MODELLING THE WITWATERSRAND BASIN:
A window into Neoarchaean-Palaeoproterozoic crustal-scale tectonics

Masters Dissertation

Marcello Molezzi
(0410892H)

School of Geosciences, University of the Witwatersrand, Private Bag 3, Wits 2050, South Africa

Supervisors:
Prof. Kim Hein
Dr. Musa Manzi

Declaration

I, *Marcello Giuseppe Molezzi*, hereby declare that this dissertation is my own work, contains no plagiarism, and that it has not been presented to any other university for the purpose of obtaining a degree.

M. G. Molezzi

2017/06/02

Date

Table of Contents

List of Figures

For convenience, figures have been included at the end of each chapter.

across the domain, and the two basement reflection anomalies separated by a narrow 'saddle'. The orientations are also illustrated in Figure 5.1 to give context with surface geology and boreholes.

List of Tables

Acknowledgements

The author would like to thank CIMERA (Centre of Excellence for Integrated Mineral and Energy Resource Analysis) for providing both bursary funding and access to software, and the University of the Witwatersrand, Johannesburg, for the Postgrad Merit Award that covered the registration fees. AngloGold Ashanti is thanked for providing the 2D reflection seismic data. The Council for Geoscience is thanked for providing access to the borehole log archives. The author would like to express his thanks and gratitude to his supervisors, Prof. Kim Hein and Dr. Musa Manzi, for their key scientific contributions and general guidance throughout this M.Sc. programme. Lastly, acknowledgement and thanks are given to Postgrad students Matt Terracin, and Ansuya Naidoo, as well as Postdoc researcher Dr. Hannah Hughes, for their constructive discussions and inputs at various times during the M.Sc. programme.

Abstract

The aim of this study was to investigate and evaluate the 3D structural architecture around the Vredefort dome in the Witwatersrand basin, in particular the unexposed southern portion. This was done in order to establish strato-tectonic relationships, first order deformation structures, and basement architecture. The outcomes provide a more detailed architecture around the central uplift that may be used in future work aimed at examining the nature of giant terrestrial impacts. In summary, the integration of borehole, surface mapping, and 2D reflection seismic data provides a well constrained 3D geological model of the dome, central uplift, and adjacent areas (covering approximately 11600 km^2). Seven structural features are discussed from the 3D modelling results. These include, (1) a normal fault in the lower West Rand Group, (2) an undulate, normal faulted truncation plane, constrained as post-West Rand Group and pre or early-Central Rand Group, (3) a truncation plane and local enhanced uplift constrained as pre to syn-VCF, (4) a listric fault system, constrained as post-Klipriviersberg Group and syn-Platberg Group, (5) a truncation plane, constrained as syn-Black Reef Formation, (6) folds, including a large asymmetric, gentle anticline here named the Vaal Dam Anticline, constrained as post-Magaliesberg Formation and pre-Vredefort impact, and (7) a listric fault across the southeastern margin of the Vredefort dome, constrained as late to post-central uplift formation. The findings support previous work by Tinker et al. (2002), Ivanov (2005), Alexandre et al. (2006), Dankert and Hein (2010), Manzi et al. (2013), Jahn and Riller (2015), and Reimold and Hoffmann (2016). However the findings oppose various parts of previous work by Friese et al. (1995), Henkel and Reimold (1998), and Reimold and Koeberl (2014). A new term is also proposed for the periclinal folds located around the central uplift, i.e., impact-type curvature-accommodation folds. This study demonstrates the importance of integrating multiple sources of data into a single 3D spatial environment in order to better refine and distinguish impact-related deformation from the pre-existing basement architecture.

Chapter 1
Introduction

1.1. Preamble/Rationale

The Neoarchaean Witwatersrand basin is one of the best documented terranes in the world. Its tectonic history is understood broadly although it lacks geometry and kinematic data (Dankert and Hein, 2010) that would help establish the geodynamic development of the basin over time. The basin represents one of the largest exposures of Neoarchaean rock on Earth, as well as hosts the Vredefort dome at its geographic centre, representing the largest (250 – 300km wide) and possibly oldest (2023 ± 4 Ma; Kamo et al., 1996) confirmed meteorite impact crater on Earth. The crater is categorised as a complex crater as it contains a central uplift peak. The crater has also undergone intense erosion, with the current surface exposure being estimated at 5 – 8km below the original surface level (Reimold and Koeberl, 2014).

According to the Planetary Science Institute, complex craters that are formed on earth exhibit diameters larger than 2 – 4km due to the relative instability of the transient crater (PSI website). Simple craters exhibit smaller diameters due to the relatively stable transient craters. The central uplift architecture of complex craters may differ slightly. For example, the Chicxulub crater has a modified central uplift that forms a peak ring (Ivanov, 2005; Morgan et al., 2000).

Only the northern half of the 400km long, 200km wide Neoarchaean Witwatersrand basin is exposed at surface (Figure 1.1). From the centre of the Vredefort dome southwards, the basin is covered by thin Palaeozoic to early Mesozoic marginal sequences of the Karoo Supergroup. Geological interpretations of the Witwatersrand basin beneath this cover have been limited to borehole and geophysical data, with rare exposures as inliers where the Karoo cover has been eroded. Additionally, geological mapping of the Vredefort dome has been limited. The northwest half of the dome is exposed at surface, while the unexposed half to the southeast is poorly constrained. However, drilling and geophysical surveys (magnetics, gravity, and 2D seismics) can be used to constrain the geometry of the dome at depth.

Several integrated geological and geophysical 2D models have been constructed to create models of the first-order structural architecture of the Vredefort dome and the Witwatersrand basin. Henkel and Reimold (1998) produced magnetic and gravity models through the dome and across the Witwatersrand basin, with added constraints from associated 2D reflection seismic data. They provided an updated magnetic section model of the central uplift region. From their two sections they interpreted tilting of the post-impact crust to the northwest, and northwest-directed thrust shortening and uplift of the southeast portion of the dome. This concurred with previous interpretations by Friese et al. (1995)

who produced 2D reflection seismic and gravity models through the dome and across the Witwatersrand basin.

Beach and Smith (2007) and Manzi et al. (2013) created first-order scale models of the structural architecture using 3D reflection seismic data and emphasised the role of fold-thrust tectonics during development of the Witwatersrand basin, and later extension tectonics and the formation of listric faults during formation of the Ventersdorp basin. However, integration of geological data in 3D using the numerous 2D reflection seismic lines in the vicinity of the dome and southeast Witwatersrand basin has not been attempted before and could provide a more accurate representation and understanding of the architecture of the dome and its formation.

Geological data can exist in various scales and forms, and can show various aspects of the same terrane. As Jones et al. (2009) point out, the preservation of data at all scales within one computer based 3D spatial interface is the primary advantage of the multi-scaled approach of 3D geological modelling. All of these aspects must come together to form the geological picture/story of the terrane. Geophysical data (e.g. magnetics, gravity, and seismics) can be used in conjunction with both geochemical data (e.g. soil sampling, rock chip sampling, and geochronology) and traditional geological data (e.g. mapping, drilling, cross sections, stratigraphy, and petrography). In a 3D geomodelling environment these datasets can be integrated in various ways.

The development of geological modelling software has taken advantage of the surge in computing advancements over the past several decades. The usefulness of integrating data in 3D space to solve geological problems was highlighted by Viljoen (1994). For example, he emphasised the significance of modelling economic reefs in the Witwatersrand basin, but was limited to simplified 3D isometric constructions of the reefs. Geomodelling as a visualisation and analysis tool is a powerful method for many types of geological work. As Zanchi et al. (2009) described, “Its main advantage is to overcome the limitations of conventional 2D representations, which suffer from lack of one dimension, and distort spatial relationships”.

The variety of uses for geological modelling are wide; however the sources of these datasets are quite similar, e.g. geological maps, cross sections, borehole data, outcrop data, geochemical data, and geophysical data. There is a general methodology that is adopted when creating geological models. Most importantly, the initial datasets must be cleaned, sorted, validated and optimised to create consistent datasets (e.g. georeferencing/projecting into one common coordinate system) (Kaufmann and Martin, 2009). Database frameworks are important in this manner and need to be optimised for geological datasets (Apel, 2006).

One of the key components of giant impacts is the preserved collapsed central uplift region at the centre of the complex crater. It is suggested that the impact force of large meteorites is sufficient to form a complex crater shape, as opposed to simple bowl-shaped craters formed by small impactors (Reimold and Koeberl, 2014). This theory can be tested by the creation of a geological model of the dome that highlights its 3D architecture and the proposed central uplift. The model can also test whether the data support process-simulation computer modelling results (numerical modelling) of the Vredefort impact such as those of Ivanov (2005).

The supracrustal sequences above the basement (Witwatersrand Supergroup, Ventersdorp Supergroup and Transvaal Supergroup) are exposed on the northern and western flanks of the dome, but their extents to the south and east are concealed and less constrained due to the Karoo Supergroup, which unconformably overlies the supracrustals. Using 2D reflection seismic and drilling datasets, it will be possible to test the extension of these rocks into the unexposed portion of the dome. These results could have important implications for the tectonic history of the Witwatersrand basin.

Thus the basin provides an excellent natural laboratory to study both Neoarchaean tectonics and giant impact events using advanced computer modelling software. The advantage of an integrated 3D model of the dome is that it can be queried and easily updated as new data becomes available. The model can also highlight relationships between structural information collected from outcrops and the underlying structural regimes. Importantly, the development of a well-constrained 3D geological model provides a foundation for further, more advanced work, such as 3D tectonic restorations.

1.2. Location and Physiography

The study area encompasses the Vredefort dome and is illustrated in Figure 1.1. The dome (centred at 27°00'S, 27°30'E) is located in the northern part of the Free State Province in South Africa. It represents the collapsed central uplift portion (now exhumed to surface level) of the complex crater structure formed by the Vredefort impact. The current surface exposure produces distinctive alternating ridges and valleys that form a semi-circular series of low hills and ridges known as the Vredefort mountain land. These highlight the extents of the erosion-resistant strata within the Ventersdorp Supergroup, Witwatersrand Supergroup, and Dominion Group, which surround a granitic gneiss core at the centre of the uplift. The Vaal River dissects the northern section of the mountain land, flowing from east to west, and intersects the granitic gneiss core near the town of Parys.

1.3. Aims and Objectives

The aim of this study is to investigate and evaluate the 3D structural architecture around the Vredefort dome in the Witwatersrand basin, in particular the unexposed southern portion, to establish strato-tectonic relationships, first order deformation structures, basement architecture, and to examine the nature of giant terrestrial impacts.

The objectives therefore include:-

- Data integration to establish a database for the dome, including datasets for drilling, geological and structural mapping, geophysics, and topographic elevation models.

- Evaluation of the quality of the legacy 2D reflection seismic data and providing interpretations of the 2D seismic lines, with a focus on the major unconformities.
- Construction of a 3D geological model of the Vredefort dome and immediate surroundings using the integrated database and seismic interpretations.
- Evaluation of the architecture of the central uplift in terms of the complex crater formation model, including investigating the first order deformation structures, and testing the support given by simulation modelling.
- Establishment of a strato-tectonic history through integration of surface mapping, drilling, seismic data interpretations and geological modelling.
- Examination of the basement contact architecture, including the depth variation around the dome and first order cross-cutting structures, and where possible resolving the internal architecture.
- Establishment of the extent of the unexposed Witwatersrand Supergroup, Ventersdorp Supergroup and Transvaal Supergroup to the south, southeast and east of the dome.
- Identification of post-impact deformation features, to test published hypotheses of post-impact deformation events.

1.4. Thesis organisation

This thesis is made up of eight chapters, followed by the list of references and the appendix. Subsequent to this introduction chapter, the regional geology of the study area will be presented in Chapter 2. Chapter 3 outlines the various methods and processes used to integrate the datasets and establish a database for the study area. Chapter 4 presents descriptions and justifications for major stratigraphic contacts encountered in the 2D reflection seismic data by way of integration with geological mapping and borehole data.

The study area is divided into three domains as there are three broad clusters of 2D reflection seismic lines. Domains 1, 2 and 3 are located west, east, and south of the dome, respectively. The 2D seismic sections are described in terms of seven major contacts that are imaged throughout the study area. These seven interfaces are used to form the eight volumes of the 3D geological model. The interfaces are described in Chapter 5 with reference to the twenty eight reflection seismic sections in the three domains, followed by a geological summary.

The seismic section interpretations provide depth information on the continuity of the major contacts. These are important in constraining the 3D geological model (in addition to the borehole information). Chapter 6 presents the 3D geological model and describes the eight volumes that have been delineated from the integration of the seismic sections, surface mapping, and borehole data. Each volume represents a particular Unit, Formation, Group or Supergroup within the stratigraphy.

Chapter 7 discusses the various aspects of the 3D geological model and seismic data interpretation results, in terms of the Vredefort impact and seven important structural features identified in the study area. These aspects include the architecture of the central uplift and the basement contact, as well as the extent of the unexposed Witwatersrand, Ventersdorp, and Transvaal supergroups to the south, southeast and east of the dome. The strato-tectonic observations are discussed in order to establish a geological history of the study area with implications for the broader Witwatersrand basin. The structural features and various seismic sections are then discussed in comparison to published work. The conclusions are presented in Chapter 8.

1.5 Acronyms and Conventions

The various acronyms and conventions used in this thesis are listed below:

- ID-TIMS = Isotope Dilution – Thermal Ionisation Mass Spectrometry
- CA-ID-TIMS = Chemical Abrasion – Isotope Dilution – Thermal Ionisation Mass Spectrometry
- SHRIMP = Sensitive High Resolution Ion Microprobe
- SRTM = Shuttle Radar Topography Mission
- VCF = Venterspost Contact Formation
- SACS = South African Council for Stratigraphy
- CGS = Council for Geoscience
- P-wave = Primary Wave
- V_p = P-wave Velocity
- Bulk Density will be referred to as Density
- ρ = Bulk Density
- RC = Reflection Coefficient
- VSP = Vertical Seismic Profiling

Note, when the words shale/mudstone are applied to pre-Karoo rocks they are used as generic terms to actually refer to low grade metamorphic rocks ranging from slate and phyllite.

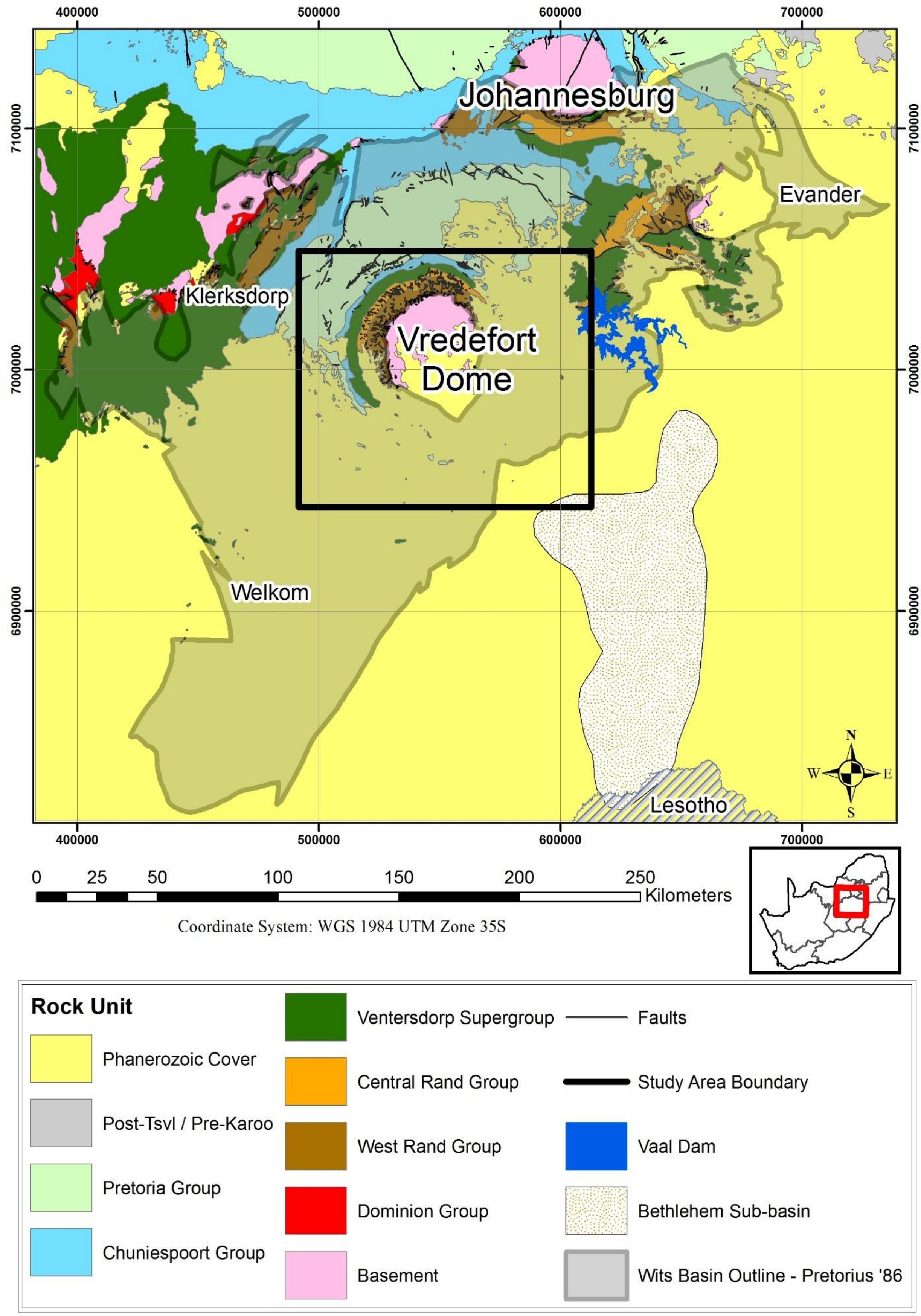


Figure 1.1 Regional geology map with the study area boundary, including the interpreted extent of the Witwatersrand basin illustrated after Pretorius (1986), and the outline of the Bethlehem sub-basin gravity anomaly.

Chapter 2
Regional Geology

The Neoarchaean Witwatersrand basin is situated in South Africa and unconformably overlies the Mesoarchean Kaapvaal craton. Several stratigraphic units are described below that correspond with the regional geology map in Figure 1.1. The units form the modelled volumes following interpretation of the 2D reflection seismic sections. Figure 2.1 illustrates these units in relation to the expected reflective boundaries of the 2D seismic sections. The cratonic basement is made up of discrete terranes dated at ca. 3.6-3.2 Ga (U-Pb ID-TIMS and SHRIMP, and Pb-Pb zircon evaporation, Poujol et al., 2003). The basement is composed of tonalite–trondhjemite–granodiorite (TTG) suites and greenstone belts that outcrop in a number of places across the craton (Poujol et al., 2003; Johnson et al., 2006).

The Witwatersrand basin is situated near the geographic centre of the Kaapvaal craton. Outcrop of the basin is limited to its northern margin (i.e. adjacent to Johannesburg, Klerksdorp, and Evander) and in the collar rocks of the Vredefort dome. The package overlying the basement (and Dominion Group) is made up of a number of stratigraphic units that form part of three major supergroups, spanning ca. 2.98-2.02 Ga, namely, the Witwatersrand Supergroup, Ventersdorp Supergroup, and Transvaal Supergroup (Appendix, Figure A). The ca. 300-180 Ma Karoo Supergroup unconformably overlies the Transvaal Supergroup (Dankert and Hein, 2010).

2.1. Dominion Group

The TTG and greenstone basement are unconformably overlain by tholeiitic andesites, quartzite and conglomerate units of the Dominion Group (Dankert and Hein, 2010). A geochronological age of 3074 ± 6 Ma (using single zircon U-PB SHRIMP, Armstrong et al., 1991) constrains the Syferfontein Formation within the Dominion Group. Generally, the metamorphic grade of the package is greenschist facies, but in the Vredefort area amphibolite facies has been recognised; Jackson (1994) estimated temperature and pressure conditions for peak metamorphism in the dome of between 550°C and 800°C at 2 – 4 kb.

Crow and Condie (1987) interpreted the tectonic setting for the Dominion Group as an incipient foreland basin adjacent to a continental margin arc system. However, Clendenin et al. (1988) interpreted that the basin development took place during continental rifting and lithospheric thinning. The proposition by Frimmel (2014) is a combination of the two, where the volcanic succession was laid down in a continental rift within a possible overall arc setting.

2.2. Witwatersrand Supergroup

A sequence of offshore marine and fluvio-deltaic shale-arenite units were deposited roughly ninety million years after the deposition of the Dominion Group. This 5150m thick package makes up the West Rand Group, the oldest package in the Witwatersrand Supergroup (Dankert and Hein, 2010). It has been divided into three subgroups, namely the Hospital Hill Subgroup, Government Subgroup, and Jeppestown Subgroup (SACS, 1980).

The Hospital Hill Subgroup has a conglomerate unit at its base (i.e., the basal unit of the Witwatersrand Supergroup). The four formations making up the rest of this subgroup consist of numerous transgression/progradation cycles of fining/coarsening upward sequences that define each formation (Johnson et al., 2006).

The top contact of the Hospital Hill Subgroup with the overlying Government Subgroup is a disconformity and marked by a mineralised, polymictic, pyritic conglomerate (Bonanza Reef or Bird Reef). The Government Subgroup is characterised by extreme instability in terms of rapid changes in the depositional environment with major disconformities that separate the six formations within the Subgroup (Appendix, Figure A). Compared to the underlying Hospital Hill Subgroup, these sequences were deposited over a much longer time period. A calculated age of 2931 ± 8 Ma (youngest age for U-Pb detrital zircon; Kositcin and Krapež, 2004) of the Rietkuil Formation in the lower Jeppestown Subgroup gives a hiatus of sixty million years from the 2991 ± 15 Ma age of the Promise Formation, which forms the base formation in the Government Subgroup.

The Jeppestown Subgroup overlies the Government Subgroup. It reflects a stable period of deposition with several transgressive/progradation sequences that define five of its six formations, with truncated progradational fluvial braid-plain quartzites in the topmost Maraisburg Formation (Johnson et al., 2006). The Crown Formation forms the sixth formation and is a major marking horizon. It consists of a series of basaltic andesites (2914 ± 8 Ma, using single zircon U-Pb SHRIMP; Armstrong et al., 1991) up to 250m thick. The truncation at the top of the Maraisburg Formation may correspond to the proposed Asazi Event at ca. 2.9 Ga of Manzi et al. (2013). This Event terminates deposition in the West Rand basin by uplift, tilting and erosion.

A basal conglomerate reef overlies the West Rand Group and forms the base of the Blyvooruitzicht Formation (2902 ± 13 Ma; youngest U-Pb detrital zircon; Kositcin and Krapež, 2004) at the base of the Central Rand Group. The Central Rand Group spans the period 2902 ± 13 Ma to 2849 ± 18 Ma (Kositcin and Krapež, 2004), or almost fifty million years. It is divided into the Johannesburg and Turffontein subgroups, and is dominated by alluvial braid-plain, lesser alluvial fan conditions, and minor marine influence. Sedimentation took place syn-tectonically with respect to folding, faulting, and uplift on the basin margins (Frimmel, 2014).

The Booysens Formation (2894 ± 7 Ma, youngest U-Pb detrital zircon; Kositcin and Krapež, 2004) is defined by a major basin-wide transgression that resulted in the deposition of a thick sequence of shale. A single basaltic unit (Bird Member of the Krugersdorp Formation) is located in the eastern half of the basin. Alluvial fan progradation into the basin resulted in deposition of thick (up to 400m) conglomerate units (Johnson et al., 2006). This package of coarse conglomerates forms the uppermost Mondeor Formation, which is the youngest formation of the Witwatersrand Supergroup, providing a minimum age to the entire package of 2849 ± 18 Ma (youngest U-Pb detrital zircon, Kositcin and Krapež, 2004).

2.3. Ventersdorp Supergroup

A hiatus of about 120 million years occurs between the Witwatersrand Supergroup and the overlying Venterspost Formation (2729 ± 19 Ma for U-Pb SHRIMP ages of igneous detrital xenotime/zircon aggregate; Kositcin et al., 2003). An auriferous immature conglomerate known as the Ventersdorp Contact Reef was formed above the unconformity (Johnson et al., 2006). The conglomerate horizon is poorly developed where the West Rand Group is the source of the sediment.

The Venterspost Formation forms the base of the Ventersdorp Supergroup (ca. 2.72-2.63 Ga). The Ventersdorp Supergroup is 9725m thick and represents an extensional rift-type sequence (Dankert and Hein, 2010). The Supergroup is divided into the Klipriviersberg and Platberg groups, and two separate overlying formations (the Allanridge and Bothaville formations) that some authors include in a third group known as the Pniel Sequence; however this group is not recognised by SACS (Johnson et al., 2006).

A shift from compressional to extensional tectonics is indicated by the development of north-northeast trending faults reported in all goldfields (Jolley et al., 2007). Extensional tectonics is characterised by the Hlukana-Platberg Event (ca. 2.7-2.64 Ga) of Manzi et al. (2013) and is possibly coeval with mantle plume heating of the lithosphere (Eriksson et al., 2002) and formation of first-order scale structures such as the West Rand and Bank faults. The extensional event progressed over time to form grabens, initiating deposition of the Platberg Group, and formation of listric faults in the underlying Klipriviersberg Group.

The Klipriviersberg Group is characterised by volcano-magmatic activity (Dankert and Hein, 2010) producing numerous tholeiitic flood basalt-dacite sequences and comagmatic dykes and sills. The volcanic activity formed a package up to 1693m thick; however the Group is separated into five formations (Alberton Formation, Orkney Formation, Jeannette Formation, Loraine Formation, and Edenville Formation). Each Formation contains multiple volcanic sequences that are differentiated based on volcanic textures and geochemistry (Johnson et al., 2006).

An unconformity separates the Klipriviersberg Group and the overlying sedimentary members of the Kameeldoorns Formation, which forms the base of the 6862m (maximum) thick Platberg Group (Dankert and Hein, 2010). The Kameeldoorns Formation is not dated so the hiatus between the two groups is not constrained. The overlying Goedgenoeg Formation has a conformable gradational contact, where interfingering volcanic units gradually end the sedimentary deposition of the Kameeldoorns Formation. Volcanism continued with the emplacement of the Makwassie Formation (2709 ± 4 Ma, from single zircon U-Pb SHRIMP; Armstrong et al., 1991) and ended within the Rietgat Formation where volcanism diminished and volcanic rocks were intercalated with sedimentary rocks (Johnson et al., 2006).

The 427m thick package of quartzite and conglomerate units of the Bothaville Formation, and the 743m thick package of volcanic units of the Allanridge Formation (Dankert and Hein, 2010) overly the Platberg Group above a pronounced unconformity. These two formations exhibit unconformable contacts with the Platberg Group and each other, therefore SACS has not incorporated them into a formal Group (Johnson et al., 2006).

2.4. Transvaal Supergroup

The Ventersdorp Supergroup was unconformably overlain by the early basin depositional sequences of the Transvaal Supergroup that formed the 200m thick auriferous Black Reef Formation (Dankert and Hein, 2010). This formation is dominated by mature quartz arenites, with lesser conglomerates and subordinate mudstones. The high acoustic impedance contrast between the higher P-wave velocity (V_p), higher bulk density (ρ) dolomite of the overlying Chuniespoort Group and the lower V_p, lower ρ extrusive rocks of the Ventersdorp Supergroup, results in a strong seismic reflector that corresponds to the Black Reef Formation (Manzi et al., 2013).

The relative age of the Black Reef Formation has been stratigraphically linked to sequences recorded elsewhere in the Transvaal Supergroup, Griqualand West, and Kanye (Botswana) basins (Johnson et al., 2006). According to Sumner and Beukes (2006) the upper facies of the Black Reef Formation correlates to the first (oldest) sequence in the Campbellrand-Malmani carbonate platform. The sequence unconformably overlies the Schmidtsdrif Subgroup (of the Ghaap Group in the Griqualand West basin) that is constrained by the basal Vryburg Formation (dated at 2642 ± 3 Ma by single zircon U-Pb SHRIMP; Martin et al., 1998). The age of the Vryburg Formation limits the maximum deposition age of the Black Reef Formation.

Proto-basins are recorded around the Transvaal Supergroup basin that underlie the Black Reef Formation and are grouped as the Wolkberg-equivalent units. The Buffelsfontein Group volcanics are included in this set by Frimmel (2014) and are dated to 2664 ± 6 Ma, therefore constraining the age for the proto-basin development. However these basins are confined to the northern parts of the Transvaal Supergroup basin; they may not be preserved in the study area. In this thesis the sequence stratigraphy of Sumner and Beukes (2006) is followed, associating the Black Reef Formation with the age of the Vryburg Formation (i.e. younger than ca. 2642 Ma).

The Chuniespoort Group overlies the Black Reef Formation and is made up of carbonate, iron formations, lacustrine and minor volcanic units, with a maximum thickness of approximately 1900m

(Dankert and Hein, 2010). The carbonate platform sequences form the base of the Group and are subdivided into five formations, the oldest of which (Oaktree Formation) dates between 2550 ± 3 Ma (single zircon Pb-evaporation; Walveren and Martini, 1995) and 2558 ± 7 Ma (single zircon U-Pb SHRIMP; Martin et al., 1998). The formations are grouped together as the Malmani Subgroup and are differentiated by chert content, stromatolite morphology, intercalated shale, and erosion surfaces (Johnson et al., 2006). Overlying these carbonate formations are the iron formations of the Penge Formation (dated at 2480 ± 6 Ma; Nelson et al., 1999; unpublished ages with no dating technique stated) and the siliciclastic Duitschland Formation, inferring that the deposition of carbonates lasted roughly 120 million years.

A hiatus of approximately 115 million years separates the Chuniespoort Group and the overlying 6000 – 7000m thick Pretoria Group. According to Manzi et al. (2013), the unconformity between the Chuniespoort and Pretoria groups produces a strong reflection seismic contrast between the overlying, lower V_p and ρ volcanic rocks of the Pretoria Group and the underlying, higher V_p and ρ dolomites of the Chuniespoort Group. The Pretoria Group is divided into sixteen formations that exhibit a series of sedimentary and volcanic sequences; these vary in thickness across the Transvaal basin. The sedimentary units include conglomerates, sandstones/quartz arenites, ironstones, shales, carbonates, turbidites, and diamictites (periglacial detritus). Volcanic sequences include the basaltic-andesites of the Hekpoort Formation (2222 ± 13 Ma, Pb-Pb whole rock; Cornell et al., 1996, and 2224 ± 21 Ma, Rb-Sr whole rock; Burger and Coertze, 1973-1974) and the tholeiitic basalt of the Machadodorp Member (undated) in the Silverton Formation (Johnson et al., 2006). Unfortunately the ages of the formations overlying the Hekpoort Formation have not been established, but these were deposited prior to the intrusion of the Bushveld Complex (dated at 2055.91 ± 0.26 Ma, using single zircon U-Pb CA-ID-TIMS; Zeh et al., 2015). This gives a relative estimate for deposition of 350 – 400 million years (Johnson et al., 2006).

2.5. Karoo Supergroup

A major unconformity exists between the Pretoria Group and the overlying subhorizontal Karoo Supergroup (preserved south of the town of Parys in the Vredefort dome) where the contact represents a hiatus of over 1.7 billion years. The base of the Karoo Supergroup is marked by the ca. 300 Ma glacial deposits of the Dwyka Group (Catuneanu at al., 2005). The overlying groups and formations represent a sedimentary basin evolution in a retroarc foreland system (Pangea construction). At ca. 187 Ma, the breakup phase of the Pangea Supercontinent initiated extrusion of continental flood basalts. These volcanic units are preserved in central South Africa as the Drakensberg Group, and are the topmost group in the Karoo Supergroup (Catuneanu at al., 2005).

2.6. Vredefort Dome

The Vredefort dome is located about 130km southwest of Johannesburg (centred at 27°00'S, 27°30'E). It represents the collapsed central uplift core (45 – 50km wide) of a giant impact structure. The final size of the crater is controversial with the diameter estimated between 172km (Ivanov, 2005) and 280km (Henkel and Reimold, 1998). The impact has been dated to 2023 ± 4 Ma (SHRIMP single-zircon U-Pb age for authigenic, unshocked zircon grains in pseudotachylite breccias and impact melt granophyre; Kamo et al., 1996); however the current surface exposure is estimated at 5 – 8km below the original impact surface level (Reimold and Koeberl, 2014). Thus the surface expression of the crater (including impact melt/breccia infill) has been eroded, and what is currently revealed is the deformed crust that was preserved below the crater.

One of the distinct features of the Vredefort crater is the rim syncline that surrounds the northern and western exposed collar rocks. This structure was first mapped by Simpson (1978), the results of which were incorporated into the 1:250,000 geology maps used in this study. However, in that study both the rim syncline and the smaller scale anticlines and synclines preserved in the Pretoria Group were suggested to have been formed during one event that was unrelated to a meteorite impact.

With the lack of direct evidence defining the crater size and shape, several impact-related features have been recognised that provide evidence for the event. These include pseudotachylite breccias (PTB), impact melt granophyre dykes, stishovite and coesite mineral occurrences, shatter cones and shock deformed zircon, monazite and quartz, the latter extensively decorated by planar deformation features (decorated PDF's) (Reimold and Koeberl, 2014). As Dankert and Hein (2010) and Reimold and Koeberl (2014) point out there are overturned supracrustal rocks in the northeast, north and west, while exposures in the south and southeast are not overturned (as determined by drill cores).

The numerical modelling of the Vredefort impact by Ivanov (2005) has characterised the geometry of the complex crater and the collapsed central uplift. The supracrustal rim around the central uplift core was overturned during crater formation as the crust rebounded from the centre outwards following centripetal rock movement (Jahn and Riller, 2015). The steep overturned rim subsequently collapsed, forming a concentric subhorizontal recumbent fold around the core. The core itself also collapsed after being exhumed from depths of about 25km. As the rebounding crust isostatically settled, the centre of the core subsided forming a root-like geometry into the middle crust.

There are a number of intrusions found in the Vredefort dome area. These consist of numerous meta-dolerite sills (metamorphic overprint), intrusive alkali granite and associated discrete mafic to ultramafic complexes, and monzodiorite. The majority of the sills are interpreted to have been emplaced during the Ventersdorp Supergroup magmatic phase, while the rest (and some of the mafic-ultramafic complexes) are attributed to the emplacement of the Bushveld Complex (indicating possible further extensions of this giant layered intrusion). Widespread in the dome is a post-impact monzodiorite intrusion known as the Anna's Rust Sheet. Rb-Sr dating gives this intrusion an age of ca. 1050 Ma, which corresponds with the Namaqua-Natal orogeny of western South Africa (Reimold and Koeberl, 2014).

2.7. Regional Stratotectonics

Several tectonic regimes have affected the Kaapvaal craton throughout the Neoarchaean and Palaeoproterozoic. Frimmel (2014) in his study of the geology and tectonics of the Kaapvaal suggested that continental rifting took place in an overall arc setting synchronous to deposition of the Dominion Group volcanics and minor sediments following basement complex stabilisation. Nearly 100 million years after the first rifting phase, passive margin basin formation of the West Rand Group was initiated concomitant to deposition of sandstones and shales, through alternating regression and transgression cycles (Johnson et al., 2006; Dankert and Hein, 2010).

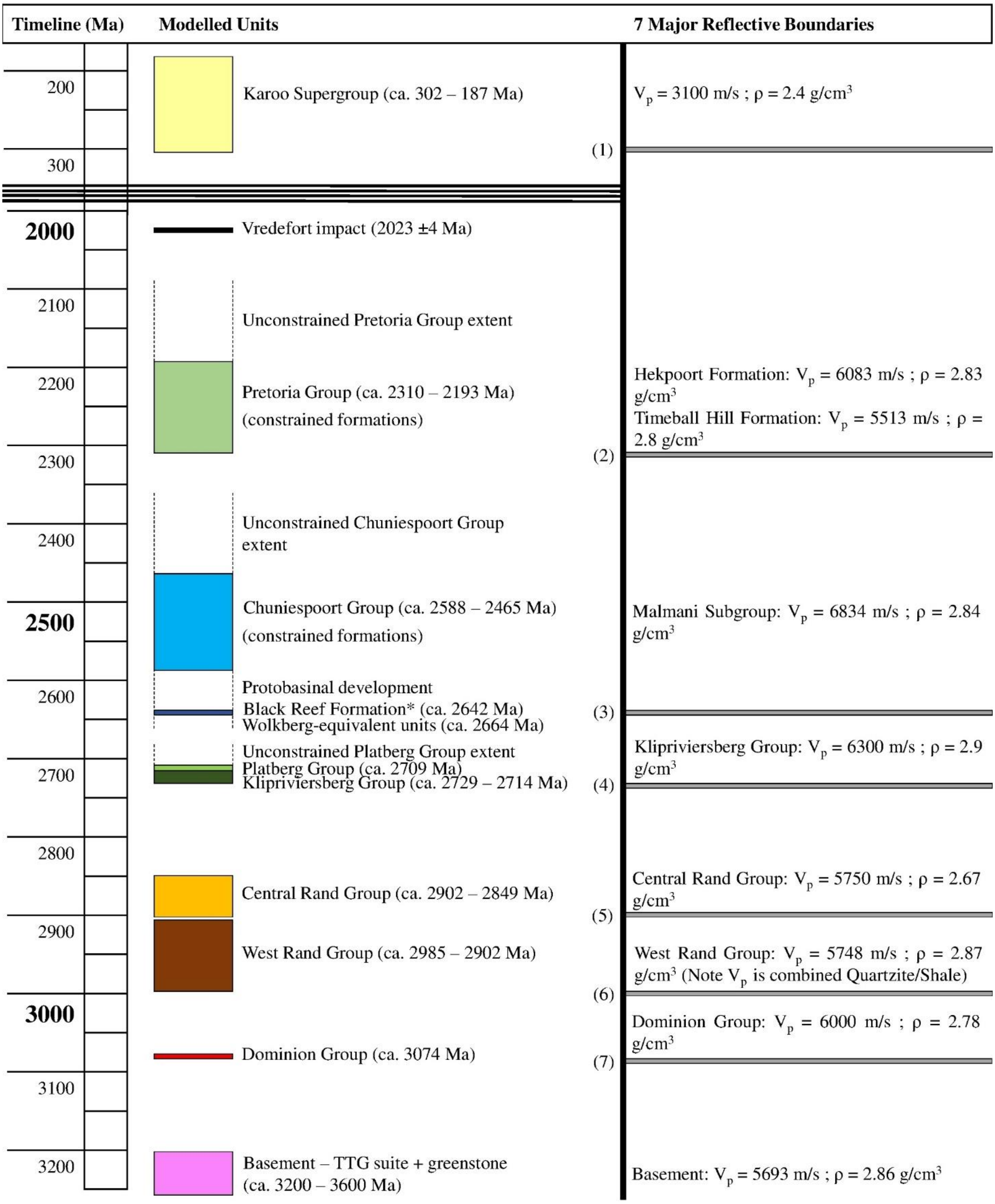
This passive margin phase lasted approximately eighty million years when sedimentation was terminated during the Asazi Event, initiating a new tectonic regime. The West Rand Group underwent uplift and tilting syn- to post-peneplation creating a regional-scale angular unconformity with the overlying Central Rand Group; as well as producing local faults and block tilting (Dankert and Hein, 2010; Manzi et al., 2013).

Extensional tectonics gave way to fold-thrust belt formation, which Frimmel (2014) interpreted as formation of a retroarc. Towards the end of the Central Rand Group, progressive shrinking of the basin is evident from the large conglomerate and boulder beds that formed by the progressive uplift and encroachment of the hinterland (Johnson et al., 2006). Dankert and Hein (2010) called this period the Umzawami Event, and suggested it was synchronous to, and/or after the deposition of the Central Rand Group and possibly also the overlying Venterspost Contact Formation. They identified basin-wide development of folding of the Central Rand Group sediments. Northwest to north-northwest trending folds were identified in the Welkom area, West Wits Line, and in the West-Central-South- and East-Rand goldfields. North to northeast trending folds were also identified in the West Wits Line, and both the West and Central Rand goldfields.

Following cessation of retroarc development, the Kaapvaal craton underwent peneplation and degradation of basin margin topographies to form the auriferous conglomerate horizons of the Venterspost Formation. This transition phase culminated in a major continental rift regime, forming a system of major faults, such as the West Rand and Bank faults. Crustal extension produced the nearly craton-wide volcanism of the Klipriviersberg Group. Extensional collapse continued with major graben formations, listric faulting of existing structures, and associated sedimentation of the Platberg Group. This tectonic event has been named the Hlukana-Platberg Event by Manzi et al. (2013). Second- and third-order scale normal faults crosscut fold-thrust belt structures and formed drag synclines and rollover anticlines in the hanging walls of initial rift structures (Dankert and Hein, 2010; Manzi et al., 2013). A period of erosion and excision followed after the final deposition of the Bothaville Formation and Allanridge Formation (Frimmel, 2014).

Several other structural indicators are grouped by Dankert and Hein (2010) as the Ukubambana fold-thrust belt event. These indicators include, folds, faults and auriferous quartz veins crosscutting the Timeball Hill Formation, and discrete hydrothermal activity at ca. 2210 Ma. The Ukubambana Event is interpreted to extend to ca. 2.0 Ga as both the Bushveld Complex (ca. 2055 Ma) and the Vredefort Impact (ca. 2023 Ma) crosscut all pre-existing structural indicators. The same structural and petrofabric indicators were ascribed to the Transvaalide orogeny, thrust-fold belt by Alexandre et al. (2006). They were able to resolve two distinct events within the Transvaalide belt, having obtained two sets of $^{40}Ar/^{39}Ar$ ages of ca. 2150 and 2042.1 ±2.9 Ma. These ages were for syn-kinematic mica taken from phyllitic rocks of the Timeball Hill Formation west of Pretoria. The phyllites are associated with low-grade metamorphism and small to medium-scale folds, cleavages, monoclines and thrusts.

The 1.7 billion year hiatus between the Pretoria Group and overlying Karoo Supergroup highlights a major unconformity and absence of geology. Other intrusions include the Pilanesberg Complex dyke swarm at ca. 1.3 – 1.1 Ga (Dankert and Hein, 2010) and the Anna’s Rust Sheet monzodiorite at ca. 1.05 Ga (Johnson et al., 2006; Reimold and Koeberl, 2014). The Karoo-aged dykes are widespread across the basin and are feeders of the continental flood basalts that covered much of southern Africa at ca. 180 Ma. This extensional regime corresponds with the major rifting event associated with the breakup of the Pangea Supercontinent, ca. 180 Ma (Catuneanu at al., 2005).



* Age of Vryburg Formation is used as an oldest depositional estimate because it constrains the Schmidtsdrif Subgroup that is overlain by the Black Reef Formation

Figure 2.1 Summary of main stratigraphic units interpreted in the 2D reflection seismic sections, including the major reflector boundaries imaged in the sections (with associated average V_p and ρ values for the dominant rock types of each unit). The Hekpoort and Timeball Hill formations form a minor reflective boundary between them but is not pronounced enough to confidently form separate units. The Platberg and Klipriviersberg groups were combined as a single unit in the interpretations. For more detailed stratigraphy/geochronology and V_p and ρ values see Table A and Table C respectively in the Appendix.

Chapter 3
Methodology

The following sections outline the methods used to collect, analyse, and combine the available datasets, and to construct the 3D geological model of the study area. The framework is illustrated in Figure 3.1 and is organised into four phases introduced below. The general framework was an adaptation of the framework presented by Kaufmann and Martin (2009), because it provided a starting point to the project. In summary, the borehole and surface mapping data were imported into Leapfrog Geo® and together with imported 2D seismic sections, were used to produce interpretations of the 2D reflection seismic sections. The seismic attributes were viewed in Kingdom Suite® to assist in better refining the interpretations. These interpretations were digitised and together with support wireframes a 3D geological model was constructed.

3.1. Phase 1

3.1.1. Surface information: topographic data, geological maps, and geophysical images

Using Global Mapper™, a 90m SRTM dataset was imported into LeapFrog Geo® to form the 3D topography surface of the study area. A variety of geological (i.e. 1:250,000 regional scale, and 1:50,000 scale for the Vredefort dome area) and geophysical (i.e. gravity and magnetics) maps were available for the geological modelling in LeapFrog Geo®. Maps that were not projected in the coordinate system WGS84 – UTM35S were re-projected prior to importing into LeapFrog Geo® because the software lacks this facility and can only georeference images based on a simple three-point user input tool. Therefore the conditioning and coordinate conversion of the maps were done using ArcGIS® and Global Mapper™ before importing into LeapFrog Geo® for further modelling (see Table A3 in the Appendix).

The structural data available for the geological model was extracted from various geology maps. A structural database does not exist at the Council for Geoscience in Pretoria. However, a total of 1002 available foliation measurements were digitised in ArcGIS®. Table A3 in the Appendix outlines the digitisation methodology.

Geophysical datasets available for the Witwatersrand basin include airborne magnetics and gravity, and 2D and 3D reflection seismics. The 3D seismic volumes are located beyond the boundaries of the study area, so have not been incorporated. The airborne gravity and magnetics were acquired by the Council for Geoscience (CGS) and flown on a grid of 250m and 500m. These datasets were not manipulated or quantitatively analysed by the author. The processed images were only used as guides during the 2D reflection seismic interpretations. The gravity data was used as a regional scale guide during the interpretations.

The magnetic data exhibit regional scale signatures of the basin where major near-surface magnetic horizons such as the magnetic shales in the West Rand Group can be identified. The magnetic formations provide a significant marker in the Witwatersrand basin on its margins as well as in the uplifted collar of the Vredefort dome. Strong magnetic signatures are represented and highlight either magnetic dykes/sills, or discrete magnetic formations (e.g. thin magnetic formations in the Chuniespoort Group dolomites). The magnetic data provided by the Council for Geoscience include, 1) total magnetic signature, 2) reduced to pole, and 3) analytical signal. These are useful datasets in terms of enhancing structural interpretations.

3.1.2. Cross-sectional information: 2D reflection seismic data

In the 1980s, the Gold Division of the Anglo American Corporation (AAC) (now known as AngloGold Ashanti) acquired 2D reflection seismic data (approximately 16000km in total) on the Kaapvaal Craton for gold/platinum exploration and deep crustal mapping (Pretorius et al., 2003). This extensive seismic program was followed by more than ten 3D reflection seismic surveys in 1990s to 2000s. These data were mainly acquired for gold and platinum mine planning and design. The aims of the surveys around the Vredefort dome were to delineate the overall extent of the gold-bearing horizons, to study the seismic response of the deformed rocks, to search for indications of new gold deposits in the area, and to extract structural information at depth. As mentioned earlier, this study only focuses on twenty eight of these 2D reflection seismic lines that fall within the vicinity of the Vredefort dome (Figure 3.2).

The 2D reflection surveys were conducted and processed through the standard acquisition and processing parameters by the AAC processing team (see Pretorius et al., 2003). The parameters for each 2D reflection seismic acquisition are summarised in Table E0 in the Appendix. The processing parameters are summarized in Table 4.1. In summary, the acquisition for all twenty eight surveys, conducted by a CGG crew (Compagnie Générale de Géophysique), took place between 1985 and 1989. Each survey was designed to overlap with the survey line grids for comparison purposes. The surveys were recorded with a vibroseis source using a fleet of two vibrators (Mertz M18). Vibrators were spaced 50m apart and lines used a 10Hz geophone spaced every 7.5m (4.16m in some lines). Total line length for the twenty eight reflection seismic surveys is ~823950m, with an average line length of ~29420m.

A recording time of six seconds was considered adequate to allow the imaging down to depths of ~4.5km, though the actual profile extends down to ~20km. For a few lines (e.g. FV-154 and OB-41) a recording time of sixteen seconds was used to image down to the crust-mantle boundary (>30km depth). The recordings were made using linear sweeps: 24s or 18s, 10 – 70 (mostly 68.5) Hz. Low frequencies are known to be less affected by attenuation and thus are good at mapping deeper horizons and identifying subtle and gradual acoustic impedance variations. High frequencies of up to 70Hz, on the other hand, were chosen to improve the imaging resolution at shallow depths and resolve statics-related problems. The chosen offset distributions were deemed appropriate to image the range of target depths in the study area. The main design and acquisition challenges included slimes dam, electrical substation, dolomite outcrop, wetland areas, thunderstorm, lightning activity, and power line (50Hz) noise. These surface conditions provided crooked-line geometries for most survey lines that compromised optimal survey geometry for better interpretation and modelling. Details about the 2D seismic data acquisition and processing, and initial interpretation of a few lines adjacent to this study area can be found in Pretorius et al. (2003).

Field processing, which provides brute stacks with elevation corrections, was done to (1) evaluate the quality of the data, (2) estimate the signal-to-noise ratio (SNR), and (3) detect and remove bad and noisy traces. The key processing steps prior to stacking of the data included geometry update, trace editing, gain recovery, minimum phase conversion of the data, linear noise removal, first-break picking, refraction and residual static corrections, velocity analysis, and muting. Subsequent processing steps on the stacked data included deconvolution, amplitude equalization, stacking, and Kirchhoff or Finite difference time migration. Data from previous borehole sonic logs in the Witwatersrand Basin goldfields suggest large velocity variations from the quartzite units (~5200 m/s) of the Witwatersrand Supergroup to the dolomite units (~6800 m/s) of the Transvaal Supergroup (Pretorius et al., 2003; Manzi et al., 2012b). As mentioned, there were no geophysical wireline logs for the surveys in the study area; so the velocity used for migration was obtained from the literature of the historical VSP, 2D and 3D seismic surveys in the area (see Pretorius et al., 1994, 2000; Manzi et al., 2012a, b). Several V_p values from the literature are listed in Table C in the Appendix. To obtain optimum V_p values for depth-conversion, a series of constant velocities were undertaken through the careful inspection of the depth-converted stacked sections. Finally, time-to-depth conversion was carried out using the constant velocity of 6000 m/s, providing a relatively good correlation between major seismic markers and borehole data. Furthermore, the depth locations obtained from these seismic sections were in agreement with those reported in the literature (Pretorius et al., 1994; Friese et al., 1995; Tinker et al., 2002; Manzi et al., 2012b).

3.1.3. Borehole information

The database of boreholes for the study area consists of 1947 borehole identifier numbers. Only the parent boreholes (roughly 755 borehole ID's) were of interest as they reported lithology data throughout the borehole length. The others were deflections from the parent boreholes that generally reported only gold assay data. It was decided to data capture (digitise) all boreholes because only 10% of the borehole logs had been digitised by the Council for Geoscience (CGS).

The boreholes are steep to subvertical, apart from those drilled in the dome collar. Downhole survey measurements were not included in the summary logs. The majority of the logs contained plan views of the borehole trace that were hand-measured by CGS personnel to calculate the overall borehole dip and azimuth. This brought an error into the geological modelling and is one of the data limitations because the x-y-z positions of the borehole traces cannot be considered accurate. However, due to the large modelled volume (roughly 226000 km^3) an error on the order of several meters does not affect the larger scale accuracy.

To optimise the data capture process, boreholes in close proximity to the 2D reflection seismic lines were prioritised to constrain the seismic interpretations at depth. The rest were used as infill data for the geological model. Of the 755 parent boreholes, only 46 were priority. These boreholes could be picked manually, but because the majority had multiple deflection ID's it was necessary to use the tools available in ArcGIS® to select all the ID's at each collar. This procedure was scalable and was used to include the rest of the Witwatersrand basin borehole database as well (which totalled 19848 boreholes ID's, including 8666 parent borehole ID's). This could help future studies using the 2D seismic sections outside of the study area. Table A5 in the Appendix outlines the process of identifying the priority boreholes.

Following data capture of the priority boreholes in the study area, the rest of the infill boreholes were further rationalised to exclude boreholes that were either too far away from the study area boundary, or were too shallow to provide adequate depth constraint (e.g. <150m deep boreholes provided no better information than the surface mapping indicated). This optimisation reduced the infill borehole parent ID count to 162 from 709. In total 208 boreholes were then captured and used in the seismic interpretation and modelling processes.

The borehole logs were individually photographed in the CGS archive room. Some logs were scanned previously. The photographs and scans were relabelled according to their borehole ID. In an Excel spreadsheet of these boreholes, additional columns were added to record deflection number, end-of-hole depths, and borehole inclination and azimuth.

The objective of digitising the borehole logs was to create a consistent, clean, well-organised dataset that could be queried easily. An Excel template was created to record various types of information extracted from the logs. This data was then imported into an Access Database that contained a range of other spreadsheets useful to the study area, including the seismic line information (e.g. line names and associated boreholes), CGS collar information (e.g. original borehole names, locations, and drill dates), borehole ID's located in the 1m collar buffer (step 4 in Table A5 in the Appendix), original CGS logs (the 10% mentioned previously), list of photographed boreholes, and priority/infill borehole lists.

The digitised log template structure is listed in Table A6 in the Appendix. Imperial units in the pre-1970 logs were converted to meters. For a number of the logs, the depth measurements of contacts were not stated. A manual calculation was required to best-estimate the depths of the contacts. The procedure is stated in Table A7 in the Appendix.

3.2. Phase 2 – Interpretation of cross-sections

3.2.1. Illustrating 2D reflection seismic sections and displaying in 3D space

The 2D seismic sections were used to interpret seven major lithological contacts for the modelling phase. The process of interpretation of each seismic line is described in Table A8 in the Appendix. The interpretations of the 2D reflection seismic lines were made dynamically. Upon completion of the initial interpretation each section was systematically added to the 3D workspace of Leapfrog Geo®. These interpretations were then modified multiple times over as new interpreted sections were added to the 3D workspace. This ensured that continuity of the imaged contacts became increasingly refined. The seismic attributes were viewed concurrently in Kingdom Suite® during this process. Borehole data was more efficiently used in Leapfrog Geo® as compared to Kingdome Suite® because the categorised information captured from the logs could be viewed far easier in the interactive 3D workspace. Surface geology maps and the aeromagnetic and gravity images were draped onto the topography in Leapfrog Geo® to provide additional constraints during the interpretation process. The interpretation of each seismic section from the various data sources was then created in ArcGIS®. Two images were created in ArcGIS®, one showing transparent interpretations overlaying the seismic amplitudes displays, and another showing the un-interpreted seismic amplitudes displays. Both images were imported into LeapFrog Geo®.

3.2.2. Split lines

A few seismic lines (BH-171, DE-512, and DV-270) were acquired from AngloGold Ashanti as split, separate lines, with each split section labelled A or B (e.g., BH-171A and BH-171B). Fortunately these split sections contained overlapping portions that could be used to tie the sections together in Leapfrog Geo®. This was done using common reference points, e.g., matching reflections common to both overlapping sections. Figure 3.3 illustrates the three split lines tied together in 3D space.

3.3. Phase 3 – Digitising

3.3.1. Vertical meshes

The 2D seismic section interpretations were created in ArcGIS® and had to be imported into Leapfrog Geo® as vertical sections. These imported interpretations were draped onto a vertical seismic section mesh. The procedure for the creation of each vertical mesh is described in Table A9 in the Appendix. Unfortunately vertical meshes are not simple to make in Leapfrog Geo® as the software prefers creating horizontal surfaces, therefore the procedure in Table A9 in the Appendix is a work-around that forces the software to create the vertical meshes. The mesh is not perfect though because where the lines are not straight the mesh warps slightly and a lateral offset of up to 150m is produced between each duplicate line trace.

3.3.2. Picking horizons

Horizons picked (i.e. picking strong reflectors) in the 2D reflection seismic sections corresponded with horizons digitised from surface mapping so that surface to depth wireframe-supports could be created in Phase 4. Horizons were picked and interpreted in ArcGIS®, then imported into LeapFrog Geo® and digitised directly in the software. Picking was not done in Kingdom Suite® as it proved inaccurate due to duplicated and disjointed shotpoints observed in every 2D seismic line (i.e. each shotpoint had two or three duplicates and short strings of shotpoints overlapped each other to form zigzag patterns over the length of the seismic line).

Picking was done for faults (i.e. areas where reflectors were discontinuous) as well. Unfortunately, the seismic lines are too sparsely separated to accurately correlate fault surfaces across seismic sections. Furthermore, Leapfrog Geo® has a limited fault representation function as faults cannot be terminated by younger units. Instead each fault penetrates the entire volume and will only terminate against other fault planes. These two characteristics hindered the representation of fault planes in the final 3D model, as (1) interpolating fault planes across large separation distances introduced additional uncertainty to the interpretations; and (2) fault systems confined between certain stratigraphic units could not be equally confined by the model as each fault penetrates through the entire model volume.

3.4. Phase 4 – Geomodelling

3.4.1. Subsurface volumes

LeapFrog Geo® has a 'Topography' function that produces 2.5D surfaces using datasets containing x, y, and z values. In this project the 90m resolution SRTM image of the study area was used. The model requires a 3D block boundary to confine the limits of the interpolations (mathematical links/extrapolations between data points that combine to create the 3D surfaces). The topography bounded the upper z-axis limit, and the 2D seismic line dataset bounded the x, y, and lower z-axis limits. The boundary cube was extended by a few kilometres to provide a small amount of additional interpolation beyond the outermost 2D seismic lines. The z-axis boundary base was set to the six second depth extent of the seismic sections (i.e. ~20km, including ~2km of additional interpolation below the sections).

3.4.2. Eight geological volumes

Eight geological volumes were created for the 3D model using the seven major interpreted lithological contacts. The volumes were generated in LeapFrog Geo® using modelling algorithms based on geochronological order. A wedge in the southeast of the study area contained no data and was cut-out of the geological model. This was done by ascribing a 'no-data' volume to this portion and assigning it to be the oldest 'package' chronologically. The volumes were created as either infill over underlying volumes, or erosive units representing major truncation horizons such as the Black Reef Formation.

3.4.3. Wireframes

Geological model volumes are defined by wireframes. For the study area the volumes were created using the interpreted wireframes of the digitised contact horizons, as well as additional support wireframes (polylines and orientation disks) that constrained the interpolations between the seismic lines. Floating polylines supported the contact location between seismic lines. Orientation disks pegged the 3D surface interpolations to borehole contacts and also indicated the facing direction that was especially important in the overturned rocks of the Vredefort dome. The wireframes were checked for logical inconsistencies.

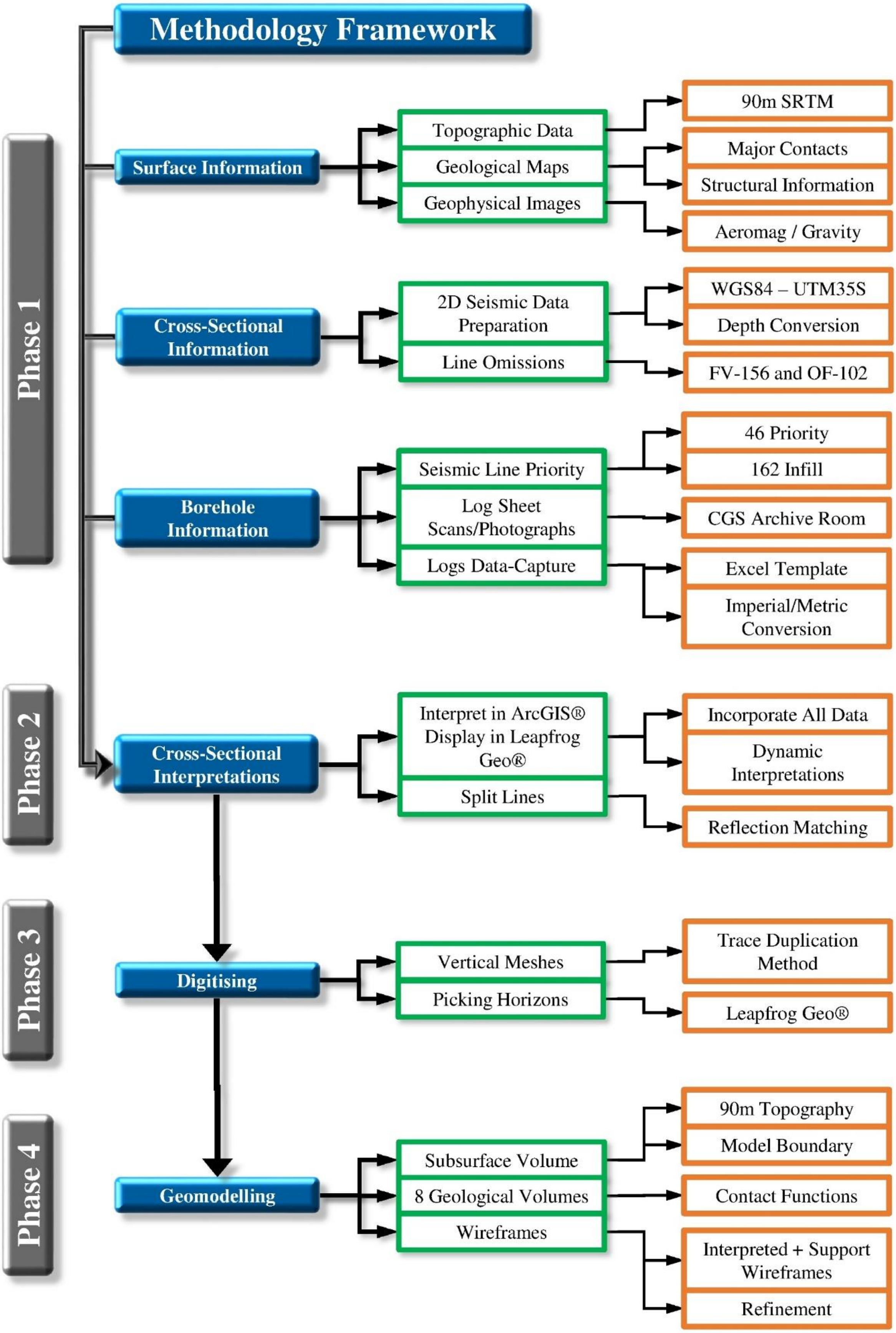


Figure 3.1 Methodology framework for the geological modelling.

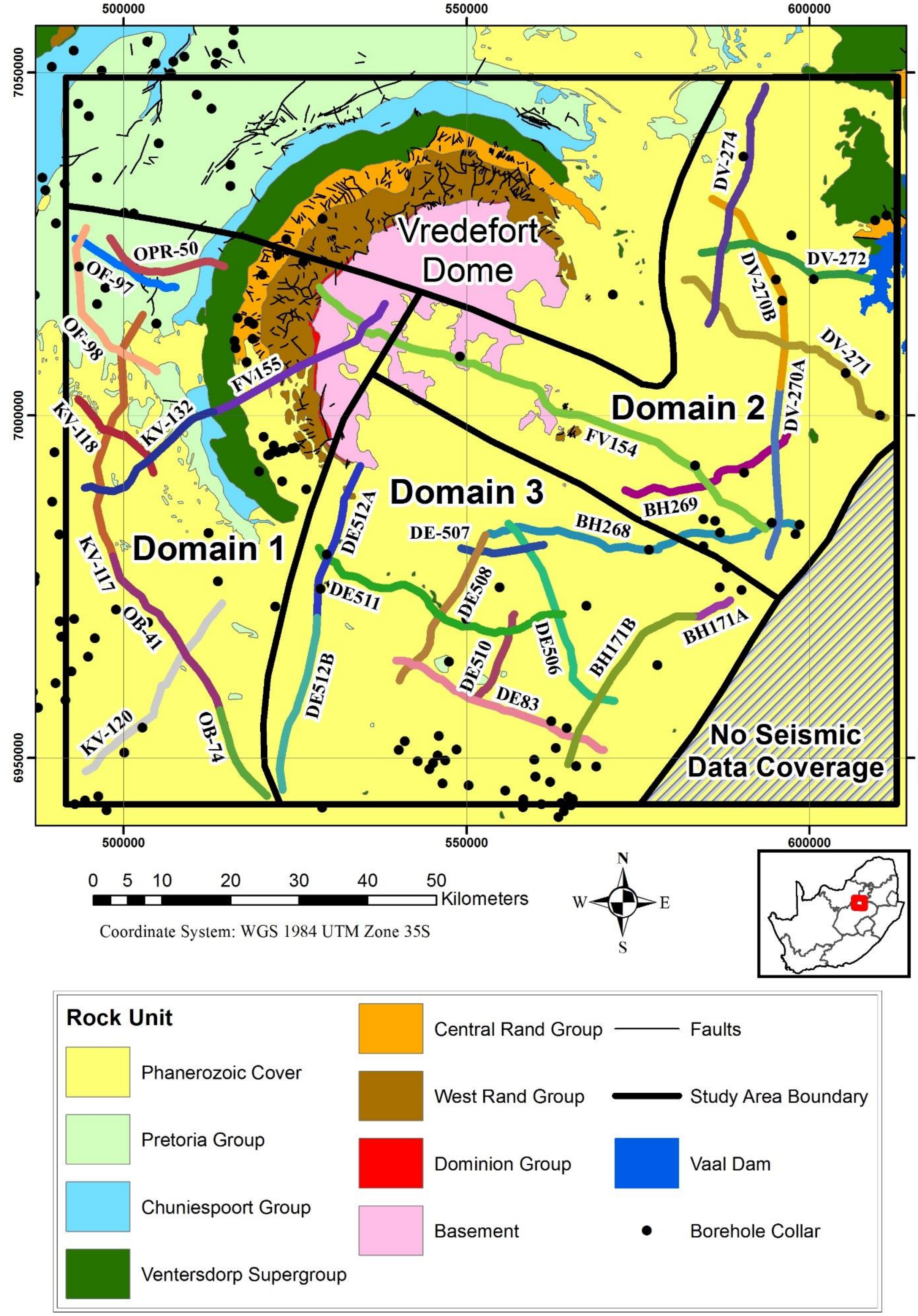


Figure 3.2 Twenty eight 2D seismic lines (including three split lines) and boreholes overlaying 1:250,000 scale geology map. The three domains are illustrated and each contains a number of cross-cutting seismic lines.

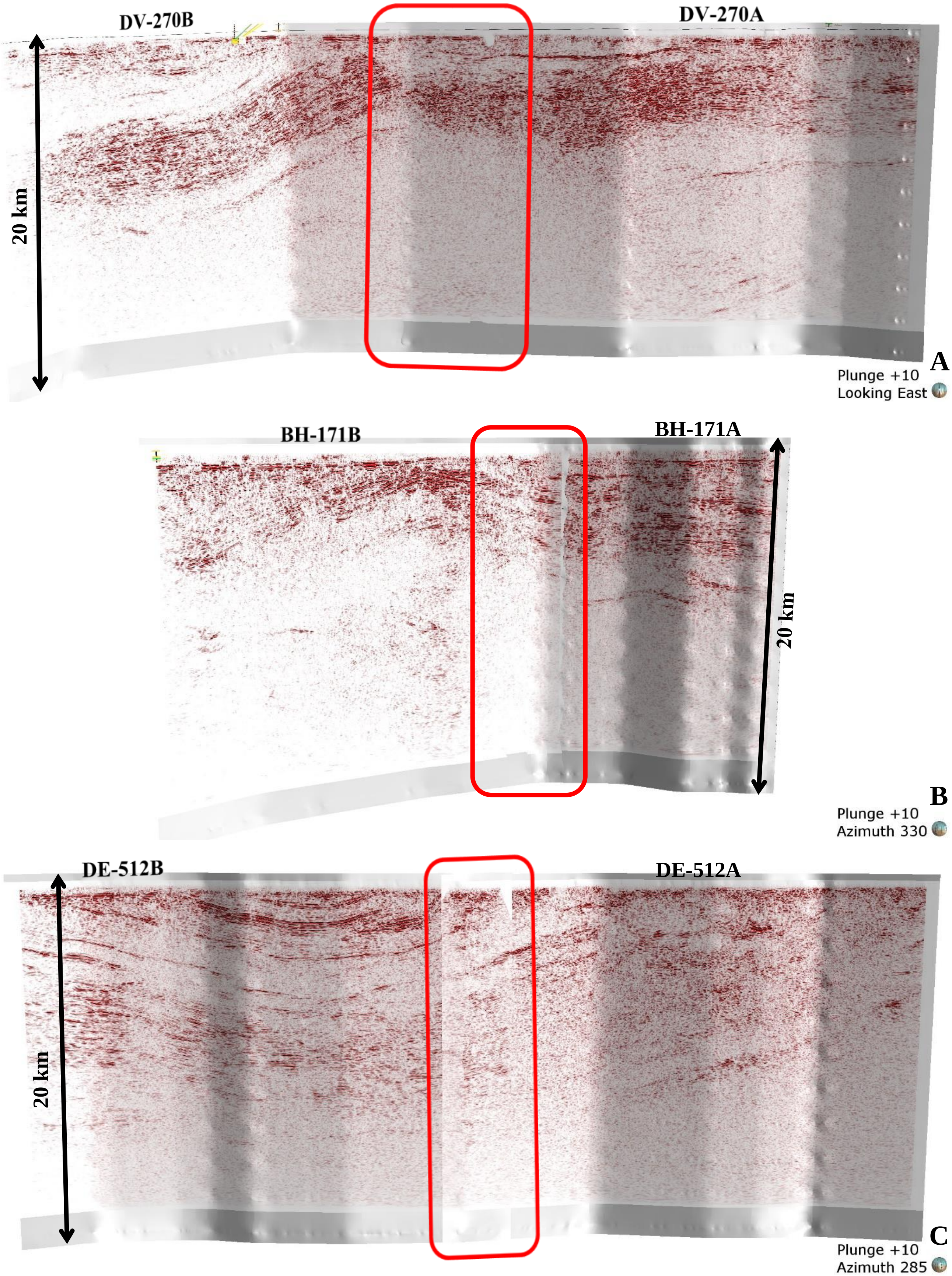


Figure 3.3 Split seismic lines tied together in Leapfrog Geo®; parity of each section is maintained. A) DV-270; B) BH-171; C) DE-512. Overlapping sections are highlighted by the red boxes.

Chapter 4
2D Seismic Data Interpretation

4.1. Introduction

The largest process in the geological modelling phase was the interpretation of each of the twenty eight 2D reflection seismic sections. Apart from line OPR-50 in Domain 1, all the seismic sections crosscut. Interpretation of the data was divided into three domains, each containing a number of cross-cutting seismic lines and links to adjacent domains. The domains are illustrated in Figure 3.2. The V_p and ρ stated throughout this text, and used during the interpretations, are illustrated in Table C in the Appendix. Supplementary information to Section 4.3 is provided in Table D in the Appendix.

The most important parameter that affects the strength of a reflected signal from a geological boundary is the contrast in acoustic impedance (product of the V_p and ρ). For a lithological boundary to generate a strong reflection, the amplitude of a reflected wave (i.e. reflection coefficient, RC) relative to an incident wave should be at least 6% of the incident energy (Salisbury et al., 2003). The RC is represented by the following equation:

$$R = (\rho 2V2 - \rho 1V1)/(\rho 2V2 + \rho 1V1)$$

The quality of data interpretation is also dependent on the accuracy of the seismic processing techniques, as well as the velocity fields used for migration and time-to-depth conversions. Although the seismic lines are relatively old, the quality of the data is good enough to image prominent, continuous geological boundaries. Sophisticated seismic attribute analysis, implemented in current advanced interpretation software packages (such as Kingdom suite® used in this work), was used to enhance the detection of horizons and faults in the data. Seismic interpretation was done by picking and tracking outstandingly clear, strong and laterally consistent seismic horizons, or imaging of prominent first-order scale faults in each line. Special attention was given to the cross-cutting lines for better tracking of the horizons.

Seismic horizons are defined as surfaces, or reflectors that the seismic interpreter selects for picking based on their lateral continuity and strong seismic amplitudes. They are either picked as a trough or peak in the amplitude-based interpretation, depending on the polarity of the data. The amplitude display shows the changes in seismic acoustic impedance and thus helps to identify changes in lithological characteristics in the data. Borehole information is crucial in constraining the initial stages of picking. In the absence of borehole controls, a reasonable estimate based on experience and literature can be made. Using this method, first-order scale faults were relatively easy to identify and picked on seismic sections (faults with a throw of 400m to 2500m).

4.2. Seismic resolution limit

For better interpretation of the reflection seismic data, it is essential to have an idea of the vertical and lateral resolution of the data based on the acquisition parameters used in these seismic surveys survey. The one-quarter dominant seismic wavelength ($\lambda/4$) is often described as the vertical resolution limit, or the tuning thickness. This is the thickness where constructive interference occurs between the wavelets reflected from the top and the base of the layer (Chopra et al., 2006; Hanneing and Paton, 2012). Based on the design, acquisition and processing parameters of the legacy 2D seismic surveys, the spatial and temporal resolutions of the datasets can be derived. For the sweep of 10 – 91 Hz, the dominant frequency of the seismic data was about 65Hz. Based on the Rayleigh quarter of dominant-wavelength criterion described by Widess (1973), and by using the average V_p of 6000 m/s, the vertical resolution is about 23m. This implies that the beds (or layers) with thickness less than 23m cannot be vertically resolved in these seismic sections. Using the Fresnel zone criterion, after migration, the horizontal resolution is equivalent to the dominant wavelength, which is approximately 92m. Therefore, geological features with spacing below these limits may not be discernible in the migrated seismic sections.

4.3. Justifications for interpreting major contacts

The variation in rock types in the study area ranges between sedimentary clastics, dolomites and volcanic rocks. Quartzite and shale ρ, including the ρ of their protoliths (i.e. sandstone and silt/mudstone) differ slightly, but the values are reasonably proportional to one another. The ρ of the weakly (if at all) metamorphosed sandstones and mudstones of the Karoo Supergroup differ by ~0.16 g/cm^3. According to Phillips and Law (1994) the regional metamorphic grade of the Witwatersrand basin (outside the collar of the dome) is lower greenschist facies (i.e. temperatures up to 400°C, and pressures up to 3kb). The ρ of these lower greenschist facies quartzite and shale units in the study area differ comparably to Karoo Supergroup sediments (see Table C in the Appendix).

Importantly, mudstones and shales are generally denser than sandstones and quartzites. The V_p and ρ contrasts would result in acoustic impedance contrasts that would produce a seismic reflection at the interface. Dolomite ρ on the other hand changes very little at lower greenschist facies grades (2.84 g/cm^3 in the metamorphosed Malmani Subgroup versus 2.86 g/cm^3 in un-metamorphosed rocks, Jones, 2003). Similarly, all volcanic units exhibit V_p and ρ values above 6000 m/s and 2.78 g/cm^3 respectively. Therefore acoustic impedance contrasts are produced at the interfaces between the volcanic rocks and the lower V_p and ρ quartzites and shales, and the higher V_p dolomites.

4.3.1. Base of the Karoo Supergroup

The variation in shale and sandstone units in the Karoo Supergroup (Johnson et al., 2006) will produce acoustic impedance contrasts at their contacts due to the variation in ρ and V_p between the rock types (i.e. 2.38 g/cm^3 in sandstone and 2.54 g/cm^3 in shale). The V_p range for the Karoo Supergroup is 3000 – 3200 m/s (Appendix, Table C), whereas the underlying strata have higher V_p and ρ (all above 5500 m/s and 2.65 g/cm^3). The increase in V_p and ρ across the contact with the underlying stratigraphy results in a significant RC, providing a strong amplitude reflection. An angular unconformity also exists between the Transvaal Supergroup and Karoo Supergroup.

4.3.2. Pretoria Group – Chuniespoort Group

From the surface mapping and borehole logs, the youngest preserved formation of the Transvaal Supergroup in the study area is the Magaliesberg Formation. The Dwaalheuwel Formation is not preserved. The Rooihoogte Formation is thinly preserved in a few boreholes on the northwest margin of the study area. Similarly the Boshoek and Silverton Formations are rarely preserved and, apart from two boreholes, the borehole logs do not report the Boshoek, Strubenkop, Daspoort, and Silverton Formations.

The stratigraphic column interpreted from the surface mapping and boreholes offers a predictable model for the expected seismic reflection stratigraphy from the 2D seismic data. The uppermost Daspoort and Magaliesberg formations observed in the study area are dominated by sandstones (Johnson et al., 2006), therefore the acoustic impedance contrast for the contact between these two formations is not large enough to produce a high amplitude reflection, due to the similar ρ of the two formations (i.e., ~2.5 g/cm^3).

The Strubenkop Formation will exhibit a stronger acoustic impedance contrast with the overlying Daspoort Formation because it consists of up to 145m of denser shale (~2.8 g/cm^3 versus ~2.6 g/cm^3), with subordinate sandstone (Johnson et al., 2006). The change in ρ at the contact between the formations will produce a low to moderate-amplitude reflection with a positive RC. The amplitude strength may depend on the heavy element content (iron and other metals) of the mudstone that will determine its ρ increase.

V_p and ρ measurements have not been published for the Strubenkop Formation; however according to Johnson et al. (2006), the Timeball Hill and Strubenkop Formations are both lacustrine deposits dominated by mudstone sequences with subordinate sandstones (with minor diamictite, conglomerate and lava members included in the Timeball Hill Formation). The two formations can therefore be assumed to be broadly similar in terms of ρ (and V_p). The Timeball Hill Formation has a published V_p of 5513 m/s and ρ of 2.67 – 2.80 g/cm^3 (Appendix, Table C). The Strubenkop Formation will have a similar, possibly slightly lower V_p and ρ due to the absence of the basal volcanic member of the Timeball Hill Formation (i.e., Bushy Bend Member).

The absence of the Dwaalheuwel Formation in the study area implies that the Strubenkop Formation unconformably overlies the basaltic andesites of the Hekpoort Formation. The V_p and ρ of the Hekpoort Formation is 6083 m/s and 2.83 g/cm^3 respectively (Appendix, Table C). Therefore a large acoustic impedance contrast with positive RC values exists between the formations. The change in V_p and ρ across the contact will produce a moderate to high-amplitude reflection interface.

The Hekpoort Formation is made up of basaltic andesites and minor pyroclastics (Johnson et al., 2006) making the formation relatively homogeneous in terms of ρ variation. On a local scale, minor pyroclastic units could lower the ρ in those areas resulting in the production of discrete discontinuous internal reflections. Due to the possible large V_p and ρ changes, the contact between the Hekpoort Formation and the underlying formations (either the Boshoek Formation or the Timeball Hill Formation) will produce a moderate to high-amplitude reflection with a negative RC. The Boshoek Formation has no published V_p and ρ measurements, but is made up of sandstones, conglomerates and diamictites that will be relatively less dense compared to the overlying volcanics of the Hekpoort Formation.

The Boshoek Formation is rarely exposed in the study area; it is reported to have a maximum thickness of only 80m over the full extent of the Transvaal Supergroup basin (Johnson et al., 2006). It may fall below the resolution limits of the 2D seismic survey (i.e. ~23m as described in Section 4.2). The lower contact of the Hekpoort Formation will most likely be with the underlying Timeball Hill formation, with a decrease in V_p and ρ of 570 m/s and 0.03 – 0.16 g/cm^3, respectively (Appendix, Table C).

According to the surface mapping, the Timeball Hill Formation in the study area is the base formation of the Pretoria Group. The Rooihoogte Formation, the stratigraphic base unit (Johnson et al., 2006), varies greatly in thickness throughout the Transvaal Supergroup basin (2 – 150m) and may only be preserved locally, or may fall below the resolution limits of the 2D seismic survey (~23m as described above). The lithological variation within the Timeball Hill Formation (mudstone, sandstone, volcanic, conglomerate, and diamictite members) may result in low to moderate-amplitude contiguous internal reflections.

The Penge Formation ironstone is not preserved in this study area according to surface mapping and boreholes. The Duitschland Formation is not explicitly reported either, but due to the absence of the Penge Formation, the carbonates that dominate this formation (Johnson et al., 2006) may be merged in the borehole logs with the underlying Malmani Subgroup dolomites. For example the borehole logs in the southern parts of the study area do not differentiate the various carbonate intervals.

The Malmani Subgroup exhibits V_p and ρ of 6600 – 6834 m/s and 2.65 – 2.84 g/cm^3 (Appendix, Table C). The variation in V_p may represent the variation in ρ due to the variable chert and shale contents in the subgroup. This subgroup may exhibit discrete, discontinuous low-amplitude internal reflections in the seismic sections. However, the dolomite (ρ of 2.84 g/cm^3) dominates the subgroup to produce the relatively high V_p of the subgroup (6600 – 6834 m/s). This suggests that the interface with the overlying

Pretoria Group will be imaged by seismics as there is an increase in V_p and ρ from the Timeball Hill Formation to the Chuniespoort Group. The large acoustic impedance contrast between the two units will produce a positive RC and moderate to high-amplitude seismic reflections.

4.3.3. Black Reef Formation

The base formation of the Transvaal Supergroup is the quartzite-dominated Black Reef Formation (Johnson et al., 2006). The borehole intersections of the Black Reef Formation in the study area exhibit a broad range of thicknesses from 2m to 100m. Therefore in some parts the formation may fall below the seismic resolution limit (23m) and the top or bottom of the formation may not be distinguished. In parts where the Black Reef Formation is thick (>23m), the V_p and ρ of the formation will come into play. The values are comparable to other sedimentary sequences (no published V_p but the ρ for the shales is 2.79 g/cm^3 and the quartzites is 2.65 g/cm^3; Jones, 2003) so will provide strong impedance contrasts with the adjacent dolomites and volcanics of the Malmani Subgroup and Ventersdorp Supergroup, respectively.

Where the formation is thinly preserved (<23m) the acoustic impedance contrast between the Chuniespoort Group and Ventersdorp Supergroup will be imaged due to the decrease in V_p from the dolomites to the volcano-sedimentary sequences, respectively (i.e. >6600 m/s in the Chuniespoort Group and <6400 m/s in the Ventersdorp Supergroup, see Table C in the Appendix). The ρ of the volcanic units in the Ventersdorp Supergroup is similar to the dolomites in the Malmani Subgroup (i.e. ~2.85 g/cm^3). However, the Platberg Group and Pniel Sequence of the Ventersdorp Supergroup exhibit a large sedimentary component that lowers the V_p and ρ of the immediate footwall to the Black Reef Formation. Interestingly, the ρ of the Klipriviersberg Group volcanics is higher than the dolomites (2.88 – 2.90 g/cm^3 versus 2.84 g/cm^3), but the V_p remains lower (6230 – 6400 m/s versus 6600 – 6834 m/s).

Surface mapping (Figure 3.2) in the study area has shown that the Allanridge and Bothaville formations of the Pniel Sequence are not preserved. However a few boreholes (i.e. 4014263, 4037657, 4037666, and 4039854) on the western and southwest margin (Figure 3.2) report volcanic units of the Allanridge Formation. Borehole 4037666 also reports pebbly quartzites and conglomerates of the Bothaville Formation. Due to the poor preservation of the Allanridge and Bothaville formations elsewhere, the footwall lithology of the contact between the Black Reef Formation and the Ventersdorp Supergroup will likely be the Platberg Group volcano-sedimentary package, or Klipriviersberg Group volcanics.

According to the measured V_p and ρ (Table C in the Appendix) of the Malmani Subgroup, Pniel Sequence (Allanridge and Bothaville formations), Platberg Group, Klipriviersberg Group, and Central Rand Group, a significant acoustic impedance contrast will be produced at the interface between the relatively higher V_p and ρ of the Malmani Subgroup and most of the underlying stratigraphy (including the Black Reef Formation). Volcanic ρ may be higher than dolomite ρ but the V_p remains higher in the dolomites. The impedance contrast will determine the strength of the reflection amplitude.

4.3.4. Venterspost Contact Formation (VCF)

The base formation of the Ventersdorp Supergroup is the Venterspost Formation (the Venterspost Contact Formation, or VCF). This formation in the study area is less than 25m thick (as indicated in Table D in the Appendix) and falls at the limit of the vertical seismic resolution (23m) of the 2D seismic surveys. The overlying and underlying lithologies to the VCF have contrasting V_p and ρ (~6300 m/s and ~2.89 g/cm^3 for the volcanics of the Klipriviersberg Group, and ~5700 m/s and ~2.76 g/cm^3 for quartzite of the Central Rand Group, see Table C in the Appendix). Therefore the change in V_p and ρ across the interface from the volcanics of the Klipriviersberg Group to the quartzites/conglomerates of the Central Rand Group will be imaged. Both groups are relatively homogeneous in terms of their individual ρ and will produce seismically transparent packages (with the exception of the Booysens Formation shale in the Central Rand Group). The drop in V_p and ρ from the Klipriviersberg Group to the Central Rand Group will form a strong acoustic impedance contrast at the interface, to produce a moderate to high-amplitude reflection with a negative RC.

The Booysens Formation in the study area has reported borehole thicknesses of between 50m and 300m (albeit apparent thicknesses of the sub-vertical boreholes) and therefore may be imaged by the reflection seismic method. It is also possible that the VCF lies in contact with the West Rand Group, as boreholes in northwest and southwest of the study area indicate (see Table D in the Appendix for details). The seismic section for the West Rand Group is unique. The seismically transparent package of the Central Rand Group will be absent where the VCF contacts the West Rand Group, and only the thick package (several kilometres) of closely-spaced reflectors of the West Rand Group will be delineated.

4.3.5. Central Rand Group – West Rand Group

The Central Rand Group is dominated by quartzite and conglomerates, with minor shale and volcanic units (Johnson et al., 2006). The V_p and ρ for the Central Rand Group is 5550 – 5779 m/s and 2.66 – 2.87 g/cm^3, respectively (Appendix, Table C). The West Rand Group is characterised by a thick series of intercalated shales, ironstones, quartzites, conglomerates, volcanic sequences and diamictites (Johnson et al., 2006). The V_p of 5748 m/s (Appendix, Table C) for the West Rand Group therefore only represents the mean V_p of a sequence of rocks that have differing ρ (2.87 – 3.15 g/cm^3).

It is suggested that due to the large variation in rock types observed in the West Rand Group stratigraphy, the package will be imaged as a series of closely-spaced, contiguous internal reflections with varying amplitudes depending on the local scale distribution of rock types. These internal reflections produce a seismic signature that is unique in the stratigraphy of the study area and therefore can be used as a guide during seismic section interpretations. The wide range of V_p and ρ contrasts, close spacing of reflections, and variable lateral extents of the sedimentary members over the Witwatersrand basin makes interpreting individual horizons within the West Rand Group difficult.

Though not included as a discrete volume contact in the modelling, the interpreted contact of the Government and Hospital Hill subgroups can be highlighted in a similar way to the horizons in the Transvaal Supergroup that provide local scale detail to each line interpretation. According to Johnson et al. (2006), the largest lithological variability is found in the Government Subgroup. This subgroup is characterised by strong changes in depositional (marine) environment and disconformities. The underlying Hospital Hill Subgroup represents a less variable depositional environment with relatively thicker successions. The thicker members will therefore produce a sequence of widely-spaced internal reflections relative to the overlying Government Subgroup. It is suggested that in some parts of the study area this wider-spaced package can be observed and therefore the contact between the two subgroups can be interpreted. The Parktown Formation, towards the base of the Hospital Hill Subgroup, is dominated by thick shale sequences and can potentially be interpreted as well.

The unconformity separating the West Rand and Central Rand groups is resolvable due to the change in V_p and ρ from the quartzite dominated Central Rand Group to the highly variable shale and quartzite units (with minor volcanics) that dominate the West Rand Group. However the contact is not seismically imaged in places where the Central Rand Group quartzite overlies the uppermost quartzites of the Maraisburg Formation of the West Rand Group due to the similar compositions. Where preserved, this formation will obscure the vertical location of the reflection by up to 200m (thickness of the Maraisburg Formation according to Johnson et al., 2006), a relatively small margin of error considering the scale of the modelling and ~18km depth extent of the sections.

4.3.6. West Rand Group – Dominion Group

The Dominion Group is not sampled by boreholes in the study area, though the surface mapping (described in Table D in the Appendix) and stratigraphic logs (according to Johnson et al., 2006) depict the Group as a relatively thin package with <800m wide surface exposures and <2000m widths reported in stratigraphic logs. It is recorded in surface mapping over an area that extends approximately 100km from the west of the study area to the collar rocks of the Vredefort dome. The preservation of the Group at depth is suggested with higher confidence in the western parts of the study area.

According to the stratigraphic logs (Johnson et al., 2006) the dominant lithology in the Dominion Group are mafic – intermediate volcanics. The ρ of the group is 2.78 g/cm^3 (Jones, 2003), though the V_p has not been published. However due to the similar composition of the basalt with that of the Hekpoort Formation and Klipriviersberg Group, the V_p can be estimated at ~6000 m/s. The V_p and ρ is slightly higher than that of the quartzite and shale expected in the overlying West Rand Group (see Table C in the Appendix). Therefore these volcanic units will provide an acoustic impedance contrast at the interface that will produce a moderate amplitude reflection (with a positive RC).

Another variable for the impedance contrasts is the ρ of the Dominion Group at the formation top. If the lithology is more felsic or sedimentary, for example if the Syferfontein Formation was dominant, the ρ would be relatively lower due to the increase in quartz content (2.65 g/cm^3, Jones, 2003) so the V_p would drop slightly. An analogy for felsic compositions is the basement TTG suite that has a V_p and ρ of 5693 m/s and 2.86 g/cm^3, respectively (Appendix, Table C). A V_p and ρ in this range would be very similar to that of the overlying West Rand Group (particularly the quartzite units of the basal Orange Grove Formation). A felsic-dominated Dominion Group would not form an acoustic impedance contrast between both the overlying Hospital Hill Subgroup and the underlying basement, thus the interface could not be imaged.

4.3.7. Basement Contact

The V_p and ρ values for the basement TTG suite and greenstones are 5693 m/s and 2.86 g/cm^3 respectively (Appendix, Table C). The type of overlying lithology is an important factor in the resolvability of the basement interface. The volcanics of the Dominion Group exhibit a relatively higher V_p compared to the TTG suite of the basement package. Therefore an acoustic impedance contrast is formed at the interface that will produce a moderate amplitude reflection. The suggested V_p for the Dominion Group is higher than the V_p for the basement despite the fact that the ρ for the Dominion Group is slightly lower than the basement ρ calculated by Niu and James (2002). However, if the mafic – intermediate volcanics in the Dominion Group are absent, only the sedimentary/felsic porphyry members of the Syferfontein and Rhenosterspruit formations would be preserved. In this case the V_p and ρ across the interface would be very similar and therefore may not be imaged.

Steps	Processing Route
1	Data reformat (convert SEGD to SEG Y)
2	Geometry application (CDP bin 2 m)
3	Trace editing
4	First-break picking and statics
5	1st RMS velocity analysis (iterative)
6	NMO mute
7	Minimum phase conversion
8	Noise attenuation (Band pass filtering and Spectral whitening)
9	Amplitude recovery: spherical divergence correction
19	Amplitude versus offset gain correction
11	Surface consistent gain correction
12	Frequency/Amplitude dependent noise attenuation
13	Zero-phase surface consistent spiking deconvolution
14	1st pass residual static corrections (iterative)
15	2nd pass RMS velocity analysis (iterative)
16	2nd pass residual static corrections (iterative)
17	NMO correction, 70% stretch mute
18	Stack
19	fx-deconvolution
20	Amplitude equalization using data window
21	Migration (Kirchhoff and Finite Difference algorithms)
22	Time-to-depth conversion (using constant velocity of 6000 m/s)

Table 4.1 Principal seismic data processing steps applied to all the seismic lines component data (courtesy of John Bell, Exploration Manager and Regional Geophysicist at AngloGold Ashanti).

Note: Due to file size constraints "Chapter 5: Analysis" has been placed in a separate pdf document.

Chapter 6
Modelling

6.1. Introduction

The creation of the 3D geological model represented the final phase of the modelling framework (Figure 3.1). The colours used in the modelled volumes correspond with Figure 1.1. The final volumes provided adequate representation of the regional scale architecture in the study area. The spatial relationships also provided insight into the formation and preservation of major stratigraphic units. These volumes are separated by seven major stratigraphic boundaries, as presented in Figure 2.1.

6.2. Digitising

Phase 3 dealt with the digitisation of datasets that formed the wireframes of the individual 3D geological volumes. Digitising the surface geology constrained the outcrop contacts. The seven contact horizons (including all the outcrop structure data) were digitised using 1:250,000 scale geology maps, including the 1:50,000 map of the Vredefort dome and collar rocks (Figure 6.2.1A). The interpreted 2D seismic sections from the three domains are displayed together in Figure 6.2.1B. The digitised surface and borehole information was combined with the seismic section interpretations to form the wireframes for each geological volume (Figure 6.2.1C).

The interpreted interfaces from the 2D reflection seismic sections were extracted as polylines (Figure 6.2.2). Faults were also digitised but were omitted from the model volume interpolations (see Chapter 3). However, faults at lithological interfaces were digitised as ‘structural contact’ polylines in order to preserve the wireframes on those contacts.

6.3. Geomodelling

Phase 4 of the modelling framework dealt with the creation of the 3D geological model following integration of all digitised datasets as wireframes. The wireframes were classified to define the contacts between the individually interpolated volumes. The interpolation between the wireframes yielded mathematically constrained volumes. However, due to the large distance between data points in some parts of the study area the interpolations exhibited greater uncertainty and produced unrealistic surface geometries. Therefore a host of additional supportive wireframes were required to adjust the interpolation into reasonable geometries.

The supportive wireframes included polylines and orientation disks, and are displayed in Figure 6.3.1A. The northern collar of the dome was unconstrained at depth; the supportive wireframes were guided by surface information and adjacent boreholes. The overturned units in the collar rocks would have been interpolated as complex shapes without these wireframes. The polylines were used in a variety of ways, for example, to fill-in large gaps, define structurally bound contacts, refine contacts between adjacent outcrops of different units, and pull surfaces upwards so that they terminated appropriately against other volumes, or the topography. Orientation disks acted as pegs in 3D space. These disks were used to snap interpolations onto boreholes and outcrop contacts, and to define the upright sides of the rendered surfaces. Some wireframes of the seismic sections were separated by large gaps that were pegged with orientation disks to provide consistent geometries of the 3D surface interpolants.

The interpolation process of the wireframes produced 3D surfaces for each contact. The process was simple, but required numerous iterations of refinement. Following each interpolation cycle, some localised inconsistencies were produced in areas of lesser data coverage. The interpolated contact surfaces for each modelled volume are displayed in Figure 6.3.1B.

The 3D rendered surfaces in Leapfrog Geo® were modelled chronologically, i.e., oldest rock packages first. The southeast part of the volume contained no data at depth. Therefore this volume was omitted by setting it as the oldest unit in the modelling workflow. The supportive wireframes and interpolated surface for this omitted volume are displayed in Figures 6.3.1A and 6.3.1B, respectively. The final geological model is displayed in Figure 6.3.2.

6.4. Model Volumes

6.4.1. Basement Volume

The wireframes for the upper contact of the basement volume are displayed in Figure 6.4.1A and the output volume is displayed in Figure 6.4.1B. A small area on the southwest margin of the dome contains a complex series of wireframes that account for an interpreted normal fault in seismic section DE-512A. The basement is intersected by two boreholes, namely, 4013818 and 4020073. However, they are located outside the study area adjacent to the northwest margin of the modelled volume. The upper contacts of the basement in these boreholes are pegged with orientation disks.

The dominant feature in the modelled volume of the basement is the Vredefort dome. The volume of the overturned northern side is estimated. However the western, southern, and eastern sides are constrained at depth. The dip is subvertical on the western side and upright and shallower on the southern side. The eastern side of the dome is less constrained compared to the west, but still exhibits upright, moderate dips. The contact geometry of the dome differs from north to south as well. The exposed northern half is subvertical to overturned. The unexposed volume in the southern half has a vertical cone geometry; it results in a slight increase in horizontal diameter from north to south than from east to west (i.e., ~46km versus ~39km).

The basement contact adjacent to the Vredefort dome varies in depth between 4km and 16km. The contact is locally elevated in several parts of the volume, including the northwest, southwest, southeast, and east. The basement elevation in the eastern half of the volume is generally several kilometres shallower than the western half.

The elevated basement contact to the east of the dome is detected across several seismic sections in Domain 2. The elevation represents the hinge zone of a proposed gentle, asymmetric, antiformal fold with an axial plane trending 035°. The geometry of the fold on its southern limb is offset by a listric fault, and is therefore less defined compared to its northern limb.

The southwestern elevated contact is interpreted across several seismic sections. A well-developed fault system is delineated in these sections, that may be associated with the elevated contact. The southeast and eastern elevated contacts create a distinct asymmetry in the rim syncline around the dome. The syncline is well developed in the western half of the basement volume. However the geometry is less defined in the southern and eastern parts due to the localised uplifts, as well as the generally shallower elevation of the basement in the eastern half.

The southeastern margin of the dome and the area ~25km southeast of it exhibits elevated basement contacts. In the seismic sections these elevated contacts are associated with anomalous internal reflections in the basement. The Karoo Supergroup unconformably overlies the West Rand Group in the uplifted area so the timing of uplift can be constrained to post-West Rand Group deposition and could be late to post-Witwatersrand Supergroup deposition and syn to pre-Klipriviersberg Group deposition. The elevated basement contact therefore formed part of the pre-existing basement architecture at the time of the Vredefort impact.

6.4.2. Dominion Group Volume

The base of the Dominion Group volume is defined by the contact with the basement volume. The upper contact surface is defined by the interpolated wireframes of the contact between the Dominion and West Rand groups. These wireframes are displayed in Figure 6.4.2A and the output volume is displayed in Figure 6.4.2B. Supportive wireframes were used in the northern half of the volume to define the general trend of the overturned units. A small area on the southwest margin of the dome contains a complex series of wireframes that accounts for an interpreted normal fault in seismic section DE-512A. Borehole 4020073 intersects the Dominion Group and is located just outside the study area in the northwest corner; the intersection in this borehole of the upper contact of the Dominion Group was pegged with an orientation disk.

The Dominion Group conforms to the basement contact geometry, but is absent in several places. These include the southwest corner of the modelled volume, the southern margin of the dome, a saddle between the two uplifts in the southeast, and east of the dome. The absence of the Group in the southwest is defined by a low-angle crosscutting fault that exhibits offset of the Dominion Group and lower West Rand Group. The fault may be related to the overlying well-developed listric fault system that is imaged in the adjacent seismic sections.

The absence of the Dominion Group on the southern margin of the dome is associated with structures imaged across several seismic sections located in Domains 2 and 3. The structures form a contact between the basement and the overlying West Rand Group. Outcrop of the Hospital Hill Subgroup in contact with the basement is exposed on the southeast margin of the dome. The absence of the Dominion Group east of the dome is associated with the listric fault imaged across several seismic sections in Domain 2. The outcrop in the northern collar of the dome exhibits an abrupt termination of the Group against a fault. East of this fault the Group is absent over the rest of the collar exposure. The interpolations had no constraints that could extend the volume and close the gap from this point in the northern collar towards the southern margin of the dome.

The Dominion Group is also absent in a saddle between two elevated basement highs in the southeast. The offsets imaged in this area of Domain 3 indicate normal and listric displacement on the flanks of the two uplifts. The interpolated surface produced thinned and absent volumes of the Group in account of the abrupt change in elevation over a relatively short distance.

6.4.3. West Rand Group Volume

The base of the West Rand Group volume is defined by the contact with the Dominion Group volume. The upper contact surface is defined by the interpolated wireframes of the contact between the West Rand and Central Rand groups. These wireframes are displayed in Figure 6.4.3A and the output volume is displayed in Figure 6.4.3B. The vast majority of the orientation disks are pegged at borehole contacts. There are 81 orientation disks in total, 14 of which are pegged on the mapped contact adjacent to the dome, 12 are supportive disks, and 55 are pegged to borehole contacts collared around the dome.

The wireframes that represent the fault-terminated interfaces on the seismic sections are relatively short in length. These short, abrupt changes in the contact form the few sharp irregularities observed on the interpolated surface. Several supportive wireframes are used as ‘pull-ups’ in the southeast portion. They are placed where the West Rand Group contacts the Ventersdorp or Karoo supergroups. This ensures that the West Rand Group surface terminates against younger crosscutting units.

The identification of geometric variation in the West Rand Group volume is not as refined as in the other units. This is due to the relatively thicker modelled volume of the Group compared to the volumes of the other units. The eastern half of the volume exhibits shallower preservation depths than the western half. The contact surface displayed in Figure 6.4.3B illustrates this variation. The interpolated contact in the eastern half is on average ~1500m below surface, whereas in the western half it averages ~6000m below surface. The rim syncline on the northern and western sides of the dome can still be identified.

The magnetic properties of the West Rand Group (Johnson et al., 2006) produce anomalies in the regional aeromagnetic surveys. These anomalies match the outcrop in the exposed collar rocks to the west and north of the dome. Due to the relatively thin Karoo Supergroup cover, the anomalies are traced to the south and east of the dome. Boreholes and surface mapping confirm the preservation of the Group below the Karoo Supergroup, providing greater confidence in the extent of the interpolation.

Truncation of the West Rand Group by younger units is interpreted in several areas. These include the northwest, southwest, southeast, and the eastern margin of the dome. The crosscutting relationships are clearly displayed in Figure 6.4.4B. All the major truncated areas of the Group are associated with the VCF interface. However a narrow ~6km long truncation that associates with the interface of the Black Reef Formation is located ~20km south of the dome, and is imaged in seismic section DE-510 (Figure 5.2.26).

6.4.4. Central Rand Group Volume

The base of the Central Rand Group volume is defined by the contact with the West Rand Group volume. The upper contact surface is defined by the interpolated wireframes of the contact between the Central Rand Group and the Ventersdorp Supergroup. These wireframes are displayed in Figure 6.4.4A and the output volume is displayed in Figure 6.4.4B. The vast majority of the orientation disks are pegged at borehole contacts. There are 137 orientation disks in total, 26 of which are pegged on the mapped contact, 10 are supportive disks, and 101 are pegged to borehole contacts scattered around the Vredefort dome.

The wireframes that represent the fault-terminated lithological interfaces on the seismic sections are relatively short in length. These short, abrupt changes in the contact form the sharp irregularities observed on the interpolated surface. The VCF wireframes that define the upper contact are modelled as an erosional surface. This ensures that the interpolated surface truncates older units, including the Central Rand Group.

The modelled volume of the Central Rand Group is similar to the West Rand Group volume in terms of overall geometry and variation in depth (from west to east). The rim syncline is observed on the western margin of the dome. The Central Rand Group on the southwest margin of the dome and the southern margin of the model boundary is elevated. This suggests that the rim syncline continues eastwards into Domain 3.

The Central Rand Group is absent in five places, similar to the West Rand Group volume described above. Four of the areas are associated with truncation by the VCF and one is associated with the truncation interface of the Black Reef Formation. The Central Rand Group is preserved in the narrow corridor in the southeast.

6.4.5. Ventersdorp Supergroup Volume

The base of the Ventersdorp Supergroup volume is defined by the contact with the Central Rand Group volume. The upper contact surface is defined by the interpolated wireframes of the contact between the Ventersdorp Supergroup and the Chuniespoort Group. These wireframes are displayed in Figure 6.4.5A and the output volume is displayed in Figure 6.4.5B. Periclinal folds exposed around the dome and imaged in the seismic sections were interpreted using the orientation disks. Roughly half of the orientation disks are pegged on borehole and mapping contacts. The rest are supportive disks for the fold interpolations and various other supportive wireframes. The wireframes of the Black Reef Formation are modelled as an erosional surface to ensure that the interpolated surface truncates older units, including the Ventersdorp Supergroup.

The Ventersdorp Supergroup volume is elevated in several places. These include the northwest corner, southwest corner, eastern margin of the model boundary, and across the southeast. With the exception of the southeast elevation, these areas possibly form part of the rim syncline around the dome. The elevated Supergroup in the southwest corner of the model boundary contacts an elevated West Rand Group volume, suggesting at least two episodes of uplift.

On the northwest margin of the modelled block the Ventersdorp Supergroup is truncated by the Black Reef Formation across a narrow area. An additional truncation is imaged in seismic sections and reported in boreholes in Domain 2 towards the hinge of the interpreted anticline. Across the hinge of the anticline, the Ventersdorp Supergroup is absent because the Karoo Supergroup unconformably overlies the Central Rand Group.

On the eastern margin of the modelled block the Ventersdorp Supergroup volume is absent in two areas. The northern area is constrained by outcrop of the Central Rand Group. The southern area is constrained by boreholes and seismic sections that indicate the Karoo Supergroup unconformably overlies the Central Rand Group.

The Ventersdorp Supergroup volume in the southeast is mostly absent across the study area based on borehole information, surface mapping, and seismic section interpretations. These indicate that the Karoo Supergroup unconformably overlies the Witwatersrand Supergroup. Surface mapping and borehole information reported a few narrow volcanic outcrops and intersections of the Klipriviersberg Group near the southeast margin of the modelled block. These constraints indicate that the uplift in the southeast of the model boundary formed prior to synchronous to emplacement of the Klipriviersberg Group.

A periclinal fold is observed in the Ventersdorp Supergroup volume to the west of the dome. The fold coincides with the surface expression ~2800m above it. A periclinal fold is also located adjacent to the southwest margin of the dome where it is covered by Quaternary sediments and the Karoo Supergroup. The slightly arcuate strike of the subvertical axial plane trends eastwards towards the dome, forming an acute angle with the margin of the dome. The fold and its arcuate axial trace is better illustrated in the overlying Chuniespoort Group volume (Figure 6.4.6B).

6.4.6. Chuniespoort Group Volume

The base of the Chuniespoort Group volume is defined by the contact with the Ventersdorp Supergroup volume. The upper contact surface is defined by the interpolated wireframes of the contact between the Chuniespoort and Pretoria groups. These wireframes are displayed in Figure 6.4.6A and the output volume is displayed in Figure 6.4.6B. The majority of orientation disks are used as the fold supports to the west and north of the dome. The borehole contacts are pegged as well. With regards to the periclinal fold adjacent to the southwest margin of the dome, the interpolation algorithms produce an artificial cuspate surface on the flank of the fold.

The Chuniespoort Group volume is confined in the south, southeast, and east. The Group on the southern and eastern margins of the modelled block exhibits dome-dipping orientations. In both instances the volume terminates against the Karoo Supergroup. It is suggested that the Group conforms to the geometry of the rim syncline around the dome; however the synclinal geometry is absent in the southeast.

The modelled volume in the southeast portion presents a variation in geometry between the Transvaal Supergroup and the older units. As described previously the Witwatersrand Supergroup is elevated in the southeast, and the Ventersdorp Supergroup is absent/truncated in the same area. A trace bisecting the gap in the Ventersdorp Supergroup exhibits a similar trend to a trace connecting the two West Rand Group volumes in the southeast. The traces exhibit an azimuth of ~147° from the southeast margin of the dome. However a bisecting trace of the absent/truncated portion of the Chuniespoort Group exhibits an azimuth of ~124°. The ~23° difference is observed in the output volume (Figure 6.4.6B).

The periclinal folds exposed in outcrops of the Pretoria Group and located west and north of the dome are expressed at depth in the Chuniespoort Group volume. As stated before, a periclinal fold is interpreted beneath the Quaternary sediments and Karoo Supergroup adjacent to the southwest margin of the dome; its fold axial trace trends acutely towards the southeast margin of the dome. However the Chuniespoort Group volume better defines the convergence of the fold with the collar rocks. The crest of the periclinal fold may be located near the narrow outcrop position of the exposed Klipriviersberg Group; possibly slightly west of it in account of the close proximity to the repeated Group in the adjacent collar rocks.

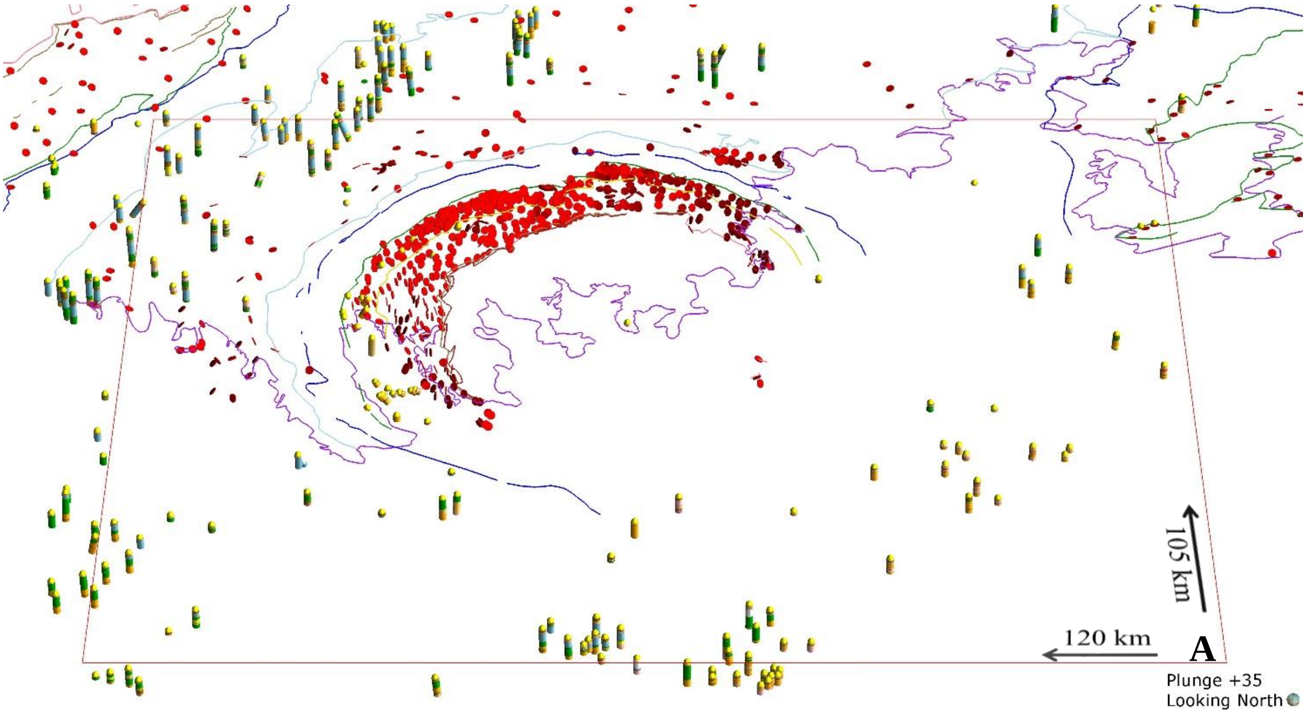
6.4.7. Pretoria Group and Phanerozoic*/Karoo Supergroup Volume*

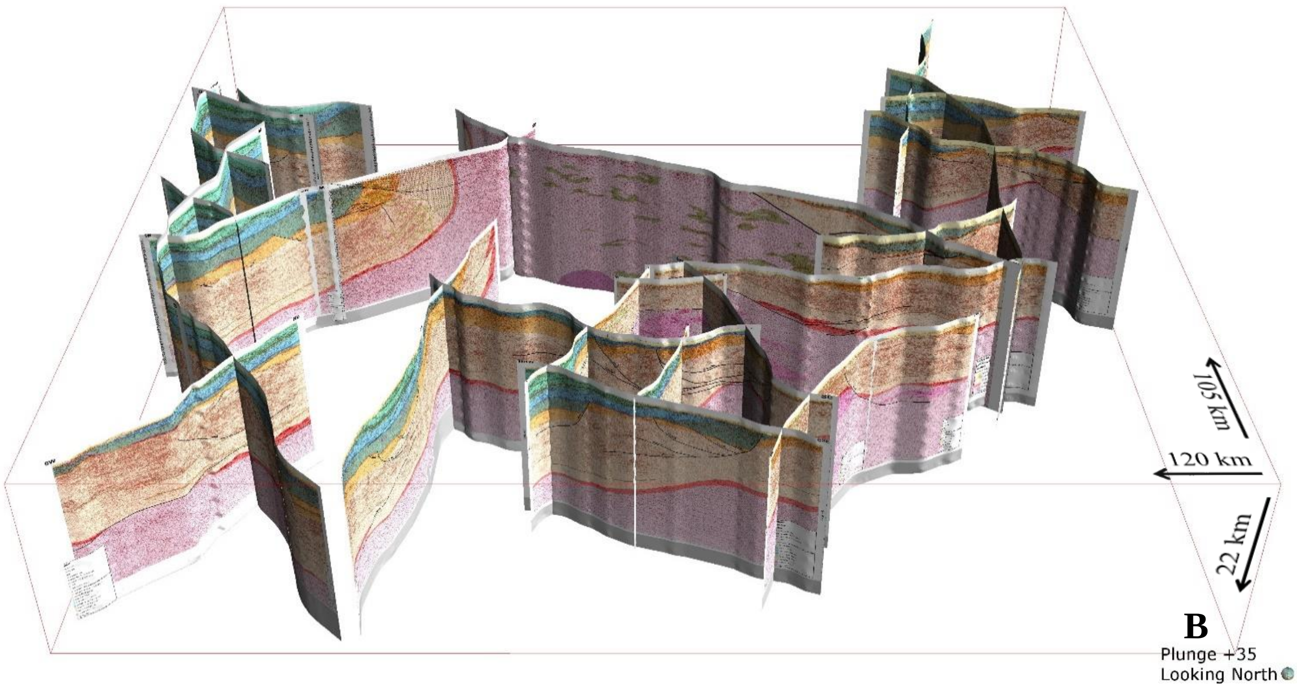
The base of the Pretoria Group volume is defined by the contact with the Chuniespoort Group volume. The upper contact surface is defined by the interpolated wireframes of the contact between the Pretoria Group and the Phanerozoic/Karoo Supergroup. The contact unconformity bounding the surface extent of the Phanerozoic/Karoo Supergroup is included in defining the upper contact surface of the Pretoria Group volume.

The Pretoria Group volume has no upper contact in the exposed outcrop to the north and west of the dome, therefore deformation that affects the Pretoria Group is not expressed by the geometry of the volume because the upper surface is defined by the topography. The truncation surface of the sub-horizontal Karoo Supergroup did not preserve the original upper contact of the Group either. However, the contact between the Pretoria and Chuniespoort groups visually enhance the geometry of the rim syncline and the periclinal fold.

The Phanerozoic/Karoo Supergroup volume is the youngest and is also interpolated as an erosional surface. The upper contact of the Phanerozoic/Karoo Supergroup volume does not require wireframes. The volume is created by filling in the 'empty' space that exists between the Pretoria Group volume and the topography. The wireframes that define the base contact of the Phanerozoic/Karoo Supergroup are displayed in Figure 6.4.7A and the output volume of the Pretoria Group is displayed in Figure 6.4.7B. The output volume of the Phanerozoic/Karoo Supergroup is displayed in Figure 6.4.7C.

In the areas where the inliers expose older units, the interpolated Phanerozoic/Karoo Supergroup contact is 'pulled' above the topography, i.e., is absent across the narrow outcrop volumes. A combination of polyline and orientation disks are used to adequately control the interpolation in these areas. The majority of the orientation disks are placed at surface, along the bounding extents of the contact unconformity between the Phanerozoic/Karoo Supergroup and the older units. Orientation disks are also pegged on borehole base contacts of the Karoo Supergroup.


105 km
120 km
A
Plunge +35
Looking North


105 km
120 km
22 km
B
Plunge +35
Looking North

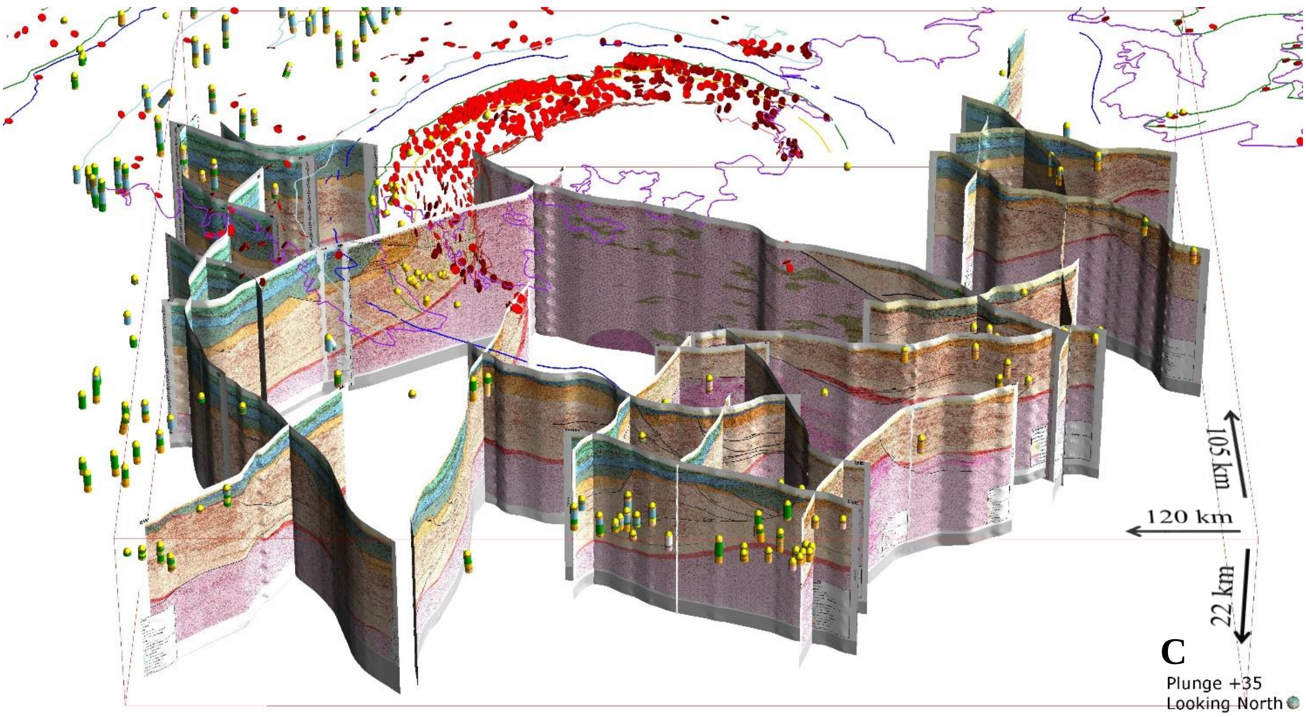
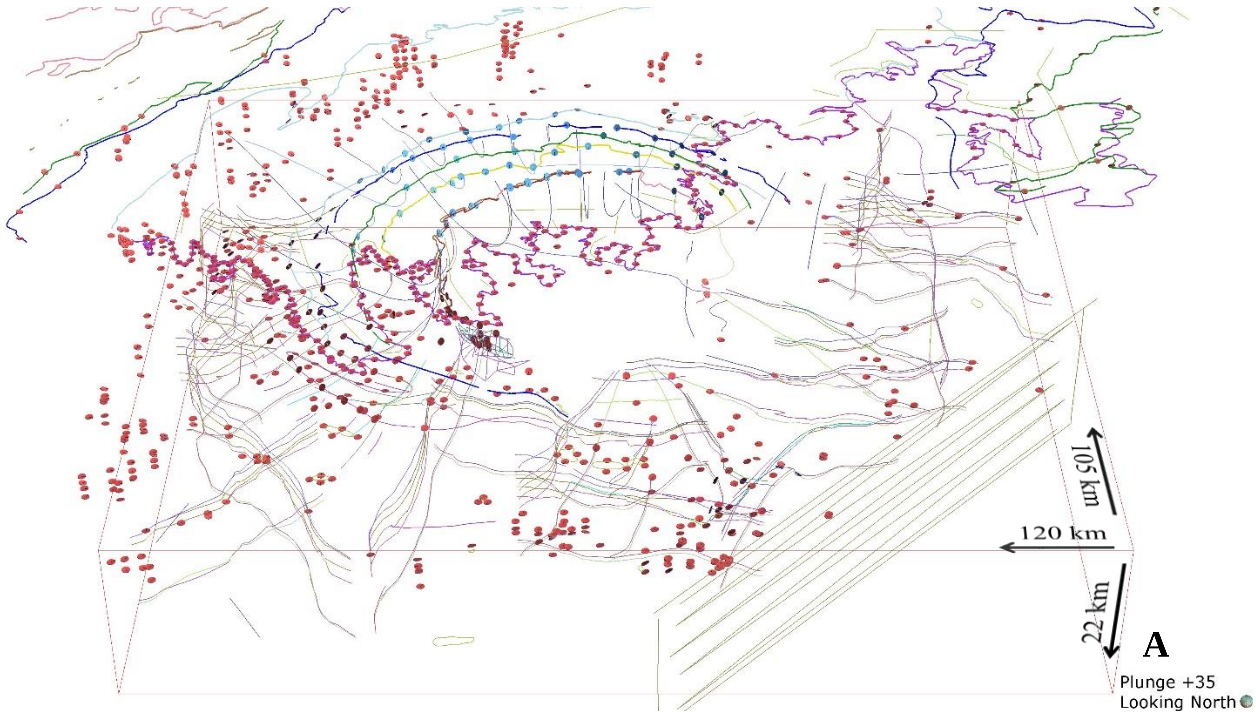


Figure 6.2.1 Three 3D views displaying various aspects of the final datasets. Note, the project boundary is included as a red square/box, and the yellow markers at the top of each borehole are collar markers. A) Looking north plunging at 35°, borehole data (lithology logs plotted) and digitised surface mapping (major contacts in the key below, and dip orientations as red disks). B) Looking north plunging at 35°, seismic line interpretations from all three domains. C) Looking north plunging at 35°, combined seismic interpretations and digitised datasets. Key: Purple = Phanerozoic/Karoo Supergroup base contact; light blue = contact Pretoria – Chuniespoort groups; dark blue = Black Reef Formation; Green = VCF; Yellow = contact Central Rand – West Rand groups; brown = contact West Rand – Dominion groups; dark red = contact Dominion Group – Basement; pink = contact Basement – Other.

Figure 6.2.2 Digitised seismic section interpretations, including polylines of the imaged contact interfaces and fault planes.



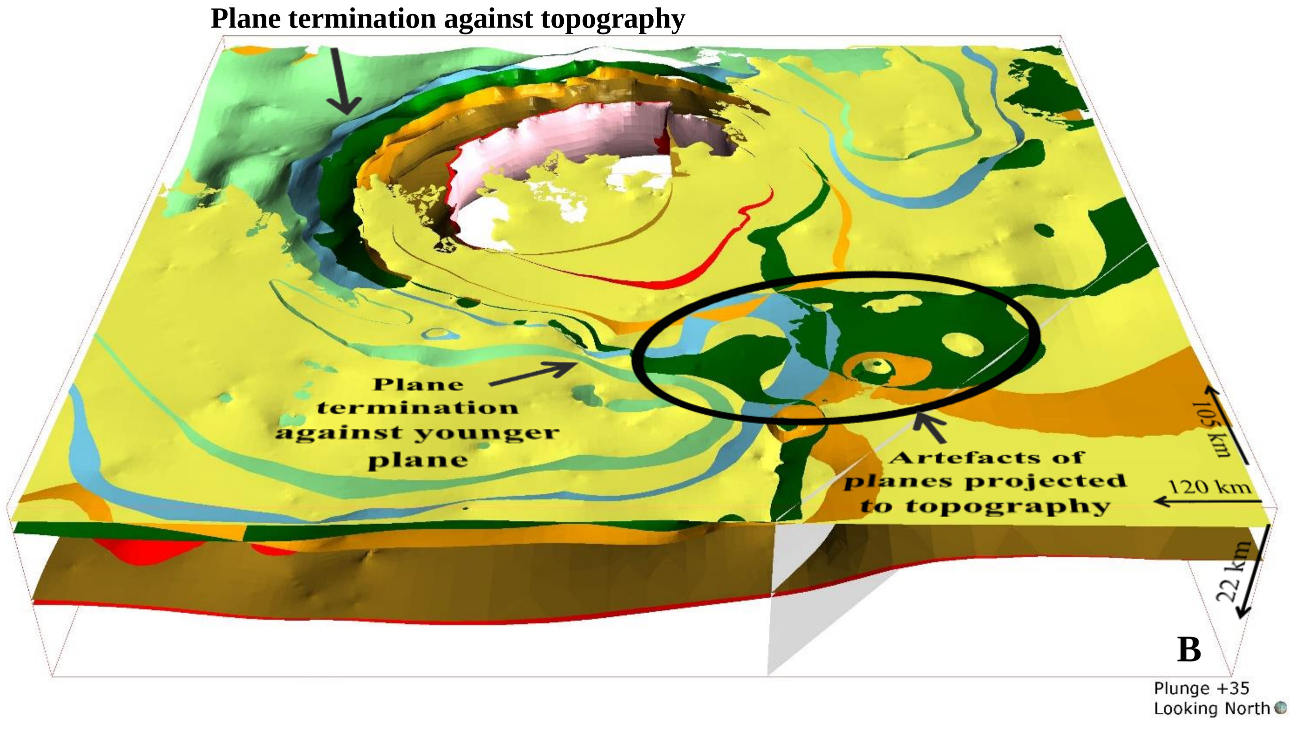
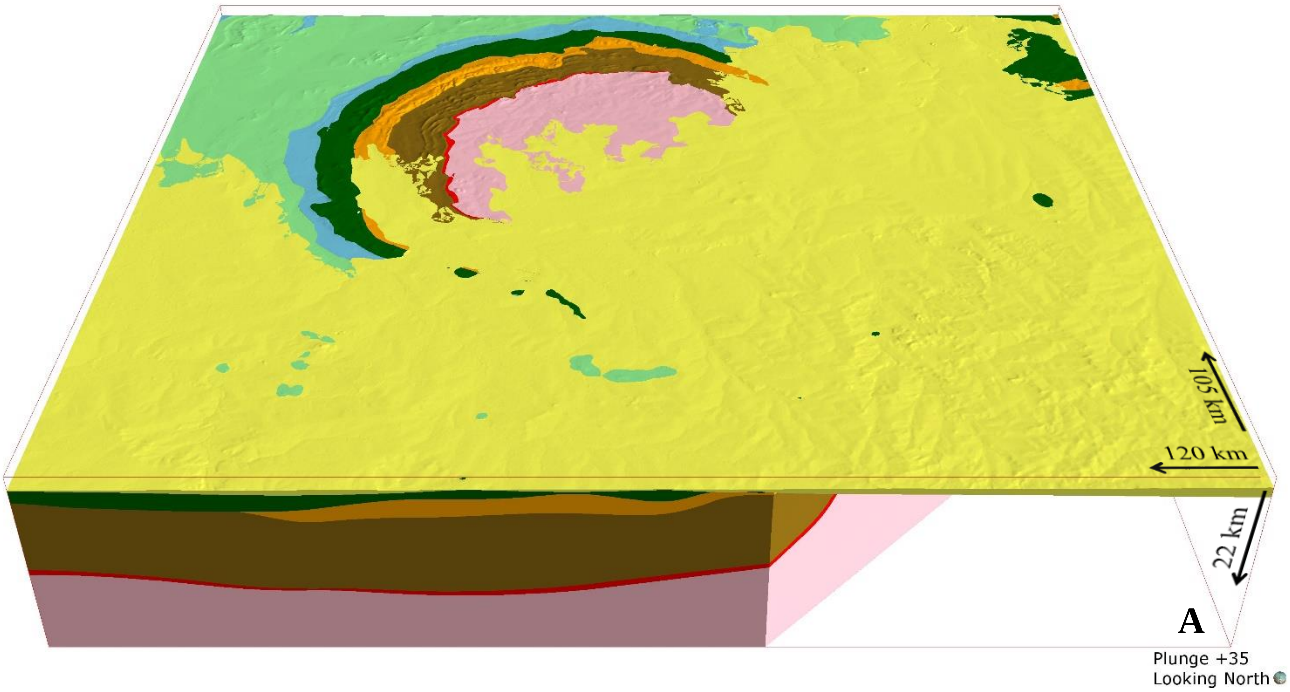


Figure 6.3.1 Wireframes. A) Wireframe polylines (various colours used for various types of wireframe lines) and orientation disks (red = upright side, blue = overturned side) used to create the eight model volumes. Wireframes in areas of poor seismic data coverage (i.e., north of the dome) are estimated using surface mapping and borehole information. B) Interpolated wireframe surfaces with parameters attributed to either 'deposit' or 'erosional' with regards to their contact relationships to older packages. The southeast corner of the study area contains no data therefore has been excluded from the modelled volume using the illustrated wireframes. The modelled volumes of each unit have to terminate against younger units or topography in various places (most commonly with the Karoo Supergroup) therefore the contact planes illustrated here have to cross younger contact planes. The planes project to infinity so are clipped by the model volume boundary and the topography. Each plane is projected to infinity beyond the termination contact between two planes this results in projected artefacts, such as in the southeast.



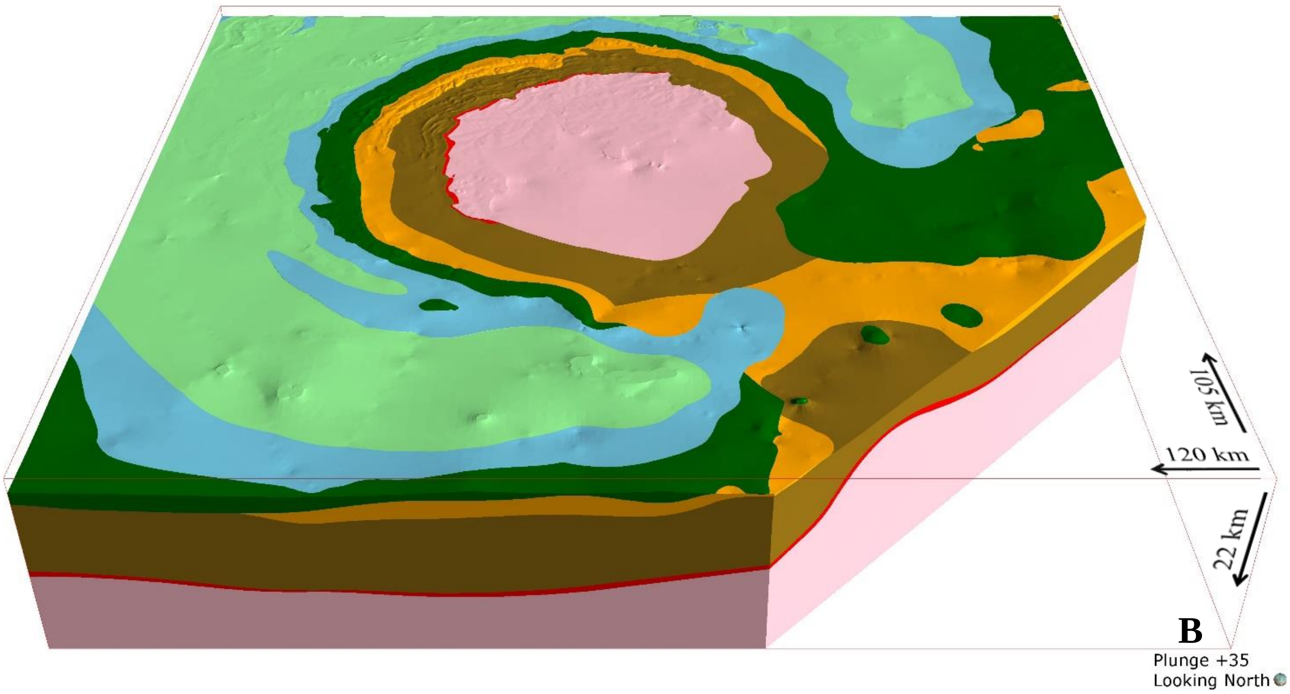
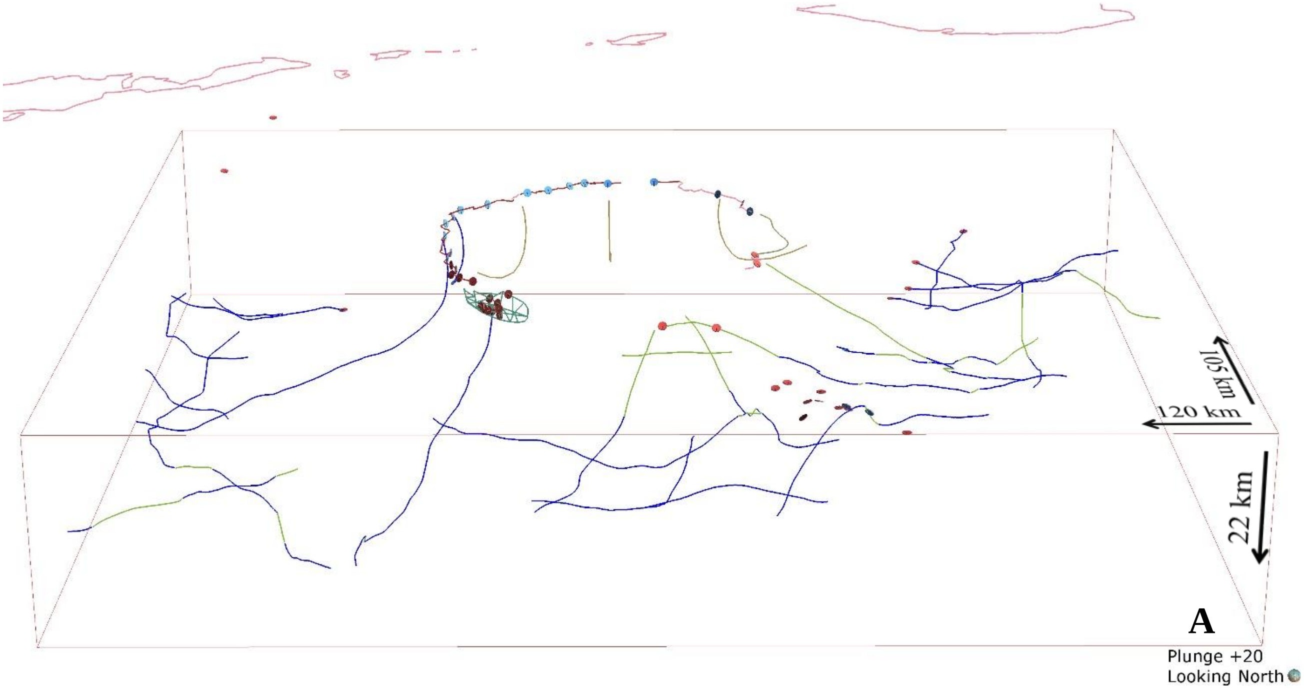


Figure 6.3.2 Eight modelled volumes. A) Model including the Phanerozoic/Karoo Supergroup cover. B) Model excluding the Phanerozoic/Karoo Supergroup cover. Colour Key: Yellow = Phanerozoic/Karoo Supergroup cover; light green = Pretoria Group; light blue = Chuniespoort Group; dark green = Ventersdorp Supergroup; orange = Central Rand Group; brown = West Rand Group; red = Dominion Group; pink = Basement.



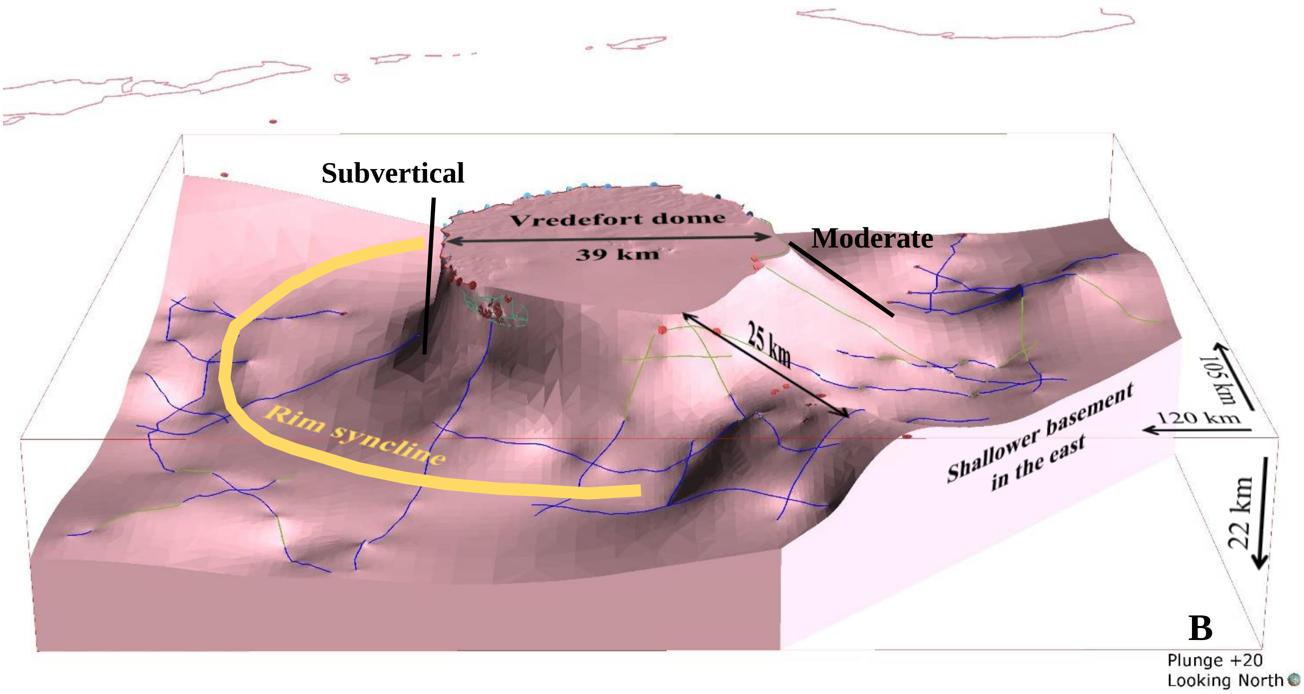
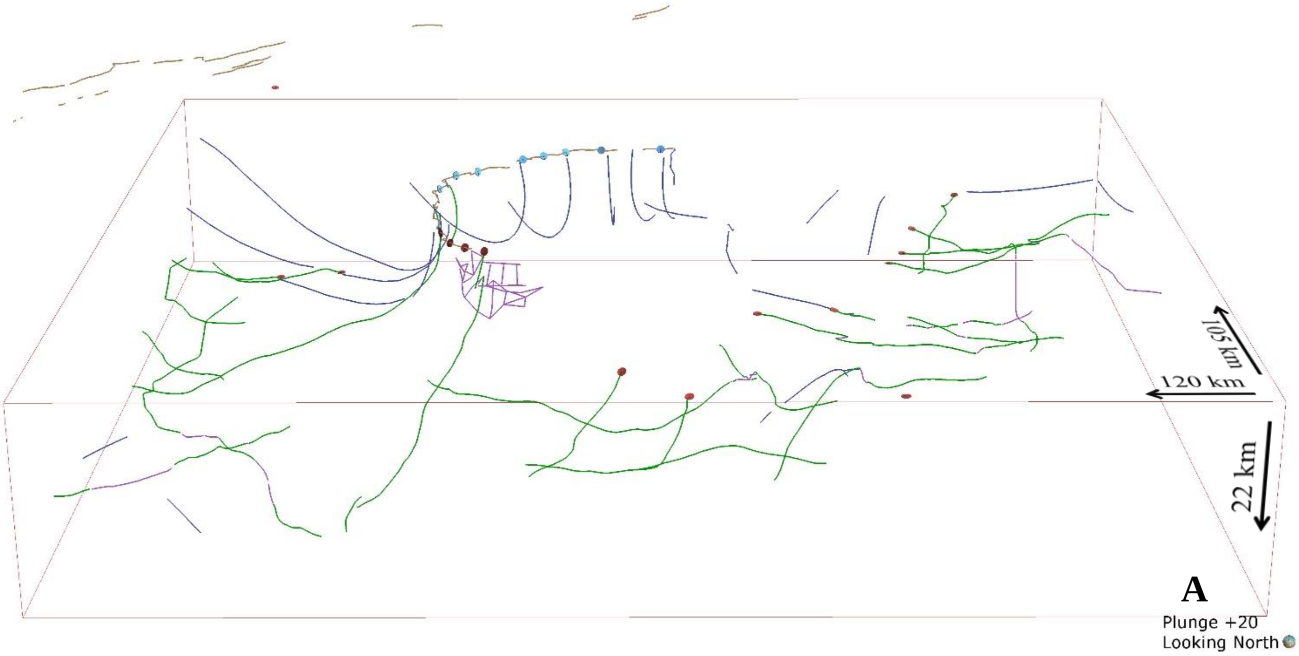


Figure 6.4.1 Model volume of the basement. A) Upper contact wireframes (lines and orientation disks). B) Interpolated volume. Green polylines represent the structure-defined contacts; blue polylines represent the unconformable lithological contacts; pink polylines represent the surface contacts; light brown polylines represent support wireframes.



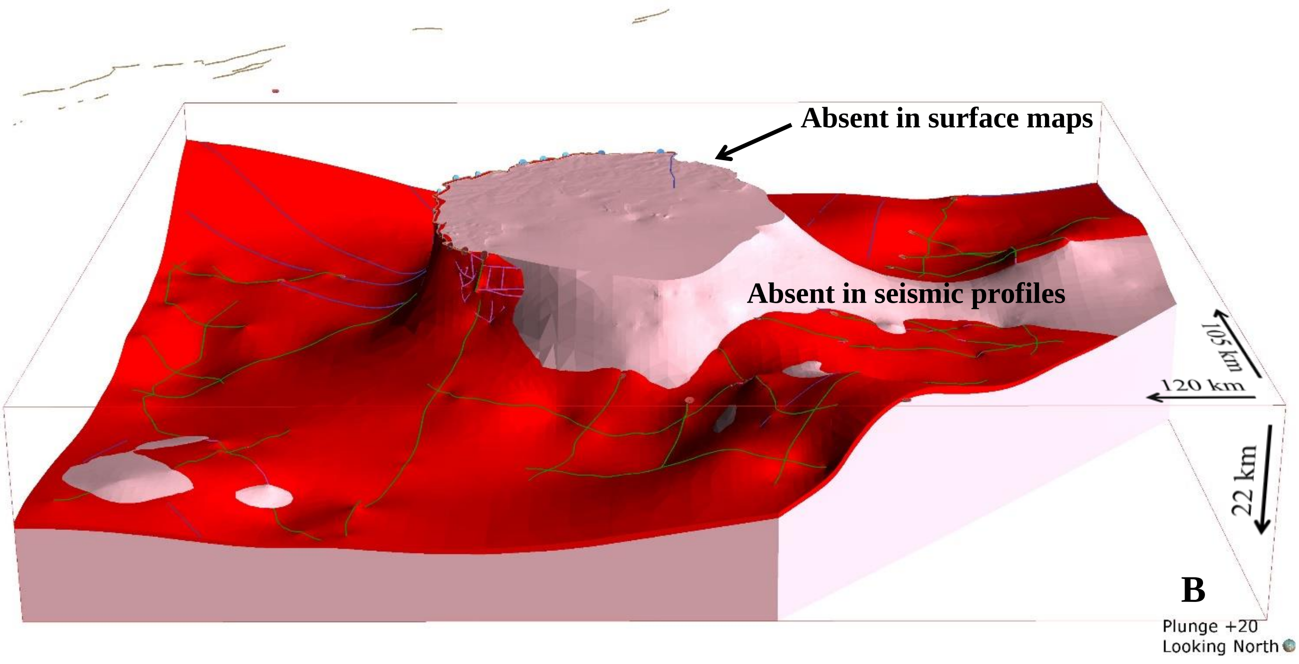
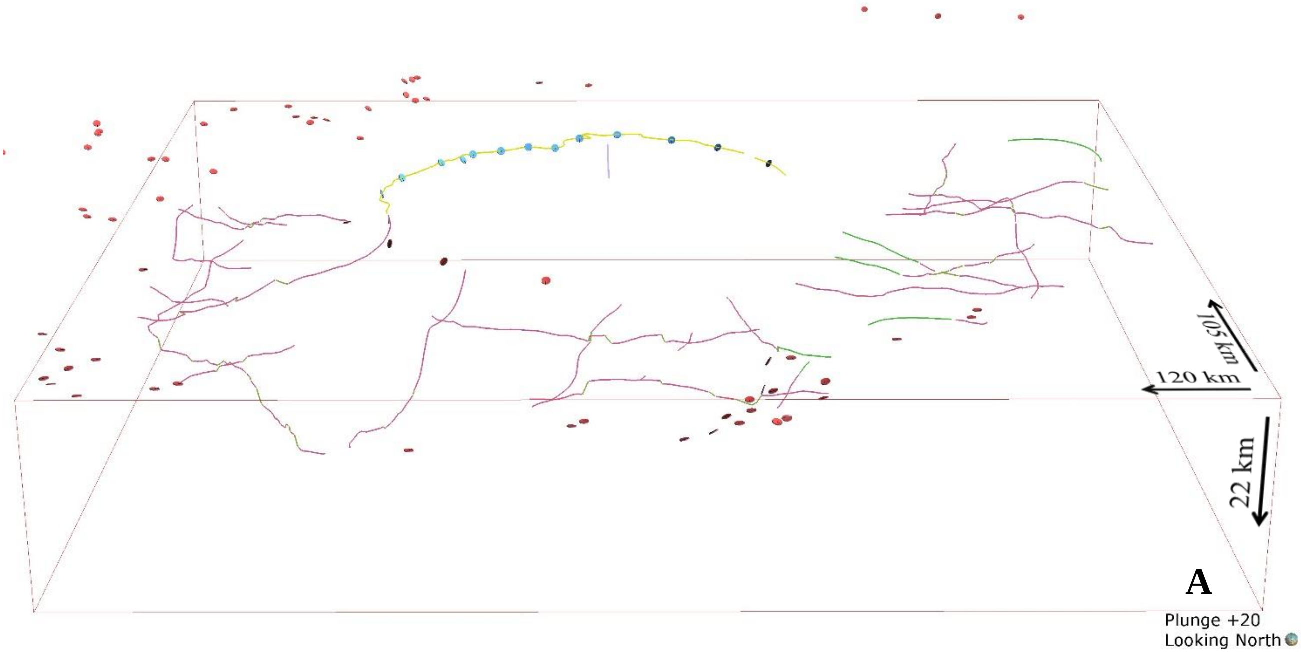


Figure 6.4.2 Modelled volume of the Dominion Group. A) Upper contact wireframes (lines and orientation disks). B) Interpolated volume. Purple polylines represent the structure-defined contacts; green polylines represent the unconformable lithological contacts; brown polylines represent the surface contacts; blue polylines represent support wireframes.



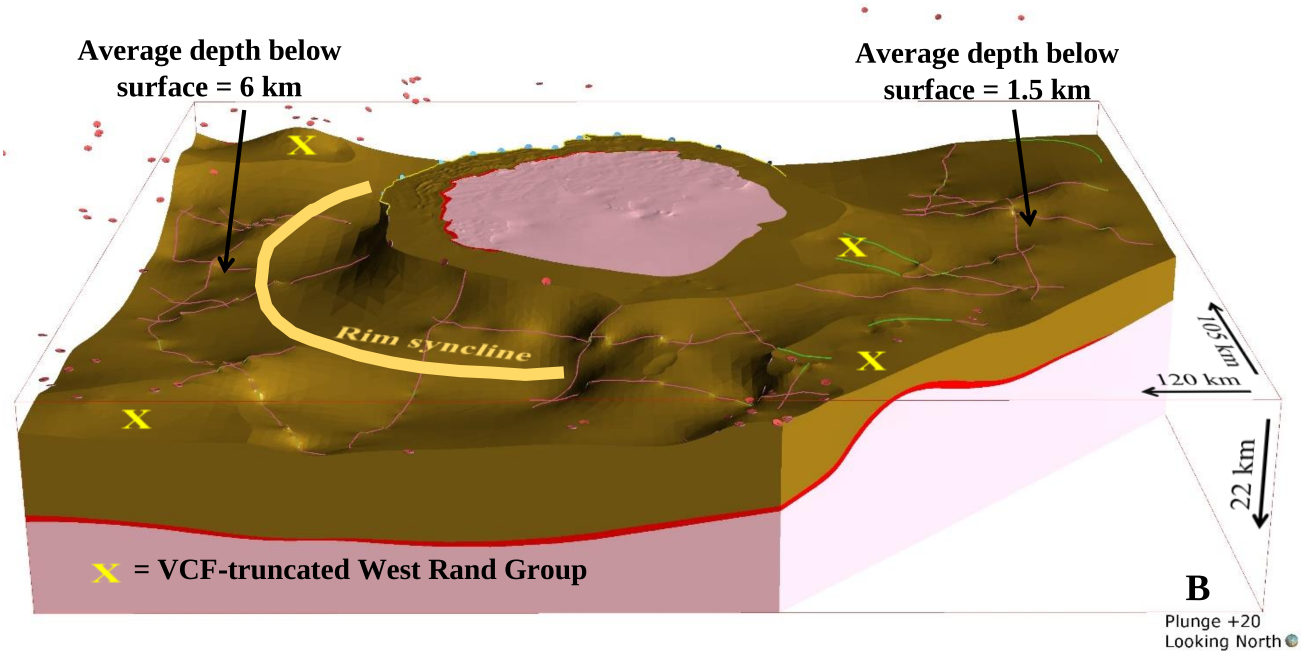


Figure 6.4.3 Modelled volume of the West Rand Group. A) Upper contact wireframes (lines and orientation disks). B) Interpolated volume. Pale green polylines represent the structure-defined contacts; purple polylines represent the unconformable lithological contacts; yellow polylines represent the surface contacts; dark green polylines represent pull-up support wireframes.

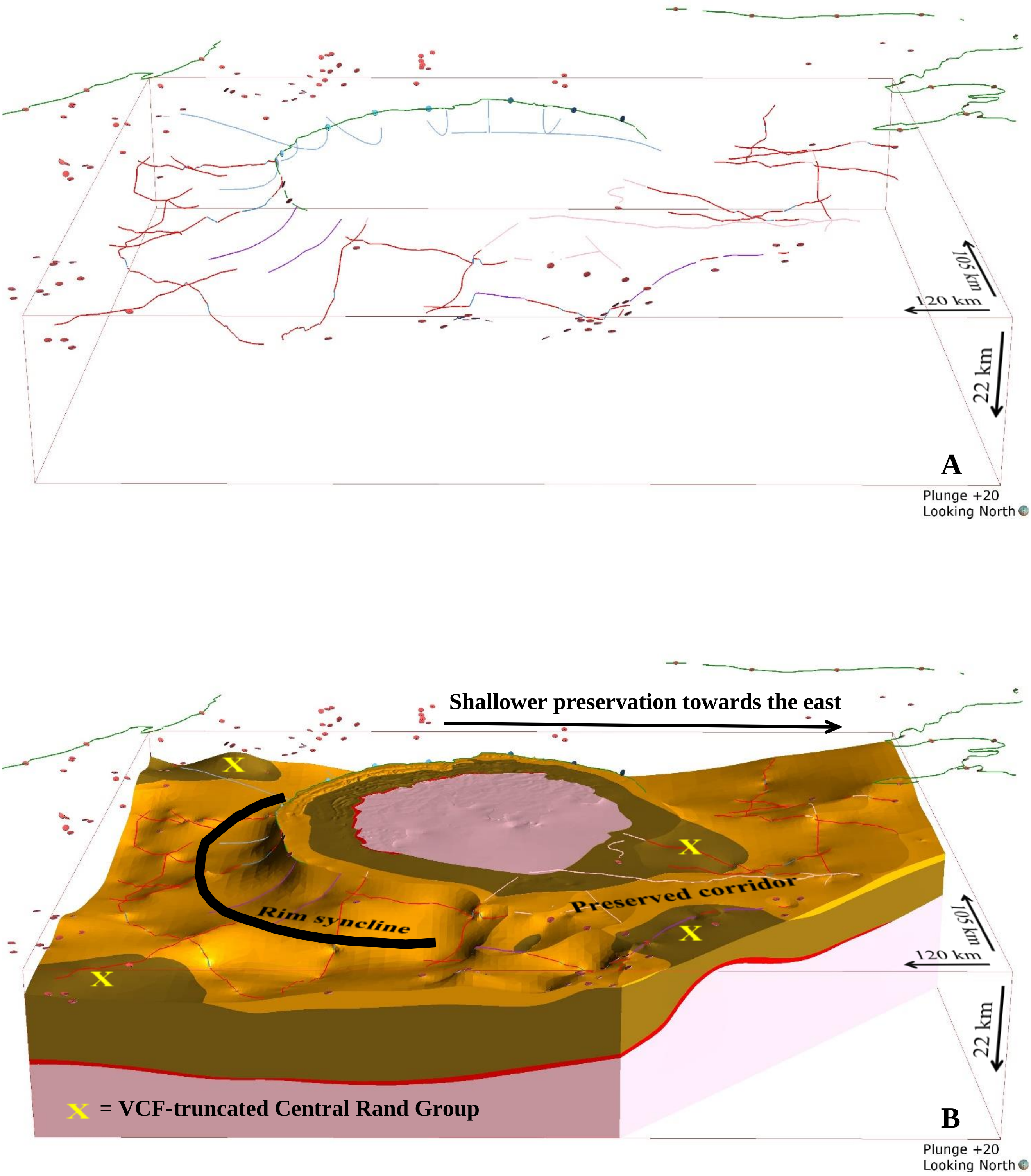


Figure 6.4.4 Modelled volume of the Central Rand Group. A) Upper contact wireframes (lines and orientation disks). B) Interpolated volume. Dark blue polylines represent the structure-defined contacts; red polylines represent the unconformable lithological contacts; green polylines represent the surface contacts; purple, pink and light blue polylines represent support wireframes.

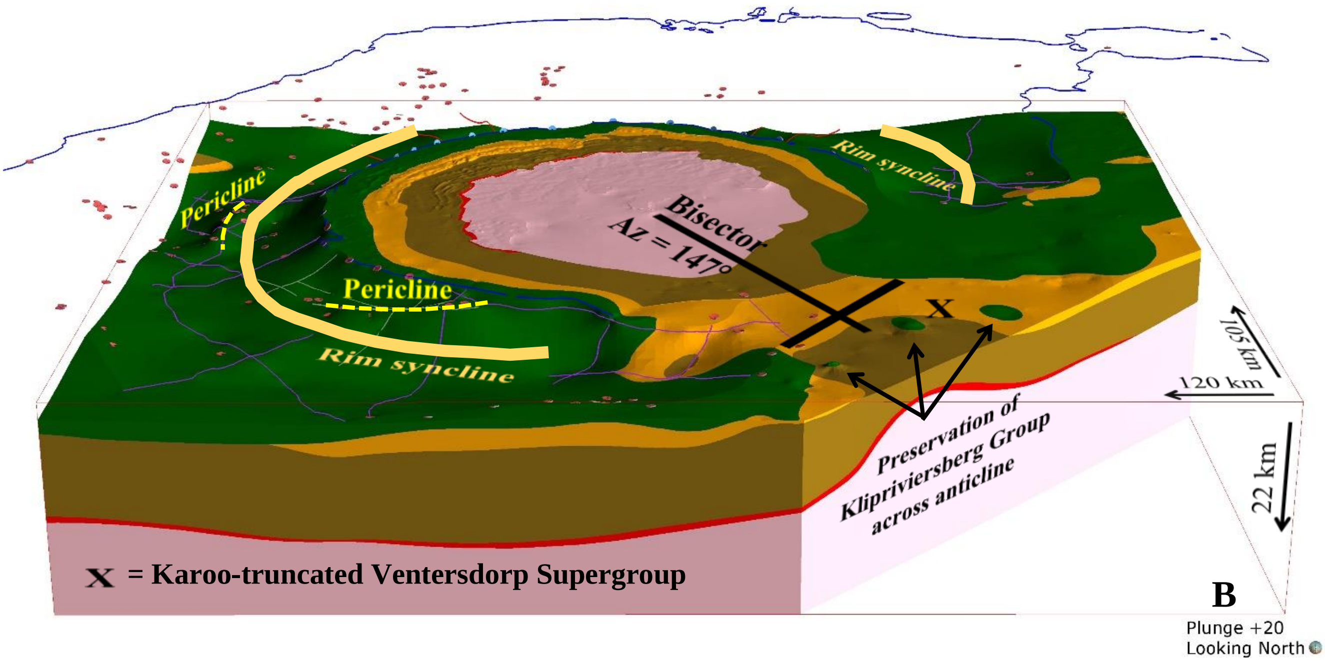


Figure 6.4.5 Modelled volume of the Ventersdorp Supergroup. A) Upper contact wireframes (lines and orientation disks). B) Interpolated volume. Purple polylines represent the unconformable lithological contacts; blue polylines represent the surface contacts; grey-green and red polylines represent support wireframes.

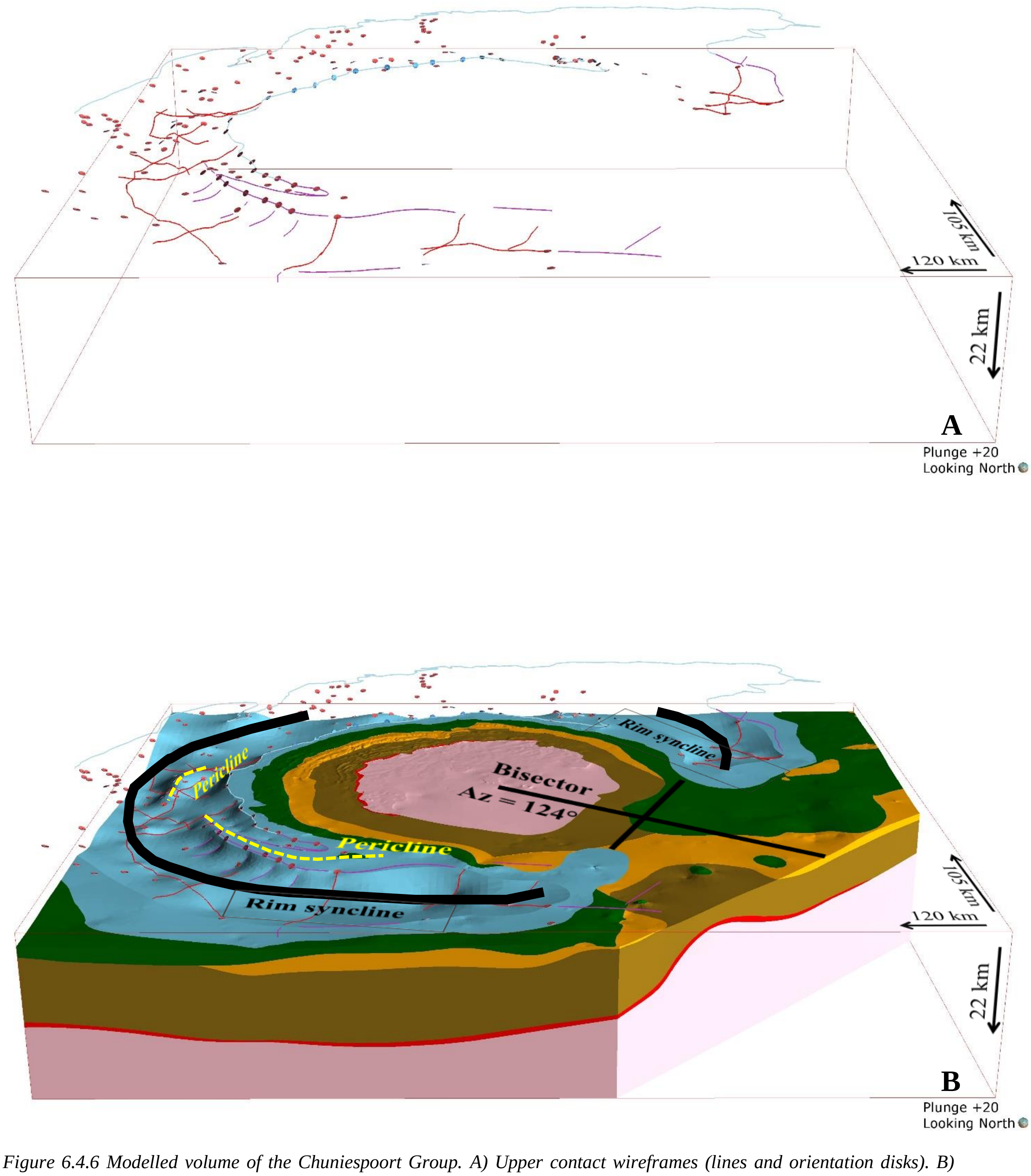


Figure 6.4.6 Modelled volume of the Chuniespoort Group. A) Upper contact wireframes (lines and orientation disks). B) Interpolated volume. Red polylines represent the unconformable lithological contacts; light blue polylines represent the surface contacts; purple polylines represent support wireframes.

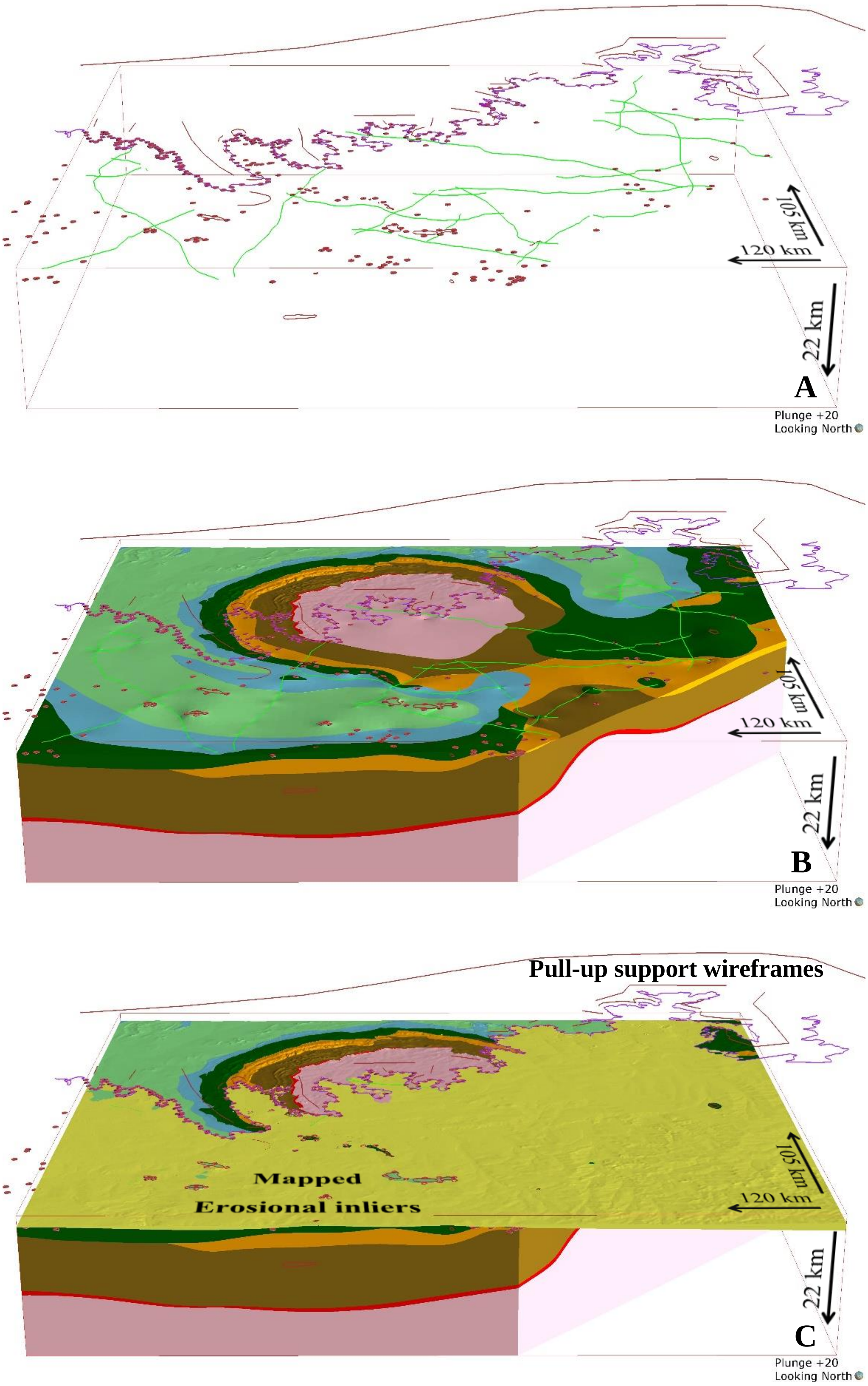


Figure 6.4.7 Modelled volumes of the Pretoria Group and Phanerozoic/Karoo Supergroup. A) Upper contact wireframes (lines and orientation disks). B) Pretoria Group interpolated volume. C) Phanerozoic/Karoo Supergroup interpolated volume. Green polylines represent the unconformable lithological contacts; purple polylines represent the surface contacts; red polylines represent support wireframes.

Chapter 7
Discussion

The stratigraphic column and geochronology for the study area is displayed in Figure A in the Appendix. The stratigraphy is divided into eight units, separated by seven major contact unconformities. The units were modelled in 3D space following the modelling framework described in Section 3. The final geological model is displayed in Figure 6.3.2.

This section presents a summary of the geological modelling, followed by comparisons between the results and published work. Three aspects of the modelling are discussed, i.e., (1) stratigraphic interpretation, (2) structural features, and (3) the Vredefort impact.

7.1. Summary

7.1.1. Stratigraphic interpretation

Several stratigraphic units are not preserved or are unlikely to be preserved in the study area (Section 4.3, and Table D in the Appendix). However the major stratigraphic units that define the eight modelled volumes are preserved. These include the Karoo, Transvaal, Ventersdorp, and Witwatersrand supergroups, as well as the Dominion Group and basement TTG suite.

The contact between the basement TTG suite and the Dominion Group is interpreted across the study area using the interface with the overlying units (Section 4.3; V_p and ρ values in Table C in the Appendix). The Dominion Group exhibits scattered, moderate amplitude reflections that form a semi-continuous 200 – 800m thick package across the seismic sections. The Group provides a reasonable estimate for the basement contact depth and its geometry. The relatively homogeneous TTG composition of the basement (Poujol et al., 2003) produces a seismically transparent package, enhancing the interface with the overlying supracrustal sequences.

The interface between the Dominion and West Rand groups was well imaged where the mafic – intermediate volcanic units of the Dominion Group are dominant. These volcanic units provided adequate V_p and ρ contrasts with the overlying sediments of the West Rand Group to produce a reflection at the interface. Domain 2 exhibited the strongest interface between the two groups, possibly due to the relatively shallower reflections as compared to Domains 1 and 3. The shallower reflections across all the seismic sections were better detected than the associated reflections at depth.

The West Rand Group above the Dominion Group was imaged as a thick package of closely-spaced, moderate to high-amplitude reflections. These reflections are produced due to the high variation in V_p and ρ of the rock types observed in the stratigraphy (Johnson et al., 2006). In seismic sections that exhibited strong internal reflections, the interface between the Government and Hospital Hill subgroups of the West Rand Group was inferred.

The interface between the West Rand and Central Rand groups is undulate and exhibits truncation of the West Rand Group. The undulate geometry suggests a period of erosion, producing an unconformable contact.

The Central Rand Group is characterised as a seismically transparent package throughout the study area. This is due to the comparable V_p and ρ of the quartzite and conglomerate units that make up the Group (Table C in the Appendix). The West Rand and Central Rand groups therefore exhibit contrasting seismic characters. This allows the interface between them to be delineated across the study area, despite the relative lack of borehole information in many parts. Unfortunately, the Booysens Formation of the Central Rand Group is poorly detected across the three domains; the shales of Kimberley Formation and the Bird Lava Member of the Krugersdorp Formation are not reported in boreholes or surface maps inside the study area.

A number of boreholes in the southeast of the study area did not provide stratigraphic details for the intersected lithologies. However, the contact between the Central Rand and West Rand groups was estimated using the thick successions of quartzite reported from borehole logs above alternating quartzite and shale units.

The VCF between the Central Rand Group and Ventersdorp Supergroup is prominent in the seismic sections. The Ventersdorp Supergroup is characterised as a seismically transparent package across most of the study area. Although both the Central Rand Group and Ventersdorp Supergroup are transparent the interface is detected due to the acoustic impedance contrast produced by the change in V_p and ρ across the contact between the two units (Table C in the Appendix). The VCF overlies the West Rand Group in four areas indicating exposure of the West Rand group by erosion prior or synchronous to deposition of the VCR. This conclusion is supported by adjacent borehole data.

The Black Reef Formation forms the base of the Transvaal Supergroup and is the most prominent interface of the seven that were delineated across the study area. The unconformity is detected due to the contrasting V_p and ρ across the interface, and is enhanced by the acute orientations of the reflections in the truncated units. In a few locations across the study area, the Ventersdorp Supergroup is truncated against the overlying Black Reef Formation indicating exposure of the Ventersdorp Supergroup by erosion prior or synchronous to deposition of the Black Reef Formation. However, the Supergroup is absent in a large area in the southeast because it is unconformably (angular unconformity) overlain by the Karoo Supergroup indicating significant erosion or removal of the supracrustal sequences prior to deposition of the Karoo Supergroup.

The Transvaal Supergroup is detected across most of the study area, exhibiting the thickest intervals in the western half. The Supergroup extends to the southern and eastern margins of the model, but is absent in the east-southeast. The thickness of the Chuniespoort Group (of the Transvaal Supergroup) is relatively consistent across all three domains, ranging between 800m and 1500m. The upper limit of the range in the boreholes is ~1900m, but the boreholes that record thicker intersections are all located outside the study area. Additionally, several boreholes report the Platberg Group unconformably overlying the Witwatersrand Supergroup, indicating that exposure and erosion took place prior to deposition of the Platberg group.

The Pretoria Group of the Transvaal Supergroup was best detected in the western half of the study area; it was either thin or absent in the eastern half. Additional outcrop inliers of the Pretoria Group in the Karoo Supergroup are exposed in the study area. These outcrops provide important constraints to the adjacent seismic sections.

The Karoo Supergroup is consistently imaged across its outcrop extents in the study area. The Supergroup is relatively thin with the deepest borehole intersection at 613.64m in the east of the study area and ~770m in the southeast from seismic sections. The Supergroup is reported as sub-horizontal in the 1:250,000 scale surface maps and this is supported by regional borehole data. The internal reflections of the Supergroup are also sub-horizontal, and the base interface is further enhanced in some parts due to the acute orientations of the truncated units below.

7.1.2. Structural features

The integration and interpretation of datasets in 3D space provided insight into the strato-tectonic architecture of the area surrounding the Vredefort dome. There are numerous model-scale strato-structural features that are interpreted in the seismic sections. These are illustrated in Figure 7.1.1 and are discussed below in chronological order. A summary of examples to these features is presented in Table 7.1.

Feature 1: A normal fault is observed in the modelled dataset and imaged in seismic section BH-268 in Domain 2 (Figure 5.2.18). It exhibits normal offset of reflections in the Dominion Group and the lower West Rand Group. It has an apparent throw of ~700m in the plane of the sections. The reflections in the lower West Rand Group are conformable across all three domains, i.e., there is no evidence of inclined reflections that terminate against distinct interfaces.

Feature 2: This feature relates to the interface between the West Rand and Central Rand groups. In some seismic sections the undulated erosional contact between the groups exhibits apparent normal offsets of 400 – 500m in the plane of the seismic sections. These are imaged in seismic sections OF-97 and OPR-50 (Figures 5.2.2 and 5.2.3, respectively). 3D projection of these faults reveal a strike of 032°and dips between 45° and 55°.

Feature 3: This feature relates to the VCF interface. The two areas in the east exhibit truncation of older units by the VCF. In the northwest and southwest of the modelled volume the boreholes report Platberg Group metasedimentary rocks unconformably overlying the Witwatersrand Supergroup; therefore the truncation is suggested to be younger and unrelated to the two in the east.

As described in Sections 6.4.4 and 6.4.5 the VCF truncates the Witwatersrand Supergroup (Figure 6.4.4B; seismic sections BH-171A and BH-171B; Figure 7.1.2). From these data, a listric fault with hangingwall rollover anticline can be delineated. However, the fault terminates against the base of the Karoo Supergroup, strongly supporting arguments that fault-fold formation took place prior to deposition of the Karoo Supergroup. The preservation of the Klipriviersberg Group either side of the fault cannot be used to constrain the timing unfortunately. The fault appears to be pre-VCF; however a rotational component to a post-VCF fault could also explain the similar elevations on either side.

Feature 4: This feature relates to the timing of the listric fault systems imaged in the study area. The most well developed system is delineated across several seismic sections in the southwest, as illustrated in Figure 7.1.3. The timing of these structures is constrained by offsets of reflections in the otherwise seismically transparent Ventersdorp Supergroup (seismic sections KV-117 and OB-74).

The faults offset the lower reflection in both seismic sections (labelled as displaced interface in Figure 7.1.3). The overlying reflection in seismic section OB-74 is continuous across the offset (labelled as continuous interface in Figure 7.1.3). The comparable, overlying reflection in seismic section KV-117 is also continuous, but is conformable with the fault orientation across the offset. It is suggested that the lower reflection represents the interface between the volcanics of the Klipriviersberg Group and the sediments of the unconformably overlying Kameeldoorns Formation.

The Goedgenoeg Formation is characterised by the introduction of volcanics that gradually cessed the sedimentary deposition of the Kameeldoorns Formation (Section 2.3). The change in V_p and ρ would produce a seismic reflection at the interface. Therefore the second reflection is suggested to represent the interface between the Kameeldoorns and Goedgenoeg formations. These observations suggest that the listric fault system is constrained as post-Klipriviersberg Group and pre to syn-Platberg Group, or extensional tectonics at that time, i.e., between ca. 2.7 Ga and ca. 2.64 Ga (Section 2).

Several other structures are interpreted to have formed during this period of extension tectonics, including:-

1. A low angle fault imaged near the basement interface (Figure 5.2.9) that may be associated with the truncation of the overlying units prior or synchronous to the deposition of the Platberg Group.
2. A smaller fault system imaged in the adjacent seismic section DE-512B. These structures are constrained to pre-Black Reef Formation due to the transparent internal reflections of the Ventersdorp Supergroup. However the close proximity of the section to the larger fault system suggests that it may be associated with it, as a marginal extent of the system. Figure 7.1.4 illustrates this proposed association, with the view aligned to the estimated strike of the imaged floor faults in each seismic section (i.e., 098°).
3. Additional listric faults imaged in the north of Domain 1 and Domain 2 (i.e., in sections OF-97 and OPR-50, and DV-274, respectively). Due to the transparent Ventersdorp Supergroup the timing of the faults in these sections can only be confined as post-VCF and pre-Black Reef

Formation. However, due to their similar structural forms they may associate with the same listric faults in the southwest, i.e., constrained as synchronous to deposition of the Platberg Group.

Feature 5: This feature relates to the interface of the Black Reef Formation. The interface is the most prominent in the seismic sections. It is enhanced by the changes in reflection orientations across the interface, between the overlying conformable units and the older acutely oriented units. As described in Section 6.4.5 the peneplation forms a truncation plane through the Ventersdorp Supergroup in a few places in the study area. Boreholes and the seismic sections imaged in the south and southeast indicate that the Black Reef Formation terminates against the Karoo Supergroup.

Feature 6: This feature relates to fold geometries in the Transvaal Supergroup. The folds are described in Section 5.2 as exhibiting gentle, long wavelength, low amplitude characteristics, and are imaged across all three domains. The youngest unit of the Transvaal Supergroup in the study area is the Magaliesberg Formation. The unit forms part of the folded sequence, therefore constraining the earliest timing of fold formation to post-Magaliesberg Formation, at 2193 ± 20 Ma (Bumby et al., 2012).

The folds are pronounced in the west, whereas a single large, asymmetric, gentle, first-order scale anticline is detected in the east in Domain 2. This fold is hereby named the Vaal Dam Anticline (VDA). The northern section of the Vaal Dam lies adjacent to the hinge zone of the anticline and is elongated along the strike of the fold axial plane (~230°). Seismic section DV-272 stops at the edge of this northern part of the Vaal Dam, with the hinge of the anticline located beneath it in the seismic section (Figure 5.2.12). The Ventersdorp Supergroup and Central Rand Group are exposed on the northern margin of the Vaal Dam, coinciding with the uplift by the anticline.

Although the folds exhibit different wavelengths and amplitudes, they have corresponding subvertical axial planes, with smaller folds representing parasitic folds to the main anticline (Figure 7.1.5). The hinge zone of the VDA in Domain 2 is truncated against the Black Reef Formation, suggesting exposure and erosion prior to deposition of that Formation. However, the Formation and the overlying Chuniespoort and Pretoria groups are uplifted towards the hinge as well, constraining the earliest timing of the fold formation to late or post-Pretoria Group.

Feature 7: The VDA in Domain 2 is crosscut by a listric fault that exhibits a rollover anticline in the downthrown hangingwall (seismic section DV-270A, Figure 5.2.15). It is suggested that listric fault development took place after the folding event described above.

Listric faults of comparable scale were imaged elsewhere in Domains 2 and 3 (Figure 7.1.6 displays the faults imaged in the seismic sections). The 3D projection of these faults forms a fault plane that extends at least 65km from the southern margin of the dome to the eastern boundary of the modelled volume.

The faults in the seismic sections preserve their listric shapes and crosscut units that lie both on the margins of the dome as well as away from the dome, on the VDA. The preservation of geometry suggests that the listric fault is reasonably undeformed by the central uplift formation. However, the reflections on the margins of the dome are not as clearly defined as the reflections across the VDA. Therefore exact crosscutting relationships and interface geometries are relatively unconstrained on the margin of the dome.

The listric fault plane trends approximately 090° over the intersection with the VDA (oblique to the 050° trend of the axial plane of the VDA). Therefore the fault is unlikely to be directly associated with the fold formation. The fault orientation changes towards the dome and trends along the margin of the dome. These orientations indicate that both the dome and the VDA define the fault orientation. It is suggested that the listric fault may be associated with the impact. The listric fault may have formed part of the central uplift formation, possibly as a late-stage collapse. The local crosscutting relationships and timing of the collapse, as either late or post-central uplift formation, requires more detailed work, possibly via borehole analysis and more refined impact simulation modelling.

According to Reimold and Koeberl (2014), 5 – 8km of the original crater has been eroded, highlighting the degree of exhumation over time since the impact. The Karoo Supergroup was deposited over the exhumed and eroded crater remnant. The Supergroup in this area was covered in parts by Quaternary sedimentation.

7.1.3. The Vredefort impact event

The deformation related to the Vredefort impact event is the dominant feature in the study area. However, it is important to define the pre-existing structural architecture in order to properly analyse impact-related deformation around the dome, particularly in the unexposed southeast. Several structural features have been presented in Section 7.1.2, and Figure 7.1.7 displays the 3D geological model highlighting the various axial traces of the folds modelled around the dome. The most prominent is the rim syncline surrounding the central uplift and core of the dome.

The concentric, asymmetric rim syncline was described by Reimold and Koeberl (2014) and reproduced in simulation modelling by Ivanov (2005). It is generally known as the Potchefstroom syncline. According to the modelled volumes in this study, the syncline is preserved entirely around the dome except in the southeast.

As described above, the hinge of a VDA in Domain 2 trends 050°. Prior to the impact, the fold hinge would have extended towards ~230° from its location in Domain 2, therefore preserving a northeast-southwest trending fold axis across the study area. The absence of the rim syncline in the southeast of the dome may be the result of the fold interference between the syncline and VDA (Figure 7.1.8). Numerical modelling of these interference patterns will be needed in order to properly test this mechanism.

In respect of the periclinal folds, a more descriptive term is proposed here. Stauffer (1988) defined the term ‘coaptation fold’ as, “The bend in a rock layer formed at the junction of two oblique, intersecting folds purely as a geometric consequence of the fitting together of the fold forms”. Lisle et al. (1990) further refined coaptation folds stating that they “…are to be expected in situations where the folding process approaches that of isometric bending, i.e. during the buckling of thin layers of relatively high competency and during flexural slip folding”. Lisle et al. (1990) further added that coaptation folds are, “topologically-necessary crumples on the flanks of domes and basins, rather than ‘bends at the intersection of two oblique intersecting folds’ and should be known as curvature-accommodation folds”.

In relation to the Vredefort dome, the rim syncline exhibits isometric bending, as illustrated in the simulation modelling of Ivanov (2005). However the rim syncline is related to an impact, not diapirism and doming, so cannot be classified together with ‘normal’ curvature-accommodation folds. On the crustal scale, the “thin layers of relatively high competency” defined by Lisle et al. (1990) could be represented by the relatively thin quartzite units preserved throughout the supracrustal package. According to Simpson (1978) “flexural slip folding” of the shale units exists in the rim syncline, further supporting the definition of curvature-accommodation folds. It is proposed that the geometry formed by the central uplift is a modified version, or sub-order, of curvature-accommodation folds, and is here termed simply as ‘impact-type curvature-accommodation’ folds.

Seismic section FV-155 bisects the central uplift on the western margin of the dome (Figure 5.2.7). Due to the proximity to the dome, the orientation of the interfaces and imaged structures are suggested to be largely associated with the central uplift formation. Part of the process of the central uplift formation includes crustal rebound of the initial transient crater followed by gravitational collapse (Ivanov, 2005; Reimold and Koeberl, 2014; Jahn and Riller, 2015). Several aspects of the interpreted section correspond with published observations, as follows:-

1. Following the transient crater formation the crustal rebound resulted in the uplift of the basement and supracrustal sequences from beneath the vaporised zone of the impact site (see Fig. 14 of Ivanov, 2005). The upward movement during the rebound would have caused intense flexure of the supracrustal sequences as they were elevated towards the surface from depth. The sequences in the deep crustal levels located in the outer arc of the synformal hinge zone of the uplift would have experienced extension and detachment as the asymmetric synformal architecture was being formed. Reimold and Hoffmann (2016) argued that voluminous pseudotachylite breccias were formed by decompression melting during the rebound phase, followed by transport into dilational sites during the gravitational collapse phase. The West Rand Group in seismic section FV-155 exhibits detached internal reflections, separated by expansive and interconnected seismically transparent zones. It is suggested that this part of the outer synformal arc may have preserved large areas of this decompression process as the stresses from the gravitational collapse phase were concentrated in the higher levels of the central uplift.

2. Anastomosing structures were delineated adjacent to the inner arc of the synformal hinge. The anastomosing interfaces differ from the intrusive interfaces as they were detected using narrow, low amplitude, distorted/stippled internal reflections in the Central Rand Group. These anastomosing structures are suggested to be associated with the down and outward collapsing phase of the central uplift following the initial rebound phase, described by Jahn and Riller (2015).
3. The gravitational collapse of the collar rocks outwards from the dome is proposed by Jahn and Riller (2015) to have led to duplication and thickening of the collar. It is suggested that the discrepancies observed between the depth extents and the surface widths in seismic section FV-155 are associated with this duplication and thickening of the collar. This section is located in an area where the collar rocks are subvertical. The section is perpendicular to strike, and the margin of the section is perpendicular to the subhorizontal orientations of the imaged units. Therefore unit widths in the section are representative of the true thickness.
4. The Central Rand Group and Ventersdorp Supergroup exhibit vertical losses of ~3000m and ~1700m, respectively. In contrast, the West Rand Group exhibits a vertical thickening of ~1600m (illustrated in Figure 7.1.9). Considering the published V_p values of the imaged units the discrepancies in the measured widths are interpreted as being unrelated to the velocity fields used for migration and Time-Depth conversion. This is because they are too large to be accounted for by the variability in the velocity fields. For instance, for an artificial discrepancy no duplication or thickening can be involved and the width of the outcrop must match the width of the imaged units at depth. However, an additional 12 seconds of two-way-travel-time is then required to make up the ~3000m vertical loss imaged in the Central Rand Group (using the V_p values in Table C in the Appendix). The recorded length of the survey is not 12 seconds longer than adjacent seismic sections (all are six second record lengths). Therefore only the V_p can be altered; however to produce the 2.875x reduction in thickness at depth compared to the outcrop, the V_p for the Central Rand Group would need to be substantially increased. The collapse-induced radial fault formation described by Jahn and Riller (2015) as the mechanism for the thickening would account for the vertical losses in the two imaged units. The V_p for the West Rand Group would need to be increased to ~6500 m/s in order for the vertical thickness to be reduced by the ~1600m discrepancy calculated between the outcrop width and the depth extent. This value is far higher than the published velocities for any of the quartzite or shale units imaged in the study area (Table C in the Appendix). Jahn and Riller (2015) described a change in radial faults to concentric, listric orientations towards the dome core that limited the magnitude of thickening during the collapse phases. This may account for the vertical thickening of the West Rand Group.

7.2. Comparison with Published Work

7.2.1. Stratigraphic interpretation

The units delineated in the study area correspond well with surface mapping and borehole information. The overall stratigraphy accords with published work (including Johnson et al, 2006; Dankert and Hein, 2010; Manzi et al., 2013; Frimmel, 2014). The Dominion Group is imaged as a narrow unit and exhibits scattered, moderate amplitude internal reflections in accordance with the arc basin and associated rifting environments described by Crow and Condie (1987), Clendenin (1988) and Frimmel (2014).

The West Rand Group is defined by a thick package of closely-spaced, moderate to high-amplitude reflections. These sequences in the seismic sections correspond with the various depositional environments and disconformities described by Johnson et al. (2006). The Asazi Event at ca. 2.9 Ga of Manzi et al. (2013) described the termination of deposition of the West Rand Group by uplift, tilting and erosion. This contact morphology is delineated across the study area with several offsets on the erosional, undulating interface. The syn-tectonic alluvial braid-plain dominated sedimentation of the Central Rand Group under a collisional regime is hypothesised by Johnson et al. (2006), Dankert and Hein (2010), and Frimmel (2014), amongst others. The majority of the Group could not be detected in the seismic sections due to the dominance of quartzite and conglomerate units (similar V_p and ρ). The low contrasting compositions throughout the Group produced a seismically transparent package.

The degradation of, and incision into the Witwatersrand Supergroup during the VCF deposition, was described by Johnson et al. (2006) and others. The incision forms an unconformity that was imaged in the seismic sections. Age constraints published by Kositcin et al. (2003) and Kositcin and Krapež (2004) support the concept of a stratigraphic hiatus and confined the formation of the unconformity to 120 million years after the deposition of the Central Rand Group.

The majority of the Ventersdorp Supergroup imaged in the seismic sections was characterised as a seismically transparent package. A few sections presented one or more good reflections that were assigned as the contact between the volcanics of the Klipriviersberg Group and the overlying volcano-sedimentary sequences of the Platberg Group. These interfaces are supported by the literature (Pretorius et al., 1987; Armstrong et al., 1991; Weder, 1994; De Wet and Hall, 1994; Johnson et al., 2006; Dankert and Hein, 2010; Manzi et al., 2013).

The Black Reef Formation in the seismic sections unconformably overlies the Witwatersrand and Ventersdorp supergroups, supporting the contact relationships defined in published work (e.g. Martin et al., 1998; Johnson et al., 2006; Sumner and Beukes, 2006; Manzi et al., 2013). The overlying Chuniespoort and Pretoria groups were detected in the seismic sections. The internal reflections of each Group coincide with stratigraphic relationships described by Pretorius et al. (1987), Weder (1994), Johnson et al. (2006), Dankert and Hein (2010), and Manzi et al. (2013).

The ~1.7 billion year hiatus between the Transvaal Supergroup and the Karoo Supergroup defines a major unconformity. This interface is imaged in seismic sections near the surface, and extends across half of the study area. The strong, contiguous internal reflections corresponds with the published V_p and ρ values (Pretorius et al., 1987; Weder, 1994; De Wet and Hall, 1994). The distribution of the Karoo Supergroup in the seismic sections also corresponds with surface mapping and borehole information, where stratigraphic relationships concur with Catuneanu et al. (2005) and Johnson et al. (2006), amongst others.

7.2.2. Structural features

Several publications present structural features and deformation events that are relevant to the study area. These include interpretations of seismic sections (Friese et al., 1995; Tinker et al., 2002), and tectonic evolution in the study area (Friese et al., 1995; Henkel and Reimold, 1998; Johnson et al., 2006; Dankert and Hein, 2010; Manzi et al., 2013; Frimmel, 2014), including the late to post-Transvaal Supergroup folding event (Alexandre et al., 2006; Dankert and Hein, 2010). In consideration of the published tectonic evolution of the study area, and following the comparisons with this study, a combined tectonic history is presented in Figure 7.2.1.

In terms of published seismic section interpretations, Tinker et al. (2002) presented an interpretation for the crosscutting seismic sections KV-117, OB-41, and OB-74 (termed by them as a single section, "OB"). Figure 7.2.2 displays the interpretations from this study and the published version. The interpretation of Tinker et al. (2002) relied upon a single borehole, labelled "A" in the publication, and an intersecting seismic section, termed "AG", as depth constraints. Borehole "A" and section "AG" are not part of the dataset in this study. For reference seismic section KV-120 intersects section OB-41 adjacent to the collar position of borehole "A".

The published borehole coincides very well with the imaged units in seismic sections KV-120, OB-41, and OB-74. The interfaces concur and the structural features are similar in both interpretations, i.e., preservation of a large horst preserved between sets of normal faults. In the area adjacent to borehole "A" Tinker et al. (2002) proposed long wavelength folds that post-date the deposition of the Hekpoort Formation. These folds coincide with the interpretations of folding presented in this study.

In comparison, the interpretation by Tinker et al. (2002) exhibits vertical exaggeration, and slight differences in the imaged depths of some interfaces. The relatively large offsets imaged adjacent to the horst block correspond with the interpretation in this study, albeit to a slightly greater vertical exaggeration in the publication. The offsets imaged in the north-northeast part of the published interpretation are very small; therefore exhibit greater subjectivity than what was accepted for this study. However the general uplift towards the horst structure is preserved in both interpretations. Overall, these two sections exhibit similar structural regimes, i.e., listric faults developed post-emplacement of the Klipriviersberg Group, peneplation during the Black Reef Formation, and post-Hekpoort Formation folding.

Several 2D reflection seismic and gravity sections were reinterpreted by Friese et al. (1995) who produced a map of the Witwatersrand basin superimposed with various structures. The interpretation includes a series of thrust faults that dominate the unexposed southeast. However, these thrusts were not imaged in the seismic sections (Figure 7.2.3). Moreover, the seismic sections do not exhibit reverse fault offsets. Instead the structural features described above provide adequate explanation to the observed preservation in the southeast. It is suggested that if the thrust faults do exist, they contain offsets that were too small to be imaged with confidence in this study.

In comparison to the structural features discussed in Section 7.1.2, the interpretations concur with the literature presented in Section 2, as well as several published tectonic events (including Johnson et al., 2006; Alexandre et al., 2006; Dankert and Hein, 2010; Manzi et al., 2013; Frimmel, 2014). The interpretation of a tectonic event after the deposition of the West Rand group and prior to deposition of the central group (the Asazi Event of Manzi et al., 2013) is supported in the study area. This was because many seismic sections exhibited an undulate, erosional interface between the West Rand and Central Rand groups. The interface also includes several localised fault offsets, with the possibility that smaller scale offsets are more frequent, but were too small to be delineated confidently.

Collisional tectonics reported by Johnson et al. (2006), Dankert and Hein (2010), and Frimmel (2014) and others, describe the closure of the Central Rand Group basin associated with folding, faulting, and uplift on the margins, particularly in the west, northwest, and north. This tectonic event is termed the Umzawami Event by Dankert and Hein (2010). Unfortunately, such structures were not imaged through the seismically transparent package of the Central Rand Group. The preservation of thrust offsets synchronous to the deposition of the Central Rand Group may have existed in the study area and exhibited offsets that were too small in scale to be imaged confidently.

A well-developed listric fault system was imaged across the study area. The system is constrained as synchronous to the deposition of the Platberg Group and extension during the Hlukana-Platberg event of Manzi et al. (2013).

The Transvaal Supergroup contains two fold systems in the seismic sections, as discussed previously. One system is associated with the Vredefort impact, the other is associated with a late to post-Transvaal Supergroup fold event. Dankert and Hein (2010) proposed the formation of a late to post-Transvaal Supergroup fold-thrust belt they named the Ukubambana Event, which they tentatively dated at ca. 2.2 – 2.0 Ga. Alexandre et al. (2006) provide further refinements to the timing of the fold-thrust belt. Their geochronological $^{40}Ar/^{39}Ar$ dates for syn-kinematic white micas in phyllites placed a deformation event at 2042.1 ± 2.9 Ma. They named the deformation the Transvaalide fold-thrust belt. A second, less well-defined date was also found, referring to an older event at ca. 2150 Ma. The better constrained fold event at 2042.1 ± 2.9 Ma is proposed as being associated with the late to post-Transvaal Supergroup fold event in this study. It is further proposed that the Ukubambana and Transvaalide fold-thrust belts are the same deformation.

7.2.3. The Vredefort impact event

The Vredefort impact has been discussed in Section 7.1.3 and the central uplift formation was described in terms of numerical modelling by Ivanov (2005). The regional emplacement and architecture is described by Reimold and Koeberl (2014), and the central uplift formation kinematics is described by Jahn and Riller (2015). For comparison with the simulation modelling of Ivanov (2005) the geological model produced in this study is overlain with Figure 13 and Figure 15B of the publication. The two published figures illustrate cross-sectional views of the central uplift formation. The two overlays are displayed in Figure 7.2.4 and Figure 7.2.5.

Figure 13 of Ivanov (2005) is overlain in Figure 7.2.4 and illustrates the formation of the central uplift 400 seconds after the impact. The deformation displays reasonable correspondence with the preserved units in the geological model. Note though that the northern extent of the geological model is only inferred and not constrained by seismic data (i.e., left side of Figure 7.2.4C and Figure 7.2.5C).

The largest difference between the simulation and the geological model was the asymmetry of the central uplift geometry. The eastern and southern extents of the geological model exhibited upright and shallow dipping units. The simulation modelling of Ivanov (2005) assumed consistent basement and supracrustal elevations. Therefore the pre-existing basement topography was not accounted for in the simulation. The subsequent partial collapse of the central uplift on the southeast margin proposed in this study was also not produced by the simulation.

An additional discrepancy illustrated in the overlays is the variation in horizontal diameters between the simulated and observed dome core. Measured from east to west, the core is ~7km wider in the simulation (Figure 7.2.5B). Measured from north to south, the core is ~3km wider in the simulation (Figure 7.2.5C). The wider simulations have therefore slightly overestimated the diameter of the core and collar rocks by ~15% on the west-east section and ~6% on the north-south section. The numerical simulation assumed that the present erosion surface was 7 – 9km below the original surface. However, a vertical shift of the estimated erosion level would not compensate for the measured discrepancies because the intersection of the geological model is already located at the level of the narrowest part of the dome in the simulation.

The rim syncline and interference with the pre-existing folds is discussed in Section 7.1.3. The proposed interference mechanism might explain the absence of the rim syncline in the southeast. However, the interference proposes a new mechanism that does not concur with earlier work by Friese et al. (1995) and Henkel and Reimold (1998).

The review of African impact structures by Reimold and Koeberl (2014) included the seismic interpretation of Friese et al. (1995) and the gravity interpretation of Henkel and Reimold (1998). To account for the central uplift asymmetry Reimold and Koeberl (2014) also proposed tilting between 3° and 30° towards the northwest prior to the impact event. The seismic interpretations by Friese et al. (1995) are discussed in Section 7.2.2, and the relative prominence of the thrust faults is put into question by the uplifts, including the anticlinal fold and the listric faults. These overshadowed the small-scale offsets of the proposed thrusts, at least in the southeast.

The absence of listric faults in the interpretations led Henkel and Reimold (1998) to suggest that the thrust faults were solely responsible for the apparent shortening and uplift of the southeast margin. They estimated the shortening to be in the order of 65km, associating the large displacement with Namaqua-Natal orogenic activity (ca. 1 – 1.2 Ga). The findings in this study do not support these published interpretations that characterise thrusting as the dominant deformation.

The gravity section presented in Reimold and Koeberl (2014) was modified after Henkel and Reimold (1998), but is referred to here because the online version of the later publication was of very poor quality copy. The gravity section exhibits an elevated basement in the southeast. This concurs with the interpretation in this study, albeit with a different explanation given by the authors. It was also not necessary to invoke tilting prior to the impact, as the interference between the VDA during the central uplift formation, discussed previously, may account for the sub-planar orientations. However, this hypothesis requires further numerical simulation or mechanical testing.

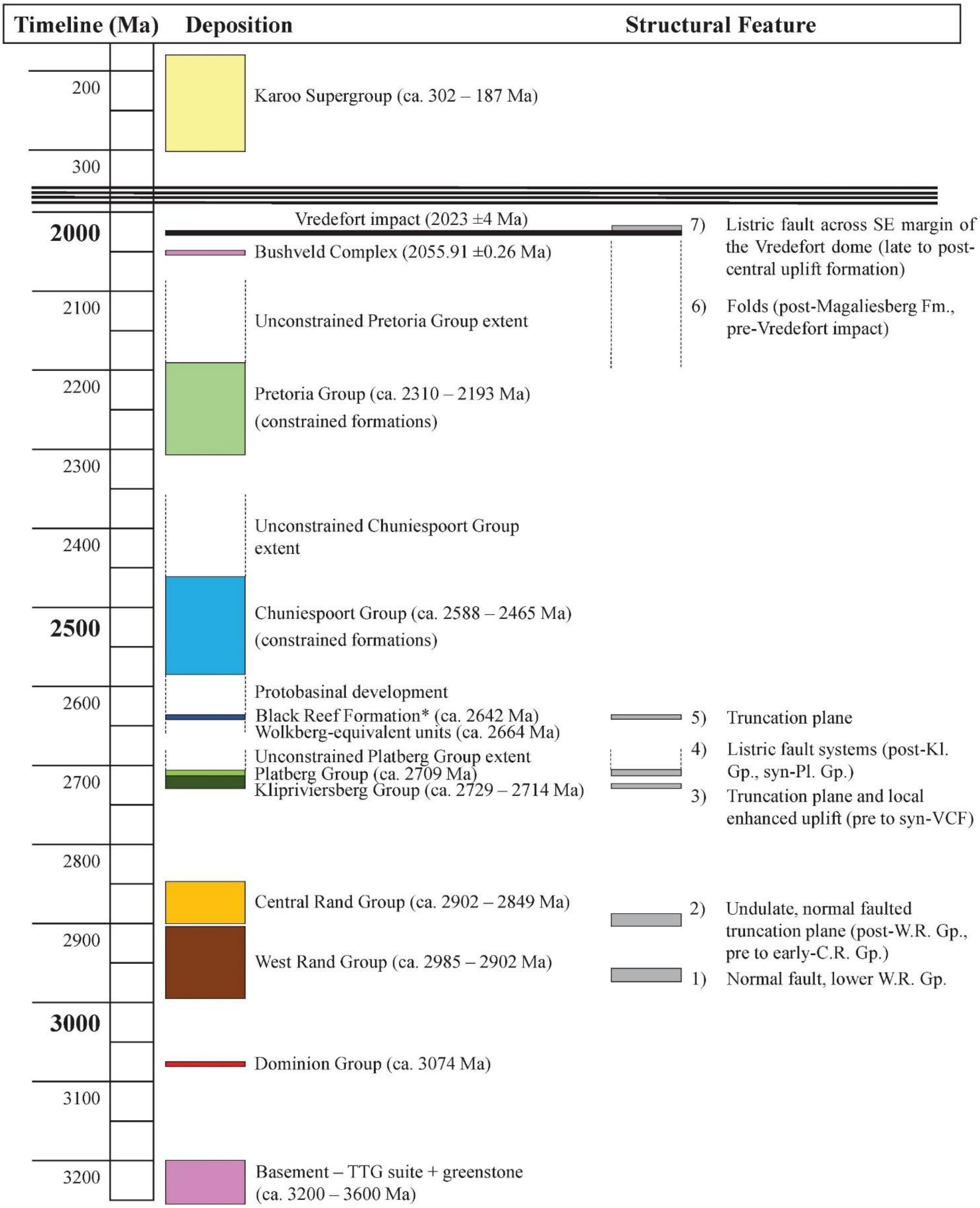
A brief note must be made here regarding the profile interpretation of seismic section FV-154 (Figure 7.2.17.2B). The mantle “spur” interpreted below the centre of the Vredefort dome is only speculative. It is unconstrained by the poorly resolved reflections in this part of the profile. It was an attempt to explain the “bulls-eye” high gravity anomaly observed over the centre of the dome, i.e., introduction of higher density upper mantle material. This speculative interpretation differs from Ivanov (2005) whose model produces a flat Moho instead.

7.3. Synthesis of work

The integration of large borehole, mapping, and geophysical datasets into a single 3D workspace has shown that both regional and local scale stratigraphic and structural relationships can be seamlessly observed and analysed. In the study area, several extracted features of the interpreted dataset provides support to published work, such as the Asazi Event, Hlukana-Platberg Event, and Ukubambana/Transvaalide Event (Alexandre et al., 2006; Dankert and Hein, 2010; Manzi et al., 2013). The results were integrated with published information about the strato-tectonic history of the Witwatersrand basin, and are illustrated together in Figure 7.2.1. Some limitations of the dataset such as seismic section quality and the seismically transparent units restricted the interpretation of structural features related to some tectonic events, such as the Umzawami fold-thrust belt of Dankert and Hein (2010).

As with all geological models, the degree of subjectivity is associated with the availability of constraining data. A limiting factor in this study was a combination of the large area (~11600 km^2), relatively widely-spaced 2D reflection seismic lines, and comparatively few boreholes (208 boreholes). As presented in Section 6, the modelled contacts had to be supported by additional wireframes to fill in the gaps between the constraining data. These limitations restricted the 3D geometric relationships required to constraint specific deformation events.

There were a few variations between the findings in this study and published works. The variations, in particular, were with regard to the southeast margin of the Vredefort dome. Previous researchers interpreted the southeast margin as a series of northeast – southwest trending normal faults (Pretorius et al., 1986), or northwest-directed Mesoproterozoic compression and thrust fault development followed by later tilting (Friese et al., 1995, and adopted by later researchers such as Henkel and Reimold, 1998, Reimold and Koeberl, 2014, amongst others). However, the findings in this study show that the southeast margin presents complicated basement topographies. The architecture around the dome was influenced by a pre-existing elevated basement, fold interference during the central uplift formation, and partial collapse of the central uplift in the southeast. However, further numerical or mechanical modelling of the impact with these constraints is recommended, to test the plausibility of these propositions.



* Age of Vryburg Formation is used as an oldest depositional estimate because it constrains the Schmidtsdrif Subgroup that is overlain by the Black Reef Formation

Figure 7.1.1 Schematic chart highlighting the seven main structural features imaged in the study area. The stratigraphy has been included as a cross-reference to the estimated timing of the structures.

Table 7.1 Summary of structural features and associated seismic section examples.

Structural Feature		Example
1)	Normal offset of Dominion and West Rand groups	Offset in seismic section BH-268 in Domain 2
2)	Normal offset of undulating erosional contact between West Rand and Central Rand groups	Offsets in seismic sections OF-97 and OPR-50 in Domain 1
3)	Truncation of the Witwatersrand Supergroup by the Ventersdorp Supergroup	VCF truncation (seismic section KV-120 in Domain 1; FV-154, BH-269, and DV-270A in Domain 2; BH-171A/B in Domain 3)
4)	Listric fault systems, post-Klipriviersberg Group, syn-Platberg Group	Seismic sections KV-120, OB-41 and OB-74 in Domain 1 show a single system; DV-274 in Domain 2; DE-512B in Domain 3
5)	Truncation of older units by the Black Reef Formation	Examples throughout the study area, exhibited in most seismic sections.
6)	Gentle, long wavelength, low amplitude folds	More pronounced in all north-south trending seismic lines in Domain 1. A single large fold termed the Vaal Dam Anticline (VDA) is imaged in seismic sections DV-270B, DV-271, and DV-272 in Domain 2.
7)	Large listric fault displaces the VDA and extends at least 65km across the southeastern margin of the Vredefort dome	Seismic sections BH-268, BH-269, FV-154, DV-270A (VDA displacement), and DV-271 (VDA displacement) in Domain 2; DE-506, DE-507, and DE-508 in Domain 3.

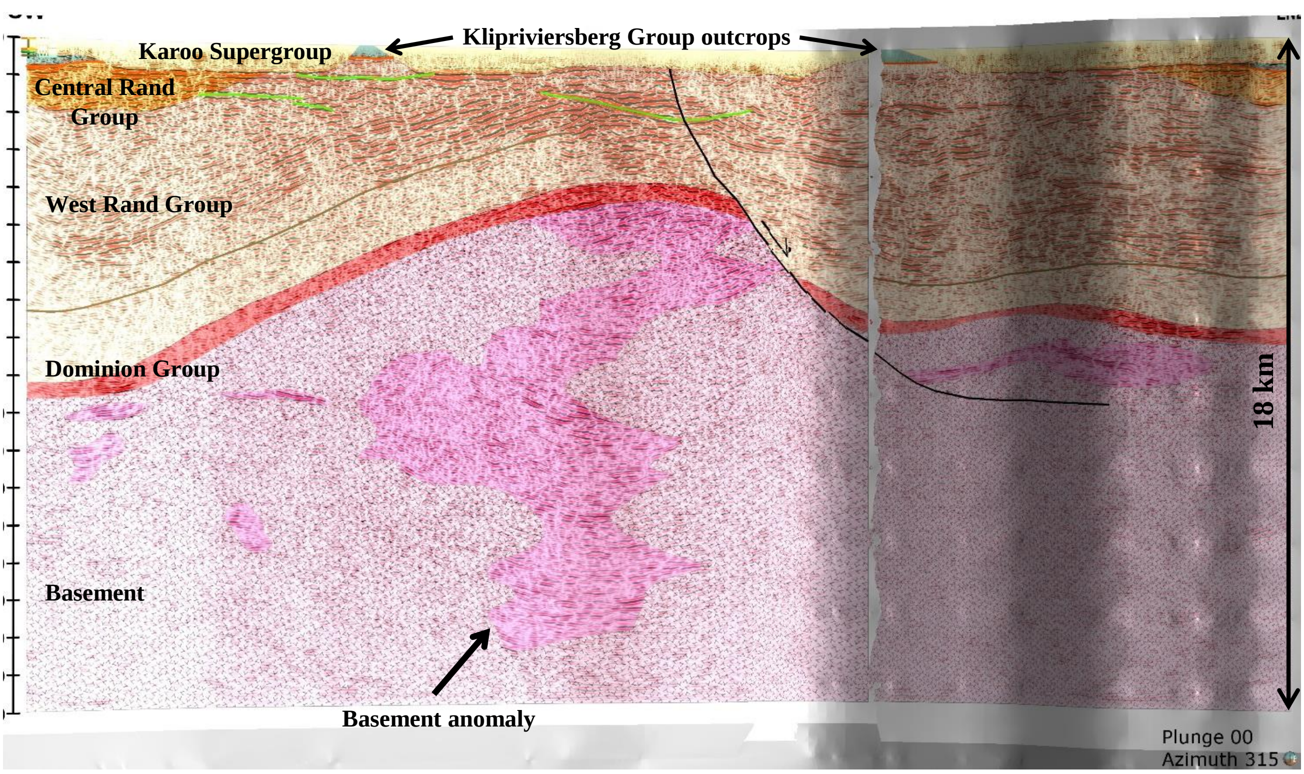


Figure 7.1.2 Seismic section BH-171 (combined BH-171A and B) visualised in 3D. Viewing orientation is looking horizontally towards 315°. An anomalous, narrow, subvertical column of strong reflections is located beneath the elevated basement.

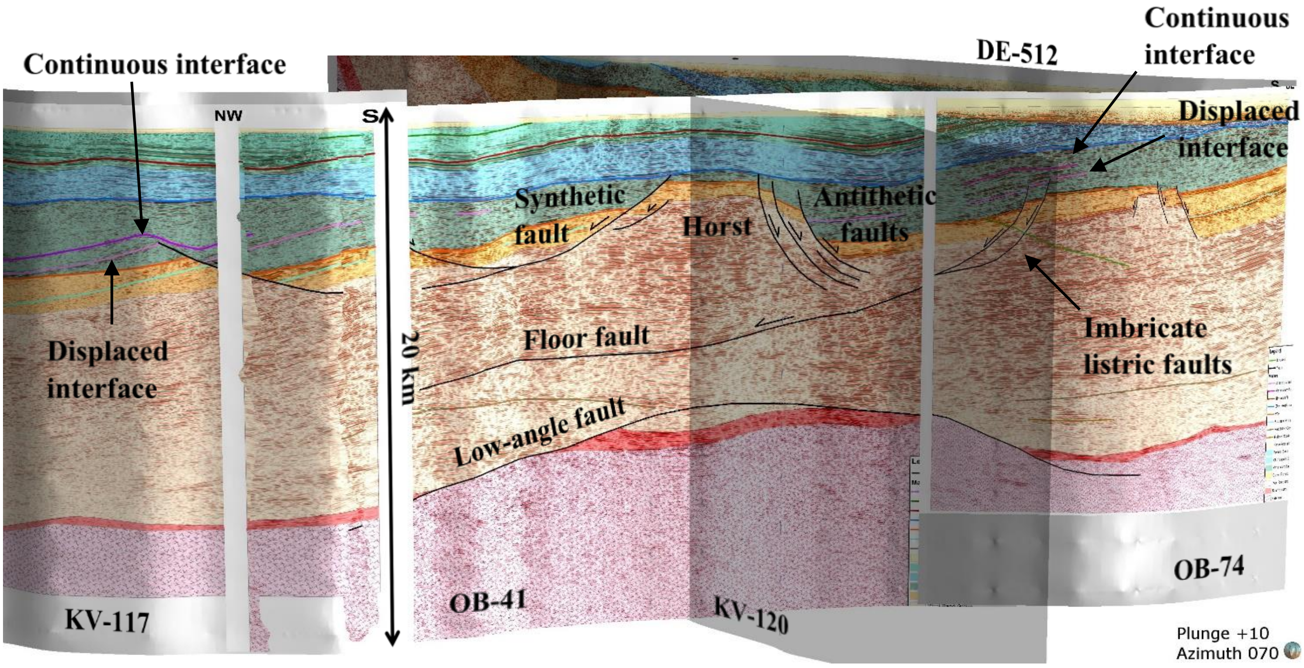


Figure 7.1.3 Well-developed listric fault system imaged in the southern half of Domain 1. Timing is constrained to post-Klipriviersberg Group and syn-Platberg Group. The structures were also imaged in seismic section KV-120, but it was made transparent for unobstructed clarity of the system. Viewing direction is towards 070° and plunging 10°.

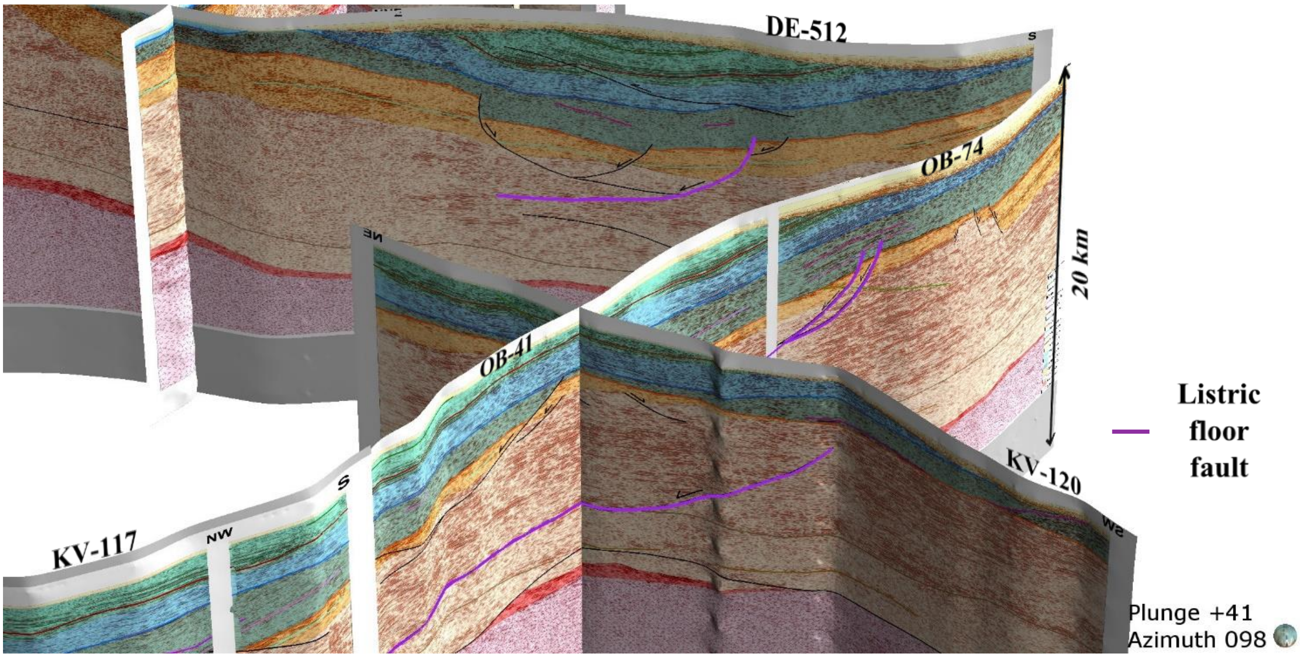


Figure 7.1.4 Floor faults of the listric fault system imaged in the southwest, projected and aligned in 3D space along a strike of 098°. The floor faults on each seismic section are highlighted in purple. The viewing direction is tilted by 41° for better perspective; note that the elevations of the fault systems are equivalent across the sections.

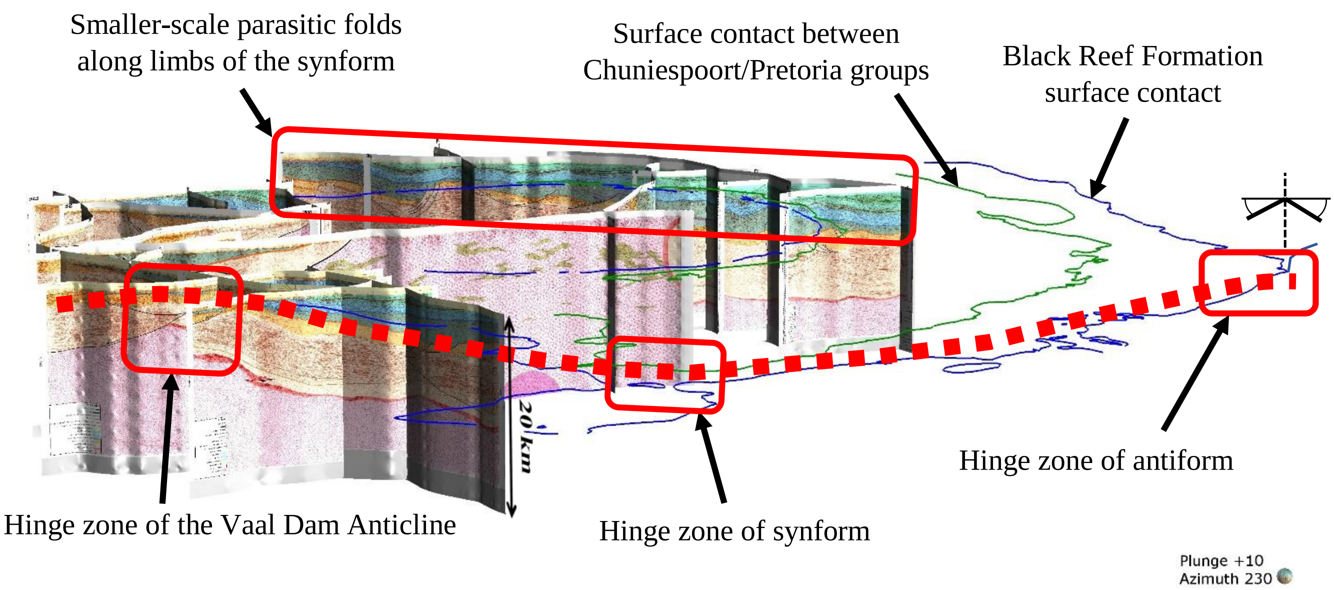


Figure 7.1.5 Estimated geometry of a proposed fold system that combines the imaged folds in the Transvaal Supergroup. The system is illustrated as a main antiform/synform pair, with parasitic folds imaged in the limb of the synform. The proposed antiformal hinge in the north corresponds with mapped outcrop and a change in dip orientation of the Black Reef Formation towards the north. The viewing direction is sub-parallel to the fold axis, i.e. ~230°, providing a cross-sectional view of the synform geometry. The plunge of 10° is not related to the folds but only provides some perspective for the reader.

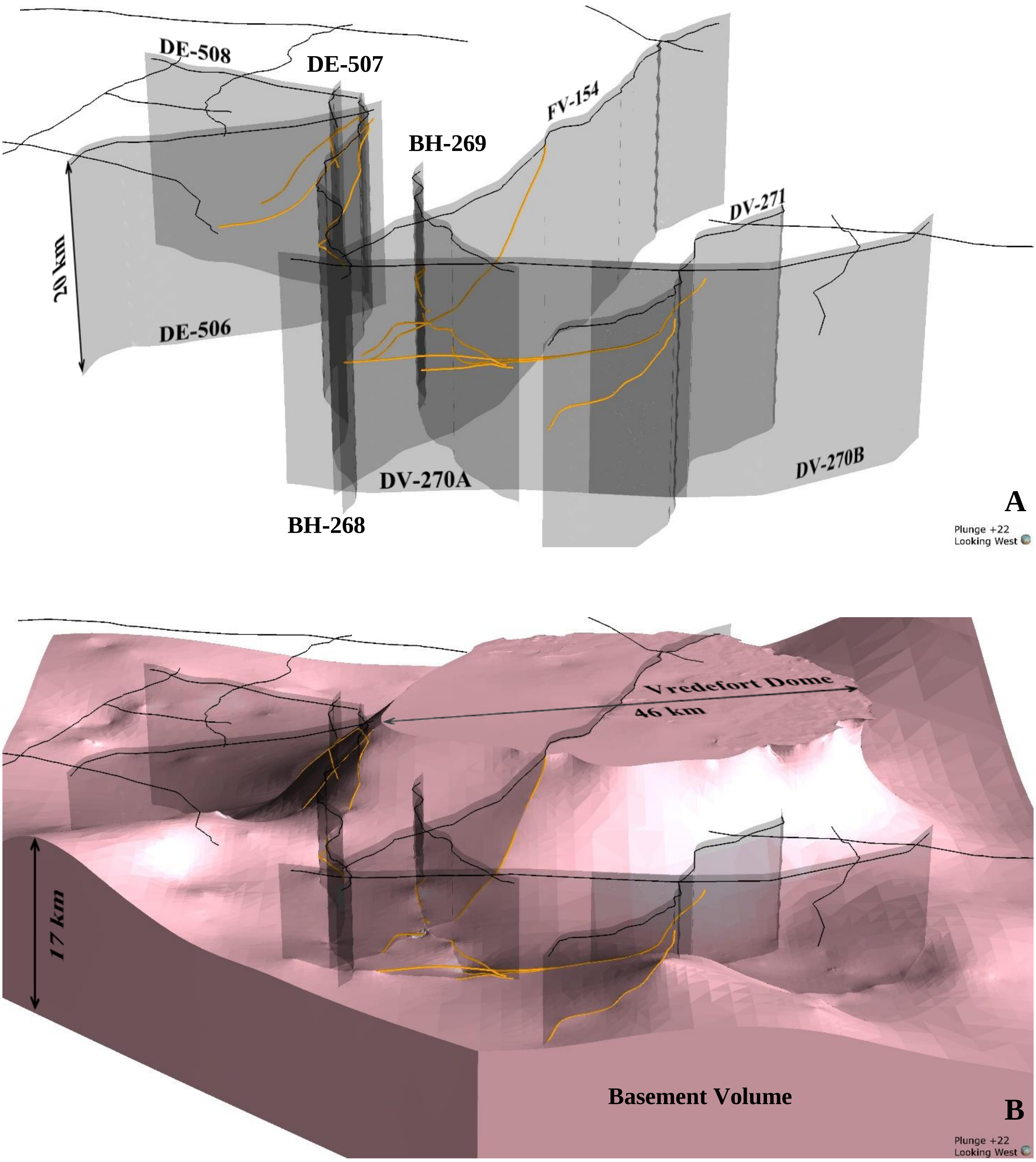


Figure 7.1.6 3D projection of the trend of low-angle and listric faults (orange) imaged in the seismic sections on the southern and eastern margin of the dome. A) Transparent seismic sections that comprised the faults. B) Equivalent view as (A) but with the basement volume included for reference. Viewing orientation is towards the west, plunging 22° for perspective.

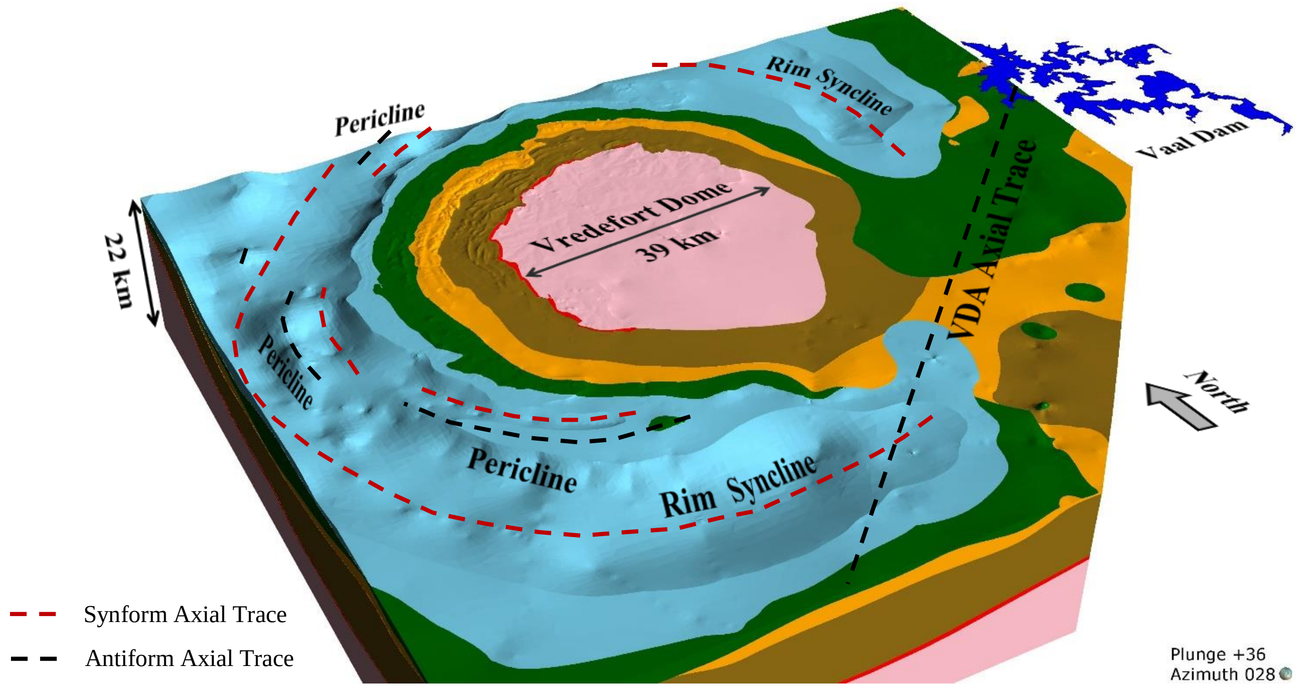


Figure 7.1.7 Geological model highlighting axial traces imaged on the contact between the Chuniespoort and Pretoria groups (i.e. the Pretoria Group volume was omitted from the view to show the contact surface). The proposed periclinal folds are preserved in the rim syncline around the dome. The Vaal Dam is included as reference to the VDA axial trace being sub-parallel to the elongate northern section of the dam. View orientation is towards 028°, plunging 36°. Key: blue = Chuniespoort Group; green = Ventersdorp Supergroup; orange = Central Rand Group; brown = West Rand Group; red = Dominion Group; pink = Basement.

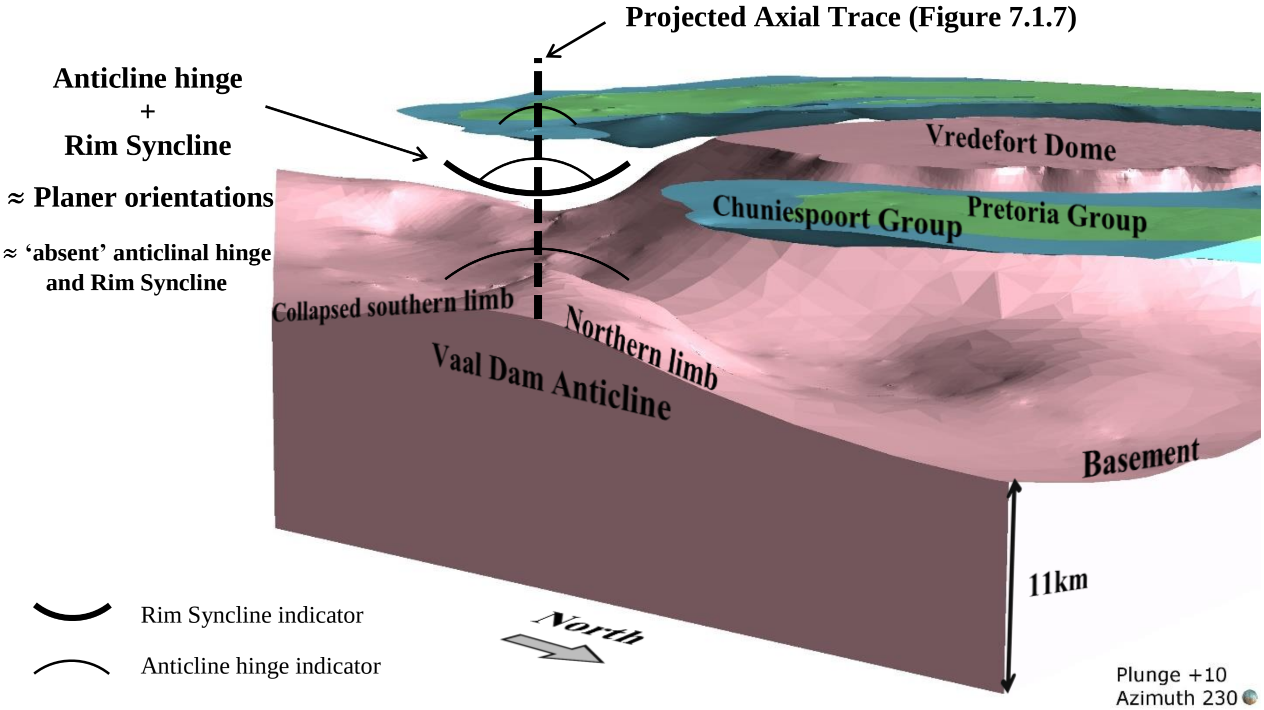


Figure 7.1.8 Proposed solution to the absence of the rim syncline in the southeast margin of the dome (i.e., fold interference mechanism). View is parallel to the axial trace of the Vaal Dam Anticline (VDA) in Domain 2. The fold axial trace projection of the VDA in the southeast margin of the dome coincides with the rim syncline projection. The proposition is made that the rim syncline, during the formation of the central uplift, interfered with the pre-existing VDA. The interference of the opposing geometries resulted in a sub-planer orientation.

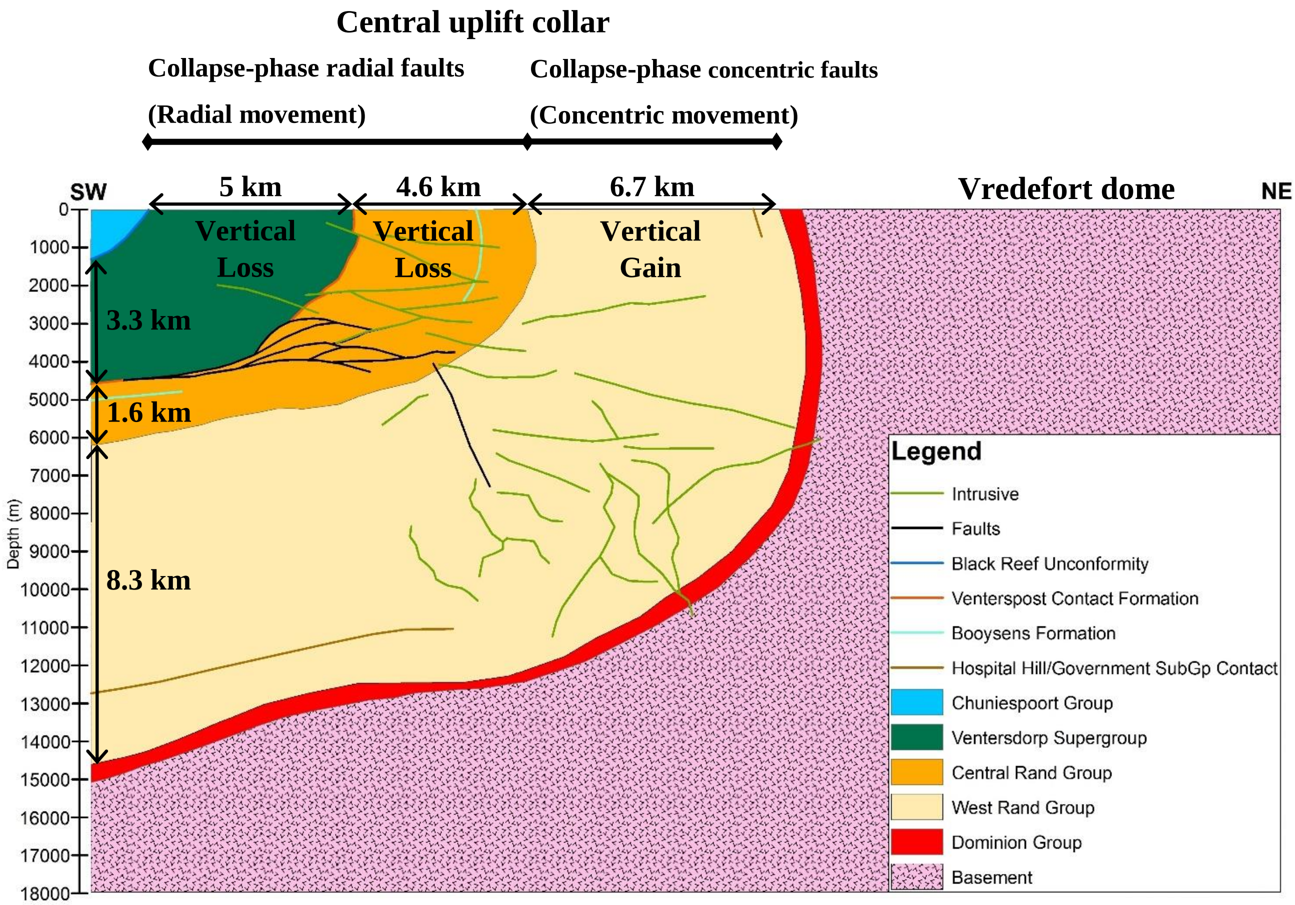
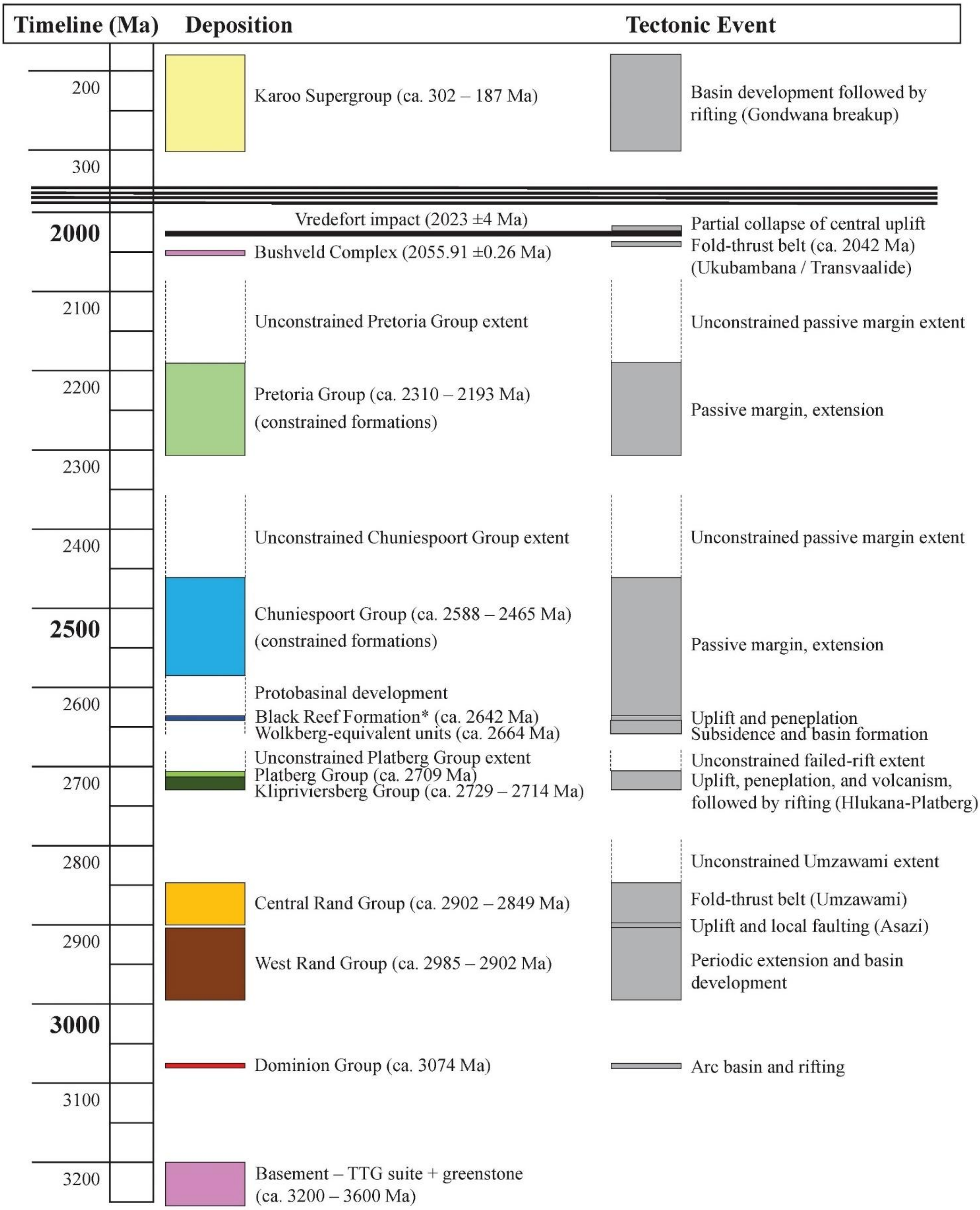


Figure 7.1.9 Interpretation of seismic section FV-155 showing the discrepancy in the vertical and horizontal thicknesses of the Ventersdorp Supergroup and the Central Rand and West Rand groups (-1.7km, -3km, and +1.6km respectively). The proposed mechanisms for the discrepancies include those described by Jahn and Riller (2015), i.e. collapse-phase radial and concentric faults. Note the scale is in parity as the vertical exaggeration is negligible at 1.03x.



* Age of Vryburg Formation is used as an oldest depositional estimate because it constrains the Schmidtsdrif Subgroup that is overlain by the Black Reef Formation

Figure 7.2.1 Schematic chart of deposition and tectonic events for the study area, incorporating findings in this study and published work.

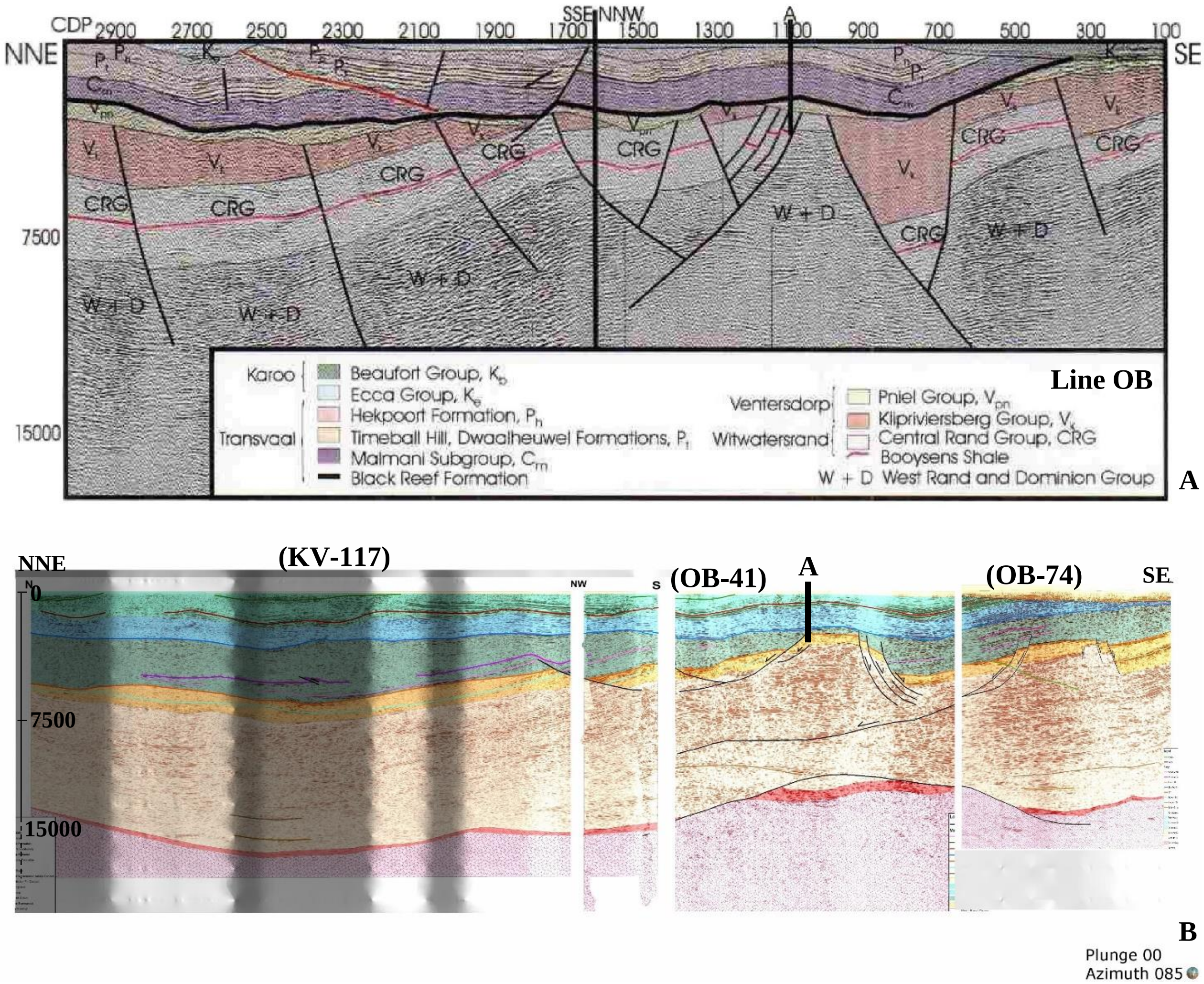


Figure 7.2.2 Interpretation comparison of Line OB from Tinker et al. (2002) with depths referenced to current study. A) Published interpretation (slightly modified) after Tinker et al. (2002) (Figure 11B in publication). B) Interpretation in this study of the same line (comprising lines KV-117, OB-41, and OB-74) with borehole "A" indicated to guide reference in both images. Note, vertical scale in (B) is in parity with horizontal scale, whereas (A) is vertically exaggerated.

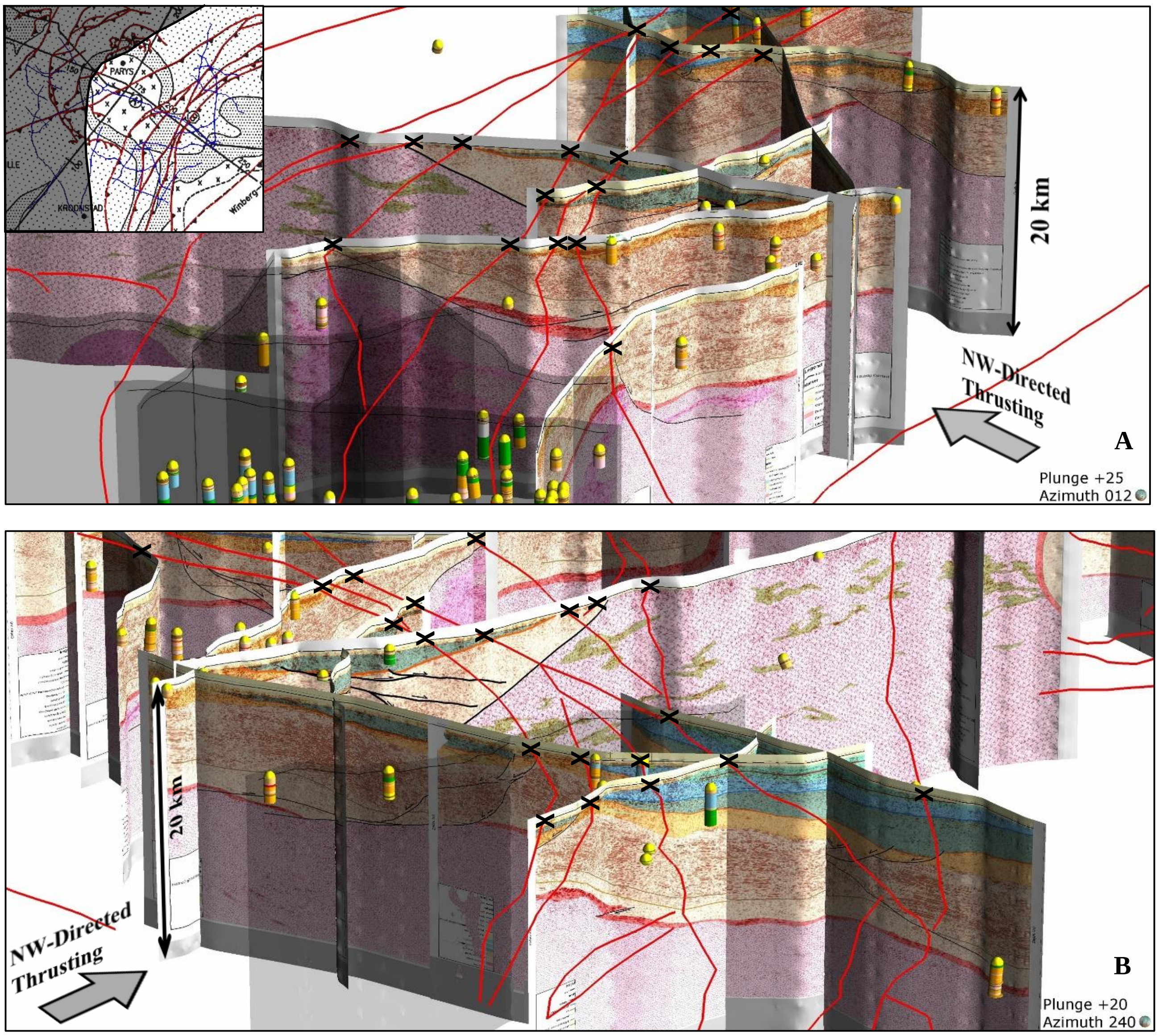


Figure 7.2.3 Complementary views A and B displaying Domains 2 and 3 with the numerous northwest-directed thrust fault traces (red) proposed in Figure 27 of Friese et al. (1995). The "X" symbols highlight the intersections between the red fault traces with the 2D seismic section interpretations. The inset image in A is a reference to the original map. The shaded portion of the inset shows areas that are not viewed in either figure. The blue polylines in the inset indicate the seismic line locations. Boreholes are also included to illustrate the data coverage and are colour-coded by lithology type (note, the yellow markers at the top of each borehole are collar markers). Leapfrog Geo® has no structural symbology for polylines so the northwest thrust direction of these faults is indicated in each view by the grey arrow. For better illustration of these intersections some obstructing seismic sections have been made transparent. Comparisons should only be made where thrust fault traces intersect seismic sections.

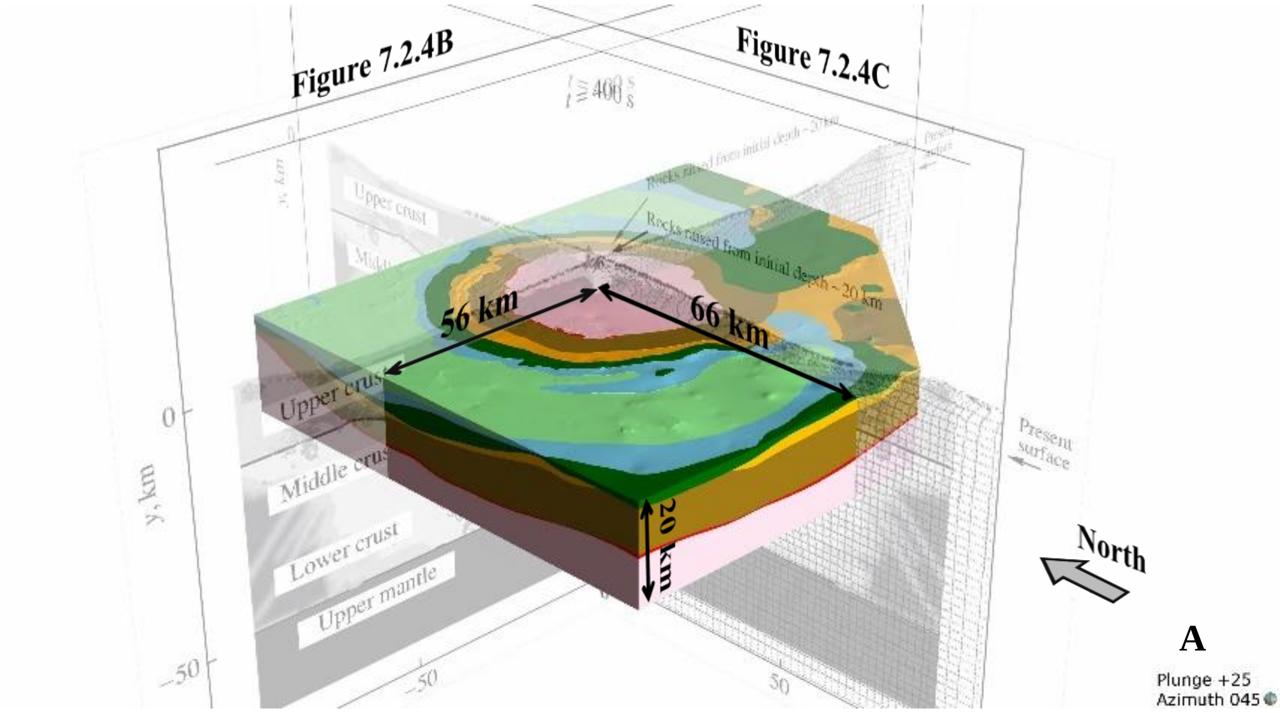
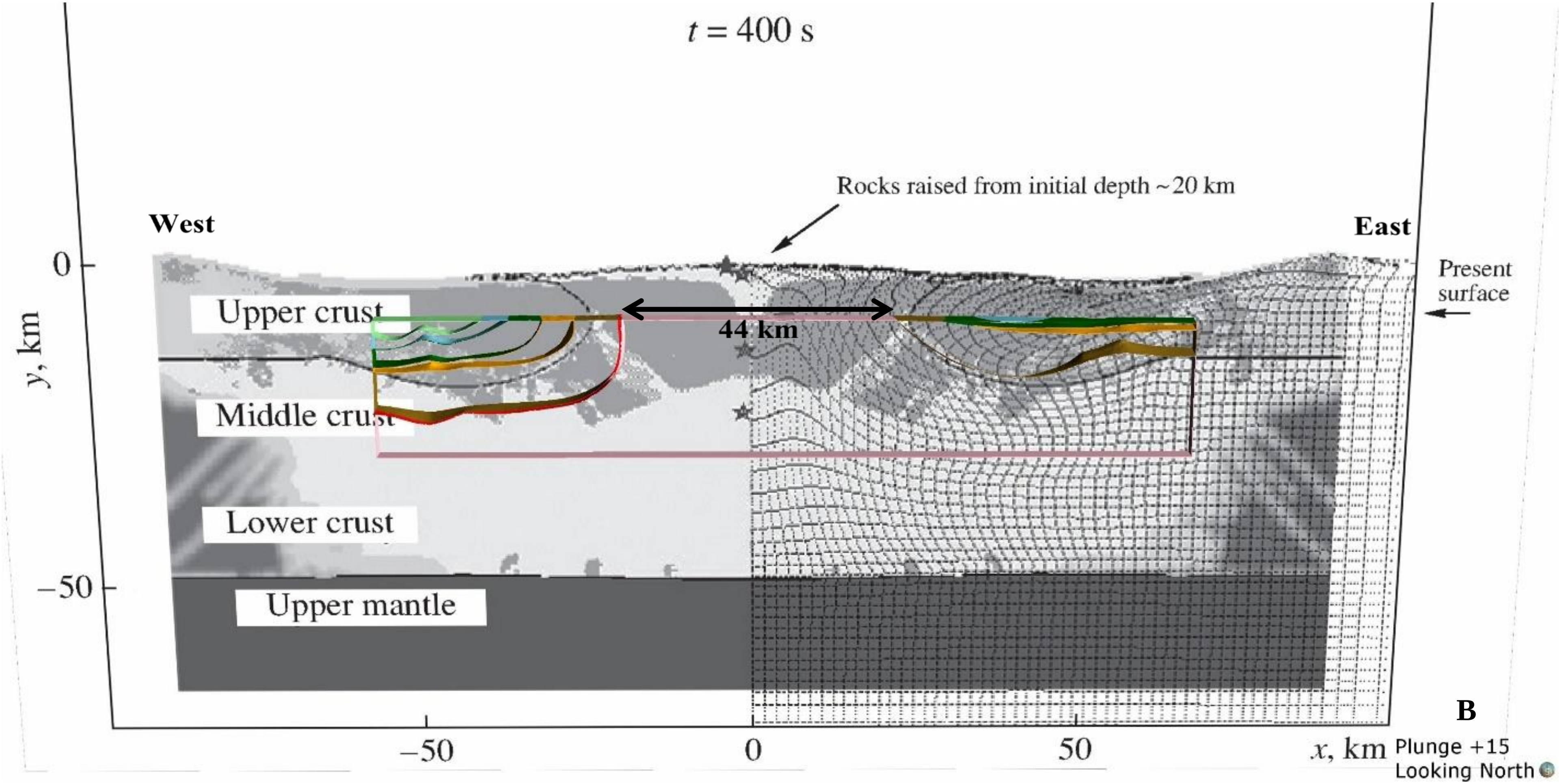
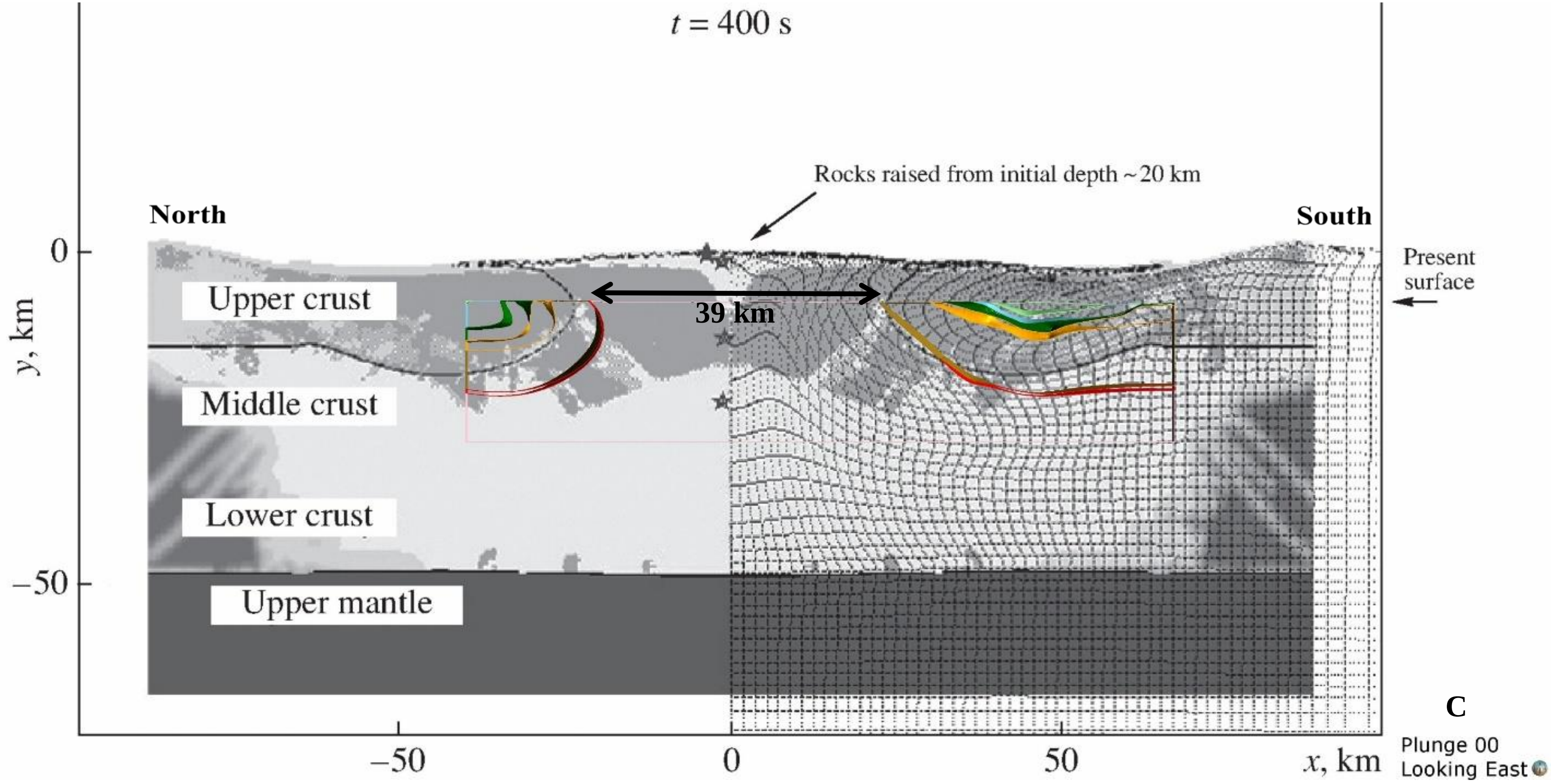


Figure 7.2.4 Geological model with duplicated overlays of Figure 13 of Ivanov (2005), highlighting the consistencies and inconsistencies between the two models. A) Overview of georeferenced figures. B) (Below) Looking north with cross section through geological model. C) (Below) Looking east with cross section though geological model.


t = 400 s
Rocks raised from initial depth ~20 km
West
East
Present surface
44 km
Upper crust
Middle crust
Lower crust
Upper mantle
y, km
0
−50
−50
0
50
x, km
B
Plunge +15
Looking North


t = 400 s
Rocks raised from initial depth ~20 km
North
South
0
Present surface
Upper crust
39 km
y, km
Middle crust
Lower crust
−50
Upper mantle
C
−50
0
50
x, km
Plunge 00
Looking East

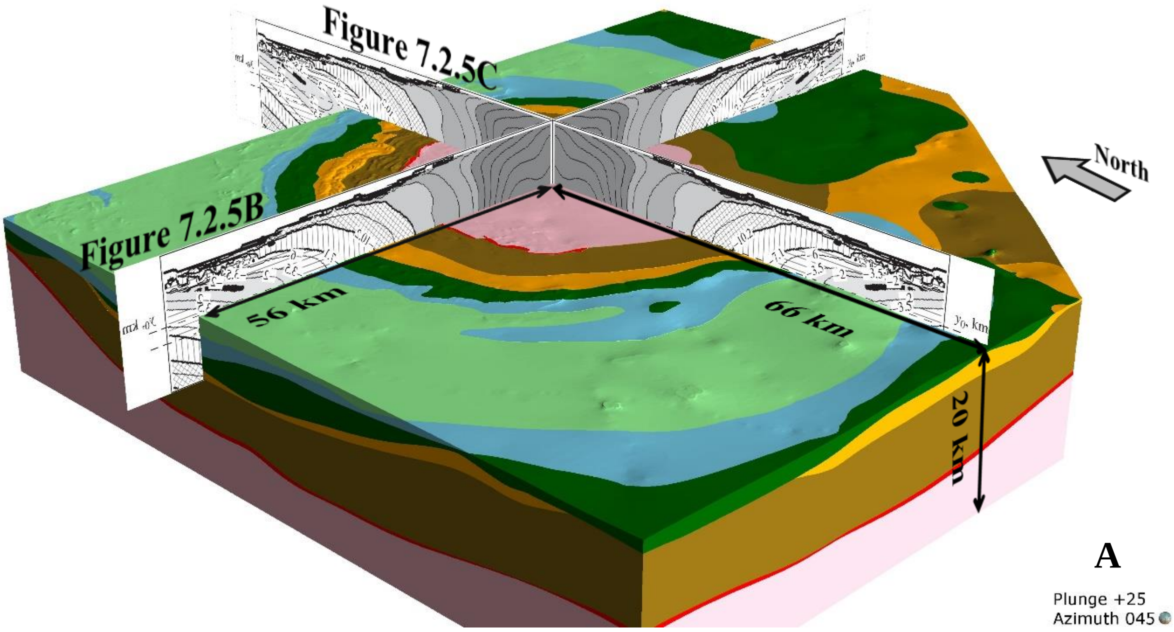
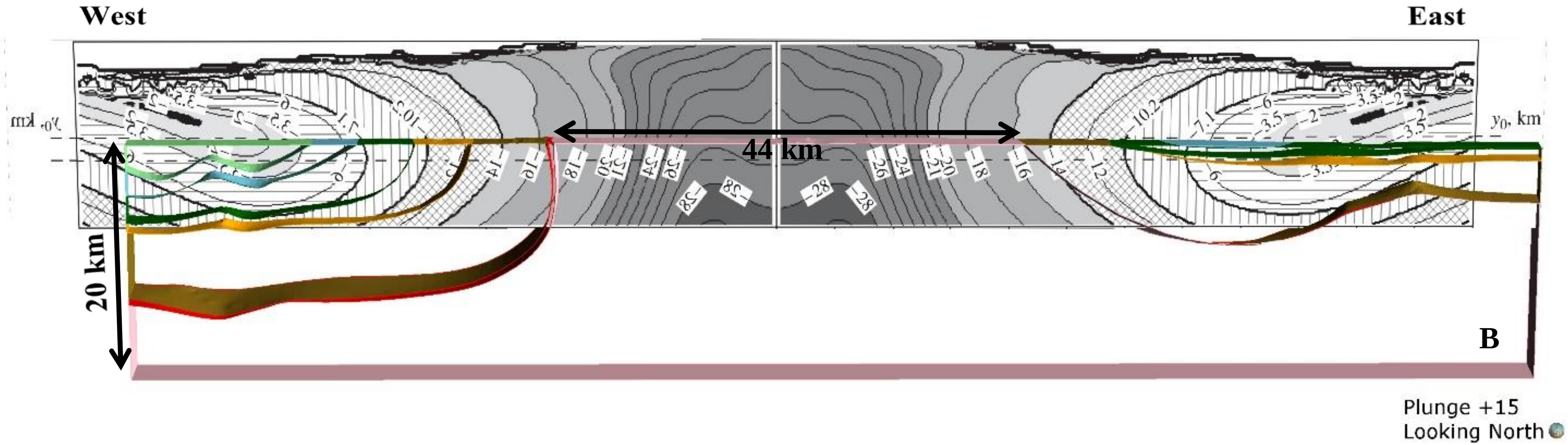
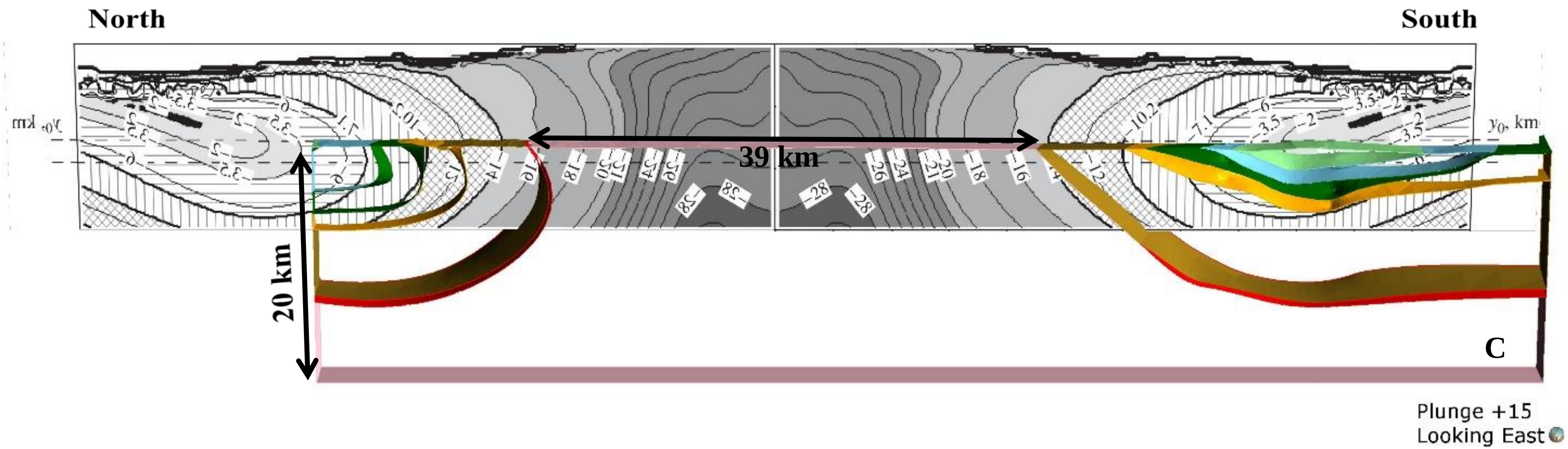


Figure 7.2.5 Geological model with overlays of duplicated Figure 15B of Ivanov (2005), highlighting the consistencies and inconsistencies between the two models. The original figure depicted only one half of the symmetrical deformation, so effectively the figure has been replicated four times for this comparison. Areas shaded in grey represent the basement and variously hatched areas are the supracrustal sequences. The dashed horizontal lines denote the range in the level of erosion to present surface (depths of 7.5km and 9.5km). The isoline labels in the figure by Ivanov (2005) represent the initial rock depth in km. The main difference is the asymmetry of the geological model. A) Overview of georeferenced figures. B) (Below) Looking north with cross section through geological model. C) (Below) Looking east with cross section though geological model.



West
East
44 km
20 km
B
Plunge +15
Looking North


North
South
39 km
20 km
C
Plunge +15
Looking East

Chapter 8
Conclusions

In summary, the borehole and surface mapping data were imported into Leapfrog Geo® and together with imported 2D reflection seismic sections, were used to produce wireframes for 3D geological modelling. Twenty eight post-stack migrated 2D reflection seismic sections were available in the study area. Several velocity values, obtained from previous VSP and borehole geophysical surveys conducted in the Witwatersrand basin, were used to constrain the seismic interpretations. The seismic sections were depth-converted using a constant velocity of 6000 m/s as there was no VSP data or borehole geophysical logs available to constrain more accurate velocity values for depth conversion.

Artificial data issues hindered picking of horizons in Kingdom Suite®. Therefore the migrated seismic sections were exported as non-georeferenced sections and picking of horizons was done in ArcGIS®. Large separation distances between the 2D seismic lines as well as limited fault functionality in Leapfrog Geo® hindered the representation of fault planes in the final 3D model.

Eight geological volumes were created for the 3D model using seven major lithological contacts. These contacts were picked from the 2D reflection seismic sections. A host of digitised seismic interface wireframes, supportive wireframes, and orientation disks were used to create the 3D surface interpolations of the contacts between the eight modelled volumes. The seven major contacts were seismically imaged in the study area. The main restrictions on the imaging included the wide coverage of the Karoo Supergroup outcrop, and the relatively sparse, in places shallow, borehole coverage.

The elevated basement in the eastern half of the study area is found to form part of a pre-existing basement architecture at the time of the Vredefort impact. A new term is proposed that refines the description of the periclines mapped at surface and imaged in the seismic data in the western half of the study area, i.e., impact-type curvature-accommodation folds. The term is a proposed sub-order of curvature-accommodation folds, itself a refined form of coaptation folds.

Seven structural features are discussed from the modelling results. These include, (1) a normal fault in the lower West Rand Group, (2) an undulate, normal faulted truncation plane, constrained as post-West Rand Group and pre or early-Central Rand Group, (3) a truncation plane and local enhanced uplift constrained as pre to syn-VCF, (4) a listric fault system, constrained as post-Klipriviersberg Group and syn-Platberg Group, (5) a truncation plane, constrained as syn-Black Reef Formation, (6) folds, constrained as post-Magaliesberg Formation and pre-Vredefort impact, and (7) a listric fault across the southeastern margin of the Vredefort dome, constrained as late to post-central uplift formation.

The Asazi Event proposed by Manzi et al. (2013) is supported in the study area. The localised extension observed in some areas provides possible evidence for local scale variation during the deformation process. Due to the seismically transparent Central Rand Group the crosscutting structures in the package were difficult to image, i.e., the Umzawami Event by Dankert and Hein (2010). The VCF and the Ventersdorp Supergroup exhibit an evolution from enhanced uplift and peneplation to rift-type extension. Rift-type extension seismically defined in the Ventersdorp Supergroup in several places in the study area supports the Hlukana-Platberg Event of Manzi et al. (2013).

The late to post-Transvaal Supergroup and pre-Vredefort impact fold events proposed by Dankert and Hein (2010) and Alexandre et al. (2006) are supported in this study. However it is proposed that the respective Ukubambana and Transvaalide fold-thrust belts described by these authors represent the same deformation event. The large asymmetric, gentle, first-order scale anticline imaged in Domain 2 is associated with this fold event, and is named here as the Vaal Dam Anticline (VDA). The interference of the rim syncline during the central uplift formation with the pre-existing VDA is proposed. This interference is suggested to explain the planar orientations of the units and absence of the rim syncline and VDA in the southeast. However this interference mechanism requires further testing.

The seismically defined structures in seismic section FV-154 are discussed in terms of the formation phases of the central uplift. A couple suggested correlations are made between the section and the central uplift formation; (1) an array of interconnected faults located in the outer arc of the synform were possibly formed during the crustal rebound phase; (2) a series of anastomosing structures in the hinge of the synform suggested to have formed in response to the gravitational collapse of the rebounded crust, as part of the accommodation structures.

In seismic section FV-154 the Central Rand Group and Ventersdorp Supergroup measured at depth, beyond the synform, exhibit vertical losses in thickness relative to the surface outcrop extent in the collar rocks. In contrast, the West Rand Group exhibits vertical gain in thickness. These depth discrepancies are interpreted as being unrelated to the velocity fields used for migration and Time-Depth conversion. This is because they are too large to be accounted for by the variability in the velocity fields. However the discrepancies can be explained by the thickening and duplication of the collar rocks, as described by Jahn and Riller (2015).

The seismic section comparisons with Tinker et al. (2002) show comparable structural regimes that depict similar tectonic events. These events include, (1) extensional deformation post-deposition of the Klipriviersberg Group, (2) peneplation during the Black Reef Formation, and (3) fold development post-deposition of the Hekpoort Formation. One major difference to Tinker et al. (2002) is that the published interpretation does not illustrate the depth association of the faults with an extensional system, as proposed in this study. However due to their significantly limited borehole and high-resolution reflection seismic data, it is suggested that their interpretation was inherently restricted.

The interpretations of thrust faults by Friese et al. (1995) are not supported in this study. Instead the findings in this study suggest that any potential thrust offsets are greatly overshadowed by the larger scale extension-dominated deformation that is absent in their interpretations. The possible thrust-associated uplift in the southeast collar rocks proposed by Friese et al. (1995) is therefore suggested to be a relatively small factor.

Later publications that adopted the interpretation by Friese et al. (1995) resulted in discrepancies between those publications and this study. These discrepancies include, (1) tilting of between 3° and 30° towards the northwest prior to the impact event by Reimold and Koeberl (2014), and (2) shortening in the southeast on the order of 65km and direct association of the large displacement with Namaqua-Natal orogenic activity by Henkel and Reimold (1998).

The simulation modelling of Ivanov (2005) is supported in this study, albeit with a few differences. These differences are largely related to the pre-existing architecture of the basement and supracrustal sequences. The modelling in this study shows a complicated architecture that was not accounted for in the relatively simplified architecture modelled by Ivanov (2005).

This study demonstrates the advantages of integrating high-resolution reflection seismic data, borehole data, and surface mapping into a single 3D spatial environment. The integration highlighted new structural relationships that benefited from the creation a robust 3D spatial platform. This enabled a deeper understanding of both the tectonic history and 3D strato-structural architecture of the Neoarchaean-Palaeoproterozoic Witwatersrand basin. The 3D spatial integration also highlights the importance of defining pre-existing basement and supracrustal architecture in order to better understand the formation and preservation of giant terrestrial impacts.

References

Alexandre, P., Andreoli, M.A.G., Jamison, A., Gibson, R.L., 2006. 40Ar/39Ar age constraints on low-grade metamorphism and cleavage development in the Transvaal Supergroup (central Kaapvaal craton, South Africa): implications for the tectonic setting of the Bushveld Igneous Complex. South African Journal of Geology 109 (3), 393-410.

Apel, M., 2006. From 3d geomodelling systems towards 3d geoscience information systems: Data model, query functionality, and data management. Computers & Geosciences 32, 222-229.

Armstrong, R.A., Compston, W., Retief, E.A., Williams, I.S., Welke, H.J., 1991. Zircon ion microprobe studies bearing on the age and evolution of the Witwatersrand triad. Precambrian Research 53, 243–266.

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. (Eds.), Deformation of the Continental Crust: The Legacy of Mike Coward. Special Publications. Geological Society, London, pp. 533–542.

Burger, A.J., Coertze, F.J., 1973–1974. Age determinations – April 1972 to March 1974. Annals of the Geological Survey of South Africa 10, 135–141.

Catuneanu, O., Wopfner, H., Erikkson, P.G., Cairncross, B., Rubidge, B.S., Smith, R.M.H., Hancox, P.J., 2005. The Karoo basins of south-central Africa. Journal of African Earth Sciences 43, 211-253.

Chopra, S., Castagna, J.P., Portniaguine, O., 2006. Seismic resolution and thin-bed reflectivity inversion. CSEG Rec. 31, 19–25.

Clendenin, C.W., Charlesworth, E.G., Maske, S., 1988. An early Proterozoic three-stage rift system, Kaapvaal Craton, South Africa. Tectonophysics 145, 73–86.

Cornell, G.H., Schütte, S.S., Eglington, B.L., 1996. The Ongeluk basaltic andesite formation in Griqualand West, South Africa: submarine alteration in a 2222 Ma Proterozoic sea. Precambrian Research 79, 101-123.

Crow, C., Condie, K.C., 1987. Geochemistry and origin of late Archaean volcanic rocks from the Rhenosterhoek Formation, Dominion Group, South Africa. Precambrian Research 37, 217-229.

Dankert, B. T., Hein, K.A.A., 2010. Evaluating the structural character and tectonic history of the Witwatersrand Basin. Precambrian Research 177, 1-22.

De Wet, J.A.J., Hall, D.A., 1994. Interpretation of the Oryx 3D seismic survey: Proceedings of the XVth CMMI Congress. South African Institute of Mining and Metallurgy 3, 259–270.

Eriksson, P.G., Condie, K.A., van der Westhuizen, W., van der Merwe, R., de Bruiyn, H., Nelson, D.R., Altermann, W., Catuneanu, O., Bumby, A.J., Lindsay, J., Cunningham, M.J., 2002. Late Archaean superplume events: a Kaapvaal-Pilbara perspective. Journal of Geodynamics 34, 207-247.

Friese, A.E.W., Charlesworth, E.G., McCarthy, T.S., 1995. Tectonic processes within the Kaapvaal Craton during the Kibaran (Greenville) Orogeny: Constraints from Structural, Geophysical and Isotopic Data in the Witwatersrand Basin and Environs. Information Circular 292. Economic Geology Research Unit, University of the Witwatersrand, Johannesburg, South Africa, 67 p.

Frimmel, H. E., 2014. A giant Mesoarchean crustal gold-enrichment episode: possible causes and consequences for exploration, in Kelley, K., and Howard, G., eds., Building Exploration Capability for the 21st Century. Society of Economic Geologists, Special Publication No. 18, 209-234.

Geological Survey: Coetzee, L.E., 1986. East Rand. *Geological Series*, Sheet 2628, 1:250,000, Pretoria: Government Printer.

Geological Survey: Smith, R., 1992. Frankfurt. *Geological Series*, Sheet 2728, 1:250,000, Pretoria: Government Printer.

Geological Survey: Wilkinson, K.J., 1986. Wes-Rand. *Geological Series*, Sheet 2626, 1:250,000, Pretoria: Government Printer.

Geological Survey (CGS): Bisschoff, A.A., Mayer, J.J., Voors, W.A., Retief, P.F., 1999. Geology of the Vredefort Dome. *Single Map Series*, Sheet Unspecified, 1:50,000, Pretoria: Council for Geoscience.

Geological Survey (CGS): Retief, P.F., 2000. Kroonstad. *Geological Series*, Sheet 2726, 1:250,000, Pretoria: Council for Geoscience.

Hanneing, A., Paton, G., 2012. Understanding thin beds using 3D seismic analysis workflows, attributes: new views on seismic imaging – their use in exploration and production. 31st Annual GCSSEPM Foundation Bob F. Perkins Research Conference 1, 322–341.

Henkel, H., Reimold, W.U., 1998. Integrated geophysical modelling of a giant, complex impact structure: anatomy of the Vredefort Structure, South Africa. Tectonophysics 287, 1-20.

Henkel, H., Reimold, W.U., 2002. Magnetic model of the central uplift of the Vredefort impact structure, South Africa. Journal of Applied Geophysics 51, 43-62.

Ivanov, B.A., 2005. Numerical modelling of the largest terrestrial meteorite craters. Solar System Research 39, 381-409. Translated from Astronomicheskii Vestnik 39, No. 5, 2005, 426–456.

Jackson, M.C., 1994. Geochemistry and metamorphic petrology of Dominion Group metavolcanics in the Vredefort area. South Africa. South African Journal of Geology 97, 62–77.

Jahn, A., Riller, U., 2015. Kinematics of large terrestrial impact crater formation inferred from structural analysis and three-dimensional block modeling of the Vredefort Dome, South Africa. In Osinski, G.R., Kring, D.A., eds., Large Meteorite Impacts and Planetary Evolution V: Geological Society of America Special Paper 518, 85–97.

Johnson, M.R., Anhaeusser, C.R., Thomas, R.J., 2006. The Geology of South Africa. Jointly by Geological Society of South Africa and Council for Geosciences, Gauteng, South Africa, 691 pp.

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 Publications 272, London, pp. 543–569.

Jones, M.Q.W., 2003. Thermal properties of stratified rocks from Witwatersrand gold mining areas. Journal of the South African Institute of Mining and Metallurgy 26 (3), 173-186.

Jones, R.R., McCaffrey, K.J.W., Clegg, P., Wilson, R.W., Holliman, N.S., Holdsworth, R.E., Imber, J., Waggot, S., 2009. Integration of regional to outcrop digital data: 3D visualisation of multi-scale geological models. Computers and Geosciences 35, 4-18.

Kamo, S.L., Reimold, W.U., Krogh, T.E., Colliston, W.P., 1996. A 2.023 Ga age for the Vredefort impact event and a first report of shock metamorphosed zircons in pseudotachylitic breccias and Granophyre. Earth and Planetary Science Letters 144, 369–387.

Kaufmann, O., Martin, T., 2009. Reprint of ‘‘3D geological modelling from boreholes, cross-sections and geological maps, application over former natural gas storages in coal mines’’ [Comput. Geosci. 34 (2008) 278–290]. Computers and Geosciences 35, 70-82.

Kositcin, N., Krapeˇz, B., 2004. Relationship between detrital zircon age-spectra and the tectonic evolution of the late Archaean Witwatersrand Basin, South Africa. Precambrian Research 129, 141–168.

Kositcin, N., McNaughton, N.J., Griffin, B.J., Fletcher, I.R., David, I., Groves, D.I., Birger Rasmussen, 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.

Lisle, R.J., Styles, P., Freeth, S.J., 1990. Fold interference structures: the influence of layer competence contrast. Tectonophysics 172, 197-200.

Manzi, M.S.D., Durrheim, R.J., Hein, K.A.A., King, N., 2012 (b). 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, 133-147.

Manzi, M.S.D., Gibson, M.A.S., Hein, K.A.A., King, N., Durrheim, R.J., 2012 (a). Application of 3D seismic techniques to evaluate ore resources in the West Wits Line goldfield and portions of the West Rand goldfield, South Africa. Geophysics 77, 163–171.

Manzi, M.S.D., Hein, K.A.A., Durrheim, R.J., King, N., 2014. 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 and Mining Sciences 66, 97-113.

Manzi, M.S.D., Hein, K.A.A., King, N., Durrheim, R.J., 2013. Neoarchaean tectonic history of the Witwatersrand Basin and Ventersdorp Supergroup: New constraints from high-resolution 3D seismic reflection data. Tectonophysics 590, 94-105.

Marques, F.O., 2012. Transform faults orthogonal to rifts: Insights from fully gravitational physical experiments. Tectonophysics 526-529, 42-47.

Martin, D.McB., Clendenin, C.W., Krapeˇz, B., McNaughton, N.J., 1998. Tectonic and geochronological constraints on late Archaean and Palaeoproterozoic stratigraphic correlation within and between the Kaapvaal and Pilbara Cratons. Journal of the Geological Society 155, 311–322.

McCarthy, T.S., Charlesworth, E.G., Stanistreet, I.G., 1986. Post-Transvaal structural features of the northern portion of the Witwatersrand Basin. Transactions of the Geological Society of South Africa 89, 311-323.

McCarthy, T.S., Stanistreet, I.G., Robb, L.J., 1990. Geological studies related to the origin of the Witwatersrand Basin and its mineralisation – an introduction and a strategy for research and exploration. South African Journal of Geology 93, 1-4.

Morgan, J.V., Warner, M.R., Collins, G.S., Melosh, H.J., Christeson, G.L., 2000. Peak-ring formation in large impact craters: geophysical constraints from Chicxulub. Earth and Planetary Letters 183, 347-354.

Muundjua, M., Hart, R.J., Gilder, S.A., Carporzen, L., Galdeano, A., 2007. Magnetic imaging of the Vredefort impact crater, South Africa. Earth and Planetary Science Letters 261, 456-468.

Nelson, D.R., Trendall, A.F., Altermann, W., 1999. Chronological correlations between the Pilbara and Kaapvaal cratons. Precambrian Research 97, 165–189.

Niu, F., James, D.E., 2002. Fine structure of the lowermost crust beneath the Kaapvaal craton and its implications for crustal formation and evolution. Earth and Planetary Science Letters 200, 121-130.

Nkosi, N.Z., Manzi, M.S.D., Drennan, G.R., Yilmaz, H., 2017. Experimental measurements of seismic velocities on core sampels and their dependence on mineralogy and stress; Witwatersrand Basin (South Africa). Studia Geophysica et Geodaetica 61, 115-144.

Phillips, N.G., Law, J.D.M., 1994. Metamorphism of the Witwatersrand gold fields: A review. Ore Geology Reviews 9, 1-31.

Planetary Science Institute, 2017. Explorer's Guide to Impact Craters: Background. <http://www.psi.edu/epo/explorecraters/background.htm> (accessed 17.05.27).

Poujol, M., Robb, L.J., Anhaeusser, C.R., Gericke, B., 2003. A review of the geochronological constraints on the evolution of the Kaapvaal Craton, South Africa. Precambrian Research 127, 181–213.

Pretorius, D.A., Brink, W.C.J., Fouche, J., 1986. Geological map of the Witwatersrand Basin. In: Anhaeusser, C.R., Maske, S. (Eds.), Mineral Deposits of Southern Africa, vol. I. Geological Society of South Africa, Johannesburg.

Pretorius, C.C., Jamison, A.A., Irons. C., 1987. Seismic exploration in the Witwatersrand Basin, RSA. Exploration '87. Proceedings Geophysical Methods: advances in the state of the Art, 22, 241-253.

Pretorius, C.C., Muller, M.R., Larroque, M., Wilkins, C., 2003, A review of 16 years of hardrock seismic of the Kaapvaal Craton, in D.W. Eaton, B. Milkereit, and M. H. Salisbury, eds., Hardrock seismic exploration, geophysical developments. Society of Exploration Geophysics 10, 247–268.

Pretorius, C.C., Steenkamp, W.H., Smith, R.G., 1994, Developments in data acquisition, processing and interpretation over ten years of deep vibroseismic surveying in South Africa: Proceedings of the 15th Congress of the Council for Mining and Metallurgical Institutions. South African Institute of Mining and Metallurgy 3, 249–258.

Pretorius, C.C., Trewick, W.F., Irons, C., 2000, Application of 3D seismics to mine planning at the Vaal Reefs gold mine, number 10 shaft, Republic of South Africa. Geophysics 65, 1862–1870.

Rasmussen, B., Bekker, A., Fletcher, I.R., 2013. Correlation of Paleoproterozoic glaciations based on U–Pb zircon ages for tuff beds in the Transvaal and Huronian Supergroups. Earth and Planetary Science Letters 382, 173-180.

Rasmussen, B., Fletcher, I.R., Muhling, J.R., 2013. Dating deposition and low-grade metamorphism by in situ U-Pb geochronology of titanite in the Paleoproterozoic Timeball Hill Formation, southern Africa. Chemical Geology 351, 29-39.

Reimold, W.U., Gibson, R.L., 1996. Geology and evolution of the Vredefort Impact structure, South Africa. Journal of African Earth Sciences 23, 125-162.

Reimold, W.U., Gibson, R.L., 2006. The melt rocks of the Vredefort impact structure – Vredefort Granophyre and pseudotachylitic breccias: implications for impact cratering and the evolution of the Witwatersrand Basin. Chemie der Erde - Geochemistry 66, 1–35.

Reimold, W.U., Hoffmann, M., Hauser, N., Schmitt, R-T., Zaag, P.T., Mohr-Westerheide, T., 2016. A geochemical contribution to the discussion about the genesis of impact-related pseudotachylite breccias: Studies of PTB in the Otavi and Kudu Quarries of the Vredefort Dome support the “In Situ Formation” hypothesis. South African Journal of Geology 119, 453-472.

Reimold, W.U., Koeberl, C., 2014. Impact structures in Africa: A review. Journal of African Earth Sciences 93, 57-175.

SACS (South African Committee for Stratigraphy), 1980. Stratigraphy of South Africa. Part 1 (Comp. L.E. Kent). Lithostratigrahy of the Republic of South Africa, South West Africa/Namibia, and the Republics of Bophuthatswana, Transkei and Venda. Handbook Geological Survey South Africa 8, 690 p.

Salisbury, M.H., Harvey, G.W., Mathews, L., 2003, The acoustic properties of ores and host rocks in hardrock terranes, in D. W. Eaton, B. Milkereit, and M. H. Salisbury, eds., Hardrock seismic exploration, geophysical developments. Society of Exploration Geophysics 10, 9–19.

Simpson, C., 1978. The structure of the rim syncline of the Vredefort Dome. Transactions of the Geological Society of South Africa 81, 115-121.

Stauffer, M.R., 1988. Fold interference structures and coaptation folds. Tectonophysics 149, 339-343.

Sumner, D.Y., Beukes, N.J., 2006. Sequence stratigraphic development of the Neoarchean Transvaal carbonate platform, Kaapvaal Craton, South Africa. Geological Society of South Africa 109, 11-22.

Tinker, J., De Wit, M., Grotzinger, J., 2002. Seismic stratigraphic constrained on Neoarchean – Paleoproterozoic evolution of the western margin of the Kaapvaal craton, South Africa. South African Journal of Geology 105, 107-134.

Van Niekerk, C.B., Burger, A.J., 1978. A new age for the Ventersdorp acidic lavas. Transactions of the Geological Society of South Africa 81, 155-163.

Viljoen, M.J., 1994. Modeling of Witwatersrand gold reefs for effective planning and mining. SAIMM 1994 Vol.3 p 131-141.

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

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, 23-48.

Weder, E.E.W., 1994. Structure of the area south of the central rand gold mines as derived from a gravity and vibroseis surveys: Proceedings of the XVth CMMI Congress. South African Institute of Mining and metallurgy 3, 271-281.

Widess, M.B., 1973. How thin is thin bed? Geophysics 38, 1176–1180.

Zanchi, A., Salvi, F., Zanchetta, S., Sterlacchini, S., Guerra, G., 2009. 3D reconstruction of complex geological bodies: Examples from the Alps. Computers and Geosciences 35, 49-69.

Zeh, A., Ovtcharova, M., Wilson, A.H., Schaltegger, U., 2015. The Bushveld Complex was emplaced and cooled in less than one million years – results of zirconology, and geotectonic implications. Earth and Planetary Letters 418, 103-114.

Appendix

Figure A. Stratigraphy with geochronology (1/3)

Supergroup	Group	Subgroup	Formation	Age (Ma)	Method
Karoo	Drakensberg			187 [5]	(vv)
			Clarens	202 - 187 [5]	Fossil assemblages
			Elliot	215 - 202 [5]	Fossil assemblages
			Molteno	237 - 216 [5]	Fossil assemblages
	Beaufort	Tarkastad	Driekoppen	249.5 - 237 [5]	Fossil assemblages
			Verkykerskop	251 - 249.5 [5]	Fossil assemblages
		Adelaide	Normandien	253.8 - 251 [5]	Fossil assemblages
			Estcourt	266 - 253.8 [5]	Fossil assemblages
	Ecca		Volksrust		
			Vryheid		
			Pietermaritzburg	270 ± 1 [5] 288 ± 3 [5]	(vv)
	Dwyka			302 ± 3 [5]	(vv)
Vredefort Impact Event				2023 ± 4 [8]	U-Pb SHRIMP
Polyphase folding, thrusting, low-grade metamorphism in Transvaal SGp				2042.1 ± 2.9 [1]	Ar-Ar Step-heating laser probe
Bushveld Complex - Rustenberg Layered Suite				2055.91 ± 0.26 [20]	U-Pb zircon CA-ID-TIMS
Low-grade tectonothermal event				2145 ± 12 [15]	U-Pb SHRIMP (vv)
Transvaal	Pretoria		Rayton		
			Dullstroom		
			Houtenbek		
			Steenkampsberg		
			Nederhorst		
			Lakenvalei		
			Vermont		
			Magaliesberg	2193 ± 20 [3]	U-Pb zircon?
			Silverton		
			Daspoort	2236 ± 13 [3]	U-Pb zircon?
			Strubenkop		
			Dwaalheuwel		
			Hekpoort	2224 ± 21 [4] 2222 ± 13 [6]	Rb-Sr whole rock (vv) Pb-Pb whole rock (vv)
			Boshoek		
			Timeball Hill	2256 ± 6 [16] 2266 ± 4 [16] 2278 ± 7 [15] 2310 ± 9 [16] 2350 [7]	U-Pb SHRIMP (vv) U-Pb SHRIMP (vv) U-Pb SHRIMP (vv) U-Pb SHRIMP (vv) (vv)
			Rooihoogte		
	Chuniespoort		Duitschland		
			Penge	2465 ± 7 [12] 2480 ± 6 [13]	U-Pb SHRIMP? Unpublished
		Malmani	Frisco		
			Eccles		
			Lyttelton		
			Monte Christo		
			Oaktree	2550 ± 3 [18] 2583 ± 5 [11] 2588 ± 7 [11]	Single zircon Pb-evap (vv) U-Pb SHRIMP (vv) U-Pb SHRIMP (vv)
			Black Reef	Undated *(2642 ± 3 [11])**	**(Vryburg Fm - U-Pb SHRIMP) (vv)*

Figure A cont. Stratigraphy with geochronology (2/3)

Supergroup	Group	Subgroup	Formation	Age (Ma)	Method
Ventersdorp			Allanridge	Undated	(vv)
			Bothaville		
	Platberg		Rietgat		
			Makwassie	2643 ± 80 [17] 2693 ± 60 [19] 2709 ± 4 [2]	ID-TIMS (vv) Pb-Pb age (vv) U-Pb zircon SHRIMP (vv)
			Goedgenoeg		
			Kameeldoorns	Undated	(vv)
	Klipriviersberg		Edenville		
			Loraine		
			Jeannette		
			Orkney		
			Alberton	2714 ± 8 [2]	U-Pb zircon SHRIMP (vv)
		East Driefontein	Westonaria		
			Venterspost	2729 ± 19 [10]	U-Pb zircon SHRIMP
Witwatersrand	Central Rand	Turffontein	Mondeor	2849 ± 18 [9]	U-Pb zircon SHRIMP
			Elsburg		
			Kimberley		
		Johannesburg	Booysens	2894 ± 7 [9]	U-Pb zircon SHRIMP
			Krugersdorp	2872 ± 6 [9]	U-Pb zircon SHRIMP
			Luipaardsvlei		
			Randfontein		
			Main		
			Blyvooruitzicht	2902 ± 13 [9]	U-Pb zircon SHRIMP
	West Rand	Jeppestown	Maraisburg		
			Roodepoort		
			Crown	2914 ± 8 [2]	U-Pb zircon SHRIMP (vv)
			Babrosco		
			Rietkuil	2931 ± 8 [9]	U-Pb zircon SHRIMP
			Koedoeslaagte		
		Government	Afrikander		
			Elandslaagte		
			Palmietfontein		
			Tusschenin		
			Coronation		
			Promise	2991 ± 15 [9]	U-Pb zircon SHRIMP
		Hospital Hill	Bonanza	2990 ± 8 [9]	U-Pb zircon SHRIMP
			Brixton		
			Parktown		
			Orange Grove	2985 ± 14 [9]	U-Pb zircon SHRIMP
	Dominion		Syferfontein	3074 ± 6 [2]	U-Pb zircon SHRIMP (vv)
			Rhenosterhoek		
			Rhenosterspruit		
Granitoid-Greenstone Basement				3600 - 3200 [14]	

Figure A cont. Stratigraphy with geochronology (3/3)

Key:

(1) Alexandre et al. (2006; Micas in Phyllite, single-grain ^{40}Ar-^{39}Ar step-heating laser probe)

(2) Armstrong et al. (1991; Single zircon U-Pb SHRIMP)

(3) Bumby et al. (2012; Compilation of previous publications, no method stated)

(4) Burger and Coertze (1973-1974; Rb-Sr whole rocks age)

(5) Catuneanu et al. (2005; Volcanic units, fossil assemblages, no methods stated)

(6) Cornell et al. (1996; Ongeluk Formation; Pb-Pb whole rock isochron)

(7) Dankert and Hein (2010; Unpublished)

(8) Kamo et al. (1996; authigenic, unshocked zircon in pseodotchylite; U-Pb SHRIMP)

(9) Kositcin and Krapež (2004; Youngest concordant detrital zircon grain)

(10) Kositcin et al. (2003; Igneous-detrital xenotime/zircon aggregate)

(11) Martin et al. (1998; Single zircon U-Pb SHRIMP)

(12) Nelson et al. (1999; Kuruman Formation. From R.A. Armstrong, no method stated)

(13) Nelson et al. (1999; Unpublished data from A.F. Trendall, no method stated)

(14) Poujol et al. (2003)

(15) Rasmussen et al. (2013; Zircons in felsic tuff bed & matrix-filling titanite cement; U-Pb SHRIMP)

(16) Rasmussen et al. (2013; Zircons in felsic tuff bed; U-Pb SHRIMP)

(17) Van Niekirk and Burger (1978; ID-TIMS)

(18) Walveren and Martini (1995; Single zircon Pb-evaporation)

(19) Walveren et al. (1990; Pb-Pb age)

(20) Zeh et al. (2015; Marginal Zone of BC; Single zircon U-Pb CA-ID-TIMS)

(vv) Volcanic or pyroclastic unit

Table A1: List of Seismic Lines		
Ordered in sequence of interpretation		
Domain 1	**Domain 2**	**Domain 3**
1. OF-98	1. DV-274	1. DE-512B
2. OF-97	2. DV-272	2. DE-512A
3. OPR-50	3. DV-271	3. DE-511
4. KV-117	4. DV-270B	4. DE-506
5. KV-118	5. DV-270A	5. BH-171B
6. KV-132	6. BH-269	6. BH-171A
7. FV-155	7. FV-154	7. DE-83
8. OB-41	8. BH-268	8. DE-510
9. KV-120		9. DE-508
10. OB-74		10. DE-507

Table A2: List of Boreholes			Borehole Count = 208			Coordinate System: WGS84 – UTM – 35S		
Borehole ID	X	Y	Borehole ID	X	Y	Borehole ID	X	Y
4001916	535205.0013	7091997.477	4014246	493527.7899	7021651.239	4020161	505134.8004	7039652.277
4001957	536734.2343	7075433.083	4014247	482982.4638	7016353.304	4020175	523724.4181	7025695.014
4001982	535034.8701	7072724.062	4014252	483532.0624	7017622.785	4020176	522478.8957	7023389.87
4001986	534834.9868	7073963.488	4014263	482855.3234	7017163.778	4020179	520238.1466	7020501.656
4002003	536334.5471	7070834.537	4014266	486031.0848	7018992.139	4020246	501469.4424	7029398.757
4002009	535284.7993	7071684.07	4014273	491403.7945	7033747.101	4020247	500112.0569	7029505.612
4002024	535434.7105	7071324.373	4014274	496121.6292	7034646.891	4020248	504771.8814	7013375.225
4002173	535159.9706	7076032.789	4014286	490154.2979	7027969.329	4020400	515553.3733	7036516.115
4002229	537284.0841	7076732.509	4014331	483468.1355	7015298.639	4020640	557862.2381	7067277.919
4003209	586873.3165	6974866.348	4014589	565421.8611	7068410.317	4020677	560751.9939	7068114.584
4003241	530337.0644	6975317.033	4019199	496151.5219	7016213.19	4020753	529017.5803	7028628.883
4013807	480133.6104	7041314.455	4019879	470062.9355	7064806.742	4021465	597354.729	7026202.62
4013808	480208.3381	7042044.342	4019894	477329.8044	7049791.736	4021718	611223.0773	7029143.288
4013811	479708.5961	7043318.794	4019899	473461.281	7063787.017	4021721	609555.3518	7028428.984
4013812	479723.8333	7043119.125	4019901	467473.7647	7064866.532	4026008	518931.8577	7073033.85
4013817	492753.021	7053190.666	4020073	501373.4459	7065851.138	4026013	519441.7792	7073128.776
4013818	496801.5257	7050291.575	4020078	518866.9153	7064080.972	4026016	518741.853	7072413.921
4013826	489539.4565	7050801.459	4020105	518206.1765	7061213.654	4026022	518362.1768	7073733.741
4013833	484106.7859	7051266.198	4020107	513710.1657	7059823.238	4026023	517542.3242	7073793.587
4013845	507286.9822	7051616.167	4020110	516093.1617	7056164.595	4026138	515505.2825	7067778.749
4013846	494952.2065	7043608.712	4020111	513400.3769	7051221.337	4026139	517878.2849	7070086.935
4013847	493417.8003	7045443.216	4020116	510682.4424	7046774.687	4026206	519541.6713	7067845.54
4014048	488605.0203	7032847.423	4020117	515943.1774	7054050.383	4026240	518284.3351	7067671.636
4014110	479568.7282	7037370.965	4020118	513400.3769	7051221.337	4026252	521077.9896	7068227.301
4014113	488175.2491	7034656.458	4020119	508866.177	7052316.014	4026642	619934.2039	7077568.233
4014127	481457.9065	7017202.66	4020120	512824.6686	7044693.611	4026643	614426.8142	7077019.1
4014237	484581.6052	7014478.888	4020122	524209.7379	7066536.213	4026644	615766.9247	7082827.189

4014238	487090.4786	7017537.792	4020130	539258.0463	7065136.578	4026645	602239.825	7077643.1
4031630	616536.3534	7056798.793	4039845	583339.1523	6992636.287	4054305	513570.4979	7052857.326
4032848	489604.5828	6987362.97	4039846	590486.3083	6991611.777	4054313	503450.8676	7054507.793
4032859	492403.3298	6962596.441	4039847	567492.2378	6972194.253	4054316	504797.9486	7058838.801
4032871	491503.7233	6958398.118	4039848	577841.7099	6963521.26	4054317	504698.0977	7051341.057
4032907	490110.0717	6960900.076	4039849	597958.0855	6982614.504	4054318	506926.9918	7049891.707
4032946	495826.7633	6967469.91	4039854	502774.9503	6954403.265	4054319	534220.8093	7066402.802
4032947	494817.1918	6964758.86	4039855	500125.0689	6950750.674	4054335	518337.3549	7013678.704
4032973	490918.8288	6967685.696	4039873	546484.9348	6946270.149	4054336	516603.6991	7014170.016
4032981	490679.0096	6969918.997	4039875	544600.7824	6948336.325	4054337	559571.0691	7066560.005
4032983	492803.0648	6970268.779	4039882	542880.562	6949535.165	4054354	590345.0778	7037741.137
4032984	498901.6346	6971606.441	4039884	545805.3325	6950350.686	4054356	595109.051	7019802.028
4032985	487055.5713	6976466.931	4039893	545105.548	6949226.185	4057334	497351.279	7018602.455
4037657	496301.5888	6944377.816	4039895	540144.8868	6951146.544	4063523	596008.8404	7016727.947
4037663	492903.0847	6943228.077	4039963	559874.3463	6949725.784	4065900	545930.3447	6953199.818
4037666	497532.0045	6942367.332	4039964	562373.1435	6955324.019	4065902	528929.7263	6942740.314
4038363	600610.9111	7019867.696	4039970	568895.4867	6948751.483	4065922	541007.2243	6952449.892
4038467	485756.1136	6971968.434	4039971	550303.4647	6945977.183	4065923	548529.1553	6951225.464
4038495	605257.9818	7006122.993	4039972	555651.2274	6945227.39	4065924	546876.6129	6949615.527
4038540	517344.6626	7058537.396	4039973	560035.1233	6947231.677	4065927	487488.2714	6957304.504
4039786	523104.6673	6990329.878	4039990	565472.0176	6944027.764	4065980	486805.6481	6959647.404
4039790	519763.8795	6991780.886	4039991	564847.2151	6944352.688	4066005	487488.2714	6957304.504
4039795	521400.8369	6994355.514	4039992	565197.0503	6943053.186	4066121	594484.3809	6984289.132
4039798	521271.5614	6994183.168	4039993	560898.9069	6943228.073	4066123	586212.9582	6984589.211
4039803	521049.3728	6994129.051	4042224	518921.0941	7013315.983	4066128	586937.5917	6982864.562
4039818	517942.2093	7007756.045	4042239	518251.4079	7013661.329	4066130	587937.3946	6977766.395
4039825	516178.1496	7010798.49	4042246	518838.7852	7011166.809	4066131	590086.4209	6974492.465
4039832	524989.3505	6995260.506	4049228	515593.2181	7033447.222	4066135	513744.1089	6975767.029
4039837	526613.5338	6989212.442	4054294	516375.9799	7064302.148	4066136	512394.6413	6982789.7
4039838	490629.0561	6982589.551	4054297	521952.4194	7063147.156	4066137	503548.4851	6969744.235
4039843	529587.1849	6979640.606	4077870	584513.748	6984864.018	4066139	522140.6001	6972093.349

4039844	549978.698	6970268.812
4066140	528737.5699	6974642.42
4066142	547429.5437	6964045.994
4066144	520437.4731	6996843.421
4225646	554839.9346	6974880.201
4213937	549054.0148	7008555.635
4066145	521915.6135	6995560.047
4066147	516327.0152	7009792.263
4066154	519741.6589	7005506.768
4066155	524542.189	6995132.469
4066156	526213.8105	7022375.946
4066285	562173.3709	6946476.893
4066437	558240.8639	6942818.237
4066445	564588.5825	6954335.941
4066449	563039.0807	6951418.57
4066451	558283.3859	6943973.862
4066471	564497.398	6943003.404
4066475	564172.4157	6942178.616
4066476	563797.5089	6943378.189
4066477	563397.855	6941353.732
4072097	523259.0749	6994782.046
4072098	522517.3952	6994582.156
4072918	560035.1233	6947231.677
4073495	512394.6662	6982814.622

4079268	487019.4788	6975701.951
4107911	504771.8814	7013375.225
4126376	584538.8615	6980889.429
4202051	576617.2047	6980373.336
4202532	610281.0689	6999959.177
4203936	489914.4692	6994560.579
4204331	565971.7791	6948776.157
4213253	598577.6084	6984039.314
4074782	494410.3412	6943758.006
4079068	571298.3489	7017603.278

Table A3: Surface information: topographic data, geological maps, and geophysical images
Conditioning and coordinate conversion of maps. Two methods could be applied: 1. Using ArcGIS®, a map layout is created of the image that includes the base coordinate system grid (WGS84 – UTM35S) in the output map. The map is exported as a tiff image and georeferenced in Leapfrog Geo® using the grid lines. A simple three-point georeferencing tool in LeapFrog Geo® is automatically initiated when importing images. The image is then loaded into the 3D modelling space and can be draped onto the topographic surface. 2. Using Global Mapper™, the georeferenced image is opened and the coordinate system is changed in the Tools menu to WGS84 – UTM35S. The image is exported as a new geotiff to be imported into Leapfrog Geo® (no georeferencing inside Leapfrog Geo® required). Global Mapper™ was also used to combine several georeferenced images and export them as a single georeferenced image. This was useful when combining geological maps so they can be viewed together, e.g. the 1:250,000 scale geology maps, several of which covered the study area. Digitised surface mapping structure points 1. In ArcGIS® create a new structure shapefile (‘Points’ type) and add new table columns for: a. Structure Type (string) b. Source Map (string) c. Strike (short integer) d. Dip (short integer) e. Dip Direction (short integer) f. Azimuth (short integer) g. Plunge (short integer) h. Supergroup (string) i. Group (string) j. Subgroup (string) k. Formation (string) l. Comments (string) m. X_WGS84_UTM35S (double integer) n. Y_WGS84_UTM35S (double integer) 2. Load available geology maps (1:1,000,000 and 1:250,000 scale maps, and a 1:50,000 scale map of Vredefort), digitise each structure point and input the information into the various columns of the structure shapefile. The x and y coordinate columns can be created using the “Add XY Coordinates” tool in the ArcToolbox application, and renaming the columns as those stated in steps 1.m and 1.n.

Table A4: Cross-Sectional Information

Summary steps for converting seismic lines to WGS84 – UTM35S:

1. In Kingdom Suite® export the shot point coordinates for the line into an excel spreadsheet (i.e. in the local grid format).
2. Convert to the LO27 coordinate system that the ArcGIS® trace shapefile is in. Pick out a reference point in the line trace to match points in both coordinate system datasets, in order to georeference the points of the local grid space as the LO27 coordinate space.
3. Find the differences between the respective X and Y coordinates of the reference points in the local grid and the LO27 grid. Generally the X difference is close to 100,000 and the Y difference is around 100. Using these two values add/subtract them to/from the rest of the local grid shot point coordinates to bring the entire line into the LO27 grid system. Plot these points in ArcGIS® to see whether adding or subtracting the values will provide the correctly orientated geometry because the projected values should match the geometry of the trace shapefile. This step requires flexibility as some lines have odd local grids. The idea is to try "fit" the line geometry of the local grid into the LO27 grid. The lines generally follow the roads so have unique non-linear geometries that makes numerically "fitting" the lines easier.
4. Prepare for UTM conversion by saving a new Excel file with only the LO27 coordinates for the shotpoints.
5. Convert to UTM. In ArcGIS® import the LO27 coordinates Excel file and save the data as a new shapefile. In the ArcToolbox find the "Projection & Transformations" menu and use the "Project" function to analyse the LO27 shapefile and output a new shapefile with a coordinate projection of WGS84 – UTM Zone 35S. In this new UTM shapefile add X and Y coordinate columns to the attribute table using the "Add XY Coordinates" function in the "Data Management Tools" => "Features" menu of the ArcToolbox. This function will add the UTM coordinates to each shotpoint in the table because this table must then be exported to a .txt file.
6. Update the Kingdom Suite® line coordinates. In a new Excel file open the .txt file of the UTM projected shotpoints. The coordinate values contain commas which Excel doesn't recognise as numbers. Use the "Find/Replace" function to replace the commas with null (i.e. replace "," with a space, " ") in order to change the value type from text to numbers. Open the Kingdom Suite® coordinate table for the specific line (World Coordinate dialog) and overwrite (Copy/Paste) the local grid shotpoint values with the UTM values in the Excel file. The line will now be projected in the WGS84 – UTM35S coordinate system.
7. Repeat steps 1 – 6 for all 28 seismic lines.

Table A5: Identification Process of Priority Boreholes for Digitising
1. Create Excel table with headings that include; a. Seismic Line # b. Borehole ID c. Borehole Depth d. Digital Log? (Y/N) e. Off Section (m) f. Comments 2. Import 2D seismic lines and boreholes (including CG-digitised lithology) into LeapFrog Geo® and analyse data as per the Excel table above. a. Start from one end of basin (e.g. north east corner); for each seismic line look for boreholes that lie close to it (parallel to the line section), preferably within a few hundred meters. b. In the Excel table record the borehole ID, borehole depth, whether the hole has an available lithology log or not, how far off section the borehole is, and comment on any specific characteristics about the borehole (e.g. on regional strike, wedge holes use same collar location etc.) c. In the seismic lines layer use the symbols window to hide lines which have been analysed, to limit duplication and confusion. d. Not all the lines have boreholes in vicinity. e. Note in a separate Excel tab which lines do not display/plot in Leapfrog (i.e. no data). 3. Access Database creation and data input. a. Open Access (file saved as "CG – Wits Basin DD") and import raw data into new tables for: i. All borehole collars. ii. All lithologies. iii. All seismic lines. b. Create a new table of seismic lines which have corresponding boreholes and import the data collected in the Excel file from step (1). c. Create a new table for lines that did not plot in Leapfrog and import the data from the Excel tab in step (2.e). d. Query the seismic lines which do not have borehole association. e. Query further the boreholes corresponding to seismic lines: i. Drillholes which have available lithology logs. ii. Boreholes which do not have available lithology logs. 4. In ArcGIS® plot the corresponding boreholes from the database table in step (3.b) and identify all the borehole ID's for each collar position (i.e. selecting both parent and deflection ID's). This step extracts boreholes with duplicated collar locations (i.e. deflection holes) that were not picked up in the LeapFrog Geo® stage. a. Create a buffer zone (1m) around each borehole collar and save the buffer as a new shapefile. This zone now overlaps all borehole ID's in that collar position.

	b.	Select the 'Clip' Function and clip the shapefile containing the borehole collars ('Input Features') with the 1m buffer shapefile ('Clip Features'). This will create a new shapefile containing all collars inside the 1 m buffer zones. Export the shapefile as a text document, i.e. to create a table of borehole collar ID's for data capture.
5.	Import the table from step (4.b) into the Access Database in a new table, e.g. 'Collar IDs in 1m Buffer'.	
6.	Go to the CG and photograph all borehole log sheets in this table for digitising.	

Table A6: Digitised Borehole Log Template Structure

1.	1st column empty	(required for importing Excel tables into the Access Database table)
2.	Borehole_ID	
3.	From_(ft)	(only recorded for logs using Imperial units)
4.	To_(ft)	(only recorded for logs using Imperial units)
5.	From_(m)	
6.	To_(m)	
7.	Thickness (m)	
8.	Lith_Type	(category placement for main lithology type e.g. Shale, Intrusive etc.)
9.	Lith_Desc	(rock description as given in log)
10.	Str_Type	(type of structure if stated in log)
11.	Marker_Horizon	(marker horizons that can be used as filters, e.g. Black Reef)
12.	Comments	(additional comments not applicable to Lith_Desc; or an extension of the Lith_Desc if the log was >250 characters long)
13.	Supergroup	(only if stated or deducible from marker horizons)
14.	Group	(only if stated or deducible from marker horizons)
15.	Subgroup	(only if stated or deducible from marker horizons)
16.	Formation	(only if stated or deducible from marker horizons)
17.	Local_Fm_Name	(local nomenclature of rock formation)

Table A7: Procedure to Estimate Depths not Stated in the Borehole Logs	
1.	With the photograph opened in Windows Photo Viewer zoom in to where there are at least two depth values in the log. Do not change the zoom level, only pan to other parts of the log.
2.	Using a ruler, measure the length (in millimetres) on the computer screen (Screen Length) of the log, between two logged depths (Depth A and Depth B) and note this distance (in an open space in the lithology log data capturing Excel spreadsheet being used).
3.	Calculate the logged thickness (in metres) between the two depths (i.e. Depth B minus Depth A = Thickness C). Note the thickness.
4.	Calculate the Ratio of logged metres per millimetre of computer screen (m/mm), i.e. Thickness C divided by Screen Length = Ratio.
5.	Using a ruler, measure the length (in millimetres) of the log, on the computer screen, from the last stated depth down to the absent measurement depth, note this distance.
6.	Multiply this distance by the Ratio (i.e. mm x m/mm = m) to estimate the logged distance (in metres) from the existing depth to the absent depth. Add this distance to the existing depth to get the value of the absent depth.

Table A8: Interpretation Process of Each Seismic Line	
1.	Commence at the surface and interpret downwards in order to use surface/near-surface constraining information (i.e. surface mapping and boreholes).
2.	Incorporate adjacent surface mapping and borehole information as well as previously interpreted cross-cutting seismic lines.
3.	Identify and justify major reflectors using given information (i.e. surface mapping, boreholes, stratigraphy, and cross-cutting seismic lines).
4.	Identify and justify minor reflectors (illustrate with discrete horizons). These horizons are not defined or continuous enough to be used in regional correlation for the geological model.
5.	Identify and justify major structural breaks in the reflectors and indicate using discrete fault horizons.
6.	Dynamic interpretation of all cross-cutting seismic line sections. Review and adjust interpreted sections as new sections are incorporated. Major reflectors must be consistent throughout the cross-cutting seismic line sections while still honouring the data.
In addition to these steps a couple important aspects were considered during the interpretations.	
1.	Honour the data with logical and simple interpretations, particularly in poorly resolved areas of the section. Therefore limit the illustrated horizons to the larger-scale, lower-order features.
2.	To avoid over-interpretation do not use excessive/overly-complicated structural interpretations to account for reflection disturbances. Some small-scale breaks (less than a couple hundred meters offset) can be incorporated within larger-scale fault systems but these must be limited.

Table A9: Procedure for Creating Each Vertical Mesh in Leapfrog Geo®	
1.	Create a new project called "Seismic Line Mesh Creation". Repeat steps 2 to 13 for each of the 28 seismic lines.
2.	Import the line trace from Kingdom Suite®.
3.	Create a new polyline for the line trace and digitise the zigzagging line trace to create a linear polyline with no breaks or zigzags.
4.	Use the "Estimate Structure Data" tool to extract the points from the polyline.
5.	Export the structure data points to a csv file.
6.	Edit the csv file in Excel to omit structural information as it is artificial, leaving only the X, Y and Z columns.
7.	Import the XYZ points back into LeapFrog Geo® and check for consistency with the original line trace. They should have the same geometries.
8.	Open the XYZ csv file in Excel and create additional Z columns of 2000m intervals, i.e. from 0m to -18000m. The original line trace is at surface elevation, around +1500m. This provides eleven set elevations for the line trace to be projected at.
9.	In LeapFrog Geo® import each depth trace interval as points (eleven traces in total including the surface points trace).
10.	Use the "Create Mesh" function and apply the surface trace as the input dataset (using 100m resolution, and ticking the 'Adaptive' parameter). a. Add the ten additional depth trace intervals to the newly created mesh to produce the final vertical mesh. b. In the properties of the mesh apply 'Snap to Data', with minimum distance of 25m.
11.	Export the final mesh and import into the main LeapFrog Geo® project.
12.	In the main LeapFrog Geo® project use the "Cross Section from Image" function and import the raw seismic line section and the interpretation. a. Georeference the two images (select Vertical Section option and correlate section surface with topography) and crop them to remove unnecessary excess that will clutter the images where there is overlapping of line traces. b. Ensure the two images are consistent with each other, i.e. no deviation of reflections between the two images.
13.	In the mesh options menu drape the georeferenced raw and interpreted sections onto the mesh. The ~19500m vertical width of the mesh should be wide enough to incorporate the georeferenced images without cutting out any parts of the section.
14.	For the 16 second data include 2000m intervals down to 48km (totalling 26 trace depths, including the surface trace).
15.	Create new polylines for horizons and faults and digitise the draped mesh images.

Table B: Other Available Datasets		
Data Type	**Data Information**	**Data Usage**
Stratigraphy by SACS	• Stratigraphic record observed in study area.	• Provides correlation of known regional stratigraphy with stratigraphy recorded by surface mapping in the study area. • Record of formations that are preserved or missing is used to guide the interpretation of the seismic line sections.
Surface Mapping	• 1:250,000 scale surface maps covering entire study area (Coetzee, 1986, Wilkinson, 1986, Smith, 1992, and Retief, 2000). • 1:50,000 scale surface map covering the Vredefort dome area (Bisschoff et al., 1999).	• Mapped stratigraphy constrains the formations in the study area, providing information on lithological preservation at depth for the seismic line interpretations. • Lithology contacts digitised for surface constraint on 3D geological model. • Structural data points captured/digitised to constrain orientations of units at surface for the 3D geological model.
Boreholes	• 208 archived hardcopy borehole logs from the Council for Geoscience. Downhole survey information is not tabulated and most logs contain plan view illustrations of the borehole trace, therefore archived borehole orientation information is limited to the plunge and azimuth measured between the collar position and the end-of-hole position. Majority of boreholes are subvertical. Some boreholes within the Vredefort dome area are more shallowly inclined.	• Captured/digitised into a borehole database and plotted in 3D workspace to constrain the seismic lines and the 3D geological model at depth.

Table C: Published P-Wave Velocities (V_p) and Bulk Densities (ρ) for Stratigraphy Encountered in the Study area					
Stratigraphic Unit	**Rock Type**	**P-Wave Velocity (m/s)**	**Bulk Density (g/cm^3)**	**Reflection Coefficient**	**Reference**
Karoo Supergroup	Various interlayered sediments (mudstone, sandstone, tillite)	3200 [2] 3195 [1] 3000 [3]	2.38 (sandstone) [4] 2.54 (mudstone) [4]		[1]Pretorius et al., 1987 [2]De Wet and Hall, 1994 [3]Weder, 1994 [4]Jones, 2003
				+0.336 [1]	[1]Pretorius et al., 1987
Hekpoort Formation	Volcanic (basaltic andesites and pyroclastics)	6083 [1]	2.83 [4]		[1]Pretorius et al., 1987 [4]Jones, 2003
				-0.068 [1]	[1]Pretorius et al., 1987
Timeball Hill Formation	Shale dominated (minor quartzite, volcanics and diamictites)	5513 [1]	2.80 (shale) [4] 2.67 (quartzite) [4]		[1]Pretorius et al., 1987 [4]Jones, 2003
				+0.143 [1]	[1]Pretorius et al., 1987
Malmani Subgroup	Dolomite (minor chert)	6834 [1] 6600 [3]	2.84 (dolomite) [4] 2.65 (chert) [4] 2.71 (shale) [4]		[1]Pretorius et al., 1987 [3]Weder, 1994 [4]Jones, 2003
				-0.061 [1]	[1]Pretorius et al., 1987
Pniel Sequence*	Allanridge Formation = quartzite, greywacke Bothaville Formation = mafic volcanics	6159 [1]	2.84 (volcanics) [4] 2.70 (quartzite) [4] 2.76 (shale) [4]		[1]Pretorius et al., 1987 [4]Jones, 2003
				-0.028 [1]	[1]Pretorius et al., 1987
Platberg Group	Various interlayered sedimentary and volcanisedimentary units (shales, quartzite, conglomerate, mafic to felsic volcanics)	5827 [1]	2.81 (volcanics) [4] 2.73 (quartzite) [4] 2.80 (shale) [4]		[1]Pretorius et al., 1987 [4]Jones, 2003

				+0.033 [1]	[1]Pretorius et al., 1987
Klipriviersberg Group	Mafic volcanics	6400 [2] 6300 [3] 6230 [1]	2.88 (volcanics) [4] 2.90 (volcanics) [5]		[1]Pretorius et al., 1987 [2]De Wet and Hall, 1994 [3]Weder, 1994 [4]Jones, 2003 [5]Manzi et al., 2014
				-0.065 [1]	[1]Pretorius et al., 1987
Central Rand Group	Quartzite and conglomerate (minor shales and rare volcanics)	5779 [1] 5750 [2] 5550 [3]	2.69 (quartzite/conglom) [4] 2.67 (quartzite) [5] 2.66 – 2.87 (quartzite) [6] 2.79 (shale) [4]		[1]Pretorius et al., 1987 [2]De Wet and Hall, 1994 [3]Weder, 1994 [4]Jones, 2003 [5]Manzi et al., 2014 [6]Nkosi et al., 2017
				+0.025 [1]	[1]Pretorius et al., 1987
West Rand Group	Various interlayered sediments (magnetic and non-magnetic shale, quartzite, conglomerate, minor diamictite and rare volcanics)	5748 [1]	2.70 (quartzite) [4] 2.87 – 3.15 (shale) [6] **		[1]Pretorius et al., 1987 [4]Jones, 2003 [6]Nkosi et al., 2017
				-0.018	This study
Dominion Group	Tholeiitic andesite (minor quartzite, conglomerate)	~6000***	2.78 (volcanics) [4]		[4]Jones, 2003
				-0.012	This study
Basement	Granitoid	5693 [1]	2.86 [7]		[1]Pretorius et al., 1987 [7]Niu and James, 2002

* The Pniel Sequence is not recognised by SACS and therefore the Bothaville and Allanridge Formations that constitute it are standalone formations (Johnson et al., 2006).

** The shale density measurements of Nkosi et al. (2017) have been used to estimate the density range of the West Rand Group shales.

*** The Dominion Group P-wave velocity was estimated with reference to the comparable rock types/bulk densities of the Hekpoort Formation and Klipriviersberg Group.

Table D: Supplementary Information for Chapter 4.3.		
Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The Karoo Supergroup covers roughly two thirds of the study area towards the south and east. Tertiary/Quaternary sediments cover parts of the south-western portion. Structural information for the Karoo Supergroup indicates a subhorizontal dip of the units throughout the study area, therefore reflection orientations will be roughly subhorizontal. Karoo Supergroup stratigraphy within the study area is limited to the Dwyka and Ecca groups with lesser exposures of the Adelaide Subgroup of the Beaufort Group.	The thickness of the Tertiary/Quaternary sediments reported in the boreholes is negligible on the regional scale as sediment depths are only a few tens of meters at most. The Karoo Supergroup does not vary greatly over the preserved area. General thickness increases towards the southern and eastern portions with maximum thickness reaching 460m depth towards the margins of the study area. Borehole 4202532 on the eastern margin reports a lower contact of 613.64m for the basal Dwyka Group tillite.
Pretoria Group – Chuniespoort Group	Surface exposures of the Transvaal Supergroup occur predominantly in the northern and western parts of the study area. There are also several narrow inliers through the Karoo Supergroup that expose the units. The mapped Pretoria and Chuniespoort groups form an arc around the Vredefort dome. The stratigraphy of the Pretoria Group reported in the study area is limited to the lower half of the stratigraphic column (i.e. Rooihoogte – Magaliesberg formations). However there are a few stratigraphic formations that are not preserved in this study area, i.e. the Rooihoogte and Dwaalheuwel formations. The Boshoek and Silverton formations are very rarely preserved in this area compared to the exposures north of the study area. The dominant and most continuous formations of the Pretoria Group in the mapped study area are the Timeball Hill, Hekpoort, Strubenkop, and Daspoort formations. The central	Borehole logs of the Pretoria Group show preservation of the stratigraphy on the western to southern margins of the study area. Borehole thickness of the group is increases towards the western and northwest sections of the study area where thicknesses range between 1400m and 2100m. The thickest report of Pretoria Group comes from borehole 4014246 that is subvertical and has an end depth of 2340.30m. However it lies entirely within the Pretoria Group and does not reach the lower contact with the Chuniespoort Group. The uppermost formation preserved in this borehole is the Magaliesberg Formation. The preservation of stratigraphy is similar to the surface mapping information. The Rooihoogte Formation is reported in a few boreholes (<40m thicknesses) in the northwest margin of the study area and is highlighted by the Bevets Member conglomerate. However in the rest of the study area the

parts of the mapped Pretoria Group also contain bedding-parallel diorite intrusions (sills).

The Chuniespoort Group stratigraphy is limited in the study area to the Malmani Subgroup. The Penge and Duitschland formations are not preserved. The contact between the Pretoria Group and the underlying Chuniespoort Group is repeated twice away from the Vredefort dome. One contact lies on the margin of the dome (forming a semi-circular ring ~35km from the centre of the dome) and the second contact lies further away and more obliquely to the dome (50 – 90km away from the centre of the dome).

The Chuniespoort Group exposed in the surface mapping is narrow (<3km) on the ring exposure around the Vredefort dome margin, with bedding orientations ranging between 40° and 70° (dipping away from the dome). The second, further exposure of the Chuniespoort Group is much wider (3 – 20km) and shallower-dipping (ranging between 10° and 20° and dipping towards the dome) compared to the dome margin exposure.

Using the stratigraphic distribution of formations and structural orientations the regional geometry of the Transvaal Supergroup in the study area exhibits a dominant asymmetric synclinal fold tangential to the Vredefort dome.

Throughout the Pretoria Group surface exposure the mapping indicates the existence of multiple elongated periclinal folds. These are interpreted through interference of varying fold orientations around the Vredefort dome. Anticlinal and synclinal fold geometries are identified using the mapped stratigraphy patterns and structural orientations plotted around the folds. The long axes

finer stratigraphy of the Transvaal Supergroup is mostly unknown in the borehole logs and is limited to clearly defined units such as the Hekpoort Formation volcanics and the Malmani Subgroup dolomites. Sedimentary units are not defined stratigraphically so the finer-detailed stratigraphy of the Pretoria Group is less constrained.

The boreholes in the southeast section of the study area do not report Pretoria Group units. Several boreholes are located on the eastern margin and but report Chuniespoort Group or lower stratigraphy. Surface mapping to the north of these boreholes indicate that the Pretoria Group, if projected on strike, under the Karoo Supergroup cover, would be preserved to the west of these boreholes so the Pretoria Group may still be preserved here.

Borehole logs of the Chuniespoort Group report 1000 – 1900m thick Malmani Subgroup dolomites, preserved in most boreholes in the study area, outside the dome, except for the SW corner and the SE section of the study area where pre-Transvaal Supergroup formations are preserved below the Karoo Supergroup cover.

The stratigraphy reported in the borehole logs for the Chuniespoort Group are similar to the surface mapping reports. The Penge Formation ironstones are not reported in any borehole. However the Duitschland Formation carbonates are not explicitly omitted from the logs as the lack of Penge Formation ironstones may result in the merging of logged carbonate sequences for the Malmani Subgroup and Duitschland Formation. The Malmani Subgroup is also not commonly differentiated into its individual formations in the study area and any carbonate sequences are grouped together as the Malmani Subgroup dolomites. Chert content reported in the

	(>12km wavelength) of the periclinal folds are all tangential to the Vredefort dome. The seismic lines in the northern part of Domain 1 intersect the mapped exposure of the Pretoria Group and at least one of the elongated periclines on the western margin of the Vredefort dome. Unfortunately the Quaternary and Karoo Supergroup cover in the rest of the study area limits the mappable extents of the Transvaal Supergroup and periclinal folds.	boreholes also varies within the undifferentiated Malmani Subgroup dolomites. The distribution of intrusion intersections in the boreholes that sample the Transvaal Supergroup exhibits a distinct lack of preservation within the reported Chuniespoort Group intervals in most of the study area. The intrusives appear to be constrained to the adjacent stratigraphy in those parts. The few boreholes located towards the eastern margin of the study area do however report several, generally thin intrusives intervals.
Black Reef Formation	The surface mapping of the Black Reef Formation in the study area limits the formation to the central uplift area, in a semi-circular arc ~32km away from the centre of the Vredefort dome, preserved at surface in the northern and western sections of the Vredefort dome. The formation is repeated further away, beyond the margins of the study area and outcrops more obliquely to the dome (70 – 100km away from the centre of the dome). The younger Quaternary sediments and Karoo Supergroup cover the potential eastern and southern outcrop extents of the formation. However with several narrow inliers showing lithologies from adjacent stratigraphy it is suggested that the formation is continuous underneath parts of the cover. The surface mapping exposures of the Black Reef Formation in the study area are indicated by a thin continuous semi-circular strip, up to 350m wide, with dips ranging between 20° and 70° (dipping away from the dome). The mapped outcrop beyond the margins of the study area are similarly narrow and continuous but are exposed over wider intervals, up to 800m, and exhibit shallower dips, ranging between 5° and 20° (dipping towards the dome). The mapped surface widths (apparent thicknesses), adjacent stratigraphy and	Borehole logs in the study area report the Black Reef Formation in a semi-circular zone around the Vredefort dome. The thickness of the formation varies but is limited to between 2m and 100m (these are borehole intervals and therefore are apparent thicknesses). The boreholes that do not report the Black Reef Formation are either boreholes that end in younger stratigraphy of the Transvaal Supergroup, or boreholes that contain no preserved Transvaal Supergroup as the Karoo Supergroup lies in contact with older stratigraphy instead (i.e. Ventersdorp or Witwatersrand Supergroups). The region where the Transvaal Supergroup is not preserved in the boreholes defines the outer limits of the semi-circular zone of Transvaal Supergroup around the Vredefort dome. This bounding region extends from the SW corner, eastwards on the southern margin, covers the entire SE section, and extends north on the eastern margin into the NE corner. There are several boreholes adjacent to and within the study area that report the Black Reef Formation (and the overlying Malmani Subgroup) in contact with the Central Rand Group quartzites, implying truncation

	bedding orientation information suggest a similar regional geometry as suggested for the overlying Chuniespoort and Pretoria Groups, i.e. a dominant asymmetric synclinal fold tangential to the Vredefort dome. The contact lithologies of the Black Reef Formation in the surface mapping are the Ventersdorp Supergroup (lower contact) and the Malmani Subgroup dolomites (upper contact). In the study area the Ventersdorp Supergroup exposure is constrained to the Klipriviersberg Group in both the 1:250000 and 1:50000 surface maps. The Kroonstad 1:250000 surface map does also contain narrow, stippled patches of Makwassie Formation volcanics (Platberg Group). It is unclear why the adjacent surface maps do not continue this stratigraphy. The sedimentary sequences of the Platberg Group (i.e. Rietgat and Kameeldoorns formations) and overlying Bothaville Formation are not reported in the surface maps in the study area.	through the Ventersdorp Supergroup. The boreholes showing this contact that lie in the study area include 4013846, 4014273, and 4014274 located in the NW corner, and 4063523 located in the eastern section. A group of boreholes adjacent to the study area in the NW corner also show this contact. These boreholes include 4013845, 4014048, 4014113, 4054313, 4054318, 4054316, and 4054317.
Venterspost Contact Formation (VCF)	The contact between the Ventersdorp Supergroup and the Central Rand Group is defined by the Venterspost Formation (here referred to as the Venterspost Contact Formation, or VCF), the base formation of the Klipriviersberg Group volcanics. This formation consists of quartzite, minor komatiitic lenses, and a basal conglomerate (Johnson et al., 2006). However it appears the surface mapping scales are too large to illustrate this formation, so only the adjacent lithologies to the contact are presented (the Klipriviersberg Group volcanics and the Central Rand Group quartzites). The surface mapping in the study area shows the contact between the Ventersdorp and Witwatersrand Supergroups as a semi-circular arc around the northern and western margins of the Vredefort dome, roughly 26 – 30 km from the centre of dome. Adjacent stratigraphy indicate the units are overturned,	Several boreholes report the Venterspost Formation in the logs, however the majority are outside the study area. A few boreholes in the study area show the formation, i.e. boreholes 4039825, 4054336, 4013847 in the NW section and 4021465, 4021721, 4021718 in the north-eastern margin. The north-eastern margin boreholes also report the Westonaria Formation above the Venterspost Formation. Borehole intersections of the VCF in the study area are only a few meters thick, whereas some boreholes to the north of the study area report much thicker intervals, 10 – 25m. Borehole logs that were digitised (archives provided by the CG) were mainly summary logs, so the lack of VCF reports in the study area boreholes could be an artefact of the summary logs not reporting the narrow interval. It is otherwise unclear why there are

	dipping between 30° and 80° towards the centre of the dome (dips getting steeper towards the SW). Outside of the study area the contact appears again in the surface mapping, though orientated obliquely to the dome, i.e. 65 – 120km from the centre of the dome. Adjacent orientations to the repeated contact are upright and much shallower dipping (between 10° and 25°) than the units observed around the dome margins, with the general dip direction trending towards the dome. These mapped surface exposures of the stratigraphy and bedding orientations adjacent to the contact suggest a similar regional-scale geometry as suggested for the overlying Ventersdorp and Transvaal Supergroups, i.e. a dominant asymmetric synclinal fold tangential to the Vredefort dome. Unlike the upright limbs of the asymmetric synclinal fold in overlying stratigraphy, the asymmetric syncline limb in the dome contact exposure is overturned.	so few VCF intervals reported in the majority of boreholes that contain the contact between the Ventersdorp and Witwatersrand Supergroups. A second possible artefact of the summary logs is that only the basal conglomerate of the Venterspost Formation has been illustrated in the logs and reported as Venterspost Formation. The rest of the VCF sedimentary sequence does not appear in the summary logs so it either does not exist in the study area or it has not been shown fully in the logs. The contact between the Ventersdorp Supergroup and underlying stratigraphy is preserved in the boreholes throughout most of the study area. As mentioned above, there are boreholes that show the Transvaal Supergroup truncating the Ventersdorp Supergroup and that come into contact with the Witwatersrand Supergroup. However there are also areas where the boreholes do not report Ventersdorp Supergroup, as they intersect the underlying stratigraphy directly below the thin Karoo Supergroup cover. These boreholes are located on the SE margin of the study area and include a number of boreholes (4077870, 4066123, 4066121, 4213253, 4039849, 4126376, 4202051, 4066130, 4066131, 4039848, 4225646, 4039844, 4204331, 4039970, 4039990, 4039991, 4039992, 4039993, 4066437, and 4066471). These boreholes form a pattern defining the boundary limits of the Ventersdorp Supergroup at depth. The boundary is confined to the SE margin of the study area where it forms a narrow strip on the margin. However around half of the boreholes form a WNW trending corridor that bisects the Ventersdorp Supergroup from the SE margin towards the

		Vredefort dome. The Ventersdorp Supergroup in boreholes adjacent to this corridor are very thinly preserved below the Karoo Supergroup cover. A few boreholes report the Ventersdorp Supergroup in contact with the West Rand Group, implying truncation of the Central Rand Group. These boreholes are 4013847, 4020116, and 4039854. Boreholes 4013847 and 4020116 are located in the NW edge of the study area, whereas 4039854 is in the SW corner. A number of boreholes report the Booysens Formation shales within the Central Rand Group. In areas where boreholes are sparsely distributed the stratigraphy interpretation in the logs may not be stated, however the shale unit is still observed within the thick quartzite interval. The borehole intervals of the Booysens Formation vary in thickness across the study area, and range between 50m and 300m.
Central Rand Group – West Rand Group	The contact between the Central Rand Group and the West Rand Group is defined by an unconformity separating the dominantly sub-aerial basin stratigraphy of the West Rand Group (Johnson et al., 2006) and the syn-tectonic alluvial braid-plain (lesser alluvial fan and minor marine conditions) sediments of the Central Rand Group (Frimmel 2014). According to the regional stratigraphy (Johnson et al., 2006) the unconformity truncates, almost entirely, the uppermost formation in the West Rand Group, i.e. the Maraisburg Formation. The surface mapping for both the 1:250000 and 1:50000 scale maps do not illustrate individual formations, only larger groupings. However, the two groups of the Witwatersrand Supergroup are divided into several subgroups that are large enough to be illustrated on the surface maps. The contact between	A number of boreholes in the study area report Witwatersrand Supergroup but relatively fewer report the contact interval between the Central Rand and West Rand groups. These intersections are distributed around the study area and include boreholes 4020753, 4003209, 4032947, 4038363, 4038495, 4039844, 4039963, 4039990, 4039991, 4039992, 4039993, 4066285, 4066471, and 4066475. According to the stratigraphic report of the West Rand Group (Johnson et al., 2006) the thickness varies throughout the Witwatersrand basin, up to 5km reported in the Klerksdorp area, to the west of the dome. However, no boreholes in the study area report the base contact of the West Rand Group with the Dominion Group or basement. This implies that the true thickness

	the Central Rand Group and the West Rand Group is the contact between the Johannesburg Subgroup and the Jeppestown Subgroup,, respectively. This contact is observed in the collar rocks of the Vredefort dome, forming an arc around the northern and western margins, ~22 – 28km from the centre of the dome. The contact outcrops again beyond the study area extents but only in a few discrete areas, i.e. in the town of Klerksdorp (80km WNW of the dome) and on the southern margin of the Johannesburg dome (100km NE of the dome). Similarly to the VCF, the surface mapping orientations of the units indicate that the contact on the dome margins is overturned and dipping steeply (50° to subvertical) towards the centre of the Vredefort dome, whereas the outcrops mapped beyond the study area boundary indicate more shallow units (30° – 50°) dipping towards the Vredefort dome. The data points are too discrete to confidently infer any regional asymmetric syncline as was inferred to for the VCF outcrop information. The mapped SW extent of the Vredefort dome however, exhibits a gradual shift from overturned to upright units that dip 50° – 70° away from the dome.	of the West Rand Group in the areas beyond the dome collar rocks cannot be reliably measured by just borehole intersections. An anomalous 130.30m intersection of granite is logged below the West Rand Group at the base of borehole 4225646 (from 1869.49m to the end of hole at 1999.79m). The borehole lies ~36km SSE of the centre of the dome and is dominated by intrusives (1217.58m, 60.88%, of intrusive rocks, including the granite, and 782.21m, 39.11%, of supracrustal sediments). The closest borehole to 4225646 is 4039844, located 6700m to the SW. This borehole is slightly deeper than 4225646 (ending at 2032.71m) but reports only 34.75m (1.71% of the borehole length) of intrusive rock, and no granite. The lack of borehole information regarding the unit orientation downhole and a bottom-contact for the granite intersection in borehole 4225646 opens the interpretation of the granite to being basement rock or possibly the top of a localised granitic sheet intruding from a deeper, main granitic body and into a structurally weak zone that was also used by adjacent intrusives.
West Rand Group – Dominion Group	The base of the West Rand Group and base of the Witwatersrand Supergroup, i.e. the Orange Grove Formation (dated at 2985 14 Ma, using U-Pb SHRIMP in detrital zircons, by Kositcin and Krapež, 2004), lies unconformably over the Dominion Group, dated at 3074 ± 6 Ma (single-zircon U-Pb in the Syferfontein Formation, Armstrong et al., 1991). The contact is observed in the surface mapping of the collar rocks around the Vredefort dome (~20 – 22km from the centre of the dome) and also in several exposures north-	Drilling information in the study area is negligible with regards to the Dominion Group. This should be expected though, as the group lies at the base of the supracrustal package that overlies the granitoid basement. Intersections with the Dominion Group will require near-surface preservation, such as the areas around the dome collar and the NW exposures. Only one borehole (4020073) digitised from the CG dataset drills through the base of the West Rand Group and intersects the Dominion

west of the study area (~78 – 94km from the centre of the dome) and west-north-west of the study area (> 110km from the centre of the dome).

The mapped exposures of the Dominion Group have been combined into one unit (100 – 400m wide) in the Vredefort dome whereas several of the NW exposures have been differentiated into the Syferfontein (clastic sediments and felsic porphyry's) and Rhenosterspruit (felsic porphyry's and minor mafic-intermediate volcanics) formations (combined width of 200 – 800m).

According to the known stratigraphy of the group (Johnson et al., 2006) the Rhenosterhoek Formation (mafic-intermediate volcanics) is the most dominant of the three formations that make up the Dominion Group. However the mapping in the NW exhibits only the other two formations with several discrete exposures mapped as a single unit under "Dominion Group". The Rhenosterhoek Formation is only observed in the surface mapping in the far WNW exposures.

From the authors own field experience in the Vredefort dome collar the mafic-intermediate volcanics are the dominant Dominion Group lithology. It is therefore tentatively suggested that the single unit mapped as Dominion Group in the Vredefort dome surface maps are associated with the mafic-intermediate component of the Dominion Group stratigraphy, i.e. the Rhenosterhoek Formation.

The structural information provided in the surface mapping exhibits comparable bedding orientations of this stratigraphic level to the overlying West Rand Group and Central Rand Group, i.e. overturned beds in the northern and western sections of the dome, dipping at 50° – 80° towards the dome, and upright units in the SW section of the dome, dipping at 60° – 80° away from

Group and basement. The intersection of the Dominion Group is 40.95m wide and is sedimentary, implying it could be from the Syferfontein Formation. Unfortunately this borehole lies ~16.5km north of the NW corner of the study area.

A second borehole (4013818) only 1.8km outside the NW corner of the study area intersects basement granite gneiss. The borehole log of the stratigraphy is very simplified and does not differentiate the sequences beyond their supergroup. Overlying the basement gneiss is a thick pyroclastic unit (748.72m interval) that has been labelled as part of the Ventersdorp Supergroup. The unit is overlain by alternating volcanic and sedimentary rocks of the Ventersdorp Supergroup, most likely from the Platberg Group. It is unclear whether the pyroclastic unit belongs to the Ventersdorp Supergroup stratigraphy or the Dominion Group stratigraphy.

	the dome. The Dominion Group in the repeated exposures NW of the study area exhibit shallower orientations, dipping 15° – 45° to the SE towards the dome.	
Basement Contact	In the study area the basement granitoids form the core rocks of the Vredefort dome. The contact with the supracrustal Dominion Group forms an arc ~18 – 21km from the centre of the dome. Adjacent units are steeply oriented, between 55° – 80°. On the northern and western margins of the dome basement contact the units are overturned and dip towards the dome, whereas in the SW margin the units are upright and dip away from the dome. A couple discrete inlier exposures of the basement contact with Orange Grove Formation quartzites are observed as well, ~20km SE of the centre of the dome. Outside the study area several other basement dome exposures have been reported, located >100km west, north, and east of the Vredefort dome. These domes include (from west to east); the Vermaas dome, Coligny dome, Hartbeesfontein dome, Westerdam dome, Johannesburg dome, and the Devon dome.	As mentioned above for the West Rand Group – Dominion Group contact there are only two boreholes (4013818 and 4020073) that intersect the basement. Both boreholes are outside the study area although the borehole 4013818 is only 1.8km north of the NW corner, therefore provides a reasonable constraint at depth of the basement contact, i.e. 4246.92m downhole depth. The overlying stratigraphy in borehole 4013818 is logged as Ventersdorp Supergroup, implying truncation through the entire Witwatersrand Supergroup and Dominion Group. Adjacent boreholes report Witwatersrand Supergroup below the Ventersdorp Supergroup so this may be a localised occurrence.

Table E0: Main 2D reflection seismic data acquisition parameters (between 1985-1989)

Note: Typical nominal fold for these reflection seismic lines is 20 – 50

Survey parameters	OF-98/97, OPR-50	KV- 117/118, OB-41/74	KV- 132/120	FV-155	DV-274/2/1/0B/0A	BH-269/8	FV-154	DE-512B/12A/11/06	BH-171B/A	DE-83	DE-510/08/07
Date	1986, 1985	1986, 1985	1986	1987	1988/9	1988	1987	1988	1987	1985	1988
Field crew	AAC	AAC	AAC	AAC	AAC	AAC	AAC	AAC	AAC	AAC	AAC
System	SN 338	SN 338	SN 338	SN 338	SN 368	SN 368	SN 338	SN 338	SN 368	SN 338	SN 338
Geophones	SM4 (10 Hz)	SM4 (10 Hz)	SM4 (10 Hz)	SM4 (10 Hz)	SM4 (10 Hz)	SM4 (10 Hz)	SM4 (10 Hz)	SM4 (10 Hz)	SM4 (10 Hz)	SM4 (10 Hz)	SM4 (10 Hz)
Data format	SEG B	SEG B	SEG B	SEG B	SEG D	SEG D	SEG B	SEG B	SEG D	SEG B	SEG B
Record length	24 s	24 s	24 s	24 s	6 s	6 s	24 s	24 s	24 s	24 s	24 s
Sample interval	4 ms	4 ms	4 ms	4 ms	4 ms	4 ms	4 ms	4 ms	4 ms	4 ms	4 ms
Profile length	27.1/16.65/19.1 km	47.7/16.3 km / 30.4/14.6 km	23.4/33.2 km	32.4 km	36.3/26.7/39.2/ 31.5/31.3 km	27.2/47.4 km	77.2 km	26.0/21.4/41.2/32. 2 km	23.6/20.1 km	33.6 km	14.0/25.1/9.1 km
System polarity	SEG	SEG	SEG	SEG	SEG	SEG	SEG	SEG	SEG	SEG	SEG
Shot line direction	NNW-SE	N-S / NW-SE	SW-NE	SW-NE	Various	WSW-ENE / W-E	WNW-ESE	Various	SW-NE / WSW-ENE	WN- ESE	SSW-NNE to W-E
Shot point separation	50 m	50 m	50 m	50 m	50 m	50 m	50 m	50 m	50 m	50 m	50 m
Total number of shot points	329 – 536	289 – 777	439 – 644	608	505 – 1017	512 – 900	1468	494 – 810	882	668	285
Receiver line direction	NNW-SE	N-S / NW-SE	SW-NE	SW-NE	Various	WSW-ENE / W-E	WNW-ESE	Various	SW-NE / WSW-ENE	WNW-ESE	SSW-NNE to W-E
Receiver point separation	7.50 m	7.50 m	7.50 m	7.50 m	4.16m - 2.08m	4.16m - 2.08m	7.50 m	7.50 m	7.50 m	7.50 m	7.50/4.16-2.08/7.0 m
No. of Channels	96	96	96	96	120	120	96	96	120	96	96
Geoph./trace	6	6	6	6	6	6	6	6	6	6	6
Vibroseis	Pelton Mk II	Pelton Mk II	Pelton Mk II	Pelton Mk II	Pelton Mk II	Pelton Mk II	Pelton Mk II	Pelton Mk II	Pelton Mk II	Pelton Mk II	Pelton Mk II
Pattern	4p x 6s	4p x 6s	4p x 6s	4p x 6s	4p x 6s	4p x 6s	4p x 6s	4p x 6s	4p x 6s	4p x 6s	4p x 6s
Sweep	10 – 68.5 Hz	10 – 68.5 Hz	10 – 68.5 Hz	10 – 68.5 Hz	10 – 61 Hz	10 – 61 Hz	10 – 68.5 Hz	10 – 68.5 Hz	10 – 61.75 Hz	10 – 68.5 Hz	10 – 68.5 Hz
Sweep length	18 s	18 s	18 s	18 s	24 s	24 s	18 s	18 s	18 s	18 s	18 s
Sweep type	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear
Gain	2^7/IFP	2^7/IFP	2^7/IFP	2^7/IFP	2^7/IFP	2^7/IFP	2^7/IFP	2^7/IFP	2^7/IFP	2^7/IFP	2^7/IFP
Low Cut	8Hz,12 dB/Oct	8Hz,12 dB/Oct	8Hz,12 dB/Oct	8Hz,12 dB/Oct	8Hz,12 dB/Oct	8Hz,12 dB/Oct	8Hz,12 dB/Oct	8Hz,12 dB/Oct	8Hz,12 dB/Oct	8Hz,12 dB/Oct	8Hz,12 dB/Oct
High Cut	90 Hz, 72 dB/Oct	90 Hz, 72 dB/Oct	90 Hz, 72 dB/Oct	90 Hz, 72 dB/Oct	62.5 Hz, 72 dB/Oct	62.5 Hz, 72 dB/Oct	90 Hz, 72 dB/Oct	90 Hz, 72 dB/Oct	62.5 Hz, 72 dB/Oct	90 Hz, 72 dB/Oct	90 Hz, 72 dB/Oct
Notch	In, 50 Hz	In, 50 Hz	In, 50 Hz	In, 50 Hz	Out	Out	Out	Out	Out	In, 50 Hz	Out
Antistatic	In	In	In	In	In	In	In	In	None	In	In
Equiv. Geoph.	In	In	In	In	In	In	In	None	In	In	None
CMA	Out	In	In	In	None	None	In	None	None	In	None
Taper	0.5 s	0.5 s	0.5 s	0.5 s	0.5 s	0.5 s	0.5 s	0.5 s	0.5 s	0.5 s	0.5 s

Table E1: Seismic Line Description	Line OF-98	Migration Type: FK

Major Contact Reflector	Surface Mapping Information	Borehole Information
Karoo Supergroup Base	No Karoo Supergroup is reported over the length of the seismic line. Alluvium is mapped in the northern half of the seismic line.	No Karoo Supergroup is reported in boreholes in the vicinity of this seismic line.
Pretoria Group – Chuniespoort Group	The surface mapping exposure over the length of the seismic line lies within the Pretoria Group, intersecting the Hekpoort, Strubenkop and Daspoort formations. As described in Table D the line also crosses over an interference/periclinal fold elongated tangentially to the Vredefort dome.	Several boreholes are located within 7km of the seismic line, one of which (4014246) lies within 200m of the line in the NNW quarter. This borehole does not reach the contact at depth but it does intersect the Hekpoort Formation between 1548.30m and 2151.50m (~600m width) downhole, constraining the formation in the seismic section. Boreholes 4014238 and 4014286 to the west of the line report the contact at 1439.89m and 1544.00m downhole,, respectively. Boreholes 4020247 and 4057334 to the east of the line report the contact at 1655.83m and 2120.80m downhole,, respectively. These contact depths provide lateral constraints to the contact on the section. Intrusive dolerites are also reported randomly within the Pretoria Group
Black Reef Formation	Not reported in the line intersection of the surface mapping	Similar to the above contact, four boreholes intersect the Black Reef Formation west and east of the line. Boreholes 4014238 and 4014286 to the west of the line report the formation at 2853.80m and 3332.00m downhole,, respectively. Boreholes 4020247 and 4057334 to the east of the line report the formation at 2947.00m and 3510.99m downhole,, respectively.
Venterspost Contact Formation (VCF)	Not reported in the line intersection of the surface mapping	Two boreholes (4014238 and 4014286, mentioned above as well) to the west of the seismic line intersect the contact between the Ventersdorp Supergroup and the underlying Witwatersrand Supergroup at 3453.43m and 4372.50m downhole,, respectively. As mentioned in Table D these borehole are two of the numerous boreholes that do not report the VCF in the logs. In the case of 4014238 though the contact is marked by a fault zone.

Central Rand Group – West Rand Group	Not reported in the line intersection of the surface mapping	The majority of boreholes adjacent to this seismic line do not intersect this contact, apart from borehole 4014263 (11km west of the line) that intersects the contact at 3082.80m downhole. The logged quartzite footwall is reported as the Roodepoort Formation of the Jeppestown Subgroup.
West Rand Group – Dominion Group	Not reported in the line intersection of the surface mapping	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies 38km north of this seismic line.
Basement Contact	Not reported in the line intersection of the surface mapping	Two boreholes intersect the basement, however they are located over 22km north of this section.

Table E2: Seismic Line Description	**Line OF-97**	**Migration Type: FK**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	No Karoo Supergroup is reported over the length of the seismic line. Alluvium is mapped in the northern half of the seismic line.	No Karoo Supergroup is reported in boreholes in the vicinity of this seismic line.
Pretoria Group – Chuniespoort Group	The surface mapping exposure over the length of the seismic line trace does not intersect the contact between the Pretoria and Chuniespoort groups, but lies entirely within the lower Pretoria Group, intersecting the Hekpoort, Strubenkop and Daspoort formations, moving into progressively	Three boreholes are located within 4km of the seismic line (i.e. 4014246, 4014286 and 4057334). A few more are located >5.5km (i.e. 4019199, 4020246, 4020247 and 4020248). They all intersect Pretoria Group at depth. Boreholes 4014286, 4020247, and 4057334 intersect the contact between the Pretoria Group and Chuniespoort Group at 1453.65m, 1655.83m, and 2091.23m downhole depths,, respectively.

	older stratigraphy towards the SE (and the dome), ending in the Hekpoort Formation surface exposure. In the SE half the line passes through the saddle between two elongated interference/periclinal folds, described in Table D, exposing the Hekpoort Formation in the hinge of the southern pericline and the Strubenkop Formation in the hinge of the northern pericline.	The Hekpoort Formation thicknesses are relatively consistent in the boreholes around the seismic line, i.e. 500 – 600m. The upper contact depths of the formation exhibits greater variation though, ranging between 300m and 1500m borehole depths. The deeper intersections occur in boreholes located perpendicular to the NW half of the seismic line. To the south-east and further NW of the line the intersections are at shallower borehole depths. The Chuniespoort Group underlies the Pretoria Group in the borehole intersections, and follows a similar trend to the overlying Hekpoort Formation intersections, i.e. the thicknesses vary slightly, between 1300m and 1800m, and the upper contact depths range between 1500m and 2100m, with the deeper intersections located perpendicular to the NW half of the seismic line.
Black Reef Formation	Not reported in the line intersection of the surface mapping, but outcrops ~5km to the east of the line trace.	Three boreholes in the vicinity of line OF-97 (<7km offset) intersect the Black Reef Formation (14 – 19m intervals) at depth. These include 4014286, 4020247, and 4057334 (with intersection depths of 3332.00m, 2947.00m, and 3510.99m,, respectively). Others boreholes are either too shallow or located further away.
Venterspost Contact Formation (VCF)	Not reported in the line intersection of the surface mapping, but outcrops ~9.5km to the east of the line trace.	Boreholes that intersect the VCF are located west of the line as these appear to be deeper than the boreholes in other areas. The borehole intersection closest to the line is observed in borehole 4014286 (3550m NW), intersecting the contact (VCF not stated in the log) between the Klipriviersberg Group and Central Rand Group at 4372.50m depth.
Central Rand Group – West Rand Group	Not reported in the line intersection of the surface mapping, but outcrops ~13km to the east of the line trace.	The majority of boreholes adjacent to this seismic line do not intersect this contact, apart from borehole 4014263 (11km west of the line) that intersects the contact at 3082.80m downhole. The logged quartzite footwall is reported as the Roodepoort Formation of the Jeppestown Subgroup.
West Rand Group – Dominion Group	Not reported in the line intersection of the surface mapping, but outcrops ~20km to the east of the line trace.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies 40km north of this seismic line.

Basement Contact	Not reported in the line intersection of the surface mapping, but outcrops ~20km to the east of the line trace.	Two boreholes intersect the basement, however they are located over 22km north of this section.

Table E3: Seismic Line Description	**Line OPR-50**	**Migration Type: FK**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	No Karoo Supergroup is reported over the length of the seismic line.	No Karoo Supergroup is reported in boreholes in the vicinity of this seismic line.
Pretoria Group – Chuniespoort Group	The surface mapping exposure of the seismic line trace contains the contact between the Pretoria and Chuniespoort groups towards the eastern margin. The stratigraphy intersected within the Pretoria Group includes the Timeball Hill, Hekpoort, Strubenkop, and Daspoort formations. The Chuniespoort Group mapped exposure contains the Malmani Subgroup and Black Reef Formation. Towards the centre of the section the outcrop is similar to the adjacent line OF-97, i.e. Hekpoort and Strubenkop formations are repeated and form part of the interference/periclinal folds described in Table D. The western half of the mapping contains diorite sills emplaced within the stratigraphy overlying the Hekpoort Formation.	Three boreholes are located ~5km from the line, i.e. 4020246 and 4020247 ~5km to the north, and 4057334 ~5km to the SW. A few other boreholes are located further away, up to 8km from the line. These include 4014246, 4014286, and 4020179. All boreholes except for two (4014246 and 4020179) extend deep enough to intersect the contact between the Pretoria and Chuniespoort groups. Intersection depths in the boreholes range between ~1550m and ~2100m. Borehole thicknesses of the Hekpoort Formation are similar to those noted for line OF-97 (i.e. 500 – 600m), with the addition of borehole 4020246 that contains a narrower intersection (~260m), though there is a large amount of thick diorite sills in this borehole that appear to slightly split up the Hekpoort Formation.
Black Reef Formation	The Black Reef Formation is intersected on the seismic line trace on surface near the eastern margin.	Two boreholes in the vicinity of line OPR-50 (<5km offset) intersect the Black Reef Formation (14 – 17m intervals) at depth. These include 4020247 and

		4057334 (with intersection depths of 2947.00m and 3510.99m,, respectively). Other boreholes are either too shallow or located further away.
Venterspost Contact Formation (VCF)	Not reported in the line intersection of the surface mapping, but outcrops ~3.3km to the east of the line trace.	Boreholes that intersect the VCF are located far to the west of the line (>8km).
Central Rand Group – West Rand Group	Not reported in the line intersection of the surface mapping, but outcrops ~7.1km to the east of the line trace.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection of the contact lies ~18km WSW of this seismic line.
West Rand Group – Dominion Group	Not reported in the line intersection of the surface mapping, but outcrops ~13km to the east of the line trace.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies 40km north of this seismic line.
Basement Contact	Not reported in the line intersection of the surface mapping, but outcrops ~13km to the east of the line trace.	Two boreholes intersect the basement, however they are located over 22km north of this section.

Table E4: Seismic Line Description	**Line KV-117**	**Migration Type: FK**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	No Karoo Supergroup is reported over the length of the seismic line because the southern two thirds of the surface mapping is reported as Quaternary-age sediments that overly the Karoo Supergroup. The northern third exposure reports several Transvaal Supergroup formations, i.e.	Boreholes located towards the north of the line do not report Karoo Supergroup. A couple boreholes (4032984 and 4203936) located ~6.5km west of the line towards the centre contain Karoo Supergroup. Another couple of boreholes (4032984 and 4066137) located south (3.9km and 6km away,,

	Hekpoort, Strubenkop, and Daspoort formations, but no Karoo Supergroup. Several inliers are reported through the Phanerozoic/Karoo Supergroup cover towards the south, exposing Transvaal Supergroup from the same three formations.	respectively) of the line also report Karoo Supergroup. Downhole depths for the lower contact of the Karoo Supergroup ranges between 113m and 179m, increasing towards the south.
Pretoria Group – Chuniespoort Group	The Transvaal Supergroup is exposed in the northern third of the seismic line. The seismic line trace over this exposure trends sub-parallel on the eastern limb of a north-south elongated dome-shaped pericline, described in Table D. The crest of the interference fold/periclinal fold is mapped as Hekpoort Formation and the limbs show progressively younging stratigraphy of the Strubenkop and Daspoort formations away from the crest. The southern limb is exposed in a region overlapping with Quaternary sediment cover and dips 15° – 20° towards the south, sub-parallel to seismic line KV-117. On the length of line KV-117 several inliers are mapped that expose either Hekpoort or Daspoort formations. The Chuniespoort Group is reported east and NW of line KV-117, however the closer exposures are in the east within the semi-circular collar rocks of the dome (4.5km – 20km from line KV-117). The mapped surface exposures of the Chuniespoort Group dip away from the dome with apparent thicknesses varying between 1500m and 3000m.	Several boreholes are located in the vicinity of the line. The closest is borehole 4020248 located ~2350m east of the northern tip. Borehole 4032984 lies ~3800m west of the southern tip. A further five boreholes lie 6200 – 6500m to the west on the length of the line. The Pretoria Group reported in these boreholes is generally unclassified, apart from the distinct volcanics of the Hekpoort Formation (locally named the Ongeluk Lavas in some places). The logged stratigraphy adjacent to the Hekpoort Formation is dominated by intrusives, corresponding with the large volume of intrusive sills observed in the surface mapping. Adjacent boreholes towards the south are much shallower than those in the northern half of the line (maximum depth of 1235.05m in borehole 4032848). These shallow boreholes report much smaller intervals of Transvaal Supergroup so appear to be sampling relatively thinner sequences.
Black Reef Formation	Not reported in the line intersection of the surface mapping, but outcrops between 7.5km and 23km east of the line trace.	Five boreholes in the vicinity of line KV-117 report the contact between the Transvaal and Ventersdorp supergroups, these are boreholes 4057334 (~6.7km NW), 4032947, 4032983, 4032985 and 4079268 (9 – 12km SW). The downhole contact depths vary between 605m and 920m.
Venterspost Contact	Not reported in the line intersection of the surface mapping, but outcrops between 13km and 28km east of the line trace.	A number of boreholes (ten) clustered >9km SW of line KV-117 report the contact between the Ventersdorp and Witwatersrand supergroups. The

Formation (VCF)		downhole depths of the contact vary between 740m and 2500m. A second cluster of seven boreholes >15km WNW of line KV-117 reports the contact. Downhole depths of the contact vary between 2300m – 4300m in this cluster.
Central Rand Group – West Rand Group	Not reported in the line intersection of the surface mapping, but outcrops between 17km and 31km east of the line trace.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection of the contact lies ~12km south of this seismic line.
West Rand Group – Dominion Group	Not reported in the line intersection of the surface mapping, but outcrops >26km to the east of the line trace.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies 50km north of this seismic line.
Basement Contact	Not reported in the line intersection of the surface mapping, but outcrops >26km to the east of the line trace.	Two boreholes intersect the basement, however they are located over 36km north of this section.

Table E5: Seismic Line Description	**Line KV-118**	**Migration Type: FK**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	No Karoo Supergroup is reported over the length of the seismic line as Quaternary-age sediments cover the area. Several inliers through the Phanerozoic/Karoo Supergroup cover are reported throughout the length of the seismic line exposing Transvaal Supergroup.	Borehole 4203936 is the closest borehole in the vicinity of the seismic line. It is located ~7600m SW and was drilled in 1947 to a depth of 664.85m. Quaternary sediments are reported down to 21m followed by Karoo Supergroup down to 113.08m. The base of the Karoo Supergroup is marked by a 6.40m thick unit of Dwyka Group tillite.
Pretoria Group – Chuniespoort Group	The inliers illustrated in the surface mapping report the Hekpoort, Strubenkop and Daspoort formations. The Hekpoort	Borehole 4203936 reports two volcanic units that are separated by a 381.10m thick shale unit (including a 62.26m thick intrusive within the shale). The upper

	Formation is dominant in the NW half of the line, while the younger formations are dominant in the SE half. The contact between the Pretoria and Chuniespoort groups at surface is mapped 8 – 15km to the east.	volcanic unit is truncated by the Dwyka Group tillite and the lower contact of the lower volcanic unit has not been reached by the borehole. The three volcanic units preserved in the Pretoria Group stratigraphy are the Machadodorp and Bushy Bend members of the Silverton and Timeball Hill formations,, respectively, and the Hekpoort Formation. It is unclear which two of these units the volcanic intervals represent. Surrounding boreholes and surface mapping suggests the units are most likely part of the Pretoria Group however.
Black Reef Formation	Not reported in the line intersection of the surface mapping, but outcrops 9 – 19km to the east of the line trace.	The closest borehole that intersects the contact between the Transvaal and Ventersdorp supergroups is borehole 4014237 and is located 15km NW of the line. A 3.14m thick interval of Black Reef Formation quartzite is preserved in this borehole. Boreholes closer to the line end in Transvaal Supergroup.
Venterspost Contact Formation (VCF)	Not reported in the line intersection of the surface mapping, but outcrops 16 – 23km to the east of the line trace.	The closest borehole that intersects the contact between the Ventersdorp and Witwatersrand supergroups is borehole 4014238 and is located 16.5km NNW of the line.
Central Rand Group – West Rand Group	Not reported in the line intersection of the surface mapping, but outcrops 21 – 28km to the east of the line trace.	The closest borehole that intersects the contact between the Central Rand and West Rand groups is borehole 4014263 and is located 18km NW of the line.
West Rand Group – Dominion Group	Not reported in the line intersection of the surface mapping, but outcrops 25 – 34km to the east of the line trace.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies 64km north of this seismic line.
Basement Contact	Not reported in the line intersection of the surface mapping, but outcrops 26 – 35km to the east of the line trace.	Two boreholes intersect the basement, however they are located over 48km north of this section.

Table E6: Seismic Line Description	Line KV-132		Migration Type: FK
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**	
Karoo Supergroup Base	About three quarters of the line trace is through Quaternary sediments with a couple of inliers adjacent to the line that expose Transvaal Supergroup. The remaining quarter of the line in the NE reports surface exposure of Transvaal and upper Ventersdorp supergroup.	This line occurs in a borehole gap where the closest borehole (4032848) is located ~5200m WSW of the line. Karoo Supergroup is preserved in the majority of boreholes surrounding the line trace (coverage is to the west, south and east only). The bottom contacts of the Karoo Supergroup in the boreholes lie 100 – 180m downhole, with 2 – 21m of Quaternary cover at surface.	
Pretoria Group – Chuniespoort Group	A few inliers are observed through the Quaternary cover that expose Hekpoort and Daspoort formations. The exposed bedrock in the NE quarter reports the lower Transvaal Supergroup (i.e. Hekpoort Formation down to the Black Reef Formation) and upper Ventersdorp Supergroup.	Boreholes 4039838 and 4203936 located ~8km SW and ~7km NW of the line report Pretoria Group, including the Hekpoort Formation. Borehole 4032848 located ~5.2km WSW of the line reports Chuniespoort Group dolomites as well. Boreholes further east of the line report Witwatersrand Supergroup.	
Black Reef Formation	The Black Reef Formation outcrops at the NE edge of the section. The surface exposure is ~280m wide and a structural measurement located ~1300m to the south indicates a dip of 40° towards 208°.	The closest borehole that intersects the contact between the Transvaal and Ventersdorp supergroups is borehole 4032985 and is located 15km SW of the line.	
Venterspost Contact Formation (VCF)	Not reported in the line intersection of the surface mapping, but outcrops ~5km to the east of the line trace.	The closest borehole that intersects the contact between the Ventersdorp and Witwatersrand supergroups is borehole 4079268 and is located 15.7 km SW of the line. Boreholes that lie closer to the line do not intersect the contact but are drilled in either the hangingwall or footwall stratigraphy.	
Central Rand Group – West Rand Group	Not reported in the line intersection of the surface mapping, but outcrops ~10km to the east of the line trace.	The closest borehole that intersects the contact between the Central Rand and West Rand groups is borehole 4014263 and is located 30km NW of the line.	

		Boreholes that lie closer to the line do not intersect the contact but are drilled in either the hangingwall or footwall stratigraphy.
West Rand Group – Dominion Group	Not reported in the line intersection of the surface mapping, but outcrops ~15km to the east of the line trace.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies 66km north of this seismic line.
Basement Contact	Not reported in the line intersection of the surface mapping, but outcrops ~16km to the east of the line trace.	Two boreholes intersect the basement, however they are located over 52km north of this section.

Table E7: Seismic Line Description	**Line FV-155**	**Migration Type: FD**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The Karoo Supergroup is preserved towards the centre of the line.	Several boreholes located ~10km south of the line report Karoo Supergroup down to ~110m. These boreholes are all inclined by 30° – 50° so the vertical depths are about half as deep as the downhole depths.
Pretoria Group – Chuniespoort Group	The SW edge of the line trace crosses the mapped Chuniespoort Group and Black Reef Formation. The contact with the Pretoria Group lies ~750m west of the line.	No adjacent boreholes contain Transvaal Supergroup. The closest borehole that preserves the contact between the Pretoria and Chuniespoort groups is borehole 4057334 located ~23km NW of the line.
Black Reef Formation	The SW edge of the line trace crosses the mapped Black Reef Formation. The surface exposure is ~280m wide and a structural measurement located ~1300m to the south indicates a dip of 40° towards 208°.	The closest borehole that intersects the contact between the Transvaal and Ventersdorp supergroups is borehole 4057334 and is located ~23km NW of the line.
Venterspost Contact Formation (VCF)	The VCF intersection of the seismic line trace lies under Karoo Supergroup cover. It is exposed ~5km to the north. No structural	Several boreholes (4039825, 4054336, 4066147 located 7 – 12km to the north, and 4039790 located ~11km to the south) are located on the mapped contact of the Ventersdorp and Witwatersrand supergroups and report the

	measurements are reported in the available surface maps of the VCF in this area.	contact at depth. Downhole depths (of the inclined boreholes) range between 50m and 175m. Borehole 4066154 located ~1.5km north report quartzite interlayered with shales (Booysens Formation) down to ~2.5km downhole, though it is likely because the borehole is sub-parallel to bedding.
Central Rand Group – West Rand Group	The Karoo Supergroup is preserved in linear sections sub-parallel to the strike of the Witwatersrand Supergroup at depth. The units cover the contact in the area adjacent to the line trace so the closest inference of the contact is located ~6.2km north of the trace. Numerous structural measurements taken in both groups adjacent to the line indicate sub-vertical orientations.	No boreholes in the vicinity of the seismic line are drilling through the contact. Several boreholes are located north and south of the line but are drilled entirely within either the Central Rand Group or West Rand Group.
West Rand Group – Dominion Group	The contact is preserved in the surface mapping towards the centre of the section. The surface exposure of the Dominion Group is ~430m wide. Several structural measurements taken in the basal Orange Grove Formation quartzites indicate shallow units (40° – 50°) dipping towards the dome (i.e. roughly eastwards).	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies 63km NNW of this seismic line.
Basement Contact	Towards the NE section, with just over a third of the length of the seismic line, the trace intersects basement granitoids at surface. The line bends around the town of Vredefort near the NE edge.	Two boreholes intersect the basement, however they are located over 52km north of this section.

Table E8: Seismic Line Description	Line OB-41	Migration Type: FK
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	Quaternary sediments and Karoo Supergroup cover the length of the seismic line, with the central part of the line being dominated by Karoo Supergroup outcrop. A few inliers are reported in the adjacent area to the line and expose lower Pretoria Group stratigraphy.	Borehole 4066137 located ~1.9km west of the line towards the centre, is the closest borehole to the line. Borehole 4032984 is slightly further away, ~4km, and several other boreholes lie >9km west and east of the line trace. Borehole 4066137 reports the base of the Karoo Supergroup (Dwyka Group tillite) at 169.16m downhole and borehole 4032984 reports a base of 179.00m.
Pretoria Group – Chuniespoort Group	A few inliers are reported adjacent to the line trace, mainly to the east. The northernmost exposure reports Daspoort Formation while the exposures further south report Hekpoort Formation (and minor Strubenkop Formation).	Boreholes 4032984 and 4066137 both intersect volcanic sequences of the Pretoria Group but do not penetrate deep enough to intersect the contact between the Pretoria and Chuniespoort groups. Chuniespoort Group are reported in boreholes further east and west of the line, with up to 1800m wide intersections.
Black Reef Formation	Not reported in the line intersection of the surface mapping, but outcrops 22 – 31km NE of the line trace.	Intersections of the contact between the Ventersdorp and Transvaal supergroups are reported in boreholes located 9 – 12km to the west on the length of the line trace. The contact depths range between 640m and 920m downhole.
Venterspost Contact Formation (VCF)	Not reported in the line intersection of the surface mapping, but outcrops 26 – 33km NE of the line trace.	A number of boreholes (twelve) located 9 – 22km west of the line trace intersect the VCF contact between 1300m and 1800m downhole. Borehole 4065902 located ~18km SE of the line reports the contact at 1114.47m downhole, and borehole 4003241 located ~23km east intersects the VCF contact at 763.78m downhole.
Central Rand Group – West Rand Group	Not reported in the line intersection of the surface mapping, but outcrops 29 – 37km NE of the line trace.	Two boreholes, 4032947 and 4039854, located ~15.5km west of the line report the contact between the Central Rand and West Rand groups, 2504.00m and 1810.41m downhole,, respectively.

West Rand Group – Dominion Group	Not reported in the line intersection of the surface mapping, but outcrops 35 – 40km NE of the line trace.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies 86km north of this seismic line.
Basement Contact	Not reported in the line intersection of the surface mapping, but outcrops 36 – 42km NE of the line trace.	Two boreholes intersect the basement, however they are located over 71km north of this section.

Table E9: Seismic Line Description	**Line KV-120**	**Migration Type: FK**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	Quaternary sediments and Karoo Supergroup dominate the surface exposure of the line trace. A few narrow inliers are reported towards the NE that expose Transvaal Supergroup.	Karoo Supergroup are intersected in all the boreholes (sixteen) in the adjacent area to the line. The deepest reported contact intersection is observed in borehole 4039855 (~1800m south of the line) that reports the contact at 385.29m downhole. The thickness varies in boreholes around the line, ranging from 120.40 – 385.29m.
Pretoria Group – Chuniespoort Group	A few narrow inliers are reported adjacent to the NE half of the line. These exposures are located ~1km, ~4km and ~9km SE of the line. The Hekpoort Formation is mapped in all the exposures while the Strubenkop Formation is included in the exposure located ~4km SE of the line.	Boreholes 4066135 and 4066139 lie 3.3km and 7.8km north and east of the NE edge,, respectively. They both intersect the contact between the Pretoria and Chuniespoort groups. Borehole 4039854 is further west of these two boreholes and lies ~600m south of the line but only intersects the Chuniespoort Group. Boreholes further west of 4039854 do not report Transvaal Supergroup, and only intersect underlying Ventersdorp Supergroup.
Black Reef Formation	Not reported in the line intersection of the surface mapping, but outcrops ~15km NE of the line trace.	Borehole 4039854, located ~600m south of the line, is the only borehole in the vicinity of the line that intersects the Black Reef Formation (i.e. the contact between the Transvaal and Ventersdorp supergroups). The borehole intersection is observed at 681.75 – 789.85m downhole. The overall borehole inclination

		measured from the collar to the end point is 89° so the depths downhole are similar to depths below surface.
Venterspost Contact Formation (VCF)	Not reported in the line intersection of the surface mapping, but outcrops ~19km NE of the line trace.	Borehole 4039854, located ~600m south of the line, reports the VCF but the footwall lithology is West Rand Group volcanics logged as the Crown Formation lava. The hangingwall unit is logged as the "Klippan" Group and consists predominantly of conglomerates, with minor quartzites and shales, which according to Johnson et al. (2006) suggests it could be part of the Kameeldoorns Formation. However towards the middle of the sequence a dolomite unit is preserved, suggesting this could also be part of the Rietgat Formation instead (Johnson et al., 2006), though the Rietgat Formation does not contain any conglomerates. Further west though borehole 4037657 (~4km south of the SW edge) intersects Central Rand, Klipriviersberg and Platberg groups. Three boreholes lie adjacent to borehole 4037657 but are too shallow to intersect the VCF. Boreholes that intersect the VCF are located further to the north (~10 – 14km north) of the line.
Central Rand Group – West Rand Group	Not reported in the line intersection of the surface mapping, but outcrops ~22km NE of the line trace.	One borehole intersects a reliable contact between the Central Rand and West Rand groups. Borehole 4032947 located ~12km north of the line intersects the contact at 2504.00m downhole. A second borehole log (4037657 located ~4km south of the line) indicates the contact as well but is less reliable. The log does not indicate stratigraphic formations and after intersecting only 240m of Central Rand Group quartzite a shale unit is intersected and logged as being part of the West Rand Group when it could also represent the Booysens Formation.
West Rand Group – Dominion Group	Not reported in the line intersection of the surface mapping, but outcrops ~27km NE of the line trace.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies 94km north of this seismic line.

Basement Contact	Not reported in the line intersection of the surface mapping, but outcrops ~28km NE of the line trace.	Two boreholes intersect the basement, however they are located over 80km north of this section.

Table E10: Seismic Line Description	**Line OB-74**	**Migration Type: FK**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	Quaternary sediments and Karoo Supergroup dominate the surface exposure of the line trace. A narrow inlier is reported ~2.5km north of the line that exposes Transvaal Supergroup.	Borehole 4065902 located ~8300m ESE of the southern edge of the line is the closest borehole and borehole 4039854 located ~11800m west of the line is the second closest. Karoo Supergroup are logged in these two boreholes down to 326m in 4065902 and 242m in 4039854.
Pretoria Group – Chuniespoort Group	A narrow inlier in the Quaternary and Karoo Supergroup cover is mapped ~2.5km north of the line. The outcrop is mapped as Hekpoort Formation.	Borehole 4065902 does not report Transvaal Supergroup as the footwall to the Karoo Supergroup is Ventersdorp Supergroup. Borehole 4039854 only reports the Chuniespoort Supergroup below the Karoo Supergroup.
Black Reef Formation	Not reported in the line intersection of the surface mapping, but outcrops ~30km north of the line trace.	Borehole 4039854 reports the Black Reef Formation from 681.75 – 789.85m downhole. The next closest intersection of this contact is in borehole 4039895 ~20km east of the line.
Venterspost Contact Formation (VCF)	Not reported in the line intersection of the surface mapping, but outcrops ~33km NNE of the line trace.	Borehole 4065902 reports the contact at 1114.47m downhole. Central Rand Group quartzites are the footwall to the VCF here. Borehole 4039854 reports the contact at 1810.41m downhole. Here the footwall is the Crown Formation volcanics of the West Rand Group.
Central Rand Group – West Rand Group	Not reported in the line intersection of the surface mapping, but outcrops ~37km NNE of the line trace.	No boreholes in the vicinity of the line intersect this contact. Borehole 4032947 is the closest intersection and is located ~21km WNW of the line.

West Rand Group – Dominion Group	Not reported in the line intersection of the surface mapping, but outcrops ~40km NE of the line trace.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies 110km north of this seismic line.
Basement Contact	Not reported in the line intersection of the surface mapping, but outcrops ~41km NE of the line trace.	Two boreholes intersect the basement, however they are located over 95km north of this section.

Table E11: Seismic Line Description	**Line DV-274**	**Migration Type: FK**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The Vryheid Formation of the Karoo Supergroup is mapped at surface throughout the length of the line with the younger Volksrust Formation mapped in the southern 5.4km. Several inliers are mapped >3km west and north of the northern half of the line. Structural information indicates subhorizontal units.	Borehole 4054354, located ~950 m west of DV-274, is the closest borehole but provides only surface constraint to the geology in that area as it is only 62.79m in length and almost entirely logged as intrusive. Four boreholes (4021465, 4038363, 4054356 and 4063523) are located between ~8.4km and ~14km east of the line, and report the base contact of the Karoo Supergroup between 247m and 278m downhole. One borehole (4079068) is located ~15km west of the line and reports the base contact at 156m downhole.
Pretoria Group – Chuniespoort Group	Inliers are mapped >3km west and north of the northern half of the line. These exposures are mapped as the Hekpoort Strubenkop and Daspoort formations in the western outcrops, and the Malmani Subgroup in the northern outcrops.	Borehole 4079068 located ~15km west of the line only contains Witwatersrand Supergroup below the Karoo Supergroup. Boreholes 4021465, 4038363, 4054356 and 4063523 located between ~8.4km and ~14km east of the line report only Chuniespoort Group below the Karoo Supergroup.
Black Reef Formation	The closest outcrop of the Black Reef Formation lies ~5.8km NE of the northern edge of the line. The outcrops (including the strike measurements) trend roughly NE – SW	The contact between the Transvaal Supergroup and underlying stratigraphy is reported in the four boreholes (4021465, 4038363, 4054356 and 4063523) that lie east of the line. The depths of the contact shallows towards the SE, and ranges

	~20km to the west of the line it is exposed in the Vredefort dome collar.	between 600.20m (in 4063523) and 1400.18m in (4021465) downhole. The footwall lithology of borehole 4063523 (the southernmost borehole of the four) is Witwatersrand Supergroup whereas the other three boreholes (4021465, 4038363 and 4054356) are in contact with the Ventersdorp Supergroup.
Venterspost Contact Formation (VCF)	Not reported in the line intersection of the surface mapping, but outcrops >11km west and east of the line. The eastern exposure extends northwards and outcrops ~6.2km ENE of the northern edge of the line. The contact between the Ventersdorp and Witwatersrand supergroups lies ~18km west and east of the line.	Boreholes 4021465, 4038363 and 4054356 mentioned above report the contact between the Ventersdorp and Witwatersrand supergroups. The thickness of the Ventersdorp Supergroup decreases towards the south. Borehole 4021465 reports the VCF bottom contact at 2520.14m downhole, with a reported interval for the Ventersdorp Supergroup of 1113.68m. Boreholes 4038363 and 4054356 report contact depths/intervals of 730.11m/123.60m and 1407.63m/180.60m, respectively.
Central Rand Group – West Rand Group	Not reported in the line intersection of the surface mapping, but outcrops ~25km west of the line trace. Turffontein Subgroup is also mapped ~18km east of the line.	Borehole 4079068, located ~15km west of the line reports Turffontein Subgroup throughout its length (673.22m final depth downhole). Borehole 4021465 (~8.4km east of the line) ends in Mondeor Formation at 2571.29m downhole. Boreholes 4054356 (~8.4km east of the line) and 4063523 (~9.6km east of the line) do not refine the Witwatersrand Supergroup stratigraphy but both end in shale units at 2685.50m and 2000.52m downhole depth, respectively. Borehole 4038363 (~14km east of the line) reports the contact between the Central Rand and West Rand groups at 1834.20m downhole (34.40m interval of intrusive logged at the contact).
West Rand Group – Dominion Group	Not reported in the line intersection of the surface mapping, but outcrops ~32km west of the line trace. However the Dominion Group is faulted out in the mapping east of this last outcrop location, preserving the contact between the West Rand Group and basement only.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies 93km WNW of this seismic line.
Basement Contact	Not reported in the line intersection of the surface mapping, but outcrops ~22km west of the line trace.	Two boreholes intersect the basement, however they are located 93 – 95km WNW of this section.

Table E12: Seismic Line Description	Line DV-272	Migration Type: FK
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The western edge of the Vaal Dam lies adjacent to the eastern end of the line. The subhorizontal Vryheid and Volksrust formations are mapped on the western and eastern halves of the line, respectively. Intrusive sills are mapped towards the eastern edge.	Four boreholes (4021465, 4038363, 4054356 and 4063523) are located adjacent to the line and report Karoo Supergroup. Borehole 4021465 is located ~3200m north of the line whereas the three other boreholes are clustered between ~500m and ~5800m south of the line. Borehole 4038363 is the closest, ~500m south of the line. All boreholes report the base of the Karoo Supergroup from 247 – 278m downhole.
Pretoria Group – Chuniespoort Group	Not reported in the line intersection of the surface mapping, but outcrops of Hekpoort Formation and Chuniespoort Group are reported >11km NNW and >18km WNW of the line trace, respectively.	Four boreholes (4021465, 4038363, 4054356 and 4063523) are located adjacent to the line and report Transvaal Supergroup. However none report Pretoria Group as the Chuniespoort Group lies in contact with the Karoo Supergroup. The maximum interval thickness of the Chuniespoort Group is reported by borehole 4021465, at 996.20m. Borehole 4054356 reports a slightly lower interval of 968.86m. However both are truncated by the Karoo Supergroup so do not preserve the total thickness. The Chuniespoort Group in boreholes 4038363 and 4063523 is much more thinly preserved below the Karoo Supergroup, at 310.80m and 340.40m, respectively.
Black Reef Formation	Not reported in the line intersection of the surface mapping, but outcrops of Black Reef Formation are reported >18km WNW of the line trace in the collar of the dome.	The Black Reef Formation is preserved in three of the four boreholes (4021465, 4038363 and 4054356) located adjacent to the line. The log of borehole 4063523 reports the contact between the Transvaal and Witwatersrand Supergroup and is the only borehole of the four to report this contact relationship. The other three boreholes report Ventersdorp Supergroup below the contact, however the two boreholes closer to 4063523 (i.e. 4038363 and 4054356) report very thin intervals (123.60m and 180.60m, respectively) of Ventersdorp Supergroup relative to the more distant 4021465 (1113.68m). The contact depth ranges between 600m and 1400m downhole.

Venterspost Contact Formation (VCF)	Not reported in the line intersection of the surface mapping, but outcrops of the contact are reported ~5.6km NNE and >14.8km WNW of the line trace. The outcrop of Central Rand Group ~5.6km NNE of the line dips gently (12° – 20°) to the NNW but contains a faulted contact with the Ventersdorp Supergroup again in the south.	Borehole 4063523 (~5.8km south) contains no preserved Ventersdorp Supergroup (i.e. no VCF), and instead the top of the Witwatersrand Supergroup is in contact with the Transvaal Supergroup. The other three boreholes in the vicinity (i.e. 4021465, 4038363 and 4054356) preserve the contact. The contact is shallower towards the SE, changing from 2520.14m downhole in borehole 4021465 to 730.11m downhole in borehole 4038363.
Central Rand Group – West Rand Group	Not reported in the line intersection of the surface mapping, but outcrops are reported >22km WNW of the line trace in the collar of the dome. The Witwatersrand Supergroup exposed in the east exhibits only the Turffontein Subgroup at surface.	Borehole 4038363 (~500m south) reports Jeppestown Subgroup below 1834.20m downhole. The contact is defined by a 34.40m wide intrusive interval in this borehole. Borehole 4063523 contains no stratigraphic log but reports a similar section as borehole 4038363 (stratigraphy is logged here). At the base of the ~1370m thick quartzite package (interpreted to be the Witwatersrand Supergroup) is a third shale unit, corresponding to the third unit in borehole 4038363 (i.e. the Jeppestown Subgroup). The first shale unit in both boreholes is very thin (15.20m in 4063523 and 33.90m in 4038363) and is logged as Kimberley Channel shales in 4038363. The second, middle shale is logged as the Booysens Formation shale in 4038363 and is 259.90m thick in 4063523 and 169.33m thick in 4038363. Both Booysens Formation intervals contain thick intrusives as well.
West Rand Group – Dominion Group	Not reported in the line intersection of the surface mapping, but outcrops >29km WNW of the line trace. However the Dominion Group is faulted out in the mapping east of this last outcrop location, preserving the contact between the West Rand Group and basement only.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies 93km NW of this seismic line.
Basement Contact	Not reported in the line intersection of the surface mapping, but outcrops ~20km west of the line trace.	Two boreholes intersect the basement, however they are located 92 – 93km WNW of this section.

Table E13: Seismic Line Description	Line DV-271	Migration Type: FK

Major Contact Reflector	Surface Mapping Information	Borehole Information
Karoo Supergroup Base	The line trace from WNW to ESE trends towards younger Karoo Supergroup stratigraphy. In the WNW edge the Vryheid Formation is exposed. Towards the centre about two thirds of the trace length is mapped as Volksrust Formation. The ESE edge is mapped as Adelaide Subgroup.	Two subvertical boreholes lie within 50m of the line, in the ESE half, i.e. 4038495 and 4202532. The Karoo Supergroup preserved in these boreholes have bottom contact downhole depths of 310.00m and 613.64m, respectively (depth increasing towards the ESE). Borehole 4038495 is less than 10m from the line. The next closest borehole is 4063528, located ~5.6km north of the line. The bottom contact downhole depth in this borehole is reported as 247.00m.
Pretoria Group – Chuniespoort Group	Not reported in the line intersection of the surface mapping, but exposures of Transvaal Supergroup outcrop ~18km NNW of the line trace.	Boreholes 4038495 and 4202532 (located <50m from the line) do not report Transvaal Supergroup. Borehole 4063523 (~5.6km north) preserved a narrow interval (340.40m) of Chuniespoort Group underlying the Karoo Supergroup.
Black Reef Formation	Not reported in the line intersection of the surface mapping, but outcrops ~18km NW of the line trace.	Boreholes 4038495 and 4202532 (located <50m from the line) do not report Transvaal Supergroup. Borehole 4063523 (~5.6km north) reports the contact between the Transvaal Supergroup and the underlying Witwatersrand Supergroup at 600.20m downhole.
Venterspost Contact Formation (VCF)	Not reported in the line intersection of the surface mapping, but outcrops ~18km NE of the line trace, and is inferred between outcrops ~15km NW of the line in the collar of the dome.	Boreholes 4063523 (~5.6km north) and 4202532 (~50m north) do not report Ventersdorp Supergroup. Borehole 4038495 (~10m from the line) reports a narrow interval (325.00m) of Ventersdorp Supergroup underlying the Karoo Supergroup. The contact with the underlying Witwatersrand Supergroup is preserved at 635.00m downhole.
Central Rand Group – West Rand Group	Not reported in the line intersection of the surface mapping, but outcrops are reported >22km WNW of the line trace in the collar of the dome. The Witwatersrand Supergroup exposed in the east exhibits only the Turffontein Subgroup at surface.	Borehole 4038495 (~10m from the line) reports the contact at 1905.20m downhole, with the Roodepoort Formation preserved down to the end of hole depth of 1955.00m. The Booysens Formation in this borehole is preserved between 1657.00m and 1772.00m downhole. Borehole 4202532 (~50m north, final depth of 1767.82m) does not reach the contact and the units underlying the Karoo Supergroup is confined entirely within the

		Central Rand Group. The Booysens Formation in this borehole is preserved between 1133.51m and 1249.80m downhole. Borehole 4063523 (~5.6km north) is less constrained as the Witwatersrand Supergroup are not defined further. However, the log is similar to borehole 4038363 (~5.5km NE of the borehole) that reports the shale intercepted at the bottom of the borehole as part of the Jeppestown Subgroup. It is suggested that borehole 4063523 was stopped when this same shale was intersected. It is standard procedure for boreholes to be stopped only when an appropriate depth below the target (e.g. the basal reefs of the Central Rand Group) has been reached, to ensure no duplication is missed at depth.
West Rand Group – Dominion Group	Not reported in the line intersection of the surface mapping, but outcrops >28km WNW of the line trace. However the Dominion Group is faulted out in the mapping east of this last outcrop location, preserving the contact between the West Rand Group and basement only.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies 92km NW of this seismic line.
Basement Contact	Not reported in the line intersection of the surface mapping, but outcrops ~17km west of the line trace.	Two boreholes intersect the basement, however they are located 90 – 92km WNW of this section.

Table E14: Seismic Line Description	**Line DV-270B**	**Migration Type: FK**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The surface mapping indicates the line trace passes through subhorizontal sequences	Towards the centre of the line boreholes 4054356 and 4063523 are located ~200m and ~150m east and west of the line, respectively. They report the base contact of the Karoo Supergroup at 256.00m and 247.00m downhole, respectively. Boreholes 4021465 and 4038363 are located

	of the Vryheid Formation in the northern half and Volksrust Formation in the southern half.	~5200m east of the line and report the base contact at 278.00m and 250.00m downhole, respectively. Borehole 4038495, located ~9200m ESE of the line, reports the base contact at 310.00m downhole.
Pretoria Group – Chuniespoort Group	Not reported in the line intersection of the surface mapping, but the contact is reported ~22.5km NW of the line in the collar rocks of the Vredefort dome. However individual exposures of Hekpoort Formation and Chuniespoort Group are located ~5km north and ~16.2km WNW of the line, respectively.	No boreholes in the vicinity of the line report the preserve the Pretoria Group. The Chuniespoort Group is in contact with the overlying Karoo Supergroup.
Black Reef Formation	Not reported in the line intersection of the surface mapping, but outcrops ~16.7km WNW of the line trace.	The contact is preserved in four of the five boreholes that lie adjacent to the line (i.e. 4021465, 4038363, 4054356 and 4063523, with the exception of borehole 4038495). The Chuniespoort Group interval thickness preserved below the Karoo Supergroup decreases towards the south, from 1122.18m in borehole 4021465 and 970.92m in borehole 4054356 to 356.50m and 353.20m in boreholes 4038363 and 4063523, respectively. Borehole 4038495, located ~9200m ESE of the line, does not report Transvaal Supergroup and reports a narrow interval of Klipriviersberg Group volcanics below the Karoo Supergroup (to 325.00m downhole).
Venterspost Contact Formation (VCF)	Not reported in the line intersection of the surface mapping, but outcrops ~13.5km east of the line trace and ~21.5km west of the line trace in the collar rocks of the Vredefort dome. An inlier located ~7.5km SE of the line exposes Edenville Formation volcanics.	The contact is preserved in four of the five boreholes that lie adjacent to the line (i.e. 4021465, 4038363, 4038495 and 4054356, with the exception of borehole 4063523). Borehole 4054356 (~200m east of the line) preserves a very narrow Ventersdorp Supergroup (180.60m) beneath the Transvaal Supergroup. The Ventersdorp Supergroup is not preserved in borehole 4063523 though (~150m west of the line and 3203m south of borehole 4054356) as the contact of the Central Rand Group is with the Transvaal Supergroup. The contact is preserved in the other boreholes but the Ventersdorp Supergroup (apart from borehole 4021465) is similarly narrow, 120 – 325m. Borehole 4021465 is the most northern of the cluster and preserves a much wider interval of Ventersdorp Supergroup (1113.68m) including a 1.50m shallow dipping (5°) intersection of VCF at the base.

Central Rand Group – West Rand Group	Not reported in the line intersection of the surface mapping, but outcrops are reported >22km WNW of the line trace in the collar of the dome. The Witwatersrand Supergroup exposed in the east exhibits only the Turffontein Subgroup at surface.	The contact is indicated in boreholes 4038363, 4038495 and 4063523. Borehole 4054356 ends in shales but these may be associated with the Booysens Formation as the formation is logged in adjacent boreholes. Borehole 4063523 has a similar lithology log to borehole 4038363 (excluding the narrow Ventersdorp Supergroup intersection) but has been logged stratigraphically whereas borehole 4063523 has only a lithology log. Borehole 4063523 intersects three shale units over the length of the quartzite/conglomerate package. The top shale unit is thin (15.20m) and corresponds to the thin unit in 4038363 (33.90m) that is logged as the Kimberley Formation shales. The thick middle shale unit (259.90m) corresponds with the thick middle shale unit in 4038363 (169.33m) that is logged as the Booysens Formation shales. The third, lowest shale unit (in which both boreholes end in so the thickness is not a constraint) is observed in both boreholes. This shale unit is logged as the Jeppestown Subgroup shales in borehole 4038363 and is suggested to be similar (i.e. of the West Rand Group) in borehole 4063528. Borehole 4038495 (~9200m ESE of the line) contains a detailed stratigraphic log and reports the contact at 1905.20m downhole.
West Rand Group – Dominion Group	Not reported in the line intersection of the surface mapping, but outcrops >30km west of the line trace. However the Dominion Group is faulted out in the mapping east of this last outcrop location, preserving the contact between the West Rand Group and basement only.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies 91km NW of this seismic line.
Basement Contact	Not reported in the line intersection of the surface mapping, but outcrops ~27km west of the line trace.	Two boreholes intersect the basement, however they are located ~91km WNW of this section.

Table E15: Seismic Line Description	Line DV-270A	Migration Type: FK
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The surface mapping indicates the line trace passes through subhorizontal sequences of the Volksrust Formation in the northern half and Adelaide Subgroup the southern half.	Fifteen boreholes are located within 10km of the line, all of which report the Karoo Supergroup from surface. The majority of the boreholes are clustered towards the south. Three boreholes (4038363, 4054356 and 4063523) are located between 5.5km and 9.5km north of the line and preserve the Karoo Supergroup base contact 247 – 256m downhole. One borehole, 4038495, is located ~9.5km east of the line and preserves the Karoo Supergroup base contact at 310m downhole. Two boreholes (4039849 and 4213253) are located east (~2.8km and ~3.2km, respectively) of the southern edge of the line. They preserve the Karoo Supergroup base contact at 476.70m (4039849) and 479.76m (4213253) downhole. Six boreholes (4039846, 4066121, 4066123, 4066128, 4077870 and 4126376) are located between ~0.9km and ~10.7km west of the southern edge of the line and preserve the Karoo Supergroup base contact 287.27 – 556.56m downhole. Three boreholes (4003209, 4066130 and 4066131) are clustered between ~6.3km and ~8.5km SW of the line and preserve the Karoo Supergroup base contact 439 – 561.75m downhole.
Pretoria Group – Chuniespoort Group	Not reported in the line intersection of the surface mapping, but the contact is reported ~42km NW of the line.	Out of the fifteen boreholes that lie within 10km of the line only the three boreholes (4038363, 4054356 and 4063523) located north of the line (between 5.5km and 9.5km away) preserve Transvaal Supergroup. However, these boreholes only report the Chuniespoort Group underlying the Karoo Supergroup.
Black Reef Formation	Not reported in the line intersection of the surface mapping, but the contact is reported ~37km NW of the line.	Out of the fifteen boreholes that lie within 10km of the line only the three boreholes (4038363, 4054356 and 4063523) that are located north of the line (between 5.5km and 9.5km away) preserve Transvaal Supergroup and the base contact with the underlying stratigraphy.
Venterspost Contact Formation (VCF)	Not reported in the line intersection of the surface mapping, but outcrops ~20km NE of the line trace and ~41km NW of the line trace in the collar rocks	Out of the fifteen boreholes that lie within 10km of the line only three boreholes preserve the Ventersdorp Supergroup, two of which intersect the base contact (i.e. the VCF). Borehole 4038495 is located ~9.5km east of the northern edge of the line and preserves the base contact of the Ventersdorp Supergroup at 635.00m downhole. Borehole 4003209 is located ~8.5km SW of the southern edge of the

	of the Vredefort dome. An inlier located ~5km east from the centre of the line exposes Edenville Formation volcanics.	line and preserves the base contact of the Ventersdorp Supergroup at 543.00m downhole. Borehole 4039846 is located ~4.7km west of the line and unlike the previous two boreholes does not intersect the base contact as the borehole was stopped 48.31m below the Karoo Supergroup, in Ventersdorp Supergroup.
Central Rand Group – West Rand Group	Not reported in the line intersection of the surface mapping, but outcrops are reported ~40km NW of the line trace in the collar of the dome. The Central Rand Group are exposed ~19.7km NE of the line and West Rand Group are exposed ~30km west of the line.	Out of the fifteen boreholes that lie within 10km of the line, fourteen preserve the Witwatersrand Supergroup. Borehole 4039846 ends in the overlying Ventersdorp Supergroup as mentioned above. Stratigraphic logs are not included for boreholes 4039849 and 4066121, located ~2700m east and ~900m west of the southern edge of the line, respectively. The lithologies in these two boreholes can be inferred from the adjacent boreholes that contain similar quartzite and shale units. The contact between the Central Rand and West Rand groups however is only intersected in three of the northern boreholes (4038363, 4038495 and 4063523) and two of the southern boreholes (4003209 and 4066121). The contact in 4066121 is inferred because it intersects a wide shale unit (from 669.65 – 960.12m downhole) interpreted to be the Booysens Formation (as reported in adjacent boreholes). A second shale unit is intersected 34.14m above the end depth of the borehole (1741.32m downhole). The borehole log is a summary log of the original and given that the borehole is stopped shortly after intersecting the second shale unit (a common practice in drilling to overshoot the target horizon and drill an adequate distance into the footwall rock) it is suggested that the targets were the conglomerate reefs of the Central Rand Group. Therefore once the underlying West Rand Group was intersected the borehole would have been stopped.
West Rand Group – Dominion Group	Not reported in the line intersection of the surface mapping, but outcrops ~46km NW of the line trace.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies 110km NW of this seismic line.
Basement Contact	Not reported in the line intersection of the surface mapping, but outcrops ~30km west of the line trace.	Two boreholes intersect the basement, however they are located 107 – 110km NW of this section.

Table E16: Seismic Line Description	Line BH-269	Migration Type: FK
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The surface mapping indicates the line trace passes through subhorizontal sequences of the Volksrust Formation in the WSW half and Adelaide Subgroup the ENE half. Quaternary sediments are reported in towards the WSW edge.	Eight boreholes are located within 10km of the line, all of which report the Karoo Supergroup from surface. The majority of the boreholes are clustered towards the south. One borehole (4039845) located ~3.2km north of the line preserves the Karoo Supergroup base contact at 337.72m downhole. Six boreholes (4066121, 4066123, 4066128, 4077870, 4126376 and 4202051) are distributed between ~4.7km and ~9.2km south of the line and report a range of base contacts of the Karoo Supergroup from 264.24 – 556.56m downhole. Borehole 4039846 is the closest borehole to the line (~870m south) and preserves the base contact of the Karoo Supergroup at 287.27m downhole.
Pretoria Group – Chuniespoort Group	Not reported in the line intersection of the surface mapping, but the contact is reported ~53km from the line in the eastern and southern parts of the Vredefort dome collar.	Boreholes <17km from the line do not report Transvaal Supergroup, only underlying stratigraphy.
Black Reef Formation	Not reported in the line intersection of the surface mapping, but the contact is reported ~50km from the line in the eastern and southern parts of the Vredefort dome collar.	Boreholes <20km from the line do not report the base contact of the Transvaal Supergroup, only underlying stratigraphy.
Venterspost Contact Formation (VCF)	Not reported in the line intersection of the surface mapping, but the contact is reported ~47km from the line in the eastern and southern parts of the Vredefort dome collar. An inlier located ~3.2km east of the line exposes Edenville Formation volcanics.	Out of the eight boreholes that lie within 10km of the line, only the two closest boreholes (4039845 and 4039846) preserved the Ventersdorp Supergroup. Unfortunately both boreholes end within the Ventersdorp Supergroup so the VCF is not constrained. Borehole 4039845 intersects an 86.56m interval of alternating dolomite and volcanics. According to Johnson et al. (2006) the Rietgat Formation contains minor dolomite units

		interbedded with the sediments and volcanics. It is suggested that this borehole interval represents the dolomite unit of the Rietgat Formation.
Central Rand Group – West Rand Group	Not reported in the line intersection of the surface mapping, but outcrops are reported 44 – 53km of the line trace in the eastern and southern parts of the Vredefort dome collar. Central Rand Group are exposed ~31km NE of the line and West Rand Group are exposed ~11km WNW of the line.	Out of the eight boreholes that lie within 10km of the line, the six boreholes (4066121, 4066123, 4066128, 4077870, 4126376 and 4202051) distributed between ~4.7km and ~9.2km south of the line preserve Witwatersrand Supergroup. However all only two of these boreholes (4066121 and 4202051) intersect the contact. The summary log of borehole 4066121 does not contain a stratigraphic log, and the summary log of borehole 4202051 broadly defines the units as part of the Witwatersrand Supergroup. However the base units of these boreholes are suggested to be part of the West Rand Group. The contact in 4066121 is inferred because it intersects a wide shale unit (from 669.65 – 960.12m downhole) interpreted to be the Booysens Formation (as reported in adjacent boreholes). A second shale unit is intersected 34.14m above the end depth of the borehole (1741.32m downhole). Given that the borehole is stopped shortly after intersecting the second shale unit (a common practice in drilling to overshoot the target horizon and drill an adequate distance into the footwall rock) it is suggested that the targets were the conglomerate reefs of the Central Rand Group. Therefore once the underlying West Rand Group was intersected the borehole would have been stopped. The contact in 4202051 is inferred because it intersects and ends in a volcanic unit below the quartzite-dominated units overlying it. There is a very thin shale interval logged ~50m above the volcanic unit but the thickness is not stated as the depth is only indicated by an arrow so could not be plotted at the scale of the log. The volcanic unit could represent either the Bird Member lava or the Crown Formation lava. Both lie below the Booysens Formation, however the thin preservation of the shale unit does not automatically imply it is part of the Booysens Formation. It is likely that it is given that there is no other shale unit preserved in the borehole. However it is also possible that the thin shale unit is part

		of the West Rand Group and the volcanic unit ~50m below it represents the Crown Formation. Similarly to the explanation of borehole 4066121 it is common practice for boreholes to be stopped a short distance below the target horizon. As observed in other boreholes the targets are commonly the conglomerate reefs of the Central Rand Group, including the basal reefs of the group. In the detailed logs the lower units of the borehole would have been described in terms of their stratigraphic placement and the volcanic unit may have therefore been deemed as the Crown Formation, after which the borehole was stopped.
West Rand Group – Dominion Group	Not reported in the line intersection of the surface mapping, but outcrops ~44km of the line trace in the eastern and southern parts of the Vredefort dome collar.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies 105km NW of this seismic line.
Basement Contact	Not reported in the line intersection of the surface mapping, but outcrops ~13km NW of the line trace.	Two boreholes intersect the basement, however they are located 98 – 105km NW of this section.

Table E17: Seismic Line Description	**Line FV-154**	**Migration Type: CAS**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The WNW quarter of the line is not covered by the Karoo Supergroup or quaternary sediments and the exposes Archaean basement. The subhorizontal Karoo Supergroup is preserved over the rest of the line extent.	Nine boreholes are located within 5km of the line, seven of which report the Karoo Supergroup from surface. The two that do not are boreholes 4066156 and 4213937, located in the WNW half of the section where no Karoo Supergroup is preserved in the surface mapping. Borehole 4039845 is the closest to the line, ~400m north. It constrains the base of the Karoo Supergroup at 337.72m downhole. Borehole 4066121 is located ~1200m NE of the ESE edge of the line, and reports the base contact at 556.56m downhole. Boreholes

		4039849 and 4213253, located ~4500 and ~5000m east of the line, respectively, report the base contact at 476.70m and 479.76m downhole, respectively. Boreholes 4066123, 4066128 and 4077870 are clustered 2800 – 4300m SE off the ESE edge, and report the base contact at 317.20m, 449.12m and 387.70m, respectively.
Pretoria Group – Chuniespoort Group	The contact is observed ~18km west of the WNW edge, in the collar rocks of the dome.	Boreholes <21km from the line do not report Transvaal Supergroup, only underlying stratigraphy.
Black Reef Formation	The contact is observed ~15km west of the WNW edge, in the collar rocks of the dome.	Boreholes <27km from the line do not report the base contact of the Transvaal Supergroup, only underlying stratigraphy.
Venterspost Contact Formation (VCF)	The contact is observed ~10km west of the WNW edge, in the collar rocks of the dome.	Two inclined boreholes (4039825 and 4054336) 12 – 15km SW of the WNW edge, in the collar rocks of the dome, preserve the contact between 175.07m and 130.14m downhole, respectively. One other borehole (4003209, subvertical) preserves the contact and is located in the vicinity of the line (~10km SW of the ESE edge). The contact is reported at 543.00m downhole. Boreholes 4039845 and 4039846, located ~400m and ~5200m NE of the line, respectively, intersect Ventersdorp Supergroup but do not intersect the base. All other boreholes preserve the underlying Witwatersrand Supergroup only.
Central Rand Group – West Rand Group	The contact is observed ~6km west of the WNW edge, in the collar rocks of the dome. Outside the collar rocks the West Rand Group is exposed 800 – 3000m north and south of the line near the centre. Aeromagnetic imaging of the region indicates the magnetic shales of the West Rand Group form a near complete ring around the dome. The observed West Rand Group exposure lies on the magnetic ring, suggesting it is a surface exposure of the collar at depth.	The boreholes in the collar rocks of the dome intersect either Central Rand Group or West Rand Group. Only one intersects the contact, inclined borehole 4020753, located ~10km north of the WNW edge that reports the contact between 334.67m and 364.24m downhole (note, an intrusive is intersected at the contact). Three subvertical boreholes located towards the ESE edge preserve the contact. Boreholes 4003209, 4066121 and 4202051 (located ~10km SW, ~1.3km NE, and ~12km SW, respectively) report the contact at 1839.86m (note, an intrusive is intersected at the contact), 1707.18m and 1597.15m (no stratigraphic log so this depth is taken from the volcanic unit, i.e. Crown Formation, preserved at the base of the borehole), respectively.

West Rand Group – Dominion Group	The contact is located ~400m from the WNW edge in the collar rocks of the dome.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies ~54km NNW of this seismic line.
Basement Contact	The contact is located at the WNW tip in the collar rocks of the dome, as well as ~750m north of the line in the SE exposure of the dome collar.	Three boreholes intersect the basement, Two are located 45 – 54km NNW of this section, and the third is located ~600m north of the line in the centre of the dome.

Table E18: Seismic Line Description	**Line BH-268**	**Migration Type: FK**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The Volksrust Formation and Adelaide Subgroup are reported over the extent of the line, with Quaternary sediments covering the western edge.	Nine subvertical boreholes are located within 4km of the western half of the line. Boreholes 4202051 and 4066121 are located ~170m and ~250m north of the line, respectively, and report the base contact of the Karoo Supergroup at 264.26m and 556.56m downhole, respectively. Boreholes 4213253 and 4066128 are located ~540m and ~600m north of the line, respectively, and report the base contact depth at 479.75m and 449.12m downhole, respectively. Borehole 4039849 is located ~1000m south of the eastern edge, and reports the base contact at 476.70m downhole. Three boreholes (4066123, 4077870 and 4126376) clustered in a zone 1800 – 2200m north and south of the line, and report base contact depths from 317.20 – 489.10m downhole. Borehole 4066130 is located ~4000m south of the line and reports the base contact at 561.75m downhole.
Pretoria Group – Chuniespoort Group	The contact is observed ~35km west of the line, in the collar rocks of the dome.	Borehole 4066142, located ~19.5km SSW of the western edge of the line reports the contact. Other boreholes closer to the line do not report Transvaal Supergroup.
Black Reef Formation	The contact is observed ~33km west of the line, in the collar rocks of the dome.	Boreholes <30km from the line do not report the base contact of the Transvaal Supergroup, only underlying stratigraphy.

Venterspost Contact Formation (VCF)	The contact is observed ~30km west of the line, in the collar rocks of the dome.	Borehole 4003209 is located ~7.1km south of the line in the western half. It is the only borehole in the vicinity that preserves the base contact of the Ventersdorp Supergroup, albeit quite shallow, at 543.00m downhole. The next closest boreholes that report the base contact are located >24km west, south and north of the line.
Central Rand Group – West Rand Group	The contact is observed ~37km NW of the line, in the collar rocks of the dome. The lower West Rand Group formations are preserved ~14km north of the line. Aeromagnetic imaging of the region indicates the magnetic shales of the West Rand Group form a near complete ring around the dome. The observed West Rand Group exposure lies on the magnetic ring, suggesting it is a surface exposure of the collar at depth.	Two boreholes, 4066121 and 4202051, lie ~250m and ~170m north of the line, respectively. The contact in 4066121 is inferred because it intersects a wide shale unit (from 669.65 – 960.12m downhole) interpreted to be the Booysens Formation (as reported in adjacent boreholes). A second shale unit is intersected 34.14m above the end depth of the borehole (1741.32m downhole). Given that the borehole is stopped shortly after intersecting the second shale unit (a common practice in drilling to overshoot the target horizon and drill an adequate distance into the footwall rock) it is suggested that the targets were the conglomerate reefs of the Central Rand Group. Therefore once the underlying West Rand Group was intersected the borehole would have been stopped. The contact in 4202051 is inferred because it intersects and ends in a volcanic unit below the quartzite-dominated units overlying it. There is a very thin shale interval logged ~50m above the volcanic unit but the thickness is not stated as the depth is only indicated by an arrow so could not be plotted at the scale of the log. The volcanic unit could represent either the Bird Member lava or the Crown Formation lava. Both lie below the Booysens Formation, however the thin preservation of the shale unit does not automatically imply it is part of the Booysens Formation. It is likely that it is given that there is no other shale unit preserved in the borehole. However it is also possible that the thin shale unit is part of the West Rand Group and the volcanic unit ~50m below it represents the Crown Formation. Similarly to the explanation of borehole 4066121 it is common practice for boreholes to be stopped a short distance below the target horizon. As observed in other boreholes the targets are commonly the conglomerate reefs of the Central Rand Group, including the basal reefs of the group. In the detailed logs the lower units of the borehole would have been described in terms of their

		stratigraphic placement and the volcanic unit may have therefore been deemed as the Crown Formation, after which the borehole was stopped.
West Rand Group – Dominion Group	The contact is located ~23km WNW of the line in the collar rocks of the dome.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies ~98km NW of this seismic line.
Basement Contact	The contact is located ~14km north of the line in the dome core exposures.	Three boreholes intersect the basement, Two are located 88 – 98km NW of this section, and the third is located ~26km NNW of the line in the centre of the dome.

Table E19: Seismic Line Description	**Line DE-512B**	**Migration Type: FK**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The subhorizontal Volksrust Formation and Adelaide Subgroup are reported over the extent of the line, with Quaternary sediments covering the majority of the southern half. Several narrow inliers are located adjacent to the line that expose underlying stratigraphy.	Four boreholes are located in the vicinity of the line. These boreholes are 4003241 (~4.7km NNE), 4065902 (~6.5km ESE), 4066139 (~6.2km west) and 4066140 (~3.6km north). Only boreholes 4065902 and 4066139 report Karoo Supergroup intersections as boreholes 4003241 and 4066140 are collared in inliers containing outcrop of underlying stratigraphy. The base contact of the Karoo Supergroup is reported between 326.00m and 342.29m by boreholes 4065902 and 4066139, respectively.
Pretoria Group – Chuniespoort Group	The contact is observed ~17km NW of the line, in the collar rocks of the dome. Narrow inliers are reported 4 – 11km west and east of the line that expose Hekpoort Formation.	Borehole 4066139 (~6.2km west) is the only borehole in the close vicinity of the line that intersects Transvaal Supergroup. The package is intersected further east and west of the line (>16km away). Unfortunately borehole 4066139 is relatively shallow (485.55m in length) but intersects the Chuniespoort Group below the Karoo Supergroup.
Black Reef Formation	The contact is observed ~18km NW of the line, in the collar rocks of the dome.	No boreholes in the vicinity intersect the Black Reef Formation. Intersections are reported in boreholes located >16km away.

Venterspost Contact Formation (VCF)	The contact is observed ~39km NW of the line, in the collar rocks of the dome.	The contact between the Ventersdorp and Witwatersrand supergroups is reported in three of the four adjacent boreholes, i.e. boreholes 4003241 (at 763.78m downhole), 4065902 (at 1114.47m downhole) and 4066140 (at 1285.95m downhole).
Central Rand Group – West Rand Group	The contact is observed ~38km NNW of the line, in the collar rocks of the dome.	Three boreholes in the vicinity intersect the Central Rand Group (4003241, 4065902 and 4066140) but none intersect the contact. Boreholes 4065902 and 4066140 report the Booysens Formation shales (locally named the Dagbreek Formation).
West Rand Group – Dominion Group	The contact is observed ~22km NNE of the line, in the collar rocks of the dome.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies ~98km NNW of this seismic line.
Basement Contact	The contact is observed ~23km NNE of the line, in the collar rocks of the dome.	Three boreholes intersect the basement, Two are located 85 – 98km NNW of this section, and the third is located ~43km NNE of the line in the centre of the dome.

Table E20: Seismic Line Description	**Line DE-512A**	**Migration Type: FK**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The majority of the line trace is mapped as Quaternary sediments or Volksrust Formation. The line trends across the depth extent of the collar rocks so there are several inliers that expose various stratigraphic units.	Three boreholes lie very close to the line towards the centre of the trace, i.e. 4003241 (~2000m east), 4039843 (~350m west) and 4066140 (~400m east). A couple boreholes lie further away, i.e. 4039837 (~5800m west) and 4066139 (~6100m west). The Karoo Supergroup is reported in four of these five boreholes (the exception being 4066140) and reports the base contact between 45.00m and 342.29m downhole. Borehole 4066140 is collared in an inlier.
Pretoria Group – Chuniespoort Group	The contact is observed ~12km west of the line, in the collar rocks of the dome. Narrow inliers are reported 4 – 9km	No Pretoria Group stratigraphy is reported in the boreholes adjacent to the line, only the underling Chuniespoort Group is preserved in boreholes 4039843 and 4066139.

	east and west of the southern tip of the line that expose Hekpoort and Strubenkop formations.	
Black Reef Formation	The contact is observed ~12km west of the line, in the collar rocks of the dome.	The contact between the Transvaal and Ventersdorp supergroups is preserved in borehole 4039843 (~350m west of the line). The base of the Black Reef Formation is reported at 258.47m downhole. Borehole 4066139 (~6.1km west of the line) is a very short borehole (485.55m end depth) and it both intersects and ends in Chuniespoort Group.
Venterspost Contact Formation (VCF)	The contact is observed ~24km NW of the line, in the collar rocks of the dome. Narrow inliers are reported <2.1km east and west of the central parts of the line that expose Klipriviersberg Group volcanics.	Boreholes 4003241 (~2000m east of the line) and 4066140 (~400m east of the line) intersect the VCF at 763.78m and 1285.95m downhole,, respectively.
Central Rand Group – West Rand Group	The contact is observed ~20km NW of the line, in the collar rocks of the dome. Narrow inliers are reported towards the NNE edge of the line that expose Government and Hospital Hill subgroups.	No boreholes in the vicinity of the line intersect the contact. Boreholes 4003241 (~2000m east of the line) and 4066140 (~400m east of the line) end in Central Rand Group (2500.60m and 2793.49m end depths,, respectively)
West Rand Group – Dominion Group	The contact is observed ~1.4km west of the NNE tip of the line, in the collar rocks of the dome.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies ~80km NNW of this seismic line.
Basement Contact	The contact is observed ~230m north of the line, in the collar rocks of the dome.	Three boreholes intersect the basement, Two are located 70 – 80km NNW of this section, and the third is located ~22km NE of the line in the centre of the dome.

Table E21: Seismic Line Description	Line DE-511		Migration Type: FK
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**	
Karoo Supergroup Base	The majority of the line trace is mapped as Quaternary sediments, Volksrust Formation or Adelaide Subgroup. The line trends adjacent several inliers that expose underlying stratigraphic units.	Seven boreholes lie adjacent to, either north or south, of the line, i.e. 4003241 (~2.2km south), 4039843 (~450m north), 4039844 (~1km north), 4039847 (~3.8km ENE), 4066140 (~3.9km south), 4066142 (~5.5km south) and 4225646 (~6.4km north). All boreholes intersect Karoo Supergroup, except borehole 4066140, with base contact depths ranging between 45.00m and 374.90m downhole.	
Pretoria Group – Chuniespoort Group	The contact is observed ~11km WNW of the line, in the collar rocks of the dome. Narrow inliers are reported 4.8 – 8.1km south of the line that expose Hekpoort Formation.	Three of the seven adjacent boreholes intersect Transvaal Supergroup, i.e. 4039843 (~450m north of the WNW edge), 4066142 (~5.5km south of the centre) and 4039847 (~3.8km ENE of the ESE edge). They all intersect the Chuniespoort Group below the Karoo Supergroup but only borehole 4066142 preserves the Pretoria Group as well, with the contact intersected at 668.27m downhole.	
Black Reef Formation	The contact is observed ~10.5km NW of the line, in the collar rocks of the dome.	Out of the seven adjacent boreholes only borehole 4039843 (~450m north of the WNW edge) intersects the contact (at 258.47m downhole) as the other two boreholes mentioned above are relatively shallow and were stopped in the Chuniespoort Group. The preservation of the Chuniespoort Group in boreholes spread across the line trace suggests that the Transvaal Supergroup in the line section could be observed, albeit at very shallow depths as the data indicates.	
Venterspost Contact Formation (VCF)	The contact is observed ~30km NW of the line, in the collar rocks of the dome. A series of narrow inliers are reported adjacent to the centre of the line between 100m and 1600m north of the line, as well as a couple	Out of the seven adjacent boreholes only three boreholes, clustered together, intersect the Ventersdorp Supergroup, i.e. 4003241 (~2.2km south of the WNW edge), 4039843 (~450m north of the WNW edge) and 4066140 (~5.5km south of the WNW edge). However, only boreholes 4003241 and 4066140 are deep enough to intersect the VCF though, at 763.78m and 1285.95m downhole,, respectively.	

	exposures ~3.1km north and south of the WNW edge. The outcrops report Klipriviersberg Group volcanics.	
Central Rand Group – West Rand Group	The contact is observed ~29km NW of the line, in the collar rocks of the dome. Inliers that expose Government and Hospital Hill subgroups are reported closer to the line, up to ~9km north of the ENE edge of the line.	Out of the seven adjacent boreholes only four boreholes report the Witwatersrand Supergroup, i.e. 4003241 and 4066140 adjacent to the WNW edge, and 4039844 and 4225646 located ~1km and ~6.4km north,, respectively towards the centre of the line. However only boreholes 4039844 and 4225646 towards the centre of the line report West Rand Group stratigraphy as well, and furthermore only borehole 4039844 intersects the contact between the Central Rand and West Rand groups as borehole 4225646 only preserves the West Rand Group below the Karoo Supergroup.
West Rand Group – Dominion Group	The contact is observed ~13km north of the ENE edge of the line, in the collar rocks of the dome.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies ~89km NNW of this seismic line.
Basement Contact	The contact is observed ~13km north of the ENE edge of the line, in the collar rocks of the dome.	Three boreholes intersect the basement, Two are located 77 – 89km NNW of this section, and the third is located ~34km north of the line in the centre of the dome. Borehole 4225646 (~6.4km north) intersects a granite from 1869.49m to the end of hole at 1999.79m. It is unclear whether this represents basement or a local-scale granitic sheet intrusion.

Table E22: Seismic Line Description	**Line DE-506**	**Migration Type: FK**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The majority of the line trace is mapped as Quaternary sediments, Volksrust Formation or Adelaide Subgroup.	Six boreholes are located within 10km of the line, i.e. 4039847 (~4.5km east), 4039848 (~8.2km east), 4039964 (~6.5km SW), 4039970 (~9.9km south), 4066445 (~5.8km south) and 4225646 (~6.6km west). The Karoo Supergroup is intersected in all six boreholes with the base contact depth ranging between 174.50m and 451.10m downhole.

Pretoria Group – Chuniespoort Group	The contact is observed ~39km west of the line, in the collar rocks of the dome. Narrow inliers are reported 10km west of the line that expose Hekpoort Formation.	One borehole out of the six intersects the Transvaal Supergroup, i.e. 4039847. However only the Chuniespoort Group is preserved in the borehole.
Black Reef Formation	The contact is observed ~36.5km west of the line, in the collar rocks of the dome.	One borehole out of the six intersects the Transvaal Supergroup, i.e. 4039847. However the borehole does not intersect the base contact with underlying stratigraphy.
Venterspost Contact Formation (VCF)	The contact is observed ~47km WNW of the line, in the collar rocks of the dome. A series of narrow inliers are reported ~15km west, and a single narrow exposure is reported ~1km south. The outcrops report Klipriviersberg Group volcanics.	Two boreholes out of the six intersect the Ventersdorp Supergroup, i.e. 4039964 and 4066445, however only borehole 4066445 intersects the base contact with the Central Rand Group, at 1234.77m downhole.
Central Rand Group – West Rand Group	The contact is observed ~42.5km NW of the line, in the collar rocks of the dome. Several exposures of lower West Rand Group are reported ~14.5km NNE of the line.	Four boreholes out of the six intersect the Witwatersrand Supergroup, i.e. 4039848, 4039970, 4066445 and 4225646. However the contact between the Central Rand and West Rand groups is not intersected by these boreholes. Instead the Central Rand Group is intersected in boreholes 4039970 and 4066445, and the West Rand Group is intersected in boreholes 4039848 and 4225646.
West Rand Group – Dominion Group	The contact is observed ~25km WNW of the line, in the collar rocks of the dome.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies ~98km NW of this seismic line.
Basement Contact	The contact is observed ~25km WNW of the line, in the collar rocks of the dome, and ~16km NNE of the line in the core rocks of the dome.	Three boreholes intersect the basement, Two are located 89 – 98km NW of this section, and the third is located ~25km NNW of the line in the centre of the dome.

Table E23: Seismic Line Description	Line BH-171B	Migration Type: FK

Major Contact Reflector	Surface Mapping Information	Borehole Information
Karoo Supergroup Base	The majority of the line trace is mapped as Quaternary sediments or Adelaide Subgroup.	21 boreholes are located within 10km of the line. The majority are clustered south of the line or towards the SW edge. Two boreholes are located adjacent to the NE half, i.e. 4039847 (~9.1km west) and 4039848 (~4.4km east). Boreholes 4039963, 4039964, 4066445 and 4066449 are clustered between 1.8km and 5.0km west of the SW edge. Boreholes 4039970 and 4204331 are located 4.0km and 1.2km east of the SW edge,, respectively. The rest of the boreholes are located SW or south of the line. These boreholes include, 4039972, 4039973, 4039990, 4039991, 4039992, 4039993, 4066285, 4066437, 4066451, 4066471, 4066475, 4066476 and 4066477. Borehole 4066449 does not report Karoo Supergroup as the underlying stratigraphy is preserved at surface at this location. The Karoo Supergroup is preserved in all other boreholes and the base contact with underlying stratigraphy ranges between 145.39m and 500.18m downhole.
Pretoria Group – Chuniespoort Group	The contact is observed ~57km WNW of the line, in the collar rocks of the dome. Narrow inliers are reported ~13.3km west of the line that expose Hekpoort Formation.	Only one borehole out of the 21 intersects the Transvaal Supergroup, i.e. 4039847. However only the Chuniespoort Group is preserved in the borehole.
Black Reef Formation	The contact is observed ~56.5km WNW of the line, in the collar rocks of the dome.	Only one borehole out of the 21 intersects the Transvaal Supergroup, i.e. 4039847. However the borehole does not intersect the base contact with underlying stratigraphy.
Venterspost Contact Formation (VCF)	The contact is observed ~72km NW of the line, in the collar rocks of the dome. A series of narrow inliers are reported ~26km WNW, and a single narrow	The Ventersdorp Supergroup is intersected in 9 of the 21 boreholes, i.e. 4039963, 4039964, 4039972, 4039973, 4066285, 4066445, 4066449, 4066451 and 4066476, all clustered in the south. The VCF is intersected in 8 of these boreholes, with the exception

	exposure is reported on the line trace towards the centre in the SW half. The outcrops report Klipriviersberg Group volcanics.	being borehole 4039964. The intersection of the VCF ranges between 495.91m and 2143.05m downhole, and becomes shallower towards the east of the borehole cluster.
Central Rand Group – West Rand Group	The contact is observed ~68km NW of the line, in the collar rocks of the dome. Several exposures of lower West Rand Group are reported ~33km NNW of the line.	Borehole 4039848 in the northern half intersects the West Rand Group over its entire length (below the Karoo Supergroup). Borehole 4039970 (~4km east of the SW edge) intersects only West Rand Group below the Karoo Supergroup. Borehole 4066449 (~2.4km west of the SW edge) intersects the West Rand Group preserved in contact with the Ventersdorp Supergroup. Boreholes 4039963, 4039990, 4039991, 4039992, 4039993, 4066285, 4066471 and 4066475 intersect the contact between 722.68m and 2946.81m, with shallower intersections towards the east of the cluster.
West Rand Group – Dominion Group	The contact is observed ~49.5km NW of the line, in the collar rocks of the dome.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies ~123km NW of this seismic line.
Basement Contact	The contact is observed ~49.5km NW of the line, in the collar rocks of the dome, and ~33km NNW of the line in the core rocks of the dome.	Three boreholes intersect the basement, Two are located 115 – 123km NW of this section, and the third is located ~49km NNW of the line in the centre of the dome.

Table E24: Seismic Line Description	**Line BH-171A**	**Migration Type: FK**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The majority of the line trace is mapped as Adelaide Subgroup.	Four boreholes are located adjacent to the line, i.e. 4003209 (~2.5km north), 4039848 (~4.4km ESE), 4066130 (~4.8km north) and 4066131 (~2.4km NE). All four preserve the Karoo Supergroup, with the base contact ranging between 374.90m and 561.75m downhole.

Pretoria Group – Chuniespoort Group	The contact is observed ~59km WNW of the line, in the collar rocks of the dome. Narrow inliers are reported ~18km WSW of the line that expose Hekpoort Formation.	The Chuniespoort Group is intersected in borehole 4039847, ~9km WNW of the line. The next closest intersection of Transvaal Supergroup is >25km from the line.
Black Reef Formation	The contact is observed ~58km WNW of the line, in the collar rocks of the dome.	The closest intersection of the Black Reef Formation is >26km from the line.
Venterspost Contact Formation (VCF)	The contact is observed ~71km NW of the line, in the collar rocks of the dome. A series of narrow inliers are reported ~29km west, and a single narrow exposure is reported ~7.8km south on the line trace of BH-171B. A single narrow exposure is reported on the line trace towards the centre in the line. The outcrops report Klipriviersberg Group volcanics.	Borehole 4003209 (~2.5km north) intersects a narrow interval (104m) of Alberton Formation volcanics in contact with the overlying Karoo Supergroup. The contact (VCF) with the Elsburg Formation is reported at 543.00m downhole. The next closest intersection of the VCF is >10km from the line.
Central Rand Group – West Rand Group	The contact is observed ~68km NW of the line, in the collar rocks of the dome. Several exposures of lower West Rand Group are reported ~31km NNW of the line.	All four of the adjacent boreholes intersect Witwatersrand Supergroup. Borehole 4066130 (~4.8km north) intersects Central Rand Group only. Borehole 4039848 (~4.4km ESE) intersects West Rand Group only. Borehole 4066131 (~2.4km NE) likely intersects Central Rand Group (not stated in log) as it is shallow (~814.73m end depth) and is dominated by quartzite. Borehole 4003209 (~2.5km north) intersects both groups, with the contact reported at 1839.86m downhole. Note, the lithology about the contact is quartzite of the overlying Main Formation and underlying Roodepoort Formation. The Roodepoort Formation quartzite intersection width is 67.14m, below which is a 93.00m wide intrusive followed by a 60.00m wide shale unit (also Roodepoort Formation) to the end of the borehole.
West Rand Group – Dominion Group	The contact is observed ~49.5km NW of the line, in the collar rocks of the dome.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies ~123km NW of this seismic line.

Basement Contact	The contact is observed ~49.5km NW of the line, in the collar rocks of the dome, and ~33km NNW of the line in the core rocks of the dome.	Three boreholes intersect the basement, Two are located 115 – 123km NW of this section, and the third is located ~49km NNW of the line in the centre of the dome.

Table E25: Seismic Line Description	**Line DE-83**	**Migration Type: FK**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The majority of the line trace is mapped as Quaternary sediments, Volksrust Formation or Adelaide Subgroup.	28 boreholes are located up to 12km SSW of the line, while only 3 boreholes are located north of the line (up to ~2.8km). The closest of these boreholes includes 4039964 and 4066445 that lie ~660m and ~1000m north of the line,, respectively, but are only separated by ~2.4km. Borehole 4066142 completes the three northern boreholes and lies ~2.8km north of the line. Boreholes south of the line that aid in constraining the section (i.e. closest on the section length) include 4039970 (~2.6km south), 4065900 (~7.1km SSW), 4065923 (~8.2km SSW), 4066449 (~2.2km south) and 4204331 (~4.1km south). Borehole 4066449 does not intersect Karoo Supergroup as it reports the underlying units from the surface. The base contact of the Karoo Supergroup is reported in the rest of the boreholes between 135.03m and 723.30m downhole.
Pretoria Group – Chuniespoort Group	The contact is observed ~30km NW of the line, in the collar rocks of the dome. Narrow inliers are reported 1.0 – 5.5km north of the WNW half of the line that expose Hekpoort Formation.	Only the three boreholes adjacent to the WNW half intersect the Transvaal Supergroup, i.e. 4065900 (~7.1km SSW), 4065923 (~8.2km SSW) and 4066142 (~2.8km north). However only borehole 4066142 reports both Pretoria and Chuniespoort groups, with the contact at 672.69m downhole. The other two boreholes report the Chuniespoort Group only.
Black Reef Formation	The contact is observed ~30km NW of the line, in the collar rocks of the dome.	Boreholes 4065900 (~7.1km SSW) and 4065923 (~8.2km SSW) preserve the contact at 2066.19m and 1435.61m downhole,, respectively.

Venterspost Contact Formation (VCF)	The contact is observed ~50km NW of the line, in the collar rocks of the dome. A series of narrow inliers are reported ~9.5km north. The outcrops report Klipriviersberg Group volcanics.	The VCF is intersected in several adjacent boreholes, i.e. 4065900 (2204.50m downhole), 4065923 (2413.56m downhole, however a 430.84m wide intrusive lies at the contact), 4066445 (123.77m downhole) and 4066449 (1702.28m downhole).
Central Rand Group – West Rand Group	The contact is observed ~48km NW of the line, in the collar rocks of the dome. Several exposures of lower West Rand Group are reported ~40km north of the line.	Boreholes 4039970 and 4066449 intersect the West Rand Group in contact with the Karoo Supergroup and Ventersdorp Supergroup,, respectively. Boreholes that intersect the contact between the Central Rand and West Rand groups are located further away (>5km south) from the adjacent boreholes that constrain the line.
West Rand Group – Dominion Group	The contact is observed ~30km NNW of the line, in the collar rocks of the dome.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies ~108km NNW of this seismic line.
Basement Contact	The contact is observed ~30km NNW of the line, in the collar rocks of the dome, and ~40km north of the line in the core rocks of the dome.	Three boreholes intersect the basement, Two are located 96 – 108km NNW of this section, and the third is located ~45km north of the line in the centre of the dome.

Table E26: Seismic Line Description	**Line DE-510**	**Migration Type: FK**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The majority of the line trace is mapped as Quaternary sediments, Volksrust Formation or Adelaide Subgroup, with a few small inliers reported towards the SSW half that expose underlying stratigraphy.	Several boreholes are located within 10km of the line trace, including 4039844 (~6.5km WNW), 4065900 (~7.5km SW), 4065923 (~7.8km SSW), 4066142 (~6.6km west) and 4225646 (~4.5km NW). All adjacent boreholes report Karoo Supergroup with base contact depths ranging between 135.03m and 723.30m downhole.

Pretoria Group – Chuniespoort Group	The contact is observed ~41km WNW of the line, in the collar rocks of the dome. Several inliers are reported at surface, intersecting the line trace in the SSW half. These outcrops expose Hekpoort Formation.	Three boreholes located within 10km of the line trace intersect the Transvaal Supergroup, i.e. 4065900 (~7.5km SW), 4065923 (~7.8km SSW) and 4066142 (~6.6km west). However only borehole 4066142 reports both the Pretoria and Chuniespoort groups, and therefore the contact (672.69m downhole). The other two boreholes only report the Chuniespoort Group underlying the Karoo Supergroup.
Black Reef Formation	The contact is observed ~40km WNW of the line, in the collar rocks of the dome.	Boreholes 4065900 (~7.5km SW) and 4065923 (~7.8km SSW) report the contact (2066.19m and 1435.61m,, respectively) below the Chuniespoort Group.
Venterspost Contact Formation (VCF)	The contact is observed ~55km NW of the line, in the collar rocks of the dome. A series of narrow inliers are reported 10 – 20km WNW. The outcrops report Klipriviersberg Group volcanics.	The Ventersdorp Supergroup is very thinly preserved in the two adjacent boreholes that intersect the package. Boreholes 4065900 (~7.5km SW) and 4065923 (~7.8km SSW) report intersection widths of 136.01m and 73.15m,, respectively. However the intersection in borehole 4065923 overlies a 473.96m thick conglomerate unit that may either be associated with the Platberg Group or the Central Rand Group so the base contact in this borehole is uncertain. The conglomerate unit also overlies a 430.84m thick intrusive intersection that separates the underlying Central Rand Group quartzites and the anomalous conglomerate.
Central Rand Group – West Rand Group	The contact is observed ~52km NW of the line, in the collar rocks of the dome. Several exposures of lower West Rand Group are reported ~28km NNE of the line.	Boreholes 4065900 (~7.5km SW) and 4065923 (~7.8km SSW) report Witwatersrand Supergroup, however they only intersect Central Rand Group stratigraphy. Boreholes 4039844 (~6.5km WNW) and 4225646 (~4.5km NW) intersect the West Rand Group and only borehole 4039844 intersects the contact, at 1975.10m downhole. Borehole 4225646 is dominated by intrusives but only intersects West Rand Group stratigraphy between the intrusive intersections.
West Rand Group – Dominion Group	The contact is observed ~33km NW of the line, in the collar rocks of the dome.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies ~110km NNW of this seismic line.
Basement Contact	The contact is observed ~33km NW of the line, in the collar rocks of the dome, and ~28km NNE of the line in the core rocks of the dome.	Three boreholes intersect the basement, Two are located 100 – 110km NW of this section, and the third is located ~39km NNW of the line in the centre of the dome.

Table E27: Seismic Line Description	Line DE-508	Migration Type: FK
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The majority of the line trace is mapped as Quaternary sediments or Volksrust Formation. Several narrow inliers reported towards the centre and the SW half expose underlying stratigraphy.	Three boreholes are located adjacent to the line, i.e. 4039844 (~3.4km east), 4066142 (~3.7km east) and 4225646 (~5.3km east). The Karoo Supergroup is reported in these boreholes, with base contact depths ranging between 135.03m and 224.64m downhole.
Pretoria Group – Chuniespoort Group	The contact is observed ~31km WNW of the line, in the collar rocks of the dome. Several inliers are reported at surface ~1.5km east of the SW half. These outcrops expose Hekpoort Formation.	The southernmost borehole (4066142, located ~3.7km east) of the three adjacent boreholes intersects Transvaal Supergroup. The other two report Witwatersrand Supergroup. Borehole 4066142 also intersects the contact between the Pretoria and Chuniespoort groups, at 668.27m downhole.
Black Reef Formation	The contact is observed ~31km WNW of the line, in the collar rocks of the dome.	No adjacent boreholes report this contact. The closest borehole that intersects this contact at depth is 4065900, located ~9.9km SE (intersecting the contact at 2066.19m downhole).
Venterspost Contact Formation (VCF)	The contact is observed ~44km WNW of the line, in the collar rocks of the dome. A series of narrow inliers are reported adjacent to the centre of the line and extending ~9.5km WNW of the line. The outcrops report Klipriviersberg Group volcanics.	No adjacent boreholes report this contact. The closest borehole that intersects this contact at depth is 4065900, located ~9.9km SE (intersecting the contact at 2204.50m downhole).
Central Rand Group – West Rand Group	The contact is observed ~41km NW of the line, in the collar rocks of the dome. Several exposures of lower West Rand Group are reported ~19km NE of the line.	Boreholes 4039844 (~3.4km east), and 4225646 (~5.3km east) report Witwatersrand Supergroup. Borehole 4225646 is dominated by intrusives but reports only West Rand Group stratigraphy. Borehole 4039844 intersects the Central Rand Group below the Karoo Supergroup down to the contact with the West Rand Group at 1975.10m downhole.

West Rand Group – Dominion Group	The contact is observed ~23km NW of the line, in the collar rocks of the dome.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies ~98km NNW of this seismic line.
Basement Contact	The contact is observed ~23km NW of the line, in the collar rocks of the dome, and ~19km NE of the line in the core rocks of the dome.	Three boreholes intersect the basement, Two are located 88 – 98km NW of this section, and the third is located ~27km north of the line in the centre of the dome.

Table E28: Seismic Line Description	**Line DE-507**	**Migration Type: FK**
Major Contact Reflector	**Surface Mapping Information**	**Borehole Information**
Karoo Supergroup Base	The line trace is mapped as Quaternary sediments and minor Volksrust Formation.	One borehole is located adjacent to the line, i.e. 4225646 ~5km south. The Karoo Supergroup is preserved in this borehole with a base contact depth of 174.50m downhole.
Pretoria Group – Chuniespoort Group	The contact is observed ~31km west of the line, in the collar rocks of the dome.	No boreholes intersect the Transvaal Supergroup in the vicinity of the line. The closest borehole that intersects the Transvaal Supergroup is borehole 4039847, ~11km SE.
Black Reef Formation	The contact is observed 30km west of the line, in the collar rocks of the dome.	No boreholes intersect the Black Reef Formation in the vicinity of the line. The closest borehole that intersects the Black Reef Formation is borehole 4065900, ~28km south.
Venterspost Contact Formation (VCF)	The contact is observed ~42km NW of the line, in the collar rocks of the dome.	No boreholes intersect the Ventersdorp Supergroup or the VCF in the vicinity of the line. The closest borehole that intersects the Ventersdorp Supergroup and VCF is borehole 4066445, ~27km SSE.
Central Rand Group – West Rand Group	The contact is observed ~40km NW of the line, in the collar rocks of the dome. Several exposures of lower West Rand Group are reported ~17km NNE of the line.	Borehole 4225646 (~5km south) intersects only West Rand Group below the Karoo Supergroup (including large intervals of intrusive rocks) to the end of hole depth of 1999.79m. Borehole 4039844 (~10km south) intersects the contact between the Central Rand and West Rand groups at 1975.10m downhole.

West Rand Group – Dominion Group	The contact is observed ~21km WNW of the line, in the collar rocks of the dome.	No boreholes intersect this contact in the adjacent area. The closest borehole intersection with Dominion Group lies ~98km NNW of this seismic line.
Basement Contact	The contact is observed ~21km WNW of the line, in the collar rocks of the dome, and ~17km NNE of the line in the core rocks of the dome.	Three boreholes intersect the basement, Two are located 88 – 98km NW of this section, and the third is located ~28km north of the line in the centre of the dome.