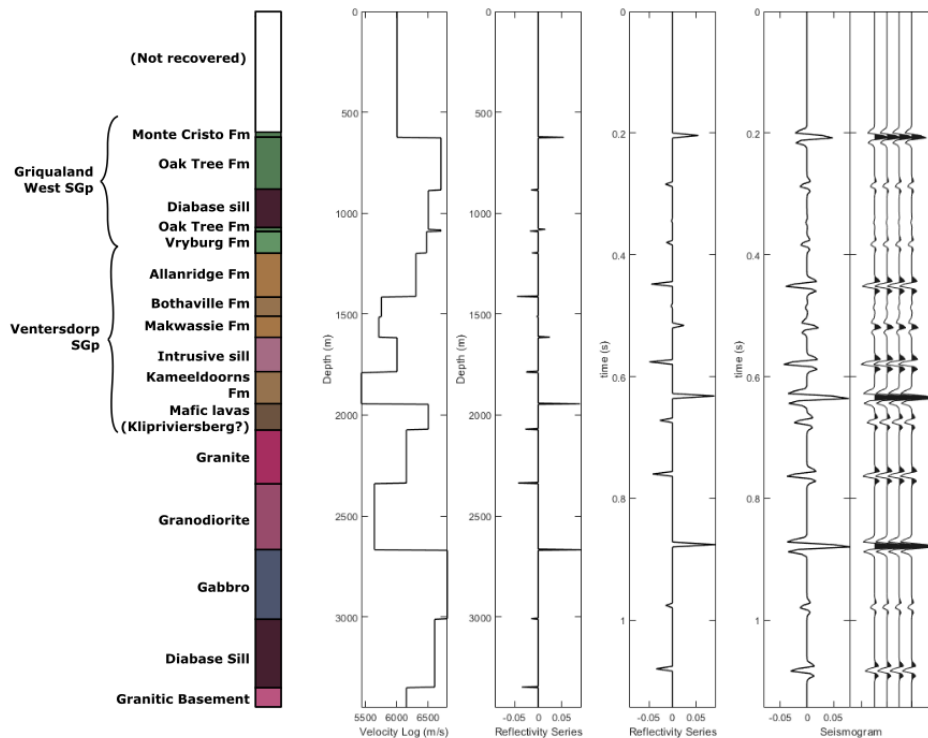


Figure 3.15: Example of synthetic seismogram calculated from sonic log measurements of borehole KHK-1 from [Paper II](#). Strong reflections are associated with intrusives within the Ventersdorp Supergroup, as well as the bases of the

Monte Cristo Formation and between the granodiorite and gabbro below the supracrustals. Figure taken from [Paper II](#).

For [Papers I and II](#), MATLAB code was developed to model borehole data in this way. The code features a graphical user interface and allows the user to select an input wavelet along with a dominant frequency for the wavelet. This code was used for Figure 3.15 and is attached in [Appendix A](#).

Deconvolution and Wiener Filters

If the convolutional inverse of $w(t)$, denoted as $w(t)^{-1}$, in [Equation 3.8](#) is found and convolved with both sides of the equation, it would yield:

$$w(t)^{-1} * s(t) = \delta(t) * e(t) = e(t) \quad (3.10)$$

where $\delta(t) = w(t)^{-1} * w(t)$ is the Kronecker delta that attains a value of 1 at $t=0$ and 0 everywhere else for discrete signals. [Equation 3.10](#) encapsulates the basic principle of deconvolution; if the inverse of the wavelet is convolved with the trace, it will yield the earth's impulse response, thus increasing the temporal resolution from a wavelength to a spike. If the wavelet is known, [Equation 3.10](#) is deterministic and can be calculated via polynomial division of the wavelet's z-transform ([Yilmaz, 1987, 94pp](#)).

However, in reality, the wavelet is rarely known and the computation of $w(t)^{-1}$ moves from being deterministic to statistical. The statistical approach of determining the coefficients of $w(t)^{-1}$ is by minimising the sum of the differences squared between a desired output say a_i , where $i=1, \dots, n$ and the actual output, b_i , given by convolving $w(t)^{-1}$ and $w(t)$, as follows:

$$a_i = a_1, a_2, \dots, a_n \quad \text{Desired Output} \quad (3.11a)$$

$$w(t)^{-1} * w(t) = b_1, b_2, \dots, b_n \quad \text{Actual Output} \quad (3.11b)$$

$$L = \sum_i (a_i - b_i)^2 \quad (3.11c)$$

$$\frac{\partial}{\partial b_i} L = 0 \quad (3.11d)$$

So, given a wavelet $w(t)$, find the coefficients of $w(t)^{-1}$, which are implicit in b_i that minimise L . [Equation 3.11d](#) is the well known least squares problem, given by a system of n equations in n unknowns.

[Wiener \(1949\)](#) generalised this notion by deriving a matrix equation that takes as input both a given wavelet, w , and its desired output, d , and gives as output the coefficients of a filter that will minimise the difference between the two inputs using the least squares method. The general form of this equation is given by ([Robinson and Treitel, 1980; Yilmaz, 1987, 95pp](#)):

$$\begin{bmatrix} T_0 & T_1 & T_2 & \cdots & T_{n-1} \\ T_1 & T_0 & T_1 & \cdots & T_{n-2} \\ T_2 & T_1 & T_0 & \cdots & T_{n-3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ T_{n-1} & T_{n-2} & T_{n-3} & \cdots & T_0 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \vdots \\ a_{n-1} \end{bmatrix} = \begin{bmatrix} V_0 \\ V_1 \\ V_2 \\ \vdots \\ V_{n-1} \end{bmatrix} \quad (3.12)$$

Here, T_i is the i^{th} lag of the autocorrelation of w , a_i is the least squares filter (or optimum Wiener filter), and V_i is the i^{th} lag of the cross-correlation between w and d . In matrix form, Equation 3.12 can be written as $TA = V$, where the symmetric matrix T is known as the Toeplitz matrix, and the solution $A = T^{-1}V$ can be solved efficiently using the Levinson Recursion algorithm (Claerbout, 1985).

Both datasets examined in this thesis (profiles KBF01 and KBF03A presented in Papers I and II, respectively) were acquired using the Vibroseis method and predictive deconvolution was used in both cases (Table 3.1). Before reviewing the theory of predictive deconvolution, spiking deconvolution is first treated briefly here as it lays a good foundation for reviewing predictive deconvolution.

Spiking Deconvolution

The goal of spiking deconvolution is to compress the wavelet into a spike (1,0,0,...). Typically, if the wavelet is minimum phase (energy is concentrated at the beginning of the wavelet) then the spike is zero lag, and if the wavelet is maximum phase (energy is concentrated at the end of the wavelet), the spike will have a lag equal to the length of the wavelet, however a maximum phase wavelet is not found in seismic surveys. A mixed phase wavelet is generally too unstable to compress to a spike (Yilmaz, 1987, 100-102pp).

This method can be performed deterministically (if the source wavelet is known), as in Equation 3.8, or statistically (if the source wavelet is unknown). In the latter case, Equation 3.12 takes the form:

$$\begin{bmatrix} T_0 & T_1 & T_2 & \cdots & T_{n-1} \\ T_1 & T_0 & T_1 & \cdots & T_{n-2} \\ T_2 & T_1 & T_0 & \cdots & T_{n-3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ T_{n-1} & T_{n-2} & T_{n-3} & \cdots & T_0 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \vdots \\ a_{n-1} \end{bmatrix} = \begin{bmatrix} T_0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad (3.13)$$

Predictive Deconvolution

Predictive deconvolution, also known as gap deconvolution, is designed to both compress the wavelet and suppress multiples following primary reflections. Multiples are caused by reverberations of reflected waves within rock layers and manifest in seismic data as duplicate reflections with later arrival times. The way multiples are suppressed while simultaneously compressing the wavelet is by setting the desired output as a time-advanced version of the input wavelet, with time shift/gap α . The resulting equation from Equation 3.12 is (Robinson and Treitel, 1980):

$$\begin{bmatrix} T_0 & T_1 & T_2 & \dots & T_{n-1} \\ T_1 & T_0 & T_1 & \dots & T_{n-2} \\ T_2 & T_1 & T_0 & \dots & T_{n-3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ T_{n-1} & T_{n-2} & T_{n-3} & \dots & T_0 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \vdots \\ a_{n-1} \end{bmatrix} = \begin{bmatrix} T_\alpha \\ T_{\alpha+1} \\ T_{\alpha+2} \\ \vdots \\ T_{\alpha+n-1} \end{bmatrix} \quad (3.14)$$

Here, the filter a_i is known as the prediction filter as it predicts the value of the input wavelet at time $t+\alpha$, given its value at t . This prediction filter yields the multiples, i.e. the predictable component of the trace. The prediction error filter, which is simply the difference between the actual output and the desired output (i.e. a time-lagged version of the input) is given by $(1, 0, 0, \dots, -a_0, -a_0, -a_0, \dots, -a_n)$, where the $-a_0$ component occurs at time $\alpha+1$ (Yilmaz, 1987, 116pp). This filter yields the unpredictable component, which is the reflectivity series of the earth model (see assumption 5 under the “Assumptions of Deconvolution” section below).

By convolving the trace with the prediction error filter, multiples within the deconvolution window are suppressed and the primary is compressed, provided both the operator length n and the prediction lag α are chosen well, as outlined below. These are treated in detail here as they are pertinent to the profiles examined in Papers I and II, as seen in Table 3.1.

The operator length should be chosen as the lag time encompassing the first transient zone in the autocorrelation of the trace (Yilmaz, 1987, 114pp). This interval of the trace autocorrelogram is most representative of the wavelet autocorrelogram (see assumption 5 under the “Assumptions of Deconvolution” section below). The prediction lag should be chosen as the time at which the trace autocorrelogram experiences its first or second non-trivial zero, as this region is what is preserved in the deconvolution. Setting this parameter to unity is equivalent to spiking deconvolution.

Predicative deconvolution was used in the prestack processing of both the seismic profiles KBF01 and KBF03A. The operator length and prediction lag were shot-dependant. Figure 3.16 demonstrates the effectiveness of predictive deconvolution taken from one of the shot gathers in profile KBF03A. Note the compression of the wavelet as well as the suppressed multiples, thus improving overall resolution.

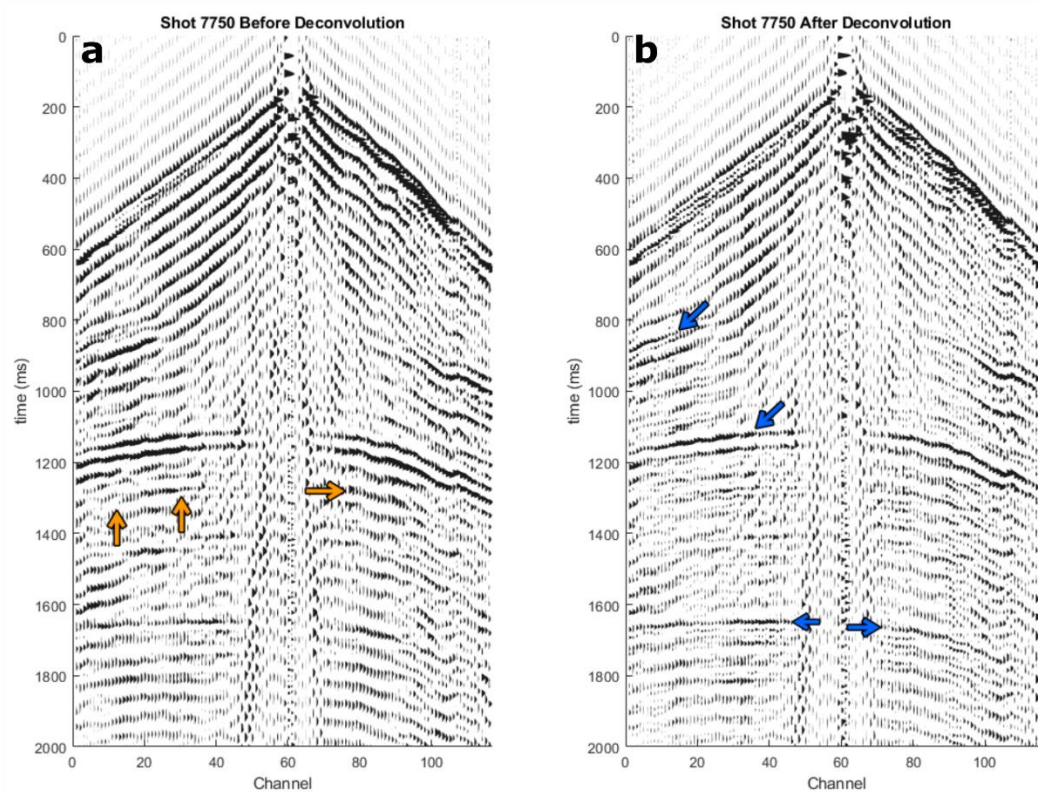


Figure 3.16: Example of predictive deconvolution taken from profile KBF03A ([Paper II](#)) before (a) and after (b). Blue arrows indicate where wavelets have been compressed and orange arrows indicate where multiples have been significantly suppressed.

Assumptions of Deconvolution

The theory as described above of deconvolution is built on a number of assumptions. However, the process has proven robust enough that if these assumptions are slightly violated, the deconvolution may still perform well ([Yilmaz, 1987, 109pp](#)). Table 3.3 below summarises these assumptions.

Assumption	Necessity	Justification
1. The earth comprises horizontal layers with constant velocities.	Implicit in the convolutional model. Non-horizontal layers would alter the reflection coefficient formula (Equation 3.9) and thus the reflectivity series.	The spread of a typical survey is generally small in comparison to the depth of investigation, hence reflected waves do not deviate much from a zero degree angle of incidence.
2. Only compressional waves are generated by the source. These waves impinge on reflection boundaries at normal incidence.	Implicit in the convolutional model. Similar to assumption 1, Equation 3.9 would cease to be valid and a more complex solution would be needed.	Similar to assumption 1: The spread of a typical survey is generally small in comparison to the depth of investigation, hence reflected waves do not deviate much from a zero degree angle of incidence. Additionally, most reflection surveys make use of the compressional waves and ignore/filter out the shear waves.
3. The wavelet is stationary: it does not change over time.	Implicit in the convolutional model. If the wavelet altered with time, Equation 3.8 would no longer be valid.	Depending on the survey, the wavelet remains relatively consistent over time. The factors that do influence it are

		absorption of high frequencies by the ground as heat energy as well as amplitude loss, as explained in Chapter 3.1 under “ <i>Amplitude Recovery</i> ”. These influences can be remedied by splitting the deconvolution into time-stages, with each stage having an independent filter.
4. Ambient noise is negligible.	In reality, Equation 3.8 should include an additional term $+n(t)$, representing the noise in the trace. If this were the case, Equation 3.8 would be too simple.	Noise is reduced as much as possible via filtering and data preparation prior to deconvolution. Whilst noise cannot be completely removed, deconvolution performs well under relaxation of this assumption (Yilmaz, 1987, 109pp). Poststack data are more robust as noise is substantially reduced via stacking.
5. Reflectivity is random.	As per the convolutional theorem*, the trace spectrum is given by the wavelet spectrum multiplied by the reflectivity series. As such, the source waveform (which is often not known) spectrum and autocorrelogram can be substituted by that of the wavelet if the reflectivity series has a flat spectrum, i.e. it is random.	A non-random reflectivity would imply cyclic deposition of sediments. This type of geology is rarely encountered but if it is, predictive deconvolution is not the optimum candidate, a different approach such as spiking deconvolution should be implemented.
6. The wavelet is minimum phase.	A wavelet that is not minimum phase is unstable and its least squares inverse will have a large error, rendering it useless.	This assumption applies to spiking deconvolution. Most impulse sources have a minimum phase character. Sources such as Vibroseis typically have a predictive deconvolution applied.

Table 3.3: A summary of the assumptions made by the convolutional model and deconvolution, as well as their necessity and their justifications. *The convolutional theorem states that convolution in the time domain is equivalent to multiplication in the frequency domain ([Yilmaz, 1987](#)).

3.5 Velocity Analysis and Stacking

Reflection seismic data contain a lot of redundancy due to the large amount of source-receiver pairs. This redundancy is exploited to greatly improve the SNR, which is achieved by binning traces into gathers that have the same midpoint, which are referred to as CMP gathers (as described under “Geometry” in [Chapter 3.1](#)) and stacking them. The term stacking refers to summing traces that have a coherent signal, which boosts that signal and attenuates incoherent signal. However, these traces cannot be stacked until the differences in travel times of their associated raypaths (due to the varying source-receiver offsets) has been accounted for. This difference, known as normal moveout (NMO), is derivative of the velocity model of the underlying geology. The goal of velocity analysis is to correct all the traces of each CMP gather to represent a zero-offset situation (as if the source and the receiver would have been located at the same point on the surface, namely the CMP). By constructing a velocity field, the NMO can be computed and the difference in traveltimes can be reversed, allowing for the NMO-corrected traces to be stacked. This section provides a brief overview of the velocity analysis conducted for profiles KBF01 and KBF03A.

Normal Moveout

As illustrated in Figure 3.17, reflections manifest in gathers (shot or CMP; wherever the offset-time domain is implicit) as hyperbolae along the time axis ([Telford et al., 1990, 155-182pp](#); [Eaton et al., 2003](#); [Dentith and Mudge, 2014](#)), constrained by a velocity parameter, v_{NMO} , known as the normal moveout velocity. The arrival time of a reflected wave, $t(x)$, at a given offset x is given by

$$t(x)^2 = t(0)^2 + \left(\frac{x}{v_{NMO}}\right)^2 \quad (3.15a)$$

where $t(0)$ is the traveltime for zero offset. This is generally the case for a stratified earth model. [Equation 3.15](#) gets more complex when multiple layers are considered and when dipping layers are introduced, as summarised in Table 3.4. However it serves as a good enough approximation provided the maximum offset is small and dips are gentle, causing the higher order terms, $C_2, C_3, \dots$, as seen in Table 3.4, to be negligible ([Heiland, 1946](#); [Yilmaz, 1987, 157-163pp](#)). The velocity in the normal moveout of the first scenario shown in Table 3.4 is simply the overlaying layer’s velocity. The normal moveout velocity of a horizontally stratified earth is equivalent to the RMS velocity, v_{RMS} , of the overlaying N layers ([Taner and Koehler, 1969](#)). The normal moveout velocity of a layered earth with arbitrary dips is a convoluted function of the dips and velocities ([Hubral and Krey, 1980](#)).

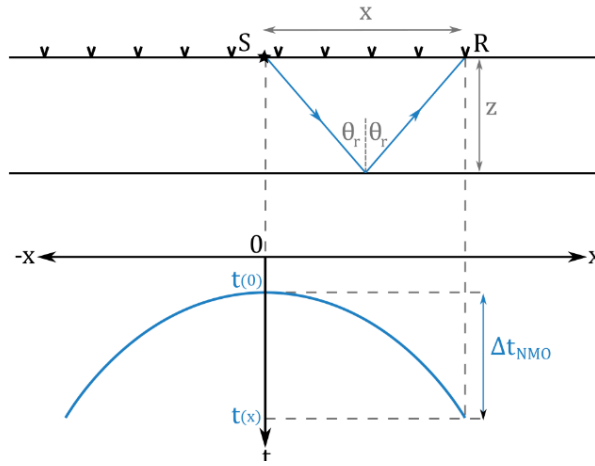
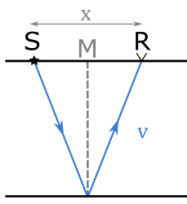
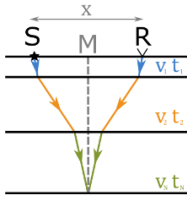
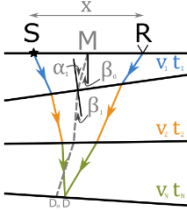


Figure 3.17: Normal moveout (Equation 3.15) illustrated using single horizontal reflector. The moveout manifests as a hyperbola in the offset-time domain.

Scenario	Moveout Equation	Associated Velocity (v_{NMO})	Symbols
<u>Single Reflector</u> 	$t(x)^2 = t(0)^2 + \frac{x^2}{v^2}$	v	S: Source R: Receiver M: Midpoint v: Layer velocity x: Offset $t(x)$: Arrival time $t(0)$: Zero-offset arrival time
<u>Multiple Reflectors</u> 	$t(x)^2 = t(0)^2 + \frac{1}{v_{NMO}^2} x^2 + C_2 x^4 + \dots$	$v_{RMS}^2 = \frac{1}{t_0} \sum_i^N v_i^2 t_i$	S: Source R: Receiver M: Midpoint v_i : i^{th} layer velocity t_i : i^{th} layer TWT t_0 : Total TWT to N^{th} layer x: Offset $t(x)$: Arrival time $t(0)$: Zero-offset arrival time C_n : Higher order terms
<u>Dipping Reflectors</u> 	$t(x)^2 = t(0)^2 + \frac{1}{v_{NMO}^2} x^2 + C_2 x^3 + \dots$	$v_{NMO}^2 = \frac{1}{t_0 \cos^2 \beta_0} \sum_i^N v_i^2 t_i \prod_k^{i-1} \frac{\cos^2 \alpha_k}{\cos^2 \beta_k}$	S: Source R: Receiver M: Midpoint v_i : i^{th} layer velocity t_i : i^{th} layer TWT

			x : Offset $t(x)$: Arrival time $t(0)$: Zero-offset arrival time C_n : Higher order terms t_0 : Total TWT to N^{th} layer
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Table 3.4: Different scenarios in which the moveout equations can be well-approximated by Equation 3.15. (Heiland 1946; Yilmaz, 1987)

The difference between $t(x)$ and $t(0)$, as illustrated in Figure 3.17, is termed the normal moveout (NMO) and is given by:

$$\Delta t_{NMO} = t(0) \left[\sqrt{1 + \left(\frac{x}{v_{NMO}} \right)^2} - 1 \right] \quad (3.15b)$$

Once the v_{NMO} of a specific reflection has been determined, it can be flattened using Equation 3.15 and summed across the traces in the CMP gather to boost the reflection in that CMP. In practice, the velocity used to stack the traces, v_{st} , is not necessarily equal to v_{NMO} as it is the velocity that produces the best stack, i.e. it is the velocity with the best hyperbolic fit for small offset, whereas v_{NMO} is the velocity with the best hyperbolic fit for all offsets.

Velocity Picking

In order to stack all traces in a survey, a velocity model in the CMP-time domain must be constructed. This velocity model consists of a stacking velocity v_{st} , as described above, for every CMP-time pair. Typically, a velocity-time function is manually picked for CMPs at regular intervals and the velocity functions for intermediate CMPs are interpolated.

There exist multiple methods for picking the velocity functions, the most conventional of which are briefly explained below (Heiland 1946; Yilmaz, 1987; Telford et al., 1990):

- **$t^2 - x^2$ analysis:** As per Equation 3.15, reflections map onto the $t^2 - x^2$ domain as linear functions with gradient $1/v_{st}^2$ and intercept $t(0)^2$. By transforming the CMP gather into this domain, linear events can be isolated and the gradient and intercepts thereof can be extracted to construct the velocity function of that gather.
- **Constant Velocity Scans:** For each CMP gather under analysis, a series of NMO-corrected gathers are displayed in a series of panels. Each panel has a constant stacking velocity for the entire gather, which runs from a lower velocity to an upper velocity with a set interval. The reflections are then analysed and the panel whose gather displays the best NMO correction for a given reflection has the corresponding velocity of that panel assigned to the time location of the reflection.

- **Constant Velocity Stack (CVS):** Similar to the constant velocity scan method. However, instead of displaying a series of NMO-corrected CMP gathers, a range of CMP gathers are selected, centred on the analysis gather, are each stacked with the constant velocity, and are displayed in a series of panels, each with an associated constant stacking velocity. The velocity that displays the best lateral continuity for a given reflection is then picked for that reflection and assigned to the velocity function of the analysis CMP at the time-location of the reflection.
- **Velocity Spectrum Method:** The velocity spectrum is a transformation of a CMP gather from the $t - x$ domain to the $t_0 - v$, where t_0 and v are zero-offset TWT and stacking velocity, respectively. The resulting transform is a measure of coherency for each t_0, v pair; a high coherency suggests that the associated velocity be used to stack the gather at time t_0 . The coherency is calculated using a variety of methods, each with pros and cons. Among the most common methods are unnormalised and normalised stacked amplitude, unnormalised and normalised crosscorrelation sum, energy-normalised crosscorrelation sum, and semblance (Yilmaz, 1987, 169-173pp).

The CVS method was used for the velocity analysis of both KBF01 and KBF03A seismic profiles, where a velocity function was picked every hundredth CMP and interpolated for intermediate CMPs. This method was chosen as it proved to be the most time-efficient method for the large-scale (<6000 CMP bins) profiles that were reprocessed, without significant expense in accuracy. Figure 3.18 gives an example of the CVS method applied to a CMP gather from seismic profile KBF03A. Reflection packages R1, R2, R3, R4 and R5 display the best stack at velocities 4500 m/s (Figure 3.18b), 6000 m/s (Figure 3.18e), 6500 m/s (Figure 3.18f), 7000 m/s (Figure 3.18g) and 6500 m/s (Figure 3.18f), respectively, hence the velocity function for CMP 3600 has these velocities picked at times 200 ms, 500 ms, 750 ms, 1500 ms and 2000 ms, respectively, and intermediate values are interpolated.

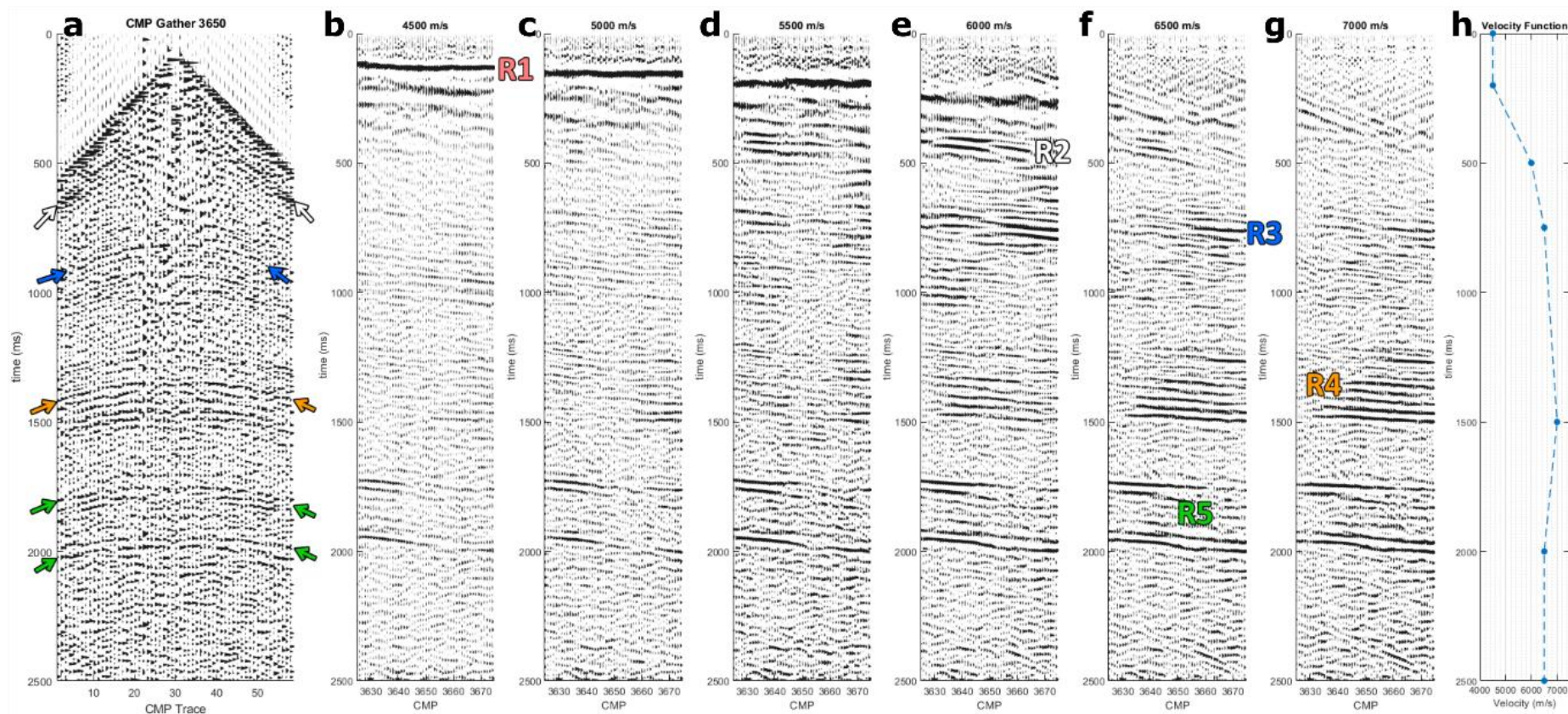


Figure 3.18: Constant velocity stack (CVS) of CMP gather 3650 and 50 neighbouring CMPs (a) from profile KBF03A ([Paper II](#)). Coloured arrows in unstacked gather (first panel) correspond to coloured reflection packages R2, R3, R4 and R5 in stack (panels b to g). Panel h shows the resulting velocity function for CMP 3650. CMP: Common midpoint.

NMO Stretch Mute

The method by which the NMO correction, Equation 3.15, is implemented is as follows. For every sample in the NMO-corrected gather, an amplitude is assigned by taking an interpolated amplitude of the four nearest samples surrounding the corresponding NMO-shifted sample, as per Equation 3.15. This, however, causes a distortion in the data's frequencies, as given by (Telford et al., 1990, 160pp; Dentith and Mudge, 2014):

$$\frac{\Delta f}{f} = \frac{\Delta t_{NMO}}{t(0)} \quad (3.16)$$

where Δf is the change in frequency after NMO correction, f is the dominant frequency, and $t(0)$ and Δt_{NMO} are found in Equations 3.15 and 3.15, respectively. This effect of frequency stretching is negligible except at shallow times and large offsets, as per Equations 3.15 and 3.16. Where the frequency stretching is big enough that it negatively impacts the stacking, it is muted. The stretch mute is quantified by a threshold percentage mute, where if the frequency stretching given by the left side of Equation 3.16 exceeds this percentage, the corresponding time samples, given by the right side of Equation 3.16 are muted. Figure 3.19 illustrates this with the same gather as in Figure 3.18 that is NMO-corrected with stretch mute percentages of 200%, 100% and 50%. The effect of NMO stretching is clearly evident in the early TWT and far offsets, while the data beyond 400 ms are relatively unaffected. Stretching of the frequencies is most apparent with the 200% mute, with substantial wavelet dilation seen in the < 200 ms region, whereas the 50% stretch mute does not show any noticeable change in frequency throughout the gather.

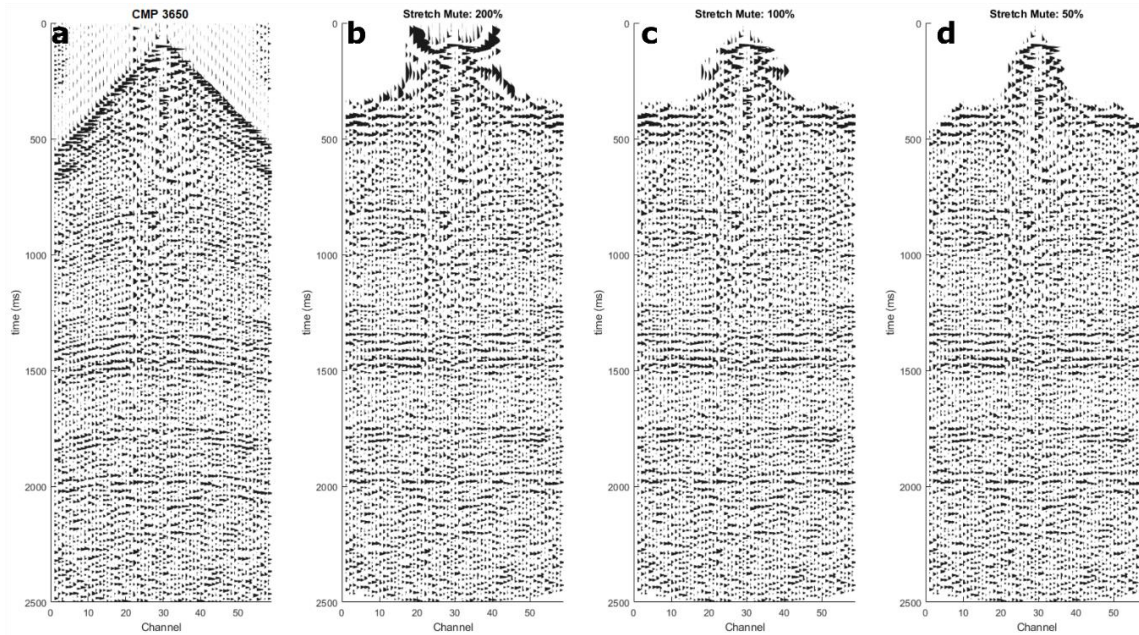


Figure 3.19: Illustration of the effects of NMO stretching and how they are mitigated using a stretch mute. The effects of the stretching are evident at shallow arrival times and far offsets. The CMP gather used here is identical to that used in Figure 3.18. NMO: Normal moveout. CMP: Common midpoint.

Residual Statics

In [Chapter 3.2](#), it was stated that prestack traces experience time delays due to the weathering layer and that these delays are remedied by both a long-wavelength correction (the refraction statics correction, as described in [Chapter 3.2](#)) and a short-wavelength correction (the residual statics correction), the latter of which is treated here. While the refraction statics correction is based on the refracted waves, the residual statics correction is based on reflected waves and requires a velocity model.

The aim of residual statics is to compute the static shift correction for each source location and each receiver location. This is based on the assumption that these shifts depend only on the surface location of the source-receiver pairs. This is most often a valid assumption as the weathering layer often has a much lower velocity than the underlying strata, leading to approximately vertical raypaths at the surface ([Hileman et al., 1968](#); [Taner et al., 1974](#); [Yilmaz, 1987, 203-206pp](#)). The static corrections based on this approximation are termed surface-consistent residual statics, and are performed once an initial velocity model is built.

The method by which the static shift of the j^{th} shot, s_j , and i^{th} receiver, r_i , is calculated is based on a least squares minimisation problem, as is the case of refraction statics ([Chapter 3.2](#)), where an inversion algorithm is used ([Chapter 3.2](#)). However, in this case, s_j and r_i are being inverted for directly. The forward model used in the inversion algorithm is ([Heiland 1946](#); [Yilmaz, 1987](#); [Telford et al., 1990, 203-206pp](#)):

$$t_{ijh} = s_j + r_i + G_{kh} + M_{kh}x_{ij}^2 \quad (3.17)$$

Here, t_{ijh} are the modelled travel times for reflected waves, G_{kh} is known as the structural term because it tracks the h^{th} horizon associated with the modelled reflection and is given by the time difference between the k^{th} CMP and a global reference CMP, and $M_{kh}x_{ij}^2$ is the difference between the imperfect moveout and the actual moveout correction associated with the h^{th} horizon. A diagram illustrating the symbols used in Equation 3.17 is given in Figure 3.20. The observed t_{ijh} values that are compared with the modelled values as per [Equation 3.17](#) are typically picked using an automated picking process, known as the pilot trace scheme, as follows. A picking window is applied to a pilot CMP, typically one with a high SNR, which has been NMO-corrected using an initial velocity model. The traces within this time gate are stacked and the stack is cross-correlated with each trace in the window and the lag time corresponding to the maximum cross-correlation (within a maximum-allowable shift constraint) is taken as the shift. This process is iterated and the updated time shift is stored as the time shift for the considered source-receiver pair. This shift is then used as the reference trace for the next CMP cross-correlation and the process repeats until all CMPs are done. A full mathematical description of this process and the least-squares implementation is given by [Yilmaz \(1987, 228-230pp\)](#). Once the residual statics have been computed, they are applied to the prestack reflection seismic data. The velocity model

is then repicked to update velocities after the static correction. The entire process can be iterated, as was done for both profiles KBF01 and KBF03A.

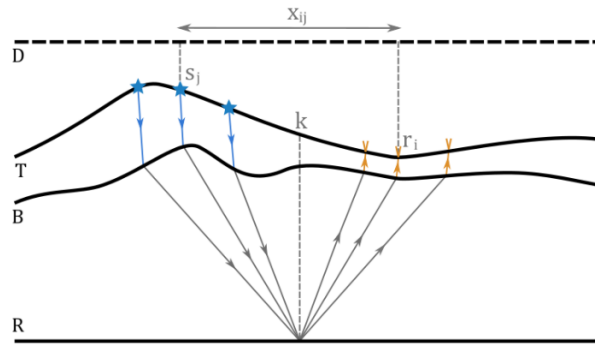


Figure 3.20: Diagram illustrating mathematical symbols for the residual statics correction, given by Equation 3.17. Blue and orange ray segments represent raypaths that cause the static shift of shots and receivers, respectively, which are approximated as vertically incident. D, T, B and R are the datum level, topography, bedrock, and reflector associated with the h^{th} (Equation 3.17) horizon, respectively. Other terms are defined in Equation 3.17.

Figure 3.21 displays a NMO-corrected CMP gather taken from profile KBF03A both before and after residual statics corrections. The pre-corrected NMO gather is based on an initial velocity model and the post-corrected gather is based on an updated velocity model after residual statics are applied. Note the evident improvement of lateral coherency in reflectors, as indicated by arrows. These corrections are short-wavelength and would not have been corrected by refraction statics.

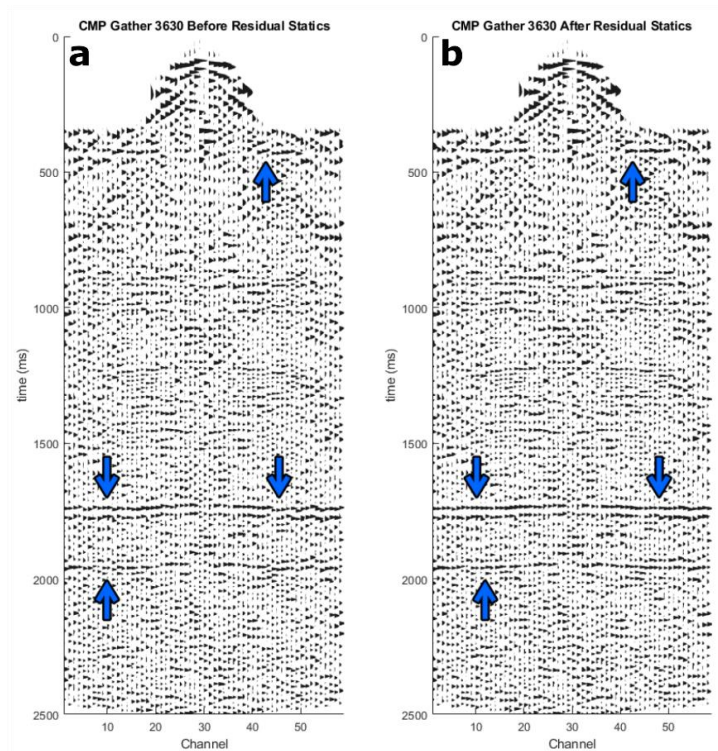


Figure 3.21: CMP gather 3630 from KBF03A (Paper II) before and after residual static corrections. Arrows indicate areas of notable improvement in reflection continuity.

3.6 Migration

Once the data have been stacked, the resulting section represents a zero-offset section with a high SNR. As such, it serves as a proxy image of the actual subsurface geology. However, this image is not entirely accurate where dipping geological features are present. The well-known illustration in Figure 3.22 shows that dipping events are misrepresented in zero-offset section as signals from these events are recorded as being located directly beneath the recording receivers, when they actually lie updip, outside of the vertical line beneath the receiver. These events are thus moved, or “migrated”, to their true positions via the process of migration. Additionally, where discontinuous geological features, such as faults, are present, diffraction of the wavefield occurs and is recorded in the stack as diffraction hyperbolae. Migration collapses these diffraction signals, resulting in a clearer subsurface image.

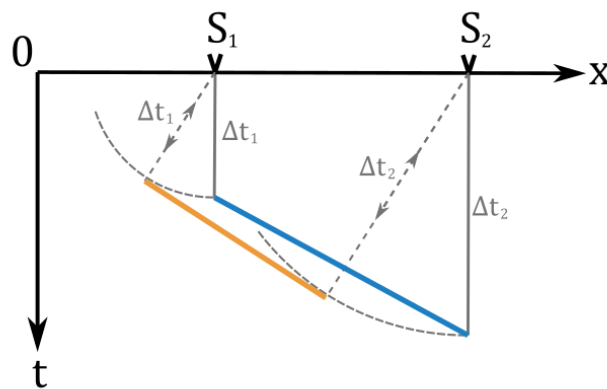


Figure 3.22: Dipping events (orange) are recorded at zero offset stations S_1 and S_2 at times Δt_1 and Δt_2 , respectively. However, the recorded signals are placed directly beneath the stations (blue) and are thus misrepresented. The overall result is that dipping reflectors appear to have more gentle dips and are shifted in the dip direction.

Many different migration algorithms exist and the field itself is a large and active field of research (see [Yilmaz, 1987, 250-263pp](#) and [Gray et al., 2001](#) for a comprehensive overview). In general, migration can either be done before or after stacking and in either the time or the depth domain, each having inherent advantages and disadvantages, depending mostly on the nature of the velocity field. As such, the type of migration is chosen based on the variation of the velocity field as summarised in Table 3.5. The migration used in both KBF01 and KBF03A profiles is a Kirchhoff poststack time migration (PSTM) and is treated here in more detail.

	Simple Geological Structure	Complex Geological Structure
Weak Lateral Velocity Variation	Poststack Time Migration	Prestack Time Migration
Strong Lateral Velocity Variation	Poststack Depth Migration	Prestack Depth Migration

Table 3.5: Typically used migration schemes depending on geological and velocity structure ([Yilmaz, 1987, 246pp](#)).

Kirchoff Migration

The foundation of Kirchoff migration is Huygen's principle; that is, that every point on the wavefront is itself a source of secondary wavelets that mutually interfere with other secondary wavelets (Huygens, 1690). These secondary wavelets from each point source spread out as a circle in the offset-depth domain and as hyperbolae in the offset-time domain (Yilmaz, 1987, 241-250pp; Gray et al., 2001). The mutual interference of the global collection of wavelets defines the new wavefront. With continuous subsurface reflectors, this interference manifests as a superposition of hyperbolae along the reflector horizon, as shown in Figure 3.23, producing a line. Where there is an abrupt discontinuity, the hyperbola located on the edge has no interference on the discontinuous side and so preserves its shape in the wavefront as shown in Figure 3.23c. This is why hyperbolae are observed along faults in stacked sections as they disrupt the continuity of reflectors.

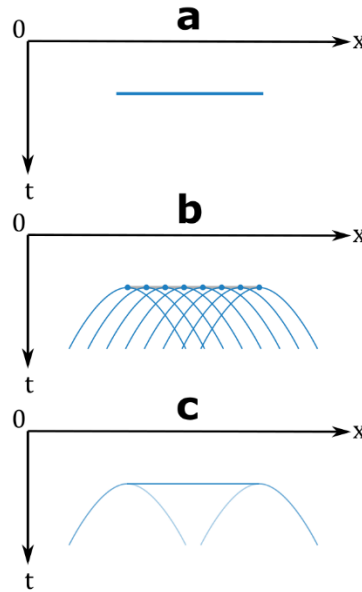


Figure 3.23: Illustration of Huygens' principle in x - t space: The reflector location (a) is given by the superposition of hyperbolae located on sampled points of the reflector (b). When all samples along the reflector are used, the hyperbolae mutually interfere and the result is (c).

The mathematical anatomy of the diffraction hyperbola is illustrated in Figure 3.24. The arrival time, $t(x_{off})$, for a given offset x_{off} from the apex of the hyperbola can be calculated to be:

$$t(x_{off})^2 = t(0)^2 + \left(\frac{2x_{off}}{v_{rms}}\right)^2 \quad (3.18)$$

where v_{rms} is the RMS velocity located at the hyperbola apex, $t(0)$.

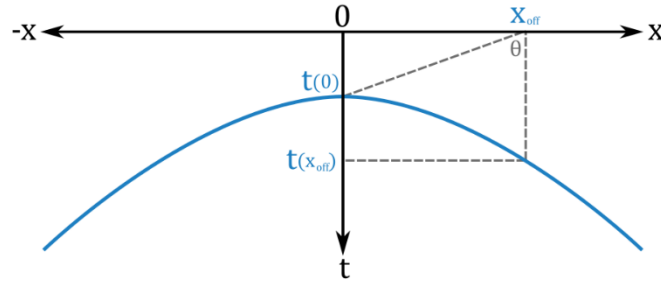


Figure 3.24: Quantifying the moveout of the diffraction hyperbola, given by Equation 3.18.

The algorithm of Kirchhoff migration is, for every $(x=x_{off}, t=t(0))$ point on the stack section, to sum the amplitudes lying on the hyperbolic trajectory, given by Equation 3.18, associated with that point and assign the result to the corresponding location of the migrated section.

Before this is done, three corrections need to be made (Heiland 1946; Yilmaz, 1987, 259pp):

1. **The obliquity factor.** This considers the amplitude dependence on the trajectory; amplitude decays when moving away from the apex due to the increasing obliquity of the wavelet. This is implemented by scaling amplitudes by $\cos(\theta)$, where θ is defined in Figure 3.24.
2. **The spherical spreading factor.** As secondary waves propagate from their source, their amplitude decays by a factor of the root distance traversed in 2D surveys.
3. **The wavelet shaping factor.** In order for the hyperbolae in Figure 3.23 to destructively interfere where the reflector is continuous, the intrinsic wavelets must have characteristic frequency and phase properties. For 2D surveys, the phase spectrum is set to a 45 degree constant and the amplitude spectrum is set proportional to the root frequency.

These can be separately implemented before filtering but a common approach that incorporates all three factors into the migration is the integral solution to the scalar wave equation (Schneider, 1978; Berryhill, 1979; Berkhout, 1980; Yilmaz, 1987, 260pp):

$$P_{out}(x, z, t) = \frac{1}{2\pi} \int \left[\frac{\cos\theta}{r^2} P_{in} \left(x_{in}, z = 0, t - \frac{r}{v_{RMS}} \right) + \left[\frac{\cos\theta}{vr} \frac{\partial}{\partial t} P_{in} \left(x_{in}, z = 0, t - \frac{r}{v_{RMS}} \right) \right] \right] dx \quad (3.19)$$

where P_{in} and P_{out} are the input and output zero-offset wavefields, respectively, θ is defined in Figure 3.24, $r = [(x_{in} - x)^2 + z^2]^{1/2}$ is the distance between input and output points, and v_{RMS} is the RMS velocity at the output point. The migrated section is obtained by setting the output values $t = 0$ and $z = vt/2$. The two terms of the integrand are the near field and far field terms in their respective order. For computational efficiency, the first term is often ignored as it contributes little due to the $1/r^2$ term.

When implementing Kirchhoff migration, three important parameters need to be given:

1. **Aperture Width.** This is the spatial width of the summation filter described above and is typically measured as the number of traces spanned by the summation. A small aperture will suppress steeply dipping events and migrate noise to coherent horizontal events and a large aperture will require high computation time and will perform poorly for data with a low SNR (Yilmaz, 1987, 269-271pp; Gray et al., 2001). That is, the aperture width should be chosen to be as high as possible but should be tempered by the presence of noise in the section and computational resources.
2. **RMS Velocity Field.** This is typically obtained from the velocities picked to stack the data (Chapter 3.5). The velocity field should be determined with as much accuracy as possible, as wrong values will negatively impact the migration (Yilmaz, 1987, 276-277pp gives an empirical measure of this impact).
3. **Maximum Dip of Migration.** This is an optional input and is useful if there is coherent noise with steep dips in the stack, typically cause by the NMO correction but can be of other origin. This parameter should be chosen to suppress such noise without compromising real events that have a steep dip.

Dip Moveout (DMO) Correction

The Kirchhoff PSTM is effective in areas with simple geology and gradual velocity changes, as described in Table 3.5, and was used in both KBF01 and KBF03A profiles as the geological settings thereof meet these requirements. However, poststack migration is not effective at resolving structures accurately where there are conflicting dips (Heiland 1946; Yilmaz, 1987, 328-345pp). This can occur in a number of ways, but the typical cause is, and the one present in profile KBF03A, where large fault zones are present and there is a superposition of stacking velocities required along a fault. To remedy this, a partial prestack migration known as the DMO correction is implemented before migration, as briefly explained here.

Where dipping layers are present, with dip angle θ , the NMO equation (Equation 3.15) becomes (Levin, 1971):

$$t(x)^2 = t(0)^2 + \left(\frac{x \cos(\theta)}{v_{NMO}} \right)^2 \quad (3.20a)$$

which can be rearranged, using the relation $\cos^2\theta + \sin^2\theta = 1$, as

$$t(x)^2 = t(0)^2 + \left(\frac{x}{v_{NMO}} \right)^2 - (xp)^2 \quad (3.20b)$$

where $p = \sin(\theta)/v_{NMO}$ is the ray parameter. The first two terms on the right side of Equation 2.3.6b are the same as before (Equation 3.15), while the last term is associated with the dip of the layer, implying that the NMO and DMO corrections can be applied in sequence. The method by which the DMO

correction is implemented is by transforming NMO-corrected common offset gathers into the $f - k$ domain. By arranging the data into common offset gathers, offset influence in Equation 3.20b is removed and dip effects are isolated. Thereafter, by transforming the data into the $f - k$ domain, the ray parameter p manifests as $p = k_x/2\omega_0$, where k_x is the wavenumber and ω_0 is the angular frequency, and can be directly removed for each common offset gather. This method of DMO is known as the Hale method (Hale, 1983) and is stable provided the vertical velocity variation is moderate.

Because the Hale method assumes the implemented velocity accurately represents the medium velocity, the stacking velocities that were picked during the NMO analysis cannot be directly used in the DMO correction. However, this issue is remedied by simply repicking NMO velocities after the DMO correction has been applied (Yilmaz, 1987, 334-345pp). Hence the DMO processing sequence involves sequentially picking first pass NMO velocities, applying the NMO correction, sorting the data into common offset gathers, applying the DMO correction based on the Hale method, applying inverse NMO using first pass velocities, repicking velocities to obtain second pass velocities, and then performing a stack and migration. This method is robust in areas of complex geology and is essentially equivalent to applying a prestack time migration.

Figure 3.25 gives an example of the effectiveness of DMO and Kirchhoff migration taken from profile KBF01. The section contains three major near-vertical normal fault zones that crosscut the strata, primarily located near CDPs 1550, 1700 and 1900, as indicated by the arrows. The faults are evidently delineated in the migrated section and are much easier to track. Note how the fault zone near CDP 1550 (blue arrows) is easily missed in the unmigrated stack but is clearly imaged in the migrated section along with the continuity of the affected strata, especially near 2400 ms, where a large series of diffraction anomalies have been collapsed. Additionally, the fault at CDP 1700 (orange arrows) bifurcates near the 1 s time mark, which is evident in the migrated section but not so clearly observed in the unmigrated stack. Finally, the fault zone at CDP 1900 (green arrows) in the stack section displays characteristic diffraction anomalies that are collapsed in the migrated section, allowing for much better tracking of the fault. The overall effect is that reflector horizons are significantly easier to track and disruptions in their continuity due to the faults are able to be restricted to much narrower zones in the migrated data.

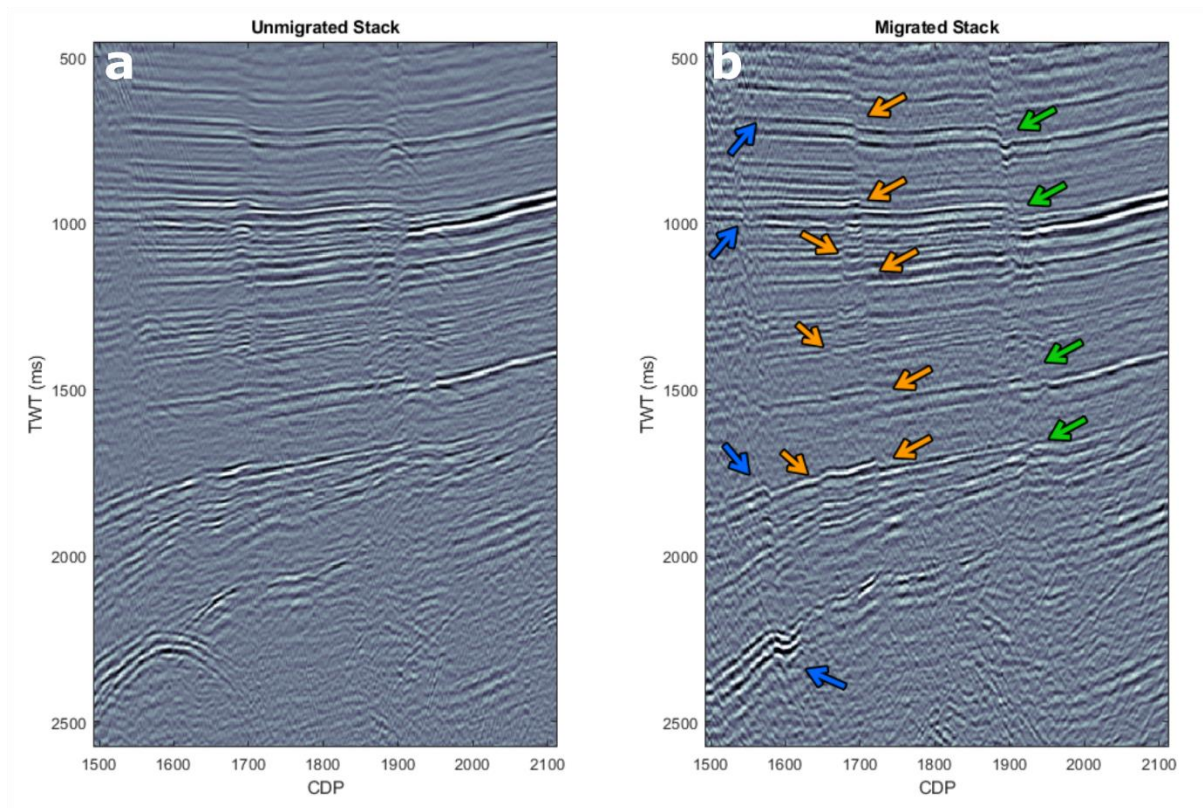


Figure 3.25: Comparison of data from profile KBF01 (Paper I) before (a) and after (b) DMO correction and migration. Arrows indicate major fault zones that are enhanced by the migration. The overall result is better imaging of reflectors and delineation of discontinuities along the reflectors. Figure taken from Paper I.

4 LEGACY REFLECTION SEISMIC DATA

There is no official definition of “Legacy Data” in the geophysical literature. It is, however, generally accepted that legacy data refers to data that are no longer in active use and have been archived, and typically in an outdated format that is not readily available.

In the reflection seismic industry, there are abundance of legacy seismic data especially in South Africa due to the country’s mineral wealth and the history of its gold reserves that were discovered in 1886 and triggered the gold rush, when the substantial gold-hosting ores of the Witwatersrand Basin were discovered. This accompanied with the wealth of platinum found in the Bushveld Igneous Complex, not to mention other resources such as iron, has resulted in many 2D and 3D reflection seismic data collection across the country, largely concentrated towards the late 1980s and early 1990s ([Durrheim, 1986](#); [Pretorius, 1989](#); [Stevenson and Durrheim, 1997](#); [de Beer, 2016](#)).

One of the main objectives of this PhD thesis is to showcase the usefulness in re-evaluating these legacy data and improve the resolution and enhance the structural interpretation. [Paper II](#) is a good example in which the 2D seismic profile KBF03A is reprocessed to substantial improvement in the imagining of geological features, both deep and shallow targets. Presented here is a brief motivation for the reprocessing of legacy reflection seismic data, as well as what preparation the data typically need to undergo before reprocessing.

4.1 The Value of Legacy Data

As technology has advanced, newer and more advanced methods of both acquiring and processing seismic data have evolved and replaced conventional methods. However, this does not mean that old data are useless. On the contrary, the reprocessing of legacy data using modern techniques and computational power has proven useful in re-evaluating geological models, updating knowledge of existing surveys and correcting any falsities in existing data. This is especially true if the legacy data were obtained before mining operations took place, rendering the study area complex and seismically noisy, thus making it difficult to acquire and process new data. It is also highly cost effective as acquisition of new seismic data is costly. With the imminence of the 4th Industrial Revolution, new technologies like machine learning and quantum computing may detect features in legacy data that were overlooked until now.

The value in reappraising legacy data is significantly showcased in the literature. For example, [Malajczuk et al. \(2016\)](#) and [Manzi et al. \(2018\)](#) demonstrated how reprocessing legacy data using current processing methods resulted in improved imaging of the subsurface structures that can better inform future research and industry. Furthermore, [Górszczyk et al. \(2015\)](#) and [Ketelhodt et al. \(2019\)](#) showed that denoising legacy data prior to reprocessing, via modern denoising methods, can substantially improve subsurface imaging. [Manzi et al. \(2020\)](#) demonstrate how the application of

modern novel seismic attributes can be used in hard rock setting to enhance legacy data for improved geological interpretation. A more detailed enquiry into the worth of reprocessing legacy data is seen in, for example, [Manzi et al. \(2019\)](#), [Malehmir et al. \(2019\)](#) and [Donoso et al. \(2020\)](#).

The following example is taken from [Paper II](#). The seismic profile was reprocessed using a modern standard processing flow outlined in Table 3.1. A comparison between the legacy and the reprocessed unmigrated stacks within certain regions, or “zooms”, of the two profiles is shown in Figure 4.1. The image shows significant improvement in the imaging of the Kalahari unconformity (black arrows), as well as the underlying dipping strata (blue arrows). In Zoom 1, the most noticeable improvements are displayed in the overlying draping co-folded layers, which resemble the Kalahari and Dwyka unconformities (white arrows). Zoom windows 2 and 3 show not only improvement in imaging the Kalahari strata, which are barely detected in the original data, but also the dipping reflectors; the pinchouts beneath the unconformity are much easier delineated and the continuity of the reflectors are significantly more easy to track, with emergent faults that are not easily seen in the legacy stack. A more detailed discussion of Figure 4.1 can be found in [Paper II](#) (Chapter 9).

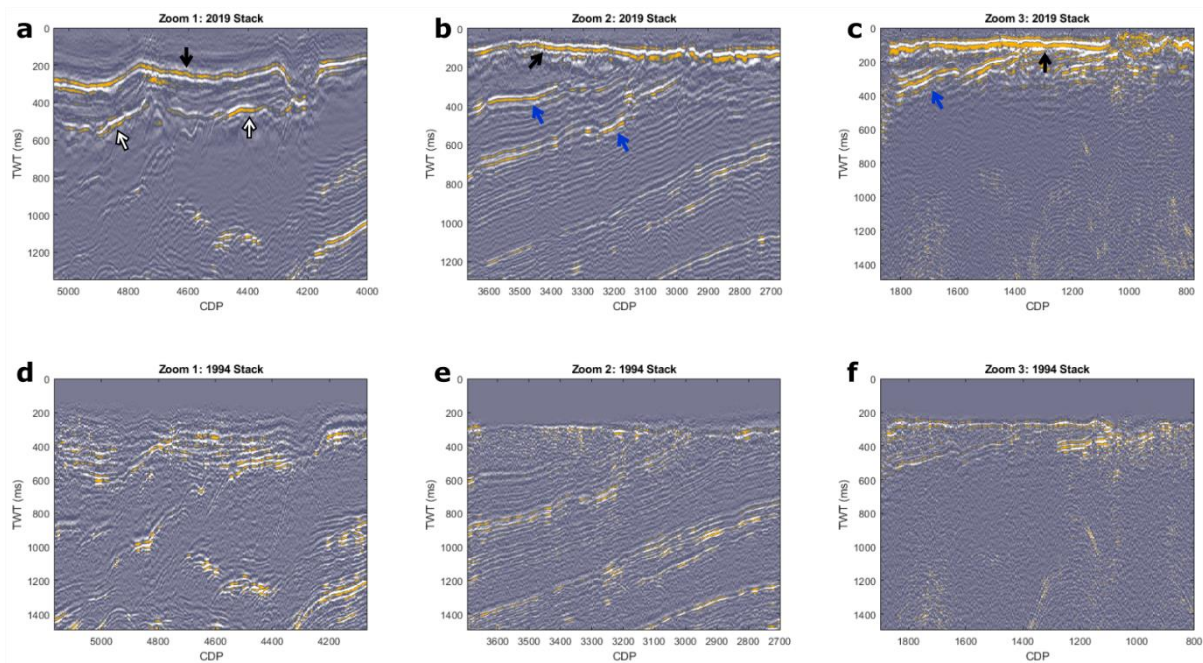


Figure 4.1: Comparison of legacy data of profile KBF03A with reprocessed profile. More details of the profile are found in [Paper II](#). Certain regions with significant improvement are shown in different window zooms. Zoom pairs a and d, b and e, d and f, each illustrate reprocessed data and legacy data, respectively. Black arrows indicate the Kalahari unconformity base reflection, white arrows indicate Dwyka unconformity base reflection, and blue arrows show significant improvements in imaging of dipping Proterozoic layers. Figure taken from [Paper II](#) and more details can be found therein.

The improvement in seismic imaging has implications both for research and industry. By enhancing data quality, subsurface features such as strata, intrusions, faults and folds can be better constrained and the overall subsurface geometry better understood. The result is a better geological model for the

investigation area. For mining industry, this is a valuable tool as target bodies that may not have been deemed as worth mining in certain regions based on interpretation of legacy data may in fact prove feasible upon reappraisal. Additionally, areas where target bodies were originally poorly imaged may be better constrained and mine planning can be updated. In general, it can be asserted that legacy seismic data are worth reprocessing especially in areas of active research or mining.

4.2 Preparation of Legacy Data

Before reprocessing legacy data, the data have to undergo some preliminary preparation. This is because the manner in which legacy data were stored may not conform to the modern standard of procedure and can lead to certain issues when attempting to process with modern processing packages. Hence the data must be inspected and altered before any processing in order for fluid handling.

Presented here are the pre-processing procedures that were applied to the legacy 2D profiles KBF01 and KBF03A, as described in detail within [Papers I and II](#) (Chapters 8 and 9), respectively.

Trace Header Editing

Reflection seismic data are typically stored in SEG-Y format that was developed by the Society of Exploration Geophysicists (SEG) in 1975. The structure of the SEG-Y format (revision 2), along with all standardizations and conventions, can be found in [Hagelund and Levin \(2017\)](#). According to these standards, a typical SEG-Y file will contain a 3200-byte textual header, for storing literal information of the survey, followed by a 400-byte binary header containing numerical information of the survey. Following these are optional additional 3200-byte textual headers. The remainder of the file contains the trace data in two clusters of information for each trace in the file. The first is the 240-byte header information of the trace that contains information of the associated trace such as its coordinates, sampling information, associated shot information, etc. The second cluster contains the actual samples of the trace. Using this convention allows traces to be grouped easily into different categories or gathers, such as shot gathers or common midpoint (CMP) gathers.

When handling legacy data, some trace headers may be stored in locations different to the modern standard set out by [Hagelund and Levin \(2017\)](#). It is thus necessary to critically analyse the trace headers and, if necessary, manually edit them. In the case of profiles KBF01 and KBF03A, some trace headers had values of -9999, such as the SOURCE_DEP and SOURCE_UPHOLE_TIME headers as seen in Figure 4.2. These values would either not be readable or, if successfully imported, would severely impact the data during processing and were subsequently zeroed before processing.

Bytes	Name	SEGY Value	Bytes	2-byte-ints	4-byte-int	4-byte IBH									
1: 4	(4) LINE	77	1: 4	0 77	77	2.38772e-39									
5: 8	(4) REEL	85	3: 6		5046272										
9: 12	(4) RECORDNUM	5694	5: 8	0 85	85	3.85709e-39									
13: 16	(4) FTRACE	77	7: 10		5570560										
17: 20	(4) SOURCENUM	1	9: 12	0 5694	5694	4.58604e-39									
21: 24	(4) CDP	724	11: 14		373161984										
25: 28	(4) CDPTRACE	77	13: 16	0 77	77	2.38772e-39									
29: 30	(2) TRTYPE	1	15: 18		5046272										
31: 32	(2) VERT_SUM	3	17: 20	0 1	1	0									
33: 34	(2) HORI_SUM	1	19: 22		65536										
35: 36	(2) USE	77	21: 24	0 724	724	4.86728e-39									
37: 40	(4) OFFSET	821	23: 26		47448064										
41: 44	(4) REC_HT	0	25: 28	0 77	77	2.38772e-39									
45: 48	(4) SOURCE_HT	0	27: 30		5046273										
49: 52	(4) SOURCE_DEP	-9999	29: 32	1 3	65539	5.38099e-43									
53: 56	(4) REC_DAT	0	31: 34		196609										
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77: 80	(4) SOURCE_Y	2973733	45: 48	0 0	0	0									
81: 84	(4) REC_X	-62669	47: 50		65535										
85: 88	(4) REC_Y	2973544	49: 52	-1 -9999	-9999	-1.17409e-38									
89: 90	(2) COORD_UNIT	0	51: 54		-655294464										
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93: 94	(2) SUBWEATH_VEL	0	55: 58		0										
95: 96	(2) SOURCE_UPHOLE_TIME	-9999	57: 60	0 0	0	0									
97: 98	(2) REC_UPHOLE_TIME	0	59: 62		0										
99:100	(2) SOURCE_STATIC	0	61: 64	0 0	0	0									
101:102	(2) REC_STATIC	-71	63: 66		0										
103:104	(2) TOTAL_STATIC	25	65: 68	0 0	0	0									
105:106	(2) LAG_TIME_A	0	67: 70		1										
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135:136	(2) SWEEP_TAPER_START	0	97:100	0 0	0	0									
137:138	(2) SWEEP_TAPER_END	0	99:102		65465										
139:140	(2) SWEEP_TAPER_TYPE	0	101:104	-71 25	-4653031	-5.23466e-39									
141:142	(2) ALIAS_FREQ	0	103:106		1638400										
143:144	(2) ALIAS_SLOPE	0	105:108	0 0	0	0									
145:146	(2) NOTCH_FREQ	0	107:110		0										
147:148	(2) NOTCH_SLOPE	0	109:112	0 0	0	0									
149:150	(2) LOW_CUT_FREQ	0	111:114		0										
151:152	(2) HIGH_CUT_FREQ	164	113:116	0 1500	1500	5.46421e-39									
153:154	(2) LOW_CUT_SLOPE	0	115:118		98308000										
155:156	(2) HIGH_CUT_SLOPE	0	117:120	4000 1	262144001	2.93874e-39									
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159:160	(2) DAY	331	121:124	36 0	2359296	1.46937e-39									
161:162	(2) HOUR	13	123:126		2										
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Claritas non-standard headers not defined															
			143:146		0										
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			167:170		65536										
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			181:184	0 0	0	0									
			183:186		371										
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			187:190		354										
			189:192	354 23	23199767	6.24488e-39									
			191:194		1507328										
			193:196	0 25	25	6.61216e-39									
			195:198		1638400										
			197:200	0 1123	1123	1.13646e-39									
			199:202		73596928										
			201:204	0 1200	1200	2.02038e-39									
			203:206		78708735										
			205:208	-1 -27	-27	-1.17549e-38									
			207:210		-1703937										
			209:212	-1 -18	-18	-1.17549e-38									
			211:214		-1179648										
			213:216	0 0	0	0									
			215:218		0										
			217:220	0 1121	1121	1.11351e-39									
			219:222		73465857										
			221:224	1 77	65613	1.38112e-41									
			223:226		5046272										
			225:228	0 1125	1125	1.15942e-39									
			227:230		73728000										
			229:232	0 6000	6000	5.46421e-39									
			231:234		393281535										
			233:236	-1 -19	-19	-1.17549e-38									
			235:238		-1179649										
			237:240	-1 -9999	-9999	-1.17409e-38									
Listing of data samples 1 to 20															
Sample	Values			Bytes/hex											
1:3	-7.5795e+10	-5.41174e+09	1.5249e+11	CA	11	A5	BC	C9	14	29	0A	4A	23	81	16
4:6	2.58998e+11	3.43607e+11	3.12722e+11	4A	3C	4D	80	4A	50	00	8C	4A	48	CF	AE
7:9	2.12034e+11	9.49707e+10	-8.99035e+09	4A	31	5E	33	4A	16	1C	B2	C9	21	7D	DD
10:12	-1.55307e+11	-2.9229e+11	-3.59254e+11	CA	24	29	0C	CA	44	0D	D4	CA	53	A5	33
13:15	-3.5985e+11	-3.23054e+11	-2.16831e+11	CA	53	CB	BF	CA	4B	37	B9	CA	32	F3	58
16:18	-4.71079e+10	1.45739e+11	3.31314e+11	C9	AF	7D	99	4A	21	EE	B4	4A	4D	23	DC
19:20	4.75614e+11	5.21482e+11		4A	6E	BC	CE	4A	79	6A	BB				

Figure 4.2: List of headers as well as 240-byte information of example trace from raw legacy data.

Moreover, some additional headers needed definition for compatibility with Globe Claritas, the processing software used. For example, “SHOTID” and “CHANNEL” are headers that Globe Claritas recognises as the shot identification and trace number within that shot, respectively, and must be associated thusly by assigning them to certain byte positions in the header. Similarly, “REC_HT”, the header containing the receiver elevation, is seen in Figure 4.2 to be zero; this is incorrect and will affect steps in the processing sequence such as elevation and refraction statics. Table 4.1 gives a summary of the alterations applied to the trace headers of profiles KBF01B and KBF03A.

Header	Allocation/Action	Location/Value
SHOTID	Byte location	9:12
CHANNEL	Byte location	13:16
SOURCE_X	Byte location	73:76
SOURCE_Y	Byte location	77:80
SOURCE_HT	Byte location	217:220
REC_X	Byte location	81:84
REC_Y	Byte location	85:88
REC_HT	Byte location	197:200
SOURCE_DEP	Set to	0
SOURCE_UPHOLE_TIME	Set to	0

Table 4.1: Summary of how the two legacy profiles KBF01 and KBF03A were prepared before processing by either zeroing incorrect trace headers or allocating byte locations within the 240-byte trace header to specific headers.

Survey Geometry

Once the header information had been corrected for both profiles KBF01B and KBF03A, the geometry of each profile had to be verified and corrected. The correction of geometry comprised two parts; firstly, unique peg identification numbers had to be assigned to both the receiver pegs and shot pegs and, secondly, receiver elevation discrepancies had to be rectified. These steps are explained in more detail below.

When handling the geometry of a survey, Globe Claritas identifies unique shot and receiver records by assigning “pegs” to the location of these records. These are simply unique identifiers of shots and traces within the global survey and are stored in the trace headers under “SHOT_PEG” and “REC_PEG”, respectively. For example, with a centre-spread survey of 120 channels per shot and single receiver roll-along, the first 120 recorded traces may all have SHOT_PEG = 1 and REC_PEG = 1:120, while the next 120 recorder traces would have SHOT_PEG = 2 and REC_PEG = 2:121 and so on.

This standard is not typically found in headers of legacy data and so peg numbers have to be defined and stored in the headers before proceeding. This was done using Matlab code that can be found in [Appendix A](#) under the function *assignPegs.m*. This function takes as input the coordinates of either the sources or the receivers in the survey, identifies and extracts unique locations and assigns identifiers to

these locations. The code then outputs a list of identifiers that directly corresponds to the input coordinates. This code was applied to the coordinates of both the receivers and the sources of each of the surveys that were reprocessed.

Upon inspection of the geometry, there appeared a discrepancy between the receiver elevations and the shot elevations. The source of this discrepancy is unknown but very evident, as shown in Figure 4.3; while the eastings and northings of both the sources and receivers follow the same line, the elevations thereof seem to disagree in such a way so as to make the topography of the receivers appear offset from that of the sources. To determine which set of elevations were correct, Shuttle Radar Topography Mission (SRTM) data were downloaded from the United States Geological Society (USGS) along the profile and compared with the elevations of the shots and receivers, as shown in the third row of Figure 4.3. The SRTM data have a lateral resolution of 1 arc-second (approximately 30 m) and a vertical resolution of 16 m. While the SRTM elevations do not exactly match those of either the shots or receivers, it is evident that the regional trend of the SRTM data is in agreement significantly more with the shot elevations than receiver elevations. The reason for local variations is most likely due to the relative uncertainty of the survey measurements and the SRTM data. Hence, the shot elevations are elected as the more accurate representation of the line topography. As such, the receiver elevations were given new values that are obtained by interpolating the shot elevations over the receiver coordinates, as shown in the fourth row of Figure 4.3. This was done by exporting the geometry header information as SPS files, extracting both receiver and source locations and elevations, interpolating using a nearest neighbour scattered interpolation in MATLAB, inserting new receiver elevations into .r file and importing new SPS files into SEG-Y headers.

The national coordinate system used in South Africa is based the Gauss Conformal Projection ([Young, 1930](#)), with each projection zone separated by 2°. The midpoints of each projection are the 17°, 19°, 21°, ..., 31° east longitudes. Up until 1999, the reference ellipsoid was the Clarke 1880 ellipsoid, after which South Africa adopted the international convention of the WGS84 ellipsoid. The notation used when referencing the former reference ellipsoid is LO17, LO19, ..., LO31 and for the latter is WG17, WG19, ..., WG31, as depending on the projection midpoint of the specific study area. The two seismic profiles that were reprocessed in this thesis were collected prior to 1999 and thus follow the former notation. Both profiles KBF01 and KBF03A referenced the LO23 projection zone. Furthermore, where the UTM standard is to label easting values “X” and northing values “Y”, which increase eastwards and northwards, respectively, the South African convention (as determined by NGI: National Geo-spatial Information, a component of the governmental Department of Rural Development and Land Reform, DRDLR) is to assign the labels “X” and “Y” to the northings and eastings, respectively, and have them increase in the southward and westward directions, respectively.

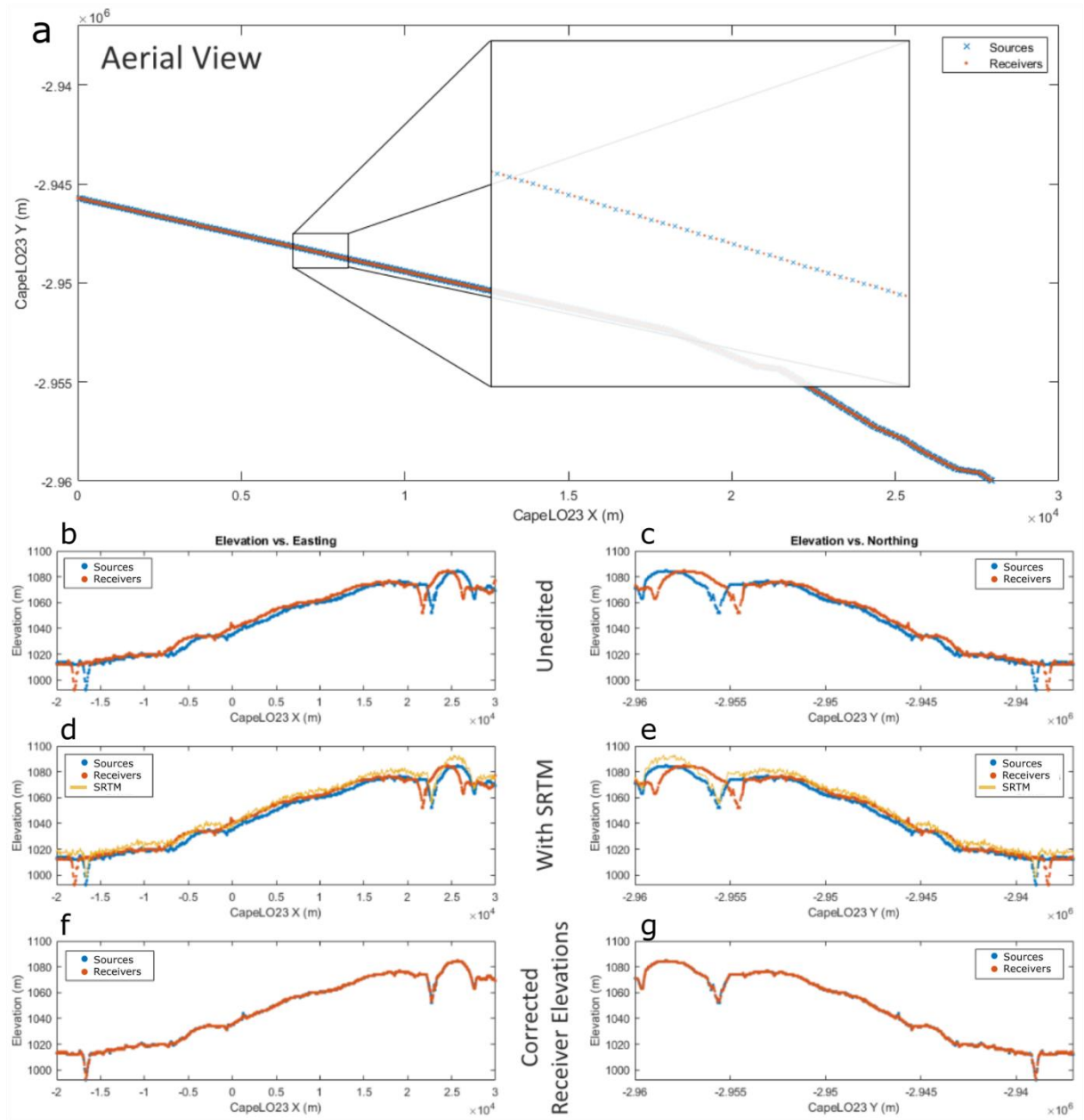


Figure 4.3: Aerial view of a portion of profile KBF03A (a) followed by elevation versus x-coordinates (b,d,f) and y-coordinates (c,e,g) of the same portion in the order of: unedited (b,c), plotted with SRTM data (d,e), and corrected receiver elevations (f,g). Coordinates are in Cape LO23 reference system.

5 SEISMIC ATTRIBUTES

Due to the high demand and reliability of the reflection seismic method, many techniques have been developed to aid the acquisition, processing and interpretation of reflection data. One such technique developed to assist with the interpretation component is seismic attribute analysis; the computation of various properties, or attributes, to improve data interpretation (e.g. [Taner et al., 1979](#); [White 1991](#); [Brown 1996](#); [Barnes, 2007](#)). In the literature, there exist many various definitions for the term seismic attribute. One definition ([Chopra and Marfurt, 2007](#)) is “any measure of seismic data that helps us visually enhance or quantify features of interpretation interest”. Most definitions are akin to this. The attributes examined here are applicable to both two and three-dimensional reflection data and are instantaneous attributes of poststack data (i.e. each attribute, like the seismic trace, is a function of time). It is important to note that attributes are purely arithmetic; calculations performed on the reflection data itself, and are not necessarily intrinsic to the geology represented by the data. It is thus necessary for a geophysicist to have an intuitive understanding of the attributes being applied so as to discern between actual geological representations and computational artefacts in the processed data.

Since their inception in the 1970s, a variety of approaches have been used in the computation of seismic attributes. Of these approaches, arguably the most used is by means of the complex trace, which was introduced by [Taner et al. \(1979\)](#) and contrasted with the then more conventional approach of Fourier analysis. In essence, complex seismic trace analysis recreates the seismic trace as a time-variable function over the complex plane ([Taner et al., 1979](#); [White, 1991](#)), setting up a convenient basis from which various seismic attributes can be derived mathematically. These instantaneous attributes, along with a novel instantaneous attribute based on symmetry that is used in [Papers II and III](#) are described here.

5.1 Instantaneous Attributes

Analytic Signal and Complex Trace Analysis

Complex trace analysis seeks to decompose an arbitrary time function $f(t)$ into its separable amplitude and phase components (Taner, 1979). In other words, $f(t)$ can be thought of as a succession of sinusoidal waves, each with a specified amplitude A and phase angle φ . The mathematical expression of this is given by

$$f(t) = A(t)\cos(\varphi(t)) \quad (5.1)$$

so that $f(t)$ can be described at any given time t_0 as an instantaneous sinusoid with a specified phase $\varphi(t_0)$ and a specified amplitude $A(t_0)$. $A(t)$ and $\varphi(t)$ are thus referred to as the instantaneous amplitude and instantaneous phase, respectively, of the function $f(t)$. This concept is illustrated in Figure 5.1; the instantaneous amplitude envelopes the signal and the phase moves the signal up or down the time scale within this envelope. In the context of reflection seismics, $f(t)$ is typically a seismic trace as a function of time t . The amplitude component, $A(t)$, is also referred to as the trace envelope of $f(t)$. The trace envelope encases all instantaneous sinusoids and is independent of phase shift, as demonstrated in Figure 5.1. The instantaneous phase, which is occasionally used interchangeably with the cosine of the instantaneous phase, resembles the seismic trace with all amplitude information removed. Equation 5.1 is the essence of complex trace analysis; that is, splitting seismic data into independent amplitude and phase information and using these components to compute properties of the data.

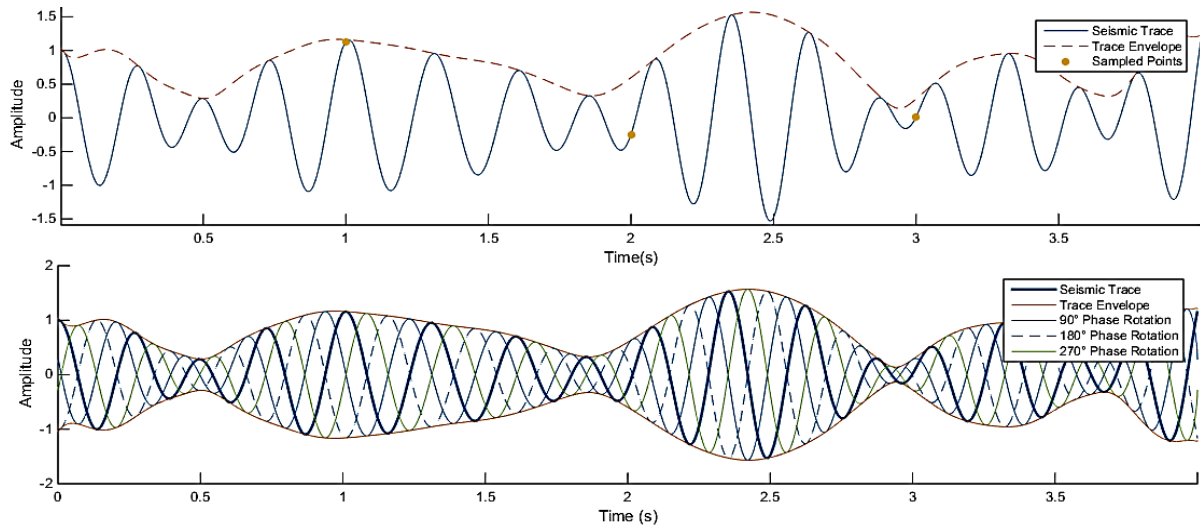


Figure 5.1: Seismic trace with trace envelope (instantaneous amplitude) as well as points sampled at 1s, 2s, and 3s from Equation 5.1 (top), and seismic trace with trace envelope and various instantaneous phase rotations (bottom). The sampled points are taken by multiplying the amplitude with the cosine of the phase at those points.

The method by which a trace is split into phase and amplitude components, Equation 5.1, is by means of the Hilbert transform (Gabor, 1946) to create what is known as the analytic signal. Also known as

the complex trace, the analytic signal, is a dual-component time function. The one component is known as the in-phase component and is given by the original seismic trace, while the other component is known as the quadrature component and is given by a 90° phase rotation of the seismic trace (Taner, 1979). The two components are thus orthogonal time functions and form the real and imaginary parts of the complex trace:

$$c(t) = f_R(t) + if_I(t) \quad (5.2)$$

where $c(t)$ is the complex trace, $f_R(t)$ is the original trace (in-phase component), i is the imaginary number and $f_I(t)$ is the quadrature trace, given by the Hilbert transform of $f_R(t)$:

$$H[f_R(t)] = f_R(t) * \frac{1}{\pi t} = \frac{1}{\pi} \int \frac{f_R(\tau)}{t-\tau} d\tau \quad (5.3)$$

In the frequency domain, the quadrature trace is obtained by multiplication with the signum function and imaginary number (Barnes, 2007). If $F_R(\omega)$ denotes the Fourier transform of $f_R(t)$, then the quadrature trace is given in the frequency domain by

$$F_I(\omega) = -i \operatorname{sgn}(\omega) \cdot F_R(\omega) \quad (5.4)$$

where $\operatorname{sgn}(x)$, known as the signum function and is the Fourier transform of $1/\pi x$, extracts the sign of x . That is, $\operatorname{sgn}(x)$ is $+1$ if x is positive, -1 if x is negative and 0 if x is 0 . As previously stated, the quadrature trace is a 90° phase shift of the real trace. This can be seen if $-i \operatorname{sgn}(\omega)$ is expanded as follows:

$$-i \operatorname{sgn}(\omega) = \begin{cases} i = e^{+i\frac{\pi}{2}}, & \omega < 0 \\ i = e^{-i\frac{\pi}{2}}, & \omega > 0 \\ 0, & \omega = 0 \end{cases} \quad (5.5)$$

Hence the negative frequency components are shifted in the complex plane by $+90^\circ$, or $\pi/2$ radians, and the positive frequency components are shifted by -90° .

Upon determining the quadrature trace, the complex trace (Equation 5.2) can be constructed. Multiplying the quadrature trace by the imaginary number i restores the positive frequency components by shifting them back -90° and further shifts the negative frequency components another -90° . Hence, when $if_I(t)$ is added to $f_R(t)$, the negative frequency components cancel and the positive frequency components add. If $C(\omega)$ and $F_R(\omega)$ denote the Fourier transforms of the complex trace $c(t)$ and the real trace $f_R(t)$, respectively, then this can be written mathematically as (Barnes, 2007):

$$S(\omega) = \begin{cases} 2F_R(\omega), & \omega > 0 \\ 0, & \omega \leq 0 \end{cases} \quad (5.6)$$

Conceptually, the analytic signal eliminates the redundancy of negative frequencies of a real-valued function (in this case the seismic trace) due to the Hermitian symmetry of its frequency spectrum. It does this without any loss of information by storing the negative frequency information in the positive

frequency components. A plot of an example complex trace is given in Figure 5.2; it has a distinctive corkscrew shape. The thickness of the corkscrew is determined by the instantaneous amplitude at any given time and the spacing of successive spirals of the corkscrew is determined by the instantaneous phase at any given time.

Once the complex trace has been computed, the instantaneous amplitude and phase are given by the magnitude and phase angle of $s(t)$, respectively. This forms the basis of complex trace analysis and is the foundation of instantaneous seismic attribute calculations (Barnes, 2007), which are discussed in further detail next.

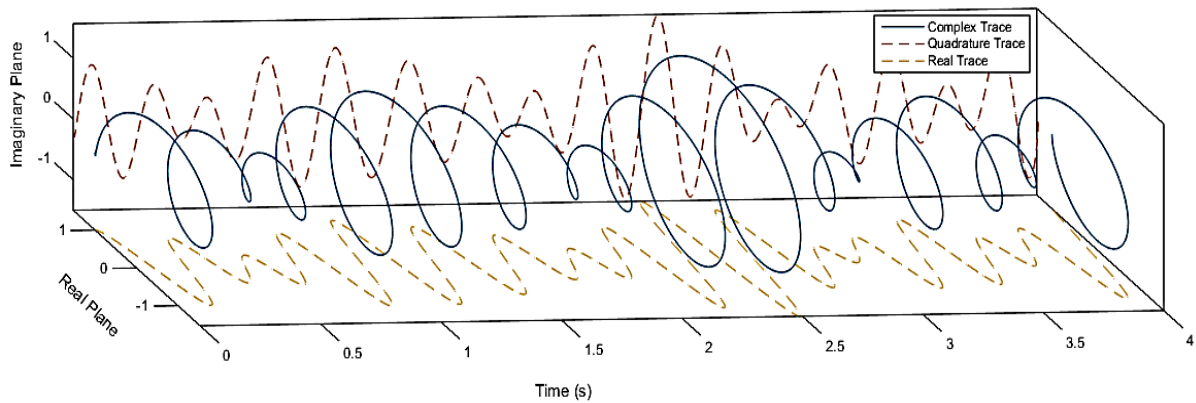


Figure 5.2: A plot of the complex seismic trace (Equation 5.2), along with the in-phase real component and the out-of-phase imaginary component. The screw-like nature is typical of the complex trace for time series such as traces.

Instantaneous Amplitude, Phase and Frequency

As mentioned, once the complex trace, $c(t)$, has been computed, the instantaneous amplitude, $A(t)$, and phase, $\varphi(t)$, (Equation 5.1) can be calculated, after which the instantaneous frequency, $f(t)$ can be calculated. These are given by:

$$A(t) = |c(t)| \quad (5.7a)$$

$$\varphi(t) = \arg \{c(t)\} \quad (5.7b)$$

$$f(t) = \frac{1}{2\pi} \frac{d\varphi(t)}{dt} \quad (5.7c)$$

An example application of these attributes to real data is given in Figure 5.3. These data are taken from profile KBF01 and are the same used to display the effects of migration in Figure 3.25. The following features are evident in the attributes.

The instantaneous amplitude attribute is given by the original trace with all phase information removed, leaving only amplitude information, which is clearly demonstrated by CDP no. 1800 in Figure 5.3. When examining the 2D section of this attribute, the first noticeable features are the two faults located at CDPs 1700 and 1900, the first of which bifurcates near 1 s TWT. This is because fault zones are areas

of poor reflectivity and thus amplitude is lost. When compared to the original data, these faults are much more easily trackable due to the high contrast in amplitudes. The amplitude attribute also assists in characterising reflection packages consisting of the first reflection and proceeding multiples, allowing for multiples to be distinguished. This is evident with the reflection package located at 1 s TWT between the two faults in the section as well as in the 1800 CDP trace.

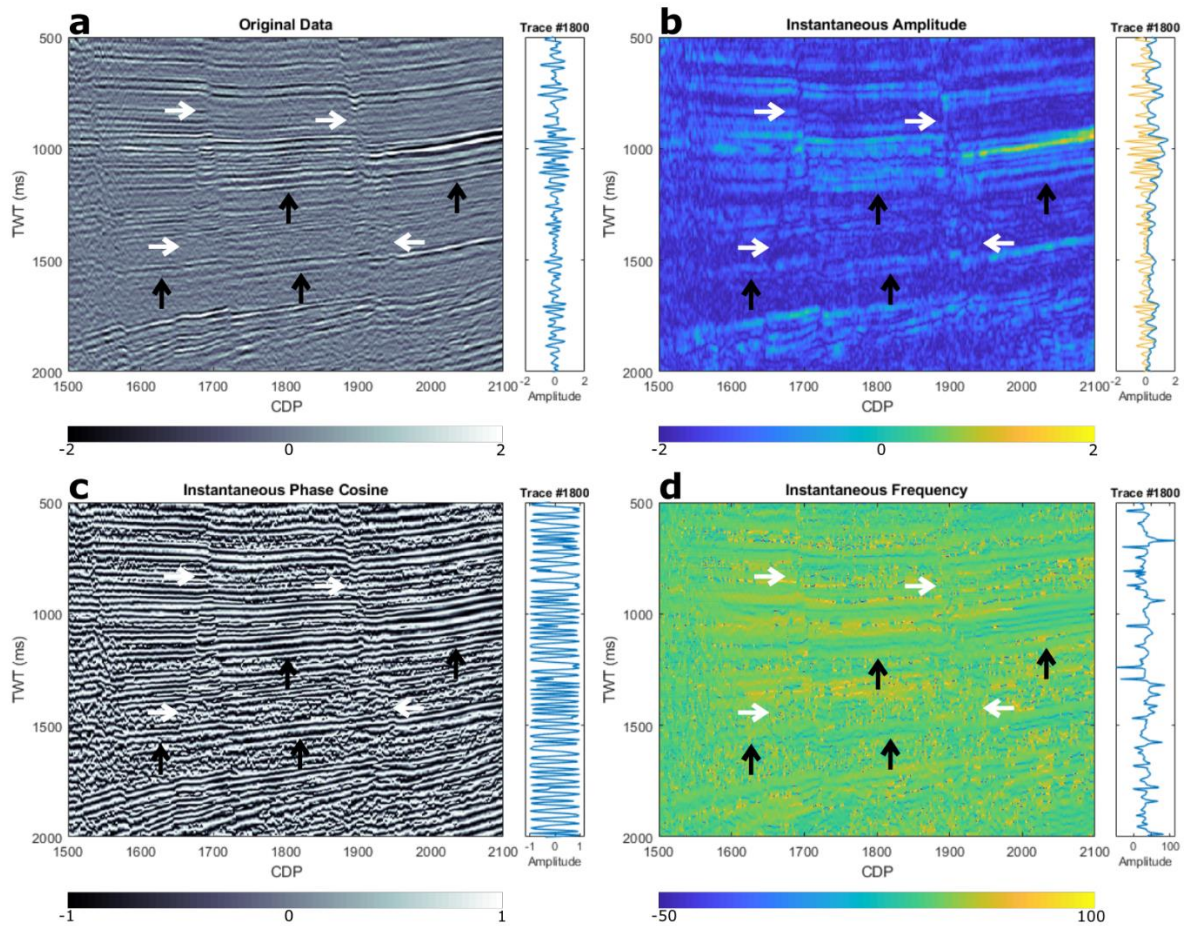


Figure 5.3: Instantaneous attributes applied to migrated data (a) from KBF01 (Paper 1). The 2D attributes b-d are shown, as well as a sample trace, CDP no. 1800, from the centre of the section. The sampled traces have had their amplitudes normalised. White arrows indicate fault zones and black arrows indicate reflections across the faults.

The instantaneous phase is rarely used in isolation for interpretation. Instead, the cosine of the phase is typically taken (Taner et al., 1979). In terms of Equation 5.7b, this is given by taking the cosine of the argument of the complex trace. The result is the original trace with all amplitude information removed, which effectively “levels” the trace so that it is evenly weighted along its entirety. As such, the instantaneous phase cosine (CP) can be viewed as the perfect AGC, which is clearly seen in both the CP section and the sampled trace no. 1800 (Figure 5.3). This means that both strong reflections and weak reflections are delineated, and is evident where there are weak reflection packages located between 1000 ms and 2000 ms TWT, most noticeably at ~1300 ms and ~1600 ms. additionally, the CP is extremely useful at tracking horizon continuity. Where the instantaneous amplitude assisted in

emphasising the fault zones and rendering them rather noticeable, the CP attribute allows the fault zones to be constrained to much narrower zones within reflection horizons. This is most evident with the composite fault near CDP 1700. This concept of identifying features in the amplitude attribute and then accurately constraining them with the CP attribute is a useful approach in which the two attributes are combined for interpretation. One drawback to the CP attribute is that, due to its high-pass nature and ability to enhance weak reflections ([White, 1991](#); [Barnes, 1996](#)), it will also emphasise inherent noise in the data, which is very clearly seen in trace no. 1800. This is another reason why the CP and amplitude attributes make a good complimentary pair, as the latter is not very prone to noise.

Lastly there is the instantaneous frequency attribute. As can be seen in Figure 5.3, this attribute does not function as a visual aid in interpretation, as the previous attributes do. Instead, the instantaneous frequency is a useful signal analysis tool. For example, if a given survey utilises a source with a characteristic frequency, signals from that source can be distinguished from signals of external nature with a separate frequency character. Another example is to investigate frequency alteration with depth, which could aid in a quality factor investigation of the rocks in the survey area. In Figure 5.3, trace no. 1800 of the instantaneous frequency makes it clear that the signal is dominated by a ~35 Hz component.

Each attribute has its own set of inherent advantages and disadvantages. The instantaneous amplitude, for example, is effective at highlighting regions of large seismic amplitude, as famously exhibited by the attribute's ability to identify hydrocarbon reservoirs based on the so-called bright spots of the data, however it fails to provide concise detail due to its low resolution, long-wavelength characteristics. The cosine of the instantaneous phase, on the other hand, removes all amplitude information and so enhances subtle details within subsurface geometries. This is however at the cost of also enhancing noise present within the data ([Barnes, 1996](#); [Barnes, 2007](#); [Chopra and Marfurt, 2007](#)). What further hinders these attributes is the crystalline nature of the hardrock setting found in South Africa; such settings are typically populated by significantly deformed igneous and metamorphic bodies, in contrast to the typically flat and simple structure of soft rock environments, that make seismic imaging in general a challenging task ([Eaton et al., 2003](#)). One of the goals of [Paper III](#) (Chapter 10) is to combine attributes in such a way as to minimise their disadvantages and combine their advantages.

5.2 Symmetry Attribute

Mathematically, symmetry manifests itself in different forms; rotational, reflectional, logical and translational to name a few (Ahmad and Cerrito, 1991; Nelsen, 1993). Of particular interest in signal processing is the symmetry, or parity, of functions. The parity of a function is described as either even or odd, as described by the following conditions:

$$f(-t) = \begin{cases} f(t), & \Leftrightarrow f(t) \text{ is even} \\ -f(t), & \Leftrightarrow f(t) \text{ is odd} \end{cases} \quad (5.8)$$

This concept can be extended to that of local parity; the parity of the neighbourhood of an arbitrary point in the function. Making use of the windowed Fourier transform (Harris 1978), the local parity of traces can be used as an attribute in each of the three spatial dimensions. The literature currently contains limited information on the application of symmetry as a seismic attribute (see, for example, Cooper, 2017; Westgate et al., 2018; Manzi et al., 2020). The method presented here utilises the Fourier transform, as described hereafter.

Symmetry and the Fourier Transform

Intuitively, an even function is reflectionally symmetrical about the y -axis and an odd function, more specifically every point lying on the function, is reflectionally symmetrical about the origin. For example, as shown in Figure 5.4, the function $f(t) = t^n$, $n \in \mathbb{N}$, is even if n is even and odd if n is odd.

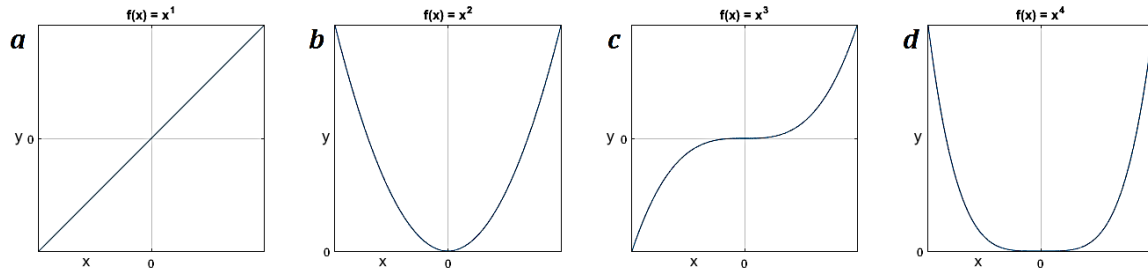


Figure 5.4: Alternating odd and even parity functions of the form $f(x) = x^n$ for different integer values [1, 4] of n . Odd functions (a,c) are reflectionally symmetry about the origin and even functions (b,d) are reflectionally symmetry about the y axis.

Any mathematical function can be decomposed into a sum of an even and an odd function. This has implications in Fourier analysis, which states that any function can be broken into a sum of sinusoids, sine and cosine functions of differing frequencies (for non-periodic functions, the sum of these functions is replaced by an integral). This is mathematically given by the Fourier transform (Fourier, 1822; Easton, 2010):

$$F(v) = \int f(t) e^{-i2\pi vt} dt = \int f(t) [\cos(2\pi vt) - i \sin(2\pi vt)] dt \quad (5.9a)$$

$$f(t) = \int F(v) e^{i2\pi vt} dt = \int F(v) [\cos(2\pi vt) + i \sin(2\pi vt)] dt \quad (5.9b)$$

The Fourier transform (FT) is given by [Equation 5.9a](#) and its inverse transform by [Equation 5.9b](#). In the case that $f(x)$ is odd, all cosine terms in [Equation 5.9a](#) disappear and $F(v)$ is purely imaginary (in the context of seismic traces, $f(t)$ is the trace as a function of time and is therefore purely real). In the case that $f(t)$ is even, all sine terms disappear and $F(v)$ is purely real. Hence a function close to symmetry will have a dominating total real component and a function close to anti-symmetry will have a dominating total imaginary component, while an asymmetric function will have equal imaginary and real components. Taking the ratio of the real and imaginary components of a function's FT can thus be used as a quantitative measure of symmetry.

Symmetry attribute

A way to quantify the symmetry S of a function is by taking the ratio of the total real and imaginary components of its FT:

$$S = \frac{\int R[F(v)]dv}{\int I[F(v)]dv + \varepsilon} \quad (5.10)$$

Where R and I denote the real and imaginary components, respectively, of the function enclosed in square brackets, and ε is a constant factor added to the denominator to avoid singularities in S . This result can then be shifted and normalised to attain values ranging from 0, a fully antisymmetric function, to 1, a fully symmetric function, with any asymmetric function attaining a value between 0 and 1:

$$S_{norm} = \frac{S - \min(S)}{\max(S) - \min(S)} \quad (5.11)$$

[Equations 5.10 and 5.11](#), however, only give a measure of global symmetry and the need arises to translate it into a form of local symmetry. This is accomplished by using a moving window in which the FT is calculated locally, that is, a windowed Fourier transform (WFT). Before the WFT is applied, the size of the window is determined by the user and a Hanning function is applied to the windowed data, to avoid edge effects ([Grandke, 1983](#)). The normalised symmetry value ([Equation 5.11](#)) is then calculated within the same window, which then replaces the data value at the centre of the window. The window then slides to the next centered value and the process is repeated to construct the symmetry data, which is then raised to a user-defined power to either sharpen or dilate the peaks. An example application of this method is provided in [Figure 5.5](#) as a proof of concept, in which the attribute is applied to 1D synthetic data. Note that the attribute attains maxima at points of symmetry in the original trace and minima at points of antisymmetry.

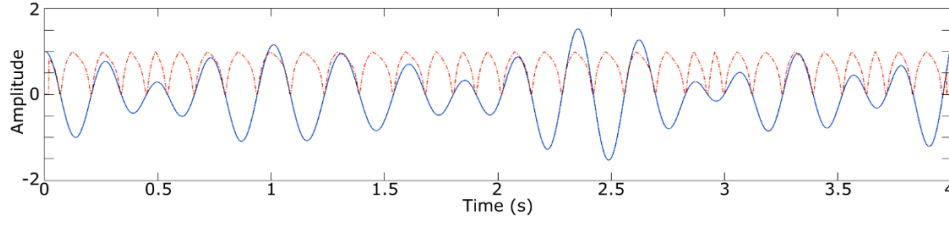


Figure 5.5: Synthetic 1D data (blue, solid) and symmetry attribute (red, dotted). The symmetry peaks at points of symmetry and attains minima at points of antisymmetry. A window of 100 ms was used.

The primary advantage of this method is that it easily extends to arbitrary dimensions by simply using the multidimensional Fourier transform (Easton 2010). In dimensions greater than one, reflectional symmetry loses uniqueness and more information is needed, such as the direction of the desired reflection azimuth. The symmetry attribute described here can thus be seen as ‘total reflectional symmetry’.

Window size and exponential power

To compute the symmetry effectively, two user inputs are required; the size of the WFT window and the power to which the symmetry attribute is raised. This section serves as a guide to the optimal values to be used. The exponential power does not have a large influence over the symmetry result and is mainly assigned on the basis of the user’s discretion. Integer values from 1 to 5 are used for the two case studies.

The symmetry attribute is applied to reflection seismic data. Accordingly, it is appropriate to express the window size in terms of the dominant wavelength of the data. This relationship is investigated here. Figure 5.6 shows a normalised real trace whose dominant period T_{dom} is 50 ms. Accompanying it are various 1D symmetry attributes with different window lengths expressed as percentages of T_{dom} , where an exponent value of three was used for all examples in Figure 5.6. As symmetry only bears true meaning with regards to the dominant wavelength when the window is at least half the dominant period (T_{dom}), it is recommended to use this as the minimum window value.

The symmetry attribute exhibits characteristics similar to an AGC as symmetry is independent of amplitude. This is most evident in the green sections of Figure 5.6, between 0.2 s and 0.4 s and centred on the 0.8 s region, where the trace has low amplitudes and the symmetry attribute equally weighs each part of the trace. It thus also amplifies any noise present in the data, requiring careful preparation and filtering of the data before application of the attribute. It is also observable that the AGC effect reduces in intensity with longer window sizes. This becomes evident when examining the green regions of each consecutive attribute, with lower amplitudes becoming more apparent with longer window sizes.

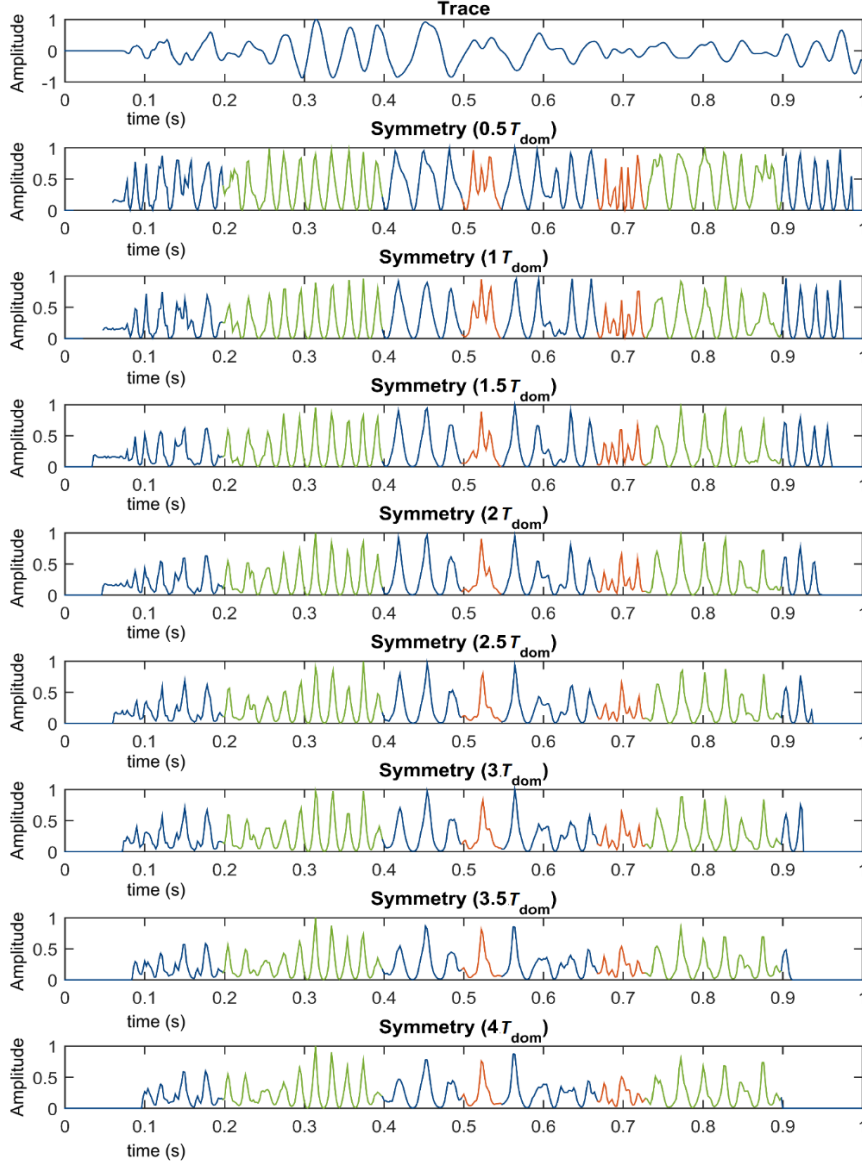


Figure 5.6: 1D Symmetry attribute applied to a real trace with varying window sizes given as fractions of the dominant period. Regions of interest are highlighted in red for the high-pass characteristics and green for AGC properties.

Another property of the symmetry attribute is its high-pass filter nature, i.e., for every wavelength of the data, the symmetry has two peaks, corresponding to the peak and the trough of the wavelength. It can therefore also be used as an edge detector. This can be seen most evidently in the red sections of the attributes in Figure 5.6. Just as with the AGC effect of the symmetry attribute, the high-pass effect also diminishes with increasing window size, which can be seen in the red section starting at 0.5 s. Over this region, the attribute with the smallest window length has three peaks that contrast with a single peak in the attribute with the longest window.

The parameters are determined based on the needs of the user. If an AGC is required then a window around the same size as the dominant period should be used, whereas a larger window, around three to four times the size of the dominant period, should be used in the case of noisy data. A shorter window

is useful for enhancing subtle features of the data with low noise levels and a longer window is better for trace sharpening while still having an AGC aspect. As with all windowed attributes, a larger window results in more data loss around the edges, as can be seen in the data edges of Figure 5.6.

In cases of two and three-dimensional data, the lateral length(s), that is the width, of the window need not be related to the wavelength (which is temporal). These dimensions are dependent on the lateral variations of seismic reflections and are left to the user's discretion.

As described in [Paper III](#), and illustrated in Figure 5.7, the symmetry attribute is calculated and then a composite attribute is subsequently constructed by creating a hue-saturation-intensity (HSI) image in which the hue component of the image is comprised of the symmetry attribute, and the intensity component is comprised of a user-selected instantaneous attribute.

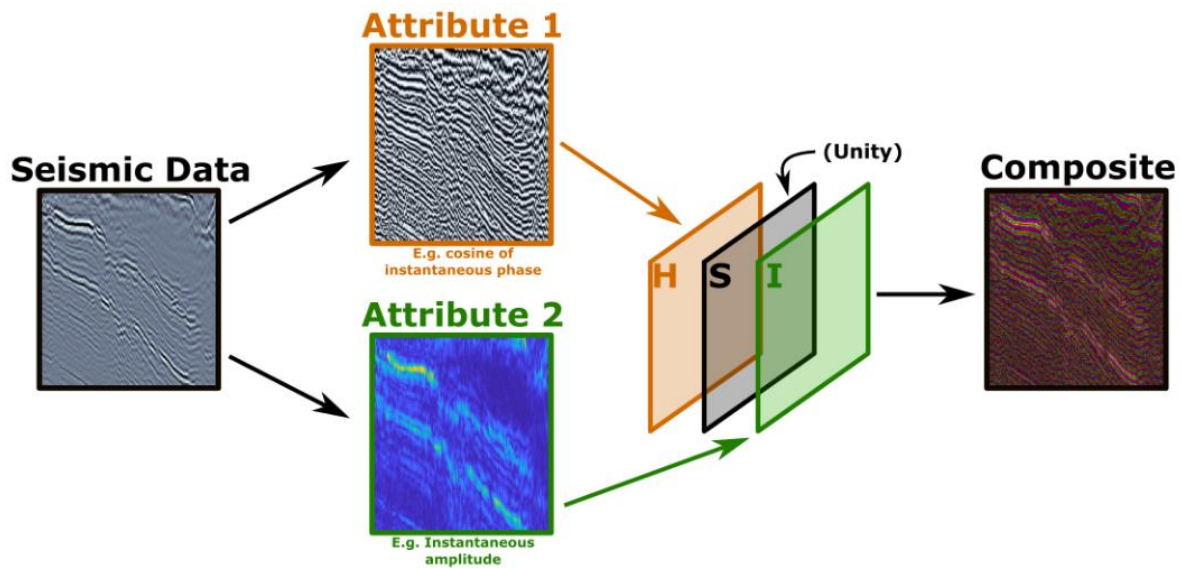


Figure 5.7: Illustration of how composite attributes were created for [Paper III](#). Two attributes are obtained from a seismic section and are assigned to the hue and intensity components of a hue-saturation-intensity image to produce the composite attribute.

The composite attributes utilised in [Paper III](#) were created by combining the cosine of the instantaneous phases with either the symmetry or the instantaneous amplitude of the data. The resulting composite attributes are termed the symmetry-paraphase composite (SPC) or the amplitude-phase composite (APC).

An example application of this attribute is shown in Figure 5.8, where the attribute is applied to the same section as described in Figure 5.3. In this case, both the instantaneous phase cosine and the instantaneous amplitude composites are shown. The reason this hybrid is created is to exploit the advantages of both the symmetry attribute and the instantaneous attributes.

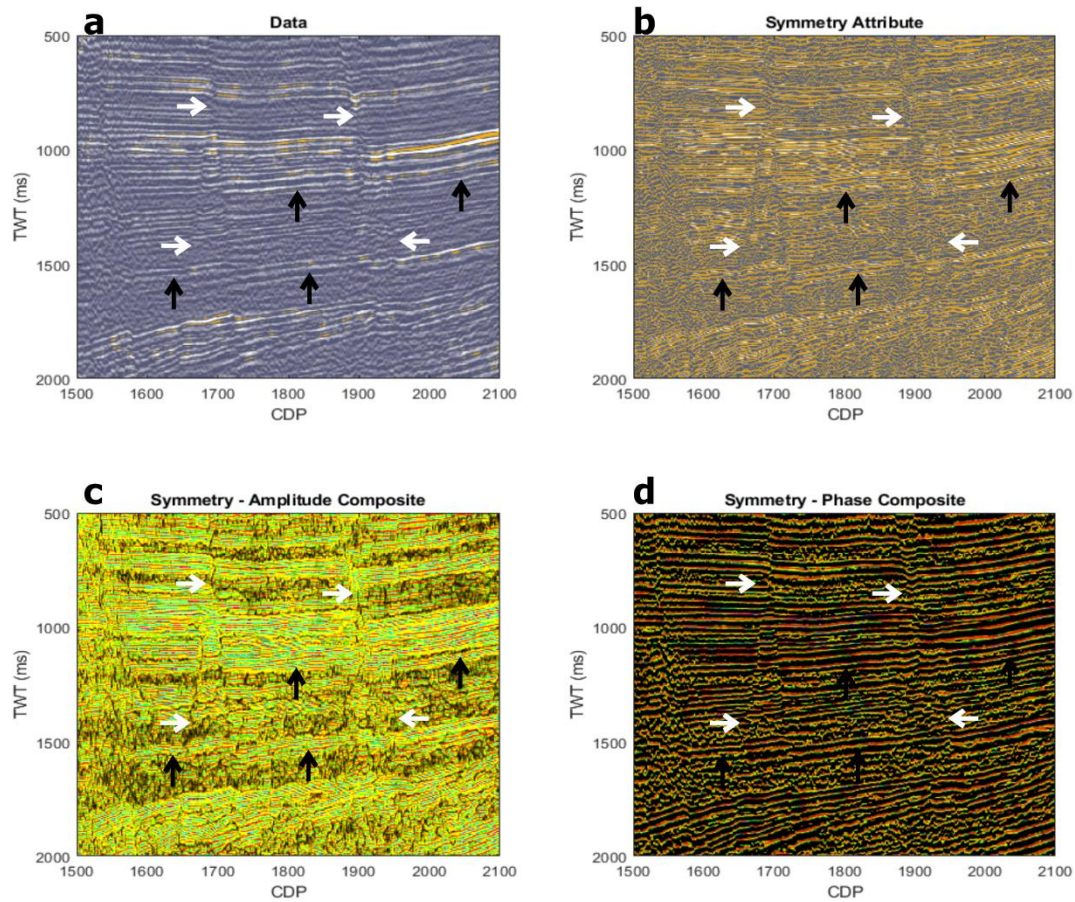


Figure 5.8: Application of symmetry composite attributes to data (a) as in Figure 5.3. Composite attributes (b-d) are hue-saturation-intensity images with symmetry attribute assigned to hue component and instantaneous amplitude or phase cosine assigned to intensity component. White arrows indicate fault zones and black arrows indicate reflections across the faults.

As seen in Figure 5.8, the symmetry attribute can be difficult to interpret unless a specific region is zoomed in on substantially. However, when tempered with the instantaneous attributes, it serves as a powerful tool. The symmetry – amplitude composite exhibits the typical bright spots that are found in the instantaneous amplitude without the loss of the lower amplitudes, due to the AGC properties of the symmetry attribute. The symmetry – phase composite illustrates all the reflections clearly but the dominant features are still evident. In summary, the symmetry – amplitude composite is useful at relating reflection packages across discontinuities and the symmetry – phase composite is useful in enhancing both strong and weak reflectors, while still being able to distinguish between the two. More details about the application of these composite attributes to real data and the enhancements of features provided thereby can be found in [Papers II and III](#) (Chapters 9 and 10).

Computational Performance

The computational cost of the symmetry attribute is quantified by timing its execution in MATLAB. Table 5.1 displays the runtime of the attribute with 2D datasets of varying size, with a fixed window

size of 10 % the dimensions of the data. Table 5.2 shows the runtime of the attribute with varying window sizes at a fixed data size of 2000 rows and 1000 columns. The computer used in this test has the following specifications:

CPU: Intel Core i7-7700HQ @ 2.80 GHz
(x64 – based)

RAM: 8 GB DDR4

Data Size (# rows x # columns)	Runtime
2000x500	2min17s
2000x1000	6min54s
2000x1500	14min38s
2000x2000	28min41s

Table 5.1: Runtime of Symmetry attribute computation code on datasets of varying sizes with fixed window size of 10 % data size.

Window Size (% of data size)	Runtime
10	6min54s
15	14min37s
20	21min16s
25	28min07s

Table 5.2: Runtime of SPC attribute computation code on datasets of varying window sizes with fixed data size of 2000 rows and 1000 columns.

6 REFERENCES

- Ahmad, A. and Cerrito, P.B. (1991). Bivariate symmetry: definitions and basic properties. *Nonparametric Statistics* 1, 165-169.
- Ahmadi, O. (2015). Application of the Seismic Reflection Method in Mineral Exploration and Crustal Imaging: Contributions to Hardrock Seismic Imaging. PhD Thesis: Uppsala University (UU) 2015.
- Alchin, D.J., Botha, W.J. (2005). The structural/stratigraphic development of the Sishen South (Welgevonden) iron ore deposit, South Africa, as deduced from ground gravity data modeling. In: *Proceedings Iron Ore 2005 Conference*. The Australasian Institute of Mining and Metallurgy, Melbourne, 29–41.
- Allen, R., Ripa, M., Jansson, N. (2008). Palaeoproterozoic volcanic- and limestone-hosted Zn-Pb-Ag-(Cu-Au) massive sulphide deposits and Fe oxide deposits in Bergslagen, Sweden. IGCP Project 502.
- Araya-Polo, M., Dahlke, T., Frogner, C., Zhang, C., Poggio, T., Hohl, D. (2017). Automated fault detection without seismic processing. *The Leading Edge* 36(3), 194-280.
- Baeten, G.J.M. (1989). Theoretical and Practical Aspects of the Vibroseis Method. PhD Thesis: Delft University of Technology, Department of Mining and Petroleum Engineering, 9-11.
- Bailey, S.W., Tyler, S.A. (1960). Clay minerals associated with the Lake Superior iron ores. *Economic Geology* 55(1), 150-175.
- Barnes, A.E. (1996). Theory of 2D complex seismic trace analysis. *Geophysics* 61(1), 12-311.
- Barnes, A.E. (2007). A tutorial on complex seismic trace analysis. *Geophysics* 72 (6), W33-W34.
- Barton, K., McAloon, W. (1999). Geophysics and geological modelling of the E-BD reservoir - part of the Sable Field development study – Block 9, Bredasdorp Basin, offshore Republic of South Africa. SOEKOR internal report #SOE-EXP-RPT-0486.
- Barton, K. (2001). Review of Sable field interpretation based on the E2000 3D seismic survey. SOEKOR internal report #SOE-EXP-RPT-0554.
- Basson, I.J., Anthonissen, C.J., McCall, M.J., Stoch, B., Britz, J., Deacon, J., Strydom, M., Cloete, E., Botha, J., Bester, M., Nel, D. (2017). Ore-structure relationships at Sishen Mine, Northern Cape, Republic of South Africa, based on fully-constrained implicit 3D modelling. *Ore Geology Reviews* 86, 825–838.
- Bau, M., Dulski, P. (1996). Distribution of yttrium and rare-earth elements in the Penge and Kuruman iron-formations, Transvaal Supergroup, South Africa. *Precambrian Research* 79(1-2), 37-55.
- Beach, A., Smith, R. (2007). Structural geometry and development of the Witwatersrand Basin, South Africa. In: Ries, A.C., Butler, R.W.H., Graham, R.H. (editors). *Deformation of the continental crust: the legacy of Mike Coward*. Geological Society, London, Special Publication, 533–542.
- Berkhout, A.J. (1980). *Seismic Migration – Imaging of Acoustic Energy by Wavefield Extrapolation*. Elsevier Science Publication Company.
- Berryhill, J.R. (1979). Wave-Equation Datuming. *Geophysics* 44, 1329-1333.
- Beukes, N.J., de Kock, M. O., Vorster, V., Ravhura, L. G., Frei, D., Gumsley, A. P., Harris, C. (2019). The age and country rock provenance of the Molopo Farms Complex: implications for Transvaal Supergroup correlation in southern Africa. *South African Journal of Geology* 122(1), 39-56.
- Bouvier, J.D., Kaars-Sijpesteijn, C.H., Kluesner, D.F., Onyejekwe, C.C., van der Paul, R.C. (1989). Three-dimensional seismic interpretation and fault sealing investigations, Nun River field, Nigeria. *American Association of Petroleum Geology Bulletin* 73 (11), 1397–1414.
- Boyd, D., Anka, Z., di Primio, R., Kuhlmann, G., de Wit, M.J. (2011). Passive margin evolution and controls on natural gas leakage in the Orange Basin, South Africa. *South African Journal of Geology* 114, 415–432.
- Bracewell, R. (1986). *The Fourier transform and its applications*. McGraw-Hill Book Company.
- Brodic, B., Malehmir, A., Bastani, M., Mehta, S., Juhlin, C., Lundberg, E., Wang, S. (2017). Multi-component digital-based seismic landstreamer and boat-towed radio-magnetotelluric acquisition systems for improved subsurface characterization in the urban environment. *First Break* 35(8), 41-47.

- Brown, A.R. (1996). Seismic attributes and their classification. *The Leading Edge* 15(10), 1090-1195.
- Buntin, S., Malehmir, A., Koyi, H., Högdahl, K., Malinowski, M., Larsson, S.A., Thybo, H., Juhlin, C., Korja, A., Górszczyk, A. (2019). Emplacement and 3D geometry of crustal-scale saucer-shaped intrusions in the Fennoscandian Shield. *Scientific Reports* 9 (10498).
- Buzlukov, V., Landa, E. Imaging improvement by prestack signal enhancement. *Geophysical Prospecting* 61(6), 1150-1158.
- Campbell, G. (1990). The seismic revolution in gold and platinum prospecting in. *South African Geophysical Association Yearbook*, 37-45.
- Campbell, G., Crotty, J.H. (1990). 3-D seismic mapping for mine planning purposes at the South Deep Prospect. *Proceedings of the International Deep Mining Conference. SAIMM Symposium Series S10(2)*, 569-597.
- Carney, M.D., Mienie, P.J. (2003). Comparison of the Sishen and Sishen South (Welgevonden) iron ore deposits, N Cape Province, South Africa. *Applied Earth Science*, 112:B5.
- Cawthorn, R.G. (2010). The Platinum Group Element Deposits of the Bushveld Complex in South Africa. *Platinum Metals Review* 54(4), 205-215.
- Chatfield, C (2004), *The Analysis of Time Series: An Introduction* (6th Edition), *Texts in Statistical Science*.
- Chen, Y., Zhang, G., Gan, S., Zhang, C. (2015). Enhancing seismic reflections using empirical mode decomposition in the flattened domain. *Journal of Applied Geophysics* 119, 99-105.
- Chopra, S., Marfurt, K. J. (2007). *Seismic Attributes for Prospect Identification and Reservoir Characterisation*. SEG Geophysical Development Series No. 11, 27-98.
- Claerbout, J. F. (1985). *Fundamentals of Geophysical Data Processing with Applications to Petroleum Prospecting*. McGraw-Hill Book Company, 141.
- Cooper, J., Lawton, D., Margrave, G. (2010). The wedge model revisited: A physical modelling experiment. *Geophysics* 75(2), 0016-8033.
- Cooper, G.R.J. (2017). *Enhancing Seismic Data Using Symmetry*. South African Geophysical Association Biennial Conference and Exhibition, 2017.
- Dankert, B.T., Hein, K.A.A. (2010). Evaluating the structural character and tectonic history of the Witwatersrand Basin. *Precambrian Research* 177(1), 1-22.
- Dehghannejad, M., Bauer, T.E., Malehmir, A., Juhlin, C., Weihed, P. (2011). Crustal geometry of the central Skellefte district, northern Sweden – constraints from reflection seismic investigations. *Tectonophysics* 524-525, 87-99.
- Dentith, M., Mudge, S. T. (2014). *Geophysics for the Mineral Exploration Geoscientist*. Cambridge University Press.
- De Beer, J. H. (2016). *The History of Geophysics in Southern Africa*. African Sun Media. ISBN: 192068980X.
- Dobrin, M. B. (1960). *Introduction to Geophysical Prospecting*. McGraw-Hill Book Company.
- Donoso, G. A., Malehmir, A., Pacheco, N., Auraujo, V., Penney, M., Carvalho, J., Spicer, B., Beach, S. (2020). Potential of legacy 2D seismic data for deep targeting and structural imaging at the Neves-Corvo massive sulphide-bearing deposit, Portugal. *Geophysical Prospecting* 68(1), 44-61.
- Durrheim, R.J. (1986). Recent reflection seismic developments in the Witwatersrand basin. In: Barazangi, M., Brown, L. (editors). *Reflection seismology, a global perspective: geodynamics series*, 13. Washington: American Geophysical Union Volume 13, 77–83.
- Easton, R.L. (2010). *Fourier Methods in Imaging*. John Wiley and Sons, Ltd, Chichester, UK, 325 - 344.
- Eaton, D.W., Milkereit, B., Salisbury, M.H. (2003). *Hardrock seismic exploration*. Geophysical Development Series No. 10. Society of Exploration Geophysicist.
- Eglington, B. M. (2006). Evolution of the Namaqua-Natal Belt, southern Africa – A geochronological and isotope geochemical review. *Journal of African Earth Sciences* 46, 93-111.
- Ellis, R. G., Oldenburg, D. W. (1994). *Applied Geophysical Inversion*. *Geophysical Journal International* 116(1), 5-11.
- Farrell, R. C. and Euwema, R. N. (1984). *Refraction Statics*. *Proceedings of the IEEE* 72(10).
- Fouch, M.J., James, D.E., VanDecar, J.C., van der Lee, S. (2004). Mantle seismic structure beneath the Kaapvaal and Zimbabwe Cratons. *Geological Society of South Africa* 107(1-2), 33-44.

- Frimmel, H.E., Hennigh, Q. (2015). First whiffs of atmospheric oxygen triggered onset of crustal gold cycle. *Mineralium Deposita* 50, 5–23.
- Frimmel, H.E. (2018). Episodic concentration of gold to ore grade through Earth's history. *Earth Science Reviews* 180, 148-158.
- Gabor, D., 1946. Theory of Communication. *The Journal of the Institute of Electrical Engineering* 93, 429-441.
- Gibson, R. L., Reimold, W. U., Stevens, G. (1998). Thermal-metamorphic signature of an impact event in the Vredefort dome, South Africa. *Geology* 26(9), 787-790.
- Gibson, M.A.S., Jolley, S.J., Barnicoat, A.C. (2000). Interpretation of the Western ultra deep levels 3D seismic survey. *The Leading Edge* 19(7), 730–735.
- Gibbs, J. W. (1898), Fourier's Series, *Nature* 59 (1522), 200.
- Górszczyk, A., Cyz, M., Malinowski, M. (2015). Improving depth imaging of legacy seismic data using curvelet-based gather conditioning: A case study from Central Poland. *Journal of Applied Geophysics* 117, 73-80.
- Grandke, T.K. (1983). Interpolation algorithms for discrete Fourier transforms of weighted signals. *IEEE Transactions on Instrumentation and Measurement* 32(2), 350-355.
- Gray, S. H., Etgen, J., Dellinger, J., Whitmore, D. (2001). Seismic Migration Problems and Solutions. *Geophysics* 66(5), 1340-1649.
- Hagelund, R., Levin, S. A. (2017). SEG-Y_r2.0: SEG-Y revision 2.0 Data Exchange format. Tulsa, OK: Society of Exploration Geophysicists.
- Harris, F.J. (1978). On the use of windows for harmonic analysis with the discrete Fourier transform. *Proceedings of the IEEE* 66 (1), 51-83.
- Hart, R. J., Andreoli, M. A. G., Tredoux, M., Moser, D., Ashwal, L. D., Eide, E. A., Webb, S. J., Brandt, D. (1997). Late Jurassic age for the Morokweng impact structure, southern Africa. *Earth and Planetary Science Letters* 147(1-4), 25-35.
- Heiland, C.A. (1946). *Geophysical Exploration*. New York Prentice Hall, Incorporated.
- Heinrich, C.A. (2015). Witwatersrand gold deposits formed by volcanic rain, anoxic rivers and Archaean life. *Nature Geoscience* 8, 206–209.
- Hall RB (1988) Hardrock versus softrock geology. In: *General Geology*. Springer US, 331–331.
- Hart, B. (2011). *Introduction to seismic interpretation*. AAPG Discovery Series 16.
- Hileman, J. A., Embree, P., Pflueger, J. C. (1968). Automated Static Corrections. *Geophysical Prospecting* 16, 326-358.
- Hubral, P. and Krey, T. (1980). Interval Velocities from Seismic Reflection Time Measurements. *SEG Monograph*.
- Huygens, C. (1690). *Treatise on Light*. Published in Leyden by Van der Aa, 1690. Translated by Silvanus P. Thompson: Macmillan, 1912; Project Gutenberg edition, 2005.
- Isiaka, A., Durrheim, R.J., Manzi, M.S.D., Andreoli, M. (2017). 3D seismic analysis of the AK Fault, Orange Basin, South Africa: Implications for hydrocarbon leakage and offshore neotectonics. *Tectonophysics* 721, 477-190.
- Jolley, S.J., Stuart, G.W., Freeman, S.R., Knipe, R.J., Kershaw, D., McAllister, E., Barnicoat, A.C., Tucker, R.F. (2007). Progressive deformation of a late orogenic thrust system, from duplex development to extensional reactivation and disruption: Witwatersrand Basin, South Africa. *Geological Society, Special Publication*, 543–69.
- Jones, A.G., R.L. Evans, M.R. Muller, M.P. Hamilton, M.P. Miensoopust, X. Garcia, P. Cole, T. Ngwisanyi, D. Hutchins, C.J.S Fourie, H. Jelsma, T. Aravanis, W. Pettit, S. Webb, J. Wasborg, and The SAMTEX Team. (2009). Area selection for diamonds using magnetotellurics: Examples from southern Africa. *Lithos* 112(1), 83-92.
- Karsli, H. (2006). Further improvement of temporal resolution of seismic data by autoregressive (AR) spectral extrapolation. *Journal of Applied Geophysics* 59(4), 324-336.
- Kearey, P., Brooks, M., Hill, I. (2009). *An introduction to geophysical exploration*. 3rd Ed. Wiley 2009.
- Ketelhodt, J., Manzi, M., Durrheim, R. (2019). Post-stack denoising of legacy reflection seismic data: implications for coalbed methane exploration, Kalahari Karoo Basin, Botswana. *Exploration Geophysics* 50(6), 667-682.
- Keyser, N. (2013). *Simplified geology of South Africa, Lesotho and Swaziland*. Council of Geoscience, South Africa.

- Khaidukov, V., Landa, E., Moser, T.J. (2004). Diffraction imaging by focusing-defocusing: An outlook on seismic superresolution. *Geophysics* 69(6), 1372-1570.
- Kirk, J., Ruiz, J., Chesley, J., Titley, S. (2003). The origin of gold in South Africa. *American Scientist* 91, 534-541.
- Krebes, E. S. (2019). *Seismic Wave Theory*. Cambridge University Press 2019. ISBN: 9781108601740.
- Levin, F. K. (1971). Apparent Velocity from Dipping Interface Reflections. *Geophysics* 36, 510-516.
- Linton, C. M. and McIver, P. (2001). *Handbook of Mathematical Techniques for Wave/Structure Interactions*. Boca Raton, FL: CRC Press.
- Luh, P. C. (1992). True-amplitude signal recovery. *The Leading Edge* 11, 13-24.
- Malajczuk, S., Saklani, R., Clark, D., Eastwell, D. (2016). Improved Subsurface Imaging and Interpretability through Broadband Reprocessing of Legacy Seismic Data. Examples from North West Shelf Australia. 25th ASEG-PESA-AIG Geophysical Conference and Exhibition, 1-8.
- Malehmir, A., Bellefleur, G. (2010). Reflection seismic imaging and physical properties of base-metal and associated iron deposits in the Bathurst Mining Camp, New Brunswick, Canada. *Ore Geology Reviews* 38(4), 319-333.
- Malehmir, A., Koivisto, E.A., Manzi, M.S.D., Cheraghi, S., Durrheim, R.J., Bellefleur, G., Wijns, C., Hein, K.A.A., King, N. (2014). A review of reflection seismic investigations in three major metallogenic regions: The Kevitsa Ni-Cu-PGE district (Finland), Witwatersrand goldfields (South Africa), and the Bathurst Mining Camp (Canada). *Ore Geology Reviews* 56, 423-441.
- Malehmir, A., Maries, G., Bäckström, E., Schön, M., Marsden, P. (2017). Developing cost-effective seismic mineral exploration methods using a landstreamer and a drophammer. *Scientific Reports* 7(1), 10325.
- Malehmir, A., Donoso, G., Markovic, M., Maries, G., Dynesius, L., Brodic, B., Pecheco, N., Marsden, P., Bäckström, E., Penney, M., Araujo, V. (2019). Smart Exploration: from legacy data to state-of-the-art data acquisition and imaging. *First Break* 37(8), 71-74.
- Manzi, M.S.D., Hein K.A.A., Durrheim, R.J. and King, N. (2013). The Ventersdorp Contact Reef model in the Kloof Gold Mine as derived from 3D seismics, geological mapping and exploration borehole datasets. *International Journal of Rock Mechanics & Mining Sciences* 66, 97-113.
- Manzi, M., Cooper, G.R.J., Malehmir, A., Durrheim, R.J., Nkosi, Z. (2015). Integrated interpretation of 3D seismic data to enhance the detection of the gold-bearing reef: Mponeng Gold mine, Witwatersrand Basin (South Africa). *Geophysical Prospecting* 63(4), 881-902.
- Manzi, M., Malehmir, A., Durrheim, R. (2018). Improved Subsurface Imaging through Re-processing of Legacy 2D Seismic Data-A Case Study from a Deep South African Gold Mine. *EAGE 2nd Conference on Geophysics for Mineral Exploration and Mining*, 1-5.
- Manzi, M., Malehmir, A., Durrheim, R. (2019). Giving the legacy seismic data the attention they deserve. *First Break* 37(8), 89-96.
- Manzi, M., Cooper, G.R.J., Malehmir, A., Durrheim, R. (2020). Improved structural interpretation of legacy 3D seismic data from Karee platinum mine (South Africa) through the application of novel seismic attributes. *Geophysical Prospecting* 68(1), 145-163.
- Markovic, M., Maries, G., Malehmir, A., von Ketelhodt, J., Bäckström, E., Schön, M., Marsden, P. (2019). Deep reflection seismic imaging of iron-oxide deposits in the Ludvika mining area of central Sweden. *Geophysical Prospecting* 68(1), 7-23.
- Mase, G. E. (1970). *Schaum's outline of continuum mechanics*. McGraw-Hill Book Company 1970. ISBN: 978-0070406636.
- Matmon, A., Hidya, A. J., Vainer, S., Crouvi, O., Fink, D., Erel, Y. (2015). New chronology for the southern Kalahari Group sediments with implications for sediment-cycle dynamics and early hominin occupation. *Quaternary Research* 84(1), 118-132.
- Meunier, J. (2011). *Seismic Acquisition from Yesterday to Tomorrow*. Society of Exploration Geophysicists 2011.
- Minter, W.E.L. (1978). A sedimentological synthesis of placer gold, uranium and pyrite concentrations in Proterozoic Witwatersrand sediments, in: Miall, A.D., (editor), *Fluvial Sedimentology Memoir*, Canadian Society Petroleum Geology 5, 801-829.
- Mkhabela, M., Manzi, M. (2017). Detection of potential methane gas pathways in deep South African gold mines. *Journal of Geophysics and Engineering* 14(4), 960-974.

- Moen, H. F. G. (1999). The Kheis tectonic subprovince, southern Africa: A lithostratigraphic perspective. *South African Journal of Geology* 102(1), 27-42.
- Mortimer, B. (1995). Report on structural geological analysis: Sishen. Internal Company Report, 71.
- Nedimović, M.R. (2003). Crooked-line 2D seismic reflection imaging in crystalline terrains: Part 1, data processing. *Geophysics* 68(1), 16-409.
- Nelsen, R.B. (1993). Some concepts of bivariate symmetry. *Nonparametric Statistics* 3, 95-101.
- Nguuri, T. K., Gore, J., James, D. E., Webb, S. J., Wright, C., Zengeni, T. G., Gwavava, O., Snoke, J. A. (2001) Crustal structure beneath southern Africa and its implications for the formation and evolution of the Kaapvaal and Zimbabwe cratons, *Geophysical Research Letters* 28, 2501–2504.
- Peng, C., Wang, M., Chazalnoel, N., Gomez, A. (2018). Subsalt imaging improvement possibilities through a combination of FWI and reflection FWI. *The Leading Edge* 37(1), 52-57.
- Phillips, G.N., Law, J.D.M. (2000). Witwatersrand goldfields: Geology, genesis and exploration. in: Hagemann, S.G. and Brown, P.E., (editors), *Gold in 2000: Society of Economic Geology Reviews* 13, 439–500.
- Phillips, G.N., and Powell, R. (2011). Origin of Witwatersrand gold: a metamorphic devolatilization-hydrothermal replacement model: *Applied Earth Sciences, Transactions of the Institute of Material, Minerals and Mining* 120, 112–129.
- Popik, S., Pevzner, R., Tertyshnikov, K., Popik, D., Urosevic, M., Shulakova, V., Glubokovskikh, S., Gurevich, B. (2020). 4D surface seismic monitoring the evolution of a small CO₂ plume during and after injection: CO₂CRC Otway Project study. *Exploration Geophysics*, DOI: 10.1080/08123985.2020.1735934.
- Pretorius, D.A. (1989). The sources of Witwatersrand gold and uranium: a continued difference of opinion. *Economic Geology Research Unit, University of Witwatersrand, Information Circular* 206, 43.
- Pretorius, C.C., Muller, M.R., Larroque, M., Wilkins, C.A. (2003). Review of 16 years of hardrock seismics on the Kaapvaal Craton. In: Eaton, D.W., Milkereit, B., Salisbury, M.H. (editors). *Hardrock seismic exploration*, Ed. 10. *Geophysical developments*, Society of Exploration Geophysicists, 247–68.
- Robinson, E. A. and Treitel, S. (1980). *Geophysical Signal Analysis*. *Apprentice Hall Inc.*
- Salas-Romero, S., Malehmir, A., Snowball, I.F., Dessirier, B. (2019). Subsurface characterization of a quick-clay vulnerable area using near-surface geophysics and hydrological modelling. *Solid Earth* 10(10), 1685-1705.
- Scales, J. A., Smith, M. L., Treitel, S. (2001). *Introductory Geophysical Inverse Theory*. *Samizdat Press*
- Scheiber-Enslin, S. E., Manzi, M. S. D. (2018). Integration of 3D reflection seismics and magnetic data for deep platinum mine planning and risk mitigation: A case study from Bushveld Complex, South Africa. *Exploration Geophysics* 49(6), 928-939.
- Schneider, W. (1978). Integral Formulation for Migration in Two and Three Dimensions. *Geophysics* 43, 49-76.
- Shell Internationale Petroleum. (March–April 1995). *Shell Processing Support Format for Land 3-D Surveys*. *Geophysics* 60(2), 317-618.
- Sibanye Gold Limited, (2014). Competent person’s report on the material assets of the Kloof operations. Libanon Business Park, Westonaria, South Africa., 104.
- Smith, A.J.B., Beukes, N.J. (2016). Palaeoproterozoic banded iron formation-hosted high-grade hematite iron ore deposits of the Transvaal Supergroup, South Africa. *Episodes* 39, 269–284.
- Soubaras, R., Dowle, R. (2010). Variable-depth streamer – a broadband marine solution. *First Break* 28(12), 89-96.
- Stettler, E.H., Prinsloo, J., Hauger, M.E. (1998). A geophysical transect between Avondale on the Kheis tectonic province and Keimoes on the Namaqua metamorphic province, South Africa. *Southern African Geophysical Review* 2, 83-93.
- Stettler, E.H., Prinsloo, J., Hauger, M.E., du Toit, M.C. (1998). A crustal geophysical model for the Kheis tectonic province, South Africa based on magnetotelluric, reflection seismic, gravity and magnetic data sets. *Southern African Geophysical Review* 3, 54-68.

- Stevenson, F., Durrheim, R.J. (1997). Reflection Seismics for Gold, Platinum and Base Metal Exploration and Mining in Southern Africa. *Proceedings of Exploration 97: Fourth Decennial International Conference on Mineral Exploration*, 391-398.
- Stevenson, F., Higgs, R.M.A., Durrheim, R.J. (2003) Seismic imaging of precious and basemetal deposits in South Africa. In: Eaton, D.W., Milkereit, B., Salisbury, M.H. (editors). *Hardrock seismic exploration*, Ed. 10. *Geophysical Developments*, 141–56.
- Stoch, B., Anthonissen, C. J., McCall, M-J., Basson, I.J., Deacon, J., Cloete, E., Botha, J., Britz, J., Strydom, M., Nel, D., Bester, M. (2017). 3D implicit modelling of the Sishen Mine: new resolution of the geometry and origin of Fe mineralisation. *Mineralium Deposita* 53, 835-853.
- Taner, M. T. and Koehler, F. (1969). Velocity Spectra – Digital Computer Derivation and Applications of Velocity Functions. *Geophysics* 39, 859-881.
- Taner, M. T., Koehler, F., Alhilali, K. A. (1974). Estimation and Correction of Near-Surface Time Anomalies. *Geophysics* 41, 441-463.
- Taner, M.T., Koehler, F., Sheriff, R.E. (1979). Complex seismic trace analysis. *Geophysics* vol. 44 no. 6. P. 1041-1063.
- Tankard, A., Welsink, H., Aukes, P., Newton, R., Stettler, E. (2012). Geodynamic interpretation of the Cape and Karoo Basins, South Africa. *Regional Geology and Tectonics: Phanerozoic Margins, Cratonic Basins and Global Tectonics Maps*, Elsevier 2012.
- Telford, W. M., Geldart, L. P., Sheriff, R. E. (1990). *Applied Geophysics* (2nd Edition). Cambridge University Press.
- Ten Kroode, F., Bergler, S., Corsten, C., de Maag, J.W., Strijbos, F., Tijhof, H. (2013). Broadband seismic data – The importance of low frequencies. *Geophysics* 78(2), WA3-WA14.
- Tinker, J., de Wit, M., Grotzinger, J. (2002). Seismic stratigraphic constraints on Neoproterozoic – Paleoproterozoic evolution of the western margin of the Kaapvaal Craton, South Africa. *South African Journal of Geology* 105, 107-134.
- Vajner, Y. (1974). The tectonic development of the Namaqua Mobile Belt and its Foreland in parts of the Northern Cape. *Precambrian Research* 14, 201.
- Van der Westhuizen, W. A., De Bruijn, H., Meintjies, P. G. (1991). The Ventersdorp Supergroup: an overview. *Journal of African Earth Sciences* 13, 83–105.
- Van Niekerk, H.S., Beukes, N.J. (2019). Revised definition/outline of the Kheis Terrane along the western margin of the Kaapvaal Craton and lithostratigraphy of the newly proposed Keis Supergroup. *South African Journal of Geology* 122(2), 187-220.
- Van Schalkwyk, J.F. (1984). The geology of the Sishen iron ore mine. M.Sc. dissertation (unpublished). Rand Afrikaans University, Johannesburg.
- Van Schalkwyk, J.F., Beukes, N.J. (1986). The Sishen iron ore deposit, Griqualand West. In: Anhaeusser, C.R. and Maske, S. (editors). *Mineral deposits of Southern Africa*, vol 1: Geological Society of South Africa, Johannesburg, 931–956.
- Vermeer, G. J. O. (2012). 3D Seismic survey design 2nd Ed. *Geophysical Reference Series* 12.
- Walraven, F., Armstrong, R.A., Kruger, F.J. (1990). A chronostratigraphic framework for the north-central Kaapvaal Craton, the Bushveld Complex and the Vredefort structure. *Tectonophysics* 171(1-4), 23-48.
- Wang, D.T., McCowan, D.W. (1989). Spherical divergence correction for seismic reflection data using slant stacks. *Geophysics* 54(5), 544-665.
- Wang, Z., Di, H., Shafiq, M.A., Alaudah, Y., AlRegib, G. (2018). Successful leveraging of image processing and machine learning in seismic structural interpretation: A review. *The Leading Edge* 37(6), 402-480.
- White, R.E. (1991). Properties of instantaneous attributes. *The Leading Edge* 10(7), 1-68.
- Widess, M. B. (1973). How thin is a thin bed?. *Geophysics* 38, 1176-1180.
- Wiener, N. (1949). Extrapolation, Interpolation, and Smoothing of Stationary Time Series. Report of the Services 19, Research Project DIC-6037 MIT.
- Westgate, M.C., Manzi, M.S.D., Cooper, G.R.J. (2018). Symmetry as an Alternative Seismic Attribute: Case Studies from the Hard Rock and Soft Rock Environments, South Africa. 80th EAGE Conference and Exhibition 2018.

- Westgate, M.C., Manzi, M.S.D., James, I., Harrison, W. (Under Review). New insights from legacy seismic data: reprocessing of legacy 2D seismic data for imaging of iron-oxide mineralisation near Sishen Mine, South Africa. *Geophysical Prospecting*.
- Wood, E.M. (2015). Soft rock reflection seismics: Exploration for oil and gas. In: de Beer, J. (editor). *The history of geophysics in South Africa*. Sun Media Stellenbosch, 473-184.
- Woodward M. J., 1992. Wave-equation tomography. *Geophysics*, 57(1), 15–26.
- Wu, Y. and McMechan, G. A. (2018). True amplitude recovery in reverse time extrapolation of plane and spherical waves. *Geophysics* 83(3), 1MJ-Z13.
- Yilmaz, O. (1987). *Seismic Data Processing*, Vol. 2. *Investigation Into Geophysics: Society of Exploration Geophysicists*, 9-345.
- Young, A.E. (1930). Review: Conformal Map Projections: Review. *The Geographical Journal* 76(4), 348-351.
- Zhao, M., Langston, C. A., Nyblade, A.A. (1999) Upper mantle velocity structure beneath southern Africa from modeling regional seismic data. *Journal of Geophysical Research* 104, 4783–4794.
- Zhdanov, M. S. (2015). *Inverse Theory and Applications in Geophysics* (2nd Edition). Elsevier.

7 PAPER SUMMARIES

7.1 Paper I: New insights from legacy seismic data: reprocessing of legacy 2D seismic data for imaging of iron-oxide mineralisation near Sishen mine, South Africa

The legacy seismic profile KBF01 presented in [Paper I](#), located roughly 140 km south of profile KBF03A presented in [Paper II](#), is comprised of two W-E trending profiles, KBF01B and KBF01C, that have a ~ 5 km overlap and have a combined length of ~ 130 km. Details of the acquisition parameters of the profile can be found in Table 8.1. Reprocessing of the seismic data proved fruitful as reflections suspected to be associated with the mineralisation were significantly enhanced. The processing sequence used is displayed in Table 3.1. Not only were reflections associated with the mineralisation recovered largely due to successful ground roll removal, but a major unconformity at the base of the mineralisation was rendered clear and coherent, allowing for quality seismic imaging.

The geological context of this paper is described in Chapter 2.1 and can be seen in Figure 1.1 and Figure 2.2. In summary, the profile is located near the boundary between the Kaapvaal Craton and the Kheis Fold Belt (Figure 1.1) and overlies complex geology with diverse stratigraphic content, contributions of which are attributed to the Ventersdorp, Griqualand-West, Olifantshoek, and Karoo Supergroups, as well as the overlying sediments of the Kalahari Group (Figure 2.2a and Figure 2.3). The primary objective of Paper I was to reprocess the legacy seismic profile with the goal of imaging potentially mineable iron-oxide mineralisation near Sishen mine, an open-pit iron mine located in the Northern Cape Province of South Africa (Figure 2.2). This mineralisation is concentrated within the Asbestos Hills Subgroup of the Griqualand-West Supergroup (Figure 2.3) and is composed mainly of Haematite and conglomeritic iron ore as well as various secondary iron deposits, evidence of which is clearly observed as high magnetic anomalies in the residual magnetic map of the area (Figure 2.2b).

To aid in delineation of the subsurface characterization of the mineralisation, the seismic data were correlated with borehole, outcrop and magnetotelluric (MT) data. The lattermost were collected in the early 2000s as part of the large scale South African Magnetotelluric Experiment (SAMTEX) project (Jones et al., 2009), and were also reprocessed and inverted for this paper as these data were seen substantially useful in characterising the highly conductive iron-oxide mineralisation in contrast to the surrounding diamictite and volcanics. The borehole data, consisting of downhole seismic velocity measurements in two boreholes, were used to calculate synthetic seismograms with the goal of characterising the reflective nature of the mineralisation and determining the feasibility of seismic imaging thereof. The synthetics showed that there is a significant acoustic impedance contrast at the top of the mineralisation, as seen in borehole VMP-1. Another significant feature in this borehole that was observed is the major unconformity within the Vryburg Formation.

The final reprocessed section was in good agreement with the predicted seismic reflectivity of the borehole synthetics, increasing the level of confidence in the reflections interpreted to be caused by the mineralisation. After the prestack processing was applied, the seismic data were stacked and migrated using a prestack dip moveout (DMO) and subsequent frequency-domain Kirchhoff migration, as described in Table 3.1, after which an f-x deconvolution filter was applied to enhance coherency of reflectors.

After processing the two individual constituents of the profile, KBF01B and KBF01C as described above, they were stitched together at the merge point determined by the map in Figure 2.2. The interpreted magnetotelluric section aided in interpretation, which was obtained by inverting the phase and apparent resistivity curves after preparation. The basic interpretation revealed that the mineralisation at the centre of the section (where the seismic profile intersects the MT line) is constrained in depth to between 500 m and 1 km, which agreed well with the seismic interpretation. The mineralisation was characterised with a resistivity of 0 – 10 Ωm , which contrasts significantly with the overlying Kalahari sediments (> 10 k Ωm) and the underlying Campbell Rand metasediments (50 – 100 Ωm). The final interpreted seismic section where the suspected mineralisation is located revealed that the metasediments hosting the iron-oxide were part of a greater synclinal feature with wavelength of about 4 km and amplitude of 1 km. The average depth and thickness of these metasediments were 900 m and 500 m respectively.

The summarised conclusions drawn from this paper are that reappraisal and appropriation of legacy seismic and MT data can have advantageous implications in exploration geophysics, despite these datasets having originally been intended for alternative goals. In this particular paper, iron-oxide hosted in metasediments of the Griqualand-West Supergroup in north-western South Africa were imaged using 2D legacy seismic data with the aid of other existing datasets, such as MT, borehole and outcrop data. These metasediments exist within the syncline with a wavelength of 4 km and an amplitude of 1 km, at a depth of 900 m and average thickness of 500 m. Additionally, these metasediments were interpreted to have multiple structural constraints that included normal faults and a possible intrusion zone that exploited existing weak zones within the subsurface.

7.2 Paper II: The structural architecture of the western margin of the Kaapvaal Craton, South Africa: New constraints from the reappraisal of high-resolution legacy reflection seismic data

The 150 km long legacy seismic profile KBF03A used in [Paper II](#) is located along the western margin of the Kaapvaal Craton. Details of the acquisition parameters of the profile can be found in Table 8.1. The geological context of this paper is described in Chapter 2.1 and can be seen in Figure 1.1 and Figure 2.2. In summary, the profile lies at the tectonic boundary of the Kaapvaal Craton and the Kheis Province, as well as near the Morokweng impact crater. Stratigraphically, the profile overlies a supracrustal

package Paleoproterozoic metasediments unconformably overlain by Phanerozoic sediments. The former comprise the Ventersdorp, Griqualand-West, and Olifantshoek supergroups, while the latter comprise the Dwyka Group of the Karoo Supergroup which is unconformably overlain by the Kalahari Supergroup. Previous interpretations of the legacy seismic profile reveal a gentle west-dipping nature of the Paleoproterozoic metasediments, which are structurally controlled by faults and folds, the most noticeable of which is the west-dipping Moshaweng fault that was interpreted previously to have a 6.5 km normal slip with minor disruptions in the overlying Phanerozoic sediments, which were interpreted to otherwise be undisturbed. However, the lack of integration of data from two boreholes found along the profile led to possible misinterpretations of the profile. The primary aim of this paper was to reprocess the seismic profile to improve the resolution for better imaging and tectonic interpretation. This was aided with outcrop, borehole, and aeromagnetic data, as well as the computation of instantaneous seismic attributes (based on those from [Paper III](#)) and a first-break traveltome tomography.

The reprocessed profile provided clearer images with a significantly better signal-to-noise ratio. In particular, a remarkable improvement in the imaging of the Dwyka and Kalahari sediments revealed that they were indeed disturbed, with numerous faults of non-preferential, steep ($>60^{\circ}$) dip, as well as west-verging folding, confirming neotectonic activity in the region. This was further verified by the application of seismic attributes to the top 400 m of the section, which highlighted further disruptions in the sediments, and is in agreement with field observations in the area. The boreholes had both lithostratigraphic information as well as velocity logs, allowing for the calculation of synthetic seismograms. This provided a reference for expected reflectivities within the profile. When correlating the seismic section with one of the boreholes, we discovered that it drastically changed the established interpretation. What was previously interpreted as the base of the Ventersdorp Supergroup was instead inferred by the borehole log to be mafic intrusions that span a significant portion of the profile. This further assisted in the interpretation of sediments affected by the Moshaweng fault. The Moshaweng fault itself, under the constraints of our improved data, proved to have more complexity than previously interpreted. With 1285 m of dip separation in a reverse sense at depth (>4 km), and a 778 m dip separation in a normal sense in the above sediments, and accompanied by antithetic normal faults that intersect an anticline in the hanging wall, a more complicated tectonic history of the fault was required to explain its geometry.

As the scope of this paper grew, two discoveries developed. Firstly, the neotectonics of the Dwyka (250 Ma) and the Kalahari (1.1-1 Ma) hold many implications that require further investigation for a more complete and comprehensive explanation. Secondly, in order to explain the more complicated nature of the Moshaweng fault and its implied tectonic history, further investigation therein are required.

7.3 Paper III: Interpretation of legacy seismic data using composite seismic attributes: Case studies from oilfields and goldfields, South Africa

A well-established and prominently used tool that has contributed significantly to seismic interpretation is the vast array of seismic attributes, each with their own advantages and disadvantages as discussed in Chapter 5. The goal of this paper was to combine seismic attributes, specifically instantaneous attributes, in such a way as to minimise their shortfalls and blend their advantages. The way in which this was done is by creating a hue-saturation-intensity (HSI) image of a selected seismic section, in which one of the two chosen attributes is assigned to the hue component of the image and the other attribute to the intensity component. This is provided with more detail in Chapter 5.2. The assortment of attributes used in a variety of such combinations were all instantaneous attributes and included the instantaneous amplitude, the cosine of the instantaneous phase, and the symmetry attribute, the latter most of which was created by taking the ratio of total imaginary and total real components of a windowed Fourier transform that slides through the data (for more detail see Chapter 5). The resulting image is a hybrid of the two input attributes and is termed a composite attribute.

These composite attributes were applied in [Paper III](#) on 3D legacy seismic data from two study areas of economic importance in South Africa, and are described in more detail in [Chapter 2.4](#). The first case study was within the West Rand Group of the Witwatersrand Basin, where two gold-bearing conglomerate horizons (reefs) were targeted. These two layers, the Ventersdorp Contact Reef (VCR) and Black Reef (BLR), as described in [Chapter 2.4](#), are both thin (~ 1.5 m thick) and are thus below the tuning thickness of the seismic data, which made it difficult to resolve these reefs despite being above the detection limit, thus justifying the need for application of complex seismic attributes.

At one location the VCR and BLR converge to produce a real-life case of the well-known wedge model, a commonly considered problem in seismic literature. This is because as two reflectors converge, the wavelets associated with each horizon overlap and both constructive and destructive interference occur, making it difficult to resolve the two horizons. In our case study, the continuity of the gold-bearing VCR is difficult to discern close to the subcrop position and thus instantaneous composite attributes were applied to the data at this position to better image the geometry thereof. The attributes applied were the cosine of the instantaneous phase (or paraphase), and two composite attributes, the first of which incorporates the symmetry attribute and the paraphase and the second of which incorporates the instantaneous amplitude and paraphase. The symmetry-paraphase composite (SPC) attribute was created by assigning the symmetry and the paraphase to the hue and intensity components, respectively, of a hue-saturation-intensity (HSI) image, and the amplitude-paraphase composite utilised the amplitude in place of the symmetry.

The continuity of the VCR near the subcrop position was better delineated, especially by the paraphase attribute and the SPC attribute. It was important to map the VCR as this was one of the primary targets

of the Kloof gold mine. Additionally, mapping of faults that affected the VCR were high priority as such disruptions could result in substantial yield loss. The SPC and APC attributes revealed a prominent fault running through both the VCR and the BLR that was significantly enhanced. Faults of this nature were particularly significant as they could have played an important role in the formation of gold

The second case study from [Paper III](#), as detailed in [Chapter 2.4](#), comes from the Bredasdorp Basin in South Africa and was an investigation into the geometry of the E-BD oil reservoir. This reservoir had a thickness of around 30 m, as per well-log data from the area, where 17 m of the reservoir contained oil. As such, the reservoir was challenging to characterise using the conventional seismic amplitude display and so the application of seismic attributes to the seismic section was justified.

A weak reflection associated with the reservoir was indicated to abruptly truncate. To investigate the continuity of this reflector, the SPC and APC attributes as described above were used as the former allowed for investigation of continuity with the absence of amplitude and the latter constrained the interpretation as it preserved the amplitude. It was noted that the continuity of this reflector could be tracked in the parasequence attribute as well as the SPC attribute, thus constraining reservoir thickness, and the APC attribute confirmed the interpretations and also highlighted the bright spots flanking the reservoir, characteristic of reservoirs in the soft rock setting.

8 PAPER I: NEW INSIGHTS FROM LEGACY SEISMIC DATA: REPROCESSING OF LEGACY 2D SEISMIC DATA FOR IMAGING OF IRON-OXIDE MINERALISATION NEAR SISHEN MINE, SOUTH AFRICA

8.1 Abstract

Two overlapping legacy seismic profiles, 130 km long end to end, were shot in the 1990s over the Kuruman Hills on the western margin of the Kaapvaal Craton in southern Africa. The 6 s profiles were aimed at investigating the crustal structure of the western Kaapvaal Craton as well as to locate potential continuation of the Witwatersrand gold-bearing horizons beneath the cover rocks, the latter of which was unsuccessful. In this study, the legacy seismic data are reprocessed and used to image the iron-oxide (mainly haematite) mineralisation found in the Kuruman Formation of the Griqualand-West Supergroup, which outcrops along the two seismic profiles. The seismic profiles are located close to the Sishen open pit iron mine, where one of the world's largest iron ore concentrations (986 Mt) is mined. The reprocessed and merged seismic data are combined with magnetic, magnetotelluric, borehole and outcrop data to constrain the interpretation, and all indicate the mineralisation host rocks to have ~500 m thickness and 950 m depth, respectively. The seismic data further reveal seismic reflections associated with multiple iron ore horizons, which are affected by a first-order scale syncline and numerous near-vertically dipping (~65–80°) normal and reverse faults of various orientations and throws, thus providing insight into the structurally-controlled iron ore mineralisation in the area. Seismic tomography and magnetotellurics characterise the sediments to have a velocity ranging between 5000 and 6000 m/s and a resistivity of < 10 Ω m. The seismic imaging of the syncline and associated structural disruptions are important for future mining purposes and plans in the area as these structures might have preserved iron-oxide mineralisation from erosion. The reprocessed data thus provide information that could be incorporated in potential future underground mine planning in the area, thus improving the resource evaluation of the iron-oxide deposit. Legacy seismic data are thus shown to hold intrinsic quality and possible untapped potential that can be realised via data reprocessing.

8.2 Introduction

Since its inception, the reflection seismic method has proven substantially useful in high-resolution subsurface imaging and cost effective mineral prospecting (e.g. Campbell and Crotty 1990; Durrheim 1986; Pretorius et al. 2003; Malehmir et al. 2017; Manzi et al. 2019a; Markovic et al. 2019), and advancements in the acquisition and processing of reflection data have been made at a rapid pace over the recent years. This does not imply, however, that legacy data has run its course and is now unusable. Indeed, reappraisal of legacy data has shown to provide valuable insights into the data (e.g. Manzi, Malehmir and Durrheim 2019b; Malehmir et al. 2019).

In mineral exploration, reflection seismics has shown to be an invaluable tool in characterising the depth and subsurface geometry of mineral-hosting rocks. This is particularly true in South Africa, where the reflection seismic method has been used to explore the wealth of metals and minerals found within the Kaapvaal Craton, including renowned gold reserves in the Witwatersrand Basin (e.g. Durrheim 1986; Pretorius et al. 2003; Manzi et al. 2015; Mkhabela and Manzi 2017; Nomqhele et al. 2017), as well as imaging of the platinum-bearing horizons in the Bushveld Complex (e.g. Campbell 1990; Scheiber-Enslin and Manzi 2018; Manzi et al. 2019a). Iron deposits, such as those in this study, have also been successfully characterised using the reflection seismic method (e.g. Malehmir and Bellefleur 2010; Maries et al. 2017; Markovic et al. 2019). Iron deposits often exhibit higher density and velocity values than their host rock, allowing for a sufficient impedance contrast that makes seismic detection of these deposits possible. The reason the reflection seismic method has seen such success is the significantly high resolution of reflection seismic data (especially when compared to other geophysical methods), allowing it to accurately constrain the boundaries of subsurface geology. For 2D and 3D seismic surveys, the ability to image expansive subsurface regions is a great advantage to being limited to a single depth constraint such as in borehole drilling.

Accompanied with the rapid advancements in technology each year is the increase in computational power and data manipulation capabilities. This allows for refining and overall improvement of the conventional seismic processing sequence, not necessarily by introducing novel processing methods but by making the existing process faster, better refined and more precise, which also minimises human error. For example, while conducting velocity analysis via constant velocity stacks, multiple stacks can now be computed quickly, allowing for real-time comparison of different velocity models that cover a greater range of velocities, allowing for a more comprehensive and robust velocity picking method. Another example is the computational ability to accurately model the seismic wavefield with denser field grids and shorter time steps, which is useful when migrating seismic events. This is applicable to both pre- and post-stack processing and the result is an overall greater signal-to-noise ratio (SNR) of the data. Additionally, new methods have been developed since the early reflection processing schemes and have also been applied to legacy data. For example, techniques from gain balancing and structurally conformal filtering (Khan et al. 2017) to random noise suppression using adaptive filtering (Jeng et al. 2009), in which the SNR is boosted by attenuating both random and coherent noise, exist to bolster the processing sequence and improve the SNR. These developments make it worthwhile to reprocess legacy data to enhance the detection of subtle geological features of interest, which was not possible with conventional interpretation tools.

In this study, two high-resolution legacy 2D seismic profiles, KBF01B and KBF01C (Figure 1a, b), are reprocessed using modern algorithms and subsequently merged with the goal of targeting iron-oxide mineralization (primarily haematite) in the Kaapvaal Craton near Sishen mine, South Africa. Through this study, we demonstrate how legacy reflection seismic data, originally designed for deep gold

exploration, can be revisited and reprocessed to explore for some of the world's largest iron-oxide deposits in South Africa and map the complex geological features that host and control these deposits. The two 6 s seismic profiles have a collective length of 130 km and were acquired in the 1990s as part of a project (known as the Kheis project) conducted by Anglo American's Gold Division (now AngloGold Ashanti) and the South African government as part of the national geophysical program (Pretorius et al. 2003). The Kheis project was aimed to investigate the crustal structure of the Kaapvaal Craton (shown in Figure 1c), as well as to search for the continuation of the economic gold-bearing horizons (known as reefs) of the Witwatersrand Basin beneath the younger Kalahari stratigraphy in the eastern and western parts of the Kaapvaal Craton, the latter of which lies across the Kheis fold belt (Figure 1). The Witwatersrand Basin (ca. 2985 and 2849 Ma) is one of the world's premier gold regions and has produced about one third of the gold ever mined, worldwide (Manzi, Hunt and Durrheim 2019c). The basin is known to host substantial resources, many of which are currently located at great depths and have been speculated to extend throughout the Kaapvaal Craton beneath the cover rocks (> 1 km).

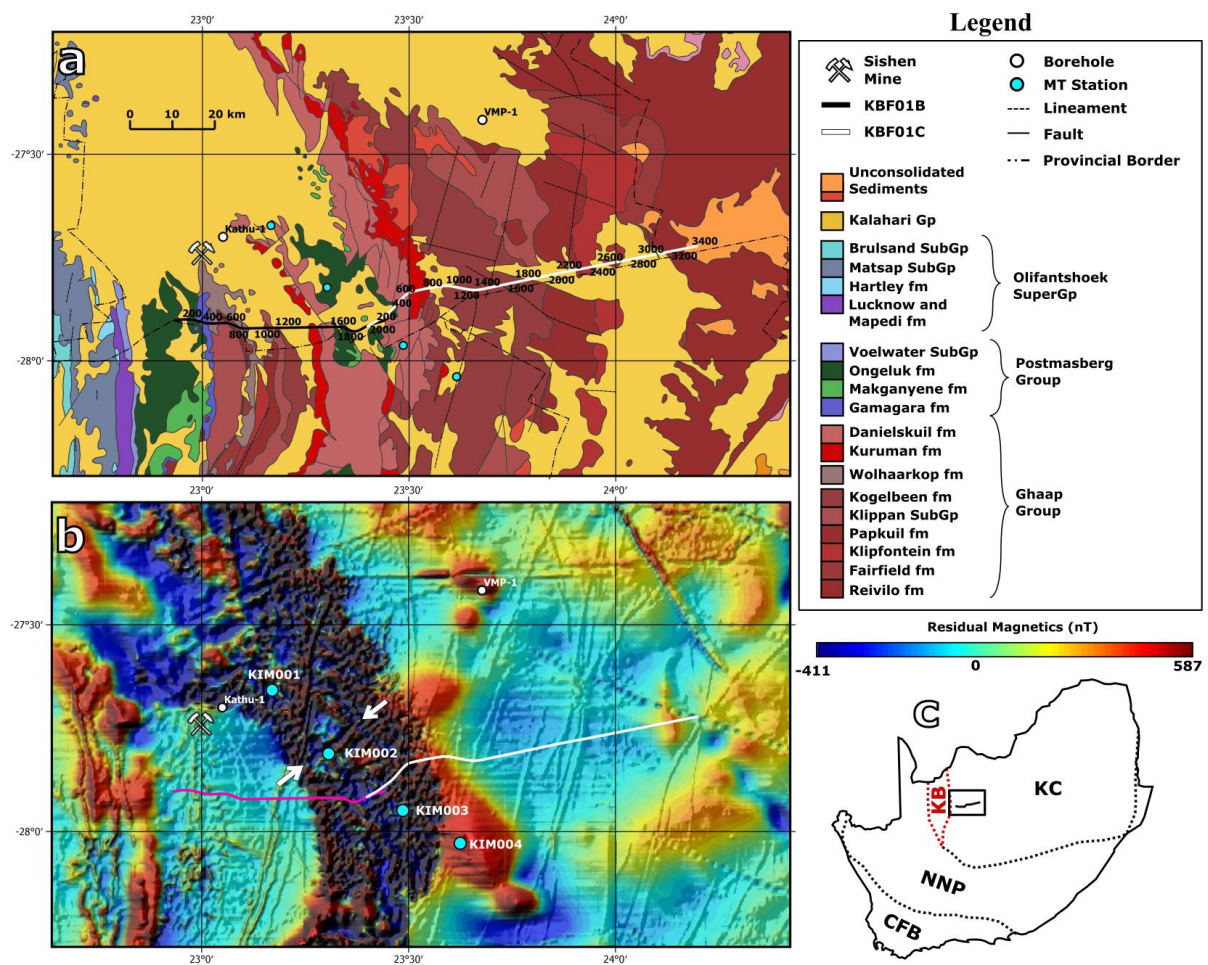


Figure 8.1: Geological map of the Kathu area (a) showing the seismic lines KBF01B and KBF01C as well as the Sishen mine, boreholes and MT stations. Also shown is the residual magnetic intensity map (b, where the white arrows indicates a possible thrust fault as seen in the magnetotelluric data) and basic tectonostratigraphic context (c).

Campbell Rand sediments in the geological map are coloured maroon to highlight the brighter red of the overlying Asbestos Hills iron-hosting sediments (with particular emphasis on the Kuruman formation). KC: Kaapvaal Craton. KB: Kheis Belt. NNP: Namaqua-Natal Province. CFB: Cape Fold Belt.

The seismic project of the Anglo American Corporation comprised a total of approximately 36 000 km of 2D reflection seismic data acquired on the eastern and western margins of the craton, as well as in the centre. The findings of the seismic profiles on the western margin, where our study area is located, showed no evidence of the Witwatersrand gold-bearing reefs to extend to such extremities (Tinker, de Wit and Grotzinger 2002; Pretorius 2003). These data have been donated to the Seismic Research Centre at the University of the Witwatersrand, which now hosts one of the world's largest hard rock seismic datasets that is providing further insight into the deep crustal structure of the Kaapvaal Craton and the mineralisation contained therein (Manzi, Malehmir and Durrheim 2019b). Supporting magnetotelluric data are also available, with four particular stations, KIM001 – KIM004, crosscutting the seismic line at the point of interest (Figure 1a, b). These data were collected as part of the South African Magnetotelluric Experiment (SAMTEX) with the aim of further investigating the crustal and terrane structure of southern Africa, with specific focus on the Kaapvaal, Rehoboth and Zimbabwe Cratons, as well as the Kheis fold belt and Namaqua-Natal mobile belt (Figure 1a) (Jones et al. 2009). The project comprised about 750 broadband, audio, and long period MT stations and the surveys were conducted during the 2000s in four phases. These MT data are especially useful in investigating iron-oxide mineralisation potential, as the iron typically has a substantial contrast in conductivity with the host rock, which in this case is mostly siliciclastic metasediments. This contrast is exploited by the MT method to highlight zones of high conductivity, aiding in constraining the target iron-oxide mineralisation. Two boreholes with geophysical logs are also located near the seismic profiles, one of which intersects the target iron-oxide mineralisation (Figure 1a). The geological map of the area confirms the iron-hosting sediments outcropping at two points along the two profiles (Figure 1a).

Sishen mine (Figure 1a) is one of the world's largest open pit iron mines and has been in operation since 1953 as part of Anglo American's Kumba project in South Africa. The mine is located near the town of Kathu in the Northern Cape Province of South Africa (Figure 1a, c) and most of the iron ore mined at Sishen is exported. In relation to the seismic lines, Sishen mine lies 10 km north of the western end of the KBF01B (western) seismic profile and just off the edge of the Kheis fold belt. The residual magnetic map (Figure 1b) shows the enhancement of the detected folding associated with the Kheis orogeny. The magnetic response observed in the map may be attributed to (1) the Banded Iron Formations (BIFs) of the Kuruman Formation (Figure 1a, b), or (2) the Hartley Formation lavas and the gabbroic sills that have intruded the quartzites and wackes of the Olifantshoek Supergroup (Stoch et al. 2017).

The region of interest for the investigation of iron-oxide mineralisation, which is conveniently located at the junction point of the MT and seismic lines, lies between the two outcrops along the seismic lines and is 30 to 50 km east of Sishen mine (Figure 1a).

The primary aim of this paper is to investigate this potential zone and to quantify the structure and extent of the lithological boundaries associated with the iron-oxide mineralisation. This involves estimating the geophysical properties (seismic velocity and resistivity) of the mineralisation as well as its geometric character within the subsurface.

8.3 Geology and Physical Properties

Geological setting and mineralisation

The geological setting of the western margin of the Kaapvaal Craton (ca. 3.60–3.20 Ga) is documented by many authors, including Van Schalkwyk and Beukes (1986), Beukes, Gutzmer and Mukhopadhy (2002), Basson et al. (2017) and Stoch et al. (2017). The location of the seismic lines is geologically diverse, with contributions from the Ventersdorp, Griqualand-West, Olifantshoek, and Karoo Supergroups, as well as the sediments of the Kalahari Group of South Africa. A simplified stratigraphic column is shown in Figure 2, along with ages of certain strata of interest. In summary, the granitic basin is unconformably overlain by the late Archaean Ventersdorp Supergroup lavas and sediments, which are made up of alkaline flood basalts and komatiites of the Klipriviersberg Group. These volcanics are in turn overlain by clastic sediments of the Platberg Group and the arenitic and basaltic Pniel Group. Deposited on top of the Ventersdorp lavas are the sediments of the Ghaap Group and the Postmasburg Group of the late Archaean to Paleoproterozoic Griqualand-West Supergroup (GWS), which is equivalent to the Transvaal Supergroup in eastern South Africa (Figure 1c, Beukes and Gutzmer 2008). The former is composed of predominantly iron-oxide-hosting sediments such as conglomerate and chert (Beukes 1986). The Campbell Rand Subgroup of the Ghaap Group is characteristic of dolomite and carbonates, which is unconformably overlain by a haematite-rich chert breccia of the Wolhaarkop Formation (Beukes and Gutzmer 2008; Beukes 1986). The overlying Asbesheuwels, “Asbestos Hills”, Subgroup features extensive iron ore horizons especially within the Kuruman Formation (Figure 2) (Stoch et al. 2017), which comprises Banded Iron Formations (BIFs), haematite and conglomeritic haematite, with occasional shale. The Postmasburg Group comprises diamictite and mafic lavas of the Makganyene and Ongeluk Formations, respectively, over which lies the middle to late Proterozoic Olifantshoek Supergroup (OS) (Figure 1 and Figure 2). This Supergroup consists primarily of sediments such as quartzite, shales, arenite and conglomerate, with amygdaloidal lavas present in the Hartley Formation (Figure 2). Lying unconformably on top of the OS are the late Phanerozoic sediments of the Karoo Supergroup that covers the majority of South Africa (Figure 1), consisting mainly of shale and

diamictite, over which unconformably lie the calcretes and sandstones of the Cenozoic Kalahari sediments.

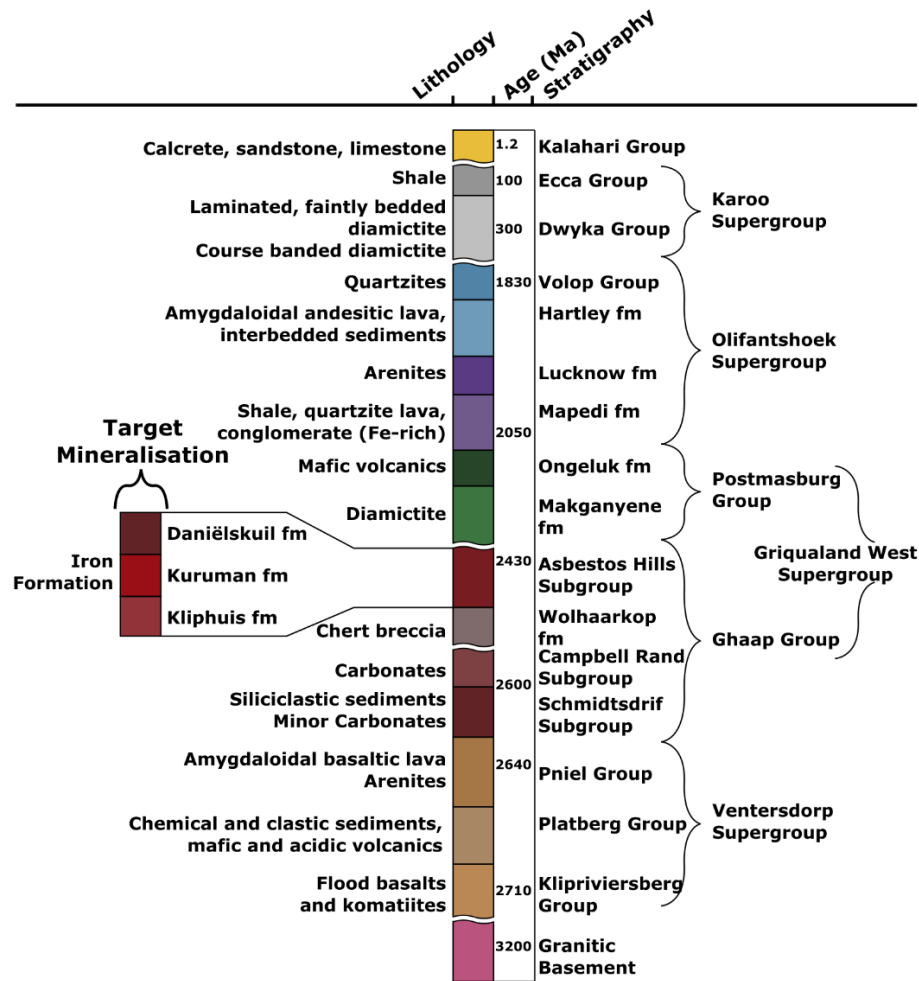


Figure 8.2: Basic lithostratigraphic column of the investigation area as well as ages of interest (after Basson et al. 2017; Stoch et al. 2017; Beukes 1986). Gaps in the column indicate unconformities. The target mineralisation, located in the formations within the Asbestos Hills Subgroup, are highlighted..

Within the region, mineralisation occurs predominantly within the GWS, producing one of South Africa's biggest magnetic anomalies as seen on the magnetic map in Figure 1b. The mineralisation is also clear in the lithostratigraphy of the GWS in the region (Figure 2) with dominant carbonate and iron mineralisation contained in the Kheis Orogeny, a fold belt that separates the Kaapvaal Craton and Namaqua Natal Belt near the border of South Africa and Botswana (Figure 1) (Moen, 1999; Vafeas et al. 2018). Of particular interest, and the target mineralisation for this investigation, is the haematite deposit hosted by the Kuruman Formation of the Asbestos Hills Subgroup in the Ghaap Group of the GWS, as well as low grade iron-oxide mineralisation in the Daniëlskuil and Kliphuis Formations (Figure 2). The Kuruman iron has a substantial history of mining in the area and remains active today with notable mines including the Beeshoek mine near Postmasburg, and the Khumani and Sishen mines

near the Kathu area (Figure 1a). The lattermost is an open pit mine and one of two mines that form part of Anglo American's iron operations in South Africa and has been in operation since 1953.

The iron deposit at Sishen mine (Figure 1a) is one of the largest globally and consists of high-grade and medium-grade haematite mineralisation ($\text{Fe} > 60\%$ and $\text{Fe} > 40\%$, respectively) that is hosted by chemical and clastic sediments within the Ghaap Group, with lower grade ($\text{Fe} < 40\%$) conglomeritic ore lying in the lower Gamagara Formation of the lower OS (Basson et al, 2017; Stoch et al. 2017). The 986 Mt reserve has multiple competing explanations for its genesis, including supergene (e.g. Wagener 1921; Beukes 1986), magmatically-driven (e.g. De Villiers 1944), hydrothermal (e.g. Du Preez 1944; Beukes, Gutzmer and Mukhopadhy 2002; Tsikos et al. 2003), and ancient lake deposition (Lake Superior-type deposition) (Beukes, Gutzmer and Mukhopadhy 2002; Stoch et al. 2017) being the prime candidates.

Physical properties

For the reflection seismic method to be effective, it requires significant acoustic impedance (the product of bulk density and P-wave velocity) contrasts between lithological boundaries. In order to test possible sources of seismic reflectivity in our study area, seismic velocity logs from boreholes VMP-1 and Kathu-1 (locations shown in Figure 1a) were obtained. Core samples for direct ultrasonic measurements were not available for this study. Synthetic seismograms were computed based on velocity logs of boreholes VMP-1 and Kathu-1, which reach depths of 2463 m and 3672 m, respectively, and are shown in Figure 3. Given the sparse velocity values, the velocity logs attain a block-like nature. No density log information was included in the logs and therefore the impedance logs were calculated based only on the seismic velocity information, which is in most cases a reasonable approximation (Yilmaz 2001, 165pp), however these were analysed and used for interpretation with caution. The temporal sampling rate used in the models was 4 ms to match that of the legacy seismic data and a Ricker wavelet with dominant frequency of 50 Hz was used in computing the seismograms with no attenuation effect applied.

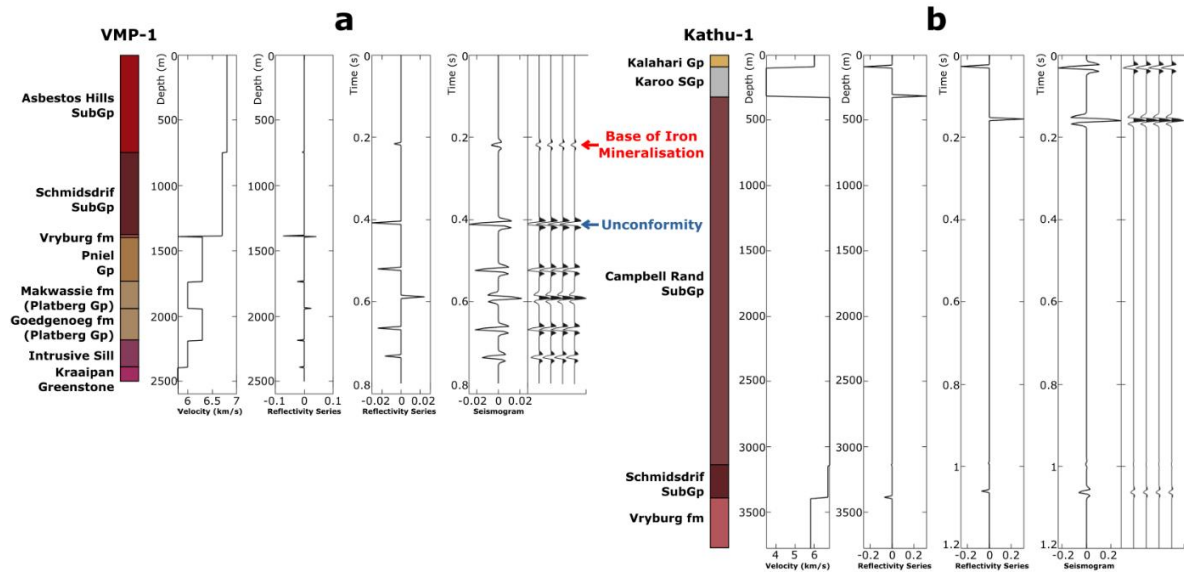


Figure 8.3: Velocities derived from sonic logs of boreholes VMP-1 and Kathu-1 (locations in Figure 1) as well as computed synthetic seismograms. Colours in the borehole logs correspond to those used in the stratigraphic column (Figure 2). Strong reflections observed in VMP-1 are associated with a major unconformity within the Vryburg Formation, as well as the interface between the Griqualand-West and Ventersdorp Supergroups. The base of the suspected mineralisation is intersected by VMP-1 and shows a low-amplitude reflection due to similarity in the impedance values of the ironstones and the host shale metasediments. A major reflection is observed in Kathu-1 between the Karoo sediments and the Campbell Rand Subgroup.

Borehole VMP-1 (Figure 3a) intersects the Asbestos Hills Subgroup of the Ghaap Group where the target Kuruman haematite is located, as well as the underlying siliciclastic Schmidtsdrif Subgroup. The calculated acoustic impedance contrast between the mineralization (primarily haematite) and sediments of the Schmidtsdrif Subgroup is sufficient to generate a reflection (as shown in Figure 3a), if the deposit is of sufficient size and not vertical, and if the data exhibit high SNR. The 5 m thick Vryburg Formation at the base of the Schmidtsdrif Subgroup is evidently below the detection limit of the 4 ms sampling rate. Lying beneath the GWS strata are the Allanridge lavas of the Pniel Group (Figure 2) followed by the Makwassie and Goedgenoeg clastics from the Platberg Group. These Ventersdorp units exhibit a strong acoustic impedance contrast with the overlying GWS sediments, where an unconformity exists, which can be used as a good lower limit indicator of the Ghaap Group sediments.

The only GWS strata present in the Kathu-1 borehole (Figure 3b) are from the Campbell Rand and Schmidtsdrif Subgroups, bypassing the target Asbestos Hills Subgroup. However, Kalahari Group and Karoo Supergroup sediments are present in the borehole, indicating a pinchout of the Asbestos Hills between the two boreholes. The acoustic impedance contrast between the Karoo Supergroup and GWS sediments in Kathu-1 (Figure 3b) is significant, producing a wavelet with amplitude tenfold the reflection strength of that between the GWS and Ventersdorp Supergroup units observed in VMP-1 (Figure 3a). The acoustic impedance contrast between the Schmidtsdrif Subgroup and the Vryburg

Formation (associated with the abovementioned unconformity that serves as lower limit indicator of mineralisation) is also significantly larger in Kathu-1 (Figure 3b) than in VMP-1 (Figure 3a).

8.4 Legacy Seismic and Magnetotelluric Data

Seismic data acquisition

We received the seismic data as raw shot gathers in SEG-Y format and the information about the acquisition parameters were obtained from both the field observers' reports that were provided to us by the company as well as the header information.

As previously mentioned, the 130 km 2D seismic line comprises two constituent parts, namely KBF01B and KBF01C, which have a 5 km long region of overlap in the middle of the survey area, as seen in Figure 1a, and each profile has a length of 85 km and 50 km, respectively. It is within this overlap region that the target iron mineralisation is located. The acquisition parameters are summarised in Table 1.

Acquisition Parameters	KBF01B	KBF01C
Survey Parameters		
Type of survey	2D crooked line	2D crooked line
Year	1994	1994
Profile Length	85 km	50 km
Trend	NEN-SWS	E-W
Spread	2975–25–X–25–2975 (m)	2975–25–X–25–2975 (m)
Nominal Fold	60	60
Average Fold	50	50
Recording System		
Recording Device	SN 338	SN 338
Sampling Rate	4 ms	4 ms
Recording Length	6 s	6 s
Sweep Length	16 s	16 s
Sweep Frequencies	15 – 75 Hz linear	15 – 75 Hz linear
Source Information		
Source Spacing	50 m	50 m
Source Type	4 Pelton MK II vibrators in a line	4 Pelton MK II vibrators in a line
Receiver Information		
Receiver Spacing	50 m	50 m
Geophone Type	10 Hz (SM4U)	10 Hz (SM4U)

Table 8.1: Acquisition parameters for lines KBF01B and KBF01C.

The two reflection seismic profiles were acquired in 1994 using Vibroseis trucks as energy sources. Both surveys were designed with a sweep length of 16 s and a frequency sweep of 15 – 75 Hz at a sampling rate of 4 ms for high-resolution imaging. The sweeps were recorded in-field and cross-correlated with the receiver traces for each shot location. The correlated traces were subsequently saved in SEG-D format before being converted to SEG-Y format. The two profiles exhibit a general W-E trend running from ~20 km south of Sishen mine in the west, over the Kuruman Hills where the mineralization

outcrops in the middle, to the border between the Northern Cape and North West Provinces in the east (Figure 1a). The terrain varies significantly along the length of the profile and so a crooked seismic line geometry following roads and valleys was chosen (Figure 1a).

Profiles KBF01B and KBF01C have a total of 1693 and 1062 shots, respectively, with 120 receivers per shot and 50 m shot and receiver spacing for both profiles. The resonance frequency of the receivers is 10 Hz (vertical single component) with a low-cut recording filter of 3 Hz. The resulting average CDP fold for this geometry is 50 with a bin size of 25 m along the profile.

Seismic data reprocessing

The processing sequence for each profile is given in Table 2. Before reprocessing commenced, however, the legacy data had to undergo some preparation, which comprised primarily of two tasks. The first was to edit the trace headers. This is because some headers, such as the source depth and source uphole time, had false values of -9999 that were subsequently zeroed. Some of the headers were not stored under the conventional titles and had to be extracted from their byte locations. The second task was to fix the geometry; while the source and receiver locations were correct and in agreement, their elevations were not in agreement and exhibited an offset. To correct for this, one set of elevations was elected as more reliable and honoured the actual topography in the area and the other set was removed and replaced with values that were interpolated from the first. The reliable elevations were determined using Shuttle Radar Topography Mission (SRTM) data, a profile of which was extracted along the seismic lines and compared with the two sets of elevations (source and receiver). The source elevations were determined to be the reliable set as they agreed with the SRTM data and the receiver elevations were offset from both the SRTM and source elevations. The receiver elevations were thus interpolated from the source elevations using nearest neighbour interpolation, which was deemed appropriate as the elevations were accurate only to the nearest meter and did not exhibit extensible variation from station to station.

Processing Step	KBF01B Parameters	KBF01C Parameters
1. Geometry + CDP binning	✓	✓
2. First break picking	✓	✓
3. Trace editing	✓	✓
4. Amplitude recovery	AGC window length: 250 ms	AGC window length: 250 ms
5. Floating datum statics correction	Fixed datum elevation: 1690 m Replacement velocity: 6000 m/s	Fixed datum elevation: 1690 m Replacement velocity: 6000 m/s
6. Refraction statics correction	RMS error < 4.5 ms	RMS error < 5 ms
7. Frequency filtering	Notch filter: 50 Hz Bandpass: 5-15-70-80 Hz	Notch filter: 50 Hz Bandpass: 5-10-65-70 Hz
8. F-K filtering	F-K mute below 3600 m/s	F-K mute below 3600 m/s
9. Predictive deconvolution	Average prediction gap: 37 ms (range of 20-60 ms) Average operator length: 100 ms (range of 80-130 ms)	Average prediction gap: 40 ms (range of 25-65 ms) Average operator length: 100 ms (range of 80-130 ms)
10. Velocity analysis	CVS	CVS

11. NMO correction	Stretch mute: 70%	Stretch mute: 70%
12. Residual statics	Repeat NMO corrections and residual statics (2 iterations)	Repeat NMO corrections and residual statics (2 iterations)
13. DMO	✓	✓
14. Stack	✓	✓
15. F-X deconvolution	✓	✓
16. Kirchhoff migration	Migration velocity: 4000 m/s Maximum allowed stretch: 50%	Migration velocity: 6000 m/s Maximum allowed stretch: 50%

Table 8.2: Processing parameters for lines KBF01B and KBF01C.

After the above preliminary corrections, which were applied to both lines, each line was processed separately but parameters such as the datum level and replacement velocity were kept consistent to preserve continuity of reflections across the profiles. Both profiles exhibited substantial contamination of 50 Hz noise most likely due to AC power lines in the region, which were filtered out using a notch filter.

After correcting and verifying the geometry, the traces were binned into common midpoint (CMP) bins. This was done by fitting a spline curve through the cloud of CMP points containing the highest number of traces and placing bins along this line every 25 m. The resulting bin lines are those shown as the seismic lines in Figure 1a and b.

Figure 4 shows shot gathers from each line before (e.g. Figure 4a) and after (e.g. Figure 4b) prestack processing, which are located at suspected mineralisation zones. The overall data quality is good with clear first breaks easily observed in the raw shot gathers (as indicated by orange arrows in Figure 4a, c), as well as clear reflections on both raw and processed shot gathers (examples of which are highlighted by red and blue arrows in Figure 4a-d). Spectral analysis of raw gathers indicates that field data contain the expected frequency range 15-75 Hz.

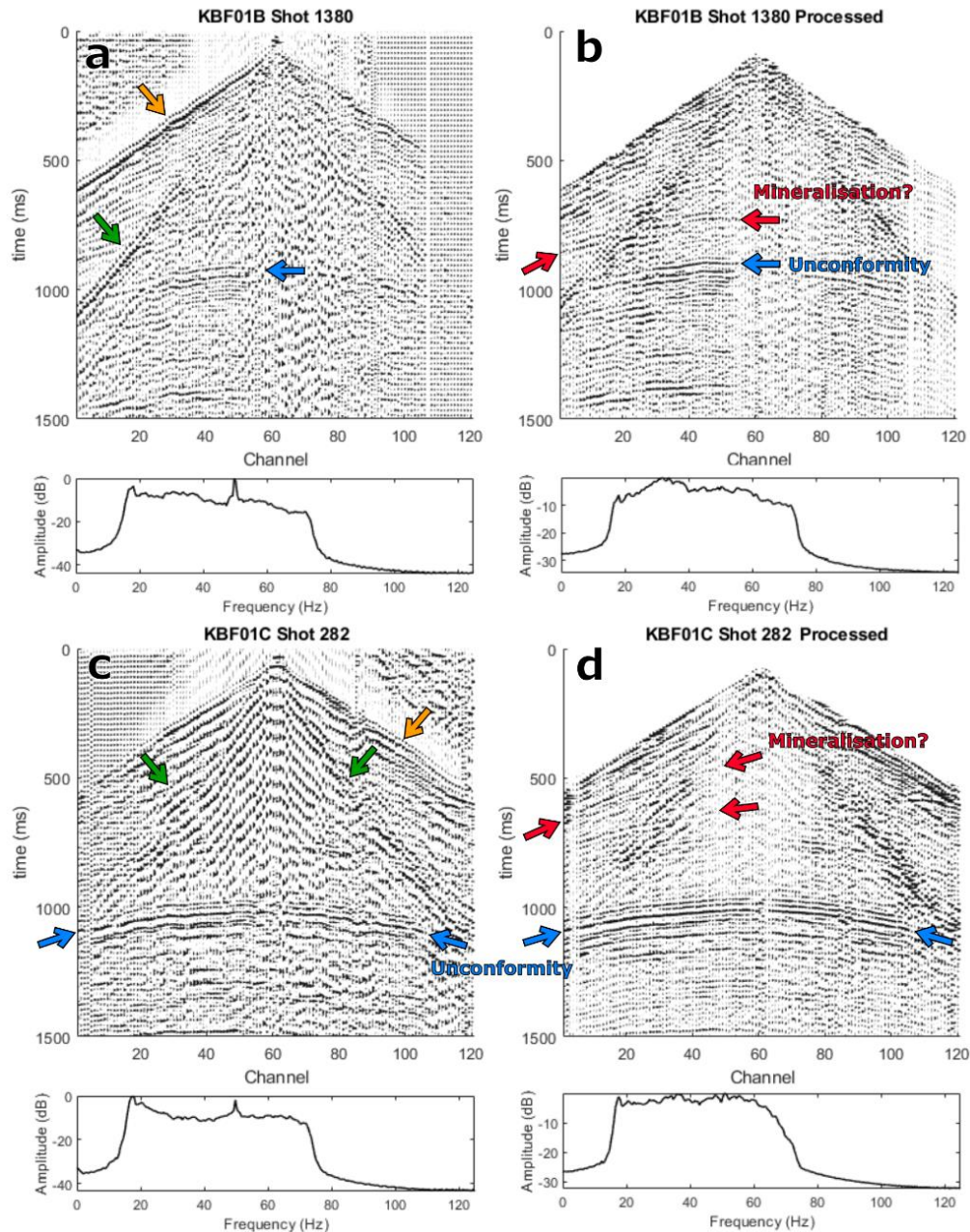


Figure 8.4: Shot gathers from line KBF01B before and after prestack processing (a,b) as well as from line KBF01C (c,d) along with the respective amplitude spectra of each gather. Orange arrows indicate first arrivals, green arrows indicate ground roll, blue arrows indicate the base of the Campbell Rand Subgroup reflection, where a major unconformity is located, and red arrows indicate possible reflections from the target iron mineralisation from the Kuruman Formation.

The traces were reduced to a floating datum. The maximum elevation along both lines is 1690 m, therefore a matching datum elevation was chosen along with a replacement velocity of 6000 m/s for the floating datum statics, as was determined by analysis of far offset first arrivals. First arrivals were then picked in the shot domain to correct for the effect of low-velocity wave propagation in the overburden (refraction static corrections). A total of 128 681 and 61 274 first breaks were picked for lines KBF01B and KBF01C, respectively, using a preliminary first order automatic method followed by precise

manual picking. Refraction statics were then computed using a least-squares inversion algorithm (e.g. Ellis and Oldenburg 1994) for the first arrivals, inverting for the weathered layer velocity and thickness along the profile. The resulting RMS error was less than 4.5 ms for KBF01B and less than 5 ms for KBF01C and the weathered layer exhibited velocities ranging from 3000 to 6500 m/s. Refraction tomograms for both profiles, which accounted for elevation and were calculated to aid in interpretation of the line, up to depths of 700 m (maximum shot gather offset was ~3000 m) are displayed in Figure 5, with both the velocities and ray paths (Figure 5a,b) being displayed (Figure 5c,d), as well as interpreted sections (Figure 5e,f). Gaps in the tomography are a result of few or no picks in the region, which in turn is likely due to a highly variable weathered layer or bad coupling of the geophones. This is a reasonable explanation due to the mountainous terrain or possible intrusions that can be seen in the magnetic map in Figure 1b. Velocity values obtained from the tomography for the Kuruman Formation range between 5000 and 6000 m/s, which is in agreement with the sonic logs (Figure 3).

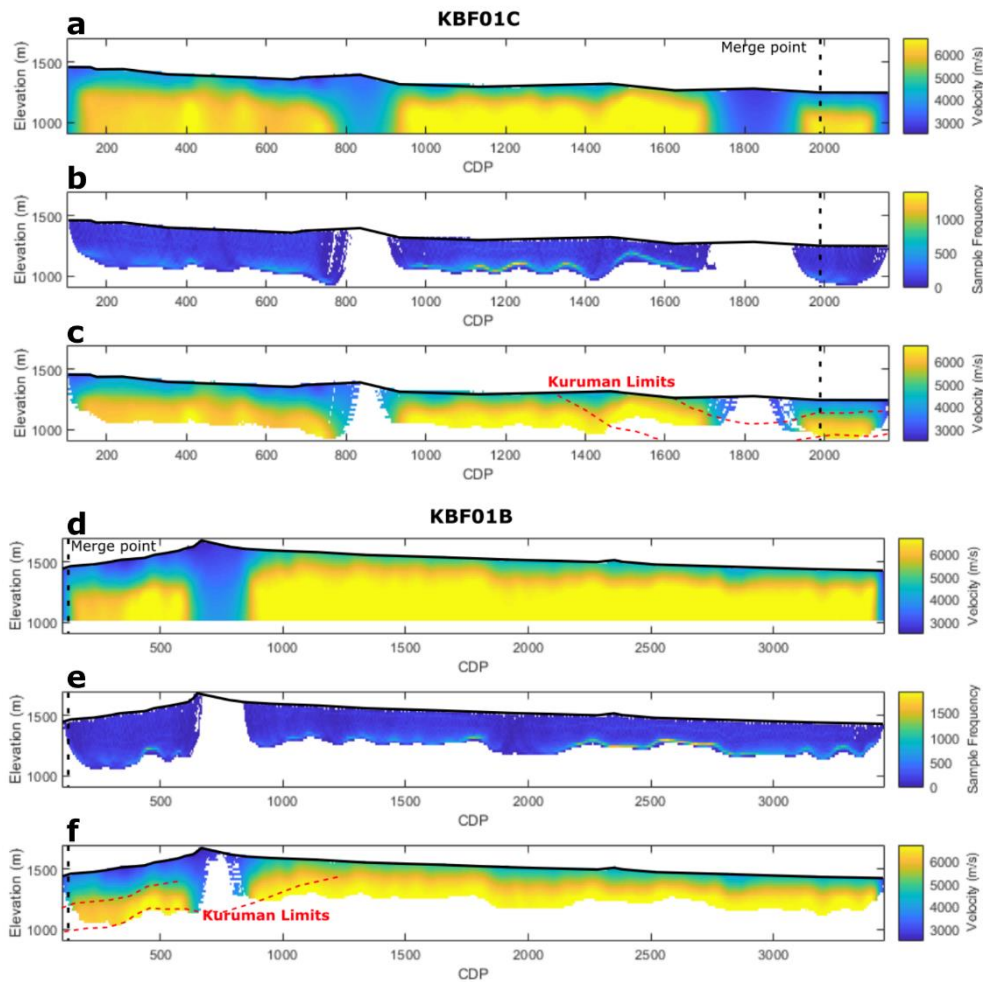


Figure 8.5: Tomographic velocity model calculated for KBF01C (a), as well as the associated raypaths (b) and basic interpreted section with focus on the Kuruman Formation (c), where velocities that have not been sampled by any raypaths have been removed. The same are shown for KBF01B (d-f).

The effect of the static corrections can be seen clearly in Figure 4 within the coherency of the ~1 s TWT reflection package, which is associated with the unconformity at the base of the Campbell Rand Subgroup (Tinker, de Wit and Grotzinger 2002), as indicated by the blue arrows in Figure 4a-d. Bad traces were then muted and any polarity reversals were corrected. To recover attenuated amplitudes, an AGC with window length 250 ms was applied to the gathers.

The prestack processing was intended to enhance the imaging of the iron-oxide mineralization that is known to be located at depths between 200 ms and 700 ms TWT (Tinker, de Wit and Grotzinger 2002). The reflections associated with the iron-oxide deposit are significantly enhanced in both shot gathers in Figure 4, as indicated by the red arrows in Figure 4b,d. Note the 50 Hz contamination in both shot gathers, between channels 90 and 120 in Shot 1380 (Figure 4a) and between channels 1 and 20 in Shot 282 (Figure 4c), the latter of which concealed the target reflection (red arrows, Figure 4d) significantly. This noise is also evident in the amplitude spectra and was remedied with a 50 Hz Notch filter. Due to its shallow location, the reflection associated with the mineralisation was substantially affected by the ground roll, evident in both gathers but especially so in gather 282 (as indicated by the green arrows in Figure 4c). This was mostly remedied by the f-k mute as well as the bandpass filter. The f-k mute was designed to mute any linear features with velocities equal to or less than the s-wave velocity, which was 3500 m/s on average. The overall result of the prestack processing is a clearer rendition of the mineralisation reflection where present, shown by the red arrows in Figure 4b,d. Note additionally the enhancement of the deeper reflections, especially the strong reflection associated with a major unconformity at the base of the Campbell Rand Subgroup located near 1 s TWT (blue arrows). The prestack processing was concluded with a shot-dependent predictive deconvolution (e.g. Yilmaz 2001, 185-203pp) where the prediction gap and operator length were determined empirically every hundredth shot and interpolated for intermediate shots.

Velocity analysis was then performed using constant velocity stacks. Prior to dip-moveout (DMO) corrections, residual static corrections (re-picking for two iterations) were applied to increase reflection coherency. The final DMO velocity model had a range of 3000–6500 m/s for both KBF01B and KBF01C, which correlates with the sonic logs as shown in Figure 3. An offset-time Kirchhoff dip-moveout (DMO) was then applied to the data, followed by stacking of the data along the CDP line with a 60% stretch mute. An f-x deconvolution (coherency filter) was applied to the stacked section to increase signal-to-noise ratio of the data. Figure 6 shows a portion of the stack before (Figure 6a) and after (Figure 6b) f-x deconvolution, where reflections are enhanced and more coherent, particularly those associated with possible mineralisation zones (shown by red arrows in Figure 6b). The unconformity located at the base of the Campbell Rand deposits (also see Figure 3b for its expected reflected strength) is also better delineated, as shown by the blue arrow, and the overall effect is that there is less noise in the overall section.

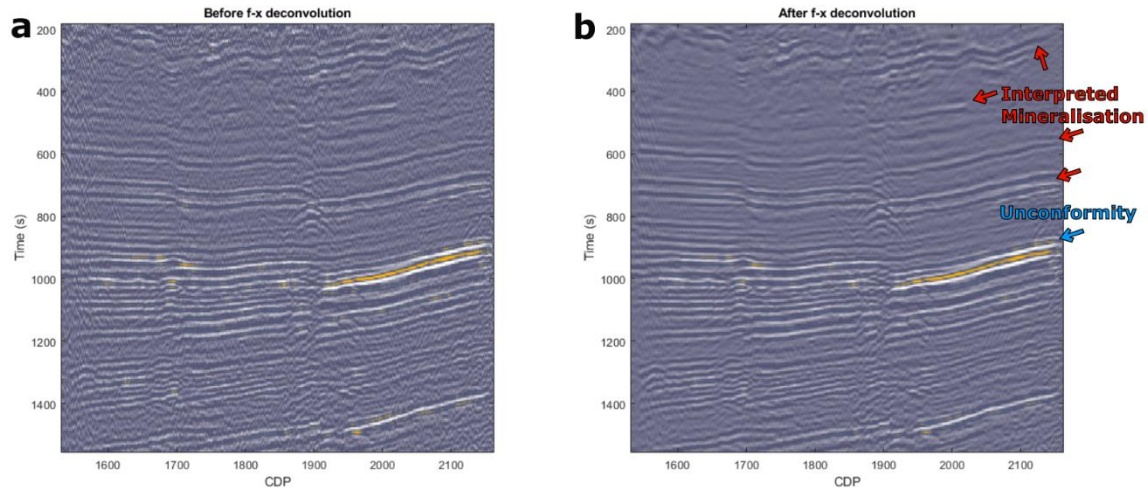


Figure 8.6: Portion of KBF01C stack before (a) and after (b) applying f-x deconvolution. The unconformity (blue arrow) marks the lower limit of the mineralisation horizons (red arrows), which have been enhanced and better imaged due to the f-x deconvolution. Ambient noise is also significantly reduced, as seen throughout the section.

Finally, the seismic data were migrated using Kirchhoff Migration as this produced the best images of the data when compared to finite difference and phase shift migration methods. The migration parameters of the lines were determined empirically and differed between the two lines due to the presence of steeper dips in line KBF01C than in line KBF01B. The confidence in the migration parameters is evident in the example given in Figure 7; two fault zones crosscutting the shallow iron-oxide deposit (indicated by red arrows), as well as the underlying strata are greatly delineated after migration (Figure 7b) and can be tracked much easier throughout the sections, as shown by the blue and orange arrows. The bifurcation of the fault near CDP 1700 (blue arrows) just above 1 s TWT is much more evident in the migrated section than in the stacked section, where the eastern limb is not very clear. Additionally, the fault near CDP 1900 (orange arrows) is easier to track after the diffraction hyperbolae in the stack section have been collapsed.

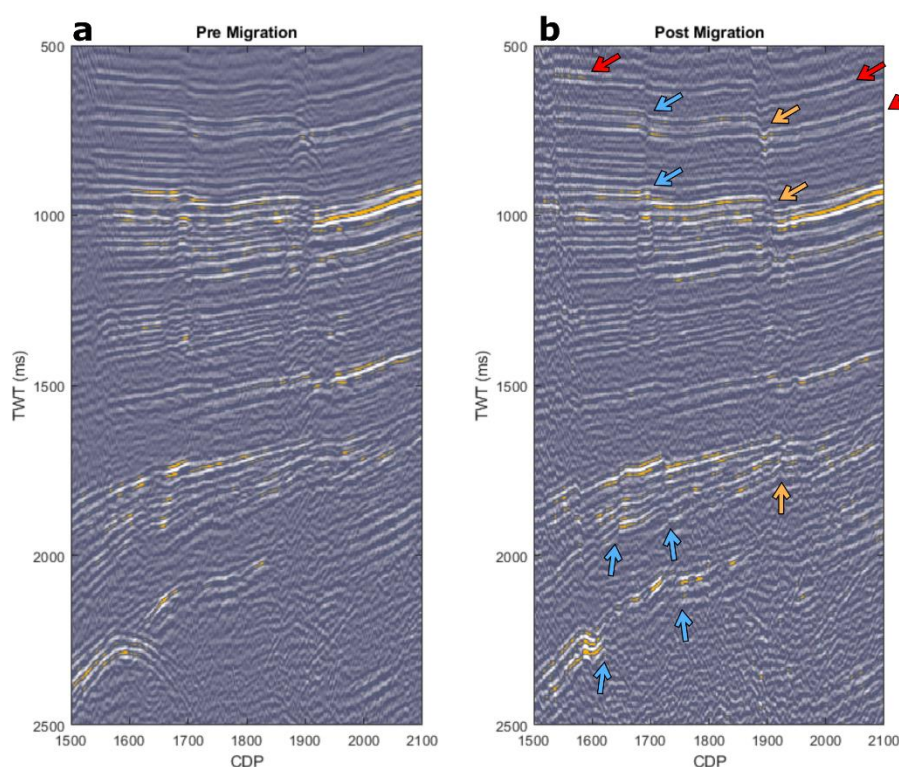


Figure 8.7: Comparison of processed section before (a) and after (b) migration. Arrows delineate faults that are clearer after migration. Blue arrows indicate fault that bifurcates near 1 s TWT and orange arrows indicate normal faulting. Red arrows indicate reflections associated with target iron mineralisation, located above the major reflection associated with an unconformity at 1 s TWT.

Magnetotelluric Data

As mentioned earlier, and shown in Figure 1a,b, magnetotelluric (MT) stations exist near the target area. These data were made available to the public by the SAMTEX Consortium (Jones et al. 2009) as both raw time series and impedance tensor estimates. For this paper, four of these stations are used to characterise the electromagnetic properties and geometry of the Asbestos Hills BIFs in the subsurface close to Sishen mine (Figure 1a). The raw time series from these data were obtained and processed as per the sequence described in Table 3. Both the raw and processed apparent resistivity and phase time series for two of the four stations are illustrated in Figure 8 with both TM and TE modes being displayed for each. The processed time series seen in Figure 8b,d,f,h are examples of those used for the inversion algorithm as described in Table 3.

Step	Processing Details
1.	Rotated the MT impedance tensor 160° to geological strike
2.	Assigned transverse magnetic (TM) and transverse electric modes (TE) TM mode trends perpendicular to geological strike TE mode trends parallel to geological strike
3.	Masked data in the MT 1 kHz dead band
4.	Masked low energy, high-frequency (> 100 Hz) data
5.	Fitted smooth D+ curves to data
6.	

Calculated 2-D conjugant gradient resistivity inverse model using code developed by Rodi and Mackie (2001). The following parameters were used in the inversion:

Starting Model	1 000 Ωm half-space
Frequency Range	0.001 – 10 000 Hz
Objective Function	Solves for smoothest variation away from starting model
Laplacian Operator	Minimises Laplacian integral
Tau Operator	3
Weighting function	Prevents model from becoming blocky
Resulting RMS	1.0

Table 8.3: Processing parameters for KIM001 – KIM004 SAMTEX magnetotelluric stations.

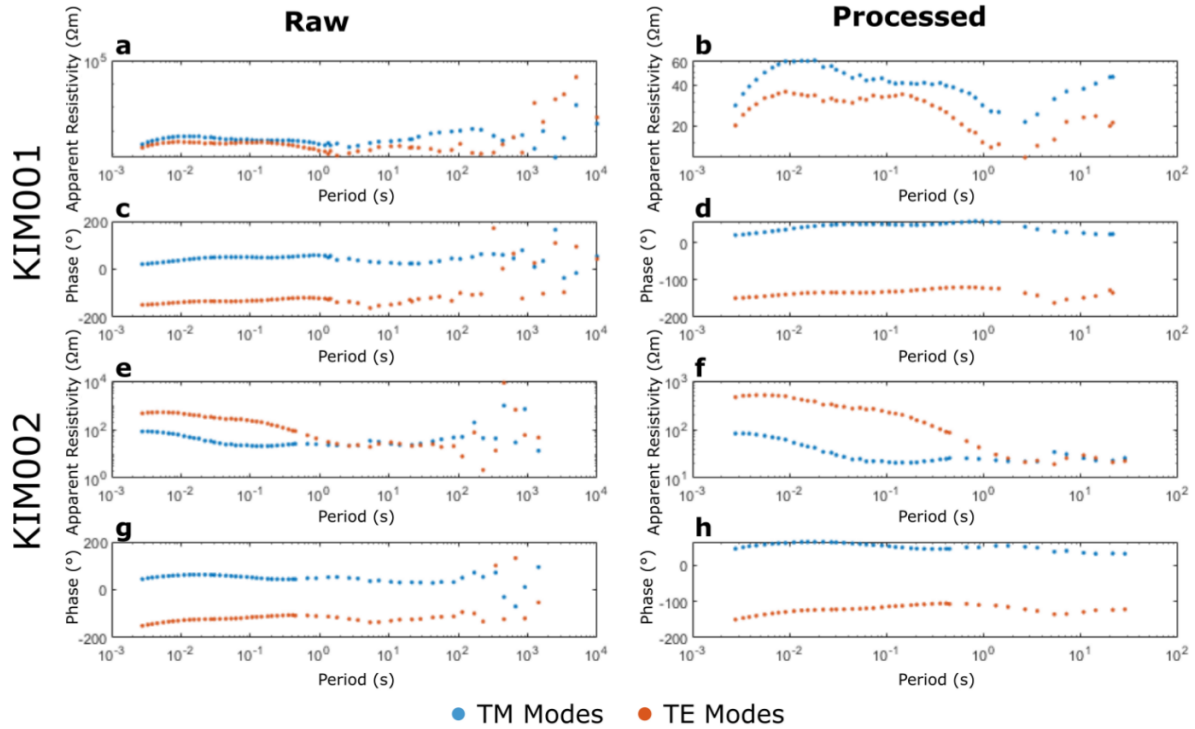


Figure 8.8: Resistivity and phase curves for MT stations KIM001 (a – d) and KIM002 (e – h) before and after processing. Both TE and TM modes are shown for each curve. The processing sequence is detailed in Table 3. The processed curves were used in the MT inversion`.

The MT data were rotated such that the X and Y directions were perpendicular and parallel to the geological strike, respectively. We then assigned transverse magnetic (TM) and transverse electric (TE) modes to the phase and resistivity curves. The TM mode is perpendicular to lithological strike direction and the TE mode is parallel to the general strike direction. We masked data points in the 1 kHz dead band as well as >31 kHz where signal strength was low. We also removed noisy spikes and fit smooth (D+) curves to the remaining data points, which relate apparent resistivity and phase time series by finding a one-dimensional earth model that best fits both parameters (Beamish and Travassos 1992).

From the edited and processed data, we calculated 1D and 2D resistivity inverse models using the conjugant gradient code developed by Rodi and Mackie (2001). The inversion parameters are detailed in Table 3. The objective function was set to find the smoothest model with a standard Laplacian

operator focusing on minimizing the integral of the gradients of the model with a Tau value of 3. This inversion methodology allows for a smooth model to be calculated from a 1000 Ωm half-space, after which the resulting smooth model is used as a starting model for a second inverse calculation that is focused on fitting the observed data.

8.5 Results

Seismic Data

A comparison between the legacy and reprocessed stack (KBF01C) is shown in Figures 9a and b, respectively. A few notable differences are evident. The ambient noise seen throughout the 1994 legacy stack is significantly reduced in the reprocessed 2019 stack section, yielding a greater signal-to-noise ratio. As such, some reflections are imaged with greater clarity, as indicated by the green arrows and the continuity of certain reflections has also been improved, as seen by the cyan arrows in Figure 9b. The reflections associated with mineralisation, indicated by red arrows, are significantly enhanced and can be more easily tracked throughout the section. Figure 9 showcases the utility of reprocessing legacy data, asserting that legacy data in general may still hold intrinsic value that may not have been entirely exploited when originally processed.

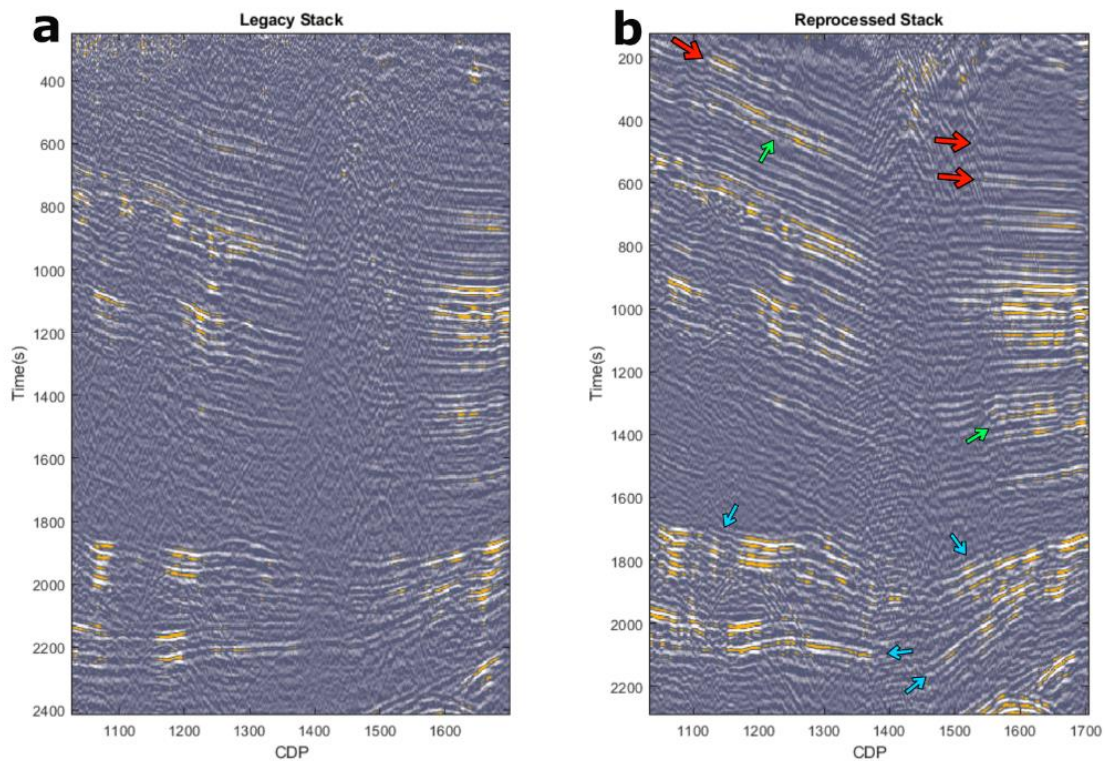


Figure 8.9: Comparison of legacy stack (1994) and reprocessed stack (2019) within a region of profile KBF01C. Green arrows indicate enhanced reflectors and cyan arrows indicate reflectors with improved continuity. Red arrows indicate reflections associated with the target mineralisation. A significant improvement in the SNR is seen in the reprocessed stack.

The two processed and migrated sections are displayed in Figure 10 up to 3 s TWT, along with outcrop data and CDP fold. Red arrows in the figure delineate potential iron-oxide mineralisation zones. Line KBF01C (Figure 10a) and KBF01B (Figure 10b) are characterised by a synclinal structure in the eastern majority of the former and western majority of the latter, contained within the black box in Figure 10a and b. This feature is most evident in the Griqualand West Supergroup strata lying above 1500 ms, and supported by the symmetric nature of the outcrops across both lines, centred on the overlap of the two lines. The strata in line KBF01B (Figure 10b) exhibit a gentle dipping nature, with high-amplitude attenuation near CDPs 700 and 2000 (shown by orange arrows), which may be attributed to the emplacement of intrusion zones comprising a series of dykes that dissect the strata. It is important to note that, as per Figure 1, line KBF01C is significantly shorter than line KBF01B and hence Figure 10a has a greater vertical exaggeration than Figure 10b. The dips (6° – 10° to the east), therefore, in Figure 10a are generally steeper for all imaged stratigraphic boundaries from the base of the Kalahari Group down through to the Ventersdorp Supergroup than those in Figure 10b, which exhibit shallow dips (3° – 7° to the west). If this is not considered, misinterpretation of the overall subsurface geometry is likely. In the eastern lower part of the KBF01B (Figure 10b) seismic section, numerous diffraction signals are observed, as shown by white arrows, and we interpret these to originate from massive isolated bodies, possibly mafic intrusions within the basement rocks.

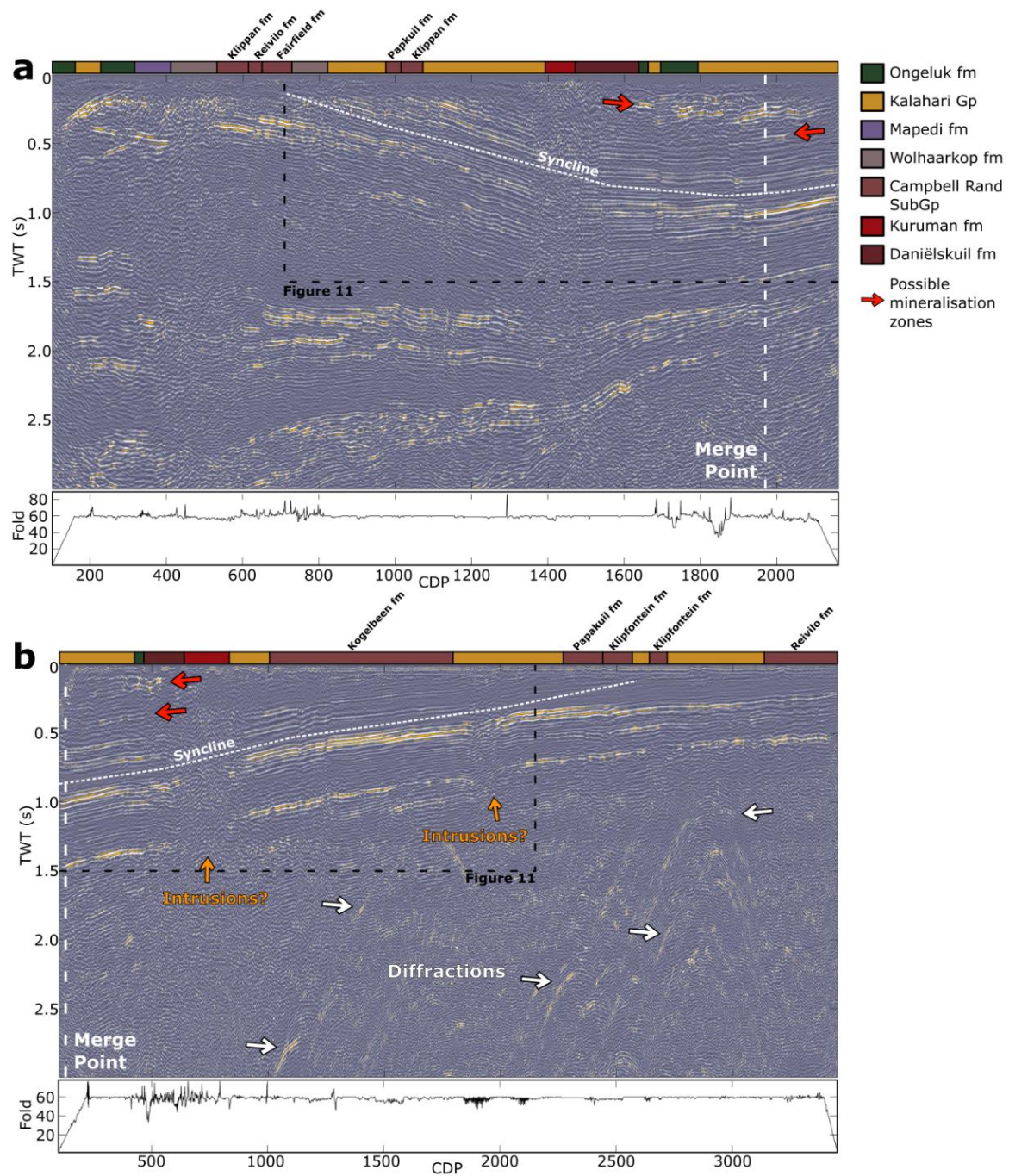


Figure 8.10: Final migrated sections for lines KBF01C (a) and KBF01B (b). Outcrops are plotted above sections and CDP folds beneath sections. Red arrows indicate zones of mineralisation, orange arrows indicate possible intrusion zones and white arrows indicate diffraction signals seen at depth. The black box outlines the focus area, which is examined in detail in Figure 11. The “Merge Point” line indicates where the two seismic lines are stitched together for Figure 11. The general syncline trend is also overlaid on the sections.

Figure 11a shows a zoomed portion of the lines after they have been mutually scaled and stitched together at the merge line (indicated by the white line in Figure 10 and the blue line in Figure 11a), as was determined by the line geometry (Figure 1). An interpretation, which is constrained by the outcrop data, is overlaid showing strong reflections at major lithological boundaries as well as major faults. The

base of the Kuruman Formation is associated with a moderate to weak reflection as expected from the synthetic seismogram in Figure 3, with reflections occurring between 500 m and 1250 m, likely due to the interlayering of the iron-oxide mineralisation with host metasediments. When examining the magnetic map (Figure 1b and Figure 11a), the Kheis anomaly is delimited by points B and C along the seismic profile (Figure 11a), which correlate well with the Kuruman outcrops. The section was converted to depth using a constant seismic velocity of 5000 m/s. A simplified geological model of the area of interest is shown in Figure 11b.

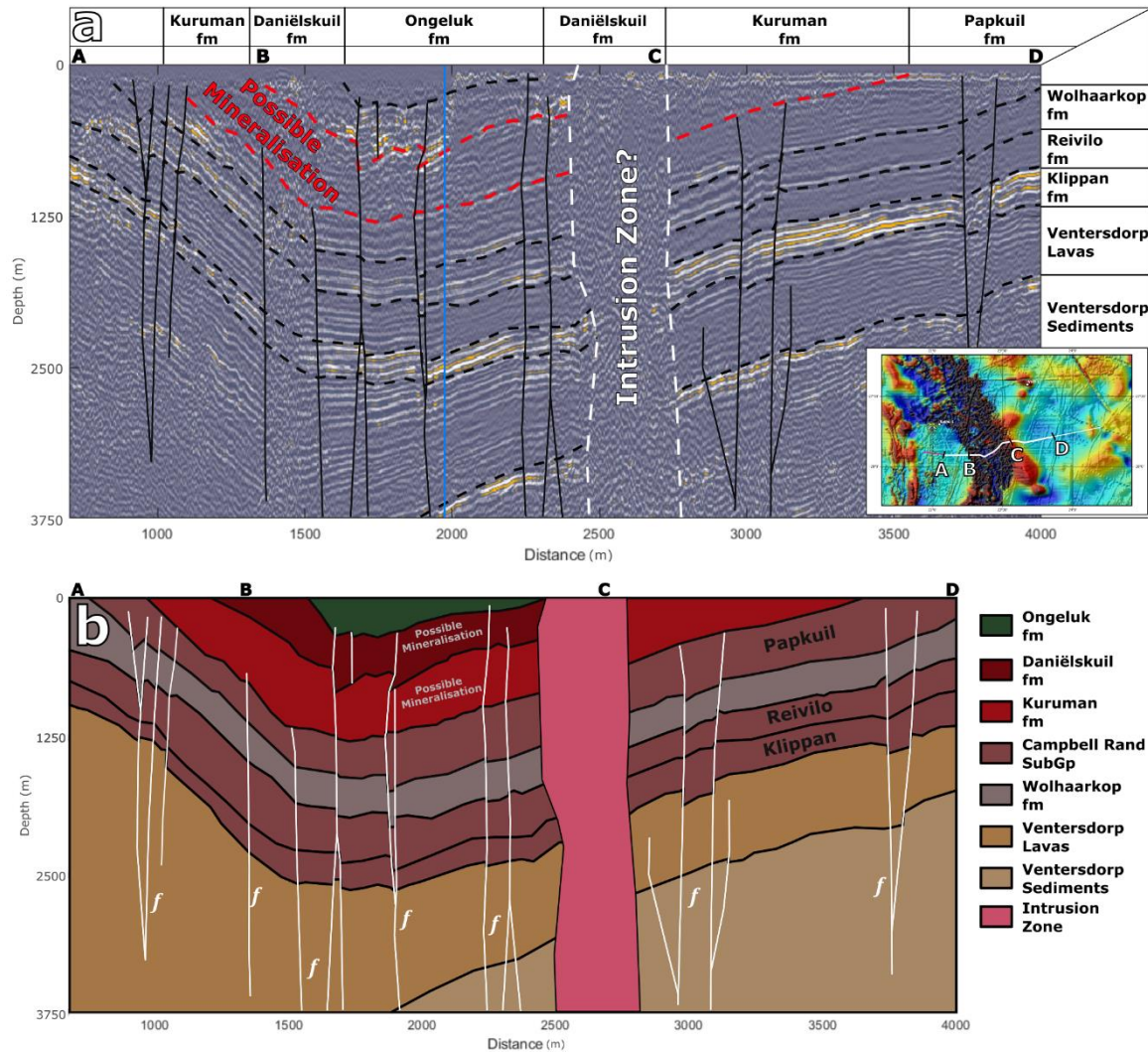


Figure 8.11: Zoomed portion of line (a) after merging the two lines, where the merging line is plotted in blue. The zoom boundaries and merging point are shown in Figure 10. A basic geological interpretation of the section is also given (b), which is based directly off of the seismic data. Also shown in (a) is the residual magnetic field of the area, identical to that in Figure 1b, with points of interest A-D labelled as well as on the seismic section and interpretation. The iron mineralisation is found primarily in the Kuruman Formation but also in the Daniëlskuil Formation, which are both intersected by faults and a possible intrusion zone.

Magnetotelluric Data

The magnetotelluric (MT) inversion results are shown in Figure 12, along with a basic interpretation. There are two evident and highly resistive ($\rho > 10 \text{ k}\Omega\text{m}$) bodies between stations KIM001 and KIM002 and between KIM002 and KIM004 that are diagonally offset, suggesting a major thrust fault zone, characterised by a poorly resistive lineament. Underlying these bodies is a generally conductive environment with values ranging from 10 to 5000 Ωm , most likely due to the carbonate and iron mineralisations within the Ghaap Group sediments.

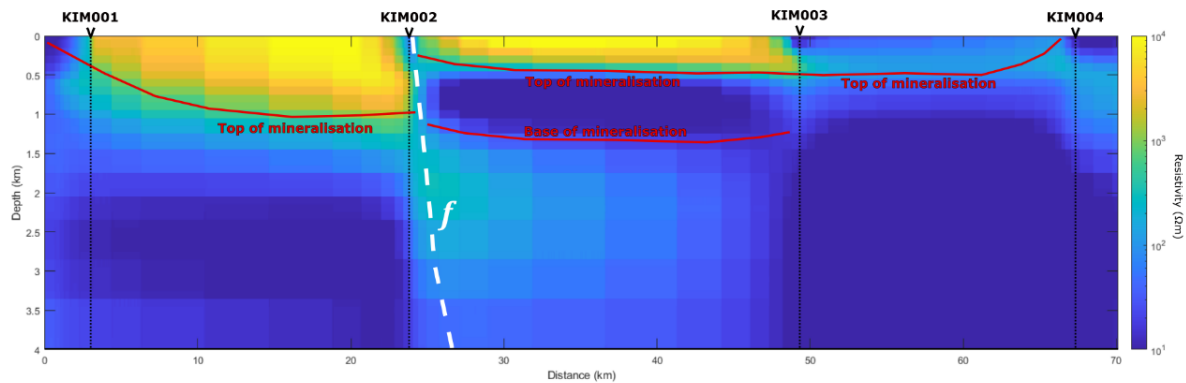


Figure 8.12: Interpreted resistivity model from magnetotelluric inversion using stations KIM001 through KIM004 (Figures 1). The top of the iron mineralisation is interpreted to be located at major high-to-low resistivity boundaries, the bottom of the iron mineralisation is difficult to interpret between station pairs KIM001-KIM002 and KIM003-KIM004 as there are no obvious contrasts at depth, possibly being masked by the shallow conductive deposits.

As per Figure 1a, the seismic line runs obliquely between stations KIM002 and KIM003. Conversely, the MT stations run parallel to, and in between, the Kuruman outcrops and intersect the seismic line at the overlap region of the two merged lines, proving fortuitous as this is where the iron-oxide mineralisation occurs (Figure 11a). In this region, there is an alternating high to low to high resistivity trend with depth, with the first inversion occurring near 500 m and the second at around 1 km, which correlates fairly well with the boundaries of mineralisation in the seismic line at the intersection point (Figure 11). Hence the proposed model consists of the haematite mineralisation occurring between ~ 500 m and ~ 1 km depth with a resistivity of 0 – 10 Ωm , which is overlain by Kalahari Group sands with resistivity $> 10 \text{ k}\Omega\text{m}$, and overlies slightly less conductive material (50 – 100 Ωm) attributed to the Campbell Rand Subgroup. Within the flanking regions outside stations KIM002 and KIM003, the lower bounds of the mineralisation become difficult to determine as no clear contrast is seen.

8.6 Interpretation and Discussion

Resolution and quality of the data

Seismic imaging of subsurface bodies relies both on impedance contrasts of the target bodies and their hosts, as well as the geometry of these bodies and whether their thicknesses are above the tuning thickness. The dominant frequency of the data is 40 Hz, yielding a wavelength of ~ 125 m (assuming a 5000 m/s velocity medium). The thickness of the banded iron formations in the vicinity of Sishen mine is documented to be > 50 m (Basson et al. 2017; Stoch et al. 2017), which is significantly larger than the tuning thickness (i.e. ~ 30 m, a quarter of the dominant wavelength; Widess 1973) of our seismic data. This indicates that we can resolve the top and bottom of these units with these seismic data. In terms of lateral resolution, with the mineralisation located at an average depth of 700 m, the Fresnel-zone width is roughly 280 m, however after 2D migration, this zone is shortened along the length of the line to about 125 m, the dominant wavelength (e.g. Yilmaz 2001, 1803-1807pp), which is equivalent to 5 CDP traces in the migrated section (Figures 10 and 11). Furthermore, weak reflections introduce ambiguity in interpretation, especially where the target mineralisation is situated (as seen in the synthetic seismogram of VMP-1 in Figure 3), which is made worse by the rugged terrain over which the reflection data were acquired; lack of coherent first breaks in areas of loose overburden impact the quality of subsurface imaging within those areas. The near-surface velocities estimated from the statics models generally correlate with the known geology as confirmed by the sonic logs (see Figure 3). Additionally, the shallow (< 1 km) occurrence of the mineralisation results in the target reflections being hampered by ground roll noise, forcing careful consideration during reprocessing (see Figure 4). In general, the geology of the subsurface structure in our study area is relatively complex and the data exhibit extensive faulting and folding that deformed the strata, including the iron-oxide hosting sediments.

Reprocessing the two lines KBF01B and KBF01C separately and merging them thereafter proved successful as the merged dataset appears fairly seamless and the reflections occurring across the merge point appear continuous. Furthermore, merging the two lines required rescaling so that the horizontal scale of each line was the same. This improves interpretation as subsurface geometry spanning both lines is well preserved. Confidence in the interpretation is further increased due to constraints from the borehole data close to the profile and outcrop data along the profile.

Benefits of Legacy Data Reappraisal

When compared to the legacy data, as shown in Figure 9, the reprocessed data provide a clearer image of the target horizons as well as the underlying strata, providing a strong indication that legacy data may contain untapped potential that can be fully realised by reprocessing the data, a topic that is rapidly growing in the seismic literature (e.g. Górszczyk, Cyz and Malinowski 2015; Malajczuk et al. 2016; Ketelhodt, Manzi and Durrheim 2019; Malehmir et al. 2019; Manzi, Malehmir and Durrheim 2019b).

By carefully reprocessing legacy data, modern and more sophisticated algorithms improve upon the potential of the data and yield results that may enhance features not evident in the original data. For example, as seen in Figure 9b, the reflections associated with the target mineralisation are more continuous and exhibit a greater amplitude. While the processing steps detailed in Table 2 are not novel and were available in 1994, we argue that the developments and computational refinements of the algorithms used in combination with experience of processing hard rock data resulted in the improved imaging shown in Figure 9b. In particular, the seismic community of the 1990s was experienced with soft rock seismics and the relatively simple velocity fields associated with the flat layering thereof. However, complex velocity fields that typically accompany hard rock settings were not so familiar (Pretorius et al. 2003).

Reprocessing the data further provides cost benefits as it bypasses the need for acquiring new data. Reacquisition of a 130 km long profile with the parameters akin to KBF01 (Table 1), comprising four vibrators and 50 m shot and receiver spacing can typically cost an estimate of 10 million ZAR (~ 500 000 EUR), which is without consideration of logistics and legal permission. This estimate is also made with the assumption that a modern survey conform to the acquisition parameters of the original survey. Further, typical modern specifications for seismic profiles would involve a broader sweep (such as 5-120 Hz) coupled with a denser source and receiver spacings (such as between 5 and 20 m). An estimated cost for such a survey is roughly 20 million ZAR (~ 1 million EUR), doubling the previous cost estimate. These costs are nullified if legacy data are reprocessed instead.

In addition to cost-effectiveness, this approach also bypasses noise contamination from sources that were not present during acquisition and are now, such as increased traffic, activity on new roads and increased nearby mining activity. By reprocessing and interpreting KBF01, we show that new geological information can be extracted from the legacy data, and thus assist with resource evaluation. There are natural shortcomings of this approach, however. The quality of the data is restricted to an extent by the quality of the original acquisition. The scope of investigation is also entirely dependent on the geometry and scope of the originally acquired data. Hence, in general, the cost benefit of legacy data reappraisal must be carefully weighed against such shortcomings thereof.

Seismic Interpretation

Interpretation of the Kuruman Formation of the Griqualand West Supergroup, where the iron-oxide mineralisation is hosted, was thus of particular interest in this study, since the formation hosts iron ore horizons. The merged data have also been used to confirm the known seismic stratigraphy and provide new insight into the relationship between major stratigraphic units in the study area.

In general, the merged seismic section is characterized by strong seismic reflections generated at major lithological contacts or unconformities across the study area from 0 to 3.8 km depths, owing to strong acoustic impedance contrasts at these boundaries. At a regional scale, these reflections have variable

strikes and dips across the seismic sections due to faulting and folding. The significant stratigraphic units imaged by the seismic method are summarized below:

- **Ventersdorp Supergroup:** The strong reflections associated with the Ventersdorp contacts observed in Figures 10 and 11 are caused by significant acoustic impedance contrast at the interface (unconformity) between relatively high-velocity (~ 6400 m/s) and dense (~ 2.90 g/cm³) basaltic lavas of the Klipriviersberg Group of Ventersdorp Supergroup and the underlying lower-velocity (~ 5693 m/s) and less-dense (~ 2.86 g/cm³) basement rocks (Granitoid). Other reflections within the Supergroup are due to the alternating ultramafic and mafic lavas of the Klipriviersberg Group and metasedimentary rocks of the Pniel and Platberg Groups; these reflections are consistent with those observed in the seismic sections across the Witwatersrand goldfields (Pretorius et al. 2003; Manzi et al. 2003). The lower part of the seismic section shows strong, distinct individual reflections. The origin of these reflections are not well known since there is no borehole information to constrain them, however it is possible that these may originate from the shales and quartzites of the upper West Rand Group of the Witwatersrand Basin, as they bear a similar seismic signature (see Manzi et al. 2013; Tinker, de Wit and Grotzinger 2002).
- **Griqualand West Supergroup:** This Supergroup is characterized by multiple strong seismic reflections. The major unconformity at the base of the Campbell Rand Subgroup exhibits a strong seismic reflection due to a significant acoustic impedance contrast between the overlying dolomites of the Campbell Rand Subgroup of the Ghaap Group (base of the Griqualand West Supergroup) and the underlying lower-velocity, less-dense sediments of the Vryberg Formation (Figure 3), which is part of the Pniel Group (upper portion of the Ventersdorp Supergroup). The second moderate seismic reflection, supported by the synthetic seismogram results in Figure 3, is generated at the contact between the upper dolomites of the Schmidtsdrift Subgroup and the Banded Iron Formations (> 50 m thick) of the Kuruman Formation, which is the main target for the iron ore mineralization. The strength of this reflection, as observed in Figure 3, is not as strong owing to relatively similar velocities and densities of the dolomites and BIFs. The Kuruman Formation is itself characterized by a package of moderate reflections, which are generated by alternating massive iron ore horizons, BIFs and shales. The strong reflection at the top of the Kuruman Formation is interpreted to have been caused by the unconformity at the contact between the shales or BIFs of the Kuruman Formation and basaltic lavas of the Ongeluk Formation of the Postmasburg Group. The presence of the unconformity is in agreement with the outcrop data seen in Figure 10 as well as the results by Basson et al. (2017) from drilling and structural mapping information in the Sishen mine.
- **Olifantshoek Supergroup:** Based on the stratigraphy (Figure 2) and the borehole information (Figure 3b), the prominent and laterally extensive reflections above the Griqualand West

Supergroup may be attributed to contacts of the basaltic lavas of the Hartely Formation and quartzitic units of the Volop Group (see Figure 2), confirming studies by Tinker, de Wit and Grotzinger (2002).

- **Karoo Supergroup and Kalahari Group:** The near surface reflections across the seismic sections may be due to the acoustic impedance contrast between the overlying Kalahari rocks and the underlying rocks of the Karoo Supergroup. This interpretation is consistent with the strong reflection coefficient produced at this boundary by the synthetic seismogram at Kathu-1 borehole (Figure 3b). However, it is worth noting that this borehole was not drilled along the seismic profile (see Figure 1).

As mentioned earlier, the seismic surveys were designed to investigate the possibility that Witwatersrand Supergroup rocks may be buried beneath younger stratigraphy in the study area. The interpretation of the seismic section with borehole data provides no clear evidence of the Witwatersrand Supergroup beneath the younger strata in our study area. However, it cannot be ruled out that these rocks exist at great depth, and may be shallower further east of our study area due to folding and faulting.

Iron-oxide mineralisation and structural character

The merged seismic profiles (Figure 11a) show a few reflections that originate from the target mineralisation of the Kuruman Formation (~ 500 and 950 m maximum thickness and depth, respectively). In general, the seismic section shows that the iron ore mineralization and its underlying (Ventersdorp Supergroup) and overlying (mainly Olifantshoek Supergroup) strata are crosscut and offset by numerous near-vertical dipping (~65–80°) normal and reverse faults of various orientations and vertical throws. The major faults (> 25 m throw) trend predominantly north-south and a few subtle ones (< 25 m throws) are too complex to interpret on the seismic section. Vertical displacements of the faults within the Kuruman Formation, as can be determined by the seismic section (Figure 11), do not exceed 60 m.

Most importantly, the merging of the two seismic profiles made possible the imaging of a syncline structure, which is the most dominant first-order-scale structure imaged by the reflection seismics in the study area, located next to the ‘data merging boundary’ across the profiles (Figures 10 and 11). The fold is open and symmetric in form, plunging shallowly north-south. The sides of the syncline are characterized by gentle dips of 5°-20°. The wavelength and amplitude of the syncline are approximately 4 km and 1 km, respectively. The faults that intersect the mineralisation zone are parallel to the fold axis of the syncline and are thus interpreted to be related to axial-plane foliation owing to the uniform strain field that occurred during the fold process (e.g. Williams 1976). As seen in the seismic sections (Figures 10 and 11), the syncline deforms the strata above, but not the base of the Kalahari Group in the area, and below the Kuruman Formation, thus constraining the timing of activity of this structure to pre-Kalahari sediments deposition. We interpret this syncline to be attributed to the easterly directed

crustal compression during the Kheis Orogeny (ca. 1.83–1.73 Ga), which exhibits a general SE – NW strike (Beukes and Smit 1987). Furthermore, the western and eastern limbs of the syncline are dissected by a series of normal fault networks, thus constraining the timing of these faults' activity to post fold formation, i.e., post-Kheis orogenic event. The eastern part of the limb is also intruded by a possible dyke swarm that attenuate the seismic amplitude across the seismic sections, which may have intruded along the weaker and faulted zones of the strata, and eliminated the iron ores. The ages for these dyke swarms are unknown. However, the faults are interpreted to have formed during the Gondwana breakup at 205 - 120 Ma, which might have caused extensional reactivation of the pre-existing fault systems.

The seismic imaging of the Kheis Orogeny-related syncline within the Kuruman Formation is important for future mining purposes in the area as this structure might have preserved iron-oxide mineralisation from erosion. Seismic data provide further evidence that the iron ore mineralisation in the southwestern margin of the Kaapvaal Craton occurs as individual ore bodies that are structurally controlled concordant as proposed by several authors, including Humphreys et al. (1988), Hilliard (1999), Stoch et al. (2017) and Basson et al. (2017). Based on the structural framework seen on the seismics, it is highly likely that these tectonic events played a major role in the exposure, development, transportation and distribution of the iron ore in the region. The lateral extent of the Kuruman Formation within the profile is just under 1,5 km, with outcrops occurring at the flanks of the syncline that strike SE-NW and the maximum depth of the formation occurs near the midpoint of these flanks (at CDP 2000 of KBF01C, Figure 1) at a mineable depth of 940 m. A borehole drilled within this region, located ~ 45 km southeast of Sishen mine, would allow for testing of the ore grading within this ore body.

Both seismic refraction and magnetotelluric (MT) models were constructed and agreed well with the reflection seismics, thus constraining our seismic interpretation. The tomography (Figure 5) assigned the seismic velocity of the Kuruman Formation to be between 5000 m/s and 6000 m/s, agreeing well with the sonic log of VMP-1 (Figure 3). The MT data (Figure 12) revealed the possibility of a significant thrust fault located just north of CDP 1600 of KBF01C (Figure 1), which correlates with a strong magnetic lineament indicated by the white arrows in the magnetic map of Figure 1b. Furthermore, the MT results support the geometry of the Kuruman Formation derived from the reflection seismics, which manifests as a highly conductive body in the MT model due to the iron mineralisation.

8.7 Conclusions

The reprocessing of two legacy 2D seismic profiles has yielded improved delineation of iron-oxide mineralisation within the Kuruman and Daniëlskuil Formations of the Griqualand-West Supergroup, located southeast of the Sishen open pit iron mine in the Northern Cape province of South Africa. Despite certain challenges associated with legacy data reappraisal, the rugged terrain over which the profiles were acquired as well as interference from intrusives, and the lack of density information within local borehole geophysical logs, the iron-oxide mineralisation has been identified with considerable

confidence that is reinforced by supporting outcrop logs along the profiles as well as magnetotelluric data, also reprocessed, showing a high conductivity zone ($< 10 \Omega\text{m}$) where the suspected iron mineralisation occurs. The metasediments hosting the iron lie within a regional syncline striking SE – NW, likely associated with the 1.83 – 1.73 Ga Kheis Orogeny, and have a depth and average thickness of 900 m and 500 m, respectively. By reprocessing legacy seismic data originally intended for gold exploration and crustal investigation, this present study demonstrates the usefulness and cost efficiency in legacy data reappraisal for iron mineralisation prospecting.

8.8 References

- Basson I.J., Anthonissen C.J., McCall M.J., Stoch B., Britz J., Deacon J., Strydom M., Cloete E., Botha J., Bester M. and Nel D. 2017. Ore-structure relationships at Sishen Mine, Northern Cape, Republic of South Africa, based on fully-constrained implicit 3D modelling. *Ore Geology Reviews* **86**, 825–838.
- Beamish D. and Travassos J.M. 1992. The use of the D^+ solution in magnetotelluric interpretation. *Journal of Applied Geophysics* **29**, 1-19.
- Beukes N. J. 1986. The Transvaal sequence in Griqualand west. *Mineral Deposits of South Africa* **1**, 819-828.
- Beukes N.J. and Smit C.A. 1987. Evidence for thrust faulting in Griqualand West, South Africa: Implications for stratigraphy and the age of the red beds. *Transactions of the Geological Society of South Africa* **90**, 378-394.
- Beukes N.J., Gutzmer J. and Mukhopadhy J. 2002. The geology and genesis of high-grade haematite iron ore deposits. *Iron Ore 2002 Conference Proceedings*. Australasian Institute of Mining and Metallurgy, 23-29.
- Beukes N. J. and Gutzmer J. 2008. Origin and paleoenvironmental significance of major iron formations at the Archean-Paleoproterozoic boundary. *Reviews in Economic Geology* **15**, 5-47.
- Campbell G. 1990. The seismic revolution in gold and platinum prospecting in South Africa. *South African Geophysical Association Yearbook*, 37-45.
- Campbell G. and Crotty J.H. 1990. 3-D seismic mapping for mine planning purposes at the South Deep Prospect. *Proceedings of the International Deep Mining Conference. SAIMM Symposium Series S10(2)*, 569-597.
- De Villiers J.E. 1944. The origin of the iron and manganese deposits in the Postmasburg and Thabazimbi area. *Transactions of the Geological Society of South Africa* **47**, 123-135.
- Du Preez J.W. 1944. The structural geology of the area east of Thabazimbi and the genesis of the associated ore. *Annals University of Stellenbosch* **22A** 264-360.
- Durrheim R.J. 1986. Recent reflection seismic developments in the Witwatersrand basin. In: *Reflection seismology, a global perspective: geodynamics series* (ed. Barazangi, M., Brown, L.). Washington: American Geophysical Union Volume **13**, 77–83.
- Ellis R. G. and Oldenburg D. W. 1994. Applied Geophysical Inversion. *Geophysical Journal International* **116(1)**, 5-11.
- Górszczyk A., Cyz M. and Malinowski M. 2015. Improving depth imaging of legacy seismic data using curvelet-based gather conditioning: A case study from Central Poland. *Journal of Applied Geophysics* **117**, 73-80.

- Hilliard P. 1999. Structural evolution and tectonostratigraphy of the Kheis Orogen and its relationship to the south western margin of the Kaapvaal Craton. *Thesis in fulfilment of Doctor of Philosophy*. University of Durban-Westville, Dept. of Geology.
- Humphreys H.C., van Bever Donker J.M., Scott W.D. and van Schalkwyk L. 1988. The early deformational history of the eastern Namaqua Province: new evidence from Prieska Copper Mines. *South African Journal of Geology* **91(2)**, 174-183.
- Jeng Y., Li Y-W., Chen C-S. and Chien H-Y. 2009. Adaptive filtering of random noise in near-surface seismic and ground-penetrating radar data. *Journal of Applied Geophysics* **68(1)**, 36-46.
- Jones A.G., Evans R.L., Muller M.R., Hamilton M.P., Miensoopust M.P., Garcia X., Cole P., Ngwisanyi, T., Hutchins D., Fourie C.J.S., Jelsma H., Aravanis T., Pettit W., Webb S., Wasborg J., and The SAMTEX Team. 2009. Area selection for diamonds using magnetotellurics: Examples from southern Africa. *Lithos* **112**, 83-92.
- Ketelhodt J., Manzi M. and Durrheim R. 2019. Post-stack denoising of legacy reflection seismic data: implications for coalbed methane exploration, Kalahari Karoo Basin, Botswana. *Exploration Geophysics* **50(6)**, 667-682.
- Khan O., Spaak M., Vial-Aussavy A., Neves F. and Qubaisi F. A. 2017. Realizing the Potential of Legacy Seismic – Getting More Value From Vintage Data. *Conference: Society of Petroleum Engineers – Abu Dhabi International Petroleum Exhibition & Conference*.
- Malajczuk S., Saklani R., Clark D. and Eastwell D. 2016. Improved Subsurface Imaging and Interpretability through Broadband Reprocessing of Legacy Seismic Data. Examples from North West Shelf Australia. *25th ASEG-PESA-AIG Geophysical Conference and Exhibition*, 1-8.
- Malehmir A. and Bellefleur G. 2010. Reflection seismic imaging and physical properties of base-metal and associated iron deposits in the Bathurst Mining Camp, New Brunswick, Canada. *Ore Geology Reviews* **38(4)**, 319-333;
- Malehmir A., Maries G., Bäckström E., Schön M. and Marsden P. 2017. Developing cost-effective seismic mineral exploration methods using a landstreamer and a drophammer. *Scientific Reports* **7(1)**, 10325.
- Malehmir A., Donoso G., Markovic M., Maries G., Dynesius L., Brodic B., Pecheco N., Marsden P., Bäckström E., Penney M. and Araujo V. 2019. Smart Exploration: from legacy data to state-of-the-art data acquisition and imaging. *First Break* **37(8)**, 71-74.
- Manzi M., Hein K.A.A., King N. and Durrheim R.J. 2003. Neoproterozoic tectonic history of the Witwatersrand Basin and Ventersdorp Supergroup: New constraints from high-resolution 3D seismic reflection data. *Tectonophysics* **590**, 94-105.
- Manzi M. S. D., Hein K. A. A., Durrheim R. J. and King, N. 2013. Seismic attribute analysis to enhance detection of thin gold-bearing reefs. South Deep gold mine, Witwatersrand Basin, South African. *Journal of Applied Geophysics* **982**, 12–28.
- Manzi M., Cooper G.R.J., Malehmir A., Durrheim R.J. and Nkosi Z. 2015. Integrated interpretation of 3D seismic data to enhance the detection of the gold-bearing reef: Mponeng Gold mine, Witwatersrand Basin (South Africa). *Geophysical Prospecting* **63(4)**, 881-902.
- Manzi M., Cooper G.R.J., Malehmir A. and Durrheim R. J. 2019a. Improved structural interpretation of legacy 3D seismic data from Karee platinum mine (South Africa) through the application of novel seismic attributes. *Geophysical Prospecting* **68(1)**, 145-163.
- Manzi M., Malehmir A. and Durrheim R. 2019b. Giving the legacy seismic data the attention they deserve. *First Break* **37(8)**, 89-96.

- Manzi M., Hunt E. J. and Durrheim R. J. 2019c. 3D Reflection Seismic Imaging for Gold and Platinum Exploration, Mine Development, and Safety. *Ore Deposits: Origin, Exploration, and Exploitation* Chapter 11, 237-256.
- Maries G., Malehmir A., Bäckström E., Schön M. and Marsden P. 2017. Reflection Seismic Imaging of Iron-oxide Deposits - An Example from Bergslagen Mining District of Sweden. *Conference: 23rd European Meeting of Environmental and Engineering Geophysics*.
- Markovic M., Maries G., Malehmir A., von Ketelhodt J., Bäckström E., Schön M. and Marsden P. 2019. Deep reflection seismic imaging of iron-oxide deposits in the Ludvika mining area of central Sweden. *Geophysical Prospecting* **68**(1), 7-23.
- Mkhabela M. and Manzi M. 2017. Detection of potential methane gas pathways in deep South African gold mines. *Journal of Geophysics and Engineering* **14**(4), 960-974.
- Moen H.F.G. 1999. The Kheis Tectonic Subprovince, southern Africa: A lithographic perspective. *South African Journal of Geology* **102**(1), 27-42.
- Nomqhele N., Manzi M., Brovko O. and Durrheim R.J. 2017. 3D seismic attributes for structural mapping and enhancement of deep gold mining: A case study from the West Wits Line goldfields, South Africa. *Exploration Geophysics* **49**(3), 345-362.
- Pretorius C.C., Muller M.R., Larroque M. and Wilkins C. 2003. A review of 16 years of hardrock seismics on the Kaapvaal Craton, Hardrock Seismic Exploration. In: *Developments in Geophysics Series*. (ed. Eaton, D., Salisbury, M. and Milkereit, B.) SEG, Houston. 2003, 247–268.
- Rodi W. and Mackie R.L. 2001. Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion. *Geophysics* **66**(1), 174-187.
- Scheiber-Enslin S. E. and Manzi M. S. D. 2018. Integration of 3D reflection seismics and magnetic data for deep platinum mine planning and risk mitigation: A case study from Bushveld Complex, South Africa. *Exploration Geophysics* **49**(6), 928-939.
- Stoch B., Anthonissen C. J., McCall M-J., Basson I.J., Deacon J., Cloete E., Botha J., Britz J., Strydom M., Nel D. and Bester M. 2017. 3D implicit modelling of the Sishen Mine: new resolution of the geometry and origin of Fe mineralisation. *Mineralium Deposita* **53**, 835-853.
- Tinker J., de Wit M. and Grotzinger J., 2002. Seismic stratigraphic constraints on Neoproterozoic – Paleoproterozoic evolution of the western margin of the Kaapvaal Craton, South Africa. *South African Journal of Geology* **105**, 107-134.
- Tsikos H., Beukes N.J., Moore J.M. and Harris C. 2003. Deposition, diagenesis and secondary enrichment of metals in the Paleoproterozoic Hotazel iron formation, Kalahari manganese field, South Africa. *Economic Geology* **98**, 1449-1462.
- Vafeas N.A., Blignaut L.C., Viljoen K.S. and Meffre S. 2018. New evidence for the early onset of supergene alteration along the Kalahari unconformity. *South African Journal of Geology* **121**(2), 157-170.
- Van Schalkwyk J. F. and Beukes N. J. 1986. The Sishen iron ore deposit, Griqualand West. *Mineral Deposits of Southern Africa*, 931-956.
- Wagener P.A. 1921. Report on the Crocodile River iron deposits: Pretoria. *Geological Survey, South Africa Memo* **17**, 65.
- Widess M.B. 1973. How thin is a thin bed? *Geophysics* **38**(6), 1176-1180.
- Williams P.F. 1976. Relationships between axial-plane foliations and strain. *Tectonophysics* **30**, 181-196.

Yilmaz O. 2001. Seismic Data Analysis: Processing, inversion and interpretation of seismic data. *Society of Exploration Geophysicists*.

9 PAPER II: THE STRUCTURAL ARCHITECTURE OF THE WESTERN MARGIN OF THE KAAPVAAL CRATON, SOUTH AFRICA: NEW CONSTRAINTS FROM THE REAPPRAISAL OF HIGH-RESOLUTION LEGACY REFLECTION SEISMIC DATA

9.1 Abstract

The seismic profile KBF03A was acquired in 1994 as part of the South African Seismic Experiment to search for outliers of the gold-bearing Witwatersrand Supergroup. This 150 km long, 6 s TWT profile straddles the western margin of the Kaapvaal Craton which is projected to be in tectonic contact with the Kheis Province along the Blackridge Thrust, and its eastern end also lies within 35-40 km of the estimated centre of the ~145 Ma Morokweng impact structure. In this study, the seismic profile has been reprocessed and reinterpreted using modern processing algorithms and seismic attribute analysis, to re-evaluate the structural architecture of the western Kaapvaal Craton. Previous interpretations of this seismic section focused mainly on the Palaeoproterozoic supracrustal successions and proposed numerous normal faults including one major west-dipping fault, named the Moshaweng Fault, which was interpreted as a normal listric fault with >6 km throw that formed during Palaeoproterozoic rifting along the western Kaapvaal Craton margin. In contrast, interpretation of the re-processed seismic section suggests that the Moshaweng Fault is a first-order-scale thrust fault that dips gently ($\sim 30^\circ$) to the west and that is characterized by a hanging wall anticline with a wavelength of ~ 1 km and an amplitude of ~ 500 m. The fault crosscuts and displaces the stratigraphic units within the Neoarchaeon to Palaeoproterozoic Ventersdorp and Griqualand West supergroups and displays a maximum apparent reverse-slip sense of ~ 1285 m at depth; however, younger strata at shallower depths display an estimated 773 m of normal slip, demonstrating a complex fault system associated with multiple episodes of deformation history. We interpret the Moshaweng Fault to have initiated as a thrust during the easterly verging crustal compression attributed to the Kheis Event at ca. 1.2 Ga, with multiple subsequent negative inversions. Furthermore, seismic attributes indicate that the Phanerozoic Karoo Supergroup and Cenozoic Kalahari Group strata are also highly deformed, exhibiting numerous second-order scale folds and both reverse and normal faults with variable orientations and displacements (≤ 100 m) related to at least 4 distinct tectonic events of <250 Ma age. Our interpretation, based on reappraisal of legacy seismic data, thus provide new constraints on the strato-structural architecture of the western edge of the Kaapvaal Craton that shows a considerably more complex and prolonged tectonic history than has been previously thought.

9.2 Introduction

The South African national geophysical program acquired several thousand kilometres of hard rock 2D reflection seismic data (~ 36 000 km in total length) across the Kaapvaal Craton in South Africa (Figure 9.1) between the 1980s and early 2000s. These legacy seismic data were acquired with the goal of providing critical insight into the formation of the craton and, more specifically, to search for possible extensions of deeply buried Neoproterozoic Witwatersrand gold-bearing horizons below younger cover sequences (Pretorius et al., 2003). Most of these legacy data, which represent one of the world's largest hard rock seismic databases, were donated to the Seismic Research Centre in the School of Geosciences at the University of the Witwatersrand in 2014 and are currently the focus of a variety of research projects on the Kaapvaal Craton (Manzi et al., 2019).

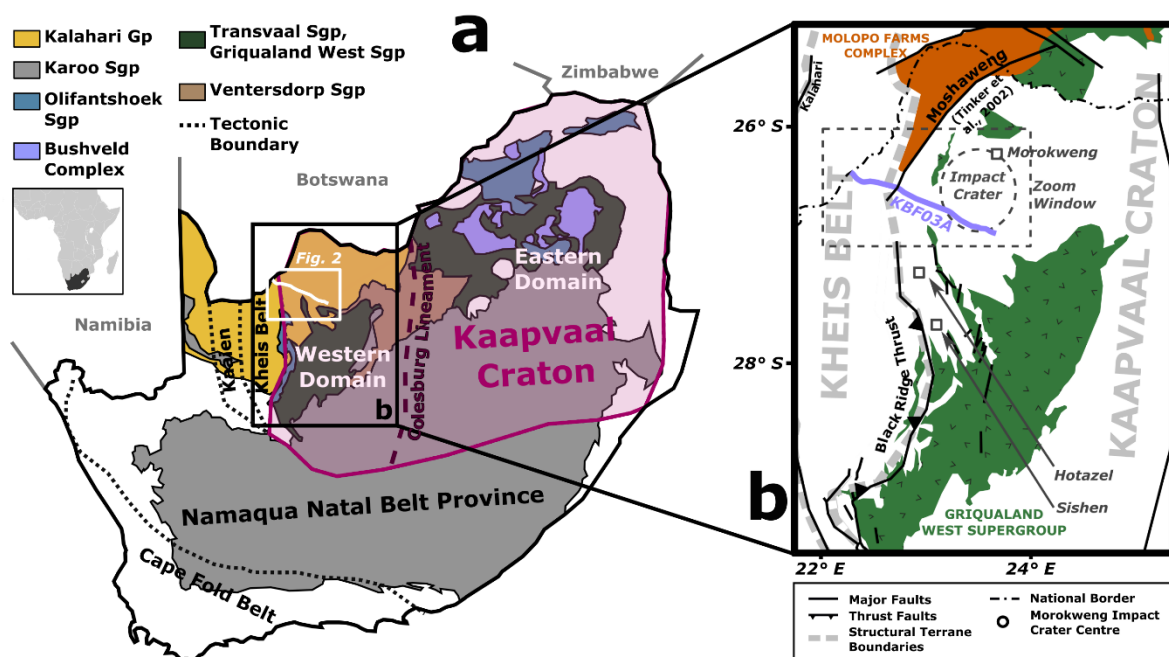


Figure 9.1: Location of KBF03A line on the Kaapvaal Craton in South Africa and its position with respect to the general tectonostratigraphy of the area (a), as well as the general regional geology in the zoom window (b). Zoom window b and the limits of Figure 9.2 are also highlighted in (a). Sources: Beukes et al. (2019); Tankard et al. (2012).

A growing theme in the recent geophysical literature is the reappraisal of legacy seismic data (Malajczuk et al., 2016; Manzi et al., 2018; Malehmir et al., 2019; Manzi et al., 2019; Donoso et al., 2020). By properly retrieving, recovering and reprocessing legacy seismic data using modern algorithms and computational techniques, the potential of the data can be more fully realised and geological features therein may be significantly enhanced and/or revealed, thus providing improved seismic constraints in complex tectonic terranes. These reprocessed legacy seismic data can then subsequently be interpreted using multiple modern seismic attributes to enhance features below the conventional seismic resolution limit (i.e., one quarter of the dominant seismic wavelength) that could

not be properly imaged using tools that were available in past decades, as well as the imaging of steeply dipping geological structures.

The Archaean Kaapvaal Craton in southern Africa (Figure 9.1a) covers an area of $\sim 1.6 \times 10^6$ km² and forms the nucleus around which the southern part of the African continent has amalgamated (Fouch et al., 2004). The craton has been extensively studied in terms of its strato-structural architecture (e.g. de Wit et al., 1992; Tinker et al., 2002), geochronological (e.g. Eglington and Armstrong, 2004; Poujol et al., 2003), geochemical (Banas et al., 2009) and geophysical (Tankard et al., 2012) character. Geophysical investigations have used data from, inter alia, the Southern African Seismic Experiment (SASE), a large scale seismic survey spanning the Kaapvaal and Zimbabwe cratons (James et al., 2001; Fouch et al., 2004). The western margin of the Kaapvaal Craton is one of its least well understood parts, primarily because of the extensive cover of Cenozoic Kalahari Group sediments but also because of its prolonged tectonic history involving multiple cycles of continental amalgamation and breakup, some of which are only poorly constrained. A contributing factor is the existence of a thin-skinned fold-and-thrust terrane, the Kheis Belt (Kheis Subprovince / Kheis Tectonic Province), along the western margin, which covers the Archaean crustal rocks up to several hundred kilometres east of the proposed craton edge (Figure 9.1).

In this study, we present the results of a reprocessed WNW-ESE-trending legacy (6 s TWT) reflection seismic profile (KBF03A), with total length of 150 km. The profile was shot from the westernmost exposures of the Archaean basement complex on the craton into the poorly exposed Kheis Belt as part of the abovementioned national geophysical programme by the Anglo American Corporation (now AngloGold Ashanti Ltd.). This survey was shot in 1994 and was designed to examine the possibility that gold-bearing rocks of the Witwatersrand Basin were continuous beneath the Kalahari Group sediments in the Kheis Tectonic Province (Tinker et al., 2002). Associated with the profile are two exploration boreholes – the 647 m deep NEV-1 and the 3420 m deep exploration borehole KHK-1 (Figure 9.2). Original interpretation of the profile ruled out the possibility of gold-bearing Witwatersrand Supergroup strata in the area (Stettler et al., 1997).

9.3 Regional geology

The Kaapvaal Craton in its current form was created during an early Neoarchaeon (~2.9 Ga) collision and suturing of two smaller continental blocks along the Colesberg Lineament (Poujol et al., 2002; Schmitz et al., 2004) (Figure 9.1). Both blocks exhibit characteristic granite-greenstone Archaean basement architecture, although the regional greenstone belt trends (ENE-WSW in the eastern block, N-S in the western block) differ strongly across the Colesberg Lineament. Compared with the eastern block, the granite-greenstone basement in the western block is poorly exposed owing to the extensive cover of younger strata. Although the western block contains evidence of >3.3 Ga xenocrystic zircons, the bulk of the granitoids are Neoarchaeon (ca. 2.9 Ga) in age, placing crust formation coeval with

deposition of the Witwatersrand Basin in the eastern block (e.g., [Poujol et al., 2002](#); [Schmitz et al., 2004](#)). Weakly deformed to undeformed granitoids of this age are exposed west of Vryburg in a region of basement uplift called the Ganyesa Dome ([Corner et al., 1997](#); [Cornell et al., 2018](#)). The age of this dome is unknown, however, it appears to deform the Palaeoproterozoic Griqualand West Supergroup, suggesting that it is younger than this 2.6 - 2.1 Ga sequence. Whilst no greenstones are exposed, [Corner et al. \(1997\)](#) suggested that a 100 x 20 km, N-S trending, magnetic anomaly within the Ganyesa Dome, informally referred to as the Linopen anomaly ([Figure 9.2c](#)), may represent a buried greenstone belt.

A lithostratigraphic column of the region is shown in [Figure 9.2e](#). Unconformably overlying the basement complex is the late Neoarchaeon Ventersdorp Supergroup ([Van der Westhuizen et al., 2006](#)). The ca. 2.78-2.79 Ga ([Gumsley et al., 2016](#)) basal mafic-ultramafic volcanics (Klipriviersberg Group) that dominate the central parts of the craton are overlain by the rift-related, alternating siliciclastic and bimodal volcanic units of the 2.74-2.72 Ga ([Kositcin et al., 2003](#)) Platberg Group. This is, in turn, overlain by the siliciclastic sedimentary and basaltic volcanic 2.64 Ga ([Eriksson et al., 2008](#)) Pniel Group.

Much of the western margin of the craton that is not covered by Cenozoic sediments is underlain by the Palaeoproterozoic (2.64 - 2.43 Ga; [Walraven and Martini, 1995](#); [Gumsley et al., 2016](#)) Griqualand West Supergroup (GWS), a correlative of the Transvaal Supergroup to the east, which comprises a basal siliciclastic unit, middle dolomitic sequence that grades upwards into banded iron formations (BIFs), and an upper siliciclastic sequence ([Eriksson et al., 2008](#)). Intrusive into the GWS is the 2.055 Ga, mafic-ultramafic, Molopo Farms Complex, a correlative of the Bushveld Complex in the central-northern parts of the craton ([Figure 9.1a](#)) ([Beukes et al., 2019](#)).

The Olifantshoek Supergroup, which overlies the GWS, is one of the least well understood stratigraphic packages on the craton. It comprises siliciclastic and lava units that were deposited between 1.93 and ~1.85 Ga ([Cornell et al., 1998](#); [Moen, 2006](#)). The Hartley Formation ([Figure 9.2e](#)) comprises basalts that have been linked both to the ENE-trending 1.92 Ga mafic Tsineng Dyke Swarm ([Alebouyeh Semami et al., 2016](#)) but also to the ~1.93 to ~1.87 Ga Moshaneng Sills in the Waterberg Basin several hundred kilometres to the east ([Hanson et al., 2004](#)) that led [Alebouyeh Semami et al. \(2016\)](#) to suggest a mantle plume originally existed close to the western edge of the craton at 1.92 Ga. [Van Niekerk and Beukes \(2019\)](#) have recently questioned the internal stratigraphy of the Olifantshoek Supergroup and its relation to rocks in the Kaaie Terrane ([Figure 9.1a](#)) that have historically been interpreted as the easternmost terrane of the 1.2-1.1 Ga Namaqua-Natal Belt ([Cornell et al., 2006](#)). In correlating several units in the Kheis Belt and Kaaie Terrane, [Van Niekerk and Beukes \(2019\)](#) have proposed that the two actually represent a single tectonic terrane. This debate has significant implications for the age and origin of the thin-skinned tectonics historically attributed to the Kheis Belt. Originally thought to have developed at 1.8-1.7 Ga via thin-skinned, east-directed thrusting prior to the amalgamation of the

Kaaien Terrane onto the western edge of the craton during the early stages of the Namaqua-Natal Orogeny (Stowe, 1986; Cornell et al., 1998), Van Niekerk and Beukes (2019) have instead suggested that the Kaaien Terrane should be considered part of the Kheis Belt and, thus, that the Kheis thrusting may be as young as 1.2 Ga. Based on this interpretation, they place the true western margin of the Kaapvaal Craton along the NW-trending distal margin of the Kaaien Terrane (Brakbosch Fault – Trooilapspan Shear Zone) approximately 200 km west of the end of the KBF03A profile (the Kalahari Line; Van Niekerk and Beukes, 2019) (Figure 9.1). Furthermore, they have proposed significant modification to the published stratigraphic subdivisions of the meta-arenitic Olifantshoek Supergroup and Kaaien Group (SACS, 1980), downgrading the former to Group status within a new, Kheis, supergroup. On the eastern side of the Kheis Belt, the KBF03A profile crosses the extrapolated N-trending boundary of the Kheis Belt (Figure 9.1b). South of the profile, this boundary, called the Kheis Front by Beukes and Smit (1987), is located along the Blackridge Thrust, which Beukes and Smit (1987) place at the contact between the Olifantshoek Supergroup and the underlying GWS. Van Niekerk and Beukes (2019) also suggested that tectonic thickening in the Kheis Belt may have been as much as 250-400%, which would be consistent with Tinker et al.'s (2002) estimate of 300% thickening of the Hartley Formation in the KBF03A profile.

The western and southern edges of the Kaapvaal Craton are demarcated by its contact with rocks of the 1.1 Ga Namaqua-Natal Belt (Cornell et al., 2006). Although the main Phanerozoic Karoo Basin lies south of the study area, outliers of glacial sediments belonging to the ca. 250 Ma Dwyka Group occur in Botswana and have been identified from boreholes within the study area (Haddon, 2004). A further feature known largely only from potential-field geophysics and borehole cores is the 145 ± 2 Ma Morokweng impact structure (Hart et al., 1997; Koeberl et al., 1997). Whilst impact-melt rock has been recovered in boreholes from an approximately 30 km wide area that coincides with a circular magnetic anomaly (Figure 9.2b), opinion is divided on the diameter of the structure, with estimates ranging from 70-80 km (Henkel et al., 2002; Koeberl et al. 1997) to as much as 340 km (Corner et al., 1997). Evidence of ~1.5 km of erosion since the early Cretaceous (Stanley et al., 2015) indicates that the currently preserved diameter is likely to be significantly smaller than the original crater diameter.

The study area lies close to the southern limit of the Kalahari Group, which covers large parts of Botswana, eastern Namibia and northwestern South Africa. This sequence of semi- to un-consolidated sands, clays, calcrete and conglomerate, up to 150-200 m thick, was originally thought to be as old as Late Cretaceous (≤ 90 Ma; Haddon and McCarthy, 2005); however, cosmogenic isotopes analysis of lower Kalahari red clays and overlying gravels has significantly revised the main depositional event of the Kalahari Group to between 1.2 and 1 Ma (Matmon et al., 2015).

9.4 First-order stratigraphic and structural features of the KBF03A profile from regional geophysics and surface geology

The surface geology, pre-Kalahari geology and the local magnetic intensity of the area around the KBF03A profile are shown in Figure 9.2a, b and c, respectively. Topographically, the profile decreases in elevation from ~940 masl to 1130 masl towards the ESE (Figure 9.2d). The profile transects a gap in the most significant topographic and outcrop feature - the Kuruman Hills - which trace the arcuate outcrop of the gently west-dipping BIFs of the Kuruman Formation of the GWS, which provide a strong magnetic signature (Figure 9.2c). The eastern end of the profile is characterized by a few outcrops of Archaean basement granite and a single outcrop of the basal Vryburg Formation of the GWS. Apart from this the profile is devoid of outcrops, however, the magnetic anomaly map provides further detail of important first-order stratigraphic and structural features.

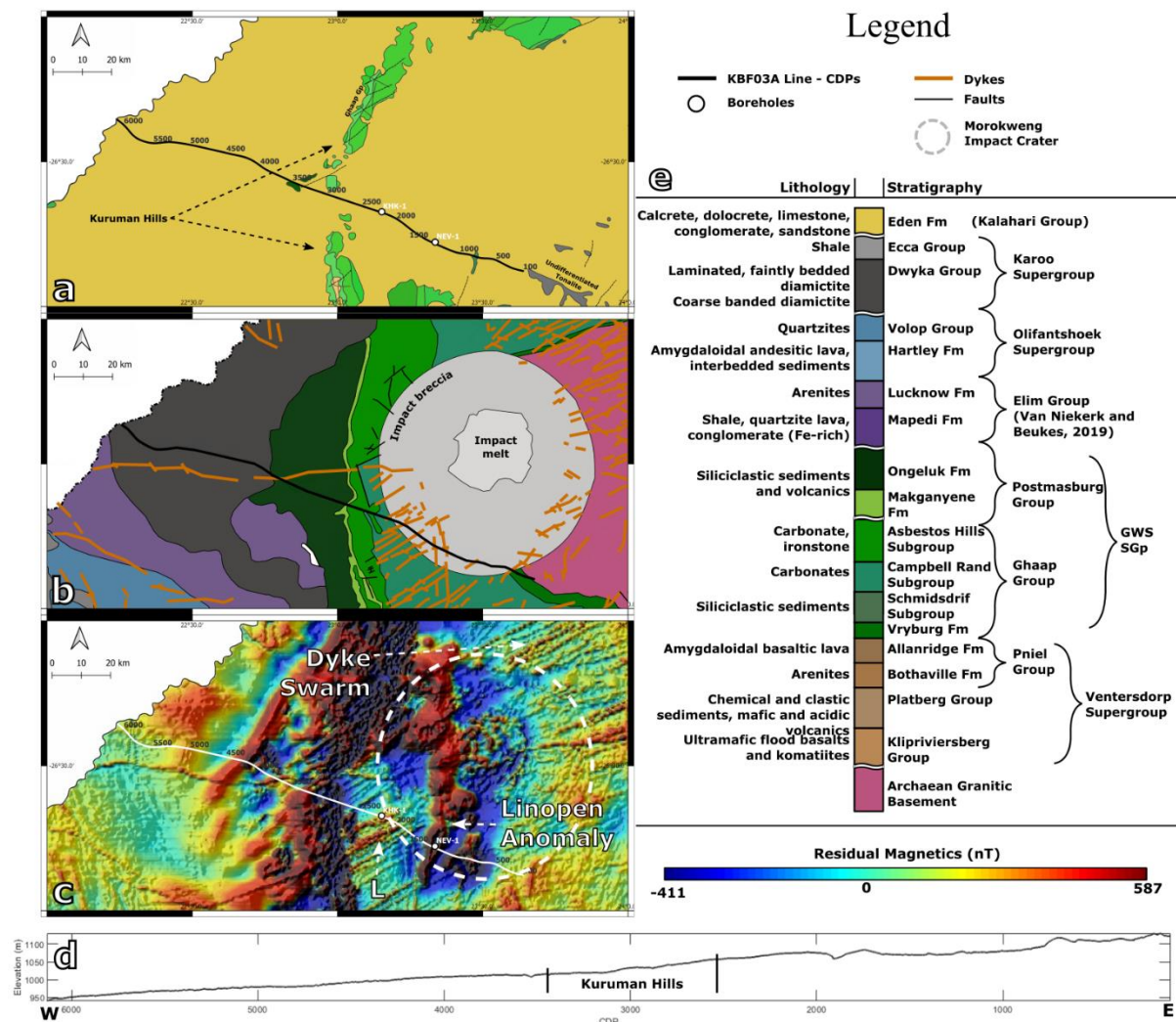


Figure 9.2: Surface geological (a), pre-Kalahari (b), and magnetic (c) maps of the region around the KBF03A line, as well as an elevation profile of the line (d). Datasets courtesy of the Council for Geoscience (2019) and sub-Kalahari map of Haddon (2005). Also shown is the general lithostratigraphy (e), where gaps represent unconformities (thicknesses are not to scale). The magnetic map was obtained by removing the regional field from the total magnetic intensity map

within the region. Main magnetic features are explained in the text. A major disruption in the profile coincides broadly with lineament L and an ~80 km diameter circle (dashed line) constructed around the inferred centre of the Morokweng impact structure that broadly coincides with changes in the magnetic character of rocks. (Note that the circle does not exactly align with the circular central geophysical anomaly of the MIS).

The limited outcrops of Neoarchaeon basement granitoids at the eastern edge of the profile correspond to the southern edge of a broad gravity low identified by [Corner et al. \(1997\)](#) and [Henkel et al. \(2002\)](#) as the Ganyesa Dome. Three distinctive aeromagnetic features are located within the dome (as labelled in [Figure 9.2c](#)): (a) a slightly sinuous, elongate-elliptical, >100 km long and <20 km wide, N-trending, magnetic high; (b) a prominent array of NNW-trending positive magnetic lineaments, and (c) a composite annular feature comprising a central strong positive (up to 350 nT), ~30 km wide magnetic anomaly that is surrounded by a ~20 km wide halo characterised by subdued magnetism that disrupts the NNW-trending lineaments.

The elongate magnetic high, informally referred to as the Linopen anomaly ([Figure 9.2b](#)), displays a similar N-S alignment to the greenstone belts in the western block of the Kaapvaal Craton ([Anhaeusser, 2019](#)). It tapers southwards towards the KBF03A profile and intersects it at the location of the shallow NEV-1 borehole ([Figure 9.2c](#)), which records vertical banded ironstone beneath GWS carbonates (see [Figure 9.4b](#)). The steep bedding and lack of correlation with known GWS stratigraphy supports the ironstone being part of an Archaean greenstone belt. The NNE-trending lineaments are consistent with the trend of the 1.92 Ga Tsineng Dyke Swarm that extends several hundred kilometres into the craton and that [Alebouyeh Semami et al. \(2016\)](#) linked to the Hartley Formation in the Olifantshoek Supergroup based on U-Pb zircon and baddeleyite geochronology and palaeomagnetic studies.

Exploration drilling into the circular area of enhanced magnetism located ~40 km north of the KBF03A profile has confirmed that it corresponds to a thick, partially eroded, impact melt sheet beneath the Kalahari Group. [Wela \(2017\)](#) proposed that the Morokweng impact structure, dated at 145 Ma, is an eroded peak-ring crater, and that the 20-km-wide zone surrounding the magnetic high corresponds to the structurally disrupted annular moat of the crater. Based on this interpretation, the KBF03A profile should intersect the southern edge of the impact structure ([Figure 9.2](#)).

The central and western segments of the profile cross a broad sequence of slightly sinuous, NNE-trending magnetic anomalies that include the banded ironstones of the Kuruman Formation. These anomalies are truncated towards the western edge of the profile by a major NE- to NNE-trending anomaly to the west of which the magnetic anomalies become less pronounced. Both [Tinker et al. \(2002\)](#), who investigated the seismic profile towards the southwestern end of this NE- to NNE-trending anomaly, and [Beukes et al. \(2019\)](#), who studied the northeastern end close to the Botswana border, attributed it to a 250 km long, west-dipping, fault that [Tinker et al. \(2002\)](#) named the Moshaweng Fault. However, whilst [Tinker et al. \(2002\)](#) interpreted its displacement as normal (albeit with possible strike-slip reactivation as well), [Beukes et al. \(2019\)](#) concluded that this fault displaced the Molopo Farms

Complex and its hanging- and footwall lithologies in a reverse sense. Significant displacement across the fault is consistent with the distinct change in the magnetic pattern to the west of the fault, which is supported by evidence from water boreholes (Smit, 1974) that confirm the presence of horizontal Dwyka Group sediments beneath the Kalahari Group west of the fault (Haddon and McCarthy, 2005).

Geological mapping and borehole studies within the region offer useful information regarding the Kalahari and Dwyka Groups. Structurally, recent mining activities in the Hotazel mine area (Figure 9.1a), 66 km south of KBF03A, expose folding, faulting and jointing in the calcretized Kalahari Group sandstones and the underlying Karoo Supergroup beds (Anton Gregory, personal communication, 2019). Field mapping results by Gabrielli (2007), 10 km east of the eastern termination of the profile, revealed a ~50 m stratigraphic profile of Kalahari Group sandstone and silicified conglomerate beds attributed to the Eden Formation (Figure 9.2e). Surface exposures of the Karoo Supergroup sediments are virtually absent in the area, but are intersected by boreholes below the Kalahari beds towards the western edge of the profile (Gabrielli, 2007). According to Haddon and McCarthy (2005) and Gabrielli (2007), the Karoo strata in the study area are entirely attributed to the Dwyka Group.

9.5 Previous Work on the KBF03A Profile

Acquisition

Acquisition

The 150-km-long, ESE-WNW trending, KBF03A reflection seismic profile was acquired using Vibroseis trucks as the seismic source. The field surface conditions and terrain required that the survey conform to a crooked-line geometry along the roads in the area, as shown in Figure 9.2a. The acquisition parameters of the seismic survey are summarized in Table 9.1.

Survey Parameters	
Type of survey	2D crooked line
Year	1994
Profile length	150 km
Trend	SES-NWN
Split spread	2975–25–X–25–2975 (m)
Nominal fold	60
Average fold	50
Recording System	
Recording device	Sarcel 338
Sampling rate	4 ms
Record length	6 s
Sweep length	16 s
Sweep frequencies	15 – 75 Hz linear
Source Information	
Source spacing	50 m
Source type	4 Pelton MK II vibrators in a line
Receiver Information	
Receiver spacing	50 m

Table 9.1: Acquisition parameters of seismic line KBF03A. Spread notation indicates source position X located at the midpoint of the two innermost receivers and the maximum offset is 2975 m in both directions.

Fortunately, the raw shot gathers and unmigrated stacked data (processed by the contractors in 1994) were received in SEG-Y format. The information regarding the acquisition parameters was obtained from the field observers' reports (in hard copy) provided by the company, however, no information was made available regarding the original processing workflow for the 1994 stacked section, which is the same data used by [Tinker et al. \(2002\)](#). We use the original stacked section to compare with our results from the reprocessed data.

According to available logs and information, different seismic spread configurations and source parameters were evaluated in order to optimize the survey acquisition parameters. The profile has a total of 3130 shot records (already cross-correlated) with 120 receivers per shot and 50 m shot and receiver spacing, and was acquired using a roll-along process. The natural frequency of the receivers is 10 Hz (vertical single component) with a low-cut analogue filter of 3 Hz. The resulting nominal CDP fold is 60 and the average CDP fold using the crooked line geometry is 50 with a bin size of 25 m parallel to the profile. The seismic survey was designed with a sweep length of 16 s and sweep frequency of 15–75 Hz at a sampling rate of 4 ms, limiting the data bandwidth to 125 Hz and thus preventing data redundancy by oversampling. The recorded sweep was cross-correlated with the Vibroseis pilot sweep for each shot location and the correlated trace was to SEG-Y format for processing. We then investigated the quality of the recorded gathers before setting up the geometry of the profile for reprocessing.

Interpretation by Tinker et al. (2002)

The first research-driven interpretation of profile KBF03A was completed by [Tinker et al. \(2002\)](#), and multiple subsequent publications have referenced this interpretation. In their study, [Tinker et al \(2002\)](#) utilised eight legacy stacked and migrated seismic profiles located along the western, northern and interior margins of the Kaapvaal Craton, that were originally processed by contractors in 1994. The western margin included the KBF03A profile investigated here.

The general interpretation by [Tinker et al. \(2002\)](#) is shown in [Figure 9.3](#). In it, the profile is dominated by the W-dipping Paleoproterozoic metasediments comprising the Ventersdorp, Griqualand-West and Olifantshoek supergroups, which are unconformably overlain by horizontal Phanerozoic sediments comprising the Dwyka Group of the Karoo Supergroup, which in turn is unconformably overlain by the horizontal Kalahari Group. The strata are interpreted to exhibit numerous structural controls, most notable of which is the west-dipping Moshaweng Fault and the associated hanging wall anticline towards the western end of the profile, which is itself cut by multiple, complex, smaller scale folds, faults and low-angle thrusts. The Hartley Formation of the Olifantshoek Supergroup (O_h in [Figure 9.3](#))

in particular was interpreted to contain multiple low-angle thrusts and folds that duplicate the reflector labelled “T”. Furthermore, [Tinker et al. \(2002\)](#) interpreted its base as an angular unconformity (“Neylan Unconformity”) overlying the metasediments of the lower Olifantshoek Supergroup (the Mapedi and Lucknow Formations, O_{ml} in [Figure 9.3](#)). This unconformity was interpreted to represent erosion of the O_{ml} reflectors near the apex of the rollover anticline, as illustrated in [Figure 9.3B](#), thus constraining the timing of faulting to syn-Olifantshoek. [Tinker et al. \(2002\)](#) also inferred erosional features such as a palaeovalley associated with the unconformity ([Figure 9.3C](#)). Multiple normal faults, interpreted to be antithetic faults associated with the Moshaweng Fault (blue lines in [Figure 9.3B](#)), were interpreted as terminating against the unconformity, providing further age constraints for their tectonic model.

Above the dipping Paleoproterozoic strata lie the horizontal Phanerozoic sediments. The Dwyka Group sediments lie unconformably on top of the inferred rollover anticline and terminate against the Moshaweng Fault and exhibit depressions that [Tinker et al. \(2002\)](#) interpreted as 10 km wide glacial valleys. The Kalahari Group sediments lie unconformably above the Dwyka Group sediments and span the entire profile, truncating both the Dwyka Group and the dipping Neoarchaeon-Palaeoproterozoic supracrustals. The only structural features noted in [Tinker et al. \(2002\)](#) regarding these sediments were a possible fluvial channel towards the western end of the profile ([Figure 9.3E](#)), and disruption by the Moshaweng fault, which they attributed to neotectonic reactivation.

The tectonic model proposed by [Tinker et al. \(2002\)](#) comprises four stages. First, a NW-SE extensional event associated with the formation of the Ventersdorp and GW supergroups and the Lucknow and Mapedi Formations of the Olifantshoek Supergroup is tied to the initiation of the Moshaweng Fault as well as antithetic faults (F3 in [Figure 9.3C](#)) and a rollover anticline in the hanging wall. The localised uplift associated with the rollover anticline in turn triggered local erosion west of the Moshaweng Fault, forming the Neylan unconformity. Second, compression caused E-verging thin-skinned thrusting within the upper Olifantshoek Supergroup (F4 in [Figure 9.3C](#)), with the basal thrust exploiting the Neylan unconformity. The compression also caused crustal thickening of the strata west of the Moshaweng Fault (though this is reversed in the case of the Ongeluk Formation, which is substantially thicker to the east as seen in [Figure 9.3C](#)), where they proposed 300 % thickening of the Hartley Formation. Third, an extensional event caused the main phase of slip of the Moshaweng Fault, which [Tinker et al. \(2002\)](#) interpreted to be ~6.5 km. This was accompanied by monoclinical flexing in the footwall east of the fault and by a further set of antithetic faults (F5 in [Figure 9.3C](#)). Based on a perceived flower structure geometry of the hanging wall faults, [Tinker et al. \(2002\)](#) suggested that the Moshaweng Fault may have also been associated with strike-slip displacement and, consequently, that this event could have been related to syn-to-post-orogenic collapse (presumably following the fold-and-thrust belt thickening). The final phase of tectonism was attributed to Phanerozoic epeirorogenic uplift associated with formation of the Dwyka unconformity and further uplift and erosion associated with the formation of the Kalahari

unconformity. [Tinker et al. \(2002\)](#) also noted minor disturbances of these Phanerozoic sediments along the Moshaweng Fault, consistent with minor reactivation, although no slip estimates were given.

The quality of the published legacy seismic profile used by [Tinker et al. \(2002\)](#) is poor by modern standards and in some cases the vertical scale of the seismic section has been significantly exaggerated, thus making judgement of their interpretations difficult. Moreover, geophysical and geological log data from two boreholes located on the profile (KHK-1 and NEV-1 as plotted in [Figure 9.2a](#)) were not consulted by [Tinker et al. \(2002\)](#). These boreholes introduce new considerations for interpreting profile KBF03A, especially within the lower units that comprise the Ventersdorp Supergroup. Thus, by reprocessing profile KBF03A, we aim to improve the data quality and reinvestigate the lithostratigraphic and structural features therein with the support of the borehole logs and seismic attributes. As examples of issues needing reinvestigation, [Tinker et al. \(2002\)](#) proposed that the Kalahari Group was deemed to be structurally undisturbed away from the Moshaweng Fault, and the only published log of KHK-1, by [Reimold et al. \(2002\)](#), differs significantly in places from the original AngloGold Ashanti log. For these reasons, a more detailed discussion of KHK-1 is provided in following sections.

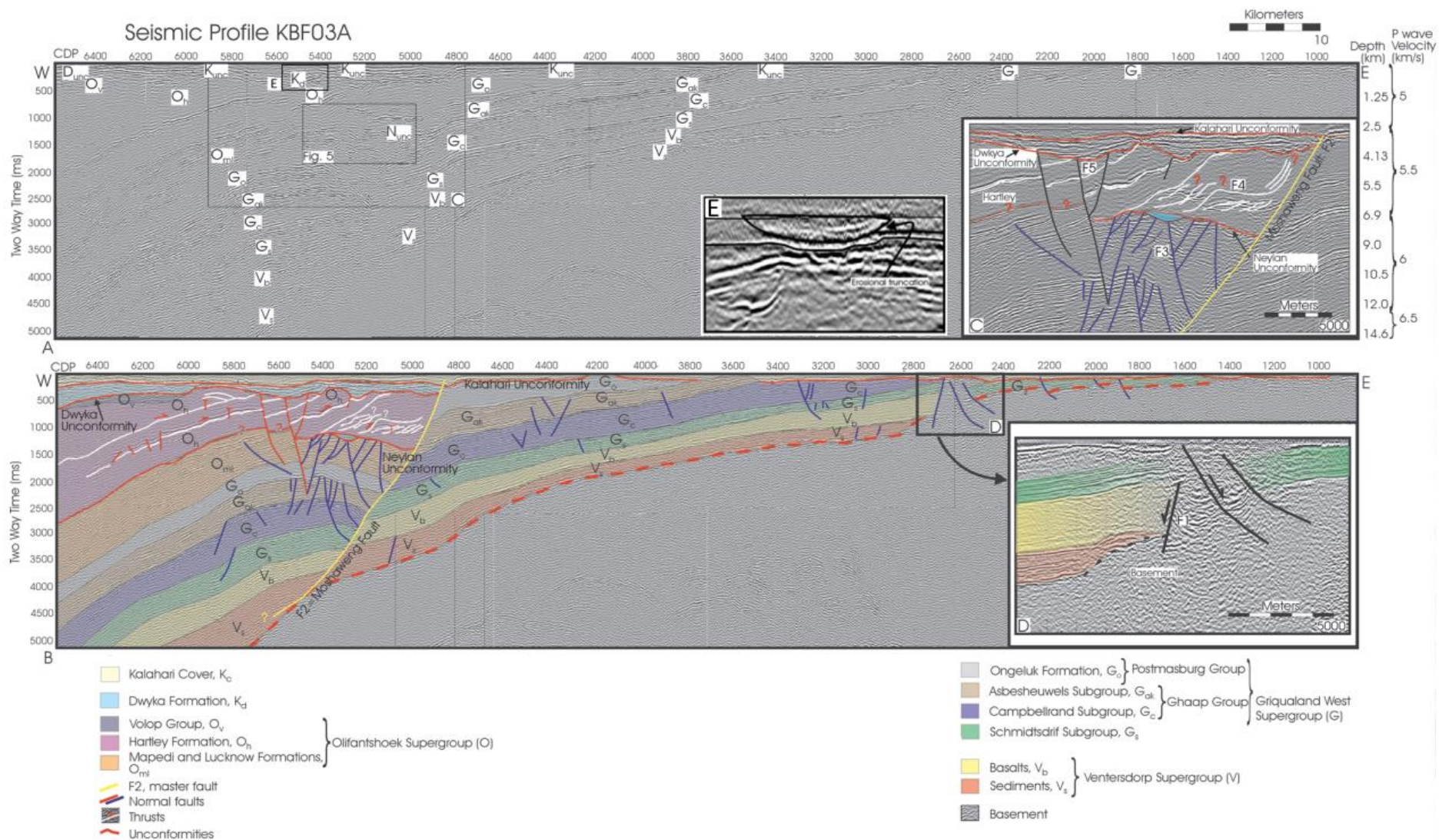


Figure 9.3: Legacy seismic section (A) along with [Tinker et al.'s \(2002\)](#) interpretation (B) with zoom windows C, D and E. Adapted from [Tinker et al. \(2002\)](#).

Boreholes and synthetic seismograms

Geophysical logging data from boreholes KHK-1 (3420 m) and NEV-1 (647 m) located along the seismic profile (Figure 9.2a) were obtained from AngloGold Ashanti and used to compute synthetic seismograms to test for notable sources of seismic reflectivity in our study area and to directly compare synthetic reflections with those in our seismic section.

Of the two boreholes, only KHK-1 has previously been interpreted for research purposes. This was done by Reimold et al. (2002), who investigated the core for possible impact-related breccias associated with the ~145 Ma Morokweng impact. The AngloGold Ashanti geophysical log, which was accompanied by seismic velocity values down the log, has been used in this study to calculate synthetic seismograms (Figure 9.4a). Both interpretations reveal a dominance of the GWS metasediments to a depth of 1200 m, followed by the Pniel and Platberg Groups of the Ventersdorp Supergroup down to a depth of 1948 m, after which divergence in interpretations occurs. Where Reimold et al. (2002) interpreted a continuous sequence of granophyre with intermittent, thin (~10 m) mafic intrusions, the AngloGold log suggests a 124 m thick layer of mafic lavas, followed by granite and granodiorite to a depth of 2669 m. Below these, Reimold et al (2002) suggest the presence of felsic volcanics, contrasting with AngloGold's interpretation of gabbro. Finally, AngloGold interpret a 340 m thick diabase sill, followed by basement granite. Reimold et al. (2002) labelled this section as “annealed granitoid”.

The boreholes KHK-1 and NEV-1, along with AngloGold's interpreted lithological and sonic logs and their respective synthetic seismograms, are shown in Figure 9.4a and Figure 9.4b, respectively. Density information was missing in the logs and, therefore, the acoustic impedance logs were calculated based only on the seismic velocity (mainly compressional velocities), which in most cases is a sufficient approximation (Yilmaz, 2001). This was done by assuming a constant bulk density throughout the log and, thus, acoustic impedance contrasts were approximated by seismic velocity contrasts. The temporal sampling rate was set to match that of the legacy seismic data (4 ms; see Table 9.1) and a Ricker wavelet with a dominant frequency of 50 Hz was used in computing the seismograms with no attenuation effect applied. Due to the missing density information, interpretation was based primarily on the lithology within the boreholes and less so on the synthetic seismograms.

Unfortunately, the top ~590 m of KHK-1 below the Kalahari Group unconformity (Figure 9.4a) was drilled using a percussion technique and was not retained (Reimold et al., 2002), thus making velocity contrasts at this boundary incalculable. Both the Reimold et al. (2002) and unpublished drilling logs indicate that the borehole intersected the Griqualand West and Ventersdorp supergroups and Archaean granitoid basement, but not Dwyka Group or Olifantshoek Supergroup rocks. Both also noted multiple mafic intrusions, but these are not well-documented and the logs disagree on their interpretation. Interpretations become more divergent in the lower third of the core and are thus discussed below in more detail.

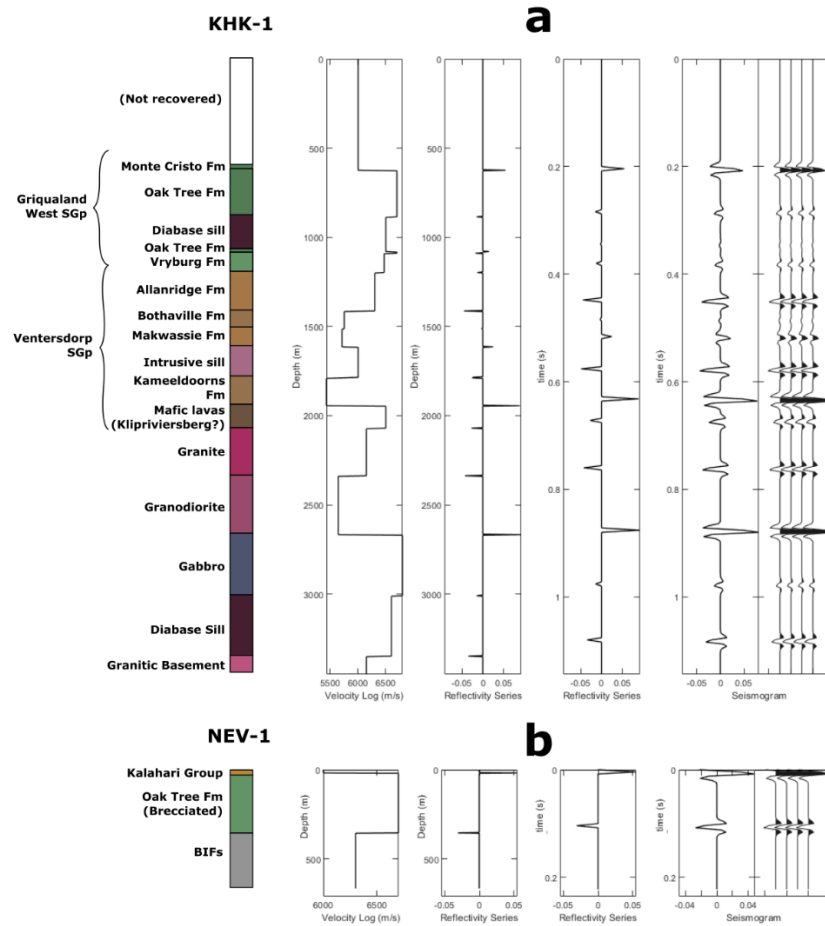


Figure 9.4: Sonic logs of boreholes KHK-1 (a) and NEV-1 (b) (locations shown in [Figure 9.2](#)) and resulting synthetic seismograms. Major reflections are observed within the Ventersdorp Supergroup in (a), as well as at the interfaces between the Monte Cristo and Oak Tree Formations as well as between near the base of the Ventersdorp Supergroup where mafic lavas underlie the Kameeldoorns Formation, with a weaker inverted reflection located at the interface between the Griqualand-West and Ventersdorp Supergroups. Further reflections are found at the boundaries of the gabbro and diabase intrusions, where the basement interface is located.

The first major reflection is located within the Griqualand West Supergroup (GWS), at the boundary between the Monte Cristo (6000 m/s) and Oak Tree Formations (6700 m/s). The synthetic seismogram does not reveal a strong velocity contrast between the base of the GWS and the Ventersdorp Supergroup, however the latter exhibits multiple internal low-amplitude reflections, with a major reflection at the boundary between the Kameeldoorns Formation (5430 m/s) and underlying mafic lavas (6500 m/s). The drilling core log tentatively assigned these lower lavas to the Archaean Kraaipan Formation. Whilst both the drilling log and that of [Reimold et al. \(2002\)](#) record only intrusive rocks below 2000 m depth, the latter did not recognise mafic lavas at all in the relevant interval. Nonetheless, they obtained a 2.74 Ga age from zircons in a felsic granophyre (equivalent to the upper “granite” interval in [Figure 9.4a](#)) from 2290 m depth. The presence of a Platberg-age intrusion and the absence of mafic lavas in the lower Platberg Group across the craton ([Van der Westerhuizen et al., 2006](#)) leads us to conclude that these lavas may represent a highly geologically depleted sequence of Klipriviersberg Group lavas. Although

Van der Westerhuizen et al. (2006) suggested that the western limit of the Klipriviersberg Group lies east of the profile based on surface exposures, the relatively close proximity of the profile to this limit, and the regional evidence of widespread post-Ventersdorp faulting (e.g., Beukes et al., 2019), make such an interpretation more plausible than that of a greenstone remnant.

Beneath the Ventersdorp Supergroup are a series of granitoids along with two mafic units (gabbro and diabase; Figure 9.4a) lying above the granitoid basement complex. As already indicated, Reimold et al. (2002) attributed the granophyric rocks equivalent to the granite-granodiorite units between the Ventersdorp Supergroup and gabbro as Platberg in age; however, they obtained an age of 2878 Ma for the lowermost granitoid intersection. This is similar to ages from the Neoarchaeon granitoid basement complex reported from the Ganyesa Dome (Cornell et al., 2018). Unfortunately, no age has yet been obtained from the gabbro unit, which is the cause of the third major velocity contrast in KHK-1 where it interfaces with the overlying granodiorite (6800 m/s and 5640 m/s, respectively). One option is that the entire plutonic package between the basement granite and the lavas is genetically related and, thus, of Platberg age. Alternatively, if the gabbro was assumed to have the same origin as the diabase sills within the log, then the fact that these sills intrude the GWS would require that it postdates the GWS (< 2.1 Ga) and is unrelated to Ventersdorp magmatism. Possible candidates in this scenario could be the Tsing (1.92 Ga), Umkondo (~1.11 Ga) or Karoo (~135 Ma) magmatic events; however, it must be noted that the gabbro is itself separated from the basement complex by a diabase, which would be expected to be intrusive into the coarser-grained rock.

The NEV-1 core log (Figure 9.4b) indicates that a significant reflection occurs at the Kalahari Group basal unconformity, in contrast to the finding of Tinker et al. (2002) who experienced difficulty defining this boundary. The drilling log identified Oak Tree Formation dolomite (GWS) below this, with its base being a tectonic contact with steeply-dipping BIF. As GWS BIF overlies dolomite in a normal stratigraphic relationship (Eriksson et al., 2006), the NEV-1 relationship implies either strong structural disruption of the GWS stratigraphy or that the BIF is older than the dolomite. Unfortunately, very little structural information accompanied the core log; however, based on the borehole's relationship to the Linopen magnetic anomaly (Figure 9.2c), we suggest that the BIF represents part of a greenstone sequence within the Archaean basement complex. The BIF exhibits a significant negative velocity contrast with the dolomite (6300 m/s and 6700 m/s, respectively). The absence of the lowermost unit of the GWS, the Vryburg Formation, beneath the dolomite here may be attributed to the structural contact.

9.6 Methodology

The principal aim of this study is to present new interpretations of the legacy KBF03A seismic profile resulting from reprocessing using modern algorithms and methods. This involved initial retrieval and recovery of the raw shot gathers, pre-stack processing and application of post-stack processing and migration to correctly enhance the mapping of reflections in space. Subsequent utilization of modern seismic attribute analyses was done to enhance the structural resolution of the reprocessed data. The data are mainly used to examine the large-scale stratigraphic and structural architecture of the Archaean-Proterozoic sequences. Focus was given to (1) the fault and fold geometries and forms, and fault-throw analysis, and (2) the relative chronology of tectonic events. In contrast to [Tinker et al. \(2002\)](#), the interpretation utilises data from the KHK-1 and NEV-1 boreholes and recent published and unpublished regional stratigraphic, geochronological and surface mapping data. In general, reprocessing of the seismic data has resulted in substantially better imaging of the stratigraphy and structural features along the seismic profile, particularly of the unconformities at the bases of the Kalahari and Dwyka groups, and of the Moshaweng Fault. It suggests an alternative interpretation for the Moshaweng Fault.

Data Reprocessing

The reprocessing workflow started with a detailed evaluation of the field observers' reports on the acquisition parameters to ensure that the recovered geometry in the trace headers was correct, some trace edits were made where trace header information was missing or incorrect. We also corrected for a number of the shots that were duplicated, as well as for incorrect shot and receiver coordinates. It was possible to recover most of this information from the existing trace headers and the reports. A summary of the reprocessing steps applied to the data is given in [Table 9.2](#).

1.	Geometry and CDP binning
2.	First break picking
3.	Trace editing
4.	Amplitude Recovery AGC window length: 500 ms
5.	Floating datum static corrections Fixed datum elevation: 1140 m Replacement velocity: 6000 m/s
6.	Refraction static corrections RMS error < 8 ms
7.	Frequency filtering Notch filter: 50 Hz Bandpass: 5-15-75-100 Hz
8.	F-K filtering F-K mute rejecting velocities below 3100 m/s
9.	Predictive deconvolution Average prediction gap: 30 ms (range of 26-40 ms) Average operator length: 100 ms (range of 80-130 ms)
10.	Velocity Analysis
11.	NMO correction Stretch mute: 60%

12. Residual statics
Repeat NMO corrections and residual statics (3 iterations)
 13. DMO
 14. Stack
 15. F-X deconvolution
 16. Migration
Kirchhoff migration velocity: 5500 m/s
Maximum allowed stretch: 50%
-

Table 9.2: Processing sequence of seismic line KBF03A.

The crooked nature of the seismic profile complicates the seismic imaging quality (e.g. [Adam et al., 1998](#)). For example, if the crooked geometry is not carefully considered in the processing stage, steeply dipping reflectors will not be imaged in the final stacked section owing to poor alignment of reflection events in common depth point (CDP) gathers. Considerable success has been achieved through different processing approaches in improving 2D crooked-line imaging in the hard rock environment, especially at crustal scale. Several possible solutions to improve crooked-line imaging in hard rock settings are documented in [Wang and West \(1991\)](#), [Kim et al. \(1992\)](#), and [Nedimović and West \(2003\)](#). The method we used was to fit a spline curve through the cloud of common midpoints on the surface with the highest number of binned traces.

[Figure 9.5](#) shows examples of the recorded shot gathers before and after initial processing. In general, the quality of the data is good with clear first breaks (indicated by red arrows in [Figure 9.5a](#)) observed in most of the shot gathers, as well as reflections (indicated by green arrows in [Figure 9.5a-c](#)). Amplitude spectral analysis of raw gathers indicates that field data contain the expected frequency range of 10-75 Hz. After binning the traces into common midpoint (CMP) bins and merging the geometry with the trace headers, first arrivals were picked in the shot gathers to correct for the effect of low-velocity wave propagation in the overburden (refraction static corrections). Bad traces were then muted and an AGC with window length 500 ms was applied to the gathers to recover attenuated amplitudes. Overall, about 375 600 first breaks were picked with a preliminary automatic method followed by a precise manual investigation to fine-tune the picked arrivals. Both floating datum statics and refraction statics were applied to the data. The profile had minimum and maximum elevations of 940 m and 1133 m, respectively, and therefore a datum elevation of 1140 m was chosen along with a replacement velocity of 6000 m/s, as was determined by analysis of far offset first arrivals. The refraction static corrections were computed using a least-squares inversion algorithm (e.g. [Ellis and Oldenburg, 1994](#)) for the first arrivals, inverting for the weathered layer velocity and thickness along the profile. The resulting RMS error was less than 8 ms and the weathered layer exhibited velocities ranging from 2000 to 3500 m/s.

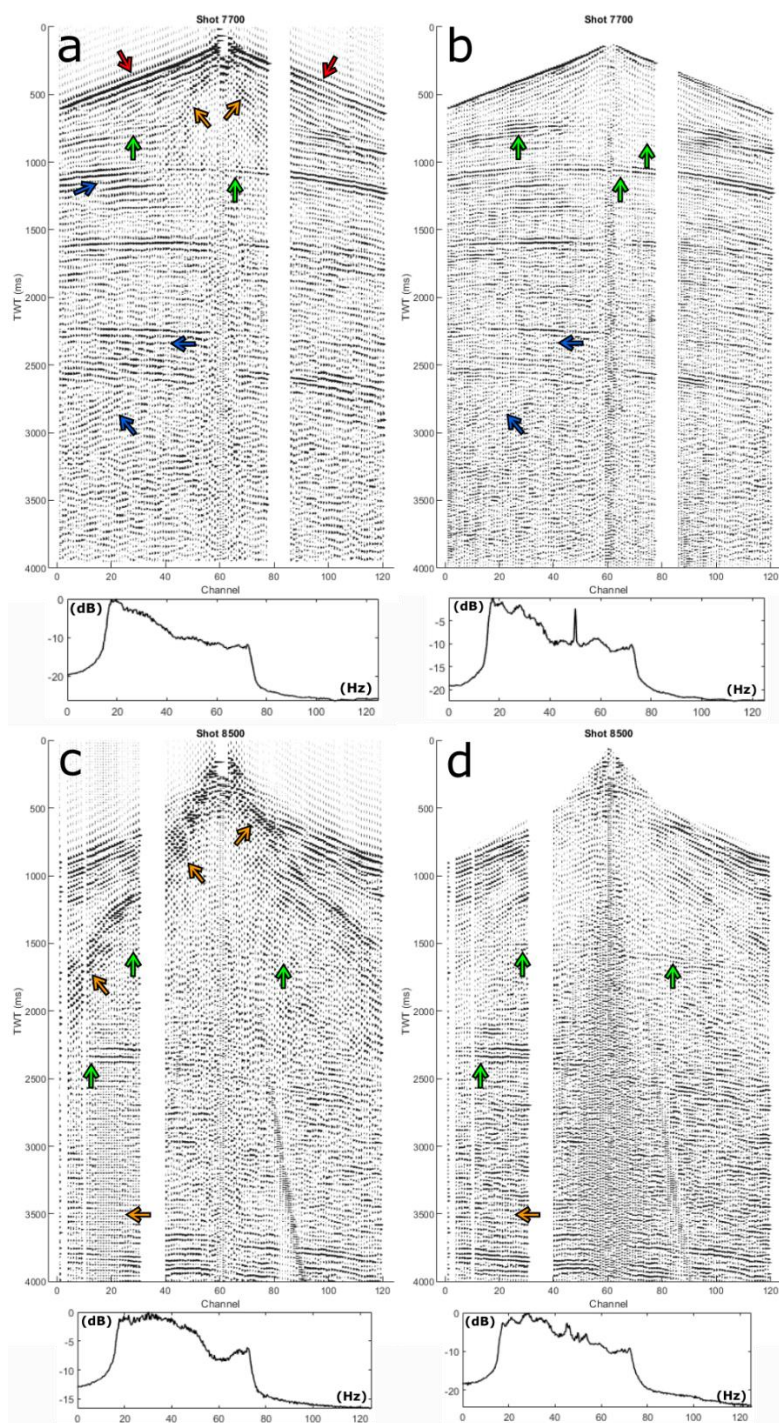


Figure 9.5: Comparison of two shot gathers (pairs a, b and c, d) both before (a and c) and after (b and d) applying the pre-stack processing flow described in [Table 9.1](#). Green arrows indicate enhanced reflections, blue arrows indicate suppressed multiples and red arrows indicate noise (ground roll, air wave and 50 Hz noise likely cause by AC power lines) that has been attenuated. The raw gathers have had a 1 s window AGC applied. Frequency spectra are shown as well.

Prestack processing comprised frequency filtering, f-k filtering and predictive deconvolution. A notch filter was used to remove a dominant 50 Hz component of the data, as indicated by the lowermost orange arrow in [Figure 9.5c, d](#), likely attributable to the presence of power lines carrying AC current

near certain regions of the survey. A bandpass filter was then applied to attenuate frequencies not contained in the sweep (i.e. 15 - 75 Hz). From shot-gather analysis, the direct s-wave arrival was determined to have an average velocity of 3100 m/s, thus an f-k mute was applied to remove any linear signal having a velocity less than 3200 m/s (or dip more than 16 ms/trace). Finally, a shot-dependent predictive deconvolution was applied with the prediction gap and operator length being specified every hundredth shot and interpolated for intermediate shots. Hence the deconvolution parameters varied across the length of the profile; the prediction gap had an average of 30 ms and ranged from 26 ms to 40 ms and the operator length had an average and range of 100 ms and 80 ms to 130 ms, respectively.

As indicated by the green arrows in [Figure 9.5](#), reflection continuity and temporal resolution is remarkably enhanced by deconvolution and frequency filtering. The deconvolution has also suppressed short-wavelength reflection multiples, as indicated by the blue arrows, and there has been significant noise reduction and signal boosting owing to the frequency, notch and f-k filtering. The 50 Hz noise can be seen in the left region of [Figure 9.5c](#) from 2 s downwards (orange arrow), which has been suppressed by the notch filter. Muted traces were already present in the raw data.

Detailed velocity analysis was performed using constant velocity stacks to generate a velocity model for dip-moveout (DMO) corrections. Prior to DMO corrections, careful residual static corrections (re-picking for three iterations) were applied to increase the coherency of the reflections. The DMO velocity model was chosen to ensure the imaging of both shallow and deep, steeply dipping reflections. The final DMO velocity model exhibited values from 3000 to 6500 m/s (the lower velocity values of 3000 to 4000 m/s are attributed to the Kalahari and Karoo sediments). An offset-time Kirchhoff dip-moveout (DMO) was then applied to the data, followed by stacking of the data along the CDP line with a 60% stretch mute. F-x deconvolution was applied to the stacked section to increase signal-to-noise ratio of the data by boosting coherent events. Several migration algorithms (e.g. Stolt, finite difference, phase shift and Kirchhoff migration methods) were tested for poststack migration. After several tests, the stack was migrated using a frequency-domain Kirchhoff migration ([Yilmaz, 2001](#)) as it produced the best images. A portion of the final migrated stack is shown in [Figure 9.6](#), showing prominent reflections (indicated by blue arrows) and the Moshaweng fault (indicated by red arrows). For interpretation, the migrated time section was converted to depth using a constant velocity of 6000 m/s.

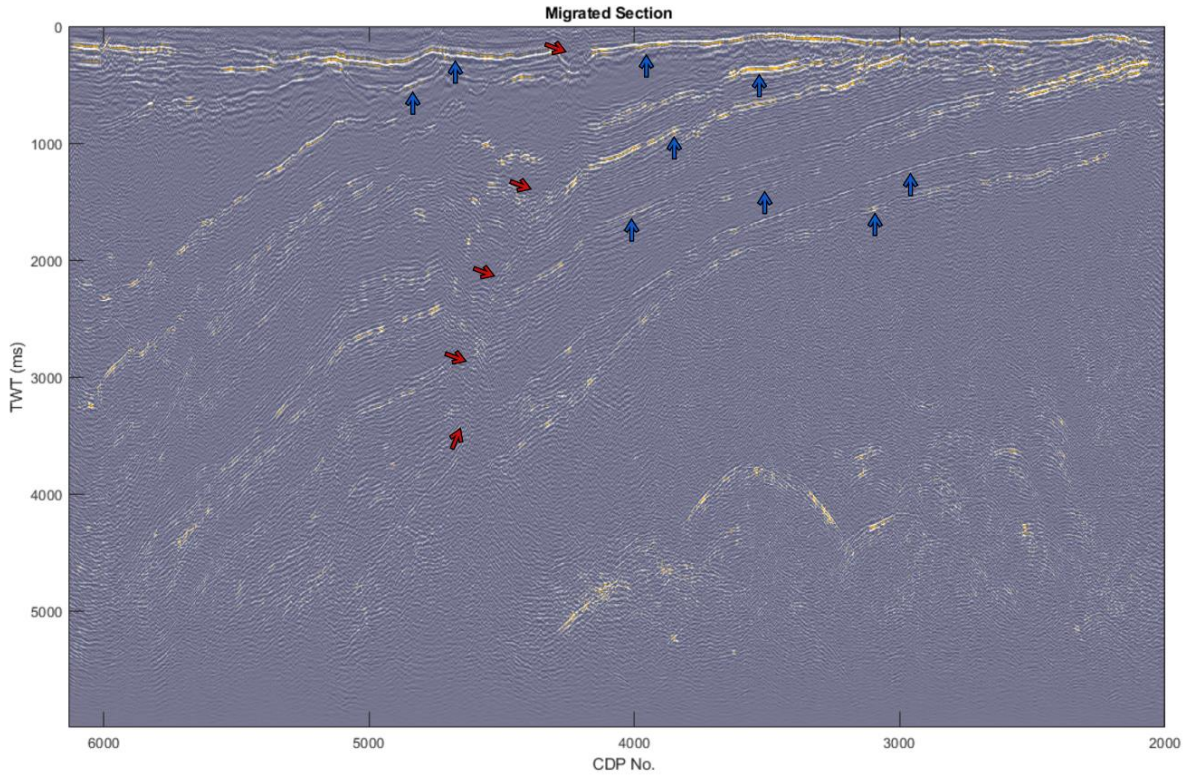


Figure 9.6: Portion of final reprocessed migrated stack after processing steps described in [Table 9.3](#). Significant reflections are labelled with blue arrows and the Moshaweng fault is labelled in red. The geology is separated into Phanerozoic sediments (flat reflectors indicated by uppermost blue arrow) and Paleoproterozoic units (dipping reflectors beneath flat reflector).

Attribute analysis

In this study, we make use of seismic attributes to enhance the detection of stratigraphic units within the Kalahari and Dwyka Groups and to examine the continuity thereof, with the aim of investigating neotectonics within these sediments such as faulting and folding. The seismic attributes used are instantaneous composite attributes as described in this section.

Instantaneous seismic attributes were first introduced by [Taner et al \(1979\)](#) and have since proven invaluable as seismic interpretation techniques to enhance the structural interpretation of the data ([Taner et al. 1979](#); [Barnes 2000](#); [White 1991](#); [Brown 1996](#)). The two core instantaneous attributes - the instantaneous amplitude $A(t)$ and instantaneous phase $\varphi(t)$ - are derived from the complex trace $c(t)$, associated with the original trace $s(t)$, as follows:

$$c(t) = s(t) + iH[s(t)]$$

$$A(t) = |c(t)|$$

$$\varphi(t) = \arg \{c(t)\}$$

Where $H[]$ is the Hilbert transform and $\arg\{\}$ is the complex argument, or angle. The cosine of the instantaneous phase, $cp = \cos(\phi(t))$, is typically used as an attribute instead of the phase itself.

Westgate et al. (2018) introduced an attribute that is a composite of either of the two instantaneous attributes and what they defined as the symmetry attribute. The composite attribute is a hue-saturation-intensity (HSI) image that is created by assigning one of the instantaneous attributes to the intensity component of the image and assigning the symmetry attribute to the hue component of the image. The symmetry attribute S is calculated by running a window through the seismic section of user-defined size and the centre value of the window is calculated to give the symmetry of the data within that window. This is done by taking a ratio of the total real component and total imaginary components of the Fourier transform of the data within the window as follows:

$$S = \frac{\int |R[F(v)]| dv}{\int |I[F(v)]| dv + \varepsilon}$$

Here, $R[]$ and $I[]$ denote the real and imaginary components, respectively, $F(v)$ is the Fourier transform of the window (with dimension that is the same as the data), and ε is a damping factor that ensures the denominator is not zero.

The advantages of this attribute, compared to the conventional attributes, are that it is able to enhance both strong and weak reflections while being able to distinguish between them, and it is also effective at tracking continuity of reflections in both hard rock and soft rock settings (Westgate et al., 2018).

9.7 Results and Seismic Interpretation

To assist in the interpretation of the line, the borehole data were examined alongside the corresponding nearest traces within the migrated section. Additionally, to investigate neotectonics of the near-surface Phanerozoic sediments, seismic attributes as well as a first break traveltimes tomography were calculated. These are presented here after a comparison between the legacy and reprocessed data sets showing the improvement in quality is given.

Comparison between legacy data and reprocessed data

In general, the seismic section exhibits similar first-order features to that of Tinker et al. (2002) (Figure 9.6 and Figure 9.3, respectively) in that it is characterized by two Phanerozoic sedimentary units, the late Carboniferous to early Permian Dwyka Group of the Karoo Supergroup and the Quaternary Kalahari Group sediments, which both lie unconformably on the broadly westward-dipping Archaean and Proterozoic units of the Ventersdorp, Griqualand West and Olifantshoek supergroups that, in turn, overlie the Archaean basement complex.

As the migrated legacy data were unavailable, the legacy unmigrated stacked section is used for comparison with the reprocessed unmigrated stacked section, as shown in Figure 9.7 and 8. Figure 9.7

comprises the majority of the profile and [Figure 9.8](#) comprises zoomed windows of both the legacy stack and the reprocessed stack. [Figure 9.7](#) is truncated at 1.5 s TWT for better display and because most improvements in the data are evident within the top 1 s. There are a few prominent differences between [Figure 9.7a](#) and [7b](#), which are examined in more detail within the coloured rectangles in [Figure 9.8](#).

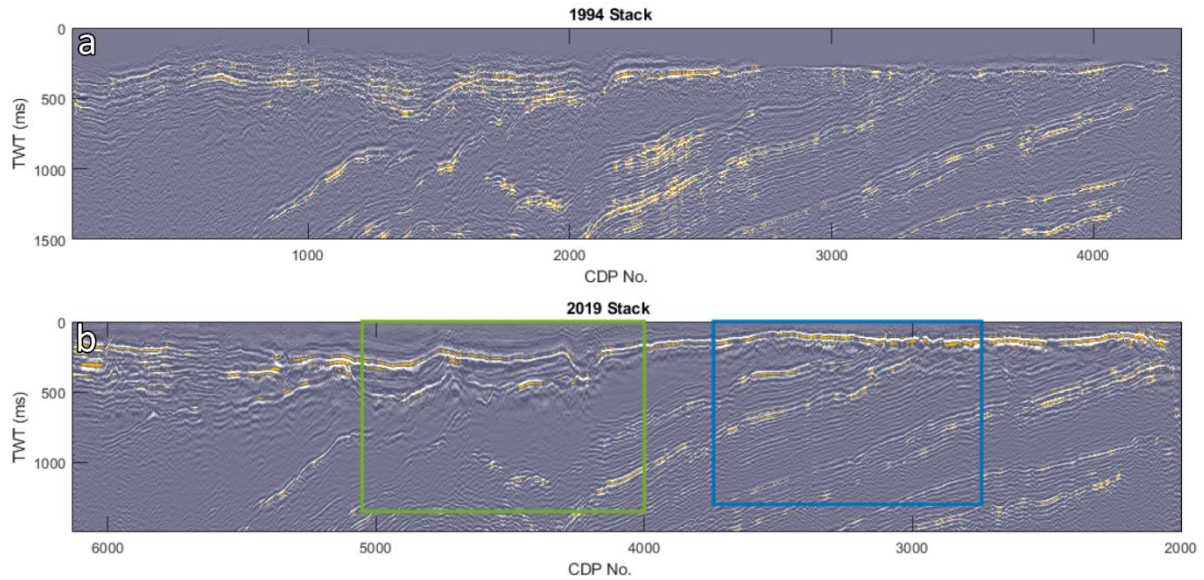


Figure 9.7: Comparison of legacy stack section (a) with reprocessed stack section (b). Regions of notable improvement are outlined in rectangles and corresponding zoomed sections are shown in [Figure 9.8](#). Note that CDP labels are different for the two datasets as our CDP bins increased from east to west (following acquisition).

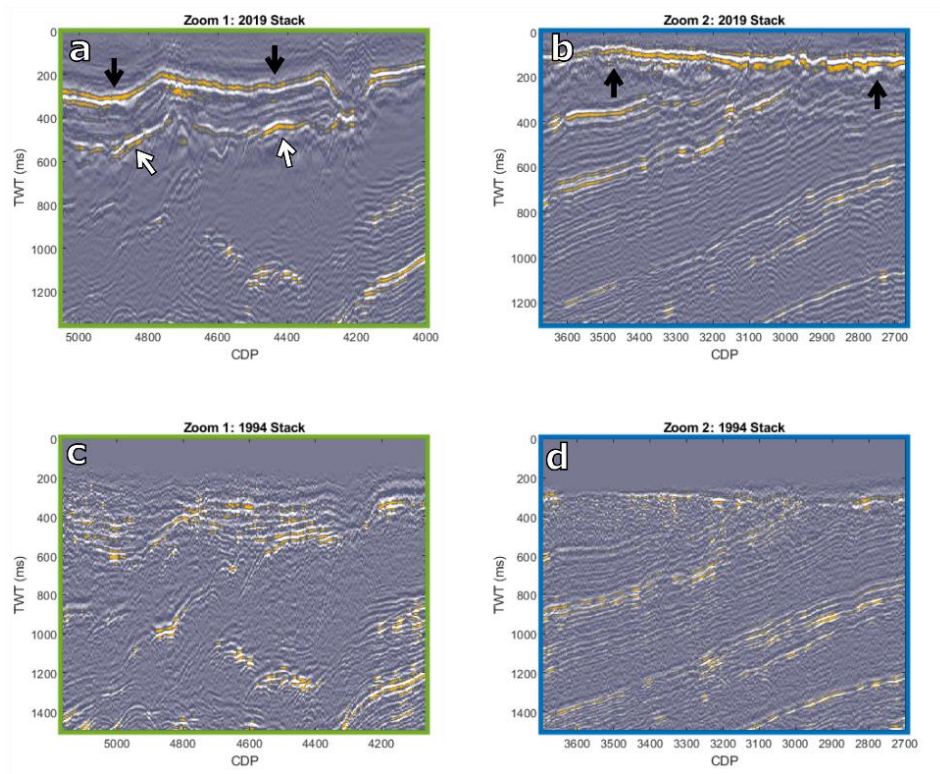


Figure 9.8: Zoomed regions of reprocessed stack (a and b) and corresponding regions of old stack (c and d). The colour of the outlined boxes correspond to those shown in Figure 9.7. White arrows indicate Dwyka unconformity and black arrows indicate Kalahari unconformity.

Figure 9.8 provides a convincing case for the value of reprocessing legacy data. Both the Dwyka (white arrows) and the Kalahari (black arrows) unconformities are significantly more clearly imaged in the 2019 reprocessed sections (Figure 9.8a,b) than in the 1994 sections (Figure 9.8c,d). Figure 9.8b clearly delineates both the dipping reflectors and the base of the overlying Kalahari Group (black arrows), which is poorly imaged in the 1994 stack (Figure 9.8d). In the 1994 data, the overall signal-to-noise ratio is poorer, preventing the reflections from being clearly imaged and blurring the junction point of the dipping layers and the unconformity. To further improve and enhance the mapping of the geological features, we applied seismic attributes to the reprocessed seismic section.

Seismic attributes applied to Phanerozoic sediments

Two instantaneous attribute composites have been computed to enhance the continuity of Kalahari Group and Dwyka Group reflections along the section and for the identification of faults, folds and other structural features along the reflections. Figure 9.9 shows different sections of the line within the top 800 ms TWT. These attributes are useful in tracking the continuity of reflections, and are thus useful in identifying faults and other disruptive features in a horizon. Such features are evident in the Kalahari Group unconformity in Zoom A and Zoom B of Figure 9.9, shown by light blue arrows, with particular attention to the Moshaweng Fault in Zoom B, which is more easily delineated in the symmetry-phase

composite. The Dwyka Group sediments also exhibit faulting in Zooms B and C in the composite attributes.

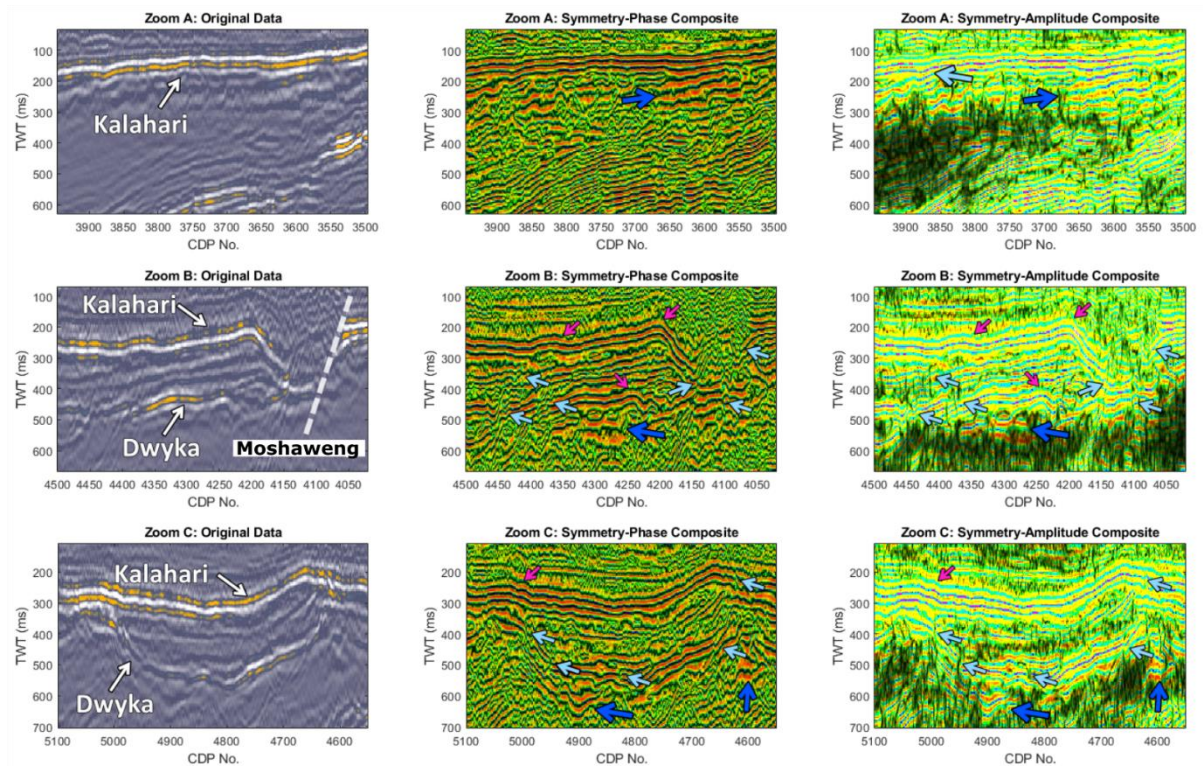


Figure 9.9: Attribute analysis: three different sections (Zooms A to C) showing, from left to right, the original data, the composite of symmetry and instantaneous phase cosine, and the composite of symmetry and instantaneous amplitude (after Westgate et al, 2018). Light blue arrows indicate faulting, pink and dark blue arrows indicate folding.

Seismic attributes also enhance subtle features in the data owing to their AGC properties, in this case warping and folding features are enhanced. Zooms A and C of Figure 9.9 illustrate significant co-folding in both the Kalahari and the Dwyka sediments, as indicated by the dark blue arrows, which are enhanced by the composite attributes. Pink arrows in Figure 9.9 show regions of substantial folding, which manifest in both the Kalahari and Dwyka unconformities.

Seismic tomography

A first break traveltime tomography up to a depth of 1200 m, which accounted for elevation, was computed using picked first breaks across the entire profile (maximum offset in shot gathers was ~ 3000 m). The velocities and ray paths are displayed in Figure 9.10a and b, respectively, as well as traces overlaying the velocities and an interpreted section in Figures 10c and d, respectively. The interpreted section merely shows proposed boundaries between strata, with faults other than the primary Moshaweng Fault not shown. The tomography shows that the seismic velocities of the Kalahari Group sediments range between 1000 m/s and 3500 m/s, whereas the well-compacted Dwyka Group sediments range between 3000 and 4000 m/s. The underlying Proterozoic and Archaean layers have velocities

larger than 5000 m/s and are clearly imaged by the tomography. These values are mostly in agreement with the borehole logs as interpreted by AngloGold, illustrated in Figure 9.4.

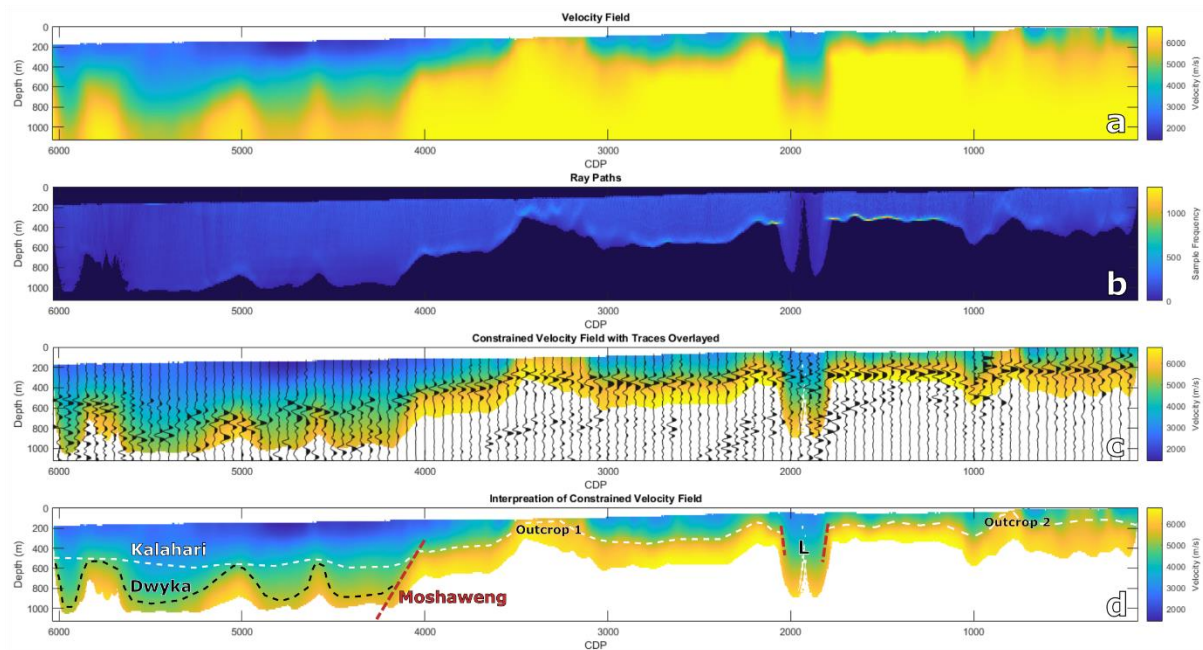


Figure 9.10: First-break traveltime tomography of seismic line constrained to 1200 m. The velocities are displayed (a), as well as the ray paths (b), and a composite in which only velocities that were sampled by at least one ray path are kept. The composite is displayed with every 50th trace of the stack overlaid (c) as well as with an interpretation (d). “L” in d corresponds to the magnetic lineament of the same label in Figure 9.2c as well as the interpreted section of Figure 9.11d.

The ray paths, shown in Figure 9.10b, sample the sediments of the Dwyka and Kalahari groups effectively, with as many as 1200 ray paths coinciding along the sediment interfaces. Most ray paths were refracted at the boundary separating the Phanerozoic sediments and Proterozoic metasediments, providing a good proxy of where this boundary lies and improving confidence in the interpretation. Figure 9.10c demonstrates good correlation between the refraction velocity model and the reprocessed stack. In this figure, every 50th trace is overlaid on the velocity model. There is good correspondence of the Kalahari Group unconformity along the majority of the profile. The Dwyka Group unconformity also has good correlation (Figure 9.10d). The strong correlation also boosts confidence in the interpretation.

The interpreted tomography is shown in Figure 9.10d. Indicated boundaries are boundaries based on velocity differences and do not incorporate faulting and short-wavelength folding. The long-wavelength folding of the Dwyka Group unconformity between CDPs 4250 and 5100, as also seen in Figure 9.7 and in detail in Figure 9.11a, is well imaged by the tomography, as well as the Moshaweng Fault at CDP 4200, where the Dwyka Group terminates. These were interpreted by Tinker et al. (2002) as palaeovalleys, however we show that they are more likely a result of faulting and folding (see Section 5.4.2). Also evident on the tomography are the two Proterozoic outcrop regions near CDPs 1000 and

3500, which are seen on the geological map (Figure 9.2a). Finally, at CDP 2000 in Figure 9.10d, the ray paths are severely disrupted, have no distinct boundary and travel to a significant depth, indicating a low-velocity zone with no clear lower boundary. This feature coincides broadly with the magnetic lineament “L” as well as the speculated 80 km rim crater of the Morokweng impact crater (Figure 9.2b), both of which lie at oblique angles to the profile.

Structural Interpretation

Kalahari Group

The Kalahari Group unconformity along the length of the profile is notably not seismically transparent, as was suggested by Tinker et al. (2002). This allows us to precisely constrain Kalahari Group thicknesses across the profile; maximum thickness is up to 200 m. The unconformity is also disrupted by steep ($>60^\circ$) faults with varying orientations and apparent normal and reverse displacements of up to 100 m, and shows evidence of folding comprising antiforms and synforms (see “An and Sn” Figure 9.11a through 9.11d). Figure 9.11a exhibits the prominent disruption by thrust faults and the large-wavelength (~ 10 km) gentle, west-verging folding, as well as significant disturbance by the Moshaweng Fault that downthrows the Kalahari Group to the west by ~ 200 m. The latter indicates that neotectonic reactivation of the Moshaweng Fault was more significant than suggested by Tinker et al. (2002).

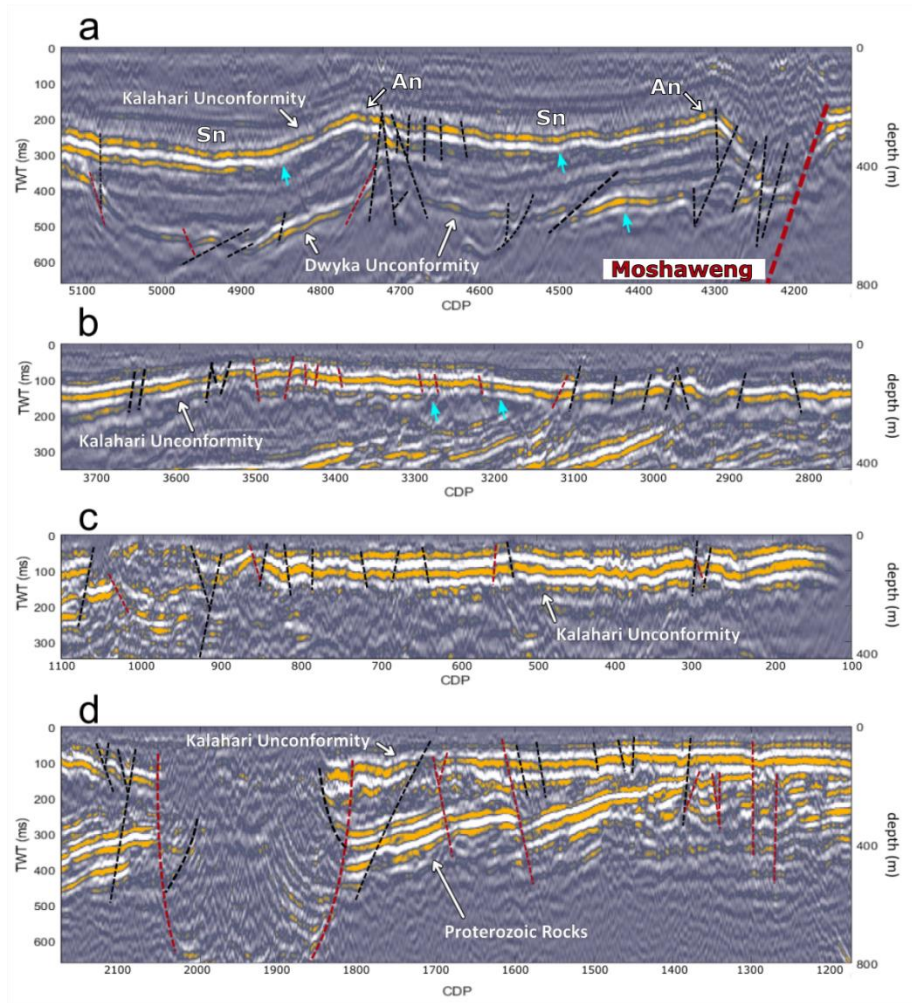


Figure 9.11: Interpretations of zoomed regions of the seismic line, focusing on the Kalahari and Karoo sediments. Black lines and red lines are indicative of thrust and normal faults, respectively, and cyan arrows denote folding. An: Antiform; Sn: Synform.

Also seen in [Figure 9.11d](#) is an ~5.5 km break in continuity between CDPs 1830 and 2050 that is flanked by relatively large-displacement (up to 200 m) faulting and more intense folding of the Kalahari Group. It is evident that this feature also displaces the west-dipping Proterozoic rocks beneath the Kalahari unconformity but the unconformity itself does not demonstrate a similar magnitude of displacement. Examination of the raw shot gathers within this zone, as shown in [Figure 9.12](#), reveals that there are no evident coherent reflections and the first breaks are virtually incoherent, with a strikingly clear disruption in reflections at both ends of the feature, to a degree where the edges of the feature can be precisely pinpointed. The lack of displacement, as observed in the GWS, within the Kalahari group suggests this anomaly to be post-GWS and pre-Kalahari, where the lack in continuity of the Kalahari can be attributed to an acquisition defect or loose ground. However, the structural interferences observed within the Kalahari at the flanks of the anomaly suggest otherwise. A plausible interpretation is that the structural interference (conceivably a fault) occurred post-GWS, displacing these strata in a normal sense, and was then reactivated post-Kalahari in a way that that resulted in no net vertical

displacement. A good candidate for this description is a normal fault that runs oblique to the profile occurring post-GWS and was reactivated as a strike-slip fault post-Kalahari.

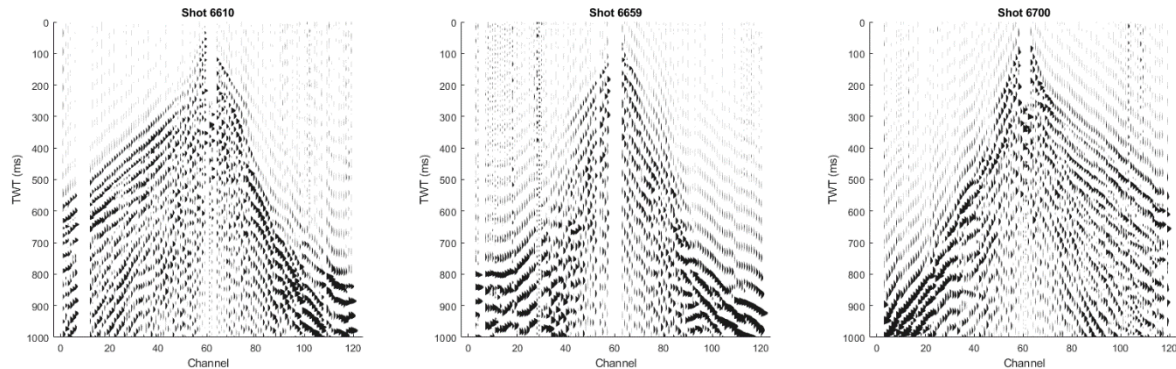


Figure 9.12: Shot gathers of shot 6610 to the West, shot 6700 to the East, and shot 6659 at the centre of the major discontinuity illustrated in [Figure 9.11d](#) and likely linked to lineament L1 in [Figure 9.2c](#). Note the collapse of first breaks within this region, from the centre of shot 6610 through shot 6659 to the centre of shot 6700, possibly caused by loose overburden, leading to bad coupling.

Karoo Supergroup

The Dwyka Group is limited to the western third (~ 45 km) of the profile and is terminated by the Moshaweng Fault at CDP 4250 ([Figure 9.11a](#)). As shown in [Figure 9.11a](#), the Dwyka unconformity is folded and is significantly disrupted by multiple thrust faults. When compared to the overlying Kalahari unconformity, there appear to be both similarities and notable differences between the structures affecting the two unconformities. Both the Dwyka and Kalahari Group rocks exhibit significant co-folding, as seen in [Figure 9.11a](#); however, the Dwyka Group strata appear to be slightly more intensely folded than those of the Kalahari Group. At CDP 4700 – 4750 both unconformities are folded and faulted; however, the west-verging antiform defined by the Kalahari unconformity is less disrupted than the Dwyka unconformity ([Figure 9.11a](#)).

The Dwyka unconformity exhibits further more substantial disruptions in its continuity (such as the minor thrust faults at CDPs 4500 and 5000 and the accompanying folding; [Figure 9.11a](#)) that are not evident, at least to the same degree, in the Kalahari unconformity, which appears to have better continuity than the Dwyka unconformity.

Borehole data

As previously mentioned, the two boreholes KHK-1 and NEV-1 ([Figure 9.4](#)) were not used by [Tinker et al. \(2002\)](#) in their interpretation of the profile. [Figure 9.13](#) shows the borehole logs as well as their associated synthetic seismograms superimposed on the migrated seismic data. There is reasonable correlation between the synthetics and the seismic section. The major reflection package within the seismic section (centred at 400 ms) is likely caused by the Campbell Rand Group metasediments

(dolomite) of the GWS, where the major velocity contrast at ~ 0.2 s in the seismogram denotes the top, which is masked by the high amplitude Kalahari unconformity in the seismic section. The bottom marks the contact with the Ventersdorp Supergroup. While the synthetic seismogram suggests a high amplitude reflection at the base of the Ventersdorp succession, this is not observed in the seismic section. This may be attributed to lack of density information within the synthetic seismogram calculations, that would have reduced the amplitude significantly. The two reflectors located at 1 s and 1.2 s TWT on the seismic section are likely related to the granodiorite – gabbro and diabase – granite contacts shown in the log, respectively. These reflectors were interpreted by [Tinker et al. \(2002\)](#) to be the respective bases of Ventersdorp lavas and sediments underlying the GWS metasediments. [Figure 9.13](#) shows this is likely not the case; instead the reflectors represent intrusions that extend towards the Moshaweng fault. The reflection located at the base of the lower diabase sill (at 1.1 s TWT) marks the basement contact, however, in contrast to [Tinker et al. \(2002\)](#), who interpreted this as the unconformable base of the Platberg Group, we suggest that the evidence is consistent with (a) a thin sequence of Klipriviersberg Group basalts beneath the Platberg Group and that, in accordance with [Reimold et al. \(2002\)](#), (b) the Klipriviersberg Group is separated from the granitoid basement complex by ~ 1350 m of intrusions, only one of which has been confirmed to be of Platberg Group age.

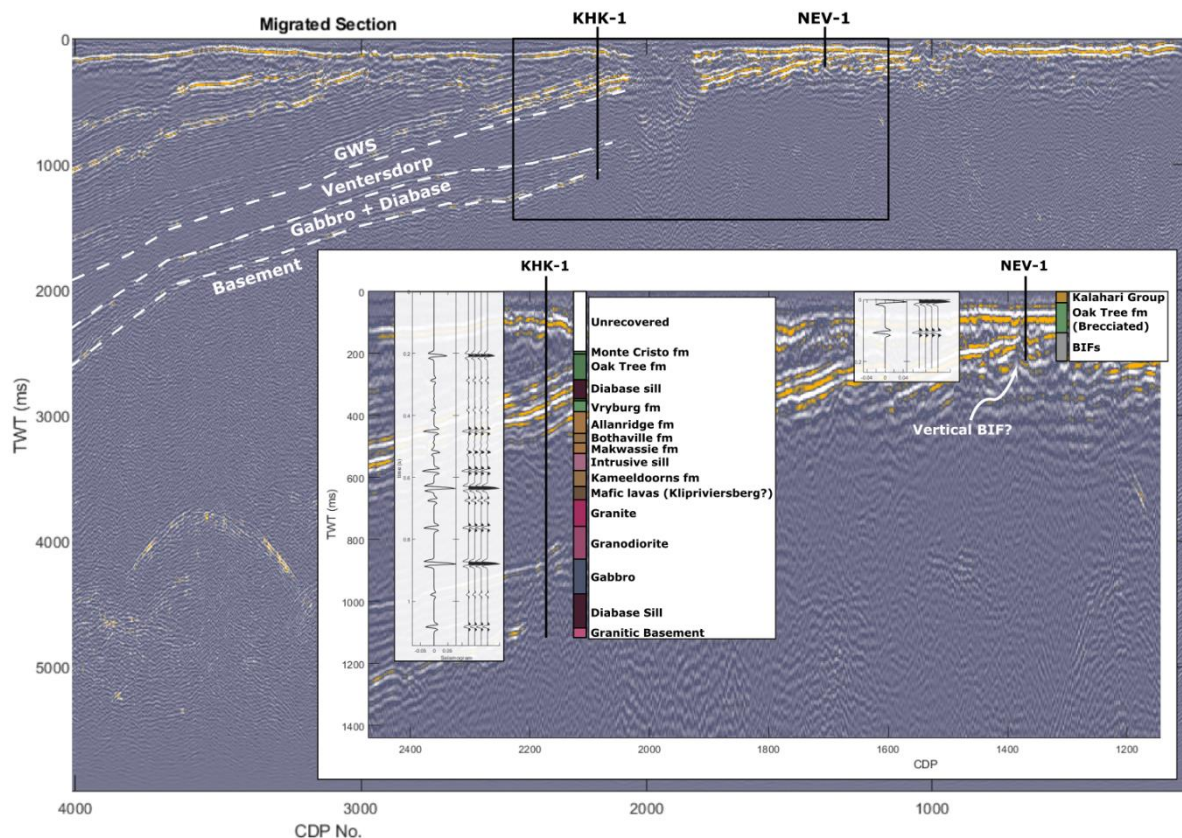


Figure 9.13: Interpretation of migrated section using borehole logs KHK-1 and NEV-1 (taken from AngloGold’s original interpretation; Klipriviersberg Formation is our interpretation of “mafic lavas”). As mentioned previously, synthetic seismograms were calculated using velocity information only and not density. Hence, the calculated

reflectivities are approximations and may not correlate well with the observed reflections (such as at the base of the Ventersdorp Supergroup).

Moshaweng Fault and anticline

Figure 9.14 displays the reprocessed section outlining the Moshaweng Fault as well as the hangingwall anticlinal fold within the Palaeoproterozoic metasediments (the Phanerozoic sediments are discussed in more detail in the previous section). The layers to the east of the fault were interpreted by extending the borehole interpretation shown in Figure 9.13, as well as the suboutcrop map shown in Figure 9.2b. Our new interpretation implies a 30° dip of the Moshaweng Fault, which exhibits complex variable slip, with reverse dip separation on the order of 1.3 km in the pre-Elim Group strata and normal dip separation on the order of 780 m in the Elim Group and Hartley Formation. This is significantly different from Tinker et al.'s (2002) interpretation of >6 km of normal dip-slip.

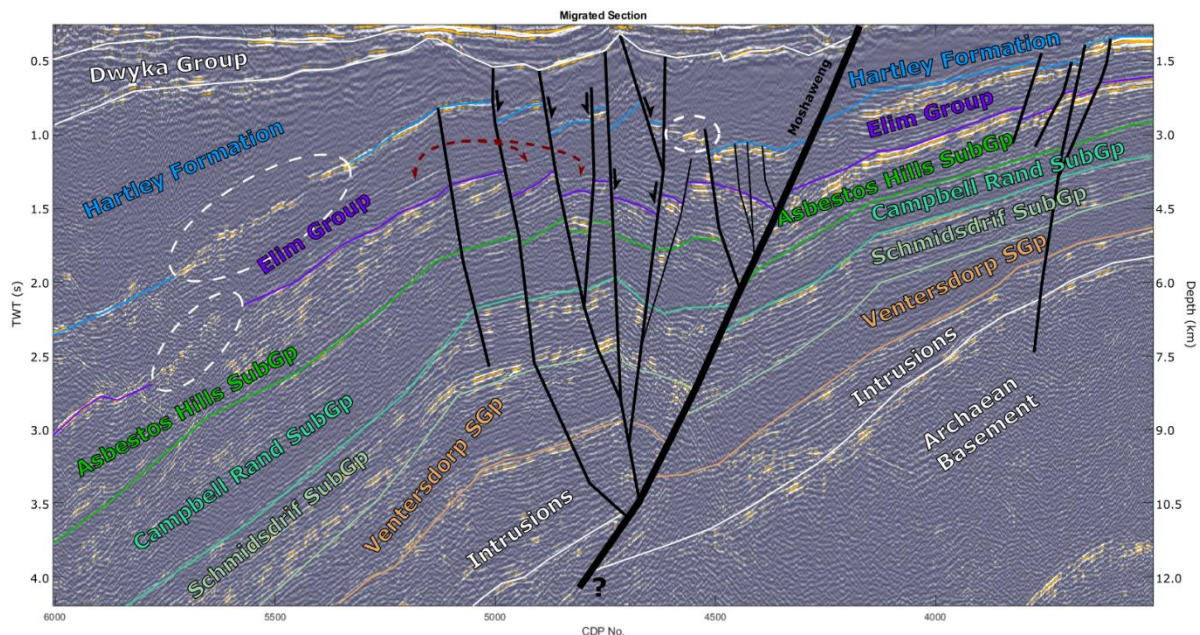


Figure 9.14: Interpretation near the Moshaweng fault in comparison to the interpretation by Tinker et al. (2002) as shown in Figure 9.3C. The proposed Neylan unconformity is not evident and the features interpreted as complex low-angle, east-verging thrusting by Tinker et al. (2002) in the Elim Group are here interpreted as the product of normal slip faults antithetic to the Moshaweng Fault that also affect the Hartley Formation. Correlation of stratigraphic units also suggests the Moshaweng fault has a significantly reduced slip. White lines indicate horizons, black lines indicate faults, white ellipses denote areas of possible thin-skinned thrusting, red arrows denote reflections with similar characteristics.

An additional difference to the interpretation of Tinker et al. (2002) is that, together with some synthetic faults, the numerous antithetic faults present in the hangingwall anticline (black lines in Figure 9.14) appear to cut the Neylan unconformity that was proposed by Tinker et al. (2002) (Figure 9.3C). Red arrows in Figure 9.14 track a single reflector between some of these fault blocks that is used as a marker for displacement. Our interpretation of the source of these offsets differs from that of Tinker et al.

(2002), who proposed disruption by shallow west-dipping thrusts. White ellipses in Figure 9.14 show the locations of a series of possible low-angle thrusts along the boundary between the Hartley Formation and the Elim Group (which was previously interpreted by Tinker et al, 2002, as the Neylan Unconformity). From our interpretation in Figure 9.14, crustal thickening is observed in all the sub-Dwyka units ranging from 30% to 140% in the Hartley Formation within the anticline, significantly less than that proposed by Tinker et al. (2002).

9.8 Discussion

Resolution of seismic data

Reprocessing the legacy seismic profile KBF03A has yielded a migrated section that is clearer, characterized by a greater signal-to-noise ratio, and has allowed for a refined interpretation. The geology over which the profile was collected is somewhat more complex than previously suggested by Tinker et al. (2002), with Karoo and Kalahari sediments exhibiting widespread normal and reverse faulting as well as significant warping and folding above a folded and faulted Precambrian basement. Our interpretation is reliant on our confidence in the resolution of the seismic data relative to Tinker et al. (2002). The dominant frequency of the final migrated section (Figure 9.6) is ~35 Hz, yielding a tuning thickness of 40 m (assuming an average medium velocity of 5500 m/s) (Widess, 1973), which is below the minimum layer thickness logged in either of the boreholes (attributed to the 100 m thick Allanridge Formation of the Ventersdorp Supergroup in borehole KHK-1; Figure 9.4a). The lateral resolution is represented in Table 9.3, where the Fresnel-zone width (Yilmaz, 2001) along the profile is calculated for depths and velocities representing our velocity model. This gives a good indication of how constrained our interpretation of the Moshawng Fault is, and also explains why the fault zone dilates with depth (Figure 9.13). Given that our focus lies mostly within the top 10 km, the maximum Fresnel-zone width does not exceed 1 km, implying features smaller than this are likely still detectable but in the form of diffractions rather than reflections (Malehmir et al., 2009).

Depth (km)	Average velocity (km/s)	Fresnel-zone width (m)
2	5.0	380
4	5.5	560
6	6.0	720
8	6.0	830
10	6.0	925
12	6.5	1055
14	6.5	1140

Table 9.3: Fresnel-zone width of KBF03A at different depths and velocities.

Seismic attributes

Although the reprocessing steps undertaken in this study have improved the quality of the data compared to the original 1994 data, conventional interpretation of the reprocessed data did not allow for the analysis of the data to their full potential, especially of neotectonic features within the Kalahari and Karoo strata. Our reprocessed data serve as the basis for generation of seismic attributes, which are an innovative way of enhancing the detection of these features in the data. For example, subtle faulting and folding can be recognized on the migrated seismic section, which was not possible with conventional amplitude-based interpretation (Figure 9.9). The prominent first-order structure known as the Moshaweng Fault (Tinker et al., 2002) has been imaged and reinterpreted using instantaneous attribute composites. Additionally, the position and orientation of structures (faults) that offset the near-surface strata have been enhanced with a high level of confidence. The Symmetry-Paraphase Composite (SPC), in particular, has enhanced weak reflections arising from lithological boundaries having minor differences in velocity and density within the Kalahari Group sediments. This is mainly owing to the attribute's insensitivity to the reflection strength of the data (Westgate et al., 2018). Owing to the presence of noise on several seismic attribute displays (e.g., Symmetry-Amplitude Composites in Figure 9.9), it was also necessary to rely strongly on borehole data to validate our seismic interpretation. Our results demonstrate that instantaneous attribute composites, with special colour coding, can improve the detection of weak reflections and provide reliable structural interpretations.

Phanerozoic-Cenozoic tectonics

The improvement in quality of imaging from reprocessing the data is most evident in the Phanerozoic Dwyka and Cenozoic Kalahari groups (Figure 9.8). The downfaulted displacement of the ~200 m of the Kalahari Group by the Moshaweng fault is consistent with extensional tectonics as suggested by Tinker et al. (2002) in their fourth tectonic phase, although the quality of their data precluded an estimate of the magnitude of displacement or the recognition of more widespread deformation. West of the Moshaweng Fault, undulation in the strata of both Kalahari and Dwyka groups are evident (Figure 9.11a). In contrast to Tinker et al. (2002) who interpreted it as a valley within the Kalahari Group (Figure 9.3E), we interpret the feature centred near CDP 4950 in Figure 9.11a as a large (~10 km wavelength) west-verging syncline. Folding is also observed in Figure 9.11c, where it is associated with thrust faulting and a major disturbance centred at CDP 1000. This disruption could be attributed to a large fault zone oriented oblique to the profile (although nothing is seen on the magnetic image; Figure 9.2), or possible hydrothermal alteration. The lack of outcrop or deeper structure in the seismic profile further hinders interpretation of this feature but the strong disruption contrasts with the comparatively uniform and continuous Kalahari unconformity seen over much of the rest of the profile. The interpreted folding and faulting within the Kalahari Group (Figure 9.11a – d) is consistent with outcrop evidence of complex post-Kalahari Group compressional tectonics seen around Hotazel (Haddon and McCarthy, 2005; Gabrielli, 2007).

Another major disruption seen within the Kalahari Group is the ~5.5 km gap in continuity near CDP 2000 (Figure 9.11d). The feature is located at the intersection point of the seismic profile and a major WSW-trending lineament, L, in the magnetic anomaly map, as shown in Figure 9.2c, as well as the possible intersection of the inferred edge of the Morokweng impact structure (Figure 9.2b,c). If this is the case, it is possible that our data is imaging the effects of a highly oblique rim fault that has thrown down the GWS sediments towards the NE (Figure 9.11d) by ~200 m, which is consistent with a crater rim fault. Such a feature may then be linked to the previously mentioned disturbance at CDP 1000, as both broadly coincide with the proposed crater rim in Figure 9.2b and c. If this anomaly does not represent a physical geological structure that is being imaged by the seismics, it might be an artefact or general lack of illumination within the seismic data attributed to, for example, poor geophone coupling or a highly variable weathered layer. However, the former is more likely as it accounts for the displacement of the GWS sediments seen in Figure 9.11d. A number of the faults within the GWS can be seen to extend into the Kalahari Group, with lesser amounts of slip (<100 m), suggesting that a pre-Kalahari Group fault in this area could have been further reactivated after deposition of the Kalahari Group.

The thickness of the Dwyka Group west of the Kuruman Hills is considerable, in excess of 471 m ~35 km north of the profile, and 731 m in the Hotazel area (Figure 9.1) (Haddon and McCarthy, 2005; Gabrielli, 2007). This great thickness has previously been attributed to the deposition of the diamictite by a glacier running along a northerly trending valley (Visser, 1983); however, this trend coincides with that of the Moshaweng Fault of Tinker et al. (2002) and Beukes et al. (2019). In the light of the evidence presented here for significant post-Dwyka tectonics, it is thus necessary to consider whether this thickness variation is caused by differential erosion or by post-Dwyka faulting. Cousins (1950) attributed thickening of Dwyka sediments along the N-S, pre-Karoo, De Bron Fault in the Free State Goldfield to preferential erosion of downfaulted less resistant strata on the western side of the fault. His palaeotopographic interpretation was based on a lack of evidence of any substantial post-Karoo faulting in the Free State Goldfield area and the extreme thickness variation over relatively short horizontal distances, reaching 800 m, in the valley. Whilst it may be possible that the Dwyka glaciation could have preferentially exploited highly fractured or softer rock along and west of the Moshaweng Fault, the scale of Cenozoic faulting alone seen in the KBF03A profile (Figure 9.11a) is of the order of 200 m, and abundant evidence exists that this was also preceded by pre-Kalahari, post-Dwyka, faulting. It is thus highly plausible that the greater proximity of the KBF03A profile to the current continental margin could indicate that Dwyka Group thickness variations along the western craton margin could reflect Gondwana rifting and younger tectonics rather than any erosional palaeotopographic causes.

Compressional tectonic features (thrust faults, folds) observed within the Dwyka Group that predate the Kalahari Group (Figure 9.11a) could be attributed to the ca. 210 Ma Cape orogeny. In this case, extensional features related to the ca. 135 Ma Gondwana rifting would overprint, and possibly reactivate

the compressional features. Similar evidence of both compressional and extensional tectonics postdating the 1.0-1.2 Ma Kalahari Group (Matmon et al., 2015) indicate a similarly complex recent history, which would have implications for older structures like the Moshaweng Fault. Both Tinker et al. (2002) and Beukes et al. (2019) proposed several hundred metres of post-Karoo normal dip-slip downthrow to the west along this fault; however, our data refine this further by showing that a lesser amount of west-side-down displacement occurred after Kalahari Group deposition. Whilst the amount of post-Kalahari Group slip appears to be of the order of ~200 m, the absence of Dwyka Group to the east of the fault would suggest a cumulative displacement of at least 400 m since Dwyka times, meaning that the earlier of the two extensional events would have involved a minimum of 200 m of slip. Near CDP 4700 (Figure 9.11a), there appears to be a horst block that has uplifted the Dwyka Group base by ~150 m closer to the Kalahari unconformity. This feature was interpreted by Tinker et al. (2002) as glacial palaeotopography but, given the better resolution in our data and considering the arguments above, we believe that movements of hundreds of metres along the Moshaweng Fault after Dwyka Group deposition are reasonable. Unfortunately, it is not possible from the data to see if the fault also accommodated a slightly earlier thrust component that was then reversed by the later extensional movements.

Paleoproterozoic stratigraphy

The new information from borehole KHK-1 (Figure 9.13) discloses a necessity to update the stratigraphic interpretation of Tinker et al. (2002). This is primarily because their interpretation of the base of the Ventersdorp Supergroup, and thus the basement unconformity, appears from borehole information to be the base of a diabase sill that interfaces with the basement. Furthermore, the borehole reveals the base of the Ventersdorp Supergroup, consisting of mafic lavas that we interpret as depleted Klipriviersberg Group and not Platberg Group as inferred by Tinker et al. (2002), overlies 1350 m of intrusive plutonic rocks that themselves include intrusive diabases. The reflections associated with these intrusions, as well as the GWS – Ventersdorp Supergroup contact, can be tracked to the Moshaweng Fault, 75 km west along the profile, thus providing an anchor for interpretation of the strata in the western block (Figure 9.14). Tinker et al. (2002) interpreted the uppermost layer in the eastern block to be GWS strata (G_0 in Figure 9.3A), however, this would imply a 300% thickening of this unit in the western block, which is inconsistent with the thickening of the other layers observed in the hanging wall (Figure 9.3). Based on the seismic character of this unit, we interpret the uppermost layer of the eastern block to be of the Hartley Formation (Figure 9.14). This would indicate a more consistent thickness of this unit across the fault. The interpretations were carried across the fault by cross-correlating traces and investigating phase characteristics on either side. This anticline is characterised by a 500 m amplitude and 10 km wavelength. Our data show that the Hartley Formation is 140% thicker in the hanging wall, contrasting with the 300% thickening proposed by Tinker et al. (2002).

Apart from the anticline, the structure of the western block (Figure 9.14) consists of a series of antithetic and synthetic faults that disrupt most of the west-dipping supracrustal package. The red arrows in Figure 9.14 track a reflection across these faults, and the middle red arrow points to a reflection that was interpreted by Tinker et al. (2002) to be a palaeovalley (Figure 9.3E), however our data suggest this reflector is instead faulted. The proposition made by Tinker et al. (2002) that this reflection delineates an unconformity (the Neylan unconformity) owing to the truncation of bedding at the apex of the anticline is not evident in our data; instead, parallel bedding can be observed along this reflection and disruptions within the anticline can be attributed entirely to faulting, with no evident erosion present. This high-angle faulting further accounts for the disturbances in the “T” reflector proposed by Tinker et al. (2002) (Figure 9.3C), which they attributed to east-verging thrusts. However, there do appear to be such thrusts (reflectors dipping slightly more steeply than bedding) further west along this reflector, as indicated by the dotted ellipses. These features would be broadly consistent with the inferred intersection of the Blackridge Thrust with the profile (Figure 9.1); however, it is important to note that, despite the increased resolution achieved through the current processing of the data, no evidence was found in the seismic profile of thin-skinned thrusting. This may be attributed to the absence from the profile of the uppermost sediments of the Olifantshoek Supergroup based on our stratigraphic interpretation.

Moshaweng Fault

The slip nature of the Moshaweng Fault appears complex, with apparent reverse slip of magnitude 1.28 km observed in the pre-Elim Group strata, apparent normal slip of magnitude 800 m observed in the Elim Group and Hartley Formation, and 200 m of normal slip post-Kalahari sediments and at least another 200 m of normal slip between the Dwyka and Kalahari Group deposition (Figure 9.11a and Figure 9.14). Whilst there is clear evidence from the variable displacement of the Dwyka and Kalahari unconformities that the fault must have been reactivated – and possibly even inverted - several times, it is less clear how many events occurred, their absolute ages, and what the actual slip direction was.

Tinker et al. (2002) proposed that the Moshaweng Fault originated as a normal listric fault that predated thin-skinned east-directed thrusting but that its main phase of movement occurred after this thrusting when it was reactivated first in a normal slip sense with or without strike-slip movement that produced the negative flower structure seen in the antithetic faults of their model (Figure 9.3C) and then again in a normal slip sense after deposition of the Kalahari Group. The flower structure geometry and apparent exceptional magnitude of inferred offset of the pre-Dwyka reflectors (6.5 km) led Tinker et al. (2002) to speculate that the main fault movement occurred during post-Kheis orogenic collapse. Apart from the lack of evidence in the profile of significant large, orogenic-scale, disruption and thickening of the supracrustal sequence, our interpretation suggests that pre-Dwyka displacement on the Moshaweng Fault was both considerably smaller and that it was primarily thrust-related. A thrust-dominated

displacement history would fit the evidence of [Beukes et al. \(2019\)](#) who concluded that the northeasterly extension of the Moshaweng Fault displaced the rocks of the Molopo Farms Complex in a reverse sense. However, it must also be recognised that no evidence has been obtained of the exact slip sense along the fault, meaning that it is equally possible that the pre-Dwyka history may have been dominated by, or involved at least some, strike-slip movement.

Using the evidence from [Beukes et al. \(2019\)](#), significant movement on the Moshaweng Fault must postdate the 2.055 Ga Molopo Farms Complex and must be either reverse or dextral strike slip, or a combination thereof. This interpretation means that a complex scissor movement to accommodate large contradictory senses of movement in different parts of the fault ([Beukes et al., 2019](#)) is no longer needed. As movement along a NE-trending strike-slip fault would be highly oblique to the plane of section, a transpressional strike-slip origin could account for both the hangingwall anticline and the variable and apparently contradictory displacements in different parts of the Archaean-Proterozoic sequence (in such a slip geometry, small angular differences in the 3-D orientation of the Palaeoproterozoic sequences could explain such variation); however, the fault has a shallow dip (30°). An oblique thrust origin would be more consistent with the low angle of dip of the fault but would then require polyphase fault inversion to explain the complex apparent offsets. Neither of these scenarios is easy to reconcile with the negative flower structure pattern invoked by [Tinker et al. \(2002\)](#); however, extensional reactivation of the original fault could have occurred (see below).

If the Moshaweng Fault originated after 2.055 Ga in a compressional environment, then the most plausible cause, and therefore timing, of thrusting would be the Kheis event. The more limited displacement of 1.2 km might be more easily reconciled with the limited thickening seen in the profile and apparent regionally in the distal parts of the Kheis Belt (e.g., [Stowe, 1986](#); [Moen, 2006](#)). As discussed previously, the age of this event has recently been revised from 1.7-1.8 Ga to 1.2 Ga by [Van Niekerk and Beukes \(2018\)](#). If the Moshaweng Fault is principally a Kheis structure, it raises questions about the nature and location of the so-called Kheis Front. [Van Niekerk and Beukes \(2019\)](#) show the Moshaweng Fault truncated by the Blackridge Thrust, based on magnetic data. It is beyond the scope of the present project to evaluate whether the Moshaweng Fault might be a splay of the Blackridge Thrust (which would require eastward revision of the northern extension of the Kheis Thrust Front), or whether it might be a reactivated pre-Kheis fault within the footwall of the Blackridge Thrust. It is also worth noting that reflections observed in the deeper crust may not represent accurate shapes due to out-of-plane seismic energy effects on 2D seismic sections ([Malehmir and Bellefleur, 2009](#)). Answers to these problems may lie in understanding the deep-level geometry of the Moshaweng Fault, possibly through a 3D seismic survey. Unfortunately, neither [Tinker et al.'s \(2002\)](#) nor our interpretation have been able to establish whether the fault extends into the basement or deflects along the basement-cover contact.

Our preferred interpretation of the subsidiary fault patterns in the Archaean-Palaeoproterozoic sequences in the KBF03A profile is that the normal faults represent a younger event than the thrusting event and that the normal-sense displacement of the Elim Formation can be attributed to the same extensional event. If thrusting is Kheis and we accept [Van Niekerk and Beukes' \(2019\)](#) revised age for the Kheis event, extension must have occurred between ~1.2 Ga and 0.25 Ga when the Dwyka Group was deposited. After 1.2 Ga the western edge of the craton underwent NE-SW convergence during the 1.1 Ga Namaqua-Natal event. Given its NE strike, the Moshaweng Fault would have been favourably oriented during NE-SW compression to accommodate extension. Far-field stresses related to the onset of the Pan African Wilson Cycle prior to 600 Ma may also be a possibility. It is, thus, plausible that negative inversion of the Moshaweng Fault masks the true extent of the earlier thrust displacement and can account for the apparent flower structure geometry seen in [Figure 9.3](#) and [Figure 9.14](#).

Despite evidence of at least two (post-Dwyka and post-Kalahari Group, respectively) compressional events, the cumulative slip displacement on the Moshaweng Fault in Phanerozoic-Cenozoic times was normal and exceeded 400 m. These events, in turn, may have reversed some of the early thrust displacement on the fault. It is, thus, possible that the Moshaweng Fault originally involved a total thrust displacement of 2-2.5 km.

9.9 Conclusions

Reprocessing the 150 km long legacy seismic profile KBF03A (6 s TWT) using a modern processing flow has yielded an improved image of the supracrustal sediment package found in the profile that spans the western margin of the Kaapvaal Craton. In particular, with the incorporation of complex seismic attributes and first-break traveltimes tomography, the better imaged 250 Ma Dwyka Group and 1.2 - 1 Ma Kalahari Group sediments exhibit multiple reverse and normal faulting ($>60^\circ$) of non-preferential orientations as well as mostly west-verging folding, implying non-trivial neotectonics within the region. Two major disturbances within the Kalahari unconformity as well as faulting of the underlying metasediments coincide with the intersection points of a 80 km diameter circle centred on the sub-Kalahari Group distribution of impact melt associated with the 145 Ma Morokweng impact crater. Incorporation of the KHK-1 (3420 m) and NEV-1 (647 m) borehole logs has resulted in a new interpretation of the Paleoproterozoic stratigraphy along the profile that contrasts with preceding interpretations. This has implications for the interpretation of the west-dipping Moshaweng Fault that disrupts these strata, previously interpreted as a 6.5 km listric normal fault. Units of the Ventersdorp, Griqualand Wwest, and Olifansthoek supergroups that dip westwards towards the fault display thickening within a km-scale hangingwall anticline west of the fault. Contrary to [Tinker et al. \(2002\)](#), a thrust origin for the Moshaweng Fault is supported by the 1285 m upward slip of the lower units in the hanging wall, the 30° western dip of the fault and the hangingwall anticline. However, 780 m of normal slip within the shallower sediments as well as a minimum of 400 m throw of the Phanerozoic sediments

reveal a more complex, multiphase tectonic history. The fault is also associated with a cluster of normal-slip antithetic faults within its hanging wall.

The implied historical tectonic succession of the Moshaweng Fault comprises post-Olifantshoek (<1.87 Ga) thrusting (minimum slip of ~2-2.5 km) triggered by east-verging folding, likely during the 1.2 Ga Kheis Orogeny, followed by a negative inversion (~773 m slip) that produced antithetic normal faults in the hanging wall. Subsequent erosion and deposition of the Dwyka Group (250 Ma) was followed by compressional (~210 Ma Cape Orogeny?) faults and folding and normal reactivation (~200 m slip; ~135 Ma Gondwana rifting?). Localised normal faulting may also have been triggered by the large Morokweng impact although this is difficult to establish unequivocally. Lastly, erosion and deposition of the Kalahari Group (1.2 – 1.0 Ma) was followed by further compressional and extensional faulting and a further ~200 m normal reactivation of the Moshaweng Fault, disrupting the Kalahari Group.

9.10 References

- Adam, E., Milkereit, B., Mareschal, M. (1998). Seismic reflection and borehole geophysical investigations in the Matagami mining camp. *Canadian Journal of Earth Science*, 35, 686-695.
- Alebouyeh Semami, F., de Kock, M.O., Söderlund, U., Gumsley, A., da Silva, R., Beukes, N.J., Armstrong, R. (2016). New U–Pb geochronologic and palaeomagnetic constraints on the late Palaeoproterozoic Hartley magmatic event: evidence for a potential large igneous province in the Kaapvaal Craton during Kalahari assembly, South Africa. *GFF* 138(1), 164-182.
- Anhaeusser, C.R. (2019). The geology and tectonic evolution of the northwest part of the Barberton Greenstone Belt, South Africa: A review. *South African Journal of Geology* 122(4), 421-454.
- Banas, A., Stachel, T., Phillips, D., Shimizu, M., Viljoen, K.S., Harris, J.W. (2009). Ancient metasomatism recorded by ultradepleted garnet inclusions in diamonds from DeBeers Pool, South Africa. *Lithos*, 112, 736– 746.
- Barnes, A.E. (2000). Weighted average seismic attributes. *Geophysics*, 65(1), 275-285.
- Beukes, N.J., Smit, C.A. (1987). New evidence for thrust faulting in Griqualand West, South Africa: Implications for stratigraphy and the age of red beds. *South African Journal of Geology* 90(4), 378-394.
- Beukes, N.J., de Kock, M.O., Vorster, V., Ravhura, L.G., Frei, D., Gumsley, A.P. , Harris, C. (2019). The age and country rock provenance of the Molopo Farms Complex: implications for Transvaal Supergroup correlation in southern Africa. *South African Journal of Geology*, 122.
- Brown, A.R. (1996). Seismic attributes and their classification. *The Leading Edge*, 15(10), 1090-1195.

- Cornell, D.H., Armstrong, R.A., Walraven, F. (1998). Geochronology of the Proterozoic Hartley Basalt formation, South Africa: constraints on the Kheis tectogenesis and the Kaapvaal Craton's earliest Wilson Cycle. *Journal of African Earth Sciences*, 26(1), 5-27.
- Cornell, D.H., Thomas, B., Moen, H.F.G., Reid, D.L., Moore, J.M., Gibson, R.L. (2006). The Namaqua-Natal Province. *African Geochronology*, 2006.
- Cornell, D.H., Minnaar, H., Frei, D., Kristoffersen, M. (2018). Precise microbeam dating defines three Archaean granitoid suites at the southwestern margin of the Kaapvaal Craton. *Precambrian Research* 304, 21-38.
- Corner, B., Reimold, W.U., Brandt, D., Koeberl, C. (1997). Morokweng impact structure, Northwest Province, South Africa: geophysical imaging and shock petrographic studies. *Earth and Planetary Science Letters* 146(1-2), 351-364.
- Cousins, C.A. (1950). Sub-Karoo contours and notes on the Karroo succssion in the Odendaalsrus area of the Orange Free State. *South African Journal of Geology* 53(1), 229-242.
- De Wit, M.J., de Ronde, C.E.J., Tredoux, M., Roering, C., Hart, R.J., Armstrong, R.A., Green, R.W.E., Peberdy, E., Hart, R.A. (1992). Formation of an Archaean continent. *Nature*, 357, 553-562.
- Donoso, G. A., Malehmir, A., Pacheco, N., Auraujo, V., Penney, M., Carvalho, J., Spicer, B., Beach, S. (2020). Potential of legacy 2D seismic data for deep targeting and structural imaging at the Neves–Corvo massive sulphide-bearing deposit, Portugal. *Geophysical Prospecting* 68(1), 44-61.
- Eglington, B.M. (2006). Evolution of the Namaqua-Natal Belt, southern Africa – A geochronological and isotope geochemical review. *Journal of African Earth Sciences*, 46, 93-111.
- Ellis, R. G., Oldenburg, D. W. (1994). Applied Geophysical Inversion. *Geophysical Journal International*, 116(1), 5-11.
- Eriksson, P.G., Banerjee, S., Nelson, D.R., Rigby, M.J., Catuneanu, O., Sarkar, S., Roberts, R.J., Ruban, D., Mtshkulu, M.N., Sunder Raju, P.V. (2008). A Kaapvaal Craton debate: Nucleus of an early small supercontinent or affected by an enhanced accretion event? *Gondwana Research*, 15(3-4), 354-372.
- Fouch, M.J., James, D.E., VanDecar, J.C., van der Lee, S. (2004). Mantle seismic structure beneath the Kaapvaal and Zimbabwe cratons. *Geological Society of South Africa*, 107(1-2), 33-44.
- Gabrielli, F. (2007). 2622 Morokweng sheet 1:250,000 scale. *South African Council for Geoscience, Pretoria*.
- Gumsley, A., Rådmann, J., Söderlund, U., Klausen, M. (2016). U–Pb baddeleyite geochronology and geochemistry of the White Mfolozi Dyke Swarm: unravelling the complexities of 2.70–2.66 Ga dyke swarms across the eastern Kaapvaal Craton, South Africa. *GFF* 138(1), 115-132.

Haddon, I.G., McCarthy, T.S. (2005). The Mesozoic - Cenozoic interior sag basins of Central Africa: The Late-Cretaceous – Cenozoic Kalahari and Okavango basins. *Journal African Earth Sciences*, 43, 316-333.

Haddon, I.G. (2004). The sub-Kalahari geology and tectonic evolution of the Kalahari basin, Southern Africa, University of the Witwatersrand, Johannesburg. *PhD thesis*, 343.

Hanson, R.E., Gose, W.A., Crowley, J.L., Ramezani, J., Bowring, S.A., Bullen, D.S., Hall, R.P., Pancake, J.A., Mukwakwami, J. (2004). Paleoproterozoic intraplate magmatism and basin development on the Kaapvaal Craton: Age, paleomagnetism and geochemistry of ~1.93 to ~1.87 Ga post-Waterberg dolerites. *South African Journal of Geology* 107(1-2), 233-254.

Hart, R.J., Andreoli, M.A.G., Tredoux, M., Moser, D., Ashwal, L.D., Eide, E.A., Webb, S.J., Brandt, D. (1997). Late Jurassic age for the Morokweng impact structure, southern Africa. *Earth and Planetary Science Letters*, 147, 25-35.

Henkel, H., Reimold, W.U., Koeberl, C. (2002). Magnetic and gravity model of the Morokweng impact structure. *Journal of Applied Geophysics*, 49, 129-147.

James, D.E., Fouch, M.J., VanDecar, J.C., van der Lee, S. (2001). Tectospheric structure beneath southern Africa. *Geophysical Research Letters*, 28(13), 2485-2488.

Kim, J., Moon, W.M., Percival, J.A., Gordon West, F. (1992). Seismic imaging of shallow reflectors in the eastern Kapuskasing structural zone, with corrections of crossdip attitudes. *Geophysical Research Letters*, 19(20), 2035-2038.

Koeberl, C. Armstrong, R.A., Reimold, W.U. (1997). Morokweng, South Africa: a large impact structure of Jurassic-Cretaceous boundary age. *Geology*, 25, 731-734.

Kositcin, N., McNaughton, N.J., Griffin, B.J., Fletcher, I.R., David, I., Groves, D.I., BirgerRasmussen, B. (2003). Textural and geochemical discrimination between xenotime of different origin in the Archaean Witwatersrand Basin, South Africa. *Geochimica et Cosmochimica Acta* 67, 709–731.

Malajczuk, S., Saklani, R., Clark, D., Eastwell, D. (2016). Improved Subsurface Imaging and Interpretability through Broadband Reprocessing of Legacy Seismic Data. Examples from North West Shelf Australia. *25th ASEG-PESA-AIG Geophysical Conference and Exhibition*, 1-8.

Malehmir, A., Bellefleur, G. (2009). 3D seismic reflection imaging of volcanic-hosted massive sulphide deposits: Insights from re-processing Halfmile Lake data, New Brunswick, Canada. *Geophysics*, 74, B209–B219.

- Malehmir, A., Donoso, G., Markovic, M., Maries, G., Dynesius, L., Brodic, B., Pecheco, N., Marsden, P., Bäckström, E Penney, M., Araujo, V. (2019). Smart Exploration: from legacy data to state-of-the-art data acquisition and imaging. *First Break*, 37(8) 71-74.
- Manzi, M., Malehmir, A., Durrheim, R. (2018). Improved Subsurface Imaging through Re-processing of Legacy 2D Seismic Data-A Case Study from a Deep South African Gold Mine. *EAGE 2nd Conference on Geophysics for Mineral Exploration and Mining*.
- Manzi, M., Malehmir, A., Durrheim, R. (2019). Giving the legacy seismic data the attention they deserve. *First Break*, 37(8), 89-96.
- Matmon, A., Hidya, A. J., Vainer, S., Crouvi, O., Fink, D., Erel, Y. (2015). New chronology for the southern Kalahari Group sediments with implications for sediment-cycle dynamics and early hominin occupation. *Quaternary Research*, 84(1), 118-132.
- Moen, H.F.G. (2008). New age constraints on the tectogenesis of the Kheis Subprovince and the evolution of the eastern Namaqua Province. *South African Journal of Geology* 111(1), 79-88.
- Nedimović, M.R., West, G.F. (2003). Crooked-line 2D seismic reflection imaging in crystalline terrains. *Geophysics*, 68(1), 16-409
- Poujol, M., Robb, L., Anhaeusser, C.R., Gericke, B. (2003). A review of the geochronological constraints on the evolution of the Kaapvaal Craton, South Africa. *Precambrian Research*, 127(1-3), 181-213.
- Pretorius, C.C., Muller, M.R., Larroque, M., and Wilkins, C. (2003). A review of 16 years of hardrock seismics on the Kaapvaal Craton, Hardrock Seismic Exploration, Eaton, D., Salisbury, M. and Milkereit, B. (eds), *Developments in Geophysics Series, SEG, Houston*. 2003, 247–268.
- Reimold, W.U., Armstrong, R.A., Koeberl, C. (2002). A deep drillcore from the Morokweng impact structure, South Africa: petrography, geochemistry, and constraints on the crater size. *Earth and Planetary Science Letters*, 201, 221-232.
- South African Committee for Stratigraphy (SACS) (1980). Stratigraphy of South Africa, part 1, Kent L.E. (ed.) In: Litho-stratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republics of Bophuthatswana, Transkei and Venda. *Handbook Geological Survey of South Africa* 8, 690 pp.
- Schmitz, M., Bowring, S.A., de Witt, M.J., Gartz, V. (2004). Subduction and terrane collision stabilize the western Kaapvaal Craton tectosphere 2.9 billion years ago. *Earth and Planetary Science Letters* 222(2), 363-376.

Smit, P.J. (1974). Geological map, sheet 2622 Morokweng, scale 1:250,000, Council for Geoscience, Pretoria (1974) one sheet.

Stanley, S.M., Ries, J.B., Hardie, L.A. (2005). Seawater chemistry, coccolithophore population growth, and the origin of Cretaceous chalk. *Geology* 33(7), 593-596.

Stettler, E.H., J. Prinsloo, M.E. Hauger, and M.C. du Toit (1997). A crustal geophysical model for the Kheis Tectonic Province, South Africa, based on magnetotelluric, reflection seismic, gravity and magnetic data sets (Abstract). TDOGS conference / PPM '97.

Stowe, C.W. (1986). Synthesis and interpretation of structures along the north- eastern boundary of the Namaqua tectonic province, South Africa. *Transactions – Geological Society of South Africa* 89(2), 185-198.

Taner, M.T., Koehler, F., Sheriff, R.E. (1979). Complex seismic trace analysis. *Geophysics*, 44(6), 1041-1063.

Tankard, A., Welsink, H., Aukes, P., Newton, R., Stettler, E. (2012). Geodynamic interpretation of the Cape and Karoo Basins, South Africa. *Regional Geology and Tectonics: Phanerozoic Margins, cratonic Basins and Global Tectonics Maps*, Elsevier 2012.

Tinker, J., de Wit, M., Grotzinger, J. (2002). Seismic stratigraphic constraints on Neoarchean – Paleoproterozoic evolution of the western margin of the Kaapvaal Craton, South Africa. *South African Journal of Geology*, 105, 107-134.

Van der Westhuizen, W.A., De Bruijn, H., Meintjies, P.G. (1991). The Ventersdorp Supergroup: an overview. *Journal of African Earth Sciences*, 13, 83–105.

Van Niekerk, H.S., Beukes, N.J. (2019). Revised definition/outline of the Kheis Terrane along the western margin of the Kaapvaal Craton and lithostratigraphy of the newly proposed Keis Supergroup. *South African Journal of Geology* 122(2), 187-220.

Visser, J.N.J. (1983). An analysis of the Permo-Carboniferous glaciation in the Marine Kalahari basin, southern Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 44, 295-315.

Walraven, F., Martini, J. (1995). Zircon Pb-evaporation age determinations of the Oak Tree Formation, Chuniespoort Group, Transvaal Sequence: implications for Transvaal- Griqualand West basin correlations. *South African Journal of Geology* 98(1), 58-67.

Wang, W., West, G. F. (1991). Stacking processes of crooked lines using the SUN/INSIGHT System. *Lithoprobe Seismic Processing Facility Newsletter*, 4, 13–18.

Wela, S.S. (2017). A lithological, petrographic and geochemical investigation of the M4 borehole core, Morokweng Impact Structure, South Africa. MSc Dissertation, University of the Witwatersrand, Johannesburg.

Westgate, M., Manzi, M., Cooper, G., Durrheim, R. (2018). Symmetry as an Alternative Seismic Attribute: Case Studies from the Hard Rock and Soft Rock Environments, South Africa. *80th EAGE Conference and Exhibition 2018*.

White, R.E. (1991). Properties of instantaneous attributes. *The Leading Edge*, 10(7), 1-68.

Widess, M.B. (1973). How thin is a thin bed? *Geophysics*, 38(6), 1176-1180.

Yilmaz, O. (2001). Seismic Data Analysis: Processing, inversion and interpretation of seismic data. *Society of Exploration Geophysicists*. doi: 10.1190/1.9781560801580. 1803-1807pp.

10 PAPER III: INTERPRETATION OF LEGACY SEISMIC DATA USING COMPOSITE SEISMIC ATTRIBUTES: CASE STUDIES FROM OILFIELDS AND GOLDFIELDS, SOUTH AFRICA

10.1 Abstract

High-resolution structural imaging using seismic attributes is of great value to the oil, gas and mineral industries, for example, to enhance the detection of thin hydrocarbon reservoirs and thin mineral deposits. However, effective selection of seismic attributes is still a challenge. We demonstrate how combining seismic attributes to create attribute composites can be used to enhance the detection and continuity of thin beds in “hard rock” and “soft rock” settings to optimise mineral and hydrocarbon exploration, respectively.

These composite attributes are created as hue-saturation-intensity (HSI) images that have different attributes assigned to the hue and intensity components of the image. The resulting attributes are hybrids that take advantage of both the involved attributes. This approach proves useful in the qualitative interpretation of the legacy reflection seismic data compared to conventional quantitative complex-trace seismic attributes such as the instantaneous amplitude, frequency and phase in their isolation. We show through two case studies that the composite attributes can illuminate geological features and emphasise seismic reflectivity and continuity of thin layered gold deposits and gas reservoirs for qualitative interpretation, ultimately assisting in optimising the mining and oil and gas industry in a cost-effective way.

10.2 Introduction

Seismic attributes are mathematical objects extracted from the seismic traces that highlight certain properties of the data, aiding in the interpretation thereof. In particular, instantaneous seismic attributes play an important role in the interpretation of reflection seismic data ([Taner et al. 1979](#)). For example, conventional seismic attributes such as instantaneous amplitude, frequency, and phase have been used worldwide in sedimentary basins to enhance the seismic interpretation of mineral deposits and hydrocarbon reservoirs, faults and channels ([Taner et al. 1979](#); [Barnes 1993](#); [Chopra et al 2006](#); [Chopra et al. 2009](#); [Chopra et al. 2011](#); [Manzi et al. 2013](#); [Manzi et al. 2015](#)).

The application of seismic attributes in hard rock environments is often more challenging than in soft rock settings due to the scattering crystalline rocks, structural complexity, strong degree of structural heterogeneity, lack of major continuous reflectors and major lateral velocity variations. The amplitude attribute, for example, helps to identify lithological changes between geological boundaries, whereas the instantaneous phase helps to provide valuable information about the lateral continuity of structures

(or reflectors). However, these attributes in isolation can have inherent shortcomings that may lead to misinterpretation.

Some of the mineral deposits and hydrocarbon reservoirs that are being explored using the reflection seismic method are thinner than the tuning thickness (Widess 1973). These ore bodies and hydrocarbon reservoirs have complex geometries and are often bounded by low contrasting acoustic impedance layers. Thus they cannot be recognized by simple seismic mapping of horizons or by looking for normal waveform anomalies. Conventional horizon picking and tracking on seismic traces with interfering wavelets do not suffice because some wavelets will show as ‘doublets’ (Chen and Sidney 1997; Manzi et al. 2013). The identification of these thin or closely spaced horizons, however, can be aided by computation of more sophisticated seismic attributes. The purpose of this paper is to demonstrate through case studies from South Africa the usefulness of using the combination of seismic attributes for complex structural interpretation.

10.3 Instantaneous Attributes

Amplitude and Phase

Taner (1979) introduced the concept of instantaneous attributes based on complex trace analysis. Since then, these attributes have been used extensively in reflection seismics and in signal processing in general.

Given a seismic trace, $s(t)$, the instantaneous phase $\varphi(t)$ and instantaneous amplitude, $A(t)$, are given by

$$\varphi(t) = \arctan \frac{H[s(t)]}{s(t)} \quad (1)$$

$$A(t) = \sqrt{s(t)^2 + H[s(t)]^2} \quad (2)$$

where H denotes the Hilbert Transform (Gabor 1946). The trace $s(t)$ can therefore be written as the product of an amplitude expression with a phase expression: $s(t) = A(t)\cos(\varphi(t))$. The term $\cos(\varphi(t))$, which encodes all phase information and is thus independent of amplitude, is sometimes used interchangeably with instantaneous phase. In the paper, it is referred to as the paraphase (Manzi et al. 2013). This allows one to investigate a trace, or a gather, with all phase information removed or with all amplitude information removed.

Symmetry

When interpreting reflection seismic data, the human eye will typically identify the continuity of seismic reflections or horizons by tracking contrasts (such as the contrast between peaks and troughs).

Westgate et al. (2018) introduced a technique that assists in enhancing detail within a wavelet along a given horizon based on the concept of symmetry. This symmetry attribute identifies and exploits certain

features of the zero-phase wavelet's anatomy (for example, being able to pin point the peaks of the wavelet, or its inflection points) and contrast them so that, instead of contrasting limbs of a wavelet as is typically done, it contrasts features of each limb. This makes it easier for the seismic interpreter to follow finer details of the zero-phase wavelet and examine the continuity thereof.

Symmetry serves as one of the good candidates for this as it can detect and distinguish maximal points, minimal points and inflection points of a given wavelet, as shown in [Figure 10.2a,b](#). In the two dimensional case, symmetry is useful in tracking subtle changes in the wavelet's anatomy along the reflection. This is illustrated in [Figure 10.2c,d](#), in which a seismic reflection that has a dilated wavelet (i.e. its period is larger) in the middle of the profile and the wavelet narrows towards the end. This feature of the reflection is not easily noticed in the original section ([Figure 10.2c](#)), however the symmetry attribute ([Figure 10.2d](#)) makes it more apparent.

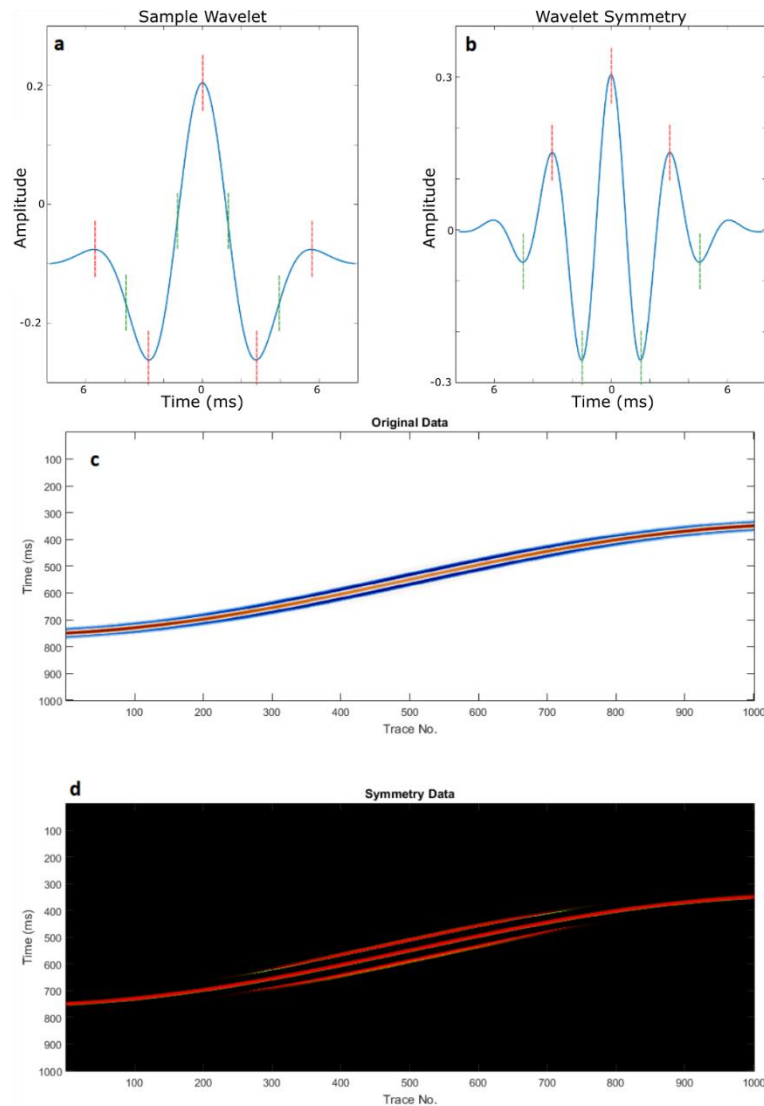


Figure 10.1: An illustration of how symmetry can be used to detect subtle changes in the wavelet along a reflection. In the one dimensional case, a sample wavelet (a) is shown with points of symmetry illustrated by red lines and points of

antisymmetry by green lines. Symmetry (b) exploits the differences between these points and contrasts them, making it easier to track.

Thus, the interpretative advantage of the symmetry of the seismic wavelet over conventional interpretation tools (e.g., seismic amplitude display) is in its ability to identify subtle changes within a limb of the wavelet, which allows for better detection of seismic layers that are, for example, below the tuning thickness (i.e., one-quarter dominant seismic wavelength ($\lambda/4$)). Below the tuning thickness, the conventional amplitude attribute display is not able to detect subtle and significant changes between the wavelets. The other advantage of using symmetry as a seismic attribute is that it is amplitude-independent, and is thus a good indicator of lateral continuities of thin layers (Chopra et al. 2006, Widess 1973). The paraphase attribute, on the other hand, is defined by Manzi et al. (2013) as the cosine of the phase. For each seismic reflection event, the paraphase represents the full 180° rotation of phase (from peak to trough) without any representation of amplitude, also making it an amplitude independent attribute. Paraphase, like symmetry, can therefore be used to define the continuity and shape of thin and weak seismic events.

The symmetry attribute is calculated by using a windowed Fourier transform (WFT) within a sliding window. At each window centre, the symmetry data point is given by the ratio of the total imaginary content of the WFT and the total real content. Mathematically, this is given by:

$$S = \frac{\int I[F(v)]dv}{\int R[F(v)]dv + \epsilon} \quad (3)$$

$$S_{norm} = \frac{S - \min(S)}{\max(S) - \min(S)} \quad (4)$$

where R and I denote the real and imaginary components, respectively, of the function enclosed in square brackets, $F(v)$, the WFT of the window, and ϵ is a constant factor added to the denominator to avoid singularities in S . S_{norm} is the normalised form of S so that the symmetry attains values between 0 and 1, for antisymmetric and symmetric, respectively. As such, S_{norm} can be viewed as the “instantaneous symmetry”.

Other recent developments of seismic symmetry attributes can be found in Yu and Kelley (2014). A symmetry attribute has also been tested in the hard rock seismic data to map platinum-bearing horizons (Westgate et al. 2018). Here we show that the symmetry attribute when used in combination with the paraphase can bring out subtle information from the stratigraphic units, facilitating mapping of the shape and continuity of thin ore bearing horizons.

10.4 Composite Attributes

Each of the instantaneous attributes has advantages and disadvantages. For example, the paraphase acts as an AGC and so displays all reflectors present, however this is at the cost of also enhancing noise. The instantaneous amplitude is not very prone to noise but it loses the detail present in the high

frequencies. The symmetry attribute enhances the high frequency detail but is also susceptible to noise and can also introduce artefacts where the data exhibits symmetry that is unrelated to the actual geology.

This suggests combining the attributes in such a way that takes full advantage of the individual attributes' benefits. This is accomplished by creating a Hue-Saturation-Intensity (HSI) image, in which one attribute is assigned to the hue component of the image and another is assigned to the intensity component of the image.

In this study, we investigate two attribute composites of this nature; a symmetry-paraphase composite (SPC) attribute as well as an amplitude-paraphase composite (APC) attribute that can help detect subtle variations in thin layering and also highlight instability in the phase wavelet.

The SPC attribute preserves the AGC effect of the symmetry as well as the weighting of the paraphase, which allows the interpreter to see all reflections while still being able to distinguish between weak and strong reflectors as well as subtle structure within the wavelet thereof. The APC attribute combines the presence of strong reflection packages found in the instantaneous amplitude with the detail in continuity of the symmetry attribute.

This study further shows that it is not sufficient to simply rely on a single attribute as a direct indicator of thin beds, especially in complex geological environments. One of the key objectives of this paper is to show that it is possible to derive attributes that can be applied to both hard rock and soft rock seismic data to significantly enhance the detection of mineral ore bodies and hydrocarbon reservoirs.

10.5 Application To Case Studies

Presented here are two case studies, one hard rock and one soft rock setting from the Witwatersrand and Bredasdorp basins, respectively, in which the SPC and APC attributes are computed and compared with the original data, as well as the paraphase. The locations of these sedimentary basins are shown on the map in [Figure 10.3](#). It is important to note that the SPC attribute is dependent on the characteristic wavelet of the seismic data. In this paper, both datasets have been converted from minimum phase to zero phase during its processing to increase the signal-to-noise ratio of the data ([Barton et al. 2001](#); [Manzi et al. 2012](#)).

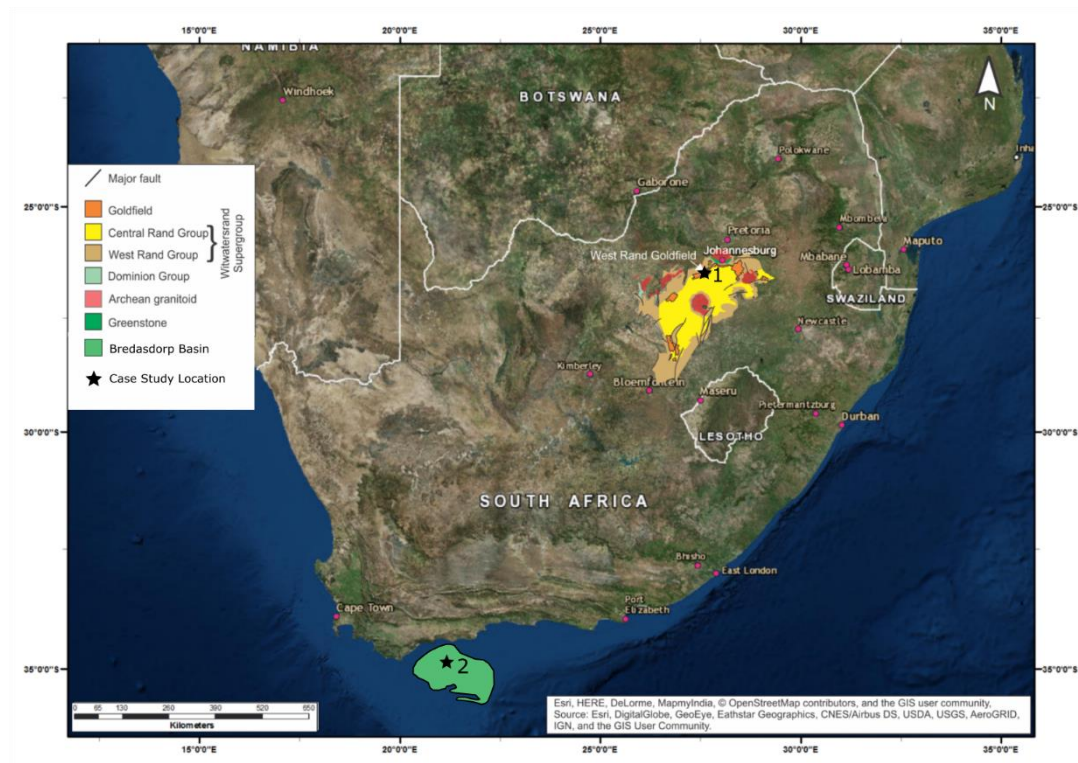


Figure 10.2: Location map of the West Rand Goldfield (location 1) in the Witwatersrand Basin and Bredasdorp Basin (location 2) in South Africa.

Case Study 1: Kloof Gold Mine, Witwatersrand Basin, South Africa

Geological setting

Our first case study is the Kloof Gold Mine, which is situated in the West Rand goldfield in the northwestern portion of the Witwatersrand Basin (Figure 10.3). Within the West Rand goldfield, there are two post-Witwatersrand mega-sequences that contain auriferous conglomerates (i.e. the Ventersdorp and Transvaal supergroups; Tucker et al. 2016). These two sequences have contributed significantly to the overall gold production of Witwatersrand mines and their mode of occurrence and stratigraphic position provide useful information on ore-forming processes. The primary gold deposit mined in the Kloof Gold Mine is the Ventersdorp Contact Reef (VCR ~ 1.5 m thick) located ~ 3.0 km below surface at the base of the Ventersdorp Supergroup (Manzi et al. 2013). The 2714 ± 8 Ma VCR represents one of the younger auriferous conglomerates (locally termed reefs) with an economic gold grade that is spatially linked to sedimentary recycling of the Witwatersrand strata. The VCR has contributed as much as 7.6 % (Au = 3952 t at 5–12 g/t) of the total Witwatersrand gold production (Frimmel 2014). Highly variable reef characteristics are attributed to the deposition of this ore body on slopes and terraces, accompanied by the continuous incision of a fluvial system. The VCR received its gold from the sedimentary recycling of underlying gold-rich sediments, the efficiency of which decreased with time (Frimmel 2018).

The 2642 ± 2 Ma Black Reef Formation, which forms the base of the Neoproterozoic to Paleoproterozoic Transvaal Supergroup, was deposited on a peneplain that developed after extrusion of the Ventersdorp volcanic rocks (Figure 10.4) (Eriksson et al. 2006). At its base, it consists of a quartz arenite unit with locally developed pyritic quartz pebble conglomerates and scattered pebbles, representing former fluvial channels, fining upwards into siltstone and in most places carbonaceous shale. The conglomerate horizon is known as the Black Reef (BLR) and is ~1.5 m thick. The BLR contains local economic concentrations of gold in conglomerates which have been, and continue to be, mined in various places within the vicinity of the Witwatersrand Basin (Henry and Master 2008). Although the areal extent of the BLR over the Witwatersrand Basin is wide, elevated gold contents have been reported only from areas in which the BLR subcrops against the VCR and Witwatersrand reefs (Figure 10.4). The BLR contributed <1 % (Au < 9 t at 1–5 g/t) to the overall Witwatersrand gold production. As in the VCR, the BLR derived much of its gold from erosion of underlying reefs. In the study area, the VCR subcrops against the Black Reef and this has important implications for the distribution of gold (Figure 10.4).

Away from the subcrop position, the BLR consists of narrow channels with discontinuous bands which are mostly barren of gold (Figure 10.4). It is therefore important to apply seismic attributes to define the VCR/BLR subcrop position since elevated gold grades are not expected to persist far beyond this zone. Drilling programs around the West Rand goldfield has shown that, where there are conglomerates within the Black Reef sediments, these have a high probability of carrying economic gold grades (Gauert et al. 2011).

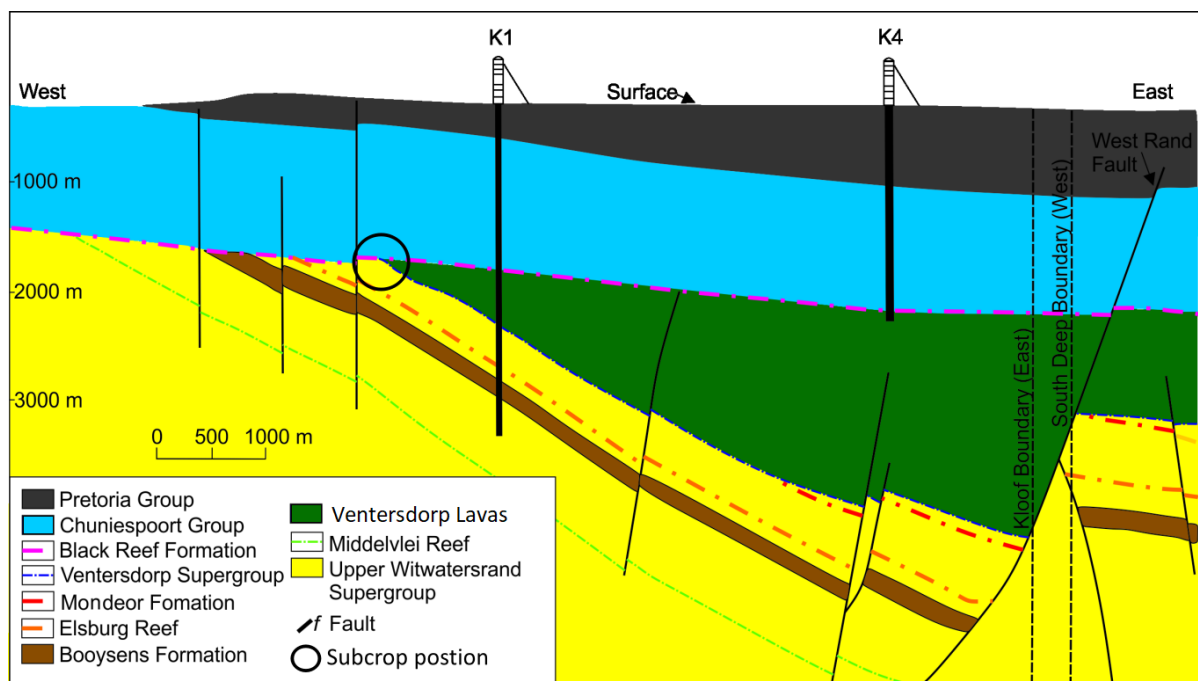


Figure 10.3: The summary of the stratigraphy of the West Wits Line goldfields across the major fault zone showing the subcrop position of the Ventersdorp Contact Reef (VCR) against the Black Reef Formation (BLR) (Sibanye Gold Limited, 2014).

Seismic data and seismic attributes

The seismic sections used for this study are extracted from a seismic volume that covers the Kloof Gold Mine (our project area) and extends to approximately 9 km depth, with an east–west extent of 6 km and north–south extent of 4 km. The acquisition parameters are summarised in [Table 10.1](#) and the processing parameters are summarised in [Table 10.2](#). The land 3D seismic data were acquired by Compagnie Générale de Géophysique (CGG) in 2003 in West Rand Goldfield. [Manzi et al. \(2012\)](#) reprocessed and produced a zero-phase pre-stack time-migrated volume that is characterised by strong reflectors from the surface to a 9 km depth, with the frequency content of approximately 10 to 95 Hz. The prestack time-migration cube serves as the basis for the application of high-quality seismic attributes. The survey was part of a program to explore for thin, tabular gold ore bodies known as reefs such as the VCR and BLR at depths between 0.5 and 3.0 km below surface. The other objective of the survey was to map geological structures (faults and dykes) that disrupt the gold ore body, which can result in a 30% potential loss of minable ore. The survey was designed with 25 m bin spacing and 1 ms sampling interval, yielding high quality data. If we assume a mean velocity of 6000–6500 m/s as estimated during processing, the dominant seismic wavelength is on the order of 100 m, and the tuning thickness ($\lambda/4$) is approximately 25 m, which is the minimum thickness required to resolve the top and bottom of these thin ore bodies (see [Manzi et al. 2012](#) for more details about the survey). Here we show that even thinner layers can be detected using the SPC and APC attributes. The initial interpretation of 3D seismic data was done using a conventional amplitude display ([Manzi et al. 2012](#)). The VCR and BLR have a thickness far less than the tuning thickness and thus could not be directly interpreted with confidence using the conventional amplitude displays.

Acquisition			Processing	
			Processing route	Parameters
Instrumentation	System	Sercel 408	Data reformat	From SEG2 to Promax internal format
	Geophones	10 Hz	Trace editing	Air-blast attenuation applied
	Data media	3490 cartridge	Geometry application	Source, receiver, offsets, etc., assigned to each trace
	Data format	SEG2 IEEE demultiplexed	Gain recovery: spherical divergence	$1/(TV^2)$ where $V = 5500$ m/s
	Record length	6 s	Surface consistent spiking deconvolution	Operator design window at 0 m offset: 100 – 2500 ms, operator length: 120 ms, white noise stabilisation: 1%
	Sample interval	2 ms	Zero-phase spectral whitening	Eight frequency windows, 500 ms sliding window
	System polarity	SEG standard	3D refraction statics	Surface layer $V_0 = 1200$ m/s (constant), seismic datum elevation: 1500 m a.m.s.l.
Parameters	Bin dimensions	25 x 25 m	Statics application	Smooth processing datum
	Survey pattern	Orthogonal	First-pass interactive velocity analysis	Every 600 m in crossline and inline directions
	Live path asymmetrical	12 lines x 108 = 1296 channels	First-pass surface consistent residual statics	Maximum power autostatics, 300 ms time gate around flattened horizons

Source	Live patch symmetrical	12 lines x 90 = 1080 channels	Interim stack: Leeudoorn and Kloof-South Deep	Data sets stacked separately, 35% stretch mute and 500-ms AGC applied
	Asymmetrical split	1-45 * 46-108 Ch 108 to the east	Prestack phase rotation and time-shift to match Leeudoorn and Kloof datasets	Leeudoorn data: time shift of -8 ms and 90° phase shift
	Symmetrical split	1-45 * 46-90	Prestack merge of Leeudoorn and Kloof datasets	Refraction statics calculated on the merged data and tied to upholes
	Shot line separation	450 m	Second-pass interactive velocity analysis	Every 600 m in crossline and inline directions
	Shot line direction	9.51°	Second-pass surface consistent residual statics application	Maximum power autostatics, 300 ms time gate around flattened horizons
	Shot line angle to receiver line	90°	CDP trim statics	Nonsurface consistent CDP statics
	Shot point separation	50 m	DMO velocity analysis	Full 3D Kirchhoff DMO using 60 m inline and crossline distance
	Total number of shot points	4155	Prestack time migration (PSTM) flow	
	Receiver line separation	400 m	First-pass PSTM velocity analysis	Full 3D Kirchhoff using velocity model from smoothed first pass PSTM velocities
	Receiver line direction	99.51°	NMO correction	Second pass velocities picked and applied
	Receiver point separation	50 m	Stack	
	Total number of receiver points	4957	Band-pass frequency filter	Time variant Ormsby zero-phase filter, 0–1400 ms: 15 / 20 – 80 / 90 Hz
	Array	Linear, 12 phones/string	Depth conversion	Using interval velocities derived from borehole data and BLR and VCR time horizons
	Array length	Variable 36-85 m	WUDLS data merge	Kloof-South Deep data depth shifted to 1830 m a.m.s.l datum and regridded to match WUDLS orientation
	Vibroseis Pattern	4 vibs inline 45 m array		
	Sweep	16 s, 12-96 Hz 4 sweeps		

Table 10.1: Acquisition and processing parameters for Witwatersrand 3D data. Table adapted from Manzi et al. (2012).

Figure 10.5 shows an example section that images the VCR and BLR horizons. However, the amplitude display of the original data (Figure 10.5a) shows a lack of continuity of the seismic reflection associated with gold mineralization (VCR), especially towards the subcrop position, i.e., the zone where the gold-bearing VCR conglomerate truncates against the BLR. The difficulty in identifying the subcrop position with the amplitude display is due to the interference caused by the overlapping seismic wavelets between reflecting horizons. Furthermore, it is difficult to consistently track the VCR reflection event in the amplitude display due to its limited lateral extent or highly variable reflection characteristics. Results in Figure 10.5b,c,d show the application of the paraphase, SPC and APC attributes respectively to the seismic section. Comparing Figure 10.5a and Figure 10.5c shows that the SPC attribute highlights the continuity of the VCR reflection and its subcrop position against the BLR (indicated by the white circle and blue arrows).

Furthermore, the SPC shows better detection of the continuity of faults between the VCR and BLR levels (indicated by white arrows in Figure 10.5). This is not surprising since the parapsy and symmetry are independent of the trace reflection magnitude and thus they make it easier to see interference, especially in seismic sections that are characterised by low amplitudes, stratigraphic terminations and complex faulting. Detecting the faults that have propagated between the VCR and BLR is important for gold exploration in the area because these structures may have transported gold-bearing fluid from the underlying conglomerate units to the BLR horizon (Nwaila et al. 2019)

When examining the APC attribute (Figure 10.5d), The VCR is enhanced and its continuity is clearer. Furthermore, the BLR horizon as well as the overlying reflection located at ~1.4 s are more easily tracked and their disturbance near CDP 80 becomes more apparent.

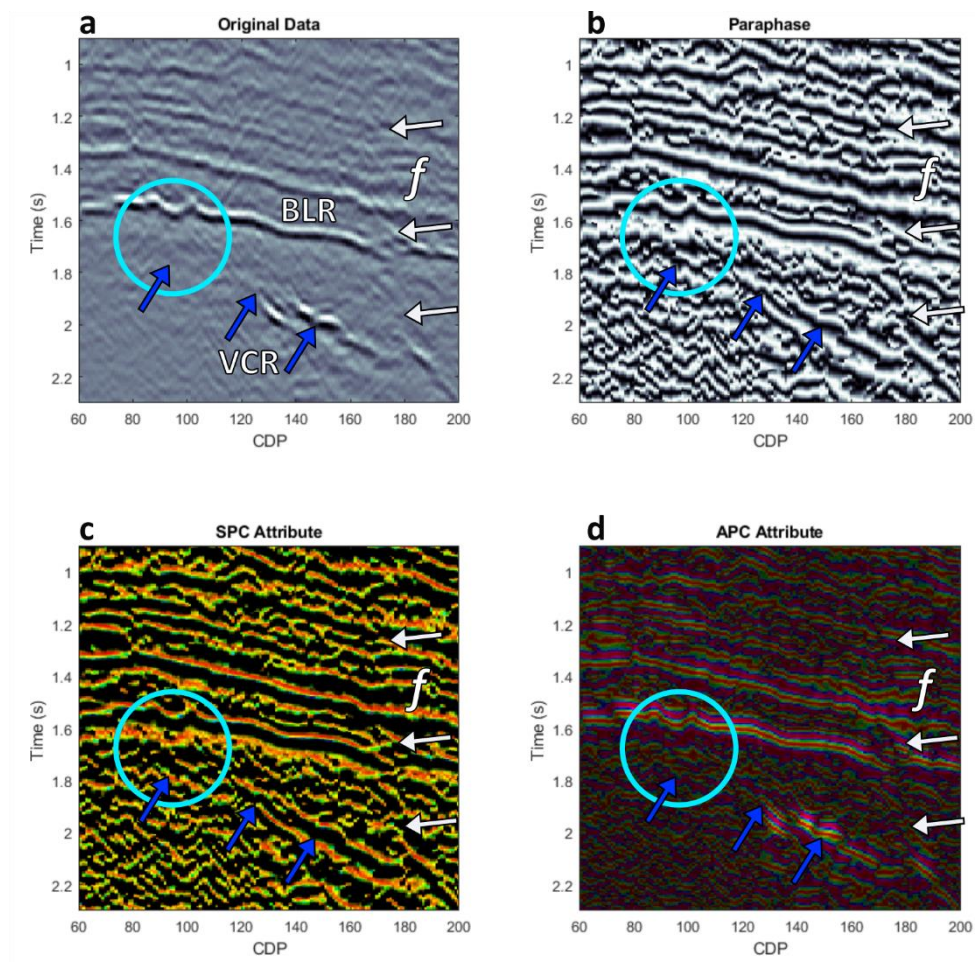


Figure 10.4: Amplitude display of the seismic section from the Kloof Gold Mine (a), as well as the paraphase (b), SPC attribute (c), and APC attribute. (d) Blue arrows and circle indicate VCR subcrop against BLR. White arrows indicate fault zone. The symmetry-paraphase composite (SPC) attribute is created by assigning the symmetry and the paraphase to the hue (shown by the colourbar) and intensity (ranging from black to full intensity) components, respectively, to a HSI image. BLR: Black Reef. VCR: Ventersdorp Contact Reef.

Figure 10.6 shows a seismic section through a known major fault zone of maximum 1.5 km throw (Manzi et al. 2012). Results obtained with the amplitude display (Figure 10.6a) generally lack evidence

of continuity and contain steep dips, which make it difficult to define the cut-off fault zone on each side of the fault (f) (as indicated by white arrows in Figure 10.6). However, the continuity of the VCR ore body is clearly visible (as shown by blue arrows) in the paraphase and SPC attributes (Figure 10.6b,c). Due to the low-amplitude nature of the section, the APC attribute (Figure 10.6d) appears sparse. However, where reflections do appear, they are easily tracked and tied across the fault.

Another notable enhancement by the SPC attribute is that of a weak reflector indicated by the red arrows, which is not very apparent in the original data. Most importantly, the SPC and APC attributes emphasize the geometric character (subtle amplitude and phase variations) of the VCR horizon across the major fault zone, which is quite difficult to see on the original data. This example illustrates the importance of the choice of seismic attributes for structural detection in the mining environment and might provide reasons why some of the early interpretation attempts that utilized conventional interpretation tools in hard rocks setting were not successful (Manzi et al. 2012).

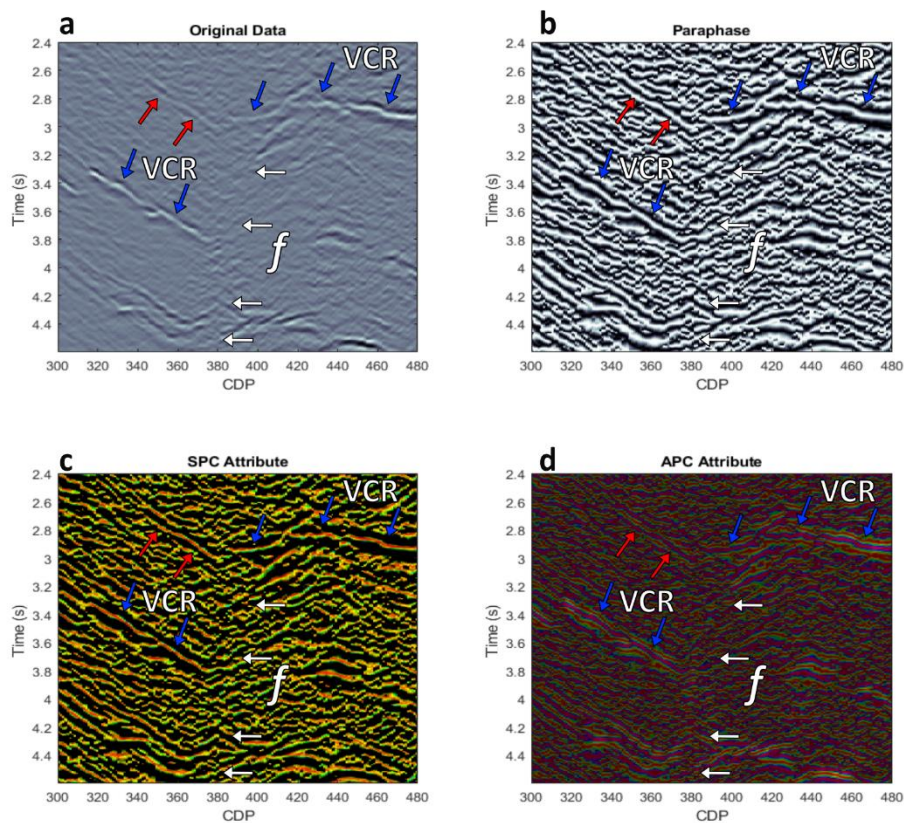


Figure 10.5: Kloof Gold Mine original data (a) through major fault zone, plotted with paraphase (b), SPC attribute (c), and APC attribute (d). The attributes highlight continuity of VCR (indicated by blue arrows) as well as fault zone (indicated by white arrows). Red arrows indicate weak reflector that is enhanced by SPC attribute. VCR: Ventersdorp Contact Reef.

Case Study 2: Bredasdorp Basin, Offshore South Coast, South Africa

Geological setting

The E-BD oil reservoir is situated at the western edge of the central Bredasdorp Basin, approximately 95 km off the south coast of South Africa (Figure 10.3). The field was discovered in 1990 when a well intersected a 30 meter thick sandstone interval with a 17 m oil column at a depth of 2.6 km below mean sea level (Barton and Grobber 1997). The well produced 8 500 barrels of oil per day. The E-BD oilfield overlies an oil and gas bearing reservoir (E-CE) with a vertical separation of approximately 30 m between them. Three wells tested the E-BD reservoir and one well has intersected both reservoirs (E-BD and E-CE) in the same wellbore. The thickest oil column found is 33 m (Barton and McAloon 1999). All E-BD wells have produced oil at commercial flow rates.

The E-BD/E-CE reservoirs are middle to lower Aptian (112 Ma) in age and consist of deep-marine channels and fan-lobe deposits (Figure 10.7). The E-BD sandstone is of good reservoir quality, with average porosity of 18% and average permeability of 380 mD (Barton and McAloon 1999). From core data, well logs and dip data, three facies types were identified. It was concluded by Barton and McAloon (1999) that the massive, amalgamated deep-marine sandstones make up a large part of the BD reservoir, representing extensive mass-flow deposits which could be classified as a turbidite system composed of three turbidity stages. The distribution of these deposits was controlled by significant erosional features on a regional unconformity which represented a prominent easterly-trending valley on the basin floor, comparable to a submarine canyon (Barton and McAloon 1999). The geometry of the E-BD reservoir is such that a significant portion is below the seismic tuning thickness. The reservoir can be classified as a ‘thin reservoir’, thus characterization thereof using conventional attributes and techniques prove to be a potentially difficult task for geoscientists due to the interference of the seismic amplitude from the top and base of the reservoir. The objective of this study is to test the effectiveness of the composite attributes in detecting the thin reservoir and closely packed stratigraphic units.

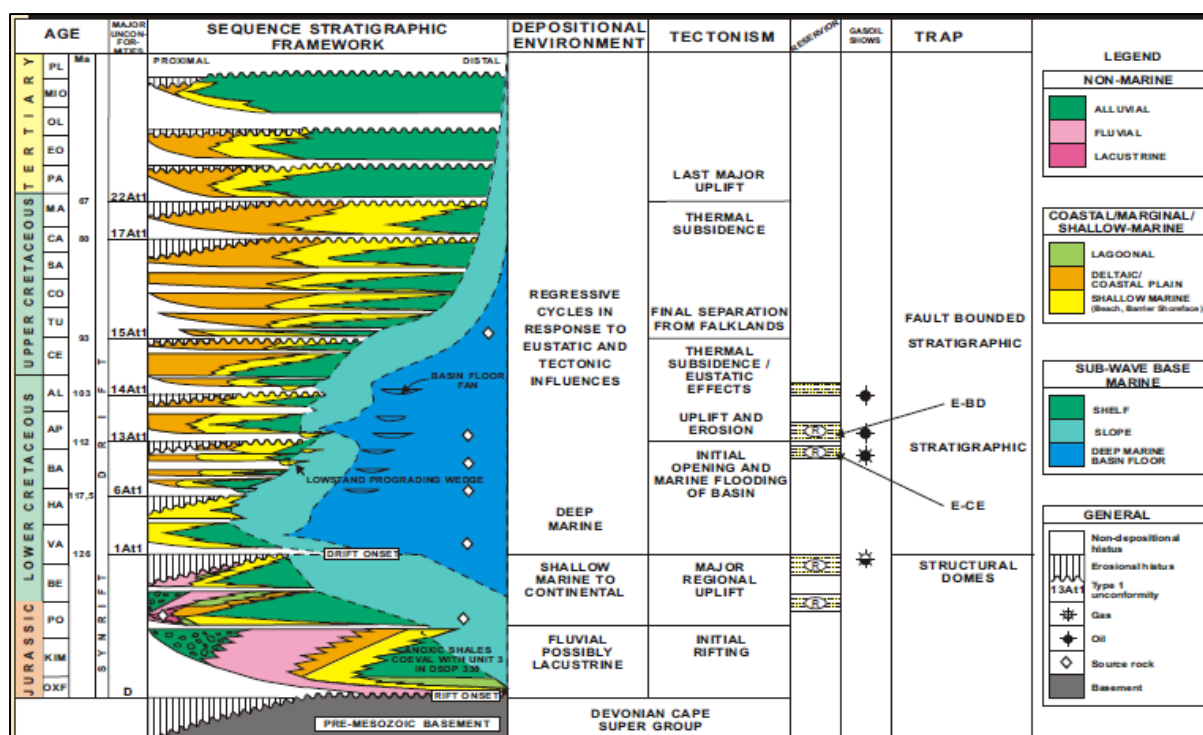


Figure 10.6: General chronostratigraphy of the Bredasdorp Basin case study area, showing Aptian Deep Marine sandstone, which is the main target for this study (modified from Barton and McAloon 1999).

Seismic data and seismic attributes

The seismic sections used in this case study are extracted from a merged 3D seismic cube consisting of surveys that were shot in 1996 and 2000. Table 10.2 summarises the processing parameters of the two datasets. The merged seamless cube provides a coverage that extends over the E-BD/E-CE reservoirs (between 1.8 and 2.1 s two-way-travel time). This merged dataset is referred to as the E2000 3D seismic volume. The dominant frequency of the zero-phase seismic data is 30 Hz. This has been estimated from the amplitude spectrum. The wavelength of the signal at the E-BD reservoir depth is approximately 125 m (Barton *et al.* 2001), providing a tuning thickness of approximately 31 m when using the average velocity of 3000 m/s.

	1996 re-processing of 1992 3D	2000 processing of E2000
Swell noise attenuation	None	Dual "SPARN" (removal of impulsive noise)
Shot noise attenuation	FK after NMO correlation	Muting in Tau-P domain
3:1 reduction	Anti-alias filter applied in combination with FK filter definition. Trace reduction done on transform back to TX.	Anti-alias filter applied pre-Tau-p transform. Trace reduction done on transform back to TX
De-reverberation	Predictive deconvolution; TX space 24ms gap, 248ms operator in	Predictive deconvolution using a 32ms gap, 120 ms operator in Tau-p space
Additional shot edits	none	Done to remove earth-leakage spiked records.
Multiple attenuation	FK	High resolution (alias protected) radon multiple attenuation.
DMO	Yes	Yes
PSTM	none	V(z) Stolt FK migration on offset volumes.
Velocity Grid	900 m X 900 m	600m x 600m
Stack		
DAS	20 ms predictive deconvolution	None

Noise Attenuation	FXY noise attenuation	FX on crosslines only
Migration	IL migration followed by XL migration	One pass migration
Zero Phasing	180° phase reversal applied	Matched with previous survey
Q compensation	None	Inverse Q applied

Table 10.2: Processing parameters of offshore Bredasdorp basin 3D cube for datasets from 1996 and 2000. Table adapted from [Barton et al. \(2001\)](#).

The SPC and APC attributes are used in an attempt to enhance the detection and continuity of the reservoir (located between 1.8 s and 2.2 s; indicated by white arrows) and thin stratigraphic units. A series of seismic sections were extracted from the 3D seismic volume to conduct attribute analysis and are shown in [Figure 10.8-9.10](#). [Figure 10.8a](#) is an example of an amplitude display of one of the seismic sections, showing seismic imaging of the reservoir located between 1.8 and 2.1 s. The data are characterised by thin reflections across the seismic section displaying variations in amplitude, strike and dip due to truncations and tuning thickness. However, it is difficult to consistently track the weaker reservoir reflection event (shown by white arrows) through the conventional amplitude display ([Figure 10.8a](#)) due to its limited lateral extent or highly variable reflection characteristics. To enhance the weaker reservoir seismic events, we again computed the paraphase, SPC and APC attributes. The former two of these attributes are particularly effective at improving the apparent continuity of reflections on seismic sections, especially continuity of the reservoir reflection event, which was not detected clearly on the amplitude display ([Figure 10.8b,c](#)). However, the SPC attribute exhibits more continuous thin reflections than the paraphase, which appears contaminated by random noise throughout the section ([Figure 10.8b,c](#)). The APC attribute emphasizes the strong reflection zones and the bright spots that flank the reservoir. Additionally, folding in the cap rock is made evident by the APC attribute.

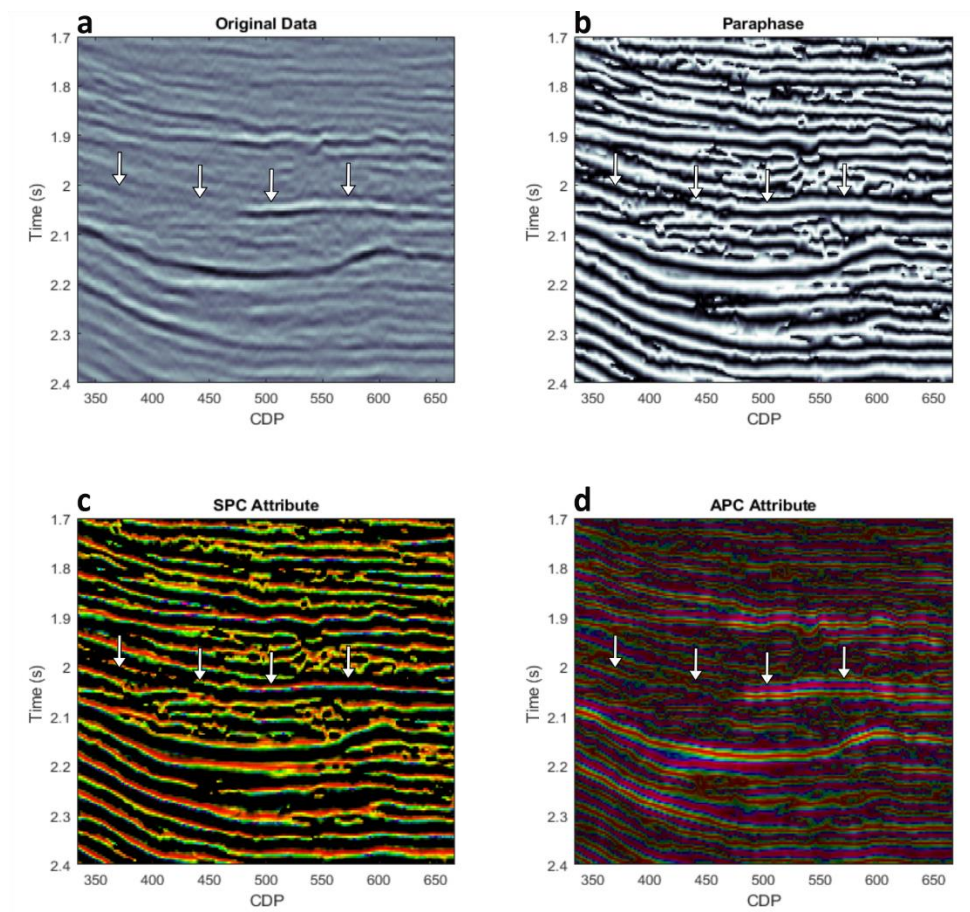


Figure 10.7: Bredasdorp Basin original data (a) plotted with paraphase (b), symmetry-paraphase composite (SPC) attribute (c), and amplitude-paraphase composite (APC) attribute (d). Arrows indicate continuity of weak reflection event associated with the reservoir, the continuity of which is enhanced by the SPC attribute.

Figure 10.9a shows the amplitude display of a seismic section that is characterised by shallowly dipping stratigraphic layers and some degree of faulting (shown by white arrows). Further inspection of the seismic section using the paraphase and SPC attribute (Figure 10.9b,c) provide clear evidence of the continuity of the reservoir (red arrows) and thin stratigraphic units (blue arrows), as well as faulting and folding (white arrows) between 2.2 and 2.8 s, while the APC (Figure 10.9d) attribute aids in tracking the fault, which appears much clearer due to the abrupt change in continuity of strong reflectors. The SPC attribute also enhances this steeply dipping fault that cuts across stratigraphic units. The detection of this feature is important since it may act as a possible conduit for gas and fluid to escape from the reservoir to the seafloor. This reservoir-fault relationship is not well defined by the conventional display (Figure 10.9a). Furthermore, enhancing faults in reservoirs is critical for evaluating prospects and characterising reservoir compartmentalisation for better hydrocarbon recovery.

In Figure 10.10a-d, attributes prove effective in enhancing the continuity of poor seismic reflections, indicated by the blue and red arrows, as well as in identifying faulting, folding, steeply dipping and edge terminated seismic events, given by the white arrows (Figure 10.10a,c,d). In general, by using a combination of attributes, we are able to enhance a wealth of seismic information that helps us quantify

reservoir characteristics better. However, it must be noted that seismic attributes are sensitive to noise in the seismic data from which they are derived. The noise in data may have different causes. The noise is generally related to a limited degree of the migration operator, velocity errors, acquisition footprint, as well as overall “random noise” from band pass filtering, f-k filtering and structure-oriented filtering. In the hard rock setting, for example, significant velocity errors will result in overlapping reflector signals, producing discontinuity and tuning artifacts that may overwhelm corresponding events associated with the subsurface geology. In the offshore setting, interbed multiples may cause similar strong artifacts. Therefore, for the seismic attributes to work effectively, the data need to be of high quality.

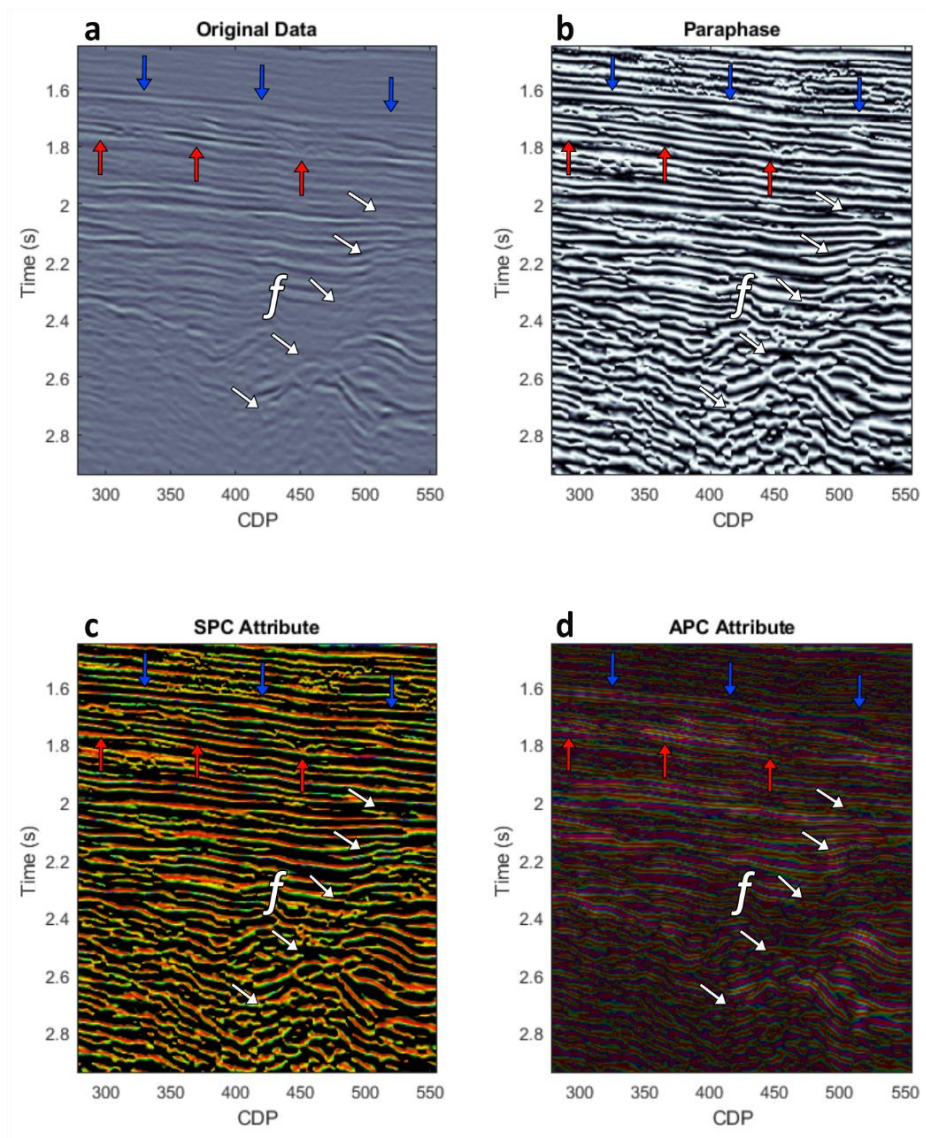


Figure 10.8: Bredasdorp Basin original data (a) plotted with paraphase (b), symmetry-paraphase composite (SPC) attribute (c), and amplitude-paraphase composite (APC) attribute (d). Coloured arrows indicate shallow weak reflections and white arrows indicate fault zone.

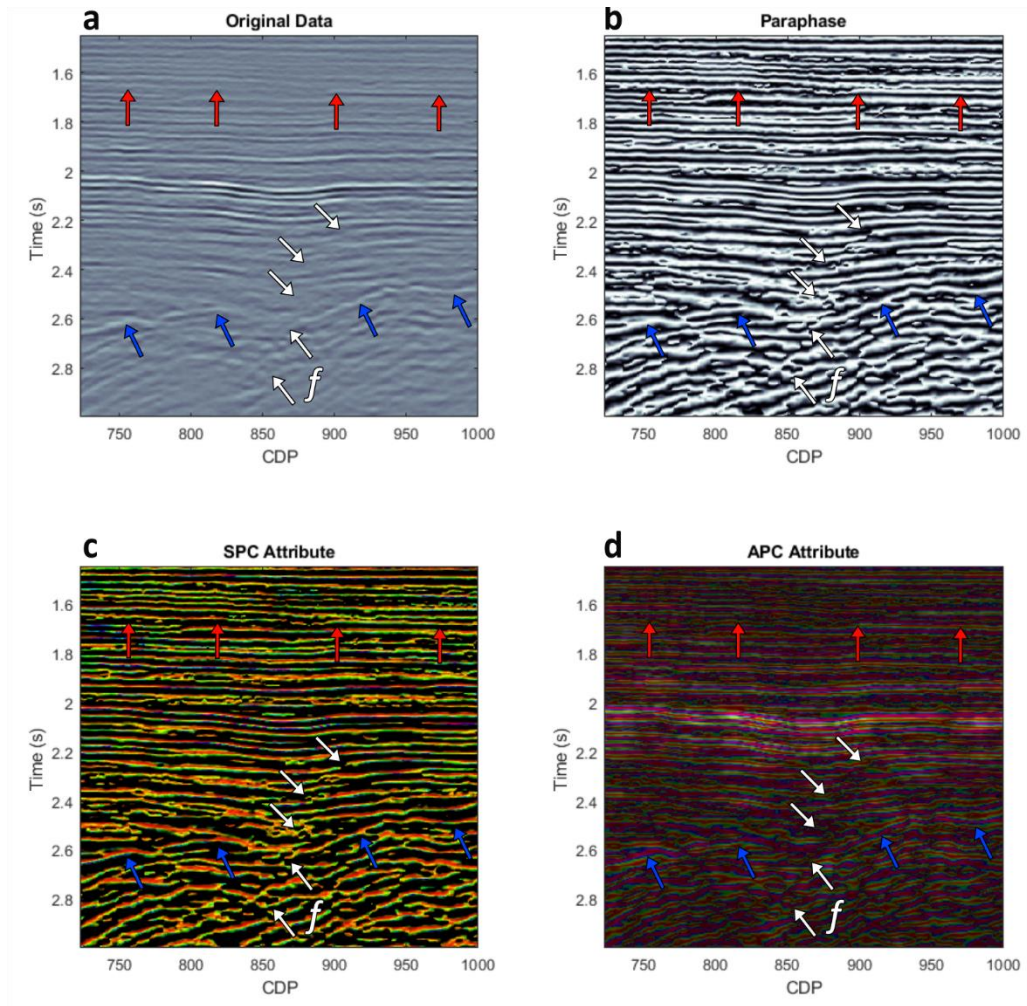


Figure 10.9: Bredasdorp Basin original data (a) plotted with paraphase (b), symmetry-paraphase composite (SPC) attribute (c), and amplitude-paraphase composite (APC) attribute (d). Coloured arrows indicate weak reflections and white arrows indicate fault zone.

10.6 Conclusions

By combining conventional instantaneous attributes, features within reflection data that are hard to detect, such as thin bedding or pinch-outs, can be enhanced and better imaged. By using this approach, the two combined attributes result in a composite that has the advantages of both attributes. This is demonstrated in this paper with the symmetry – paraphase and amplitude – paraphase attribute pairs.

In terms of resolution, the SPC attribute can aid in distinguishing between two closely spaced reflectors and is also effective at identifying both strong and weak reflectors while still being able to distinguish between them. The APC attribute is useful at identifying zones of strong reflectivity and bright spots, without losing high-frequency information within these regions which is typically the case with the instantaneous amplitude

The results also demonstrate that these composite attributes can play an important role in positioning the structural location of thin, layered ore bodies and reservoirs. The first case study in which the SPC

attribute is applied to data from the Kloof Gold Mine in South Africa reveals that the attribute assists in delineating the Ventersdorp Contact Reef, a gold-bearing horizon of interest whose thickness is below the tuning thickness of the seismic data. Along with the APC attribute, the SPC attribute also enhanced the detection of a fault zone that dissected the Ventersdorp Contact Reef.

The second case study demonstrated the use of the SPC and APC attributes in characterising the geometry of an oil reservoir amidst geological structures such as faulting and folding. The imaging of both weak and strong reflections in the vicinity of the reservoir were also enhanced by the composite attributes, proving useful in hydrocarbon exploration scenarios.

Interpretation using the composite attributes can thus help optimise the mining and oil and gas industry in a cost-effective way. By combining attributes in this way, an effective seismic attribute is produced that is useful tool for data interpretation.

10.7 References

Barnes, A.E. (1993). Instantaneous spectral bandwidth and dominant frequency with applications to seismic reflection data. *Geophysics* 58, 419–428.

Barton, K. and Grobblers, N. (1997). Re-appraisal of the E-CE / E-BD oil and gas fields based upon the 1996 reprocessing of the 3-D seismic data. SOEKOR internal report #SOE-EXP-RPT-0430.

Barton, K. and McAloon, W. (1999). Geophysics and geological modelling of the E-BD reservoir - part of the Sable Field development study – Block 9, Bredasdorp Basin, offshore Republic of South Africa. SOEKOR internal report #SOE-EXP-RPT-0486

Barton, K., Tönsing, T. and Turner, J. (2001). Evaluation of the prospectivity of the Western-Central Bredasdorp Basin using the E2000 data volume. *SOEKOR internal report #SOE-EXP-RPT-0570*.

Chen, Q. and Sidney, S. (1997). Seismic attribute technology for reservoir forecasting and monitoring. *The Leading Edge* 16, 445–448.

Chopra S., Castagna, J., Portniaguine, O. (2006). Seismic resolution and thin-bed reflectivity inversion. *Canadian Society of Exploration Geophysicists Recorder* 1, 19–25.

Chopra, S., Castagna, J. Xu, Y. (2009). Thin-bed reflectivity inversion and some applications. *First Break* 27, 17–24 pp.

Chopra, S. (2011). Extracting meaningful information from seismic attributes. *Canadian Society of Exploration Geophysicists Recorder* 36, 369–12.

Eriksson, P.G., Altermann, W., Hartzer, F.J. (2006). The Transvaal supergroup and precursors. In: Johnson, M.R., Anhaeusser, C.R., Thomas, R.J. (Eds.), the Geology of South Africa. Geological Society of South Africa, Johannesburg, 237–260.

Frimmel, H.E. (2018). Episodic concentration of gold to ore grade through Earth's history: *Earth Science Reviews* 180, 148-158.

Frimmel, H.E. (2014). A giant Mesoarchean crustal gold-enrichment episode: Possible causes and consequences for exploration, in Kelley, K., and Golden, H. C., eds., *Building Exploration Capability for the 21st Century: Society of Economic Geologists, Special Publication 18*, 209-234.

Gabor, D. (1946). Theory of communication. *Journal of Inst. Electelectrical Engineering*, vol. 93, pp. 429-457, 1946.

Gauert, C.D.K., Brauns, M., Batchelor, D., Simon, R. (2011). Gold provenance of the Black Reef conglomerate, West and East Rand, South Africa, in Barra, F., Reich, M., Campos, E., and Tornos, F., eds., *Proceedings of the 11th Biennial SGA Meeting: Let's Talk Ore Deposits: Antofagasta, Ediciones Universidad Católica del Norte 1*, 232–234.

Nwaila, G.T., Manzi, M.S.D., Kirk, J., Maselela, H.K., Durrheim, R.J., Rose, D.H., Nwaila, P.C., Bam, L.C. and Khumalo, T. (2019). Recycling of palaeoplacer gold through mechanical and post-depositional mobilisation in the Neoarchaeon Black Reef Formation, South Africa. *Journal of Geology*, 127, 137-166.

Henry, G. and Master, S. (2008). Black Reef Project. Council for Scientific and Industrial Research (CSIR) and University of the Witwatersrand, Johannesburg, 1-61.

Manzi, M.S.D., Durrheim, R.J., Hein, K.A.A. and King, N. (2012). 3D edge detection seismic attributes used to map potential conduits for water and methane in deep gold mines in the Witwatersrand Basin, South Africa. *Geophysics* 77(5), WC133-WC147.

Manzi, M.S.D., Hein K.A.A., Durrheim, R.J. and King, N. (2013). Seismic attribute analysis to enhance detection of thin gold-bearing reefs. South Deep gold mine, Witwatersrand Basin, South African. *Journal of Applied Geophysics* 982, 12–28.

Manzi M., Cooper G., Malehmir A., Durrheim R. and Nkosi Z. (2015). Integrated interpretation of 3D seismic data to enhance the detection of the gold-bearing reef: Mponeng Gold mine, Witwatersrand Basin (South Africa). *Geophysical Prospecting* 63, 881-902.

Sibanye Gold Limited, (2014). Competent person's report on the material assets of the Kloof operations. Libanon Business Park, Westonaria, South Africa., p. 104.

Taner, M.T., Koehler, F., Sheriff, R.E. (1979). Complex seismic trace analysis. *Geophysics* 44, 1041–1063.

Tucker, R.F., Viljoen, R.P., Viljoen, M.J. (2016). A review of the Witwatersrand Basin – the world's greatest goldfield. *Episodes* 39, 105–133.

Westgate, M.C., Manzi, M.S.D., Cooper, G.R.J. (2018). Symmetry as an Alternative Seismic Attribute: Case Studies from the Hard Rock and Soft Rock Environments, South Africa. *80th EAGE Conference and Exhibition 2018*.

Widess, M. (1973). How thin is a thin bed? *Geophysics*, 38 (6), 1176-1180.

Yu, Y. and Kelley, C. 2014, Determining Seismic Stratigraphic Features Using Dip-Guided Symmetry Attribute, *AAPG 2014 Annual Convention & Exhibition* in Houston, Texas, USA.

11 CONCLUSIONS AND OUTLOOK

11.1 Conclusions

This thesis has shown that through various processing and interpretation techniques, legacy reflection seismic data can be revived to yield improved high-resolution imaging of complex subsurface geology and structure, stretching the potential of the data beyond their original purpose and interpretation. [Paper I](#) demonstrated that by reprocessing legacy seismic data from raw shot gathers, the data can be repurposed for iron-oxide exploration. Originally intended for deep (>3 km) gold exploration, the reprocessed KBF01 seismic profile located along the western margin of the Kaapvaal Craton was reappropriated to quantify the subsurface characteristics of iron-oxide mineralisation located near Sishen mine. Integrating the seismic data with legacy magnetotelluric data allowed for comprehensive characterisation of the iron-oxide-hosting metasediments from the Griqualand-West Supergroup, revealing them to be located at a depth of 950 m with an average thickness of 500 m within a first-order syncline with wavelength and amplitude of 4 km and 1 km, respectively, thus assisting in the prospects of future potential mining endeavours.

[Paper II](#) demonstrated that reprocessing legacy seismic data can deepen our understanding of tectonically significant regions and provide insight into the developmental history of South Africa's crustal elements. Located along the interface of the Kheis Province and Kaapvaal Craton and close to the ~145 Ma Morokweng impact structure, all rendered challenging to investigate owing to the expansive Kalahari cover, the KBF03A seismic profile, also originally intended for gold exploration, proved to be an ideal tool for enquiry into the regional tectonic history. The reprocessed profile not only substantially improved the imaging of the Kalahari and Dwyka unconformities in the area, it also revealed these Phanerozoic sediments to have significant disruptions comprising evenly conjugated normal and reverse faults (<100 m slip) as well as west-verging folds with 10 km wavelengths, implying non-trivial neotectonic activity. These neotectonics features were made more evident by enhancement of the data by instantaneous seismic attributes that are used in [Paper III](#). Furthermore, integrating the seismic data with two sets of borehole data colinear with the profile revealed that previously established interpretations of this profile within the literature were significantly less plausible. Not least of these interpretations was the Moshaweng fault that was initially inferred to be a normal listric fault with 6.5 km slip. However, our reprocessed data suggested a reverse mechanism as the main phase of the 30° dipping fault, with a subsequent negative inversion and multiple reactivations.

In [Paper III](#), application of novel seismic attributes to legacy 3D seismic data revealed better imaging of economic zones of interest, as showcased in two case studies. The first case study showed how these attributes enhanced the imaging of two gold-bearing horizons, the Ventersdorp Contact Reef and the Black Reef, within the Witwatersrand Basin, both of which were below the tuning thickness of the data. The second case study, located in the offshore Bredasdorp Basin, involved better geometric

characterisation of the Sable oil and gas field subsurface geometry. Furthermore, [Paper III](#) established the effectiveness of symmetry as a seismic attribute as well as composite attributes, which are hybrids of two selected instantaneous attributes.

11.2 Outlook

While this thesis has shown the value of legacy seismic data reappraisal, there is further potential to which these data can be assessed. With the imminence of the fourth industrial revolution, techniques that are flooding the literature such as machine learning, neural networks, and diffraction imaging can be used to further investigate legacy seismic data, taking full advantage of data that were acquired in environments that are now contaminated with noise. In particular, it would be interesting to apply machine learning algorithms to the reprocessed profiles with the goal of automatic fault identification and characterisation. In profile KBF03A, large-scale diffraction anomalies were observed deep (>14 km) in the Archaean basement, imploring for diffraction analysis to investigate any structural elements within the basement.

The implications of the immense shift in interpretation of profile KBF03A due to better imaging clarity and borehole integration are many and potentiate further studies into the tectonic history of the region. In particular, the paper has evolved into the potential for two papers; one that would investigate the neotectonics of the Phanerozoic sediments that are evidenced by the reprocessed profile and another that would re-evaluate the tectonic model of the formation of the Moshaweng fault. My co-authors and I intend on investigating these two areas in the near future.

APPENDICES

A. Matlab Code used during PhD

Throughout the course of my Ph.D., I developed Matlab codes to perform various tasks. Three major sets of code were developed and are described here. The code has been appended to this thesis in the form of Matlab-compatible files and, in the case of the standalone SynthSeis program, includes the executable (.exe) file.

1. **SynthSeis Program:** The primary functionality of this code is to generate synthetic seismograms using velocity and density logs. The code comprises a series of .m functions that call upon each other and have been compiled using the Matlab compiler into a standalone program that can run on any computer that has the Matlab Runtime Environment (also appended to this thesis) installed. The program, which features a fully functional graphical user interface (GUI) and support system, reads in an Excel spreadsheet containing the log data, allowing the user to generate a synthetic seismogram, which can then be exported as a .png image or into another spreadsheet as a time series for further manipulation or display options. This code has been used for multiple studies within Wits University ranging from Honours level to PhD and even Postdoctoral and academic level studies, and was used in both [Paper I](#) and [Paper II](#).
2. **Symmetry and composite attributes:** [Paper III](#) (Chapter 10) details how composite attributes are constructed for advanced attribute analysis on two case studies within South Africa, as well as how symmetry was incorporated as one of these attributes. The Matlab code that was developed to calculate both the composite attributes and the symmetry attribute is contained within one .m file and is presented here. The function's input is a 2D seismic section in the form of an m-by-n matrix whose n columns are the traces of the section and whose m rows are the time samples of the section, as well as the window size of the windowed Fourier transform (WFT) used and the dilation exponent (more details in Chapter 10). It then outputs a display of the composite attributes as well as a variable that contains the symmetry attribute.
3. **Survey peg ID assignments:** As discussed in Chapter 4, the legacy data from both [Paper I](#) and [Paper II](#). One of the preparatory steps was to assign unique identities to source and receiver pegs within the survey based on the unique locations of these pegs. The single .m function that does this takes as a series of coordinates that, in general, contain duplicates (such as the sources or receivers in a survey), identifies and extracts unique locations and assigns identifiers to these locations. The code then outputs a list of identifiers that directly corresponds to the input coordinates list.

A.1. SynthSeis Program

The compiled SynthSeis standalone program is a simple executable (.exe) file that was compiled using the Matlab Compiler. This file is appended to this thesis and can be run on any machine that has the Matlab Runtime Environment installed (freely downloadable at <https://www.mathworks.com/products/compiler/matlab-runtime.html>). It comprises a series Matlab .m files that contain the scientific, logistic and data-flow components that form the backbone of the program, as well as a series of Matlab .fig files that store the GUI layouts, along with associated image files (.png or .jpg) that populate the GUI. The files that are required for the program to run within Matlab (i.e. if the standalone executable is not being used) are listed in Table A.1.1 along with their function in the program.

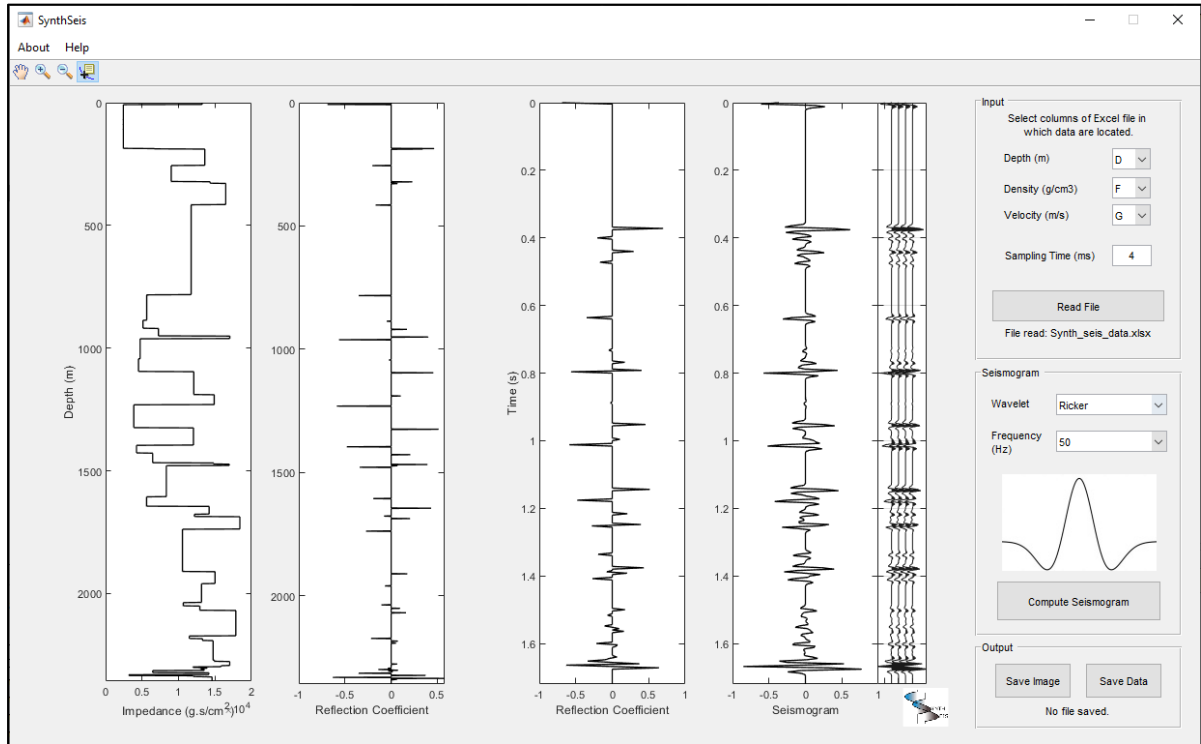
The primary purpose for the development of this program was for internal use by the geophysics department at the University of the Witwatersrand. Licensed software that perform similar functions such as Kingdom and Petrel were not always readily available to all students due to limited licenses. This was remedied by developing original, internal code that could be used freely by all students in the department.

All .m functions were coded by me, with the exception of the *wiggle.m* function, which was developed by Rodrigo S. Portugal (2012) who made it freely available to the Mathworks community. This function plots matrices as variable area wiggle plots, typically used when displaying seismic traces, and is thus not essential to the core functionality of the program. Note that this file is not appended to the thesis.

File	Function
SynthSeis.m	Main function that contains protocols for main GUI elements, such as buttons and dropdown menus. Within this function, the data that is output from <i>readSeis.m</i> is used to create synthetic seismograms by convolving one of the wavelet functions with the acoustic impedance log.
readSeis.m	Imports data from Excel file, strips numerical data and assigns variables to respective values. Uses <i>padDt.m</i> to create regularly sampled time series of density, velocity and acoustic impedance.
padDt.m	Takes values sampled at random intervals and regularises the sampling, padding intermediate values.
wmin.m	Creates a minimum phase wavelet with input dominant frequency and time interval.
wrick.m	Creates a Ricker wavelet with input dominant frequency and time interval.
wormsby.m	Creates an Ormsby wavelet with input dominant frequency and time interval.
wmorl.m	Creates a Morlet wavelet with input dominant frequency and time interval.
wiggle.m	Plots data as variable area wiggle plots. Credit: Rodrigo S. Portugal (2012).
Instructions.m	Code containing instructions for “Help” dialogue.
About.m	Code containing instructions for “About” dialogue.
SynthSeis.fig	GUI layout for parent function <i>SynthSeis.m</i> .
Instructions.fig	GUI layout for <i>Instructions.m</i> function.
About.fig	GUI layout for <i>Help.m</i> function.
About.jpg	Image used in <i>About.fig</i> .
M.jpg	Image used for Morlet wavelet in <i>SynthSeis.fig</i> .
Mm.jpg	Image used for minimum phase wavelet in <i>SynthSeis.fig</i> .
O.jpg	Image used for Ormsby wavelet in <i>SynthSeis.fig</i> .
R.jpg	Image used for Ricker wavelet in <i>SynthSeis.fig</i> .

Table A.1.1: List of files needed for SynthSeis program.

Also accompanying this thesis is a sample Excel spreadsheet, “SynthSeisExample.xlsx”, typically used as input for the SynthSeis program. A screenshot of the parent GUI of SynthSeis is given in Figure A.1.1. The main display area plots the calculated acoustic impedance log and reflectivity function versus depth, as well as the reflectivity and computed synthetic seismogram versus time.

**Figure A.1.1: Layout of main window of SynthSeis program, as well as labels of various components.**

On the right hand side, there are three panels labelled “Input”, “Seismogram”, and “Output”, illustrating the flow of the program. The input is required to be any version of Excel file that contains the depth (to layer base, in m), density (in g/cm^3), and velocity (in m/s) values in three separate columns all within the first ten columns of the file, headings are permitted. To read in such a file, the user is required to specify the column labels of the respective variables in the dropdown menus contained within the Input panel (in the case of the “SynthSeisExample.xlsx”, the user would specify C, D and E, respectively), after which a selected sampling interval of the synthetic seismogram is specified and the “Read File” button is pressed. This opens a dialogue box that prompts the user to navigate to and select the desired input file. Once the file is read, the first three plots will be populated.

The user can then compute the synthetic seismogram by selecting what type of wavelet is desired along with the dominant frequency to be used in the Seismogram panel. After these have been specified, the seismogram can be computed by pushing the “Compute Seismogram” button, which will populate the

fourth and last plot with the seismogram. The user may alter the wavelet type and dominant frequency and recompute the seismogram.

Once a satisfactory seismogram has been created, the user may export the results either as a simple PNG image, or as a set of time series stored in a new Excel file. This is done by selecting either (or both) of the respective buttons found in the Output panel. If the user exports the data into a spreadsheet, the output Excel file will contain six columns of data that contain the following variables in order: depth; impedance log in depth; reflection coefficient in depth; time; reflection coefficient in time, seismogram amplitude in time. The “About” and “Help” prompts in the toolbar will display additional information about SynthSeis, as well as instructions on how to use the program as outlined here.

Below is a copy of all the code found in the .m files:

SynthSeis.m

```
function varargout = SynthSeis(varargin)
% SYNTHSEIS MATLAB code for SynthSeis.fig
%   SYNTHSEIS, by itself, creates a new SYNTHSEIS or raises the existing
%   singleton*.
%
%   H = SYNTHSEIS returns the handle to a new SYNTHSEIS or the handle to
%   the existing singleton*.
%
%   SYNTHSEIS('CALLBACK',hObject,eventData,handles,...) calls the local
%   function named CALLBACK in SYNTHSEIS.M with the given input arguments.
%
%   SYNTHSEIS('Property','Value',...) creates a new SYNTHSEIS or raises the
%   existing singleton*. Starting from the left, property value pairs are
%   applied to the GUI before SynthSeis_OpeningFcn gets called. An
%   unrecognized property name or invalid value makes property application
%   stop. All inputs are passed to SynthSeis_OpeningFcn via varargin.
%
%   *See GUI Options on GUIDE's Tools menu. Choose "GUI allows only one
%   instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help SynthSeis

% Last Modified by GUIDE v2.5 18-Dec-2019 11:45:51

% hObject    handle to axes3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles     empty - handles not created until after all CreateFcns called

% Begin initialization code
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                  'gui_Singleton',   gui_Singleton, ...
                  'gui_OpeningFcn',  @SynthSeis_OpeningFcn, ...
                  'gui_OutputFcn',  @SynthSeis_OutputFcn, ...
                  'gui_LayoutFcn',   [], ...
                  'gui_Callback',    []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
```

```

[varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
%
% OPENING FUNCTION
% Initiates all handles for global variables as well as GUI elements
function SynthSeis_OpeningFcn(hObject, eventdata, handles, varargin)

%Initial Variables
handles.t = linspace(0,100,1000);
handles.dt = 0.004;
handles.z = linspace(0,100,1000);
handles.dz = handles.z(2)-handles.z(1);
handles.Zt = zeros(1000,1);
handles.dZt = zeros(1000,1);
handles.Zz = zeros(1000,1);
handles.dZz = zeros(1000,1);
handles.dZw = zeros(1000,4);
handles.wvtype = 1;
handles.fm = 50;
handles.sgm = zeros(1000,1);
handles.sgmw = zeros(1000,4);

%Load Wavelet Pics and Logo
handles.im(:,:,1) = imread('R.jpg');
handles.im(:,:,2) = imread('O.jpg');
handles.im(:,:,3) = imread('M.jpg');
handles.im(:,:,4) = imread('Mm.jpg');
handles.lgo = imread('SSProg.png');
imshow(handles.im(:,:,1), 'Parent', handles.axes4); ...
    handles.axes4.HandleVisibility = 'off';
imshow(handles.lgo, 'Parent', handles.axes5); ...
    handles.axes5.HandleVisibility = 'off';

%Create axes and initial plots and set properties
handles.text6.String = 'No file read';
handles.plot1 = plot(handles.axes1, handles.Zz, handles.z);
handles.plot2 = plot(handles.axes7, handles.dZz, handles.z);
handles.plot3 = plot(handles.axes2, handles.dZt, handles.t);
handles.plot4 = plot(handles.axes3, handles.sgm, handles.t);
handles.plot4a = plot(handles.axes9, handles.sgm, handles.t); ...
    handles.axes9.YGrid = 'on'; handles.axes9.XTickLabel = []; ...
    handles.axes9.YTickLabel = [];
set(handles.plot1, 'Linewidth', 1, 'Color', 'k');
set(handles.plot2, 'Linewidth', 1, 'Color', 'k');
set(handles.plot3, 'Linewidth', 1, 'Color', 'k');
set(handles.plot4, 'Linewidth', 1, 'Color', 'k');
set(handles.plot4a, 'Linewidth', 1, 'Color', 'k');
handles.axes1.YDir = 'reverse';
handles.axes2.YDir = 'reverse';
handles.axes3.YDir = 'reverse';
handles.axes7.YDir = 'reverse';
handles.axes9.YDir = 'reverse'; %wigggle(handles.t, 1:4, handles.sgmw);
linkaxes([handles.axes1, handles.axes7], 'y');
linkaxes([handles.axes2, handles.axes3, handles.axes9], 'y');
set(get(handles.axes1, 'XLabel'), 'String', 'Impedance (g.s/cm^2)');
set(get(handles.axes1, 'YLabel'), 'String', 'Depth (m)');
set(get(handles.axes7, 'XLabel'), 'String', 'Reflection Coefficient');
set(get(handles.axes2, 'XLabel'), 'String', 'Reflection Coefficient');
set(get(handles.axes2, 'YLabel'), 'String', 'Time (s)');
set(get(handles.axes3, 'XLabel'), 'String', 'Seismogram');

% Choose default command line output for SynthSeis
handles.output = hObject;
% Update handles structure

```

```

guidata(hObject, handles);

% OUTPUT FUNTION
%Trivial for this programme
function varargout = SynthSeis_OutputFcn(hObject, eventdata, handles)
varargout{1} = handles.output;
%

% CREATION AND DELETION FUNCTIONS
% Creates or Deletes GUI elements with specific instantiation code if
% necessary.
%
function popupmenu1_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function popupmenu2_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function popupmenu3_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function popupmenu7_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function popupmenu8_CreateFcn(hObject, eventdata, handles)
hObject.Value = 5;
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function axes1_CreateFcn(hObject, eventdata, handles)

function axes3_CreateFcn(hObject, eventdata, handles)

function axes4_CreateFcn(hObject, eventdata, handles)

function text6_CreateFcn(hObject, eventdata, handles)

function text6_DeleteFcn(hObject, eventdata, handles)

function text14_CreateFcn(hObject, eventdata, handles)
hObject.String = 'No file saved.';

function edit1_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
%

% CALLBACKS FOR GUI ELEMENTS
% These functions exeute when associated GUI element is interacted with.

```

```

%
function popupmenu1_Callback(hObject, eventdata, handles)
val = hObject.Value;
str = hObject.String;
handles.crho = str{val};
guidata(hObject,handles);

function popupmenu2_Callback(hObject, eventdata, handles)
val = hObject.Value;
str = hObject.String;
handles.cv = str(val);
guidata(hObject,handles);

function popupmenu3_Callback(hObject, eventdata, handles)
val = hObject.Value;
str = hObject.String;
handles.cz = str(val);
guidata(hObject,handles);

function popupmenu7_Callback(hObject, eventdata, handles)
% hObject      handle to popupmenu7 (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      structure with handles and user data (see GUIDATA)
wt = hObject.Value;
handles.wvtype = wt;
imshow(handles.im(:,:,wt),'Parent',handles.axes4); handles.axes4.HandleVisibility
= 'off';
guidata(hObject,handles)

function popupmenu8_Callback(hObject, eventdata, handles)
handles.fm = hObject.Value*10;
guidata(hObject,handles)

function pushbutton1_Callback(hObject, eventdata, handles)
set(handles.figure1, 'pointer', 'watch');
drawnow;
try
    handles.dt = str2double(handles.edit1.String)/1000;

[handles.t,handles.z,handles.dz,handles.Zt,handles.dZt,handles.Zz,handles.dZz,fname]
= readSeis(handles.crho,handles.cv,handles.cz,handles.dt);
handles.sgm = zeros(length(handles.t),1);
handles.text6.String = ['File read: ',fname];
handles.plot1.XData = handles.Zz; handles.plot1.YData = handles.z; ...
    handles.axes1.YLim=[0,max(handles.z)];
handles.plot2.XData = handles.dZz; handles.plot2.YData = handles.z; ...
    handles.axes7.YLim=[0,max(handles.z)];
handles.plot3.XData = handles.dZt; handles.plot3.YData = handles.t; ...
    handles.axes2.YLim=[0,max(handles.t)];
handles.plot4.XData = handles.sgm; handles.plot4.YData = handles.t; ...
    handles.axes3.YLim=[0,max(handles.t)];
handles.plot4a.XData = handles.sgm; handles.plot4a.YData = handles.t;...
    handles.axes9.YLim=[0,max(handles.t)];
    handles.axes9.YGrid='on'; handles.axes9.XTickLabel = [];...
    handles.axes9.YTickLabel = [];
    guidata(hObject,handles);
catch ME
    error(ME.message)
end
set(handles.figure1, 'pointer', 'arrow')

function pushbutton3_Callback(hObject, eventdata, handles)
handles.dt = str2double(handles.edit1.String)/1000;
switch handles.wvtype

```

```

        case 1
            wv = wrick(handles.fm,handles.dt);
        case 2
            wv = wormsby(handles.fm,handles.dt);
        case 3
            wv = wmorl(handles.fm,handles.dt);
        case 4
            wv = wmin(handles.fm,handles.dt);
    end
    tmp = conv(wv,handles.dZt);
    handles.sgm = tmp(ceil(0.5*length(wv)):end-floor(0.5*length(wv)));
    handles.plot4.XData = handles.sgm;
    cla(handles.axes9); hold(handles.axes9,'on'); ...
        wiggle(handles.t.',1:4,repmat(handles.sgm,1,4),'2kK',handles.axes9); ...
        hold(handles.axes9,'off'); handles.axes9.XLim=[-1,6]; ...
        handles.axes9.YLim=[0,max(handles.t)]; handles.axes9.YGrid='on';...
        handles.axes9.XTickLabel = []; handles.axes9.YTickLabel = [];
    guidata(hObject,handles)

function pushbutton4_Callback(hObject, eventdata, handles)
rect = [1 1 998 679];
tempclr = get(handles.figure1,'Color');
set(handles.figure1,'Color',[1,1,1]);
im = getframe(handles.figure1,rect);
set(handles.figure1,'Color',tempclr);
try
[FileName,PathName] = uiputfile('SSData.png');
delete([PathName,FileName]);
imwrite(im.cdata,[PathName FileName],'png');
handles.text14.String = ['Image saved: ' FileName];
catch
end
guidata(hObject,handles)

function pushbutton5_Callback(hObject, eventdata, handles)
switch handles.wvtype
    case 1
        tmp = 'Ricker';
    case 2
        tmp = 'Ormsby';
    case 3
        tmp = 'wmorl';
    case 4
        tmp = 'Min Phase';
end

[FileName,PathName] = uiputfile('SSData.xls');
headers = {'Depth (m)' 'Impedence (Pa.s/m3)' 'Reflection Coefficient in depth'};
dta = [handles.z handles.Zz handles.dZz];
dtaW = [headers;num2cell(dta)];
delete([PathName,FileName]);
xlswrite([PathName FileName],dtaW);
headers = {'Time (s)' 'Reflection Coefficient in time' ['Seismogram Amplitude (Using ' tmp ' wavelet)']};
dta = [handles.t handles.dZt handles.sgm];
dtaW = [headers;num2cell(dta)];
xlswrite([PathName FileName],dtaW,1,'D1');
handles.text14.String = ['Data saved: ' FileName];

guidata(hObject, handles);

function About_Callback(hObject, eventdata, handles)
About

function Help_Callback(hObject, eventdata, handles)
Instructions

```

```

function edit1_Callback(hObject, eventdata, handles)

function Untitled_1_Callback(hObject, eventdata, handles)

%END OF FUNCTION_____

```

readSeis.m

```

function [t,ztmp,dz,Zt,dZt,Zz,dZz,FileName] = readSeis(Crho,Cv,Cz,dt)
%READSEIS reads a user-specified Excel file, extracts depth, density and
%velocity measurements of borehole data, and outputs the acoustic
%impedence log in time
[FileName,PathName] = uigetfile('*.xls*','Select the data file');
fname = [PathName,FileName];

% rho = xlsread(fname,[Crho,':',Crho]);
% v = xlsread(fname,[Cv,':',Cv]);
% twt = xlsread(fname,[Ctwt,':',Ctwt]);

[num,~,raw] = xlsread(fname);
snum = size(num); sraw = size(raw);

Crho = conv2int(Crho); Cv = conv2int(Cv); Cz = conv2int(Cz);

indrow = sraw(1)-snum(1)+1;
rho = cell2mat(raw(indrow:end,Crho));
v = cell2mat(raw(indrow:end,Cv));
z = cell2mat(raw(indrow:end,Cz));
dz = min(diff(z));
ztmp = (0:dz:max(z)+10*dz).';

twt = zeros(size(z)); twt(1)=2*z(1)/v(1);
for n=2:length(z)
    twt(n) = twt(n-1)+2*(z(n)-z(n-1))/v(n);
end
t = (0:dt:max(twt)+10*dt).';

% _____Depth_____
l = length(z);
L = length(ztmp);

for j=1:l
    [ind(j) ind(j)] = min(abs(ztmp-z(j)));
end
ind=ind.';

RHO = padDt(rho,ind);
RHO(end+1:L)=RHO(end);

V = padDt(v,ind);
V(end+1:L)=V(end);

Zz = RHO.*V;

temp = conv(Zz,[1;1]);
denom = temp(2:end-1);
num = diff(Zz);
dZz = [num(:)./denom(:);0];
ind=[];

```

```

% _____ Time _____
l = length(twt);
L = length(t);

for j=1:l
    [ind(j) ind(j)] = min(abs(t-twt(j)));
end
ind=ind.';

RHO = padDt(rho,ind);
RHO(end+1:L)=RHO(end);

V = padDt(v,ind);
V(end+1:L)=V(end);

Zt = RHO.*V;

temp = conv(Zt,[1;1]);
denom = temp(2:end-1);
num = diff(Zt);
dZt = [num(:)./denom(:);0];
end

function out = conv2s(in)
switch in
    case 1
        out = 'A';
    case 2
        out = 'B';
    case 3
        out = 'C';
    case 4
        out = 'D';
    case 5
        out = 'E';
    case 6
        out = 'F';
    case 7
        out = 'G';
    case 8
        out = 'H';
    case 9
        out = 'I';
    case 10
        out = 'J';
end
end

function out = conv2int(in)
switch in
    case 'A'
        out = 1;
    case 'B'
        out = 2;
    case 'C'
        out = 3;
    case 'D'
        out = 4;
    case 'E'
        out = 5;
    case 'F'
        out = 6;
    case 'G'
        out = 7;
    case 'H'
        out = 8;

```

```

        case 'I'
            out = 9;
        case 'J'
            out = 10;
    end
end
end

```

padDt.m

wmin.m

```

function w = wmin(fm,dt)

t = 0:dt:1/fm*1.5;
s = sin(2*pi*fm*t);
e = exp(-1.75*fm*t);
wtmp = e.*s;

w=zeros(size(wtmp));
w=[w,wtmp];

end

```

wrick.m

```

function R = wrick(fm,dt)

TD = sqrt(6)/(pi*fm);
t = -1.2*TD:dt:1.2*TD;

tt = (pi*fm*t).^2;
R = (1-2*tt).*exp(-tt);

end

```

wormsby.m

```

function A = wormsby(fm,dt)

t = -0.2:dt:0.2;
f1=fm-10; f2=f1+5; f3=fm+5; f4=f3+5;

A = pi/(f4-f3)*(f4^2*sinc(f4*t).^2-f3^2*sinc(f3*t).^2)-pi/(f2-
f1)*(f2^2*sinc(f2*t).^2-f1^2*sinc(f1*t).^2);

end

```

wmorl.m

```

function M = wmorl(fm,dt)

P = 100;
a = (2*fm/4)^2*log(P);

TD = 4/(2*fm);

```

```

t = -1*TD:dt:1*TD;

M = cos(2*pi*fm*t).*exp(-a*t.^2);

end

```

Instructions.m

```

function varargout = Instructions(varargin)

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                  'gui_Singleton',   gui_Singleton, ...
                  'gui_OpeningFcn', @Instructions_OpeningFcn, ...
                  'gui_OutputFcn',  @Instructions_OutputFcn, ...
                  'gui_LayoutFcn',  [], ...
                  'gui_Callback',    []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before Instructions is made visible.
function Instructions_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles     structure with handles and user data (see GUIDATA)
% varargin    command line arguments to Instructions (see VARARGIN)

% Choose default command line output for Instructions
handles.output = hObject;

handles.output = hObject;

handles.im = imread('About.jpg');
imshow(handles.im,'Parent',handles.axes1); handles.axes1.HandleVisibility = 'off';
% Update handles structure
guidata(hObject, handles);

% UIWAIT makes Instructions wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command line.
function varargout = Instructions_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles     structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;

```

About.m

```
function varargout = About(varargin)

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                  'gui_Singleton',   gui_Singleton, ...
                  'gui_OpeningFcn', @About_OpeningFcn, ...
                  'gui_OutputFcn',  @About_OutputFcn, ...
                  'gui_LayoutFcn',  [], ...
                  'gui_Callback',    []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before About is made visible.
function About_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles     structure with handles and user data (see GUIDATA)
% varargin   command line arguments to About (see VARARGIN)

% Choose default command line output for About
handles.output = hObject;

handles.im = imread('About.jpg');
imshow(handles.im,'Parent',handles.axes1); handles.axes1.HandleVisibility = 'off';
% Update handles structure
guidata(hObject, handles);

% UIWAIT makes About wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command line.
function varargout = About_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles     structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;
```

A.2. Symmetry and Composite Attributes

The symmetry attribute as well as the composite attributes are described in Chapters 5 and 10. These are computed using a single .m file, *symmetry2.m*, that takes as input three variables: data, wsize, and pow and outputs a single variable out. The inputs correspond to the input seismic section as a Matlab matrix, the window size of the windowed Fourier transform (this can either be a single number which will create a square window whose sides are the input number, or it can be a two-vector, which will create a rectangular window whose number of rows and columns correspond the first and second numbers, respectively), and the power to which the output data is raised, respectively. The window size and exponent are detailed in Chapter 5. The output variable is the calculated symmetry attribute. Below is the code used for this function:

```
function out = symmetry2(data,wsize,pow)
%
%SYMMETRY takes in reflection data and, using input parameters 'wsize' and
%'pow', calculates a two dimensional symmetry attribute using the windowed
%Fourier transform. It then outputs the symmetry attribute, and two
%composites using the instantaneous amplitude and instantaneous phase.
%These composites are also plotted alongside the data and the symmetry
%attribute.
%
% Michael Westgate, 2018
% University of the Witwatersrand
%
s = size(wsize);
if min(s)==1
    wsize = [wsize wsize];
end

s = size(data);
w = hann2(wsize);
out = zeros(s);
tmp=zeros(s(1)-wsize(1)+1,s(2)-wsize(2)+1);

for count1 = 1:s(1)-wsize(1)+1
    for count2 = 1:s(2)-wsize(2)+1
        ftin = w.*data(count1:count1+wsize(1)-1,count2:count2+wsize(2)-1);
        ft = fft2(ftin);
        I = sum(abs(imag(ft(:)))));
        R = sum(abs(real(ft(:)))));
        k = 0.0001*sqrt(I^2+R^2);
        phi = atan(I./(R+k));
        tmp(count1,count2) = abs(phi);
    end
end

tmp = (tmp./max(abs(tmp(:))))).^pow;

[nr,nc] = size(tmp);
r = ceil(wsize(1)/2);
c = ceil(wsize(2)/2);
out(r:r+nr-1,c:c+nc-1) = tmp;

%-----Non Symmetry Section-----
%Instantaneous attributes
h = hilbert(data);
A = abs(h);
```

```

phi = unwrap(angle(h));
cphi = cos(phi);

figure;
%Construct and plot composites
C1(:,:,1) = out; C1(:,:,2) = ones(s); C1(:,:,3) = abs(cphi);
rgb = hsv2rgb(C1);
subplot(1,4,3); image(rgb); ax(3) = gca;
title('Symmetry - Phase Composite')

C2(:,:,1) = out; C2(:,:,2) = ones(s); C2(:,:,3) = A/max(A(:));
rgb = hsv2rgb(C2);
subplot(1,4,4); image(rgb); ax(4) = gca;
title('Symmetry - Amplitude Composite')

%BELOW IS FOR SWAPPING COMPONENTS OF COMPOSITES
% C3(:,:,1) = A; C3(:,:,2) = ones(s); C3(:,:,3) = out;
% rgb = hsv2rgb(C3);
% subplot(2,4,5); image(rgb); ax(5) = gca;
% title('Amplitude - Symmetry Composite')
%
% C4(:,:,1) = cphi; C4(:,:,2) = ones(s); C4(:,:,3) = out;
% rgb = hsv2rgb(C4);
% subplot(2,4,6); image(rgb); ax(6) = gca;
% title('Phase - Symmetry Composite')

%Plot original data and symmetry attribute
subplot(1,4,1); imagesc(data); ax(1) = gca;
title('Original Data'); colormap jet

subplot(1,4,2); imagesc(out); ax(2) = gca;
title('Symmetry Attribute'); colormap jet

linkaxes(ax);

end

function out = hann2(w)
[m,n] = meshgrid(0:w(2)-1,0:w(1)-1);
out = sin(pi*m/w(2)).^2.*sin(pi*n/w(1)).^2;
end

```

A.3. Survey peg ID assignments

As described in Chapter 4, preparation of the two legacy seismic profiles involved, among other tasks, assigning unique identifiers to locations within the survey that were occupied by multiple sources or receivers throughout the survey. The code below was used to accomplish this. The two inputs `px` and `py` are column vectors that contain the x and y coordinates, respectively, of all the source/receiver pegs found within the survey (as would be seen in the `sps` files, for example). The output, `peg`, is a column vector with same length as `px` and `py` that contains unique identifiers with direct correspondence to the values in the `px` and `py` vectors.

```
function peg = assignPegs(px,py)
%ASSIGNPEGS assigns peg identities to unique pairs of x-y peg coordinates.
%   Coordinate pairs within seismic geometry can be repeated at random
%   within a survey. ASSIGNPEGS asses input geometry pairs and assigns a
%   unique identifier to unique x-y pairs.
% INPUT
%   px : Column vector containing x coordinates of pegs.
%   py : Column vector containing y coordinates of pegs.
% OUTPUT
%   pegs : Column vector of same length as px and py containing
%   corresponding peg number.

p = [px,py];
[Unq, ~, ib] = unique(p, 'rows');
indices = accumarray(ib, find(ib), [], @(rows){rows});

s = length(px);
sU = length(Unq(:,1));

indicesmin = zeros(size(indices));
for n=1:sU
    indicesmin(n)=min(indices{n});
end
indicesmin = indicesmin.';

k=1;
for n=1:max(indicesmin)
    for m=1:sU
        if indicesmin(m)==n
            ind(m)= k;
            k=k+1;
        end
    end
end
ind=ind(:);

Unqpeg=zeros(sU,1);
tf = ismember(Unq,[0,0], 'rows')

if max(tf) == 0
    zeroind = min(ind)-1;
else
    zeroind = indicesmin(tf==1);
end

for n=1:sU
    if ind(n)<zeroind
        Unqpeg(n)=ind(n)+99;
    end
end
```

```

elseif ind(n)==zeroind
    Unqpeg(n)=50;
elseif ind(n)>zeroind
    Unqpeg(n)=ind(n)+98;
end
end

peg = zeros(s,1);
for n=1:s
    for m=1:sU
        if px(n)==Unq(m,1) && py(n)==Unq(m,2)
            peg(n)=Unqpeg(m);
        end
    end
end
end

```

B. Peer-Reviewed Extended Abstracts

The following extended abstracts were peer-reviewed throughout the course of my PhD and are attached in subsequent pages:

- Westgate, M., Manzi, M., Malehmir, A. (2019). Reassessment of Legacy 2D Seismic Reflection Data from the Kaapvaal Craton using Unconventional Methods. 16th SAGA Biennial Conference & Exhibition 2019.
- Westgate, M., Manzi, M., Cooper, G., Durrheim, R. (2019). An alternative reflection seismic interpretation approach based on symmetry: Case studies from oilfield and goldfield data in South Africa. 8th International Geosciences Student Conference 2019.
- Westgate, M., Manzi, M., Cooper, G., Durrheim, R. (2018). Symmetry as an Alternative Seismic Attribute: Case Studies from the Hard Rock and Soft Rock Environments, South Africa. 80th EAGE Conference and Exhibition 2018.
- Westgate, M., Manzi, M., Cooper, G., Durrheim, R. (2017). Theoretical Overview of Complex Seismic Attributes and Applications to Soft and Hard Rock Environments in South Africa. 15th SAGA Biennial Conference & Exhibition 2017.

Reassessment of Legacy 2D Seismic Reflection Data from the Kaapvaal Craton using Unconventional Methods.

M. Westgate¹, M. Manzi²

1. University of the Witwatersrand, South Africa,
michael.westgate@students.wits.ac.za

2. University of the Witwatersrand, South Africa,
musa.manzi@wits.ac.za

BIOGRAPHY

Michael Westgate is a doctoral candidate in Geophysics. He specialises in computational seismic analysis under the supervision of Professor Musa Manzi.

The focus of Michael's research is comprised of seismic reflection data processing techniques, coding seismic analysis and interpretation programmes and diffraction imaging. He codeveloped an unconventional seismic attribute based on symmetry, along with Prof. M. Manzi and Prof. G. Cooper, that was awarded the Best Student Paper Award at SAGA 2017.

SUMMARY

The reprocessing of legacy data is important in updating knowledge of existing surveys, maintaining coherency in processing conventions, and correcting any falsities in existing data.

The legacy data used here were collected and processed by Anglo American (now AngloGold Ashanti) in 1994 over the Sishen mine near the western edge of the Kaapvaal craton. Our goal is to reassess this data and improve on the quality of the processing used.

By implementing updated and unconventional processing methods (pre-stack attribute analysis, diffraction imaging and modern migration techniques to name a few), we are able to correct errors in the processed data and maximise the potential of the legacy data.

In this abstract, we present one of these methods used in the Sishen mine data; pre-stack instantaneous frequency analysis with the goal of assisting in first break picking. This unconventional technique proves useful in creating accurate picks in Vibroseis data by eliminating correlation anomalies that result from the Vibroseis method. It does this by exploiting the difference in frequencies between these anomalies and the real data.

Creating accurate picks improves the quality of the data processing and preserves the integrity of the data.

Key words: seismic, legacy, instantaneous, frequency, Vibroseis.

INTRODUCTION

The seismic reflection method has proved to be a significantly reliable and invaluable method for mineral and hydrocarbon exploration. It is thus important to maintain modern quality standards especially with legacy data that have been processed with outdated methods. It can also save time and money to rather reprocess legacy data than reconduct an entire survey (Manzi et al, 2018; Malajczuk et al, 2016).

The Sishen open pit mine in the Northern Cape of South Africa is one of the largest open pit mines in the world and is valued for its iron ore production. Legacy Vibroseis data collected in the region was processed in 1994 by Anglo America (now AngloGold Ashanti). These data may contain significant details of the region that outdated processing methods may not have detected. This prompts the reprocessing of these data with modern processing methods.

We intend on conducting, among other methods, diffraction analysis, pre-stack and post-stack migration, and comprehensive attribute analysis, both before and after processing.

Due to the limited content that can be covered in an abstract, we present here one of the methods used: pre-processing instantaneous attribute analysis. We recall the convolutional model applied to the Vibroseis method and show how the instantaneous frequency attribute can be used to mitigate correlation anomalies in the data by frequency decomposition in the time-domain. By eliminating these anomalies, we can easily identify first breaks, allowing us to conduct accurate first break picking.

DATA AND SETTING

Parameters of survey

The 2D survey was conducted in 1994 with the objective of mapping gold and iron-oxide hosts in the region (Manzi et al, 2018). Table 1 below summarizes the survey parameters.

Type	2D Seismic Profile
Year	1994
Line Direction	E-W
Line Length	200 km
Recording Device	SN 338
Sampling Rate	4 ms
Recording Length	6 s
Sweep Length	16 s

Sweep	15 - 75 Hz
Source Spacing	50 m
Receiver Spacing	25 m
Geophone Type	10 Hz (SM4U)

Table 1. List of relevant parameters of the legacy data survey.

Location of study area

The seismic survey was conducted over Sishen Mine in the Northern Cape province of South Africa. A map of the area is given in Figure 1. Sishen Mine lies within the Kaapvaal Craton, along the western edge, and has been mined for ore since 1953 (Manzi et al, 2018).

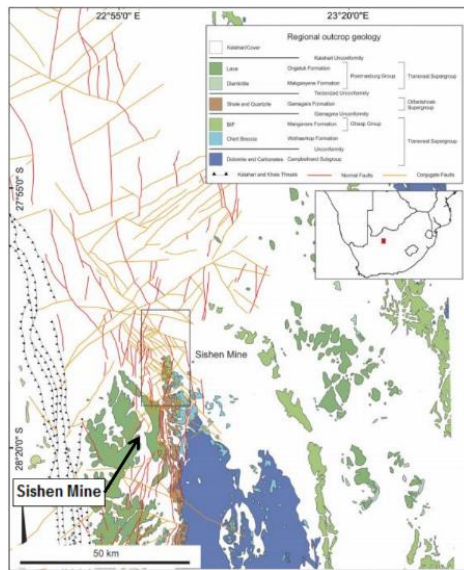


Figure 1: Geological surface map of Sishen Mine and its location within South Africa.

Original legacy data

Figure 2 below shows the original data both before and after processing as well as interpretations by Manzi et al (2018). Figure 2a is a shot gather resulting from a cross correlation of the sweep signal and the earth response of the sweep signal. There are possible subtle reflectors in the raw data, as indicated in Figure 2a. Correlation anomalies, also indicated, introduce difficulties when picking first breaks as they are heard to distinguish from the first arrivals.

The processed data, shown in Figure 2b, shows a variety of structural features. The interpretation (Manzi et al, 2018) suggests multiple fault zones, unconformities and strata.

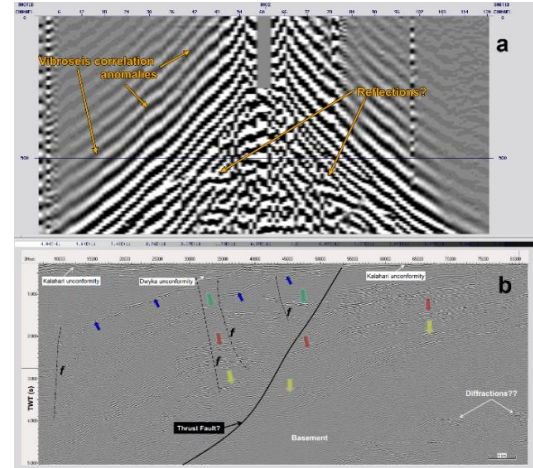


Figure 2: Original legacy data pre-processed (a) and post-processed (b). Blue arrows indicate mineralized hematite units, red arrows delineate the roof of the Ventersdorp sediments and green arrows indicate the top of the Olifantshoek Supergroup. Interpretation by Manzi et al, 2018.

By using modern processing techniques, we can both verify and improve upon the interpretation of the legacy data.

Some of the processing techniques used on this data are applying seismic pre-stack attributes to generate more accurate and reliable first break picks and mitigate human error due to anomalies like those indicated in Figure 2a. We also compare and contrast pre-stack and post-stack migration. Diffraction imaging is useful in collapsing diffractions shown in Figure 2b, allowing us to interpret the region more accurately. In this abstract, we demonstrate the usefulness of frequency analysis in generating more reliable first break picks.

THEORY: PRE-PROCESSING FREQUENCY ANALYSIS AND FIRST BREAK PICKS

As stated in the Introduction, the scope of processing techniques cannot be succinctly covered in a single abstract so we focus here on one of the methods used: pre-stack frequency analysis and its assistance in first break picks.

Vibroseis correlation

The legacy data have been acquired by the conventional Vibroseis method. The simplified convolutional earth model associated therewith states that the observed signal, $r(t)$, is given by the convolution of the sweep signal, $s(t)$, and the earth reflectivity function, $e(t)$ (Yilmaz, 1987):

$$r(t) = s(t) * e(t) \quad (1)$$

This is illustrated in Figure 3. The sweep signal $s(t)$ typically runs linearly from a lower frequency to a higher

frequency in a finite time known as the sweep length (Yilmaz, 1987; Baeten, 1989), also illustrated in Figure 3. The observed signal is then cross-correlated with the sweep signal, resulting in

$$r'(t) = r(t) \otimes s(t) = k(t) * e(t) \quad (2)$$

where $r'(t)$ is the new trace, $\otimes$ resembles cross-correlation and $k(t)$ is the Klauder wavelet, given by the autocorrelation of the sweep signal (Baeten, 1989). The purpose of moving from Equation 1 to Equation 2, as detailed in Yilmaz (1987), is to reduce the time-expanded earth response of the sweep signal to a localised wavelet, given by the Klauder wavelet, while reattaining the broadband information content. The cross-correlation process is illustrated in Figure 3.

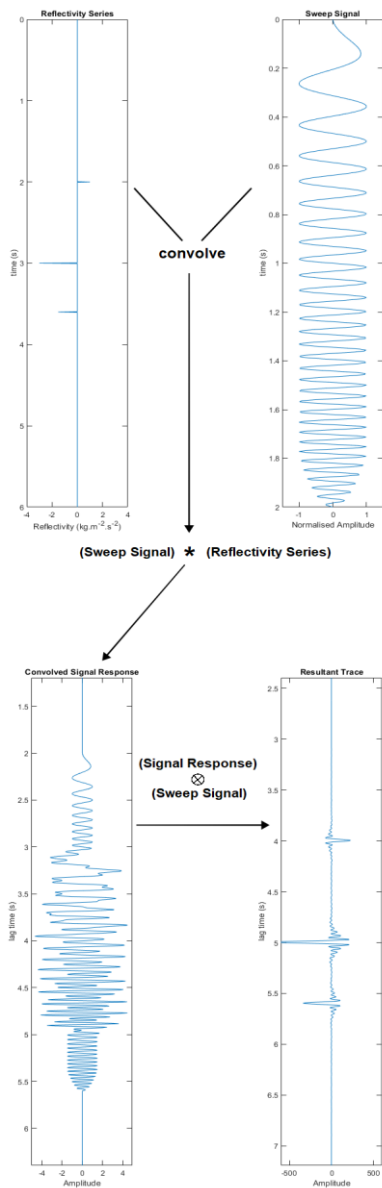


Figure 3: The convolutional model associated with the Vibroseis method: the observed response is modelled as the convolution of the sweep signal (top right) and the earth reflectivity function (top left). To localise the reflections, the response (bottom left) is cross-correlated with the sweep signal, as stated in Equations 1 and 2, to give the final trace (bottom right).

A problem that arises is that correlation artefacts are produced, as illustrated in Figure 2a, that can introduce difficulties in identifying first breaks. When examining Figure 2a, it is clear that there is a range of frequencies before the first break (associated with the correlation artefacts), after which there is a continuous frequency (associated with the desired data). The goal is to define the boundary between these two regions and we do this by exploiting the difference in their frequency content.

Application of instantaneous frequency to raw data

The best way to delineate the shift in frequency content of the data as described in the previous section is to calculate the instantaneous frequency (Taner, 1979). The instantaneous frequency of a signal is given by the scaled time-derivative of the phase of the signal's Hilbert Transform (Taner, 1979; Barnes, 2007), which is the convolution of the signal with $1/\pi t$:

$$H(s)(t) = \frac{1}{\pi} \int \frac{s(\tau)}{t-\tau} d\tau \quad (3a)$$

$$f(t) = \frac{1}{2\pi} \frac{d\phi}{dt} = \frac{1}{2\pi} \frac{d}{dt} \arctan \left[\frac{Im(H)}{Re(H)} \right] \quad (3b)$$

Here, $H(s)(t)$ is the Hilbert transform of the time-dependant signal $s(t)$, $f(t)$ is the instantaneous frequency of $s(t)$, $\phi(t)$ is the instantaneous phase of $s(t)$, and $Im(H)$ and $Re(H)$ are the imaginary and real parts of H , respectively.

Figure 4 below shows the instantaneous frequency of one of the traces extracted from the shot gather shown in Figure 2a. The first break can be seen at around 500 ms, as indicated by the red line. At this point, there is an abrupt change in the instantaneous frequency; it levels out to a roughly constant value characterised by the Klauder wavelet. This contrast allows for better discernment between the Vibroseis correlation anomaly and the reflection data, thus defining the first break boundary. The instantaneous frequency can therefore be used as an aid in determining first breaks, which is demonstrated with a real shot gather in the Results section.

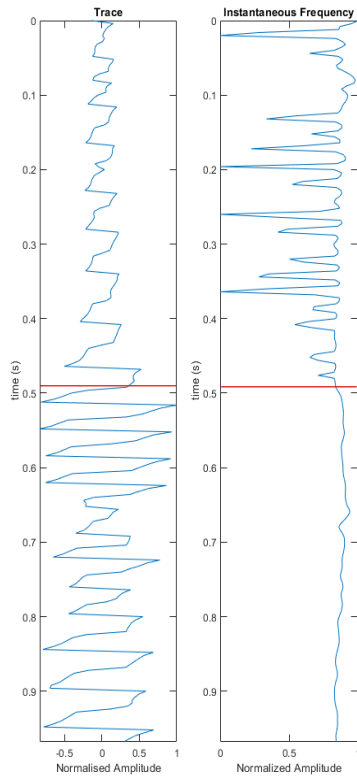


Figure 4: Trace extracted from shot gather in Figure 2 (left) and instantaneous frequency of trace (right), both normalised. Red line indicates first break.

RESULTS

Figure 5 below displays one of the shot gathers of the legacy data. It is difficult to discern where the first breaks lie due to the aforementioned correlation anomaly.

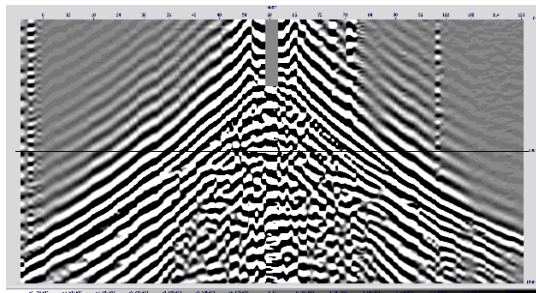


Figure 5: Shot gather from legacy data with unclear first breaks.

Applying the instantaneous frequency attribute, as shown in Figure 6a, the first breaks become significantly more discernible. The proposed first break picks are also displayed in Figure 6a and again on the original shot gather in Figure 6b.

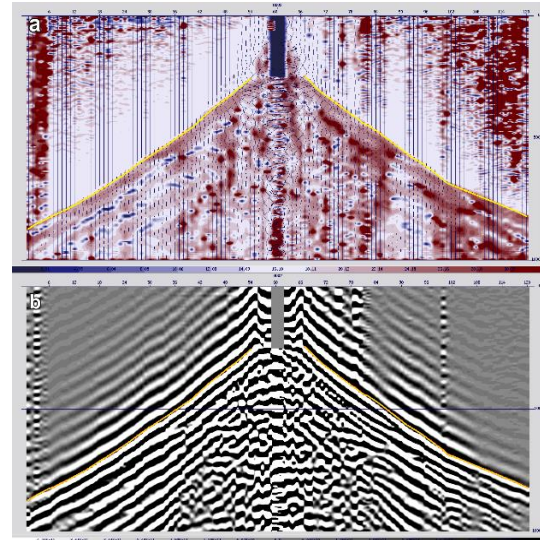


Figure 6: Instantaneous Frequency attribute of gather from Figure 5 with proposed first break picks in orange (a) and original gather with picks overlaid in orange (b).

As is always the case when working with seismic attributes, the instantaneous frequency should not be viewed as independent or more fundamental than the original data itself. Rather, it is simply an aid for visual interpretation; in this case, an aid in discerning first breaks.

CONCLUSIONS

Legacy data can be improved by modern and unconventional processing techniques, as shown with legacy data from the Western Kaapvaal region. For example, Vibroseis correlation anomalies in the data hinder accurate first break picking resulting in potential damage to data integrity. This can be mitigated by seismic attribute analysis of the pre-processed data.

By using the instantaneous frequency attribute to exploit the difference in the frequency content of the anomalies and the desired data, we easily detect first breaks in the pre-processed data and are able to conduct more reliable first break picking, preserving data integrity and realising its potential. This unconventional method of picking can be used in cross-correlated Vibroseis data.

In carrying this research further, other processing techniques that will be applied to the legacy data include pre-stack and post-stack migration analysis, diffraction imaging and post-processing attribute analysis.

ACKNOWLEDGMENTS

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REFERENCES

- Barnes, A.E., 2007. A tutorial on complex seismic trace analysis. *Geophysics* vol. 72 no.6. P. W33-W34.
- Malajczuk, S., Saklani, R., Clark, D., Eastwell, D., 2016, Improved Subsurface Imaging and Interpretability through Broadband Reprocessing of Legacy Seismic Data. Examples from North West Shelf Australia. 25th ASEG-PESA-AIG Geophysical Conference and Exhibition, 1-8.
- Manzi, M., Malehmir, A., Durrheim, R., 2018, Improved Subsurface Imaging through Re-processing of Legacy 2D Seismic Data-A Case Study from a Deep South African Gold Mine. EAGE 2nd Conference on Geophysics for Mineral Exploration and Mining.
- Manzi, M., Malehmir, A., Durrheim, R., Juhlin, C., 2018, Reappraisal of legacy data for seismic imaging of iron-oxide mineralisation on the western margin of the Kaapvaal Craton, South Africa. EAGE 2nd Conference on Geophysics for Mineral Exploration and Mining.
- Taner, M.T., Koehler, F., Sheriff, R.E., 1979. Complex seismic trace analysis. *Geophysics* vol. 44 no. 6. P. 1041-1063

Symmetry as an Alternative Seismic Attribute: Case Studies from the Hard Rock and Soft Rock Environments, South Africa

Introduction

The concept of symmetry pervades many different facets of everyday life, including art, nature, music, architecture, science and mathematics. In theoretical physics, symmetry is one of the most powerful tools as essentially all physical laws of nature have their roots in symmetry.

In reflection seismology, seismic attributes play an important role in the interpretation of data. These are mathematical objects extracted from the seismic traces that highlight certain properties of the data, aiding in the interpretation thereof.

This paper seeks to unify these two concepts by presenting reflectional symmetry (or parity) as a possible seismic attribute candidate. The symmetry attribute is applied to both one-dimensional and two-dimensional datasets and its use as a seismic attribute is examined.

Method

In the mathematical sense, symmetry manifests itself in different forms; rotational, reflectional, logical and translational to name a few. Of particular interest in signal processing is the symmetry, or parity, of functions. A function $f(x)$ has even parity if $f(-x) = f(x)$ and odd parity if $f(-x) = -f(x)$. This concept can be extended to that of local parity; the parity of the neighbourhood of an arbitrary point in the function. Making use of the windowed Fourier transform (Harris, 1978), the local parity of traces can be used as an attribute in each of the three spatial dimensions.

It can be proven that any mathematical function can be decomposed into a sum of an even and an odd function. This has implications in Fourier analysis, which states that any function can be broken into a sum of sinusoids, sine and cosine functions of differing frequencies (for non-periodic functions, the sum of these functions is replaced by an integral). This is mathematically given by the well-known Fourier transform (Easton, 2010):

$$F(v) = \int f(x)e^{-i2\pi vx} dx = \int f(x)[\cos(2\pi vx) - i \sin(2\pi vx)] dx \quad (1)$$

$$f(x) = \int F(v)e^{i2\pi vx} dx = \int F(v)[\cos(2\pi vx) + i \sin(2\pi vx)] dx \quad (2)$$

The Fourier transform is given by Equation 1 and its inverse transform by Equation 2. In the case that $f(x)$ is odd, all cosine terms in Equation 2 disappear and $F(v)$ is purely imaginary (in the context of seismic traces, $f(x)$ is the trace as a function of time and is therefore purely real). In the case that $f(x)$ is even, all sine terms disappear and $F(v)$ is purely real. Hence a function close to symmetry will have a dominating total real component and a function close to anti-symmetry will have a dominating total imaginary component, while an asymmetric function will have equal imaginary and real components. Taking the ratio of the real and imaginary components of a function's Fourier transform can thus be used as a quantitative measure of symmetry. The result is then normalized so as to range from zero (antisymmetrical) to one (symmetrical), as shown by Equations 3 and 4:

$$S = \int R[F(v)]dv / \int I[F(v)]dv + \varepsilon \quad (3)$$

$$S_{norm} = S / S_{max} \quad (4)$$

Where R and I denote the real and imaginary components, respectively, of the function enclosed in square brackets and ε is a damping factor that prevents singularities in S . S_{max} is defined as the maximum absolute value of S .

Equation 4, however, only gives a measure of global symmetry and the need arises to translate it into a form of local symmetry. This is accomplished by using a moving window in which the Fourier transform is calculated locally, that is, a windowed Fourier transform (WFT). A value of local symmetry is then calculated from the WFT.

Results

Figure 1 below shows the symmetry attribute applied to a simple sinusoid. It is clear that the attribute attains maxima at points of symmetry (peaks and troughs) in the data and minima at points of antisymmetry (inflection points). It is apparent that the symmetry attribute has a high-pass filter nature; for every one cycle of the sinusoid there are two cycles of symmetry.

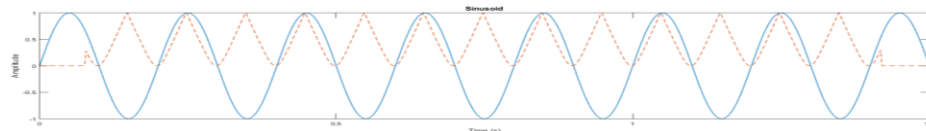


Figure 1 Symmetry attribute (orange) applied to sinusoid (blue).

Figure 2 shows the symmetry attribute applied to a line taken from real 3D reflection data obtained by CGG over the Western Bushveld Complex in South Africa. The high-pass nature of the attribute is evident, as well as AGC characteristics due to the fact that symmetry is not amplitude-dependent. Also shown in Figure 2 are two attribute composites; these are obtained by creating HSI images in which the symmetry attribute is assigned to the hue component of the image and an additional attribute (in this case, the instantaneous phase and instantaneous amplitude) is assigned to the intensity component. These composites are effective at delineating weak reflectors (as shown by the arrows) as well as picking up vertical discontinuities in the data (as shown by the ellipses).

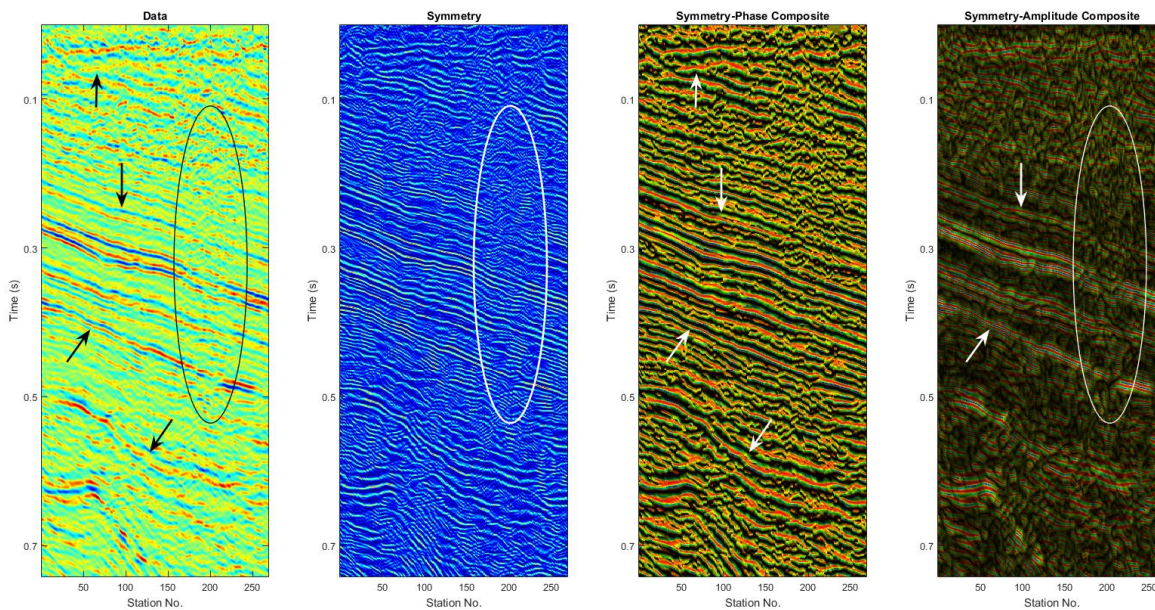


Figure 2 (Left to right) Original 2D data; symmetry attribute; symmetry-phase composite; symmetry-amplitude composite. Arrows indicate weak reflectors and ellipses indicate vertical anomaly.

Conclusion

Local symmetry of seismic traces can be used as a seismic attribute that acts as an effective automatic gain control and edge detector as well as enhancing subtle features. When combined with other attributes, the symmetry attribute is helpful at picking up weak reflectors and lateral discontinuities.

References

- Easton, R. L. (2010) Multidimensional Fourier Transforms, in Fourier Methods in Imaging, John Wiley & Sons, Ltd, Chichester, UK.
- Harris, F. J. (1978). On the use of windows for harmonic analysis with the discrete Fourier transform. Proceedings of the IEEE. Vol. 66. No. 1.

Theoretical Overview of Complex Seismic Attributes and Applications to Soft and Hard Rock Environments in South Africa

M. Westgate¹, M. Manzi²

1. School of Geosciences, University of the Witwatersrand, South Africa,
michael.westgate@hotmail.com

2. School of Geosciences, University of the Witwatersrand, South Africa, musa.manzi@wits.ac.za

BIOGRAPHY

Michael Westgate is a Master's student at the University of the Witwatersrand. He has attained a B.Sc. degree majoring in physics and advanced earth sciences as well as an Honours degree in geophysics for which he received a first class honorary award from SAGA. His honours year project involved investigating the theoretical and mathematical principles on which the analytic signal and resulting reflection seismic attributes are based.

SUMMARY

Since their inception in the 1970s, seismic attributes have grown in both number and theoretical complexity and have played a significant role in (reflection) seismic data interpretation and in seismic attribute analysis. The most common method of calculating these attributes is by means of the complex trace, a notion that also came forth in the 1970s which incorporates the analytic signal into seismic processing. The introduction of the complex trace into reflection seismology brought about the concepts of instantaneous frequency and phase and the trace envelope, each of which notably contrast the then conventionally used Fourier analysis approach. Examples of other fundamental attributes that can be computed using complex trace analysis include apparent polarity, bandwidth, Q-factor, dip and azimuth. Included in this study is the verification of the effectiveness of several attributes. The instantaneous phase proves useful at singling out strata truncations and toplap features and bedding is accentuated by the instantaneous amplitude. Apparent dip and semblance can be used to locate vertically anomalous structures such as gas escape features.

Key words: analytic, signal, reflection, seismology, attributes.

INTRODUCTION

The field of reflection seismology has evolved to become one of the most demanded geophysical methods, especially with the growth of the hydrocarbon industry. This growth in complexity has thus led to the development of numerous mathematical tricks and techniques that aid in the processing and interpretation of reflection data.

Among these various techniques is the customary interpretation tool of seismic attribute analysis, which has grown to be a highly valued tool for seismologists.

Seismic attributes can be broadly defined as quantitative properties of seismic reflection data that aid in the interpretation thereof. Since their origin, over two hundred attributes have been formulated to aid in data interpretation, many of which are instantaneous attributes.

While the procedure of calculating various attributes is not unique, the most common approach is by means of complex seismic trace, or analytical signal. This is a complex time-dependent trace that acts as a platform by which desired attributes are obtained.

Presented here is the theoretical grounding upon which complex trace analysis lies as well as the basic mathematical derivations of common seismic attributes via the complex trace. These concepts are then applied to synthetic data for reference and to real data to determine robustness. This real data is comprised of both soft and hard rock environments specific to South Africa (such as the Algoa and Witwatersrand basins).

COMPLEX TRACE ANALYSIS

The complex trace allows one to decompose a seismic trace into local separable amplitude and phase components, both instantaneous. Thus the original trace $s(t)$ can be described at each time t as an instantaneous sinusoid with an amplitude $A(t)$ and a phase $\phi(t)$ (Taner, 1979):

$$s(t) = A(t)\cos(\phi(t)) \quad (1)$$

This is accomplished by applying the Hilbert transform $H(t)$ to the original trace and constructing a complex trace with real component $s(t)$ and imaginary component $H(t)$, as shown in Equation 2. The Hilbert transform rotates the input function in the frequency domain by -90° for positive frequencies and 90° for negative frequencies. Multiplying this result by a further 90° by multiplication with the imaginary number i renders the complex trace with no negative frequency content and double the positive frequency content.

$$c(t) = s(t) + iH(t) \quad (2)$$

Since $s(t)$ and $H(t)$ are out of phase, the complex trace $c(t)$ attains a corkscrew-like appearance in the time-dependent argand plane, as shown in Figure 1. A multitude of seismic attributes can then be derived

through various mathematical manipulations of Equation 2 (Barnes, 2007).

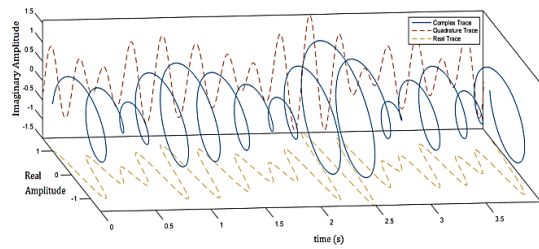


Figure 1: Complex trace derived from synthetic seismic trace. Real and imaginary components are given by orange and red dashed lines, respectively.

SEISMIC ATTRIBUTES

From Equation 2, three base or fundamental attributes are calculated and further attributes are derived through different combinations of these attributes. The fundamental attributes include the reflection strength, given by the instantaneous amplitude of Equation 1, the instantaneous phase and phase cosine, and the instantaneous frequency, which is the time derivative of the phase.

The reflection strength is proportional to the reflection coefficient, hence the name, making it useful at emphasising strong reflectors and isolating horizons as well as eliminating polarity bias. The cosine of the instantaneous phase embodies the trace with all amplitude information removed, making for the perfect automatic gain control (Barnes, 2007). It is very rarely used for amplitude gain, however, due to its property of enhancing noise content as well as signal content. The phase cosine is also useful at highlighting bedding and determining lateral continuity. The instantaneous frequency is the scaled time-derivative of the instantaneous phase and is a good edge detector, allowing for discernment of closely spaced layers (Subrahmanyam, 2008). Other attributes include quality factor, bandwidth, dip and semblance.

It is important to note that attributes are purely arithmetic; calculations are performed on the reflection data itself, and are not necessarily intrinsic to the geology represented by the data. It is thus necessary for a geophysicist to have an intuitive understanding of the attributes being applied so as to discern between actual geological representations and computational artefacts in the processed data. Attributes are designed purely as an aid to interpretation of the original data and should not be seen as original themselves, i.e. they are typically combined with the original data for interpretation and are not interpreted individually. In this paper, however, they are examined individually as a means of emphasising their specific use.

APPLICATION TO DATA

Multiple attributes are applied to both synthetic and real 2D seismic reflection data. Some examples are shown in Figures 2 to 4. The synthetic data in Figure 2 is a simple crude model resembling folded strata truncated by overlying flat strata. This model is solely intended to illustrate the use of a particular attribute, the calculated apparent dip, which takes on positive values for one anticlinal limb and negative values for the adjacent limb. This attribute thus acts as a contour map of sorts that connects regions with the same apparent dip.

Figure 3 shows an arbitrary line extracted from a 3D seismic survey conducted over the western goldfields of the Witwatersrand Basin by Sibanye Gold Ltd. Calculating the cosine of the instantaneous phase attribute allows for better discernment between flat strata and underlying truncated dipping strata as well as highlighting strong reflectors and bedding continuity. Chaotic reflections in the dipping strata also become more apparent with this attribute.

The third section, shown in Figure 4, is real data taken from a Zululand onshore basin 2D survey conducted by Soekor Ltd. in the 1960s. This data exhibits a central vertical anomaly, proposed to be a gas escape feature. This feature is emphasised by the accompanying semblance attribute, which is designed to enhance the contrast and quantify similarities and differences between adjacent seismic traces. It is therefore also useful at detecting vertical structures like dykes or faults.

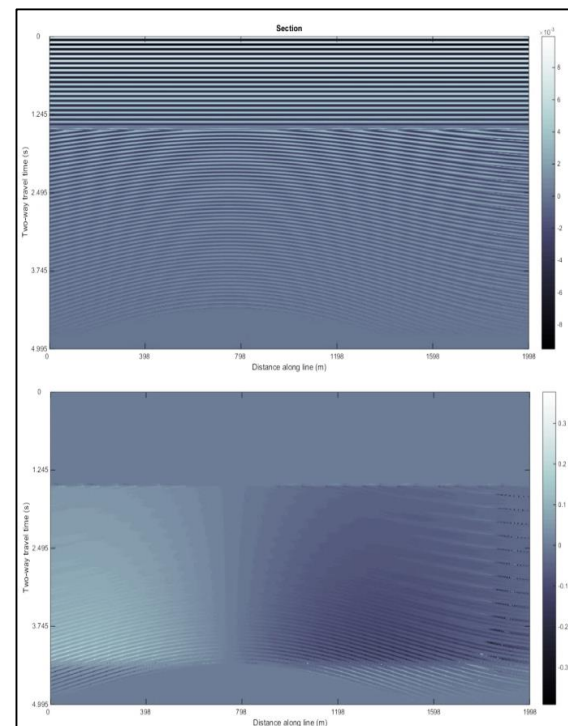


Figure 2: (Top) Synthetic section resembling ideal truncated folding. (Bottom) Apparent dip attribute

that is more positively inclined for upward dipping and more negatively inclined for downward dipping.

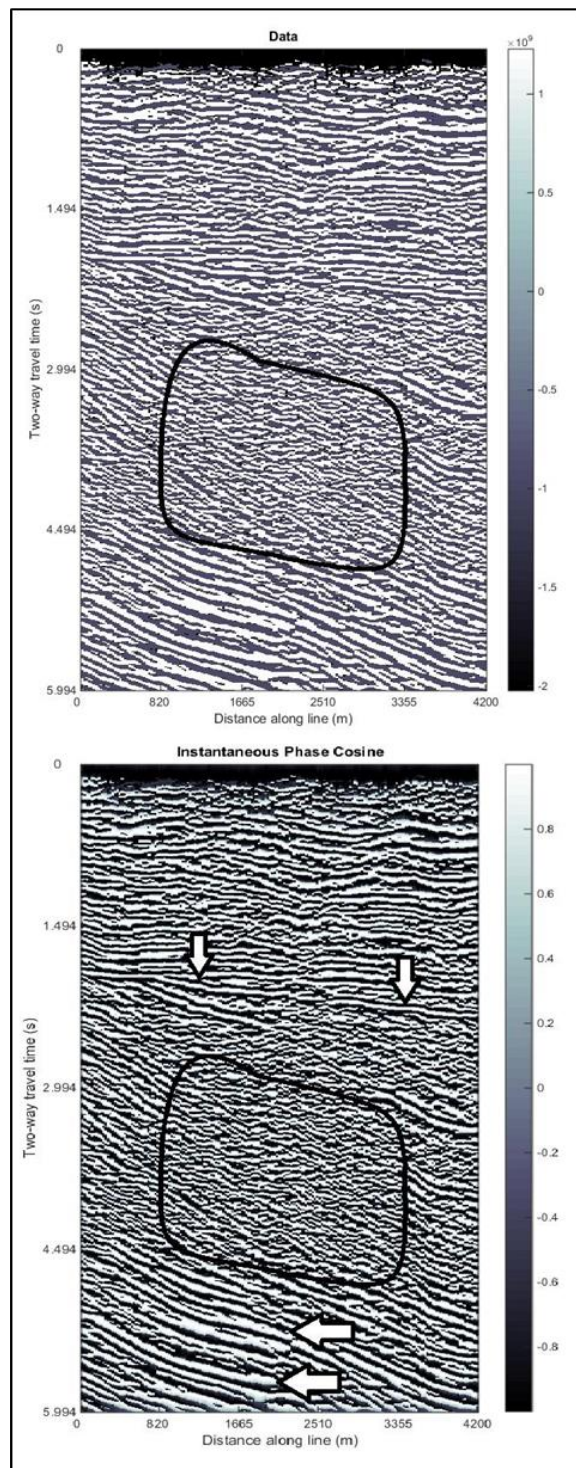


Figure 3: (Top) Original Sibanye Gold Ltd. section. (Bottom) Cosine of instantaneous phase attribute. Arrows indicate strong reflections and black outline demarks chaotic reflections.

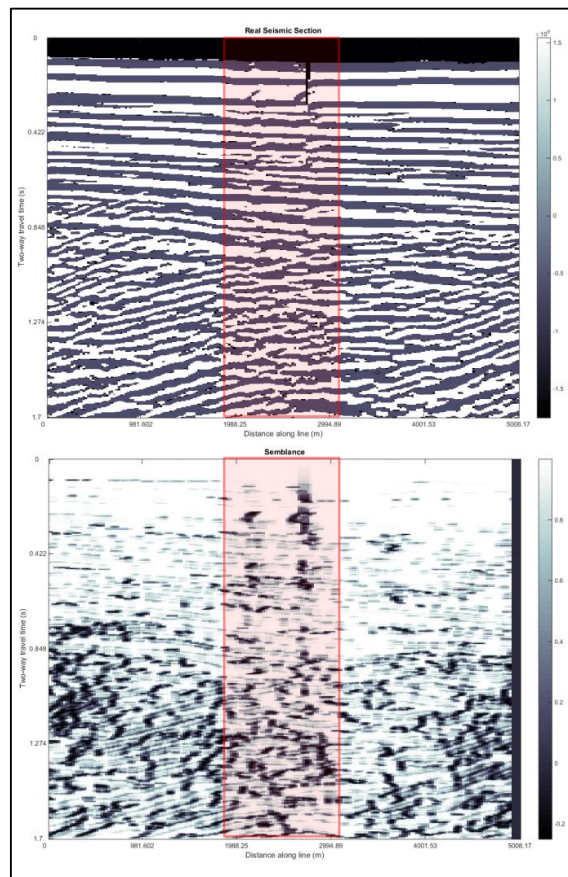


Figure 4: (Top) Original onshore Soekor Ltd. seismic section containing vertical anomaly. (Bottom) Semblance attribute emphasising central vertical feature.

CONCLUSIONS

To this day, seismic reflection attributes prove to be valuable interpretive tools for seismologists and their use in the analysis of hydrocarbon-targeted data is valuable. The most common means by which these attributes are calculated is the mathematical notion of the complex seismic trace.

Different attributes, such as instantaneous phase, amplitude and apparent dip, are useful for identifying and emphasising various geological features, such as folding, gas escapes, and seismic features like toplap while reflection continuity and bedding is emphasised by the cosine of the instantaneous phase. These attributes behave as expected in South African hard and soft rock environments.

An intuitive and comprehensive understanding of seismic reflection attributes is necessary before application to data so as to be aware of computational artefacts that could mislead interpretation and result in false geological inferences.

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REFERENCES

- Barnes, A.E., 2007, A tutorial on complex trace analysis. *Geophysics*, 72(6), 33-34.
- Chopra, S., Marfurt, K. J., 2007. *Seismic Attributes for Prospect Identification and Reservoir Characterisation*. SEG Geophysical Development Series No. 11. P. 27-98.
- Manzi, M., 2015. Integrated interpretation of 3D seismic data to enhance the detection of gold-bearing reef: Mponeng Gold mine, Witwatersrand Basin (South Africa). *Geophysical Prospecting* vol. 63. P. 890-893.
- Marfurt, K. J., Alves, T. M., 2014. Pitfalls and limitations in seismic attribute interpretation of tectonic features. *Interpretation* vol. 3 no. 1. P. A5-A15.
- Subrahmanyam, D. and Rao, P.H., 2008, Seismic attributes – A review. 7th International Conference & Exposition on Petroleum Geophysics, 398-404.
- Taner, M.T., Koehler, F. and Sheriff, R.E., 1979, Complex seismic trace analysis, *Geophysics*, 44(6), 1041 – 1063.