

Evaluation of the Magnetotelluric TC 150 instrument for geophysical groundwater exploration

T van Wyk



orcid.org/0000-0003-0742-8475

Dissertation accepted in fulfilment of the requirements for the degree *Master of Science in Environmental Sciences with Hydrology and Geohydrology* at the North-West University

Supervisor: Mr J Koch

Graduation May 2021

24203696

I would like to dedicate this study to my mother who passed away three months into the study. Her drive and determination are what motivated this study until completion.

"Die leier op die hoogste trap

Het nie geklim met enkele stap;

Wyl ander sorgloos slaap en droom,

Het hul gewerk tot oggend soom"

Sonia van Wyk (16 October 1967-10 March 2018)

Kopiereg©2018 Noordwes-Universiteit (Potchefstroomkampus)

Copyright©2018 North-West University (Potchefstroom Campus)

Alle regte voorbehou / All rights reserved

PREFACE

Although the title of this dissertation is “Evaluation of the Magnetotelluric TC 150 instrument for geophysical groundwater exploration” a more accurate title would be “A Multi Geophysical Technique Evaluation for the Groundwater Potential of a Dolerite dyke in the Northwest Province”. Due to administrative and time constraints the original title was not amended.

ACKNOWLEDGEMENTS

First of all, I would like to thank God for the opportunity to study and explore the depths of science and the extent of human curiosity. Without Him, my life would be insignificant.

My dear father. Thank you for what you have taught me in life. Thank you for your spirit for life, science and most of all, religion to guide me on the right path through life. Thank you for your unfailing support and love during this study. It is a privilege being your son.

I would also like to express my gratitude to the rest of my family: Daan van Wyk(jr), Michelle van Wyk, Wilko and Karien. Without your faith, motivation, love, early morning phone calls and unfailing support, this study would never have finished. I love you all dearly!

My Supervisor, Jaco Koch. Thank you for your knowledge, experience, support and kind heart that you have shared with me from my first – to my last year on the university. I will remember your patient approach forever.

To my colleague and dear friend, Ruan Ainsley. Thank you for your support, positivity, belief and help with this study. Without your insight, capabilities and knowledge, the data of this study would not have been a success. I cherish your friendship.

To all the colleagues that helped me with all the fieldwork associated with this study, you have been a great help and I owe you many thanks.

To Dirk Stigter, thank you for your support in providing the ABEM Terrameter LS2 for this study. Thank you for your attitude towards science and research.

Thank you, Matthew Dambhuis for taking the time out of a very busy schedule to provide your knowledge and experience of the private sector, to the results of this study. It is much appreciated.

To my friend, rock climbing buddy and colleague, Niël Kriel. Your friendship, spirit and support are strong pillars in my life. May we share our passion for the mountains and science forevermore!

My sister, Maryna Kok. Thank you for your wisdom, patience, love and understanding. I cherish you deeply. Also, thanks to the Kok-family Theuns, Marina, Theunis and Christof, for accepting and loving me.

Last, but not least, my best friend and fiancé, Hybrecht (Hasie) Dupper. Your love, spirit and drive are great inspirations in my life. I love you dearly and thank you for the enormous effort you have put in this study. Without your patience, yet impatience, this study would never have been completed. You have supported me throughout the whole extent of this study, I promise to love you far beyond the extend of this study.

ABSTRACT

Freshwater is the most important resource for life on planet Earth. This natural resource is, however in great danger of being depleted and polluted to an irreparable extend. As surface water is currently the main source of fresh water, scientists explore for new sources that can lighten the load on surface water systems. Groundwater is an easy substitute for surface water. Scientific studies has thus shifted focus from surface water to exploration of groundwater sources. Geophysics is one of the methods that are commonly employed during groundwater exploration projects.

Three well-known methods in the subject of geophysical groundwater exploration were employed during this study. These three methods include Electrical Resistivity (ER), Electromagnetic (EM) and Magnetic (MAG). Common geological structures that will be focussed on during the employment of these three methods for groundwater exploration include hard-rock crystalline basement terrains. These terrains are very popular in geophysical groundwater exploration projects due to secondary permeability and porosity which occur within faults, fractures, dyke contacts and deeply weathered zones. The three instruments that were chosen to carry out the measurements of the above methods include the ABEM Terrameter LS 2, the EM 34-3 and the Proton Memory Magnetometer (G5).

Accurate and successful results of the above-mentioned methods can be obtained by using the methods together, in order to compare the results. As Geophysical surveys tend to be very expensive, certain groundwater exploration projects do not have the budget to employ more than one instrument for a particular study. It is thus very important to determine the success of various methods when employed to survey a dolerite dyke for groundwater exploration purposes. As a result, this study focused on employing the above-mentioned instruments to determine their success in delineating a known dolerite dyke.

Upon the successful completion of the fieldwork, the data of each instrument were processed into contoured maps (making use of Surfer 14 software) and 2D graphs. By analysing the various results that were retrieved by the three instruments, it was concluded that the ABEM Terrameter LS 2, The EM34-3 and the Proton Memory Magnetometer (G5) were successful in delineating the dolerite dyke. These instruments were successful as they produce results that were clear and comparable with one another.

Key terms: ABEM Terrameter LS 2; EM34-3; Proton Memory Magnetometer (G5); Groundwater; Exploration.

TABLE OF CONTENTS

PREFACE	I
ACKNOWLEDGEMENTS	I
ABSTRACT	III
CHAPTER 1 INTRODUCTION	1
1.1 Motivation	3
1.2 Hypotheses	3
1.3 Aims and Objectives	3
1.3.1 Aims	3
1.3.2 Objectives.....	3
CHAPTER 2: LITERATURE STUDY	5
2.1 Geophysical Groundwater Exploration.....	5
2.1.1 Electrical Resistivity Methods	5
2.1.2 Electromagnetic Methods	5
2.1.3 Magnetic Methods	6
2.2 Geophysical Methodology	6
2.2.1 Electrical and Magnetic Geophysical Methods.....	6
2.2.2 Electrical Resistivity method	7
2.2.2.1 Electrical Resistivity	7
2.2.2.1.1 The resistivity of Rocks and Minerals.....	8
2.2.2.1.2 Apparent Resistivity and True Resistivity	11
2.2.2.1.3 Electrode Arrays	12

2.2.2.1.4	Noise Associated with Electrical Methods.....	15
2.2.2.2	Instrumentation.....	15
2.2.2.2.1	ABEM Terrameter LS 2	15
2.2.2.3	Advantages and Disadvantages between the ER and the EM	17
2.2.3	Electromagnetic Methods	18
2.2.3.1	Background	18
2.2.3.2	Basic EM Theory	20
2.2.3.2.1	Alternating field fundamentals.....	20
2.2.3.2.2	Sine Functions and Vector Diagrams.....	20
2.2.3.2.3	Complex Quantities	22
2.2.3.2.4	Impedance in an Inductive Circuit.....	23
2.2.3.2.5	Maxwell Equations.....	24
2.2.3.2.6	Magnetic Vector Potential	27
2.2.3.2.7	Attenuation of EM Fields and Depth Penetration	28
2.2.3.2.8	Phase Relation between Primary and Secondary Fields:.....	29
2.2.3.2.9	Real and Imaginary Components of EM	31
2.2.3.2.10	The Elliptic polarisation of the EM Field	32
2.2.3.2.11	Boundary Conditions	33
2.2.3.3	Noise and Limitations Associated with the Electromagnetic (EM) Method	34
2.2.3.3.1	Noise	34
2.2.3.3.2	Limitations	34
2.2.3.4	Types of EM Systems.....	34
2.2.3.4.1	Small Loop Systems	35

2.2.3.4.2	Slingram	38
2.2.3.4.3	Ground Conductivity Meters	39
2.2.3.5	Instrumentation.....	40
2.2.3.5.1	EM34-3.....	40
2.2.4	Magnetic Method	43
2.2.4.1	History and Background	43
2.2.4.2	The Magnetic Properties of Rocks and Minerals.....	44
2.2.4.3	Principles and Elementary Theory	45
2.2.4.3.1	Poles Dipoles and Magnetisation.....	45
2.2.4.3.2	Geomagnetic Field	46
2.2.4.4	Magnetic Intensity.....	49
2.2.4.4.1	International Geomagnetic Reference Field (IGRF)	49
2.2.4.4.2	Magnetic Intensity of Mineral- and Geological Bodies.....	51
2.2.4.5	Induced and Remnant Magnetism	52
2.2.4.6	Magnetic Susceptibility	53
2.2.4.6.1	Susceptibility of Rocks and Minerals.....	54
2.2.4.7	Diamagnetism, Paramagnetism and Ferromagnetism	54
2.2.4.8	Remanent Magnetism and the Königsberger Ratios	55
2.2.4.9	Noise	56
2.2.4.10	Magnetic instruments.....	57
2.2.4.10.1	Proton Memory Magnetometer - Model G5.....	58
CHAPTER 3 METHODOLOGY.....		60

3.1	Study Area	60
3.1.1	Climate	60
3.1.2	Vegetation	61
3.1.3	Introductory Geology	61
3.1.4	Stratigraphic Geology	62
3.1.5	Regional geology	66
3.2	Instrumentation used in this study	67
3.2.1	ABEM Terrameter LS 2	67
3.2.2	Electro Magnetometer – Model 34-3.....	69
3.2.3	Proton Memory Magnetometer – Model G5	69
CHAPTER 4	RESULTS AND DISCUSSION	72
4.1	ABEM Terrameter LS 2.....	72
4.1.1	Traverse 1	72
4.1.2	Traverse 2	75
4.1.3	Traverse 3	77
4.2	EM 34-3.....	79
4.2.1	Horizontal Dipole	79
4.2.2	Vertical Dipole	80
4.3	Proton Memory Magnetometer – Model G5	82
CHAPTER 5	CONCLUSION	87
CHAPTER 6	RECOMMENDATIONS	88
BIBLIOGRAPHY		89

APPENDICES	96
-------------------------	-----------

List of Simbols

α	Alpha
A	Inductive Limit
B	Magnetic Flux Density
c	Free Constant
D	Electric Flux Density
e	emf
E	Electric Field Density
G	Greens Function
H	Magnetic Field Density
i	$\sqrt{-1}$
I	Current
j	Electric Dipole Moment
J	Current Density
k	Wavenumber
l	Horizontal Scale Parameter
L	Inductance
$\underline{L}$	Inductance Matrix
m	Magnetic Dipole Moment
M	Magnetization
N	Depolarization Factor
P	Electric Polarization
q	Charge Density
r	Spherical Radius
R	Resistance
$\underline{R}$	Resistance Matrix
s	Thickness
t	Time
$u(t)$	Step Function
U	Distribution of Magnetization
$x; y; z$	Cartesian Coordinates
$\underline{Z}$	Impedance Matrix
α	Current Channeling Number
β	Half-space Response Parameter
γ	Inductive Response Parameter
δ	Skin Depth

$\delta(t)$	Delta Function
ε	Dielectric permittivity
ε_0	Dielectric permittivity of free space
θ	Spherical Coordinate
K_e	Dielectric Susceptibility
K_μ	Magnetic Susceptibility
K_v	Relative Ohmic Susceptibility
λ	Spatial Wavelength
Λ	Propagation Wavelength
μ	Magnetic Permeability
μ_0	Magnetic Permeability of Free Space
ρ	Cylindrical-coordinate Radius
σ	Conductivity
τ	Time Constant
ϕ	Spherical Coordinate
Φ	Flux
ω	Angular Frequency
X_a	Anomalous
X_b	Body
X_c	Conduction
X_h	Halfspace
$X_i; X_j$	Index
X_r	Receiver
X_t	Transmitter
X^E	Electric Field
X^H	Magnetic Field
X^j	Electric Dipole Source
X^m	Magnetic Dipole Source
X^p	Primary
X^s	Secondary
X^r	Source

List of Abbreviations

1D	One dimensional
2D	Two dimensional
3D	Three dimensional
AC	Alternating Current
AUX	Auxiliary
BGS	British Geological Survey
BIF	Banded Iron-Formation
CD	Compact Disc
CGS	Centimetre, Gram and Second
CMOS	Complementary metal-oxide-semiconductor
CWEM	Continuous Wave Electromagnetic
DC	Direct Current
EM	Electromagnetic
Emf	Electromotive Force
ER	Electrical Resistivity
FDEM	Frequency Domain Electromagnetic
GCM	Ground Conductivity meters
GPR	Ground-Penetrating Radar
GPS	Global Positioning System
HP	Horizontal Dipole
HLEM	Horizontal Loop Electromagnetic (Systems)
IAGA	International Association of Geomagnetism and Aeronomy
IGRF	International Geomagnetic Reference Field
Im	Imaginary
IP	Induced Polarisation
LAN	Local Area Network
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LEO	Low Earth-Orbiting
Ma	Millions of years/Mega Annum
MIP	Magnetic Induced Polarisation
NMR	Nuclear Magnetic Resonance
PC	Personal Computer
PPM	Proton Precession Magnetometer
PPT	Parts per thousand

Re	Real
SD	Secure Digital
SI	International System of Units (<i>Système International</i>)
SIM	Subscriber Identification Module
SP	Self Potential
TEM	Time Domain Electromagnetic
TRM	Thermoremanent Magnetisation
UI	User Interface
USB	Universal Serial Bus
UXO	Unexploded Ordnance
VD	Vertical Dipole
VES	Vertical Electric Sounding
VLF	Very Low Frequency

List of Equations

α	Alpha.....X
A	Inductive LimitX
B	Magnetic Flux DensityX
c	Free ConstantX
D	Electric Flux Density.....X
e	emf.....X
E	Electric Field Density.....X
G	Greens FunctionX
H	Magnetic Field Density.....X
i	-1X
I	Current.....X
j	Electric Dipole MomentX
J	Current DensityX
k	Wavenumber.....X
l	Horizontal Scale ParameterX
L	InductanceX
$\underline{L}$	Inductance Matrix.....X
m	Magnetic Dipole Moment.....X
M	Magnetization.....X
N	Depolarization FactorX
P	Electric Polarization.....X

q	Charge Density	X
r	Spherical Radius	X
R	Resistance	X
$\underline{R}$	Resistance Matrix	X
s	Thickness.....	X
t	Time.....	X
$u(t)$	Step Functioin	X
U	Distribution of Magnetization	X
$x; y; z$	Cartesian Coordinates	X
$\underline{Z}$	Impedance Matrix	X
α	Current Channeling Number	X
β	Half-space Response Parameter	X
γ	Inductive Response Parameter	X
δ	Skin Depth	X
$\delta(t)$	Delta Function.....	xi
ε	Dielectric permittivity	xi
ε_0	Dielectric permittivity of free space	xi
θ	Spherical Coordinate.....	xi
Ke	Dielectric Susceptibility	xi
$K\mu$	Magnetic Susceptibility.....	xi
Kv	Relative Ohmic Susceptibility	xi
λ	Spatial Wavelength	xi

Λ	Propagation Wavelength.....	xi
μ	Magnetic Permeability.....	xi
μ_0	Magnetic Permeability of Free Space.....	xi
ρ	Cylindrical-coordinate Radius.....	xi
σ	Conductivity	xi
τ	Time Constant.....	xi
ϕ	Spherical Coordinate.....	xi
Φ	Flux	xi
ω	Angular Frequency.....	xi
X_a	Anomalous.....	xi
X_b	Body	xi
X_c	Conduction.....	xi
X_h	Halfspace.....	xi
$X_i; X_j$	Index.....	xi
X_r	Receiver.....	xi
X_t	Transmitter.....	xi
X_E	Electric Field	xi
X_H	Magnetic Field.....	xi
X_j	Electric Dipole Source.....	xi
X_m	Magnetic Dipole Source	xi
X_p	Primary	xi
X_s	Secondary.....	xi

<i>X_r</i>	Source	xi
<i>Equation 1: The general form of Ohm's law (Keller & Frischknecht, 1966; Van Zijl, 1987; Zohdy et al., 1974; Harman, 2001; Milsom, 2003; Lowrie, 2007).</i>		
		7
<i>Equation 2: Resistivity of a conducting cylinder (Sharma, 1985; Van Zijl, 1987; Zohdy et al., 1974; Harman, 2001; Milsom, 2003; Lowrie, 2007).</i>		
		8
<i>Equation 3: Formation equation (Sharma, 1985).</i>		
		9
<i>Equation 4: Current density (Samouëlian et al., 2005; Lowrie, 2007).</i>		
		11
<i>Equation 5: Potential calculation for homogeneous subsurface (Milsom, 2003; Samouëlian et al., 2005).</i>		
		11
<i>Equation 6: Potential difference between four electrodes (Milsom, 2003; Samouëlian et al., 2005; Lowrie, 2007).</i>		
		11
<i>Equation 7: Resistivity between four electrodes (Milsom, 2003; Samouëlian et al., 2005)</i>		
		12
<i>Equation 8: The impedance of a coil with resistance, R in series with self-inductance, L (Van Zijl, 1986).</i>		
		23
<i>Equation 9: Mathematical expression for obtaining the amplitude of the voltage from Function 3 (Van Zijl, 1986)</i>		
		23
<i>Equation 10: Mathematical expression for obtaining the phase lead on the voltage (Van Zijl, 1986)</i>		
		24
<i>Equation 11: Mathematical statement of Faraday's Law (Telford et al., 1976; Sharma, 1985; Van Zijl, 1986; Cochran & Heinrich, 2004; Thidé, 2004).</i>		
		24
<i>Equation 12: Mathematical statement of Ampere's Law (Telford et al., 1976; Sharma, 1985; Van Zijl, 1986; Cochran & Heinrich, 2004; Thidé, 2004).</i>		
		24
<i>Equation 13: Mathematical statement of Gauss's law (Telford et al., 1976; Sharma, 1985; Van Zijl, 1986; Cochran & Heinrich, 2004; Thidé, 2004).</i>		
		24
<i>Equation 14: Mathematical statement of Coulomb's Law (Telford et al., 1976; Sharma, 1985; Van Zijl, 1986; Cochran & Heinrich, 2004; Thidé, 2004).</i>		
		24

<i>Equation 15: Mathematical relationship between electric displacement and electric field intensity (Sharma, 1985).</i>	25
<i>Equation 16: Equation 16: Mathematical relationship between magnetic induction/flux density and magnetising field intensity (Sharma, 1985).</i>	25
<i>Equation 17: Mathematical relationship between electric current density and electric field intensity (Sharma, 1985).</i>	25
<i>Equation 18: A reduced mathematical statement for Faraday's law (Telford et al., 1976 & Sharma, 1985).</i>	25
<i>Equation 19: A reduced mathematical statement for Ampere's law (Telford et al., 1976 & Sharma, 1985).</i>	25
<i>Equation 20: Reduced mathematical statement of Faraday's law for a nonconducting environment (Telford et al., 1976 & Sharma 1985; Guenther, 2015).</i>	26
<i>Equation 21: Reduced mathematical statement of Ampere's law for a nonconducting environment (Telford et al., 1976 & Sharma 1985).</i>	26
<i>Equation 22: Reduced mathematical statement of Faraday's law for a conducting environment (Telford et al., 1976 & Sharma 1985).</i>	26
<i>Equation 23: Reduced mathematical statement of Ampere's law for a conducting environment (Telford et al., 1976 & Sharma 1985).</i>	26
<i>Equation 24: Mathematical equation for magnetic induction (Telford et al., 1976)</i>	27
<i>Equation 25: Processed equation from combining Equations 11 and 24 (Telford et al., 1976).</i>	27
<i>Equation 26: Processed equation from combining Equations 20 and 24 (Telford et al., 1976).</i>	27
<i>Equation 27: Vector Identity as given by Telford et al. (1976).</i>	27
<i>Equation 28: Magnetic vector potential in terms of the processed equation for Ampere's law (Telford et al., 1976).</i>	27
<i>Equation 29: Magnetic vector potential in terms of the processed equation for Faraday's law (Telford et al., 1976).</i>	28

<i>Equation 30: Magnetic vector Potential for EM fields (Telford et al., 1976).</i>	28
<i>Equation 31: Mathematical expression by which the skin depth of an EM wave can be calculated (Telford et al., 1976 & Sharma 1985).</i>	28
<i>Equation 32: Mathematical representation of an induction prospecting system (Sharma, 1985).</i>	29
<i>Equation 33: Mathematical representation of the phase lag (Sharma, 1985).</i>	30
<i>Equation 34: Mathematical representation of the Eddy currents flowing in the conductor (Sharma, 1985).</i>	30
<i>Equation 35: Mathematical representation of the phase lag between the secondary field S and the induced emf E_s (Sharma, 1985).</i>	31
<i>Equation 36: Mathematical representation of the phase lag between the primary, P- and secondary, S-fields (Sharma, 1985).</i>	31
<i>Equation 37: Mathematical relationship of the ratio Re/Im and the phase angle ϕ (Sharma, 1985).</i>	32
<i>Equation 38: Processed equation for the P wave (Sharma, 1985).</i>	32
<i>Equation 39: Processed equation for the S wave (Sharma, 1985).</i>	32
<i>Equation 40: Mathematical equation for an ellipse (Sharma, 1985).</i>	32
<i>Equation 41: Mathematical statement that the electric field relating to the interface is continuous (Telford et al., 1976).</i>	33
<i>Equation 42: Mathematical statement that the magnetic field relating to the interface is continuous (Telford et al., 1976).</i>	33
<i>Equation 43: Mathematical statement that the current density normal to the interface is continuous (Telford et al., 1976).</i>	33
<i>Equation 44: Mathematical statement that the magnetic flux, normal to the interface, is continuous (Telford et al., 1976).</i>	33
<i>Equation 45: Mathematical expression of the induction number (Reynolds, 2011).</i>	39

<i>Equation 46: Mathematical expression of the ratio between the primary - and secondary magnetic fields (Reynolds, 2011).</i>	<i>39</i>
<i>Equation 47: Mathematical expression for determining the apparent conductivity when using GCM instruments. The subscript “q” represents the quadrature component. (Reynolds, 2011)</i>	<i>40</i>
<i>Equation 48: Mathematical relationship between the geomagnetic elements (Sharma, 1985).....</i>	<i>49</i>
<i>Equation 49: Mathematical form of the IGRF equation for determining the main field as a negative gradient of the scalar potential V (Reynolds, 2011).</i>	<i>50</i>
<i>Equation 50: Mathematical expression of the magnetic intensity of a bar magnet (Sharma, 1985).....</i>	<i>51</i>
<i>Equation 51: Mathematical expression of the magnetic moment of a bar magnet (Sharma, 1985).....</i>	<i>52</i>
<i>Equation 52: Mathematical expression of the magnetic intensity with regards to the unit volume V (Sharma, 1985).</i>	<i>52</i>
<i>Equation 53: Relationship between the induced magnetisation is proportional and parallel to the applied field. (Roux et al., 1980; Sharma, 1985; Reynolds, 2011)</i>	<i>53</i>
<i>Equation 54: Mathematical relationship between the induced magnetisation and susceptibility, with regards to the geomagnetic field. (Sharma, 1985).....</i>	<i>53</i>
<i>Equation 55: Mathematical expression of the Königsberger ratio with regards to the Earth’s magnetic field (at a specific locality) and the susceptibility of the particular rocks. (Reynolds, 2011)</i>	<i>56</i>
<i>Equation 56: Susceptibility of the dolerite dyke (Roux, 1980)</i>	<i>86</i>

List of Tables

<i>Table 2-1: Resistivities of common rocks and ore minerals (Milsom, 2003).</i>	10
<i>Table 2-2: Common electrode arrays and their geometric factors (Telford et al., 1976; Milsom, 2003).</i>	13
<i>Table 2-3: Summarised EM systems (Reynolds, 2011).</i>	37
<i>Table 2-4: Exploration depth of the EM 34-3 with regards to coil orientation (McNeill, 1980).....</i>	41
<i>Table 2-5: EM 34-3 Instrumental specifications (McNeill, 1980; GEONICS, 2003; Milsom, 2003).....</i>	42

List of Figures

<i>Figure 1-1: The inter-relationships that exist between the various sub-disciplines of Applied Geophysics (adapted from Reynolds, 2011).....</i>	<i>2</i>
<i>Figure 2-1: The concept of resistivity in a conducting cylinder (Van Zijl, 1986; Reynolds, 2011).....</i>	<i>8</i>
<i>Figure 2-2: Representation of current flow and hemispherical equipotential lines in a homogeneous subsurface. The unit vector field indicates the directions of the current density (J) and thus the electric field (E). (Herman, 2001)</i>	<i>12</i>
<i>Figure 2-3: The ABEM Terrameter LS 2 geoelectrical imaging system (Terrameter, 2012).</i>	<i>16</i>
<i>Figure 2-4: The User Interface Panel. (T van Wyk, 2019).....</i>	<i>17</i>
<i>Figure 2-5: Graphical representation of a sine function which represents an alternating field (Adapted from Van Zijl, 1986).</i>	<i>21</i>
<i>Figure 2-6: Revolving vector (Adapted from Van Zijl, 1986).....</i>	<i>21</i>
<i>Figure 2-7: Vector diagram in the form of complex numbers (Adapted from Van Zijl, 1986). ...</i>	<i>23</i>
<i>Figure 2-8: A generalised visualisation of an induction prospecting system (Grant and West, 1965; as cited by Sharma, 1985).....</i>	<i>30</i>
<i>Figure 2-9: Vector diagram of the relationship between fields P, S and R (Sharma, 1985; as reconstructed by the Author, 2019).....</i>	<i>32</i>
<i>Figure 2-10: Coil systems for EM surveys (Milsom, 2003).</i>	<i>38</i>
<i>Figure 2-11: Example of the EM 34-3 Ground Conductivity Meter, measuring the horizontal dipole (GEONICS, 2003).</i>	<i>42</i>
<i>Figure 2-12: Visual representation of a dipole, made up of various equally strong positive and negative point sources, grouped very closely together (Milsom, 2003).....</i>	<i>46</i>
<i>Figure 2-13: The geomagnetic field that resembles a very big dipole (Sharma, 1985; Milsom, 2003).</i>	<i>46</i>

<i>Figure 2-14: Visual representation of the geomagnetic field, as it does not align with the spin axis (true geographical north) of the Earth. (Rumpf, 2012).....</i>	<i>48</i>
<i>Figure 2-15: Diagrammatic representation of the main elements of the geomagnetic field. The elements D and I are the declination and inclination, respectively, of the total field vector, F (Sharma, 1985).</i>	<i>49</i>
<i>Figure 2-16: The 13th generation IGRF total field Intensity as given by the BGS (2020).</i>	<i>51</i>
<i>Figure 2-17: Diagrammatic representation of the vector summation of induced and remanent intensities of magnetisation. (Reynolds, 2011)</i>	<i>53</i>
<i>Figure 2-18: Proton Memory Magnetometer Model G5 (GEOTRON, 2019).</i>	<i>59</i>
<i>Figure 3-1: Locality map of the study area, Modderfontein 383IP.</i>	<i>61</i>
<i>Figure 3-2: Stratigraphic summary of the Transvaal Supergroup as given by Eriksson et al. (2001).....</i>	<i>63</i>
<i>Figure 3-3: The regional geology that occurs in the vicinity of Modderfontein 383IP.</i>	<i>66</i>
<i>Figure 3-4: ABEM Terrameter LS 2 displaying a pseudo section while measuring during the fieldwork of this study. (T van Wyk, 2019)</i>	<i>68</i>
<i>Figure 3-5: Stainless steel electrodes and cable connection during the fieldwork of this study. (T van Wyk, 2019).</i>	<i>68</i>
<i>Figure 3-6: Example of the EM 34-3 in the field during the fieldwork of this study (Author, 2019).....</i>	<i>69</i>
<i>Figure 3-7: The G5 field-setup as was done for this project (Autor, 2018).</i>	<i>70</i>
<i>Figure 3-8: An example of the digital display after a measurement has been taken (Author, 2019).....</i>	<i>71</i>
<i>Figure 4-1: Pseudo Section of the apparent resistivity data as measured by the ABEM Terrameter LS 2 on “Traverse 1”. (Res2Dinv, 2019)</i>	<i>74</i>
<i>Figure 4-2: Pseudo Section of the apparent resistivity data as measured by the ABEM Terrameter LS 2 on Traverse 2. (Res2Dinv, 2019).....</i>	<i>76</i>

<i>Figure 4-3: Pseudo Section of the apparent resistivity data as measured by the ABEM Terrameter LS 2 on Traverse 3. (Res2Dinv, 2019).....</i>	<i>78</i>
<i>Figure 4-4: Interpolated results (all three traverses) of the EM 34-3 for the HD, as measured during the fieldwork of this study. (Surfer, 2020).....</i>	<i>80</i>
<i>Figure 4-5: Interpolated results (all three traverses) of the EM 34-3 for the VD, as measured during the fieldwork of this study. (Surfer, 2020).....</i>	<i>82</i>
<i>Figure 4-6: The contour map of the magnetic intensity as measured by the Proton Memory Magnetometer (G5). (Surfer, 2020)</i>	<i>85</i>

CHAPTER 1 INTRODUCTION

According to sources such as Goldman and Neubauer (1993), Pereira *et al.* (2002), Wester *et al.* (2003), Blignaut and Van Heerden (2004), Otieno and Ochieng (2004), Rijsberman (2004) Gan *et al.* (2013), Mekonnen and Hoekstra (2016) and Shishaye & Abdi (2016), water is the most precious resource on the planet for the simple reason that it sustains life. Due to factors such as climate change, population growth, urbanisation and industrialisation the need for water has increased drastically and diversified widely.

Mekonnen and Hoekstra (2016) and Shishaye and Abdi (2016) state that surface water and groundwater are the most important factor that drives any form of development. Groundwater is the alternative when surface water is not sufficient, provided that there is a sufficient quantity with a desired quality (Mekonnen & Hoekstra, 2016; Shishaye & Abdi, 2016). According to Shishaye and Abdi (2016), the focus has since shifted to groundwater exploration methods. These methods are areal -, surface -, subsurface - and esoteric methods. In this study, the main focus was set on the use of surface geophysical methods.

Goldsheider and Drew (2007) and Reynolds (2011) defined and outlined the science of geophysics from an understanding of the earth, moon and planets to investigations of the earth's crust and near-surface for economical and practical purposes. Applied geophysics is the branch of geophysics that is concerned with the latter mentioned, near-surface exploration (Goldsheider & Drew, 2007; Reynolds, 2011). In recent years, the applications of geophysics have broadened to the extent that other subdisciplines of applied geophysics were born, as Reynolds (2011) describe, which include:

- Environmental Geophysics (Concerned with polluted and contaminated site investigations);
- Engineering Geophysics (Concerned with structures and materials);
- Agro – geophysics (Concerned with agriculture and soil science);
- Archaeo – geophysics (Concerned with geophysics in archaeological investigations);
- Bio – Geophysics (Concerned with the geological indication of the presence of microbial activity in geological materials);
- Forensic Geophysics (Concerned with the application of geophysical methods during investigations that might come before the court of law);
- Glacio – Geophysics (Concerned with the geophysics in the subject of glaciology) and;
- Hydro – Geophysics (Concerned with geophysics in groundwater investigations).

Due to the purpose of certain investigations and projects, some of the abovementioned sub-disciplines might overlap (Reynolds, 2011). To demonstrate the extent of this statement, Reynolds (2011) have constructed the figure below to visualise how interconnected these sub-disciplines can be.

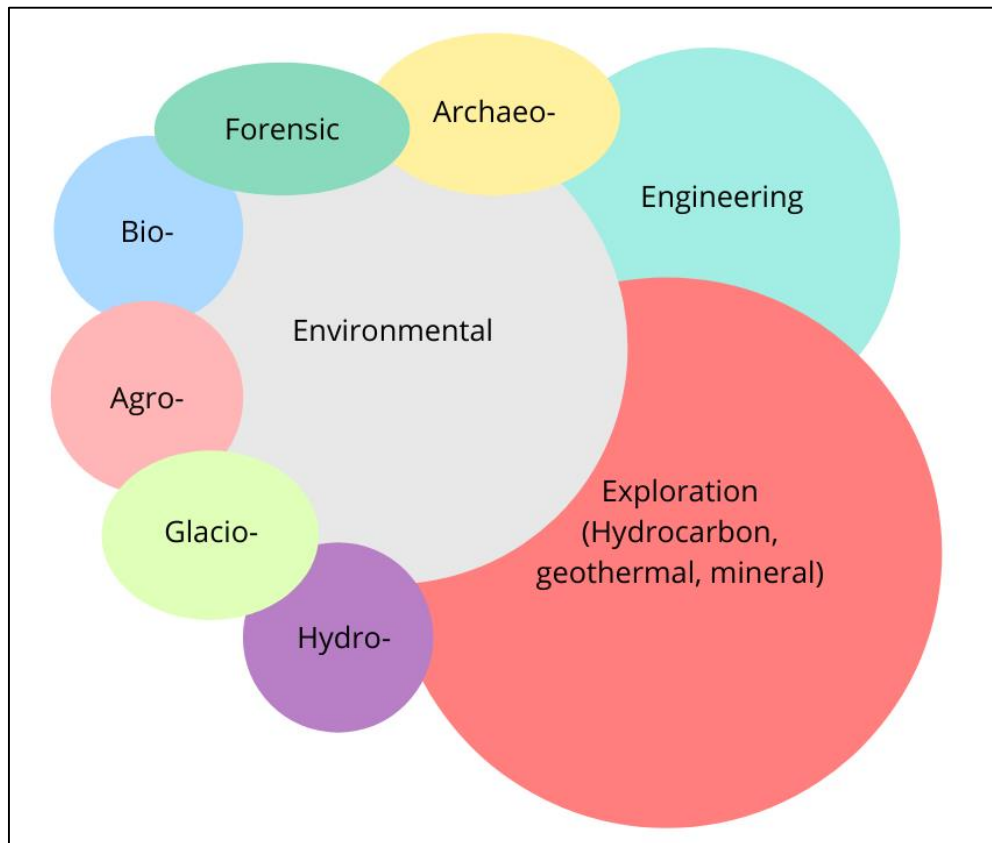


Figure 1-1: The inter-relationships that exist between the various sub-disciplines of Applied Geophysics (adapted from Reynolds, 2011)

Geophysical methods play an important role in groundwater resource mapping as well as water quality evaluations. Over the past few years, the applications of geophysics for groundwater exploration have increased dramatically with the rapid development of computer packages and associated numerical modelling solutions. (Gwazah, 2014; Shishaye & Abdi, 2016)

Reynolds (2011) mentions two very important advantages for the use of geophysics over conventional methods. The first of these is that geophysical methods are environmentally benign (no disturbance of subsurface material). The other includes the fact that geophysical surveys can be done rapidly over a large area at a relatively low cost.

Milsom (2003) and Reynolds (2011) stated that geophysical methods measure the physical properties that are encountered in the geology, sediments, water and voids. Geophysical methods can be classified into two distinct types, active and passive. Active methods generate and transmit artificial signals into the subsurface. The artificial signals then alter the characteristics of these

signals to be those of the materials through which they travel. These altered signals can then be measured and interpreted by detectors. On the other hand, passive methods detect variations in the natural magnetic and gravitational fields of the Earth.

1.1 Motivation

Chegbeleh *et al.* (2009) and Reynolds (2011) stated that it is more effective to employ various geophysical methods for a particular study. The chances of success are so much better with various sources of comparable data. However, as stated by various authors including Zohdy *et al.* (1974), Mc Neill (1990), Milsom (2003) and Sharma and Baranwal (2005) geophysical surveys tend to be expensive. Projects and studies might be limited by a small financial budget. Small budgets can also preclude the use of various geophysical methods. Accordingly, the need exists to employ a single geophysical method or instrument, that would be able to complete a particular survey effectively and successful.

1.2 Hypotheses

It is hypothesised that the three geophysical instruments – ABEM Terrameter LS 2, EM34-3 and Magnetometer (G5) will be successful in delineating a dolerite dyke from shallow to deep. It is further hypothesised that these instruments will produce comparable results that would verify the success of delineating the dolerite dyke.

1.3 Aims and Objectives

1.3.1 Aims

The primary aim of this study is to evaluate the success of each of the three instruments in delineating the dolerite dyke. A secondary aim is to determine the comparability of the results obtained from each of the three instruments.

1.3.2 Objectives

The following objectives were identified to guide this study to meet the above-mentioned aims. The objectives are as follow:

- Conduct a preliminary site visit to determine the precise location and length of the traverse lines that need to be followed by each instrument;
- Identify and employ capable scientists to help with the execution of the fieldwork;
- Execute the fieldwork for each instrument individually as the results of each instrument may be influenced by another;

- Export the digitally saved data from the ABEM Terrameter LS 2 instrument to a personal computer (PC) and manually read in the data obtained from the EM 34-3 and G5 magnetometer instruments into Microsoft Excel;
- Process all gathered data into an analysable format for further interpretation.

CHAPTER 2: LITERATURE STUDY

2.1 Geophysical Groundwater Exploration

Geophysical methods have accomplished great success in the past few decades for exploring of groundwater resources (Hasbrouck and Morgan, 2003). There are a variety of geophysical methods that have been employed for the use of groundwater exploration projects and studies and these are:

- Electrical Resistivity (ER);
- Frequency Domain Electromagnetics (FDEM);
- Magnetic methods.

2.1.1 Electrical Resistivity Methods

Sharma and Baranwal (2005) and Ranganai *et al.* (2018) stated that the ER method has been widely used all around the world in many countries for various purposes. The most important of these is groundwater exploration. Sharma and Baranwal (2005) and Ranganai *et al.* (2018) further stated that the direct current (DC) ER method for conducting a vertical electric sounding (VES) Schlumberger Sounding Technique, has proven to be very successful for conducting groundwater exploration projects. The reason for this being the fact that groundwater bearing zones display low resistivities with regards to the surrounding geology. As Sharma and Baranwal (2005) as well as Ranganai *et al.* (2018) explains, this method is popular for studies concerning groundwater exploration in hard rock areas such as contain fractured granite dykes. Although studies that consist of hard rock, proved to be challenging as wells must be located precisely to be successful (Hasbrouck & Morgan, 2003; Sharma & Baranwal, 2005).

2.1.2 Electromagnetic Methods

Zohdy *et al.* (1974) stated that there is limited applicability for the FDEM method in groundwater exploration studies. This statement has been supported by Mc Neill *et al.* (1986) & Mc Neill (1990) by mentioning that EM methods have originally been developed for the mining sector for exploring electrically conductive, massive sulphide ores. In recent years, however, EM methods are used to detect and measure small conductivity changes in the subsurface that are caused by the presence of groundwater (Mc Neill *et al.*, 1981; Mc Neill, 1990; Chegbeleh *et al.*, 2009). The latter statement is strengthened by Sharma and Baranwal (2005) that documented that the very low frequency (VLF) EM method has proven to be successful in mapping the resistivity variation between boundaries of fracture zones which have a high degree of conductivity, due to the

presence of groundwater. This statement is strengthened by Makhokha and Fourie (2015) that describes that due to the conductivity contrast between dolerite dykes and the surrounding strata, the EM method has been proven to be successful in delineating dolerite dykes.

2.1.3 Magnetic Methods

Zohdy *et al.* (1974) and Ranganai and Ebinger (2007) stated that the best aquifers are found in sedimentary rocks and not crystalline basement terrains. However, sedimentary rocks are usually not magnetic. Sedimentary rocks are thus never directly a geophysical target during magnetic projects. It is, however, possible to find usable groundwater in hard-rock crystalline basement terrains as a result of secondary permeability and porosity which occur within faults, fractures, dyke contacts and deeply weathered zones. Campbell (as cited by Fourie, 1998) stated that basic intrusions such as dunite pipes and dolerite dykes contain supplemental magnetite. As a result, magnetic methods can be used during groundwater exploration projects to delineate dolerite dykes and sills (Zohdy *et al.*, 1974 and Ranganai & Ebinger 2007).

2.2 Geophysical Methodology

2.2.1 Electrical and Magnetic Geophysical Methods

Telford *et al.* (1976) and Milsom (2003) described geophysical surveys as the measuring of the amplitudes (sizes) of voltages or magnetic fields that are related to electrical currents passing through the subsurface. These currents can be of natural origin being caused by natural oxidation-reduction reactions or changes in the atmospheric - or ionosphere magnetic fields, but generally, most are generated artificially. The latter can be generated through direct injection (e.g. electrodes penetrating the ground), capacitive coupling or through EM induction. There are a variety of methods available which make use of a single field of force or an anomalous property. These methods include:

- Gravitation;
- Magnetism;
- Electricity and;
- Radioactivity.

When using electrical methods, it involves the measuring of potentials, currents and EM fields, which occur naturally or are generated artificially. These measurements can also be made in a variety of ways to suit the type of study best, depending on the range of variation in the conductivity and resistivity of the inhomogeneous subsurface.

Surveys that involves direct injection of current into the subsurface through stainless steel electrodes are known as DC surveys, even though in reality the DC is reversed at regular intervals to cancel out some natural background noise. Surveys in which currents are driven by electric fields, either through electrodes, or capacitively (rather than inductively) are termed Galvanic. In other surveys in which currents are made to flow inductively are referred to as EM surveys (Telford *et al.*, 1976 & Milsom, 2003). In this study, three electrical methods will be discussed in detail, they include, ER, EM and AMT.

2.2.2 Electrical Resistivity method

The method of sending an electrical current through the subsurface by making use of stainless-steel electrodes can be employed in several different ways. The most commonly known method consists of a sensitive ammeter to which a pair of electrodes is connected through which a current is driven through the ground and another pair of electrodes that map the resulting potential difference in the subsurface. As a result of the potential difference, and thorough knowledge of the applied current and the electrode separation, it is then possible to map the apparent resistivity of the flow path of the current through the subsurface. (Keller & Frischknecht, 1966; Sharma, 1985)

The above-mentioned theory is depending on the state of the subsurface (its homogeneity and inhomogeneity). As the soil and the geology of the subsurface are mostly inhomogeneous, the electrical current is distorted and deflected from the normal flow paths. The study of ER thus refers to measuring the variation in current flow in subsurface conditions. This method of electrical resistivity, for geophysics, was perfected in the early 1920s by the Geophysicist Conrad Schlumberger in the fields of Normandy, northern France. (Keller & Frischknecht, 1966; Sharma, 1985; Zohdy *et al.*, 1974; Samsudin *et al.*, 2007)

2.2.2.1 Electrical Resistivity

The basics of ER originate with the concept of Ohm's law (Equation 1) which describes the resistance (R), measured in ohm in a length of wire:

$$R = \frac{\Delta V}{I}$$

*Equation 1: The general form of Ohm's law (Keller & Frischknecht, 1966; Van Zijl, 1987; Zohdy *et al.*, 1974; Harman, 2001; Milsom, 2003; Lowrie, 2007).*

Where ΔV is the potential difference, measured in volts, between the two ends of the wire and I is the intensity of the current, measured in amps, flowing through the wire. The resistivity of the

opposite faces of material (Figure 2-1) of length L and cross-sectional area A and resistance R is expressed as ρ , as can be seen in Equation 2:

$$\rho = \frac{RA}{L}$$

Equation 2: Resistivity of a conducting cylinder (Sharma, 1985; Van Zijl, 1987; Zohdy et al., 1974; Harman, 2001; Milsom, 2003; Lowrie, 2007).

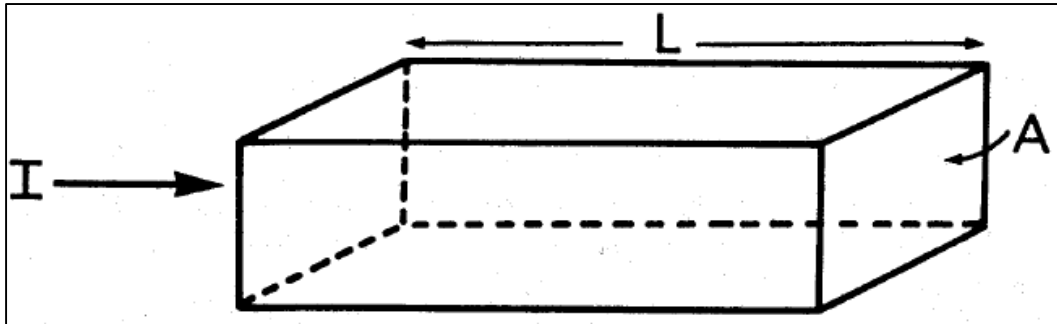


Figure 2-1: The concept of resistivity in a conducting cylinder (Van Zijl, 1986; Reynolds, 2011).

The *Système International* (SI) unit for resistivity (ρ) (in geophysical context) is ohmmeter (Ωm). Conductivity σ is the reciprocal of resistivity and is measured in milli-Siemens per meter (mS/m), also known as mhosu. (Sharma, 1985; Van Zijl, 1986; Zohdy et al., 1974; Harman, 2001; Milsom, 2003; Lowrie, 2007)

2.2.2.1.1 The resistivity of Rocks and Minerals

The electrical properties of rocks and minerals that enable scientists to conduct electrical geophysical surveys for groundwater exploration projects are based on the amount of conductivity within the subsurface. To determine the resistivity of rocks and minerals, electrical current must be passed through the ground, thus the conductivity of the subsurface is of great importance. As most rock-forming minerals are very bad conductors the conductivity of the subsurface is essentially depending on the amount of ground water present, the salinity of the water and the degree of saturation or amount of distribution of ground water throughout the pore spaces within the rock (Zohdy et al., 1974 & Milsom, 2003). In hard rock geology, ground water is found in the cracks and fractures of the rock. The yield of the ground water is depends on the size of the fractures and their interconnectivity (Sharma & Baranwal, 2005).

As explained by Sharma (1985) the resistivity within rocks is a highly varying factor. In hard and solid igneous and metamorphic rocks, with very low porosity, conduction will mainly take place in existing cracks and fissures. In porous sedimentary formations, conduction will depend on the degree of porosity, interconnectivity of the pores and saturation. In such sedimentary rocks, the

resistivity (ρ) of the rock is equal to the resistivity of the water (ρ_w) and is called the apparent resistivity (Sharma, 1985; Van Zijl, 1986; Milsom, 2003). The formation factor (F) thus tends to be equal to 1 for certain formations according to the following formation equation:

$$F = \frac{\rho}{\rho_w}$$

Equation 3: Formation equation (Sharma, 1985).

It is also clear that the resistivity varies, not only, between different geological formations, but also within a certain formation. There is no direct, established correlation or formula for determination between lithology and resistivity. It is none the less, possible to follow a broad classification such as displayed in

Table **2-1**.

Table 2-1: Resistivities of common rocks and ore minerals (Milsom, 2003).

Resistivities of common rocks and ore minerals	
Common rocks	Ωm
Topsoil	50-100
Loose sand	500-5000
Gravel	100-600
Clay	1-100
Weathered bedrock	100-1000
Sandstone	200-8000
Limestone	500-10 000
Greenstone	500-200 000
Gabbro	100-500 000
Granite	200-100 000
Basalt	200-100 000
Graphitic shist	10-500
Slates	500-500 000
Quartzite	500-800 000
Ore Minerals	
Pirite (ores)	0,01-100
Pyrrhotite	0,001-0,01
Chalcopyrite	0,005-0,1
Galena	0,001-100
Sphalerite	1000-1 000 000
Magnetite	0,01-1000
Cassiterite	0,001-10 000
Hematite	0,01-1 000 000

Another property of rocks that frequently occur in resistivity studies is that of anisotropy. Anisotropy refers to two directions of current flow within a particular formation and it has a significant effect on the resistivity of that particular formation. The directions, as set out by Van Zijl (1986), are:

- Transverse resistivity – if the current flow is in the direction of the normal geological stratification (lower resistivity known as S-value);

- Longitudinal resistivity – if the current flow is perpendicular to the normal geological stratification (higher resistivity known as T-values).

2.2.2.1.2 Apparent Resistivity and True Resistivity

In a homogeneous subsurface, electrical equipotential lines are hemispherical when the current electrodes are located at the surface (Figure 2-2). The current density, for all the radial directions, can then be calculated through Equation 4:

$$J = \frac{I}{2\pi r^2}$$

Equation 4: Current density (Samouëlian et al., 2005; Lowrie, 2007).

Where J is the current density (A/m²) and 2πr² represents the surface of a hemispherical sphere with the radius (r). The potential (V) can then be expressed as:

$$V = \frac{\rho I}{2\pi r}$$

Equation 5: Potential calculation for homogeneous subsurface (Milsom, 2003; Samouëlian et al., 2005).

As previously mentioned, the most common method of measuring ER requires the use of four electrodes, two current electrodes (A and B) and two potential electrodes (M and N). The potential difference measured between the four electrodes is then given by Equation 6:

$$\Delta V = \frac{\rho I}{2\pi} \left[\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN} \right]$$

Equation 6: Potential difference between four electrodes (Milsom, 2003; Samouëlian et al., 2005; Lowrie, 2007).

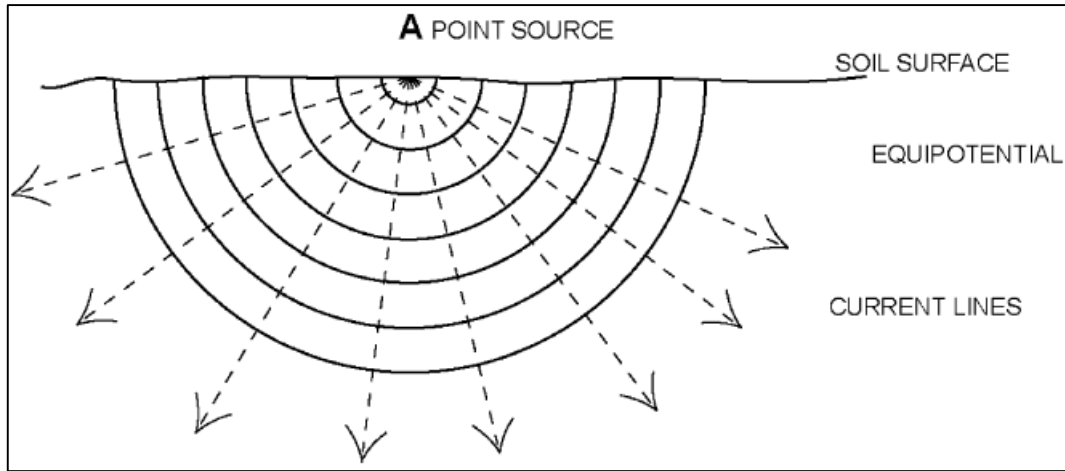


Figure 2-2: Representation of current flow and hemispherical equipotential lines in a homogeneous subsurface. The unit vector field indicates the directions of the current density (J) and thus the electric field (E). (Herman, 2001)

Where AM , BM , AN and BN represent the geometrical distance between A and M , B and M , A and N and B and N . The resistivity can then be calculated by using Equation 7:

$$\rho = \left[\frac{2\pi}{\left(\frac{1}{AM}\right) - \left(\frac{1}{BM}\right) - \left(\frac{1}{AN}\right) + \left(\frac{1}{BN}\right)} \right] \frac{\Delta V}{I}$$

$$\therefore \rho = K \frac{\Delta V}{I}$$

Equation 7: Resistivity between four electrodes (Milsom, 2003; Samouëlian et al., 2005)

Where K represents the geometric factor (also given as G in some texts), measured in meters that depends on the electrode arrangement between A , B , M and N . (Sharma, 1985; Milsom, 2003; Samouëlian et al., 2005)

In the case of an inhomogeneous subsurface, the resistivity, as calculated by Equation 7, will vary with each electrode spacing as well as with a change in surface location. The calculated resistivity is then known as the apparent resistivity (ρ_a). The apparent resistivity is a formal concept and not an average of subsurface formation resistivity.

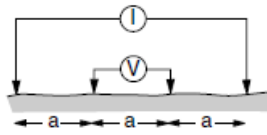
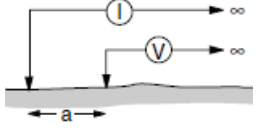
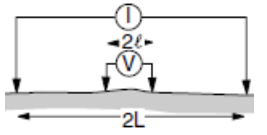
2.2.2.1.3 Electrode Arrays

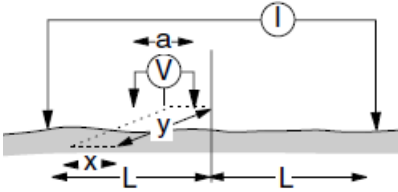
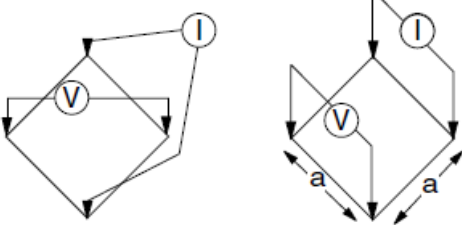
Table 2-2 display some common electrode arrays and their geometric factors which include the following (Milsom, 2003):

- Wenner array – The most commonly used point-electrode system in the field and well supported by scientific literature and computer packages. The Wenner array is the most popular array against which all other arrays are often tested.

- Two-electrode (pole-pole) array – The most popular array that is used in the field of archaeology as it is possible to be operated rapidly by a single person. The most popular array, that is used as a standard for well-logging projects.
- Schlumberger array – The only array to rival the Wenner array in popularity and supporting scientific literature all of which relates to the best array with small distances between the M and N electrodes. The Wenner - and Schlumberger arrays are the most popular arrays used for electrical depth sounding.
- Gradient array – The most used array for reconnaissance work. If powerful generators are available, it is possible to measure a large number of readings on parallel traverses without moving the current electrodes.
- Dipole-dipole (Eltran) array – An array which is very popular in the field of IP as the complete separation between current and voltage electrodes reduces the sensitivity to inductive noise. Also, an array which is supported by a large number of scientific literature.
- Pole-dipole array – The array that is very unpopular as it produces asymmetric anomalies that are difficult to interpret compared to those created by symmetrical arrays.
- Square array – An array that is inconvenient to use but can produce vital information about the subsurface homogeneity and inhomogeneity to an experienced interpreter.

Table 2-2: Common electrode arrays and their geometric factors (Telford et al., 1976; Milsom, 2003).

Electrode Array	Configuration	Geometric Factor
Wenner		$\rho_a = 2\pi a \frac{V}{I}$
Two-electrode (pole-pole)		$\rho_a = 2\pi a \frac{V}{I}$
Schlumberger		Exact $\rho_a = \pi \frac{L^2 - l^2}{2l} \frac{V}{I}$ Ideal dipole '2l' $\therefore \rho_a = \pi \frac{L^2}{2l} \frac{V}{I}$

Electrode Array	Configuration	Geometric Factor
Gradient		Ideal Dipole $'a'\rho_a =$ $\pi \frac{L^2}{a} K \frac{V}{I}$ Where $K = 2\pi \left[\frac{1-x}{[y^2 + (1+x)^2]^{3/2}} + \frac{1-x}{[y^2 + (1+x)^2]^{3/2}} \right]$
Dipole-dipole		$\rho_a = \pi n(n+1)(n+2)a \frac{V}{I}$
Pole-dipole		$\rho_a = 2\pi n(n+1)a \frac{V}{I}$
Square array		$\rho_a = \frac{2\pi a}{2 - \sqrt{2}} \frac{V}{I}$

When choosing the correct array for a particular project, Milsom (2003) states that it is important to consider a few factors such as:

- The ease of manoeuvrability, thus the array that comprises of the least electrodes, the smallest equipment and the most lightweight;
- The depth of investigation;
- The amount that the particular array will be influenced by near-surface effects and;
- The amount of the array's influence-ability by noise.

As mentioned above, when choosing a certain array for a particular study, it is very important to take into consideration the depth of investigation. All arrays have different depths of investigation

associated with them, although it is very hard to determine the exact depth of investigation before a study. The reason for this is that the depth at which a fraction of current penetrates the subsurface depends on the geological layering, as well as the current electrode separation. The positions of the voltage electrodes control which part of the current field that is being surveyed. As the Wenner and Schlumberger arrays are very similar, their depth penetration is likely to be very similar for similar total array lengths. For each array, the total depth penetration depends on the resistivity contrast between geological anomalies and the background noise, but generally, it is equal to the half of the spacing between the outer electrodes. (Milsom, 2003)

2.2.2.1.4 Noise Associated with Electrical Methods

During geophysical surveys, a signal is the object of the survey and noise is anything that is measured that contain no useful information (Milsom, 2003). These sources of noise influence the data obtained negatively, resulting in unreliable data (Chegbeleh *et al.*, 2009). There is a lot of work in the field of geophysics that focus on improving the signal-to-noise-ratio (Milsom, 2003). Sources of noise as set out by McNeill (1980) and Milsom (2003) are the following:

- Stray EM signals (Inductive noise);
- Heavy rain (source of seismic noise);
- Power lines and/or;
- Small inhomogeneities that are located near the potential electrodes can cause significant error in measurements.

2.2.2.2 Instrumentation

In the field of geophysics, several different ER instruments are used to obtain resistivity data of the subsurface. In this chapter, only the two instruments used during this study will be described briefly. The instrument the ABEM Terrameter LS 2 (produced by ABEM in Sundbyberg, Sweden).

2.2.2.2.1 ABEM Terrameter LS 2

The ABEM Terrameter LS 2 is a state-of-the-art data acquisition system for features such as self-potential, ER as well as time-domain IP. The ABEM Terrameter LS 2 is equipped with a built-in GPS that automatically logs the instrumental position during data acquisition – if adequate GPS signal reception is available. The ABEM instrument is fully compatible with the existing parts of the ABEM Lund Imaging systems, such as electrode cables, cable joints, cable jumpers, electrodes and electrode selectors for survey expansion. In Figure 2-3: The ABEM Terrameter LS 2 geoelectrical imaging system (Terrameter, 2012)., the complete system can be seen. (Terrameter, 2012)



Figure 2-3: The ABEM Terrameter LS 2 geoelectrical imaging system (Terrameter, 2012).

The ABEM Terrameter LS 2, and all of its accessories, comply with the following requirements of the EC:

- Low Voltage Directive 73/23/EEG and 93/68/EEG;
- EM Compatibility Directive 89/336/EEG and;
- With amendments 92/31/EEG and 93/68/EEG.

The incorporated Firmware makes it possible to control the Terrameter LS2. The Firmware supports the multi-electrode survey systems for 2D and 3D ER, IP - and Self Potential (SP) Imaging and Monitoring. The instrument makes use of a clear, instructive and graphical User Interface which is very simplistic to follow. (Terrameter, 2012)

The instrument makes it possible to view the measured multi-electrode resistivity imaging data in the form of a pseudo section during – or post measuring. However, to fully invert the data, external software such as Aarhus Workbench (from Aarhus GeoSoftware), Res2Dinv and Res3Dinv (from Geomoto Software), is required. Data transfer from the Terrameter LS2 to a computer (equipped with the aforementioned software) is made simple using USB – and RJ- 45 Local Area Network (LAN) ports. (Terrameter, 2012)

Another unique feature of the Terrameter LS 2, is the user interface panel through which all interactions with the Terrameter LS 2 are done. All the parts of the user interface panel can be seen in Figure 2-4. On the user interface panel, there are two Light Emitting Diodes (LED's) that

shine through the same LED window (indicated by the red circle in Figure 2-4). A red LED indicates that the disk is active, the green LED is a “heartbeat indicator” that the software is running. (Terrameter, 2012)



Figure 2-4: The User Interface Panel. (T van Wyk, 2019)

2.2.2.3 Advantages and Disadvantages between the ER and the EM

Conventional resistivity - and EM methods form both parts of electrical geophysical methods. As such these two methods are very closely related in terms of their advantages and disadvantages. The advantages of the EM method tend to be a disadvantage for conventional resistivity methods and vice versa.

The advantages of EM methods, as discussed by Sharma (1985), McNeill (1990), Goldman & Neubauer (1993), Sharma & Baranwal (2005), Chegbeleh *et al.* (2009), are as follows:

- EM methods, unlike DC resistivity, do not make use of electrodes, penetrating the surface, thus EM surveys tend to be faster than conventional resistivity methods;
- As a result of faster surveys, the EM method tends to be more cost-effective than conventional resistivity methods;
- Since the current flow of EM methods takes place through magnetic induction and not ground-penetrative electrodes (as is the case with conventional resistivity methods), EM methods can be used in areas of very shallow - or outcropping hard rock;

- Ground-connection is not necessary when using the EM method as many EM systems can be employed from an aircraft, ships as well as inside boreholes.
- Inductive EM methods provide a better resolution of electrical equivalence than the conventional resistivity methods;
- EM methods are more suitable for projects concerning conductive material than resistivity methods that are more suited for projects concerning resistive material;
- The exploration depth of most EM methods tends to be larger, in terms of measurement configuration, than most conventional resistivity methods, thus the spatial resolution of EM methods, especially the central loop sounding technique, tends to be better than most conventional resistivity methods and;
- The EM method is capable of revealing steeply dipping conducting bodies in the EM profile, whereas conventional resistivity methods are more effective in locating deeper weathered zones, where a good contrast between the weathered zone and the fresh crystalline rock can be observed.

The disadvantages of the EM method, as discussed by McNeill (1990), Sharma and Baranwal (2005), Chegbeleh *et al.* (2009), are as follow:

- Relatively high equipment costs concerning conventional resistivity methods;
- Some of the EM systems (such as the GEONICS EM-34) is limited to a maximum exploration depth of 60 m, whereas conventional resistivity methods can be used to investigate aquifers that are situated deeper than 100m;
- It is also important to have a good understanding of EM theory for interpreting the data, state of the art data interpretation has not yet been developed for EM methods as in conventional resistivity methods and;

2.2.3 Electromagnetic Methods

2.2.3.1 Background

Telford *et al.* (1976) and Sharma (1985) state that during EM measurements, a primary field induces an alternating current (AC) into the subsurface, which creates secondary EM fields which are then measured. This procedure, in most methods, entails that a primary field is created by passing an AC current through a coil or along a wire which is placed over the ground. The primary field spreads out in space, on the surface and in the subsurface, thus inducing currents in the subsurface-conducting bodies, corresponding with the laws of EM induction. These currents create secondary EM fields, which distort the primary field (which can act as noise for conventional resistivity methods) (Telford *et al.*, 1976; Sharma, 1985; McNeill, 1990; Milsom, 2003). The resulting total field can then be detected by a proper receiving coil and will prove to

differ from primary fields in intensity, direction and phase and will thus also reveal the presence and locations of subsurface conductors. (Telford *et al.*, 1976 & Sharma, 1985)

The main and original application of the EM method is in the mining industry, focusing on mineral exploration. The target is then usually bodies of high electrical conductivity, which includes metallic ores and particularly massive sulphide ores. (Telford *et al.*, 1976; Sharma, 1985; McNeill, 1990; Van Zijl, 1986; Milsom, 2003; Zhdanov, 2010). Other applications of the EM method, as set out by Reynolds (2011), include:

- Delineating faults, shears and thin conducting veins;
- Locating, that which is considered as noise during normal geological exploration buried pipes and cables;
- Groundwater exploration;
- Mineral resource evaluation;
- Hydrocarbon exploration;
- Monitoring hydrocarbon reservoirs;
- Mapping contamination Plumes;
- Geothermal Resource investigations;
- Contaminated Land mapping;
- Landfill surveys;
- Detection of natural and artificial cavities;
- Geological mapping;
- Permafrost mapping;
- Brownfield Site mapping;
- Unexploded Ordnance (UXO);
- Sea-ice thickness mapping and;
- Archaeological mapping.

Not all of these applications apply to all EM methods, for instance, ground-penetrating radar (GPR) (not part of this study) is not very suitable for investigations that involve landfills, the reason for this being the high ambient conductivity and similar high attenuation of radio waves with depth. GPR cannot be used for ground conductivity mapping during archaeological investigations due to insufficient resolution. (Reynolds, 2011)

2.2.3.2 Basic EM Theory

2.2.3.2.1 Alternating field fundamentals

Van Zijl (1986) stated that EM surveys are based on the study of alternating fields in the subsurface of the Earth. Thus, it is very important to briefly understand the basic principles of alternating fields and their characteristics.

2.2.3.2.2 Sine Functions and Vector Diagrams

An alternating field with the frequency f and period $T=1/f$ can be represented by the following function:

$$y = A \sin \omega t$$

Function 1: Sine function for and AC (Van Zijl, 1986).

Where t represents time, A represents amplitude and ω

represents angular frequency ($\omega=2\pi f$). Function 1 can be seen in Figure 2-5 as a sine function represented by the curve “a”.

$$y = A \sin(\omega t + \phi)$$

Function 2: Sine function of an AC signal exposed to a shift in phase (Van Zijl, 1986).

Function 2 is very similar to that of Function 1, except that it is phase shifted. A curve representing Function 2 can also be seen in Figure 2-5 as curve “b”. The phase difference between these Functions is equal to the angle Φ , thus Function 2 leads Function 1 by the angle Φ which is also known as the phase. As such, an alternating field is completely defined by frequency, time and phase. (Van Zijl, 1986)

Figure 2-6 represents these amplitude and phase relations of an alternating field with a specific frequency, by a revolving vector. Function 1 can be seen in Figure 2-6 as a vector OP = Amplitude (A) revolving anticlockwise, with an angular velocity ω around the origin O with an amplitude A .

The point of origin, found at $t=0$ is found along the x-axis, while the angle POX after time t is equal to ωt , thus the projection of the vector on the y-axis is equal to $A \sin \omega t$. The amplitude at any time is given by the projected vector on the y-axis. A single period is reached when $\omega t = 2\pi$. (Van Zijl, 1986)

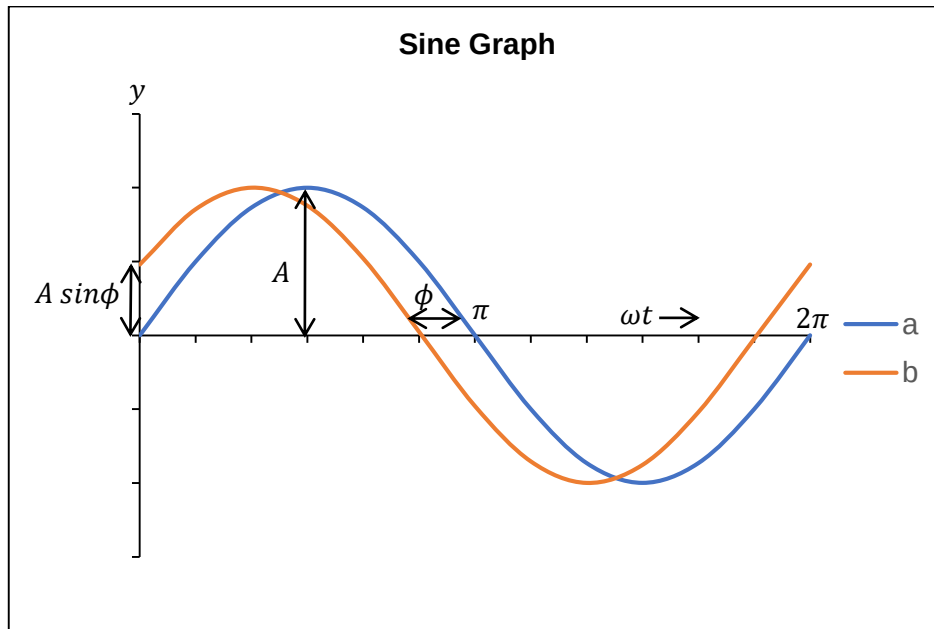


Figure 2-5: Graphical representation of a sine function which represents an alternating field (Adapted from Van Zijl, 1986).

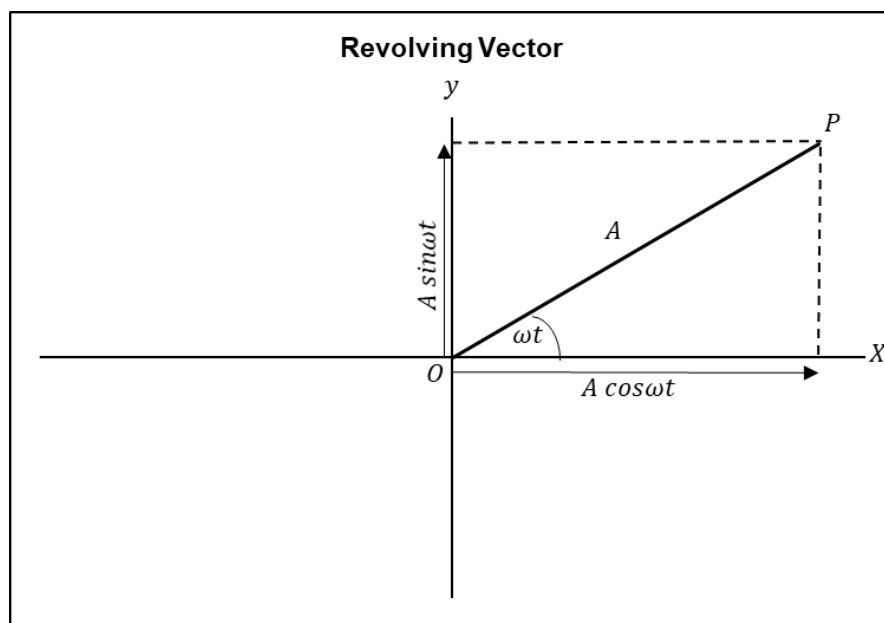


Figure 2-6: Revolving vector (Adapted from Van Zijl, 1986).

2.2.3.2.3 Complex Quantities

By making use of complex quantities, the OP vector (Figure 2-6) can be redefined as:

$$OP = r \angle \phi$$

$$\therefore = x + iy$$

Function 3: OP vector defined by complex quantities (Van Zijl, 1986).

Where $r = \sqrt{x^2 + y^2}$, $\phi = \tan^{-1} x/y$, x represents the “real”/ in-phase component ($= r \cos \phi$) and y represents the “imaginary”/ out-of-phase/ quadrature component ($= r \sin \phi$). Also, $r \angle \phi$ represents the line with a length of r , making an angle Φ with the real (Re) axis.

The sum of the “real” (Re) and “imaginary” (Im) component, is represented by $x+iy$ and called a complex number. The Re and Im components will be discussed in more detail in subsection

2.2.2.5. In Function 3, $i = \sqrt{-1}$ which originates from the fact that a vector, multiplied by “-1” represents a vector with equal length, but opposite direction. Thus, by multiplying a vector with “-1”, it results in a 180° rotation (or π radians) of the vector. When multiplying the same vector by $\sqrt{-1}$ it results in a 90° rotation (or $\pi/2$ radians) in an anticlockwise direction. When multiplying the vector by $(-1)^{\phi/\pi}$ results in rotation by an angle of Φ . (Van Zijl, 1986)

All these relations can be seen in Figure 2-6; thus, the OP vector can be rewritten as:

$$OP = x + iy$$

$$\therefore = r(\cos \phi + i \sin \phi)$$

Function 4: Rewrite of the OP vector in terms of r , i and Φ (Van Zijl, 1986).

It is possible to prove that:

$$\cos \phi \pm i \sin \phi = e^{\pm i \phi}$$

Function 5: Further adaptation for the terms on the right-hand side of Function 4 (Van Zijl, 1986).

Where the exponential function $e^{\pm i \phi} = (-1)^{\pm \phi/\pi}$. The exponent on the right-hand side is an operator when with which multiplied with, results in a rotation of angle $\pm \phi$ and constant length. From Function 4, it is possible to write $OP = r e^{\pm i \phi}$. Thus, the alternating field quantity is:

$$y = A \sin(\omega t + \phi)$$

Function 6: The Im part of $Ae^{i\phi}e^{i\omega t}$ (Van Zijl, 1986).

Finally, it is important to keep in mind that the differentiation is equal to the multiplication by ω and the phase advance $\pi/2$. To describe the behaviour of the amplitude and phase of EM fields in terms of in-phase (Re) and out-of-phase (Im) components, vector diagrams (as depicted by Figure 2-7) are used extensively. (Van Zijl, 1986)

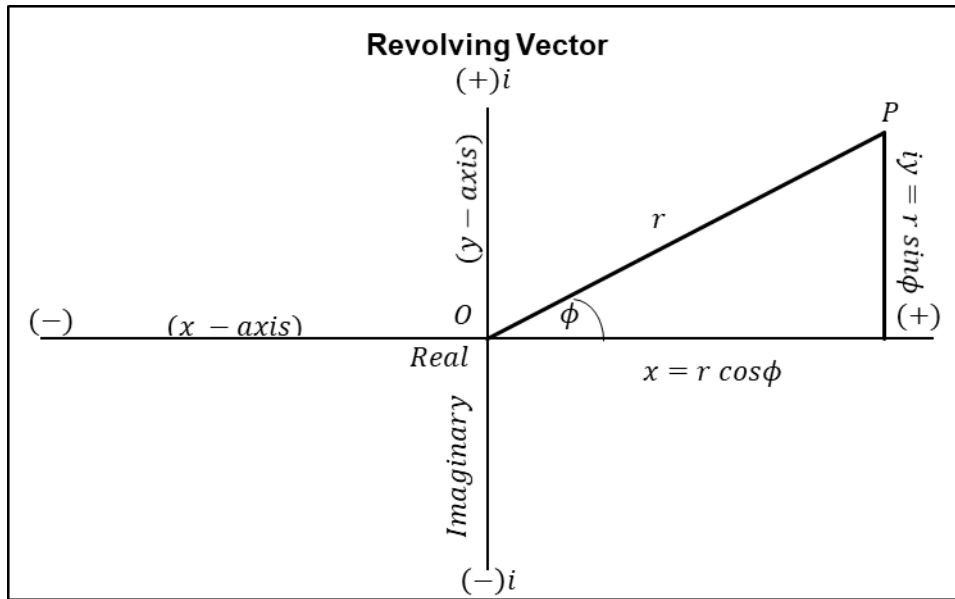


Figure 2-7: Vector diagram in the form of complex numbers (Adapted from Van Zijl, 1986).

2.2.3.2.4 Impedance in an Inductive Circuit

By making use of the above-mentioned complex notation, it is possible to determine the impedance of a coil where the resistance, R is in series with the self-inductance, L . The impedance of a coil is then defined by Equation 8:

$$Z = V/I$$

$$\therefore = R + I\omega L$$

Equation 8: The impedance of a coil with resistance, R in series with self-inductance, L (Van Zijl, 1986)

Where V represents the total voltage drop and I represent the current of the system. According to Function 3, the amplitude of the voltage is:

$$|V| = I \sqrt{R^2 + \omega^2 L^2}$$

Equation 9: Mathematical expression for obtaining the amplitude of the voltage from Function 3 (Van Zijl, 1986)

And the phase leads the voltage by:

$$\phi = \tan^{-1} \omega L/R$$

Equation 10: Mathematical expression for obtaining the phase lead on the voltage (Van Zijl, 1986)

2.2.3.2.5 Maxwell Equations

According to Telford *et al.* (1976), Sharma (1985), Van Zijl (1986), Cochran & Heinrich (2004) and Thidé (2004) EM and MT waves are complex, thus it is very useful to discuss the elementary development of EM theory. The relationship between current and magnetic fields (thus the propagation and attenuation of EM waves) were compiled to be known as the four Maxwell equations. These four equations can be used to calculate the magnetic field distribution that automatically produces the space- and time-averaged fields. The four Maxwell equations that relate the electric and magnetic field vectors are the following:

$$\nabla \cdot E = -\frac{\partial B}{\partial t}$$

Equation 11: Mathematical statement of Faraday's Law (Telford et al., 1976; Sharma, 1985; Van Zijl, 1986; Cochran & Heinrich, 2004; Thidé, 2004).

$$\nabla \cdot H = J + \frac{\partial D}{\partial t}$$

Equation 12: Mathematical statement of Ampere's Law (Telford et al., 1976; Sharma, 1985; Van Zijl, 1986; Cochran & Heinrich, 2004; Thidé, 2004).

$$\nabla \cdot B = 0$$

Equation 13: Mathematical statement of Gauss's law (Telford et al., 1976; Sharma, 1985; Van Zijl, 1986; Cochran & Heinrich, 2004; Thidé, 2004).

$$\nabla \cdot D = \rho_c$$

Equation 14: Mathematical statement of Coulomb's Law (Telford et al., 1976; Sharma, 1985; Van Zijl, 1986; Cochran & Heinrich, 2004; Thidé, 2004).

Where E represents the electric field intensity (V/m), J represents current density (A/m²), H represents the magnetising field intensity in Ampere per meter (A/m), B represents the magnetic flux density (Wb/m²), D represents the electric displacement (C/m²) and ρ_c represents the electric charge density (C/m³) (Telford *et al.*, 1976; Sharma, 1985; Van Zijl, 1986; Cochran & Heinrich, 2004; Thidé, 2004; Guenther, 2015).

Equation 11 is the mathematical representation of Faraday's law which states that in the case of a time-varying magnetic field, an electric field is present in such a manner that the total electromotive force (emf) that are generated, around any closed path is directly proportional to

the negative rate of change in the magnetic flux. Equation 12 is the mathematical representation of Ampere's law which states that the flow of current creates a magnetic field in space, which is directly proportional to the total current (conduction + displacement currents). Equation 13 is a mathematical representation of Gauss's law, which states that single magnetic poles do not exist. Equation 14 is the mathematical representation of Coulomb's law which states that the lines of magnetic fields are bound to electric charges. (Telford *et al.*, 1976; Sharma, 1985; Van Zijl, 1986; Guenther, 2015)

When making use of the following three relationships between the above-mentioned vectors, Maxwell's equations can be reduced to only two vectors. The three relationships, as set out by Sharma (1985), are:

$$D = \epsilon E$$

Equation 15: Mathematical relationship between electric displacement and electric field intensity (Sharma, 1985).

$$B = \mu H$$

Equation 16: Mathematical relationship between magnetic induction/flux density and magnetising field intensity (Sharma, 1985).

$$J = \sigma E$$

Equation 17: Mathematical relationship between electric current density and electric field intensity (Sharma, 1985).

Where ϵ represents the dielectric capacitively (F/m), μ represents the magnetic permeability (H/m) and σ represents the electric conductivity (mho/m) of the medium (Telford *et al.*, 1976 & Sharma, 1985).

The reduced Maxwell equations comprise only of the vectors E and H. When presuming (for E and H) time dependence of the form $H(t)=H_0e^{i\omega t}$, where $\omega=2\pi f$ is the angular frequency for the field, the Maxwell vector equations are:

$$\nabla^2 E = i\omega\mu\sigma E - \epsilon\mu\omega^2 E$$

*Equation 18: A reduced mathematical statement for Faraday's law (Telford *et al.*, 1976 & Sharma, 1985).*

$$\nabla^2 H = i\omega\mu\sigma H - \epsilon\mu\omega^2 H$$

*Equation 19: A reduced mathematical statement for Ampere's law (Telford *et al.*, 1976 & Sharma, 1985).*

The two terms on the right-hand side of equation 18 and 19 relate to conduction and displacement currents respectively. In an isotropic, homogeneous medium in which the physical properties ϵ , μ and σ are present, these two EM equations form the basis for the propagation of electric and magnetic field vectors (Telford *et al.*, 1976 & Sharma 1985).

In an environment of air and poorly conducting rocks, the dielectric capacitive, the magnetic permeability and the electric conductivity is equal to, $\epsilon=\epsilon_0=9\times10^{-12}$ F/m, $\mu=\mu_0=4\pi\times10^{-7}$ H/m and $\sigma=0$ mho/m. During typical EM field measurements, the typical frequency employed is about 1000 Hz ($\omega \sim 6000$ rad/s). When these physical parameters are present, both the real and imaginary components become so small that the right-hand terms of Equation 18 and 19 are practically reduced to zero (Telford *et al.*, 1976 & Sharma 1985). Thus, for a non-conductive medium (comprising of the above-mentioned parameters) the field equations, as set out by Telford *et al.* (1976) & Sharma (1985), for E and H becomes:

$$\nabla^2 E = 0$$

Equation 20: Reduced mathematical statement of Faraday's law for a nonconducting environment (Telford et al., 1976 & Sharma 1985; Guenther, 2015).

$$\nabla^2 H = 0$$

Equation 21: Reduced mathematical statement of Ampere's law for a nonconducting environment (Telford et al., 1976 & Sharma 1985).

In an environment comprising of moderate to high conductivity (such as saline groundwater, massive sulphide ores and graphite) the physical parameters change to $\epsilon\approx10\epsilon_0$ F/m, $\mu\approx\mu_0$ H/m and $\sigma\approx1\cdot10^{-3}$ mho/m. With these physical parameters, the first term, on the right-hand side, of Equation 18 and 19 becomes important, while the second term is still negligible. Thus, for an environment of appreciable conductivity, the field equations, as set out by Telford *et al.*, 1976) & Sharma (1985), for E and H, becomes:

$$\nabla^2 E = i\omega\mu\sigma E$$

Equation 22: Reduced mathematical statement of Faraday's law for a conducting environment (Telford et al., 1976 & Sharma 1985).

$$\nabla^2 H = i\omega\mu\sigma H$$

Equation 23: Reduced mathematical statement of Ampere's law for a conducting environment (Telford et al., 1976 & Sharma 1985).

Concerning the attenuation of EM fields and the generation of induced fields, the magnitude of the term $\omega\mu\sigma$ is of great physical importance. (Telford *et al.*, 1976 & Sharma 1985)

2.2.3.2.6 Magnetic Vector Potential

According to Telford *et al.* (1976), in general, potential theory, it is better to obtain the field vectors by solving problems by starting with the potential and making appropriate differentiation. In the field of EM, the same rule applies, thus by starting with the vector magnetic potential, it is possible to derive both electric and magnetic field vectors. This potential can be defined in terms of magnetic induction:

$$\nabla \times A = B$$

Equation 24: Mathematical equation for magnetic induction (Telford et al., 1976)

When combining Equation 11 and 24, it is possible to write the following equation:

$$E = -\frac{\partial A}{\partial t}$$

Equation 25: Processed equation from combining Equations 11 and 24 (Telford et al., 1976).

Again, from combining Equations 20 and 24, it is possible to write the following equation:

$$\nabla^2 \cdot A = 0$$

Equation 26: Processed equation from combining Equations 20 and 24 (Telford et al., 1976).

By taking the curl of Equation 24 and combining it to the following vector identity (only valid in rectangular coordinates):

$$\nabla \times \nabla \times A = \nabla(\nabla \cdot A) - \nabla \cdot \nabla A$$

$$\therefore = \nabla(\nabla \cdot A) - \nabla^2 A$$

Equation 27: Vector Identity as given by Telford et al. (1976).

As well as combining it to Equations 12, 15, 16, 17, 25 and 26, it is possible to write:

$$\nabla \times \nabla \times A = \nabla(\nabla \cdot A) - \nabla^2 A$$

$$\therefore = -\nabla^2 A$$

$$\therefore = \nabla \times B$$

$$\therefore = \mu \nabla \times H$$

Equation 28: Magnetic vector potential in terms of the processed equation for Ampere's law (Telford et al., 1976).

As well as:

$$\nabla^2 = -\mu \nabla \times H$$

$$\therefore = -\mu \sigma E - \mu \epsilon \frac{\partial E}{\partial t}$$

$$\therefore = \mu \sigma \frac{\partial A}{\partial t} + \mu \epsilon \frac{\partial^2 A}{\partial t^2}$$

Equation 29: Magnetic vector potential in terms of the processed equation for Faraday's law (Telford et al., 1976).

As already mentioned in section 2.2.2.1, the second term on the right-hand side is negligible. Thus, the vector magnetic potential for E and H satisfies Laplace's equation for a poorly conducting environment, as well as the diffusion equation when σ is large enough. (Telford et al., 1976)

Furthermore, when combining Equations 15, 16, 17 and 29, it is possible to write:

$$\begin{aligned}\nabla^2 A &= -\mu\sigma E \\ \therefore &= -\mu J\end{aligned}$$

Equation 30: Magnetic vector Potential for EM fields (Telford et al., 1976).

The magnetic vector potential has great physical significance in calculating EM fields, but have no significant meaning for the scalar potential in gravitation- and electrostatics. (Telford et al., 1976).

2.2.3.2.7 Attenuation of EM Fields and Depth Penetration

Telford et al. (1976) & Sharma (1985) state that all EM fields that are produced externally from a conductor (free space) are attenuated with the distance of the internal conductor. The rate of EM field attenuation is depending on frequency (f) and conductivity (σ). A Solution for Equation 19 and 20 can be calculated for a plane wave that is propagated (generated) vertically downwards in a half-space of conductivity σ . The solution states that, physically, the field (E or H) on the surface, is attenuated in amplitude by $e^{-\alpha z}$, at a depth z, where $\alpha = \sqrt{\omega\mu\sigma/2}$.

The skin depth is the depth (z_s) at which the amplitude, of the EM wave, is reduced to $1/e$ (37%) of its surface value. The skin depth (also frequently referred to as the depth of penetration of an EM wave) is given by Equation 31:

$$\begin{aligned}z_s &= \frac{503.8}{\sqrt{\sigma f}} \\ \therefore &= 503.8\sqrt{\rho/f}\end{aligned}$$

Equation 31: Mathematical expression by which the skin depth of an EM wave can be calculated (Telford et al., 1976 & Sharma 1985).

Where ρ ($\rho=1/\sigma$) represents the resistivity (Ωm) and f represents the frequency (Hz) of the EM wave. Sharma (1985) states that it is important to consider the skin depth is only a theoretical suggestion. In general field practice, the depth of penetration is influenced by several factors, such as:

- Instrumental noise;
- The magnitude of stray anomalies, caused by near-surface conductivity variations and/or;
- The geometry of the subsurface conductor.

Raynolds (2011) mentions that there are some instrument manufacturers that, apart from the theoretical skin depth, specify the effective depth of their instruments. One of these manufacturers includes GEONICS Limited, which specify the depth of penetration of their Frequency-domain electromagnetic (FEM) systems (EM38, EM31 and EM34) as a function of the inter-coil separation.

2.2.3.2.8 Phase Relation between Primary and Secondary Fields:

A visualised representation of an induction prospecting system can be seen in Figure 2-10. Sharma (1985) states that during induction, AC with a frequency of $\omega/2\pi$ and strength I_p circulate in a source coil and produce a primary field P in the surrounding environment. This primary field is directly proportional to and in phase with I_p . This process can be represented mathematically by Equation 32:

$$P = KI_p \sin \omega t$$

Equation 32: Mathematical representation of an induction prospecting system (Sharma, 1985).

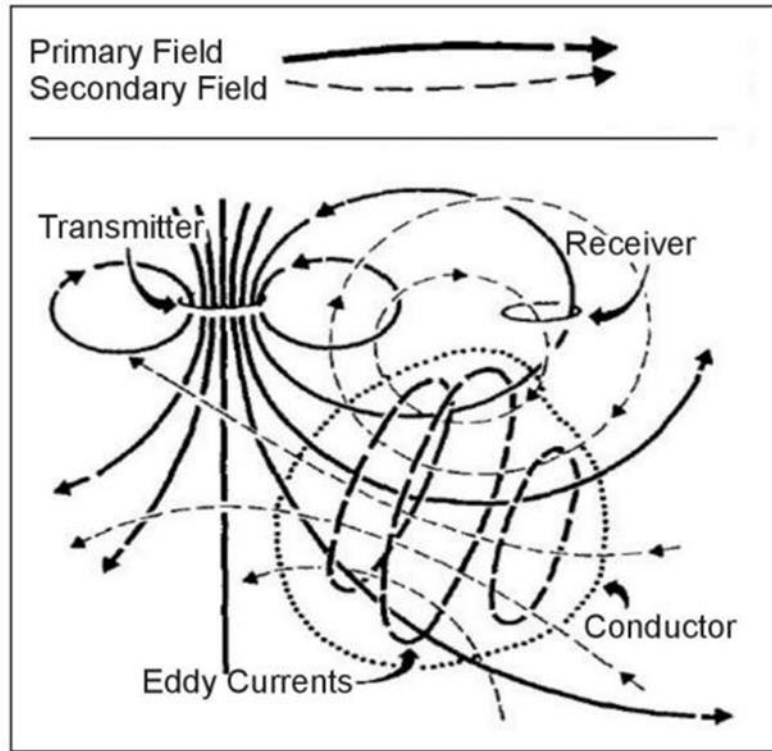


Figure 2-8: A generalised visualisation of an induction prospecting system (Grant and West, 1965; as cited by Sharma, 1985).

Where K depends on the number of turns in the coil, the area of the coil and the geometry of the whole system. Furthermore, when the primary field P acts on an electric circuit, the induced emf, in the conductor, is directly proportional to P which lags behind P by a quarter of a period. This process can be traced back to the fundamental law of induction as set out by Faraday's law. The above-mentioned phase lag, in terms of angle, can be expressed in terms of Equation 33:

$$\text{Phase lag } (E_s \text{ relative to } P) = \pi/2$$

Equation 33: Mathematical representation of the phase lag (Sharma, 1985).

When Z_s (which equal to $R_s + i\omega L_s$) represents the effective impedance of the conductor with resistance R_s and inductance L_s . The induced Eddy currents, flowing in the conductor, will then be:

$$I_s = E_s / Z_s$$

Equation 34: Mathematical representation of the Eddy currents flowing in the conductor (Sharma, 1985).

Both the current I_s , and its produced secondary magnetic field S , lag behind the induced emf E_s , by a phase lag Φ which depends on the particular properties of the conductor like an electric circuit. The phase lag Φ can be calculated by the relationship $\tan \phi = \omega L_s / 0R_s$ and can be given as:

$$\text{Phase lag (S relative to } E_s) = \phi = \tan^{-1}(\omega L_s/R_s)$$

Equation 35: Mathematical representation of the phase lag between the secondary field S and the induced emf E_s (Sharma, 1985).

By adding Equations 33 and 35, it is possible to obtain the total phase difference between the primary, P- and secondary, S-fields which then results in Equation 36:

$$\text{Phase lag (S relative to P)} = \frac{\pi}{2} + \phi$$

$$\therefore \frac{\pi}{2} + \tan^{-1}\left(\frac{\omega L_s}{R_s}\right)$$

Equation 36: Mathematical representation of the phase lag between the primary, P- and secondary, S-fields (Sharma, 1985).

Out of the above mentioned, it is clear that in the case of the presence of a very good conductor ($\omega L_s/R_s \rightarrow \infty$ and $\phi = \pi/2$) the phase lag of the secondary field S is nearly 180° behind the primary phase P. Also, it is clear that in the presence of a very weak conductor ($\omega L_s/R_s \rightarrow 0$ and $\phi \rightarrow 0$), the phase lag of the secondary field S is 90° behind the primary field P. The phase lag of the secondary field S therefore can be seen as a measure of the conductivity of the anomaly. (Sharma, 1985)

2.2.3.2.9 Real and Imaginary Components of EM

When combining the primary - and secondary fields it produces a resultant field R which is measured by a detector. Figure 2-9 illustrates the relationship between these three fields in the form of a vector diagram.

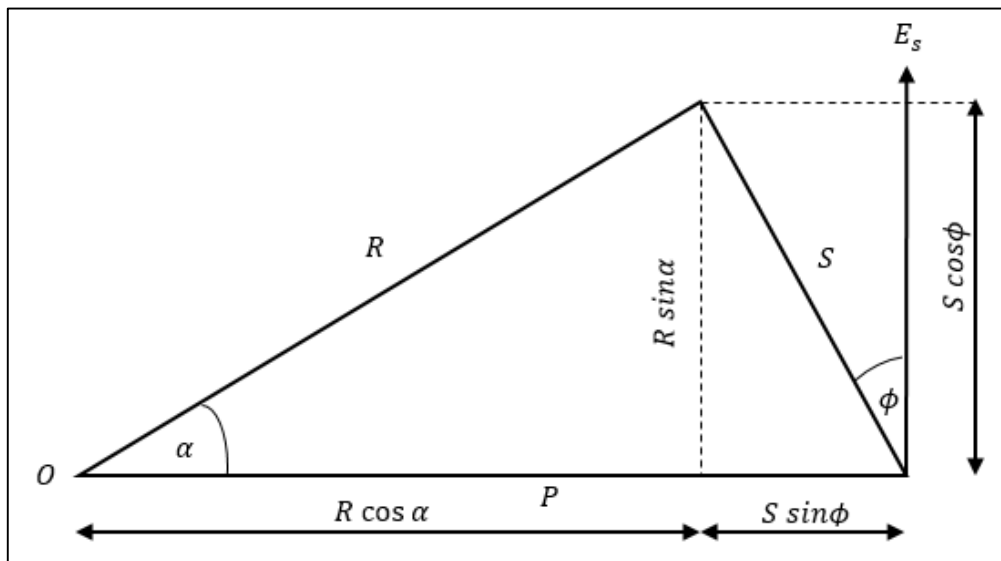


Figure 2-9: Vector diagram of the relationship between fields P, S and R (Sharma, 1985; as reconstructed by the Author, 2019).

The “real” or in-phase component (Figure 2-9), represents the component of R in-phase with P, thus $R \cos \alpha$. The quadrature or out-of-phase component is the 90° out-of-phase component, $R \sin \alpha$. (Sharma, 1985)

The secondary S field can also be resolved into a real component of the magnitude $S \sin \phi$, as well as an imaginary component $S \cos \phi$. Equation 37 relates the phase angle ϕ to the ratio of the amplitude of the real (Re) and imaginary (Im) components of the secondary S field. (Sharma, 1985)

$$\frac{Re}{Im} = \tan \phi$$

$$\therefore = \omega L_s / R_s$$

Equation 37: Mathematical relationship of the ratio Re/Im and the phase angle ϕ (Sharma, 1985)

The larger ratio between Re and Im, the better the conductor. Sharma (1985) stated that the quadrature component is real and that there is nothing imaginary about it. The terms “real” and “imaginary” originates from AC circuit theory and are used with no regards to their meanings as written up in a dictionary.

2.2.3.2.10 The Elliptic polarisation of the EM Field

Telford *et al.* (1976) and Sharma (1985) stated that in the case where a subsurface geological conductor gets induced with a primary field, the resultant field, measured by a detector, is a combination of the primary - and secondary fields. From the phase relations (discussed in section 2.2.2.3) it is possible to write the following expressions for P and S:

$$P = A \sin \omega t$$

Equation 38: Processed equation for the P wave (Sharma, 1985).

$$S = B \sin(\omega t - \frac{\pi}{2} - \phi)$$

Equation 39: Processed equation for the S wave (Sharma, 1985).

Where A and B respectively represent functions of the geometry of the transmitter, conductor as well as the detector (Sharma, 1985). When combining Equations 38 and 39 and eliminating ωt the result is the mathematical equation for an ellipse:

$$\frac{P^2}{A^2} + \frac{S^2}{B^2} - \frac{2PS \sin \phi}{AB} = \cos^2 \phi$$

Equation 40: Mathematical equation for an ellipse (Sharma, 1985).

Equation 40 describes a special scenario where the two, P and S fields are oriented at right angles to one another. Never the less, it is clear that the result of the P and S waves, regardless of the number of secondary fields their directions, phases and amplitudes, is represented by R whose tip traces out of an ellipse at a rate of $\omega/2\pi$ times per second. (Telford *et al.*, 1976 & Sharma, 1985)

It is possible for the polarization ellipse, to lie in any space plane, either tilted off horizontally or vertical. It is also possible to orient the search coil manually to lie in a similar plane as the ellipse to obtain a true null signal. Furthermore, when setting the coil normal to the matching plane of the ellipse and measuring the maximum and minimum induced signals while completing a full revolution, the major and minor axes of the ellipse is obtained. It is these axes that determine the amplitudes that determine the real and imaginary components of the resultant R field. Determination the polarisation ellipse formed the base of some of the early EM methods such as VLF and AMT (also known as tilt-angle methods). (Telford *et al.*, 1976 & Sharma, 1985; Reynolds, 2011)

2.2.3.2.11 Boundary Conditions

Telford *et al.* (1976) mention that during EM measurements, as in resistivity, there are boundary conditions for EM fields at interfaces where the conductivity σ changed significantly. Telford *et al.* (1976) also state that all EM field must comply with these boundary conditions, at all times. These boundary conditions can be derived from Equation 11 and Equation 12 as:

$$n \times (E_1 \times E_2) = 0$$

Equation 41: Mathematical statement that the electric field relating to the interface is continuous (Telford et al., 1976).

$$n \times (H_1 - H_2) = 0$$

Equation 42: Mathematical statement that the magnetic field relating to the interface is continuous (Telford et al., 1976).

$$n \cdot (\sigma_1 E_1 - \sigma_2 E_2) = 0$$

Equation 43: Mathematical statement that the current density normal to the interface is continuous (Telford et al., 1976).

$$n \cdot (\mu_1 H_1 - \mu_2 H_2) = 0$$

Equation 44: Mathematical statement that the magnetic flux, normal to the interface, is continuous (Telford et al., 1976).

2.2.3.3 Noise and Limitations Associated with the Electromagnetic (EM) Method

2.2.3.3.1 Noise

During all EM surveys, it is important to keep in mind that there exist factors that influence EM data to the point that it is inaccurate and unreliable. These factors are collectively called “noise”. Noise can exist in the form of environmental variations (natural) or man-made (cultural). Environmental variations that might have a significant effect on EM data include overburden conductivity which might influence the signal penetration and the depicted shape of the anomalies. When conducting surveys in countries that are characterised by a hot and dry climate, salts accumulate in the overburden which might rise the surface-conductivity high enough that FEM methods prove to be ineffective. In South Africa ferricrete and calcrete is responsible for high conductivities resulting in noise. This phenomenon has since been addressed by the use of TEM methods. (Hasbrouck, 2003; Milsom, 2003; Chegbeleh *et al.*, 2009)

Other cultural noise covers a wide variety of features that might act as actual conductors, one of which include roads, alongside magnetic conductors may be buried. Another source of noise, which is frequently located during field surveys is power - and or telephone lines crossing the study area. These power - and telephone lines cause a major problem as it is not always possible to change the study area and these lines transmit signals, which might interfere with the frequency of the instrument, despite the rejection filters. (Hasbrouck, 2003; Milsom, 2003; Chegbeleh *et al.*, 2009)

2.2.3.3.2 Limitations

During most EM investigations, discrete - and horizontally layered conductors must be used in combination, thus resulting in greater demands on-field personal as well as the data-interpreters (Milsom, 2003). Milsom (2003) furthermore mentioned two limiting factors for the EM method:

- Edie currents, induced into the ground, create a discrete anomaly which might contain information on the conductivity of the conductor, as well as its location;
- Apparent conductivity can be obtained by analysing surface effects that are created by horizontal currents induced in horizontal media.

2.2.3.4 Types of EM Systems

According to Reynolds (2011), EM methods can be classified into two main categories, time-domain (TEM) and frequency-domain (FEM). FEM (also known as the continuous wave CWEM) methods are characterised by the use and measurements of sine waves. During FEM measurements, a sinusoidal current (input current), emitted from a transmitter, consists of a

frequency (f) and period ($T=1/f$). The secondary field (output current), generated by the subsurface conductor, can also be characterised as a sine wave with the same frequency as the input current, but different in phase (ϕ) and amplitude (A) (depending on the electrical properties of the conductor). It is thus, evident that FEM is based on the measurement of the amplitude and phase of the induced EM field (Van Zijl, 1986; Reynolds, 2011; Brantax, 2019).

During TEM measurements (also known as transient EM methods), the input current can be characterised as a series of single pulses, which in turn creates an output voltage, measured at the various time-intervals once the transmitter has been switched off. To minimise noise, the measurements can be stacked together. (Van Zijl, 1986; Reynolds, 2011; Brantax, 2019)

Furthermore, as Reynolds (2011) stated, under FEM and TEM, EM methods can be further classified either as passive - or active methods. During passive methods, naturally existing ground signals are utilised (as is the case with MT methods), whereas during active methods, and artificial transmitter is utilised, either in the near-field (as is the case with ground conductivity meters) or far-field (as is the case of VLF mapping). In Table 2-3 a basic classification of EM systems is summarised, based on Reynolds (2011).

For this study, not all of the EM methods, as summarised in Table 2-3, will be discussed, only those that are of particular interest with regards to the EM 34-3 instrument (used during the fieldwork of this study). Small-loop dual-coil systems will be discussed in more detail.

2.2.3.4.1 Small Loop Systems

According to McNeill (as cited by Reynolds, 2011), moving-source and dual-coil systems (small loop systems) are one of the most popular methods for EM surveying in the fields of environmental - and engineering geophysics. Small loop systems are classified as FEM and consists of two, current-carrying wire, bent into small loops, one of which is the transmitter and the other the receiver (separated by a fixed distance and moved along the survey line). These two coils create a magnetic dipole field which can be varied by alternating the current. The varying magnetic field creates the flow of current in nearby conductors. The point from where the actual measurement is taken is usually the midpoint between the transmitter - and receiver coils. The nature of the conductor and the geometry of the system determine the shape of the anomaly. The amplitude of the anomaly depends on the magnetic moment of the coil, which is directly proportional to the number of turns in the coil, the areas of the coil and the amount of current circulating within the coil. (Milsom, 2003; Reynolds, 2011)

According to the plane in which the windings of wire are oriented, the coils are described as horizontal, or vertical. When the windings orientate in a horizontal position, they have a vertical axis and is described as vertical dipoles (VD). Vertically oriented windings have a horizontal axis

and are described as horizontal dipoles (HD). Systems must also be characterised according to the coupling between them (maximum, minimum or variable) and by whether the transmitter - and receiver coils are coplanar, coaxial or orthogonal (Figure 2-10). (Milsom, 2003; Reynolds, 2011)

As can be seen in Figure 2-10, maximum coupled coils include coplanar and coaxial coils since the primary flux of the transmitter - and receiver coils act along the same axis. Maximum- coupled systems are known to be only slightly affected by small misalignments but are very sensitive to changes in coil separation. Minimum-coupled coils include orthogonal coils, which are not affected easily by coil separation, but small misalignments may cause large errors. Thus maximum-coupled systems are favoured over the minimum-coupled systems as it is much easier to keep the coil separation constant than the alignment of the coils.

With regards to Table 2-3, grounded wires measure the electric field by measuring the potential difference per length. Fluxgate magnetometers measure the magnetic field or its time derivative. Natural EM sources are usually one dimensional (1D) sources, while long wire (long edge of a large loop) systems are 2D sources and magnetic dipole (small loop) systems are three dimensional (3D) sources. Receivers can act as FEM or TEM, or even as both. The term “galvanic” (as it is used in Table 2-3), indicates the process of injecting current into the subsurface using steel electrodes. (Reynolds, 2011)

Table 2-3: Summarised EM systems (Reynolds, 2011).

Transmitter Type		Receiver Type			
		Ground Wire	Both Wire and Small Coil	Small Coil (Ground)	Small Coil (Air)
<i>Grounded Wire</i>	Galvanic	Induced Polarisation (IP)			
		Resistivity		Magnetometric Resistivity (MMR)	
	Inductive		CSAMT	Magnetic Induced Polarisation (MIP)	
				Some TEM systems	
<i>Small Loop</i>				Slingram	Airborne EM
				Horizontal - loop EM	Time-domain towed - bird
				Vertical - loop EM	Helicopter rigid - boom
				Tilt - angle method	
				Ground conductivity meters (GCM)	
				Coincident loop	
				Borehole systems	
<i>Large loop (long wire)</i>				Large - loop systems	
				Sundberg method	
				Turam	
				Many TEM systems	
				Borehole systems	
<i>Plane-wave</i>	Vertical Antenna		VLF - resistivity		
	Natural	Telluric Currents			
	Geometric Field				

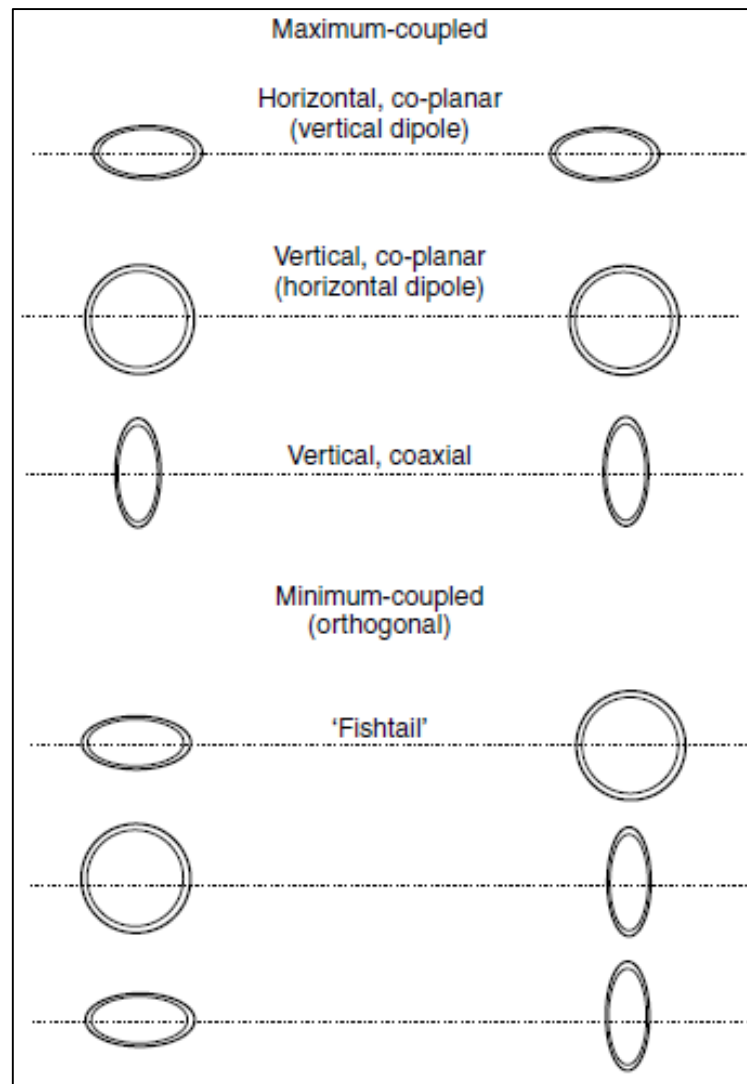


Figure 2-10: Coil systems for EM surveys (Milsom, 2003).

2.2.3.4.2 Slingram

During a Slingram survey, the flow of eddy currents is limited due to the EM response of an anomaly that is inversely proportional to the self-inductance and directly proportional to the mutual inductance with the transmitter - and receiver coils. To the contrary, anomalies are presented in the form of percentages of the primary field and as such, are inversely proportional to the mutual inductance of the transmitter - and receiver coils, thus as a result, determining the field strength of the primary field. (Milsom, 2003)

Milsom (2003) states that, besides ground conductivity meters, most of the Slingram systems, functions at <1000 Hz. Also, the multi-frequency systems, which have gained much popularity over recent years, normally function at <5000Hz. Measurable anomalies may be produced by narrow and poor conductors, but only at the highest frequencies, or none at all. As previously mentioned, ground conductivity meters (GCM) are associated as a Slingram-style system, other

EM methods that are also associated with Slingram-style systems are Boliden, EM Gun, MaxMin as well as Ronka EM methods. (Milsom, 2003; Reynolds, 2011)

2.2.3.4.3 Ground Conductivity Meters

In principle, a GCM responds to the conductivity composition of the subsurface material. During operation, the eddy currents are known to be small and the phase shifts tend to be close to 90°. The apparent resistivity, of the ground, is directly proportional to the ratio of the primary (in-phase) and secondary (out-of-phase, quadrature component) magnetic fields. The apparent conductivity of the ground is thus, directly proportional to the quadrature component. During field surveys, to obtain a measurable signal, it is occasionally necessary to make use of relatively high frequencies. The depth of investigation is, mostly, determined by the coil spacing (a constant distance of 1 m to 100 m). (Milsom, 2003; Reynolds, 2011)

GEONICS Limited manufactures two very popular GCM instruments, the EM-31 and EM-34. These instruments measure the apparent conductivity (mS/m) of the ground, as direct reading of the quadrature component, milliohms/meter (the SI equivalent are milliSiemens/meter mS/m). Furthermore, the in-phase component is measured in the form of parts per thousand (ppt). One major advantage of these instruments is that they can be used during investigations that involve taking measurements over land and water. When working with GCM instruments, such as those made by GEONICS, it is important to keep the induction number (B) in mind. The induction number is determined by the ratio of the inter coil-spacing(s) divided by the skin depth (z_s). As can be seen in Equations 45 - 47, the apparent conductivity (σ_a) is directly proportional to the ratio between the primary - and secondary magnetic fields when the induction number is less than one. (Milsom, 2003; Beamish, 2011; Reynolds, 2011)

The skin depth is given by Equation 31; the induction number is thus given by Equation 45:

$$\Gamma_s = (2i)^{\frac{1}{2}}s/\delta$$

$$\therefore = (2i)^{1/2}B \text{ (as } B = s/\delta)$$

Equation 45: Mathematical expression of the induction number (Reynolds, 2011).

Where $\Gamma = (i\omega\mu_0\sigma)^{1/2}$ and s represents the inter-coil separation (m). The ratio between the primary (H_p) - secondary (H_s) magnetic fields, at the receiver, at low induction numbers, is given by Equation 46:

$$H_s/H_p \approx iB^2/2$$

$$\therefore = i\omega\mu_0\sigma s^2/4$$

Equation 46: Mathematical expression of the ratio between the primary - and secondary magnetic fields (Reynolds, 2011).

An instrument is programmed to measure the conductivity and the secondary magnetic field, at a selected frequency (f), a predetermined inter-coil separation and a designed response to the primary magnetic field. The apparent conductivity can then be determined by Equation 47:

$$\sigma_a = \left(\frac{4}{\omega\mu_0 S^2}\right)\left(\frac{H_s}{H_p}\right)_q$$

Equation 47: Mathematical expression for determining the apparent conductivity when using GCM instruments. The subscript “q” represents the quadrature component. (Reynolds, 2011)

In reality, the subsurface is made up of varying geological layers, from weathered materials to solid matrix, containing pore spaces that may, or may not be saturated with groundwater, thus may be conductive. These geological layers consist of varying conductivity, that contributes to the measured apparent conductivity. All instruments are designed to give the apparent conductivity as a function of frequency. (Reynolds, 2011)

2.2.3.5 Instrumentation

During this study, the EM34-3, also known as a Ground Conductivity Meter, from GEONICS (Canada) was used for the same purpose as the previously mentioned instruments, to survey a dolerite dyke. According to McNeill (1980) the advantages of resistivity for engineering geophysical surveys and the disadvantages of conventional resistivity methods that led GEONICS Limited to explore the possibility of developing inductive EM methods to replace conventional resistivity methods. Thus, the EM-31 and EM 34-3 was developed, which enabled the possibility to map the subsurface conductivity at a very fast pace.

2.2.3.5.1 EM34-3

Santos (2004) states that the EM 34-3 by GEONICS is a very popular instrument when investigating shallow conductive structures, thus the instrumentation is very popular in the fields of hydrogeological and environmental studies. The basic instrumentation of the EM 34-3 includes two coils, one of which is the transmitter (charged with an AC at a specific frequency, related to the inter-coil spacing), the other, the receiver, linked by two lightweight shielded cables. The transmitter creates a magnetic field (primary field) that induces an electrical current into the ground, these currents, in turn, create a secondary magnetic field that is detected (together with the primary field) by the receiver. The depth of investigation is depended on the inter-coil spacing (which determines the frequency of the energising field) as well as the coil orientation (vertical - or horizontal dipole) as can be seen in Table 2-4. (Santos, 2004)

Table 2-4: Exploration depth of the EM 34-3 with regards to coil orientation (McNeill, 1980).

Inter-coil spacing (m)	Exploration depth (m)	
	Horizontal Dipole	Vertical Dipole
10	7,5	15
20	15	30
40	30	60

The EM34-3 works on the same inductive technique as the EM 31-MK 2, which allows measurements without requiring ground contact or penetrative electrodes. The EM 34-3 makes use of three inter-coil spacings, 10 m, 20 m and 40 m, thus providing variable depths of exploration up to a maximum depth of 60m. The EM 34-3 enables the possibility of relating six measurements to a single location using three inter-coil spacings and two dipole modes (horizontal and vertical) available for each spacing. With software such as IX1D and ENIGMA, multiple measurements can be used to model the geological profile. (McNeill, 1980; GEONICS, 2003)

The EM 34-3 is a two-person, simple to operate instrument that has proven to be very useful for both hydrologists and geologists. The EM 34-3 has a wide range of applications that the instrument can be used for which include the detection and delineation of groundwater contamination, groundwater exploration; in the vertical dipole, the EM 34-3 is very sensitive to vertical geologic structures and thus widely used for projects featuring fractured and faulted bedrock systems. (McNeill, 1980; GEONICS, 2003)



Figure 2-11: Example of the EM 34-3 Ground Conductivity Meter, measuring the horizontal dipole (GEONICS, 2003).

McNeill (1980) states that the EM 34-3 has an effective investigation depth range of 7.5 m to 60m which makes the EM 34-3 applicable for projects comprising of the following:

- Delineating regions of permafrost (frozen pore water);
- Locating gravel;
- Extending known gravel deposits;
- Mapping saline intrusions;
- Detecting cavities in carbonate rocks;
- Mapping pollution plumes in groundwater
- Mapping bedrock topography;
- Mapping terrain conductivity for electrical grounding and;
- General geological mapping (soil types, faults and fracture zones, etc.).

Table 2-5: EM 34-3 Instrumental specifications (McNeill, 1980; GEONICS, 2003; Milsom, 2003).

Specification	Technical Parameter
Measured Quantities	The EM 34-3 measure the apparent conductivity in milli-siemens per metre ($\frac{mS}{m}$);
Inter-coil Spacings and Operating Frequency	At 10m spacings, the EM 34-3 operate at a frequency of about 6.4 kHz; At 20 m spacings, the EM 34-3 operate at a frequency of about 1.6 kHz; At 40 m spacings, the EM 34-3 operate at a frequency of about 0.4 kHz;
Conductivity Ranges	The EM 34-3 operate at conductivity ranges of 10, 100, 1000 mS/m;
Measurement Resolution	The EM 34-3 measures at a resolution of ± 0.1 % of the full scale;
Measurement Accuracy	The EM 34-3 consists of the accuracy of $\pm 5\%$ at 20 mS/m;
Noise Levels	The EM 34-3 are constantly exposed to the constant noise of 0.2 mS/m (can be greater in the presence of high powerline interference);

2.2.4 Magnetic Method

2.2.4.1 History and Background

Telford *et al.* (1976), Sharma (1985), Milsom (2003) and Reynolds (2011) stated that the magnetic method, in principle, originates from a very rich history in the field of magnetism. Telford *et al.* (1976), Sharma (1985) and Reynolds (2011) state that magnetite ($FeO \cdot Fe_2O_3$) was used by the Chinese as early as the second century as a primitive way of finding direction. It wasn't until the twelfth century that the famous explorer, Marco Polo, brought the first magnetic compasses to Europe from China. The book *De Magnete*, by William Gilbert (1600), was the first scientific publishing of the Earth's magnetic field and magnetic associated phenomena. In the 1640s scientists in Sweden took measurements of the variations in the Earth's magnetic field to locate iron ore deposits. Thalen and Tiberg (1870), developed instrumentation that could measure various components of the Earth's magnetic field rapidly and accurately for routine prospecting (Telford *et al.*, 1976; Sharma 1985; Milsom 2003; Reynolds 2011).

Adholf Schmidt (1915) developed the first balance magnetometer, which was a breakthrough for the field of magnetic geophysics as it enabled widespread execution of magnetic surveys. During the Second World War, as with all technology, geophysics received a lot of attention and thus grew rapidly, which resulted in the development of more efficient, reliable and accurate instruments. Optical absorption magnetometers were developed during the 1960s, which enabled short measuring time with high sensitivities, which have since proved to be ideal for airborne magnetic surveys. Magnetic gradiometers have been used since the early 1970s (Sharma, 1985; Reynolds, 2011).

Milsom (2003) states that the magnetic method is still a very popular geophysical method in the 21st century, despite the limited magnetic properties of rocks and minerals. Because the gravity - and magnetic methods have so much in common, the two methods have been used together in projects all over the world to complement each other. The two methods are also known to be used together, during large exploration surveys before seismic surveys are carried out. It has been found, however, that the magnetic map, when compared with the gravity map, is generally more complex and the field variations are unpredictable and localised. (Telford *et al.*, 1976; Milsom, 2003)

According to Telford *et al.* (1976), when comparing the magnetic method with the gravity method, there are some advantages and disadvantages, also with regards to other geophysical methods. These are:

- The precise interpretation of magnetic data is much more difficult than that of gravity;

- Magnetic field measurements are much easier, faster, cheaper and simpler than other geophysical methods;
- The magnetic method is the most versatile method of all the geophysical prospecting methods.

According to Sharma (1985), the range of the magnetic method, including the various fields of geomagnetism, rock magnetism, palaeomagnetism and magnetic prospecting is so wide, that its applications cannot be covered in full. It is, however, according to Roux *et al.* (1980) and Reynolds (2011) possible to divide the applications of the magnetic method into two main categories, location and mapping. These two categories can be seen as small-scale investigations (locating) and large-scale investigations (mapping). The applications can be summarised as:

- Location:
 - Pipes, cables and ferric metallic objects;
 - Buried military ordnance such as shells, bombs;
 - Buried metal drums of containment such as toxic waste and;
 - Concealed mine shafts and adits.
- Mapping:
 - Archaeological remains;
 - Magnetic iron ore deposits;
 - Concealed basic igneous dykes capable of forming barrier zones that might contribute to the accumulation of groundwater;
 - Metallic ore deposits that may contain magnetic minerals;
 - Magnetite rich zones;
 - Geological structures that may contain or have influenced the deposition and concentration of economically valuable minerals, as well as indicate the presence of oil and gas;
 - Geological boundaries that exist between magnetically contrasting lithologies, including faults or;
 - Large scale geological structures.

Roux *et al.* (1980) state that magnetic data are very useful in the fields of environmental science as well as civil engineering.

2.2.4.2 The Magnetic Properties of Rocks and Minerals

Three main minerals occur widely in the Earth's crust that contains magnetic properties, these are magnetite, pyrrhotite ($Fe_{1-x}S$) and ilmenite $[(Fe, Ti)_2O_2]$. Of these three, magnetite is the most common and forms major and minor constituents of a wide array of different rock types. Massive iron ore deposits form where major concentrations of magnetite occur. (Roux *et al.*, 1980)

Geological formations containing magnetic minerals tend to behave like large subsurface magnets. These formations will thus have a magnetic field associated around them. The strength of the magnetic field depends on the concentration of the magnetic minerals present. This local magnetic field will superimpose on the magnetic field of the Earth (also known as the geomagnetic field). When taking magnetic measurements in close vicinity of these geological structures (bearing a magnetic field), the measurements will indicate a divergence from the undisturbed geomagnetic field, indicating an anomaly. These anomalies, big or small, will cause variations (increase or decrease) in the geomagnetic field. These variations depend on their depth, degree of magnetisation and direction of magnetisation and the orientation of the geological formation with regards to the geomagnetic field (Roux *et al.*, 1980; Milsom, 2003). The instruments are not only able to distinguish between small differences in magnetic strengths between various geological bodies, but also measure permanent magnetic anomalies such as dolerite dykes or magnetic iron ores (Roux *et al.*, 1980; Milsom, 2003).

2.2.4.3 Principles and Elementary Theory

2.2.4.3.1 Poles Dipoles and Magnetisation

It is important to understand the concept of a magnetic dipole to understand the behaviour of magnetic matter, ranging from the smallest particles to the whole Earth. A magnetic dipole is made up of positive and negative point sources of equal strength, structured at a very small distance apart (as can be seen in Figure 2-14). The magnetic strength (lines of flux, as can be seen in Figure 2-15) of a dipole is stronger at its point sources (poles) and weaker around its middle (equator). It is, however, possible to consider, mathematically, that a dipole consists of two magnetic poles of strength $+m$ and $-m$, whose physical size and separation are infinitely small. When a dipole is placed in a magnetic field, it tends to rotate and establish a magnetic moment, which can be expressed as $M=ml$, which is nonetheless finite. When considering all of the above-mentioned physical attributes, a dipole represents a perfect elementary magnet. When considering a solid body of matter, the magnetisation is defined by the body's magnetic moment per unit volume and is a vector, thus having direction and magnitude. (Sharma, 1985; Milsom, 2003)

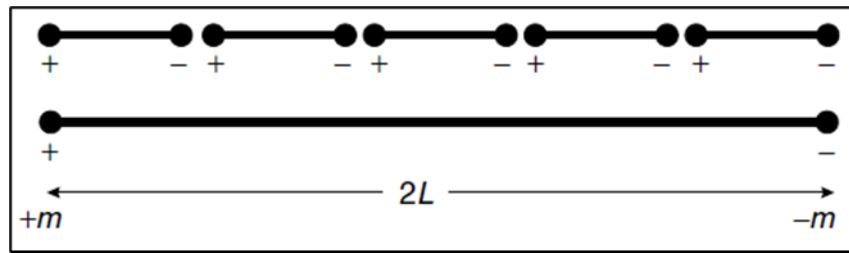


Figure 2-12: Visual representation of a dipole, made up of various equally strong positive and negative point sources, grouped very closely together (Milsom, 2003).

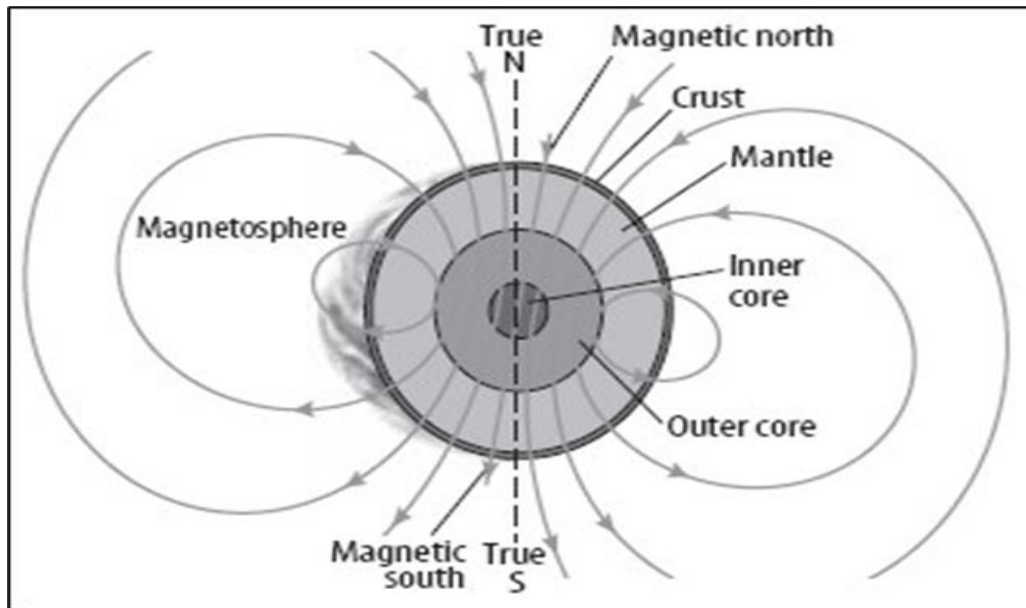


Figure 2-13: The geomagnetic field that resembles a very big dipole (Sharma, 1985; Milsom, 2003).

2.2.4.3.2 Geomagnetic Field

The geomagnetic field can be understood as a large bar-magnet situated at the centre of the Earth. Breiner (1999) and Milsom (2003) states that the origin of the geomagnetic field is not well understood, but it is thought to be the result of electric currents, circulating in the fluid outer core, but it can be largely modelled as a dipole source at the centre of the Earth. Reynolds (2011) states that the factors that contribute to the overall existence of the geomagnetic field include:

- External ionosphere and magnetosphere currents, associated with the Van Allen radiation belts;
- Currents induced into the Earth by external field variations and;
- The permanent (remnant) magnetisations of crustal rocks.

The geomagnetic field is, according to Reynolds (2011), very important for the survival of life on Earth as it forms the main force field that protects the Earth from harmful radiation from the sun. The size of the geomagnetic field is proportional to one-third of the Earth's diameter in length and

does not align precisely with the spin-axis of the Earth (Figure 2-14). When extending the geomagnetic field from the centre of the Earth to the surface, the result is two geomagnetic poles. These poles do not align with the geographical poles of the Earth as it does not align with the spin axis of the Earth, as stated above.

The positions of the geomagnetic poles change with time, with varying rates of movement. The position of the north geometric pole was in 2010 approximately, according to Reynolds (2011), 80.2°N and 71.98°W, which positioned it on the eastern side of Ellesmere Island, in the Canadian Arctic Archipelago. The geomagnetic north is moving northwest at a rate of 50km/yr. If the geomagnetic north continues its current speed and direction, it should reach cross the Arctic Ocean and arrive at Severnaja Zeml'A, and island situated off the northern coast of Russia, by 2050. The position of the northern dip pole, in 2010, was at 85.19°N and 133.16°W. The position of the southern magnetic dip pole was in 2010, at 64.44°S and 137.44°E, which positioned it offshore from the Adélie Coast of Greater Antarctica, moving northwards at a rate of 5 to 10 km/yr. The position of the southern magnetic pole was in 2010 at 80.02°S and 108.02°E and moving in the direction of the geodetic South Pole (Roux *et al.*, 1980; Breiner, 1999; Reynolds, 2011; Rumpf, 2012).

As can also be noticed from Figure 2-16, the direction of the geomagnetic field is vertical at the magnetic poles, and horizontal at the magnetic equator. The lines of flux, indicating higher intensity with a density of flux lines, prove that the field intensity is much higher at the magnetic poles than at the magnetic equator (as is the case with a dipole). It is important to keep these two statements in mind, as it is a fundamental aspect when exploring anomalies and determining their direction and magnitude. (Roux *et al.*, 1980; Breiner, 1999; Reynolds, 2011; Rumpf, 2012)

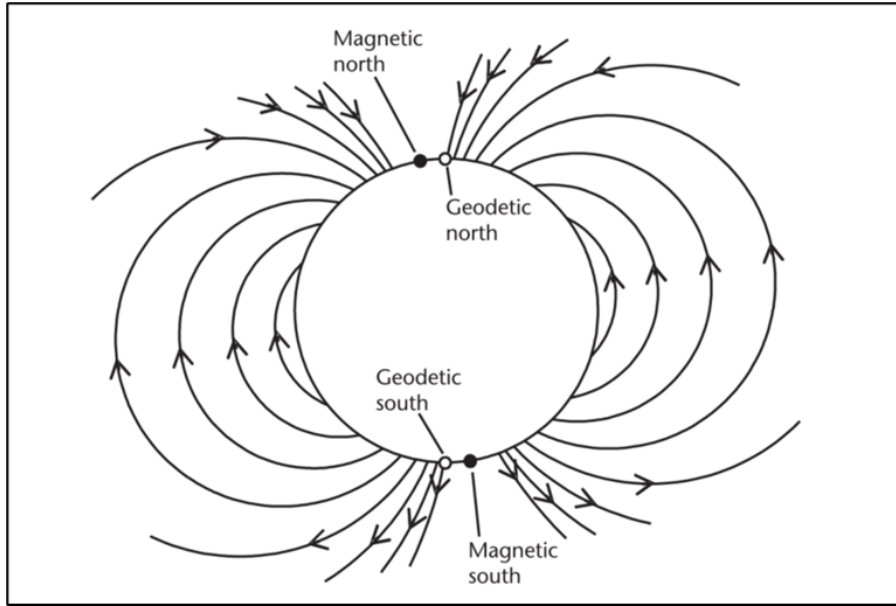


Figure 2-14: Visual representation of the geomagnetic field, as it does not align with the spin axis (true geographical north) of the Earth. (Rumpf, 2012).

According to Roux *et al.* (1980) and Sharma (1985) for the geomagnetic field (F) (a vector quantity) to be fully understood for its magnitude and direction at any point, three elements should be taken into account. These three elements are:

- Vertical Component (Z);
- Horizontal Component (H) and;
- Declination (D).

Sharma (1985) stated that the declination (D) represents the angle between the direction of the horizontal component (magnetic north) and the true geographical north. The three elements can be chosen alternatively, but the combination, as stated above are the most common. An alternative set of elements include:

- Total Field Intensity (F);
- Inclination (I), concerning the horizontal component;
- Declination (D).

These elements can also be seen as geographical coordinates where they serve the purpose of the north (X), east (Y) and vertically downward (Z) (as can be seen in Figure 2-15). All the quantities (X , Y , Z , D , I , H and F) are collectively known as geomagnetic elements. By making use of Equation 49, data can be converted from one set of elements to another:

$$F = \sqrt{X^2 + Y^2 + Z^2}$$

$$\therefore = \sqrt{H^2 + Z^2}$$

$$\therefore \tan I = Z/H;$$

$$\therefore X = H \cos D;$$

$$\therefore Y = H \sin D;$$

$$\therefore Z = F \sin I$$

Equation 48: Mathematical relationship between the geomagnetic elements (Sharma, 1985).

Sharma (1985) stated that the vertical plane through F and H is known as the local magnetic meridian, and the plane through X and Z is known as the geographical meridian.

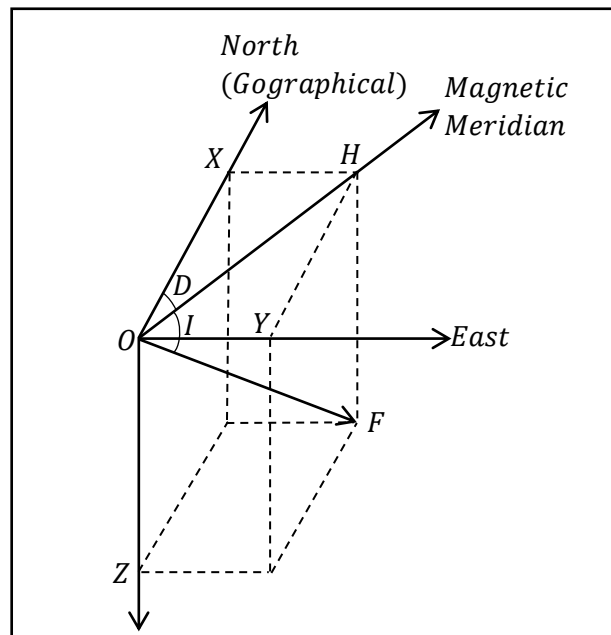


Figure 2-15: Diagrammatic representation of the main elements of the geomagnetic field. The elements D and I are the declination and inclination, respectively, of the total field vector, F (Sharma, 1985).

2.2.4.4 Magnetic Intensity

2.2.4.4.1 International Geomagnetic Reference Field (IGRF)

Sharma (1985) stated that since the emergence of satellites that are dedicated to measuring the total geomagnetic field, and its various vector components (H, Z), the global coverage, as well as, the improvement of data quality for analysis of the geomagnetic field, has dramatically improved. Sharma (1985), Reynolds (2011), Thébault *et al.* (2015) and British Geological Survey (BGS) (2020) states that the International Geomagnetic Reference Field (IGRF) serves as an internationally excepted standard that provides the reliable spatial distribution of the geomagnetic field. The IGRF consists of a series of mathematical models that describe the internal part of the

geomagnetic field in increments of 5 years (known as epochs), from the late 1900s to the present. The production and maintenance of the IGRF is the responsibility of an international team of scientists under the authority of the International Association of Geomagnetism and Aeronomy (IAGA), since 1965. The IGRF is made possible by the collaborative work between magnetic field modellers and other institutes responsible for the collection and processing of magnetic field data which are gathered from magnetic observatories, ground surveys as well as low Earth-Orbiting (LEO) satellites. Some of the scientific fields of study for which the IGRF are used include the following as set out by Thébault *et al.* (2015):

- The dynamics of the Earth's core field;
- Space weather;
- Local magnetic anomalies that are imprinted on the Earth's crust and;
- Orientation information for personal - and commercial organisations.

The IGRF model must get updated frequently (every five years) to account for continues temporal changes of the geomagnetic field that are caused by the Earth's outer core.

The five-year period between IGRF revisions is sufficiently short to keep its applicability as a reference model in applications which requires a fixed reference standard. Currently, the IGRF is in its 13th generation (2020-2025) as can be seen in Figure 2-18. The main field of the IGRF is calculated according to a few mathematical formulas, however, Reynolds (2011) stated that the main field is equal to the negative gradient of the scalar potential (V) (as can be seen in *Equation 50*). Sharma (1985), Reynolds (2011), Thébault *et al.* (2015) and BGS (2020)

$$V(r, \theta, \lambda, t) = R \sum_{n=1}^{n_{max}} (R/r)^{n+1} \sum_{m=0}^n (g_n^m(t) \cos m \lambda + h_n^m(t) \sin m \lambda) P_n^m(\theta)$$

Equation 49: Mathematical form of the IGRF equation for determining the main field as a negative gradient of the scalar potential V (Reynolds, 2011).

Where r, θ, λ represents the geocentric coordinates, r represents the distance from the centre of the Earth, θ represents the colatitude (e.g. 90° - latitude) and λ represents the longitude. The reference radius R (6371.2 km). The coefficients $g_n^m(t)$ and $h_n^m(t)$ represents the Schmidt semi-normalised association Legendre functions of degree n and order m . (Reynolds, 2011; Thébault *et al.* 2015)

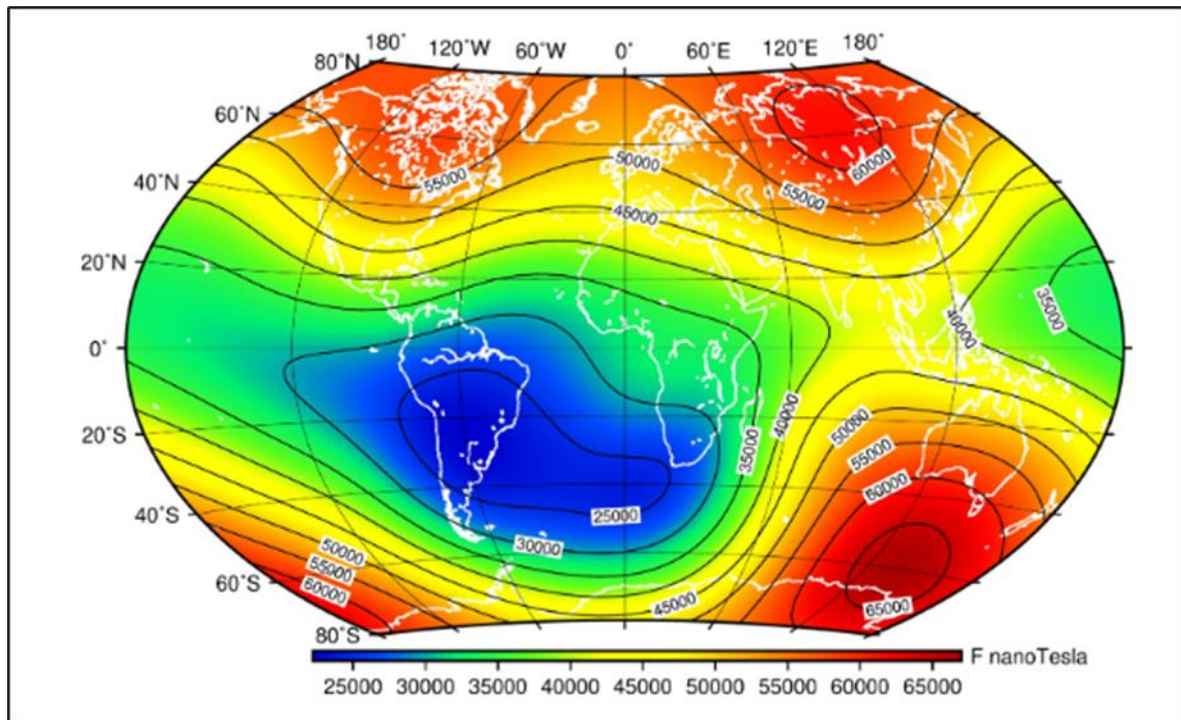


Figure 2-16: The 13th generation IGRF total field Intensity as given by the BGS (2020).

2.2.4.4.2 Magnetic Intensity of Mineral- and Geological Bodies

As are evident from Figure 18, the intensity of the geomagnetic field varies across the globe Roux *et al.* (1980) and Breiner (1999). The magnetic intensity of locally found mineral and geological bodies are, however, based on the principle of a bar magnet that consists of a series of individual elementary magnets (individual dipoles) that are oriented, parallel to each other, along the same axis of the whole bar magnet. The magnetic intensity of the whole bar magnet is made up by the individual north and south poles of the elementary magnets that cancel one another out, except at the end faces of the whole bar magnet. In reality, the whole bar magnet will consist of a surface concentration that is made up by free positive (N) and negative (S) poles of a total strength (for instance “m”) at both ends of the whole magnet. When considering a bar magnet of length (l), having a cross-sectional area (A) that can be assumed to be uniformly magnetised in the direction of l, the magnetic intensity of the whole bar magnet can be expressed as a measure between the pole strength per unit area at each end and can be expressed as:

$$J = M/A \left(\frac{\text{amp.metre}}{\text{metre}^2} \right)$$

Equation 50: Mathematical expression of the magnetic intensity of a bar magnet (Sharma, 1985).

Where J is measured in A/m. Alternatively, J can be defined in terms of the magnetic moment, M. The bar magnets magnetic moment is then expressed as the product of:

$$M = ml(\text{amp.metre}^2)$$

Equation 51: Mathematical expression of the magnetic moment of a bar magnet (Sharma, 1985).

If the volume of the bar magnet is expressed as V, and by combining Equations 51 and 52, it is possible to express J as:

$$J = \frac{ml}{V}$$

$$\therefore J = M/V$$

Equation 52: Mathematical expression of the magnetic intensity with regards to the unit volume V (Sharma, 1985).

It is thus evident that the magnetic intensity of a uniformly magnetised bar magnet (magnetic mineral- or geological body), at any point, can be defined by its magnetic moment per unit volume. As the magnetic moment (M) is a directly measurable entity (in Am²), it serves as the most important parameter in a magnetised body. The above-mentioned statement corresponds with the magnetic moment of a small, plane electric current loop, which is defined by the product of the current and loop area (in Am²). In the case of a uniformly magnetised body, the direction and magnitude of the J remain constant throughout the body. Uniform magnetisation for homogeneous bodies of spherical or ellipsoidal shape is only approximately correct. The magnetic intensity is a fundamental quantity for understanding the magnetic state of a body. (Sharma, 1985; Reynolds, 2011)

2.2.4.5 Induced and Remnant Magnetism

Reynolds (2011) mentioned that there exist two types of magnetism, induced - and remnant magnetism. Induced magnetism refers to the magnetism of an object that is induced by an applied field (H) and depends primarily on the susceptibility of that object. The induced intensity of magnetisation is known as J_i. Permanent or remnant magnetism is based upon the absence of an applied field (H), thus referring to the measurable intensity of magnetisation that is sustained by the objects internal field strength due to the permeability in magnetic particles. The magnetic intensity of permanent or remnant magnetism is known as J_r. (Sharma, 1985 & Reynolds, 2011)

And an object that has magnetic minerals will have an induced as well as permanent magnetisation. These two magnetisations may have different directions in magnitude and intensity (*Figure 2-17*). The resultant magnitude and intensity of J dictate both the amplitude as well as the shape of an anomaly, respectively.

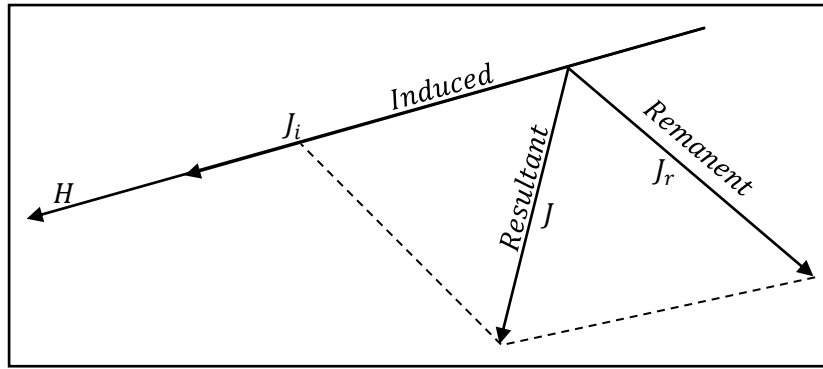


Figure 2-17: Diagrammatic representation of the vector summation of induced and remanent intensities of magnetisation. (Reynolds, 2011)

2.2.4.6 Magnetic Susceptibility

According to Roux *et al.* (1980), MacDonald *et al.* (2001) and Reynolds (2011), the magnetic susceptibility of a material refers to the measurement that determines the degree to which a material is susceptible of being magnetised. In other words, a magnetisable body can be temporarily magnetised, when exposed to an external magnetic field (H), that is also lost when the applied field is removed. (Roux *et al.*, 1980; Sharma, 1985; Reynolds, 2011)

The following relationship (Equation 54) describes the susceptibility of materials for which the induced magnetisation, J_i is parallel and also proportional to the applied field H :

$$J_i = kH$$

Equation 53: Relationship between the induced magnetisation is proportional and parallel to the applied field. (Roux *et al.*, 1980; Sharma, 1985; Reynolds, 2011)

Where k represents the magnetic susceptibility, the characteristic constant for magnetisable material. Since the quantities of J_i and H is measured in the same quantities (A/m), the quantity of k is “dimensionless”. The quantities of J_i and H can also be measured in the unrationalised version of the centimetre, gram and second (CGS) EM system, where J_i is then measured in Amp/cm and H in units of $1/4\pi$ absolute Amp/cm. The magnitude of k is then expressed as 4π that of the unrationalised CGS EM system. (Breiner, 1973; Sharma, 1985)

By making use of Equation 55, it is possible to obtain the induced magnetisation (J_i) in a rocking body which has a susceptibility (k), due to the Earth's field (F) (measured in tesla), by simply replacing the H with F/μ_0 :

$$J_i = k\left(\frac{F}{\mu_0}\right)$$

Equation 54: Mathematical relationship between the induced magnetisation and susceptibility, with regards to the geomagnetic field. (Sharma, 1985)

It is important to keep in mind that F represents the geomagnetic field in terms of flux density and that μ_0 represents the magnetic permeability of the material in question. (Sharma, 1985)

2.2.4.6.1 Susceptibility of Rocks and Minerals

The susceptibility of rocks and minerals can be either positive (indicating paramagnetism) or negative (indicating diamagnetism). Rocks that possess the highest susceptibilities, tend to have large concentrations of Ferro - and/or ferromagnetic minerals (MacDonald *et al.*, 2001; Reynolds, 2011). As a result, rocks that are basic or ultrabasic of nature have the highest susceptibilities, acidic igneous - and metamorphic rocks have intermediate to low susceptibilities and sedimentary rocks generally have very low susceptibilities (MacDonald *et al.*, 2001; Reynolds, 2011). A compilation of susceptibility values for various rocks and minerals (according to the rationalised SI units) can be found in *Field Geophysics* by John Milsom (2003) and *An Introduction to Applied and Environmental Geophysics* by John M. Reynolds (2011) (Roux *et al.*, 1980; Sharma, 1985; Milsom, 2003; Reynolds 2011)

2.2.4.7 Diamagnetism, Paramagnetism and Ferromagnetism

With regards to magnetic susceptibility, it can be summarised that diamagnetic substances have a negative susceptibility and that paramagnetic and ferromagnetic substances have a positive susceptibility. To understand how substances can be classified as diamagnetic, paramagnetic and ferromagnetic, it is important to keep in mind the fundamental physics behind the behaviour and movement of electrons. As a result of electron spin and the orbital motion of electrons around the nucleus of an atom, it can be said that all atoms comprise of a magnetic moment. The quantum theory states that two electrons can exist together in the same state (electron shell), but only if they spin in opposite directions. As a result of the coexistence of these paired electrons, the overall magnetic moment balances out to be zero. In the absence of an applied external field, for the most substances, the spin magnetic moments of adjoining atoms are randomly distributed, thus there exist an absence of an overall magnetisation. (Sharma, 1985; Reynolds, 2011)

When encountering a diamagnetic mineral, all the electron shells are full (no unpaired electrons), as is the case with the mineral, halite. When an external force is applied to halite, a magnetisation is induced upon the mineral. The resultant electron orbit creates a magnetic field that conflict with that of the applied field, thus resulting in a negative susceptibility. (Sharma, 1985; Reynolds, 2011)

Some minerals contain electron shells that are not full, thus unpaired electrons. The unpaired electrons create an unbalanced spin magnetic moment and thus weak magnetic interactions between atoms. Materials containing unbalanced electron shells are known as paramagnetic materials. Other minerals that fall into this category is amphiboles, pyroxenes, olivines, garnets and biotites. When and the external force is applied, the magnetic moments tend to align into the

same direction, however, this process is slowed down by thermal agitation. As a result, paramagnetic materials comprise of a positive susceptibility but tend to decrease inversely with the absolute temperature according to the Curie-Weiss law. Between paramagnetism and diamagnetism, the latter tends to be at least an order of magnitude weaker than paramagnetism. (Sharma 1985; Reynolds, 2011)

As is the case with paramagnetic materials, ferromagnetic materials also comprise of a positive, but large susceptibility (Sharma 1985; Reynolds, 2011). Two factors that determine the degree of susceptibility of ferromagnetic materials are temperature and the applied magnetic field strength (Sharma 1985; Reynolds, 2011). The cause of the large susceptibility for ferromagnetic materials can be explained by the spin moments of unpaired electrons that are magnetically coupled due to the very strong interaction between adjacent atoms and the overlapping of electron orbits (Sharma 1985; Reynolds, 2011). As a result, a small grain, in which magnetic coupling takes place, forms what is known as a single magnetic domain that is responsible for the strong spontaneous magnetisation (also present in the absence of externally applied field) (Sharma 1985; Reynolds, 2011). The magnetic coupling of ferromagnetic materials can be in such a manner that the magnetic moments are parallel aligned, or anti-parallel (as is the case with an antiferromagnetic substance). In the geological world, ferromagnetic materials are very scarce, but some metals include, cobalt (Co), nickel (Ni) and iron (Fe). All three of these metals comprise a parallel alignment of magnetic moments. As previously mentioned, temperature plays a significant role in the degree of susceptibility of ferromagnetic materials, when the temperature of a substance rises above the Curie temperature (T_c), ferromagnetism disappears, as a result of severely restricted interatomic coupling and the mineral subsequently behaves as paramagnetic (Sharma 1985; Reynolds, 2011).

2.2.4.8 Remanent Magnetism and the Königsberger Ratios

Sharma (1985), Milsom (2003) and Reynolds (2011) stated that most rocks that are found in the upper part of the Earth's crust exhibit a natural remnant magnetisation (NRM), that are not related to the Earth's present magnetic field, but rather to the magnetic field that was present during the rock's formation. A list of the various processes by which remnant magnetisation can form in rocks can be seen in Reynolds (2011) as discussed by Tarling (1983), Sharma (1985) and Merrill (1990) as well as Gubbins and Bervera (2007).

The primary remnant magnetisation, however, forms during the cooling and solidification period of an igneous rock's formation, from above the Curie temperature (depending on the magnetic minerals contained) to the normal surface temperature (Thermoremanent Magnetisation-TRM) (MacDonald *et al.*, 2001; Reynolds, 2011). At a later stage in a rock's history, it is, however, possible for it to acquire a secondary remnant magnetisation, known as chemical or viscous or

post-depositional remnant magnetisation. The latter is especially true for thermally metamorphosed rocks.

The intensity of remnant magnetisation is often particularly large for igneous and thermally metamorphosed rocks and can often exceed that of induced magnetisation. The ratio between the natural remnant magnetisation and the induced magnetisation (induced by the current Earth's field (F) at the specific location), is known as the Königsberger ratio (Q). The Königsberger ratio can be expressed as:

$$Q = J_r / k \left(\frac{F}{\mu_0} \right)$$

Equation 55: Mathematical expression of the Königsberger ratio with regards to the Earth's magnetic field (at a specific locality) and the susceptibility of the particular rocks. (Reynolds, 2011)

Nagata (1961) as cited by Sharma (1985) and Reynolds (2011), has drawn up a table containing values of the Königsberger ratio for rocks at specific localities. It is evident from these tables that, as is the case with susceptibility, the Königsberger ratio can differ for the same rock type at different localities. It is, therefore, necessary to keep the following generalisations for Q in mind as set out by Nagata (1961) as cited by Sharma (1985) and Reynolds (2011):

- For slowly crystallised rocks in continental areas, Q~1 with regards to igneous - and thermally metamorphosed rocks;
- For many rapidly quenched basaltic rocks (such as oceanic basalts), Q~30-50;
- For volcanic rocks Q~10;
- Except for special cases of iron ores, Q<1 for sedimentary and metamorphosed rocks.

Sharma (1985) and Reynolds (2011) also stated that the direction of a rock's remnant magnetisation may be different from that of the ambient induced field at a specific location. The resultant magnetisation ($J=J_i+J_r$) will thus give rise to characteristic magnetic anomalies. (Sharma, 1985; Reynolds, 2011)

2.2.4.9 Noise

The term "noise", its meaning and effects on various geophysical instruments have already been discussed widely in this study, especially with regards to ER, EM and MT. Roux *et al.* (1980) and Reynolds (2011) discussed the effects of noise that are associated with the magnetic method. During magnetic surveys, surface magnetic noise can be associated with magnetic variations that exist in the surface soil and geology and may be in the order of 5 to 20 nT, varying from station to station. When encountering magnetic rich minerals and geology such as magnetite ores or banded ironstone, the magnetic variations may be considerably larger. When using the proton

magnetometer, surface noise can be limited by mounting the sensor on a large pole (as will be discussed shortly), thus distancing the sensor from the factors responsible for the noise.

Some factors cause external magnetic noise to any magnetic instrument, these may include personal items that the operator may have on him/her such as keys, wristwatch, pocketknife, cell phone, geological hammer or any other magnetic object or signal related object that may interfere with the magnetometer. Other site-related factors include telephone lines and power lines, wire (used for fencing), electric railway lines, buried pipelines and scrap metal, cars and electrified railways, underground mine installations as well as magnetic storms. These types of noise are easily recognisable and will cause variations in readings at the same station. It is then important that the operator take several readings to establish an average degree of interference. In the case of a magnetic storm, it is important to cease all operations until the storm has passed. It is always very important that the operator be vigilant in the field and to identify any factors that may cause noise, and to exclude the affected data from the survey. (Roux *et al.*, 1980 & Reynolds, 2011)

2.2.4.10 Magnetic instruments

The most popular portable magnetic instruments include Fluxgate -, Proton Precession Magnetometer (PPM), Alkali Vapour -, Schmidt Field Balance -, Dip Needle - and some other special-purpose magnetometer instruments (Breiner 1973; Breiner, 1999; Roux *et al.*, 1980). For this study, the proton precession magnetometer will be discussed in detail.

The PPM is a scalar magnetometer that falls, according to Reynolds (2011), in the category of Resonance magnetometers along with the alkali vapour magnetometer. The PPM is the more popular instrument of the two and is commonly used in geophysical projects that include, geophysical research, magnetic field mapping, the measuring of the magnetic properties of ferromagnetic objects, conductivity mapping, as well as many more geophysical related projects (Breiner, 1973; Breiner, 1999; Schlinger, 1990; Ruhunusiri & Jayananda, 2008). The principles of the PPM have a rich history that is documented by many authors such as Breiner (1973), Roux *et al.* (1980), Sharma (1985), Schlinger (1990), Breiner (1999), MacDonald *et al.* (2001), Milsom (2003), Ruhunusiri and Jayananda (2008), Reynolds (2011) and Koehler (2012). According to these authors, the PPM consists of a sensor bottle that contains a proton-rich fluid (water or kerosene) with a suitable coil of copper wrapped around it. The sensor is situated on a long (2 m) pole and connected to a measuring apparatus with a cable. The Hydrogen protons, in the sensor, align themselves in the direction of the ambient magnetic field. When a temporary (polarising) magnetic field is applied to the hydrogen nuclei, in the sensor, the protons orient themselves in the direction of the temporary field (50 to 100 times stronger, and at right angles to that of the ambient field). When the temporary polarising field is removed, the protons will realign with the ambient field. When the protons change their alignment, process or rotate on the same manner

as a gyroscope around the ambient field at the Lamor precession frequency (proportional to the ambient magnetic field strength).

Some advantages of the PPM include the ease and speed that, a single operator, can operate the instrument, as well as its portability. The measurements that are made by the proton precession magnetometer are accurate up to 0.1 nT, which is sufficient for projects that include groundwater exploration surveys of large anomalies such as dolerite dykes. Another advantage of the PPM is that the sensor is built on a long pole to increase the distance between the sensor and cultural noise and rubble buried underneath the ground surface. It is not necessary to orientate the sensor, as the precession frequency is only a function of the field strength. Recent PPM produce a readout of the field strength in the form of nanoteslas and the subsequent data can be automatically transferred into a data logger to be downloaded onto a computer. There are also some disadvantages associated with the PPM such as the decrease in accuracy in areas of a high magnetic gradient. The measurement time of the PPM has proven to be a disadvantage when working with airborne surveys, this is, however not a problem when working with portable ground PPM. (Sharma, 1985; MacDonald *et al.*, 2001; Reynolds, 2011)

2.2.4.10.1 Proton Memory Magnetometer - Model G5

During this study, the Proton Memory Magnetometer - Model G5 (Figure 2-18) from GEOTRON Systems (further referred to only as “G5”) due to the instruments availability and the writer’s familiarity with the instrument, regarding similar projects.

According to the GEOTRON website GEOTRON (2019) and the instrument’s user manual, GEOTRON (2014), the G5 is a very strong and reliable instrument that was designed to maximise the quality and quantity of geophysical data by increasing the operator’s productivity. The instrument does not only measure and displays the total magnetic field of the earth, but it also displays the difference between the present and previous readings and stores all measured readings on its internal, non-volatile memory (GEOTRON, 2014; Hlatywayo & Sakala, 2014)



Figure 2-18: Proton Memory Magnetometer Model G5 (GEOTRON, 2019).

CHAPTER 3 METHODOLOGY

3.1 Study Area

The study area that was chosen for this project is known as the farm, Modderfontein 383IP (Figure 3-1). The farm is situated in the North West province (South Africa) approximately twenty kilometres north west of Potchefstroom. The area proved to be ideal for this study as it is situated close to Potchefstroom and consists of known geology as well as a dolerite/diabase dyke (Figure 3-3). The traverse lines are indicated by three red lines that are also visible in Figure 3-3. The traverse lines were chosen parallel 50 m apart, perpendicular. The station spacing for each instrument was chosen according to the specifications of each instrument with the desired depth of the investigation in mind. This will be discussed later in this chapter.

3.1.1 Climate

According to Kruger (2004), the study area falls in a grassland type of climatic region known as the Dry Highveld Grassland region. The climatic properties that are associated with the Dry Highveld Grassland region include precipitation that ranges from ± 450 mm in western parts of the region to ± 700 mm in the northern border of the region. The region is characterised with a rainy season that reaches its maximum during the months of December and January (in the northern parts of the region) and February to March in the western and southern parts of the region. The region consists of some high lying areas that might experience snowfall during winter months. The wind direction of the region is known to be highly variable, but Kruger (2004) stated that the average wind direction tends to be from the North to North-East.

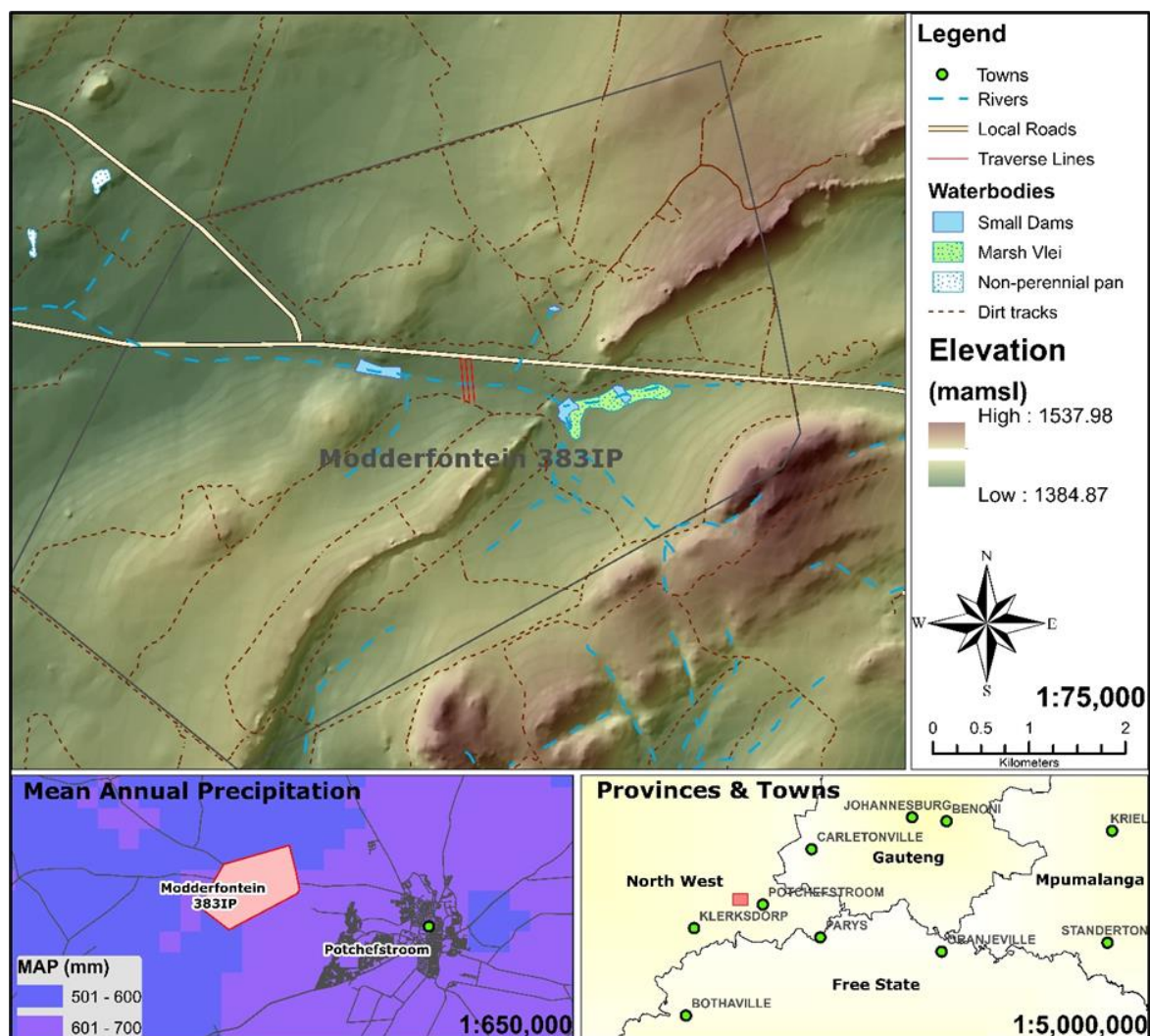


Figure 3-1: Locality map of the study area, Modderfontein 383IP.

3.1.2 Vegetation

Kruger (2004) stated that the Dry Highveld Grassland region is mainly vegetated with grassland, trees may be found along watercourses. The Grass species that can be found in the region include Giant Speargrass – *Trachypogon spicatus*, Broadleaf Bluestem – *Diheteropogon amplexans*, Caterpillar Grass – *Harpochloa falx*, White Buffalograss – *Panicum coloratum*, Weeping Lovegrass – *Eragrostis curvula* and Redgrass – *Themeda Triandra*. Tree vegetation that occurs in the region includes *Acacia* and Mountain Karee – *Rhus leptodictya*. (Kruger, 2004)

3.1.3 Introductory Geology

Johnson *et al.* (2006) stated that South Africa comprise a rich geological history that forms part of the Earth's history for over 3600 million years (Ma). Johnson *et al.* (2006) provided a very good description of the stratigraphic classification, used to classify the complex geology of South Africa.

On the other hand, McCarthy (2013) provided an informative and very well illustrated evolution of the geology of South Africa.

McCarthy (2013) stated that stratigraphy includes the study of geological formations and their interrelationships. McCarthy (2013) described the geological stratigraphy for South Africa as all geological rocks that belong to the same period, as they formed during a single event, are known as a Supergroup. The nomenclature of Supergroups is usually based upon the regions where it is the best exposed (e.g. the Karoo Supergroup underlies the Karoo Region). (McCarthy, 2013)

Supergroups consist of different layers of geological formations that belong to a single period of accumulation with each of these formations representing unique conditions of accumulation. The oldest formations will usually be located at the bottom of the stratigraphic cross-section with the youngest covering the top formations. Due to variations in accumulation, Supergroups can be subdivided into formations of smaller entities (which is based upon the rocks present). McCarthy (2013) order these formations hierarchically as:

- Groups;
- Subgroups;
- Formations;
- Members and;
- Beds.

As Beds are usually associated with the youngest formations, they represent individual layers. Similarly, as the Supergroups, all these smaller formations are also named according to the regions where they are the best exposed. (McCarthy, 2013; Johnson *et al.*, 2006)

3.1.4 Stratigraphic Geology

As discussed in section 3.1.3 South Africa comprise of a wide range of stratigraphy units. For this study, however, the focus will be placed on Figure 3-3 and the stratigraphic formations it displays as the regional geology of the Modderfontein 383IP farm. As is evident from Figure 3-3, the surveyed area is underlain by two primary formations that include the Timeball Hill Formation of the Pretoria Group and the Malmani Subgroup of the Chuniespoort Group. Both the Pretoria - and the Chuniespoort Groups form part of the Transvaal Supergroup (Johnson *et al.*, 2006). Figure 3-2 summarises the stratigraphy of the Transvaal Supergroup as given by Eriksson *et al.* (2001)

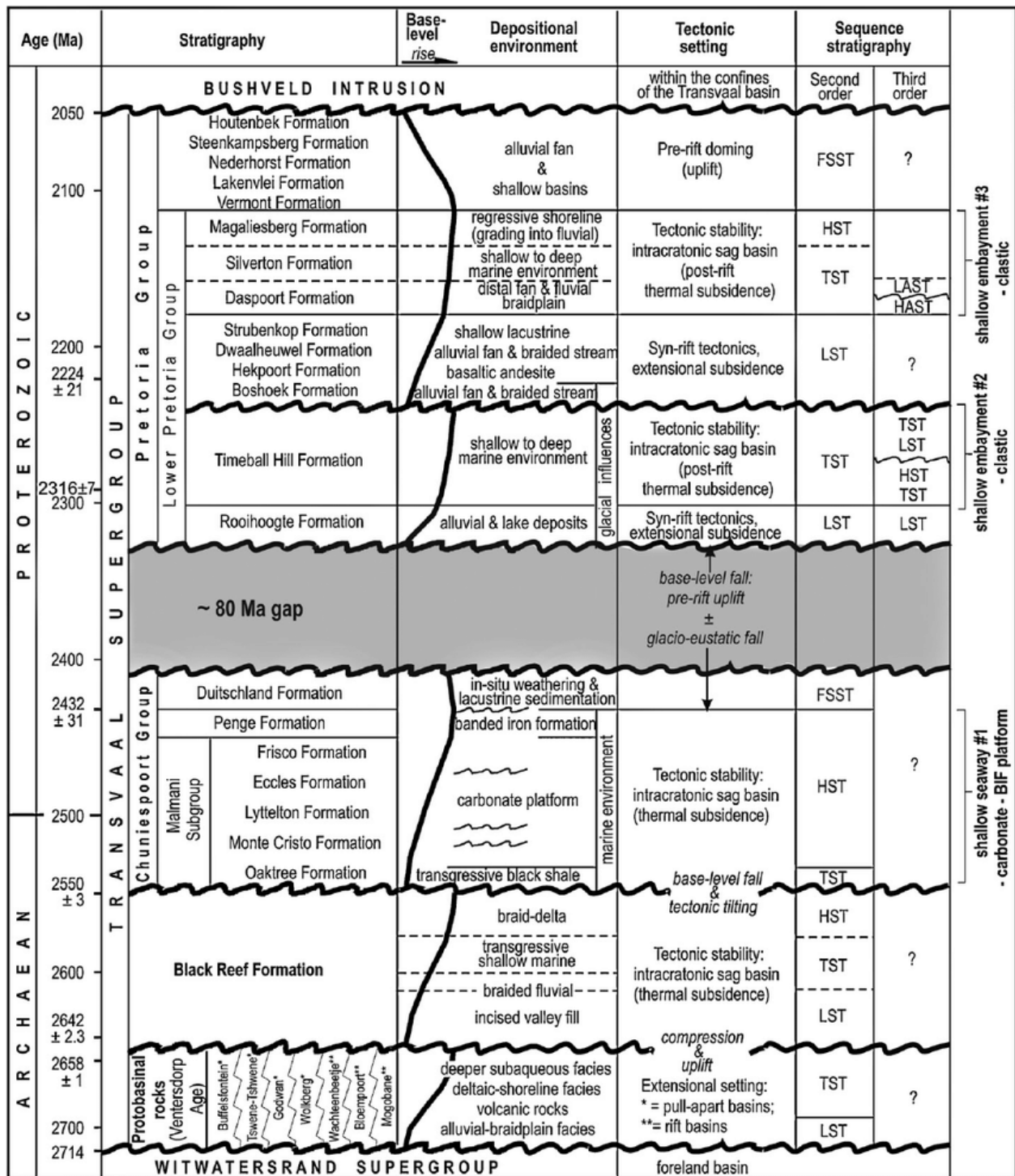


Figure 3-2: Stratigraphic summary of the Transvaal Supergroup as given by Eriksson et al. (2001).

Johnson et al. (2006) describe that the Transvaal Supergroup formed during the late Archean and early Proterozoic periods (Figure 3-2). Johnson et al. (2006) further described that the Transvaal supergroup is mainly comprised of three basins, namely the Transvaal Basin, the Griqualand West Basin and the Kanye Basin. Two of these (Transvaal and Griqualand West) is situated in South Africa, while the Kanye basin is situated in Botswana. The Griqualand West basin can also be further subdivided into the Prieska and Ghaap - Plateau subbasins. Within these three

structural basins, the preserved succession is very similar, with the best correlation being that of the lower chemical sedimentary units and the poorest for the upper clastic sedimentary and volcanic units. Except for the volcanic precursor rocks of the Kanye Formation, parts of the Griqualand West Basin and the protobasinal Transvaal rocks, the geometry of the Transvaal Supergroup, over the three basins is known to be essentially stratiform. During the period of roughly 2060 Ma, the rocks of the Transvaal Basin were intruded by the Bushveld Complex and as a result, the Magaliesberg Formation of the Pretoria Group formed the floor rocks in most areas. Johnson *et al.* (2006) describe that in most areas, the Transvaal Supergroup strata dip to the centrally located Bushveld Complex. Johnson *et al.* (2006) also stated that the Transvaal Supergroup overlies the Archaean basement, the Witwatersrand – and Verntersdorp Supergroups.

According to Johnson *et al.* (2006), the Transvaal Supergroup portrays not only significant geological history, but also contribute significantly to the knowledge of the history of life on earth as it surrounds one of the world's earliest carbonate platform successions. These successions house very well preserved and extensive stromatolites as well as a very well-preserved record of cyanobacterial and bacterial evolution. The Transvaal Supergroup are also very well known for its economical significands as the aforementioned carbonates are overlain by laterally extensive banded iron-formation (BIF) which contain some of the world's largest iron and asbestos deposits. The Transvaal Supergroup also accommodate the world's largest Manganese (Mn) deposits which overlay the Hekpoort-Ongeluk flood basalts in the Griqualand West Basin. Some of South Africa's structurally controlled gold and Mississippi Valley-type base metal deposits are also found hidden within this Supergroup. Johnson *et al.* (2006) also mentioned the potential for sedimentary-exhalative ore deposits within this Supergroup. (Johnson *et al.*, 2006)

Figure 3-3 indicates that the study area is underlain mainly by two subgroup formations namely the Malmani Subgroup of the Chuniespoort Group and the Timeball Hill form the Pretoria Group. According to Johnson *et al.* (2006), the Malmani Subgroup of the Transvaal Basin has a thickness of about 200 m and can be subdivided into five formations according to chert content, stromatolite morphology, shales and erosion surfaces. These five Formations include:

- Oaktree;
- Monte Christo;
- Lyttelton;
- Eccles and;
- Frisco.

Johnson *et al.* (2006) described that Eriksson and Truswell (1974) as well as Eriksson *et al.* (1975) worked on and succeeded in developing a tidal palaeo-environmental model for the Malmani

Subgroup that extended a range from supratidal flat stromatolitic mats to intertidal columnar stromatolites, together with a subtidal zone that is characterised by very large stromatolitic domes. Furthermore, Johnson *et al.* (2006) stated that Clendenin (1989) discovered unconformity bounded sequences within the Chuniespoort Group and as a result subdivided the Malmani epeiric sea sediments into four time-stratigraphic units, known as “packages”. Clendenin moreover recognised a fifth “package” of basinal sediments in the Griqualand West Basin and as a result, proposed a carbonate ramp depositional model for the Malmani and Campbell Rand Subgroups. Within this model, the south-westerly inclined carbonate ramp extended into a shallow basin, with mixed depositions of carbonate/shale - and iron formations. As a result, three facies belts were identified, ranging from the shallow basin, a subtidal platform to peritidal facies. As the axis for this basin, a northeast-southwest trendline (passing approximately east of Vryburg and Prieska) were identified. The sedimentation was attributed to being the work of extensional tectonics, which reflect three successive rift stages. (Johnson *et al.*, 2006)

On the other hand, Johnson *et al.* (2006) described that the situation is much more complicated in the Griqualand West Basin, compared with the Transvaal Basin, as the basin is divided into two sub-basins with different sedimentary histories. Johnson *et al.* (2006) stated that the Campbell Rand Subgroup of the Ghaap Plateau Sub-basin is estimated to be 1600 m thick. To the contrary, the Kathu stratigraphic borehole revealed the subgroup to be much thicker, at least 2500m thick, with the top part removed by the Palaeozoic Dwyka glaciation. Johnson *et al.* (2006)

Catuneanu & Eriksson (2000) stated that the Timeball Hill Formation accommodates a thickness of more than 1100 m and is situated in the Northern part of the Transvaal Basin. The formation accommodates three sedimentary members known as lower and upper shale members and the Klapperkop Quartzite Member (which separate the two shale members. Johnson *et al.* (2006) described that the Timeball Hill Formation consists of thick shales and subordinate sandstones that are assigned to a fluvio-deltaic basin-fill sedimentation system. Johnson *et al.* (2006) described furthermore that the Bushy bend lava Member, consisting of a black shale facies that are associated (throughout the whole basin) with lavas and pyroclastic rocks, reflects suspension sedimentation and fumarolic eruptions. Subsequently, Johnson *et al.* (2006) described that rhythmically interbedded mudstones/siltstones, as well as fine grained sandstones, are known as turbidite deposits. These deposits follow up into the Klapperkop Quartzite Member which are interpreted as fluvio-deltaic sandstones that fed the more distal turbidites. Johnson *et al.* (2006) furthermore explained that an upper shale member repeats the black shale and rhythmite facies also include, in the Mokopane (Potgietersrus) area, a more proximal, inferred fluvial arkose wedge while in the Pretoria area, diamictites and associated wackes. Due to tectonic instability, the upper Timebal Hill shales, situated in the East of the basin, underwent extensive soft-sediment deformation. These have subsequently led to the succeeding immature fan deposits of the

Boshoek formation and the flood basalts of the Hekpoort formation. (Catuneanu & Eriksson, 2000; Johnson *et al.*, 2006)

3.1.5 Regional geology

The Northwestern section of Modderfontein 383IP farm is underlain by dolomites of the Malmani Subgroup. Other units include the Boshoek - as well as the Hekpoort Subgroups (to the East and South-East). Rocks of the Transvaal Supergroup have a North-East, South-West strike direction and they are dissected by one East-West direction dolerite dyke. According to Lenhardt (2012) the contact with underlying Rooihoogte Subgroup is sharp, being represented by the refinement surface at the base of the Lower Shale Member of the Timeball Hill Formation. Steyn (2017) also mentioned that the surveyed area comprises mainly of shale, especially South of the geological structure and quartzite, conglomerate, breccia and diamictite to the North.

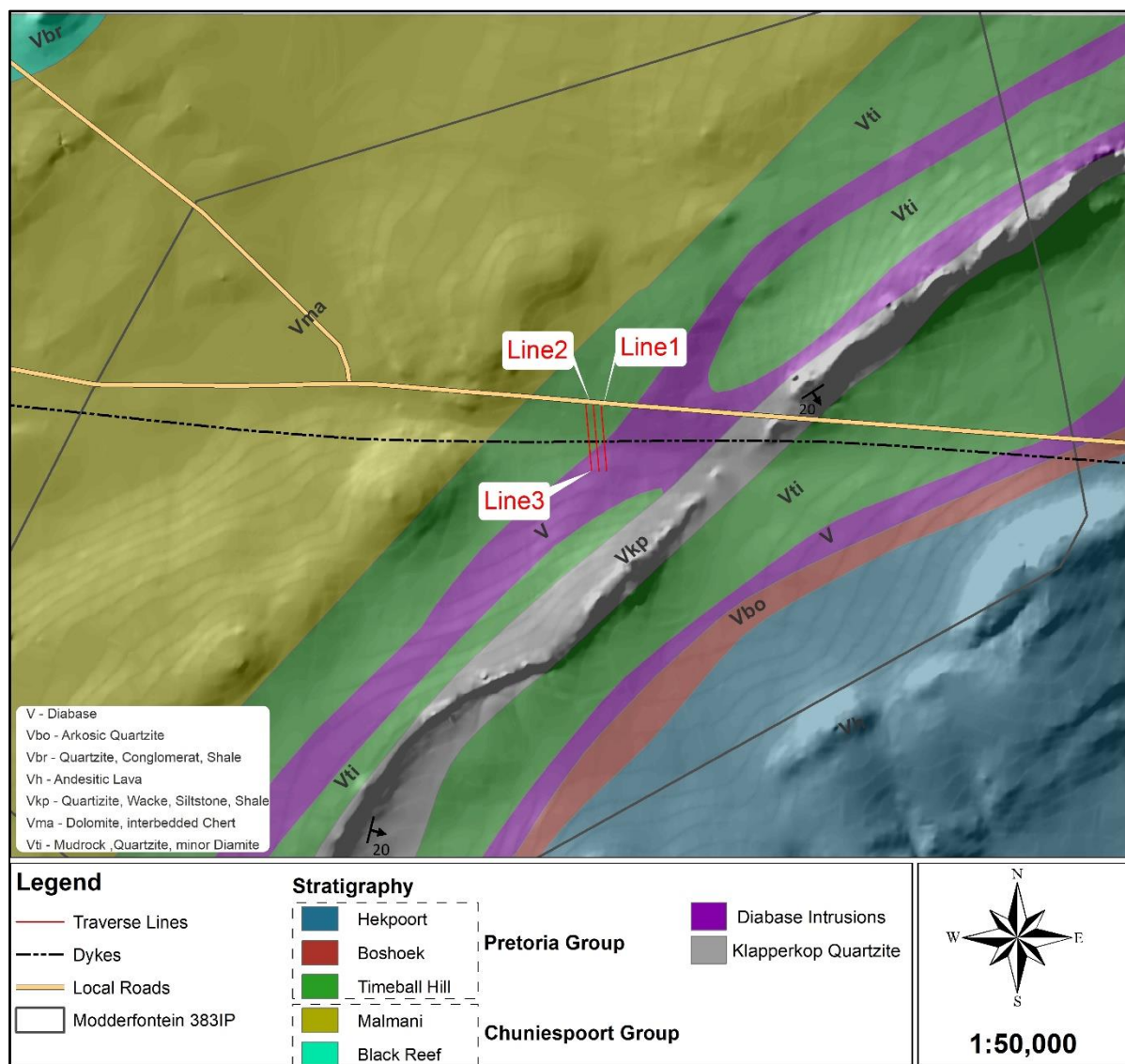


Figure 3-3: The regional geology that occurs in the vicinity of Modderfontein 383IP.

All the above mentioned rocks form part of the Timeball Hill Formation, and more specifically, the Klapperkop Quartzite Member. Other rocks that occur in the study area include andesite of the Hekpoort Formation, dolomite from the Chuniespoort Group as well as siltstone from the Klapperkop Quartzite Member. The best identifiable outcrop on the study area is quartzite from the Klapperkop Quartzite Member, which is oriented in a North-East, South-West direction (Figure 3-3). (Steyn, 2017)

3.2 Instrumentation used in this study

The regional geology map (Figure 3-3) was studied thoroughly to determine the location of the dolerite dyke. The traverse layout selected was a 50 m spacing between traverse lines.

During measurement, all three instruments followed the same path over all three traverses (namely Traverse 1, Traverse 2 and Traverse 3 as seen in Figure 3-3) from South to North. Each location where an instrumental reading was taken, is called station. The base station interval differs for each instrument according to instrumental methodology. Coordinates of each base station was obtained by using a GPS. During measurement, the instruments were not used simultaneously on the three traverses, as this can influence the result of each instrument (noise).

3.2.1 ABEM Terrameter LS 2

The ABEM Terrameter LS 2 measures the apparent ER variation over all three traverses. Measuring was conducted by means of a roll-along survey. As explained by ABEM (2016) the instrument utilizes four-electrode cables, accompanied with stainless steel electrodes that penetrate the surface. The electrode cables comprise a length of 105 m, consisting of electrode spacings that vary between 3 m, 5 m and 10 m x ± 21 take-outs (± 21 electrodes per cable/electrode positions). The electrode spacing and number take-outs depend on the type of study and depth of investigation.

The investigation depth of >60 m was chosen. Electrode cables of configuration (4 x 21) were chosen for a normal 2D ER survey, based on the roll-along method. The cables thus connected to 21 stainless steel electrodes with 5 m spacing between each electrode. At each station (during a roll-along survey) the instrument collects 748 data points. Each electrode must be wetted with water before measuring.

After each roll-along survey is completed, the data must be exported by making use of a USB flash drive. The ABEM Terrameter LS 2 exports the data in Dat. File format which then must be read into a data inversion program such as Res2dinv to display a readable pseudo section. Instrumental working and electrode layout are displayed in (Figure 3-4 and Figure 3-5). A

minimum of four people was chosen to help with the intensity of work that the ABEM Terrameter LS 2 demands.



Figure 3-4: ABEM Terrameter LS 2 displaying a pseudo section while measuring during the fieldwork of this study. (T van Wyk, 2019)



Figure 3-5: Stainless steel electrodes and cable connection during the fieldwork of this study. (T van Wyk, 2019).

3.2.2 Electro Magnetometer – Model 34-3

The EM 34-3 measures the electrical conductivity variation in the subsurface. The instrument consists of a transmitter and receiver as well as two copper coils. The instrument incorporates three inter-coil spacings (also known as reference cables) 10 m, 20 m and 40 m which enables the EM 34-3 to explore a depth range of 7.5 m-60 m. As the dyke was expected at a depth of ± 30 m, the 40 m inter-coil was chosen to be the most suitable for this study. In order to overlap the measurements and increase data resolution, the station spacing was chosen to be 20 m. The measured data was documented manually on a datasheet, along with the station number. Data was manually transferred to Microsoft Excel for further data processing.

The data processing for the EM 34-3 included interpolating the raw data into Surfer 14 to generate contoured maps of the HD and VD. The raw data were smoothened (using a three-point running average) to eliminate short-wavelength peaks. From the gathered data 2D graphs were plotted – conductivity (mS/m) over horizontal distance (m) – for each traverse (Appendix 5 to Appendix 7).

A minimum of two people was chosen to help conduct the measurements of the EM 34-3. Figure 3-6 display the equipment needed to survey with the EM 34-3.



Figure 3-6: Example of the EM 34-3 in the field during the fieldwork of this study (Author, 2019).

3.2.3 Proton Memory Magnetometer – Model G5

The G5 measures the magnetic intensity variation of the subsurface. The instrument was chosen for its ease to use, familiarity to the operators and its proven effectiveness in the field of subsurface geological and groundwater exploration.

A base station reading was taken before and after the survey started to determine the magnetic drift that may influence the readings in the form of noise. The instrument was manually tuned for

a magnetic field strength of 28 000 nT. The station spacing was chosen to be 10 m. The measured data was documented manually on a datasheet, along with the station number. Data was manually transferred to Microsoft Excel for further data processing. Only one person is needed to operate the G5 effectively. The field setup for the G5 can be seen in Figure 3-7. The display setup can be seen in Figure 3-8. All personal items (such as cell phones, pocketknives and wrist watches) that might contribute to noise were removed and stored away before the field procedures commenced.

The data were processed into a contoured map (Surfer14) of the magnetic intensity variation. The data were furthermore processed by smoothing the curves and eliminating short wavelength peaks. The smoothing of the data was done using a three-point average. The resultant data were plotted into 2D graphs of magnetic intensity (nT) against horizontal distance (m) (Appendix 10 to Appendix 11).

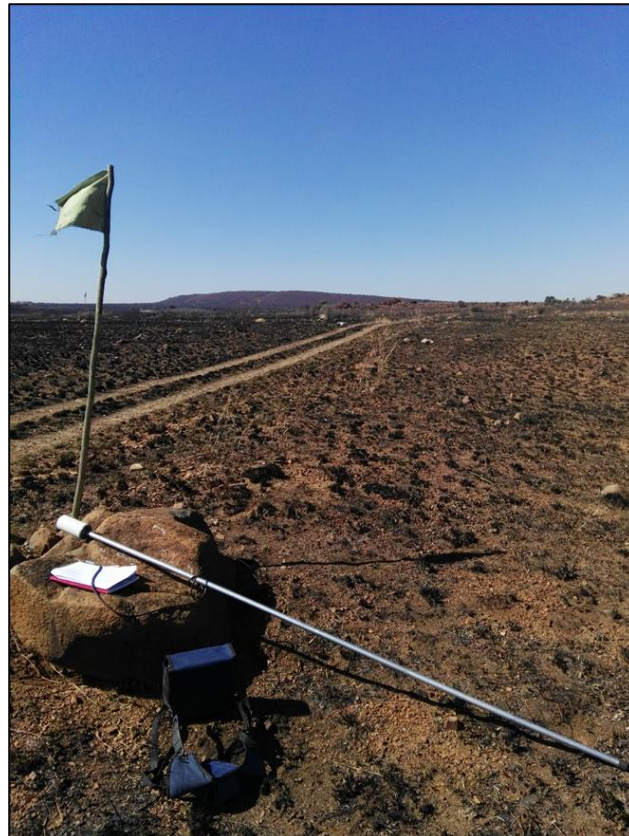


Figure 3-7: The G5 field-setup as was done for this project (Autor, 2018).

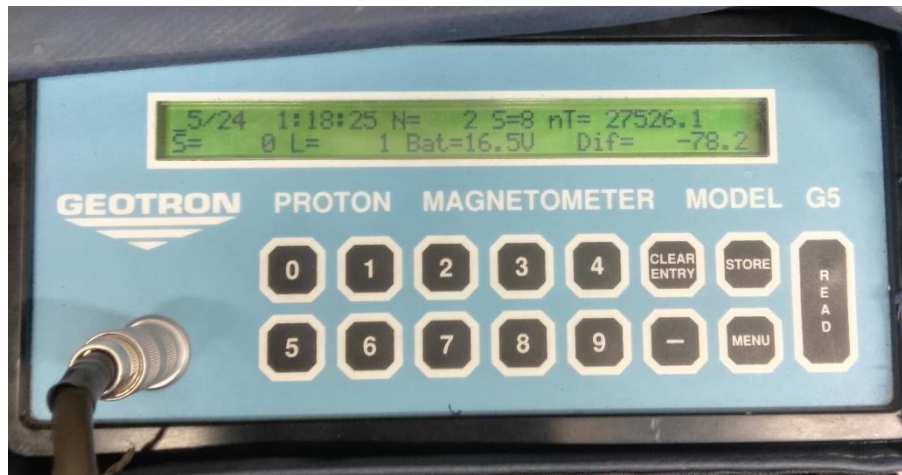


Figure 3-8: An example of the digital display after a measurement has been taken (Author, 2019)

CHAPTER 4 RESULTS AND DISCUSSION

The results of the ABEM Terrameter LS 2 (ER), EM 34-3, and G5 will be displayed and discussed. It is important to keep in mind that all these methods measure subsurface variations according to each methods' measuring unit:

- ER method measures apparent resistivity variation;
- EM method measures apparent conductivity variation;
- The magnetic method measures the magnetic field intensity variation.

4.1 ABEM Terrameter LS 2

4.1.1 Traverse 1

Figures 4-1, 4-2 and 4-3 display the pseudo sections of the apparent resistivity variation as it was measured by the ABEM Terrameter LS 2 as traversed during the fieldwork of this study. Ohm/m is used as the measurement of resistivity. This can be observed on the legend of the pseudo section. The scale indicates that higher resistivity is displayed in increasing red colour and lower resistivity is displayed in increasing blue colour. Based on the colour variation displayed by Figure 4-1, 4-2 and 4-3 that the ABEM Terrameter LS 2 was successful in mapping zones of higher-and lower resistivity.

By studying Figure 4-1 thoroughly, it is possible to identify five anomalies in the data set. Two of these are associated with a variation in low resistivity values (23.9-61.2 ohm/m) and the other three are associated with a variation in high resistivity value (1026-6713 ohm/m). The low resistivity anomalies are numbered 1 and 2 and encircled in black, while the three high resistivity anomalies are numbered 1, 2 and 3 - circled in red. Figure 4-1 furthermore displays a layer of very low resistivity values on the top of the Pseudo section. With an increase in depth, Figure 4-1 displays a gradual increase in resistivity.

The first anomaly numbered and encircled in black is a natural water channel as documented during the fieldwork. There is some uncertainty revolving around this water channel as it is unclear if it has been made by previous farmers as a waterway, drainage line or if it formed naturally as a natural drainage line. The second anomaly numbered (2) and encircled in black, is associated with a weathered zone that formed South of the dolerite dyke.

Molaba (2017) and Chandra *et al.* (2020) showed that during crystallisation of the intrusive dolerite dyke, cracks and fissures form at the contact between the dyke and the surrounding strata. These cracks and fissures may become the host medium for groundwater infiltration which initiates the

process of weathering. Molaba (2017) and Chandra *et al.* (2020) describes that weathered-and fractured areas are known for lower resistivities as these areas are prone to be filled with groundwater. The second anomaly numbered (2) and encircled in black is therefore considered to represent a weathered zone.

The three anomalies numbered and encircled in red is expected to be the result of the geological variation. The first of these is expected to be a quartzite layer as random outcrops of quartzite were encountered during the fieldwork for this study. The random outcrops were only encountered to the North and South of the survey area, not in the middle. This anomaly also displays very high values of resistivity ($>1\ 026\ \text{ohm/m}$) which corresponds to prior knowledge that quartzite, according to Milsom (2003) and Reynolds (2011) is associated with high values of resistivity. This statement is further strengthened by the presence of the Klapperkop Quartzite Member which form part of the immediate geology of the study area.

Furthermore, Molaba (2017) stated that it can be expected that there is a gradual increase in resistivity with depth, due to an increase in lithostatic pressure and possible increasing temperature. This might be the cause of the second red anomaly.

The third anomaly encircled in red is expected to be the dolerite dyke, since the horizontal location of the anomaly corresponds with the location where the dyke is expected (Figure 3-3). The amount of resistivity that the anomaly display is also very high ($>1\ 026\ \text{ohm/m}$), which corresponds to the resistivity values provided by Milsom (2003) and Reynolds (2011).

During the fieldwork of this study, it was noted that the surface soil resembled a dark brown colour that was dry and cracked, thus possibly indicating high clay content. It is, therefore, possible that the.

Milsom (2003) and Reynolds (2011) mentioned that clayey soils are associated with very low resistivities (1-100 ohm/m). A zone of very low resistivity (0-30 ohm/m) that is visible on top of the pseudo section (displayed in blue), are therefore considered to indicate high clay content in the soil. Fey (2010) showed that 15%-30% of the soil in the study are vertic soils, thus indicating the possibility of high clay content in the A-horizon.

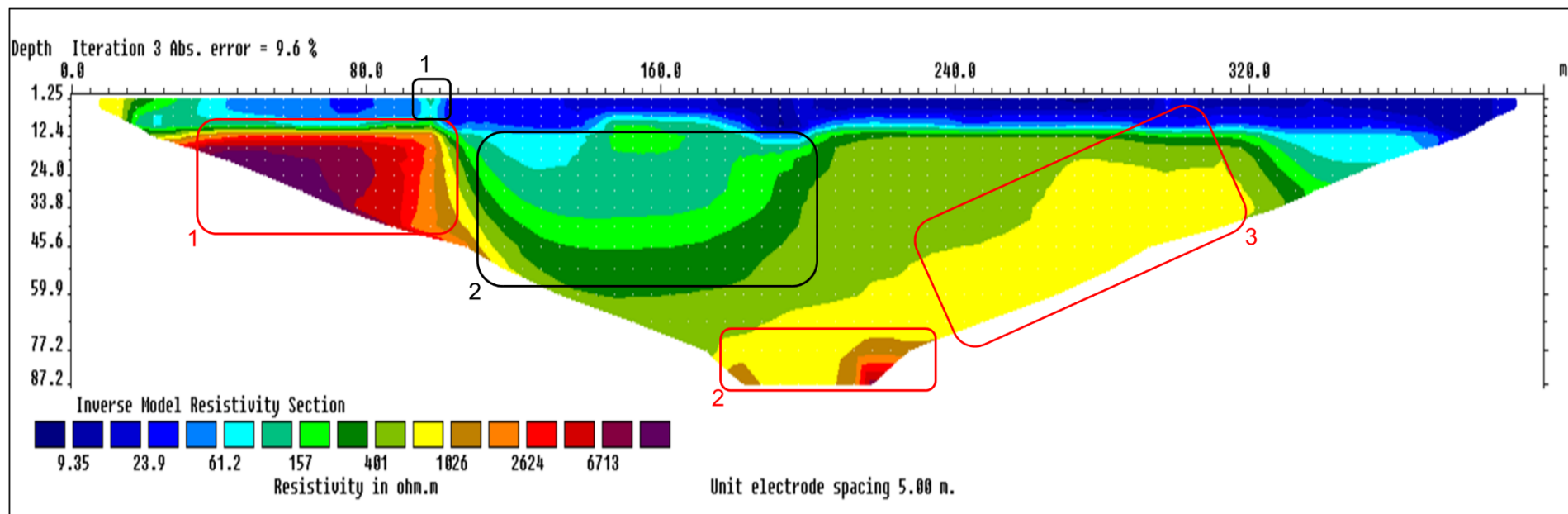


Figure 4-1: Pseudo Section of the apparent resistivity data as measured by the ABEM Terrameter LS 2 on "Traverse 1". (Res2Dinv, 2019)

4.1.2 Traverse 2

As previously mentioned, Figure 4-2 displays the pseudo section of the second traverse as measured by the ABEM Terrameter LS2 during the fieldwork of this study.

There are, however, minor differences in the display of the five anomalies. It seems that the natural water channel had a much bigger influence in the data of traverse two than that of traverse one. The weathered zone also seems to have extended deeper and wider when compared with Figure 4-1. The reason for this might be that the dyke is less visible in Figure 4-2, compared with Figure 4-1. It would seem as if the dyke is found deeper in Figure 4-2. The reason for this is explained by Steyn (2017) that this dyke forms part of the Pilanesberg dyke swarm that was activated by the Vredefort meteorite impact event. The possibility exists that the dyke experienced some form of deformation during the impact event that might explain the greater depth at which the dyke is found. The quartzite anomaly also displays less significant in Figure 4-2 when compared to Figure 4-1. It is unclear as to why the quartzite layer displays differently. It may be due to a directional change in the quartzite formation between traverse 1 and traverse two. The effects of lithostatic pressure and possible increasing temperature are also still visible in Figure 4-2. As in Figure 4-1, the clay layer (blue zone on top of the pseudo section is also clearly visible in Figure 4-2.

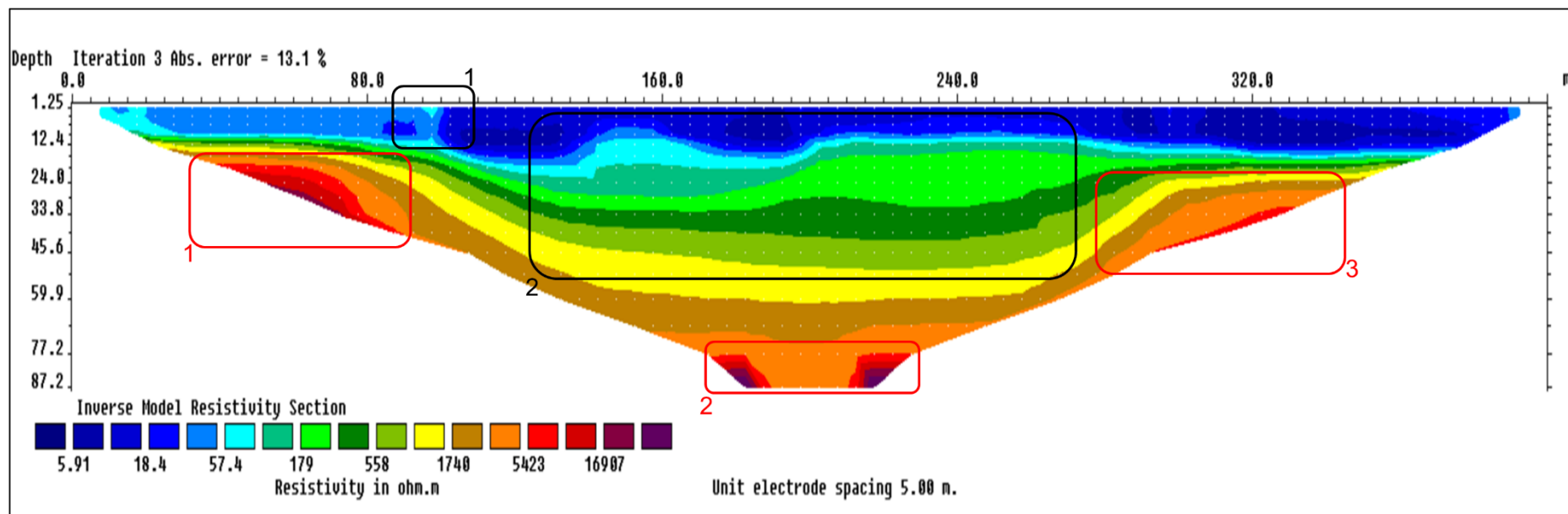


Figure 4-2: Pseudo Section of the apparent resistivity data as measured by the ABEM Terrameter LS 2 on Traverse 2. (Res2Dinv, 2019)

4.1.3 Traverse 3

As previously mentioned, Figure 4-3 display the pseudo section of the third traverse as measured by the ABEM Terrameter LS2 during the fieldwork of this study.

There are, however (as is the case with Figure 4-2) minor differences in the display of the five anomalies. It seems that the natural water channel displays very similarly as in Figure 4-1. The quartzite layer also displays a similar geometry than that of Traverse 1, however still less when compared with Figure 4-1. The weathered zone extended even wider in Figure 4-3 when compared with Figure 4-2 and the dolerite dyke also display even less. As in Figure 4-1 and Figure 4-2 the clay layer (blue zone on top of the pseudo section) is ever-present throughout all three traverses. The reason for the possible increase in depth of the dolerite dyke, is the same as explained for Traverse 2.

As previously mentioned, it is still unclear as to the reason for the variation in the display of the quartzite layer, however, this exceeds the scope of this study. The reason for the extension and deepening of the weathered zone is still due to the visible deepening of the dolerite dyke.

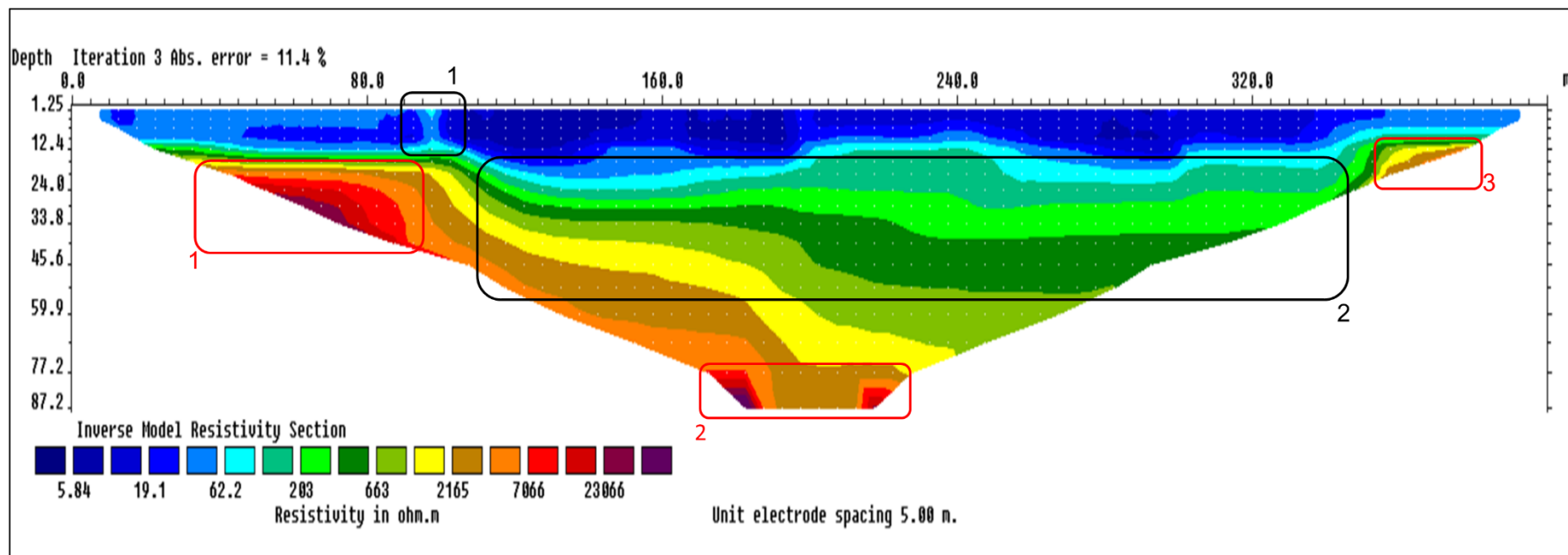


Figure 4-3: Pseudo Section of the apparent resistivity data as measured by the ABEM Terrameter LS 2 on Traverse 3. (Res2Dinv, 2019)

4.2 EM 34-3

4.2.1 Horizontal Dipole

Figure 4-4 display the contoured map of the apparent conductivity variation as measured by the EM 34-3 for the HD. The electrical conductivity was measured in mS/m. Zones of different conductivity are portrayed by different colours of intensity, as indicated by the scale displayed on Figure 4-4. Based on the colour variation displayed in Figure 4-4 it is evident that EM 34-3 was successful in measuring varying zones of electrical conductivity.

As stated by André and Lambot (2014), McNeill (1980), Milsom (2003) and (Reynolds (2011) the HD configuration is very sensitive to shallow subsurface anomalies as this configuration's response is maximum at the surface and decreases as the depth increases. It can thus be expected that the HD would portray shallow surface anomalies. Figure 4-4 display an anomaly representing high conductivity values (22 mS/m-26 mS/m). This anomaly is encircled in red. It can also be seen that this anomaly extends in an East-West direction. It is thus safe to assume that the anomaly is not limited to the surveyed area. It is, however, noted that the anomaly does not extend in a North-South direction. By further examination of Figure 4-4, it is noted that there are two smaller anomalies housed within the main anomaly. These two smaller anomalies represent much higher conductivity (28 mS/m-34 mS/m) compared with the main anomaly. These two anomalies are numbered (1 & 2) and encircled in black.

The only other surface feature identified in the resistivity data that compare with that of Figure 4-4 is the aforementioned clay layer. According to McNeill (1980) and Milsom (2003), clay tends to be a very good conductor as clay have a very small particle size, thus resulting in having a very big surface area per unit volume which absorb a great number of ions. These absorbed ions create an ionic charge, rather than electrolytic charge. (McNeill 1980; Milsom, 2003)

The two anomalies numbered (1 & 2) and encircled in red, is expected to be zones of deeper clay content or perhaps zones containing groundwater. These two anomalies compare very well with Figure 4-1 to Figure 4-3 as they also indicate varying zones of very low resistivity in comparable surface locations.

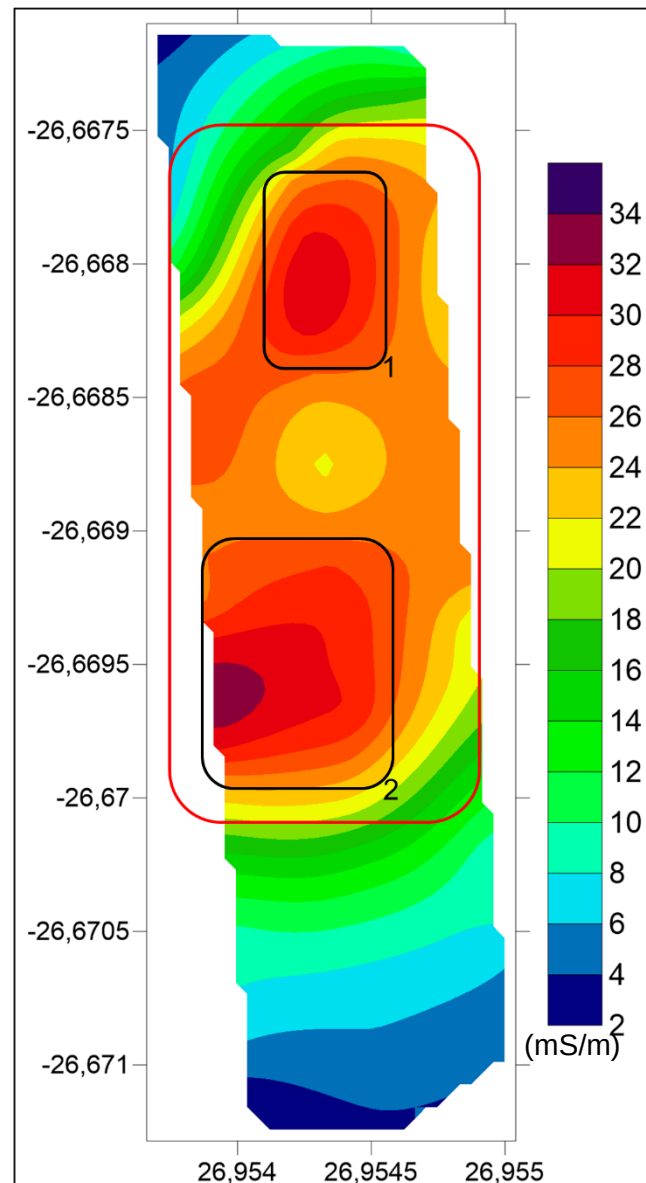


Figure 4-4: Interpolated results (all three traverses) of the EM 34-3 for the HD, as measured during the fieldwork of this study. (Surfer, 2020)

4.2.2 Vertical Dipole

Figure 4-5 display the contoured map of the apparent conductivity variation as measured by the EM 34-3 for the VD. The electrical conductivity was measured in mS/m. Zones of different conductivity are portrayed by different colours of intensity as indicated by the scale displayed on Figure 4-5. Based on the colour variation displayed in Figure 4-5, it is evident that EM 34-3 was successful in measuring varying zones of electrical conductivity.

André and Lambot (2014), McNeill (1980), Milsom (2003) and Reynolds (2011) stated that the relative intensity of the VD increases with depth, with minimal intensity at the surface. The VD configuration is thus most sensitive to deep subsurface anomalies. Figure 4-5 display four

anomalies numbered (1-4) and encircled in black. All four of these anomalies are associated with higher electrical conductivity (4 mS/m-14 mS/m).

It is unclear what the first anomaly might be as the location of the anomaly do not correspond to any of the previous anomalies measured by the ER data.

The second anomaly is expected to be the dolerite dyke as its horizontal location corresponds with that of the predetermined location of the dyke, as well as that portrayed by the ER data. As discussed in Electromagnetic Methods, Makhokha and Fourie (2015) state that due to the conductivity contrast that occur between dolerite dykes and the surrounding geology, dolerite dykes tend to display a higher conductivity than the surrounding geological strata.

The third anomaly is expected to be the weathered zone as its horizontal location corresponds with that portrayed by the ER data. This statement is further strengthened by Molaba (2017) that states that subsurface weathered zones will display high conductivity. The reason for this is electrolytic conduction caused by groundwater penetrating the weathered zone (Molaba, 2017).

The fourth anomaly is expected to be the natural water channel as its location correspond very well with the location determined during the fieldwork of this study as well as that portrayed by the ER data. This statement is strengthened by Molaba (2017) that describes there are electrolytic conduction that are associated with infiltrated groundwater.

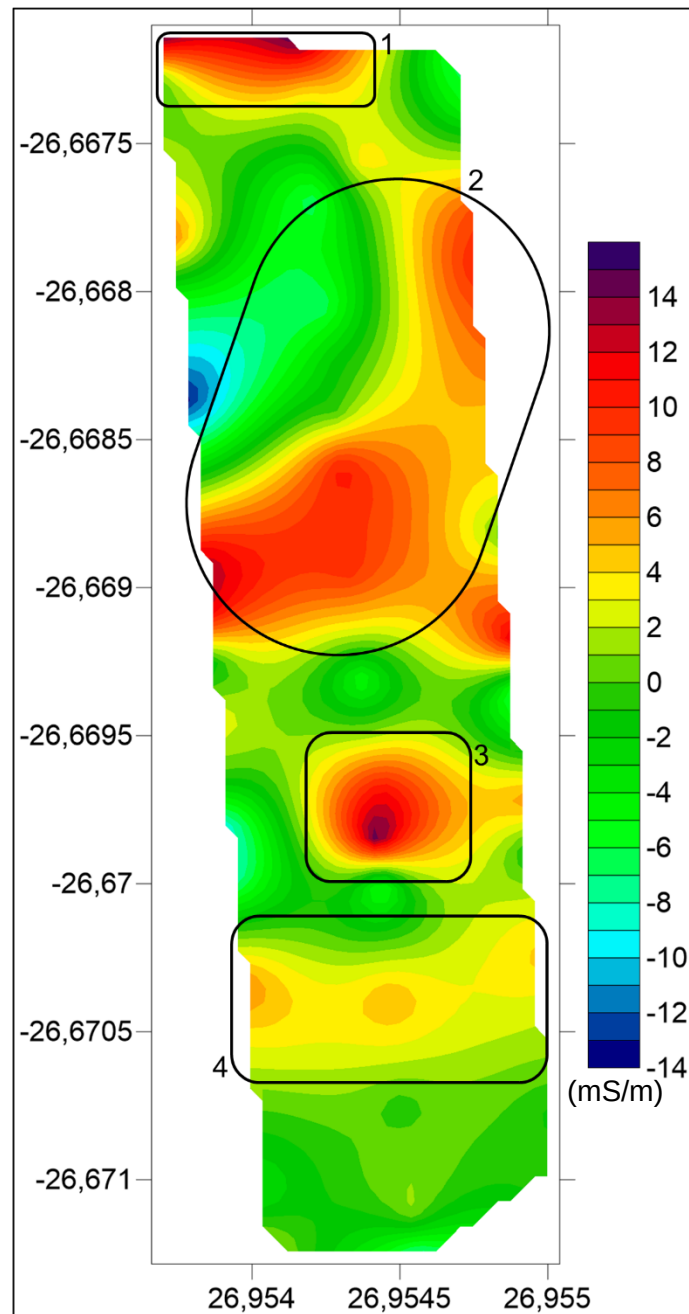


Figure 4-5: Interpolated results (all three traverses) of the EM 34-3 for the VD, as measured during the fieldwork of this study. (Surfer, 2020)

4.3 Proton Memory Magnetometer – Model G5

Bevan (2006) is of meaning that there are three types of analysis to be applied when interpreting magnetic results. These three include anomaly description, archaeological identification and analytical interpretation. An anomaly description summarises and counts the number of anomalies in a specific survey, it may include some categorisation of the shape and amplitude of the anomaly. Archaeological identification is based on archaeological remnants, which require good background knowledge of archaeology. An analytical interpretation requires geophysical knowledge with regards to quantitative and qualitative anomaly

description as well as the susceptibility of rocks and minerals. (Roux *et al.*, 1980 & Bevan, 2006)

The magnetic data of this study were interpreted through quantitative (shape and size) and qualitative (depth, size, shape, dip angle and susceptibility) methods. Appendix 11 indicates the qualitative properties.

Figure 4-6 display a contoured map (produced by Surfer 14) of the variation in magnetic intensity as it was measured during the fieldwork of this project. The magnetic intensity was measured in nT. Zones of varying magnetic intensity are portrayed by different colours of intensity as indicated by the scale. Based on the colour variation displayed by Figure 4-6, it is evident that the G5 was successful in measuring varying zones of magnetic susceptibility.

By further studying Figure 4-6, two anomalies are visible, one of which is associated with low values (27 600-27 800 nT) of magnetic intensity (numbered and encircled in black). The other anomaly is associated with high values (28 500-29 000 nT) of magnetic intensity (numbered and encircled in red).

The anomaly numbered (1) and encircled in black is associated with the weathered zone that is also clearly visible in Traverse 1 of the ER data. Syukri *et al.* (2017) showed that weathered zones are associated with low values of magnetic susceptibility. This statement is further strengthened by the similar comparison that can be seen between the location of the weathered zone as indicated by the ER results and the location indicated by Figure 4-6.

The anomaly numbered (1) and encircled in red is expected to be the dolerite dyke as it displays high values of magnetic intensity in the vicinity that corresponds with the predetermined location of the dyke Makhoka & Fourie (2015) stated that dolerite dykes are generally strongly magnetic. Reynolds (2011) also mentioned that basic and ultra-basic igneous rocks have the highest magnetic intensities. Upon further investigation of the anomaly, it is noted that the anomaly does not align linearly, but rather curve in an East-West direction. This statement is proven by the Zero Point of each traverse (indicating the centre of the dyke as encountered on each traverse). The Zero line was determined using the E-line method (Appendix 11). The Zero Point of the dyke for each traverse was thus determined to be ± 320 m for the first traverse and ± 350 m for the second – and third traverses.

Appendix 10 present a line graph that displays a 2D profile of the magnetic results that is portrayed in Figure 4-6. Roux *et al.* (1980) described the shape of anomalies in order to determine the anomaly's depth and dip angle. As is evident from Appendix 10, the anomaly takes the shape of a thin dyke in the Southern Hemisphere (South Africa) with the strike into the page (dipping to the South) at 60° .

As can be seen in Appendix 10, the maximum height of the amplitudes of the anomaly over three traverses is different, thus possibly indicating a different depth underneath the surface. The various depths (z) of the anomaly over all three traverses have been determined using Sokolov's method (S). The method is based on determining the intersections between the maximum slope, the Zero Line and the horizontal tangent to the curve maximum (Appendix 11). The various depths have thus been determined to be ± 24 m for the first traverse and ± 30 m for the second – and third traverses. It should be noted how Bevan (2006) described that when determining the depth of the anomaly on this manner, the depth includes the actual depth of the anomaly as well as the height of the sensor above the ground. It is thus possible to extract 2 m (pole length) from each depth. It is also important to keep in mind that the depth is the depth from the surface to the top of the anomaly (thus the shallowest part of the anomaly). (Roux *et al.*, 1980; Milsom, 2003; Bevan, 2006)

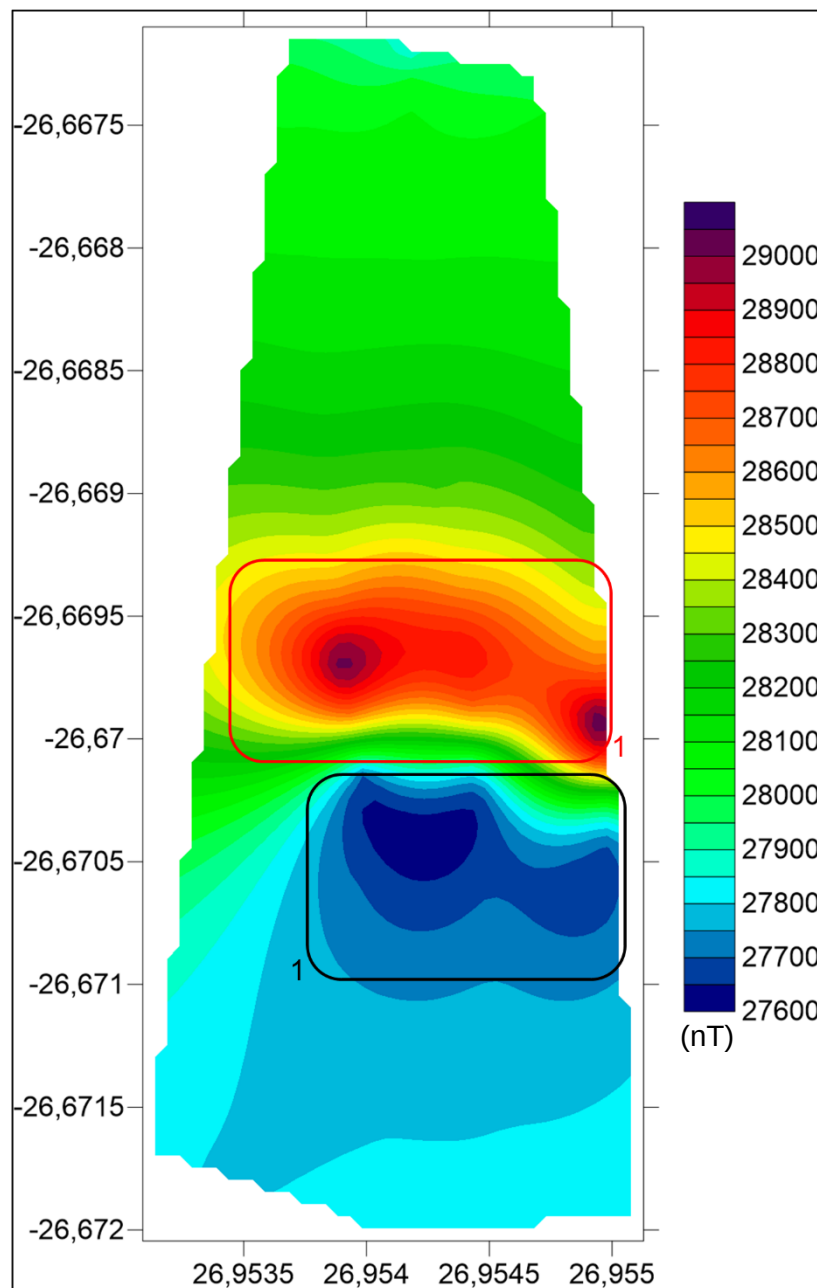


Figure 4-6: The contour map of the magnetic intensity as measured by the Proton Memory Magnetometer (G5). (Surfer, 2020)

The susceptibility of the dolerite dyke was calculated by making use of Equation 56 as given by Roux *et al.* (1980):

$$k = \frac{0.5 \times 4\pi \times Z \times \Delta T}{W \times H_T}$$

$$\therefore = \frac{0.5 \times 4\pi \times 28m \times 960nT}{46.67m \times 28000nT}$$

$$\therefore k = 0.129 \text{ SI units}$$

Equation 56: Susceptibility of the dolerite dyke (Roux, 1980)

Where k represents the susceptibility (SI. Units), Z represents the average depth (m), ΔT represents the total amplitude of the magnetic field of the anomaly (nT), W represents the average width of the body (m) and H_T represents The Earth's magnetic field (nT)

CHAPTER 5 CONCLUSION

Geophysical surveying for groundwater exploration tends to focus very often on hard-rock crystalline basement terrains. These terrains are popular for secondary porosity and permeability which occur in faults, fractures, dyke contacts as well as deeply weathered zones. Some of the geophysical methods that are very popular for conducting groundwater exploration projects include ER, EM and MAG. All of these methods have been utilised during this project, for the main purpose of delineating a dolerite dyke. It is generally accepted that the best results are generated when more than one geophysical method is used. However, geophysical methods should be used together, geophysical surveys tend to be very expensive. Groundwater exploration projects might not have a very big budget for geophysics. It is thus important to know which geophysical method would be most successful when the project involves delineating a dolerite dyke.

The following objectives were met by identifying the anomalies as displayed by the data gathered by the four instruments. These objectives include conducting a preliminary site visit and determining the location for traversing. Temporary employment of capable scientists that helped to conduct the fieldwork. During the fieldwork, every instrument was utilised to measure all three traverses individually. All the measured data were successfully exported to a personal computer for further processing. The data were further processed into an analysable format for further processing. The successful completion of these objectives resulted in discussing the data and delivering the conclusions.

It is concluded that the ABEM Terrameter LS 2, EM 34-3 and Proton Memory Magnetometer (G5) delivered successful results that corresponded with all known information. It is further concluded that the results were comparable with one another. By comparing the results of these three instruments, it was determined that a weathering zone, a quartzite layer, clay layer and dolerite dyke were successfully identified and delineated.

CHAPTER 6 RECOMMENDATIONS

Successful results were obtained by the ABEM Terrameter LS 2, the EM 34-3 and the Proton Memory Magnetometer (G5). This study however only focussed on delineating a dolerite dyke, it is thus recommended that these instruments be further tested on other geological features such as dolerite sills.

Based on the data provided by this study a drilling project is recommended at the site.

BIBLIOGRAPHY

- André, F. & Lambot, S. 2014. Intrinsic modelling of near-field electromagnetic induction antennas for layered medium characterization. *IEEE Transactions on Geoscience and Remote Sensing*, 52(11):7457-7469.
- Beamish, D. 2011. Low induction number, ground conductivity meters: A correction procedure in the absence of magnetic effects. *Journal of Applied Geophysics*, 75(2):244-253.
- Bevan, B. 2006. Understanding magnetic maps. *Unpublished manuscript, Geosight, Weems, Virginia*.
- Blignaut, J. & Van Heerden, J. 2009. The impact of water scarcity on economic development initiatives. *Water South Africa* 35(4).
- Brantax. 2019. *Frequency domain (fd) and time-domain (td)*
<http://www.brantax.com/brantax-services/services/geophysics/geophysical-methods/electromagnetic/frequency-domain-fd-and-time-domain-td/> 22 Nov. 2019.
- Breiner, S. 1973. *Applications manual for portable magnetometers*. 395. Geometrics Sunnyvale, California.
- Breiner, S. 1999. *Applications manual for portable magnetometers*: San Jose, Geometrics. Inc.
- British Geological Survey. 2020. <https://www.bgs.ac.uk/geological-research/> accessed 13 May 2020
- Catuneanu, O. & Eriksson, P.G. 2002. Sequence stratigraphy of the Precambrian Rooihogte–Timeball Hill rift succession, Transvaal Basin, South Africa. *Sedimentary Geology*, 147(1-2):71-88.
- Chandra, S., Dewandel, B., Kumar, D. & Ahmed, S. Electrical Resistivity Modeling of Quartz Reef and Dolerite Dyke in Granite Hard Rocks.
- Chegbelah, L.P., Akudago, J.A., Nishigaki, M. & Edusei, S.N.K. 2009. Electromagnetic geophysical survey for groundwater exploration in the Voltaian of northern Ghana. *Journal of environmental hydrology*, 17:1-16.

- Cochran, J.F. & Heinrich, B. 2004. *Applications of Maxwell's Equations*. John F. Cochran, Bretislav Heinrich.
- Cyril, A.G. 2014. Geophysical investigation of groundwater potential of Kongo Campus, ABU, Zaria-Nigeria. *European Journal of Educational Studies*, 7(1):1-7.
- Fey, M. 2010. *Soils of South Africa*. Cambridge University Press.
- Frischknecht, F.C., Labson, V., Spies, B.R. & Anderson, W.L. 1991. Profiling methods using small sources. *Electromagnetic methods in applied geophysics*, 2(part A):105-270.
- Gan, F., Chen, Y., Zhao, W., Chen, Y. & Liu, W. 2013. Integrated Geophysical Methods for Groundwater Exploration in a Karst Area with or Without Thin Cover—A Case Study from Tai'an City, Shandong Province, China.
- Garcia, X. & Jones, A.G. 2002. Atmospheric sources for audio-magnetotelluric (AMT) sounding. *Geophysics*, 67(2):448-458.
- GEONICS Limited. 2003. Geophysical instrumentation for exploration and the environment. Unit 8. <http://www.geonics.com> Date of access: 15 Oct. 2019.
- Geotron. 2014. Geotron Model G5 Proton Memory Magnetometer <http://geotron.co.za/new-%20site/magnetometer.htm> 10 Jan. 2019
- Goldman, M. & Neubauer, F. 1994. Groundwater exploration using integrated geophysical techniques. *Surveys in geophysics*, 15(3):331-361.
- Goldscheider, N. & Drew, D. 2014. *Methods in Karst hydrogeology: IAH: International Contributions to Hydrogeology*, 26. Crc Press.
- Gubbins, D. & Herrero-Bervera, E. 2007. *Encyclopedia of geomagnetism and paleomagnetism*. Springer Science & Business Media.
- Guenther, B. 2015. *Modern Optics*. Oxford University Press.
- Hasbrouck, J. & Gp, R. 2003. Deep groundwater exploration using geophysics. *Southwest Hydrology*, 2(4):6-7.
- Herman, R. 2001. An introduction to electrical resistivity in geophysics. *American Journal of Physics*, 69(9):943-952.
- Hermance, J.F. & Thayer, R.E. 1975. The telluric-magnetotelluric method. *Geophysics*,

40(4):664-668.

Hlatywayo, D.J. & Sakala, E. 2014. International Journal of Geography and Geology. *International Journal*, 3(1):9-29.

Johnson, M., Anhaeuser, C. & Thomas, R.J. 2006. The Geology of South Africa. In.: Geological Society of South Africa.

Jones, A.G., Evans, R.L., Muller, M.R., Hamilton, M.P., Miensoopust, M.P., Garcia, X., ...

Fourie, C. 2009. Area selection for diamonds using magnetotellurics: Examples from southern Africa. *Lithos*, 112:83-92.

Kato, Y. & Kikuchi, T. 1950. On the Phase Difference of Earth Current Induced by the Changes of the Earth's Magnetic Field.(Part I). *Science reports of the Tohoku University. Ser. 5, Geophysics*, 2(2):138-141.

Keller, G.V. & Frischknecht, F.C. 1966. Electrical methods in geophysical prospecting.

Koch, J. 2014. *Migration and gamma ray assessment of uranium on a gold tailings disposal facility*.

Koehler, J.A. 2012. Proton precession magnetometers, revision 3.

Kruger, A. 2004. *Climate of South Africa: climate regions*. South African Weather Service.

Lenhardt, N., Eriksson, P.G., Catuneanu, O. & Bumby, A.J. 2012. Nature of and controls on volcanism in the ca. 2.32–2.06 Ga Pretoria Group, Transvaal Supergroup, Kaapvaal craton, South Africa. *Precambrian Research*, 214:106-123.

Lowrie, W. 2007. Fundamentals of Geophysics. Published in the United States of America by Cambridge University Press. *New York*.

MacDonald, A., Davies, J. & Peart, R. 2001. Geophysical methods for locating groundwater in low permeability sedimentary rocks: examples from southeast Nigeria. *Journal of African Earth Sciences*, 32(1):115-131.

Makhokha, D. & Fourie, F. 2016. *A systematic approach to the interpretation of conductivity anomalies across intrusive dolerite dykes and sills in the Karoo Supergroup*. MSc thesis. University of the Free State, Bloemfontein.

McCarthy, T. 2013. *The story of earth & life: a southern African perspective on a 4.6-billion-*

year journey. Penguin Random House South Africa.

McDougall, J.M., Tarling, D.H. & Warren, S.E. 1983. The magnetic sourcing of obsidian samples from Mediterranean and Near Eastern sources. *Journal of Archaeological Science*, 10(5):441-452.

McNeill, J. 1980. Electromagnetic terrain conductivity measurement at low induction numbers.

McNeill, J. 1988. Advances in electromagnetic methods for groundwater studies. In. 1st EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems. European Association of Geoscientists & Engineers. pp. cp-214-00003.

McNeill, J.D. 1990. Use of electromagnetic methods for groundwater studies. *Geotechnical and environmental geophysics*, 1(5):191-218.

Mekonnen, M.M. & Hoekstra, A.Y. 2016. Four billion people facing severe water scarcity. *Science advances*, 2(2):e1500323.

Milsom, J. 2003. *Field geophysics*. 25. John Wiley and Sons.

Otieno, F.A. & Ochieng, G.M. 2004. Water management tools as a means of averting a possible water scarcity in South Africa by the year 2025. *Water Sa*, 30(5):120-124.

Palacky, G., Ritsema, I. & De Jong, S. 1981. Electromagnetic prospecting for groundwater in Precambrian terrains in the Republic of Upper Volta. *Geophysical prospecting*, 29(6):932-955.

Pereira, L.S., Oweis, T. & Zairi, A. 2002. Irrigation management under water scarcity.

PQWT. 2017. *Water detector case share*. Hunan: Hunan Puqi Geological Exploration Equipment Institute. *Agricultural water management*, 57(3):175-206.

Ranganai, R. & Ebinger, C. 2008. Aeromagnetic and Landsat TM structural interpretation for identifying regional groundwater exploration targets, south-central Zimbabwe Craton. *Journal of Applied Geophysics*, 65(2):73-83.

Reynolds, J.M. 2011. *An introduction to applied and environmental geophysics*. John Wiley & Sons.

Rijsberman, F.R. 2006. Water scarcity: fact or fiction? *Agricultural water management*, 80(1-

3):5-22.

Ritz, M., Descloitres, M., Robineau, B. & Courteaud, M. 1997. Audiomagnetotelluric prospecting for groundwater in the Baril coastal area, Piton de la Fournaise Volcano, Reunion Island. *Geophysics*, 62(3):758-762.

Roux, A., Biesheuvel, K., Corner, B. & Goddard, P. 1980. Geophysical field manual for technicians. *The magnetic method*, (1).

Ruhunusiri, W. & Jayananda, M. 2008. Construction of a proton magnetometer. In. Proceedings of the Technical Sessions.

Rumpf, C. 2012. Development and Investigation of a Hybrid Navigation Solution for a Lander Demonstrator.

Rumpf, H. 2012. *Particle technology*. 1. Springer Science & Business Media.

Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A. & Richard, G. 2005. Electrical resistivity survey in soil science: a review. *Soil and Tillage research*, 83(2):173-193.

Samsudin, A.R., Rahman, M.T.A., Rahim, B.-e.E., Yaacop, R., Yaacob, L.M. & WZW. Resistivity surveying of contaminated municipal landfill site in taiping town, perak, nw peninsular, Malaysia.

Santos, F.A.M. 2004. 1-D laterally constrained inversion of EM34 profiling data. *Journal of Applied Geophysics*, 56(2):123-134.

Schlinger, C.M. 1990. Magnetometer and gradiometer surveys for detection of underground storage tanks. *Bulletin of the Association of Engineering Geologists*, 27(1):37-50.

Sharma, P.V. 1985. Geophysical methods in geology.

Sharma, S. & Baranwal, V. 2005. Delineation of groundwater-bearing fracture zones in a hard rock area integrating very low frequency electromagnetic and resistivity data. *Journal of Applied geophysics*, 57(2):155-166.

Shishaye, H. & Abdi, S. 2016. Groundwater exploration for water well site locations using geophysical survey methods. *Hydrol. Curr. Res*, 7(1).

Steyn, CG. 2017. Modderfontein 838 IP geophysical report: identify drill locations for water supply. (Unpublished Work).

- Strangway, D., Swift Jr, C. & Holmer, R. 1973. The application of audio-frequency magnetotellurics (AMT) to mineral exploration. *Geophysics*, 38(6):1159-1175.
- Sultan, S., Mekhemer, H.M., Santos, F. & Alla, M.A. 2009. Geophysical measurements for subsurface mapping and groundwater exploration at the central part of the Sinai Peninsula, Egypt. *Arabian journal for science and engineering*, 34(1):103.
- Telford, W., Geldart, L., Sheriff, R. & Keys, D. 1976. Applied Geophysics Cambridge University Press. *Cambridge*, 860.
- Terrameter, L. 2012. Instruction Manual. ABEM.
- Thébault, E., Finlay, C.C., Beggan, C.D., Alken, P., Aubert, J., Barrois, O., ... Brocco, L. 2015. International geomagnetic reference field: the 12th generation. *Earth, Planets and Space*, 67(1):79.
- Thidé, B. 2004. *Electromagnetic field theory*. Upsilon books Uppsala.
- Tikhonov, A. 1950. On determining electrical characteristics of the deep layers of the Earth's crust. In. Doklady. Citeseer. pp. 295-297.
- Valenta, J. 2015. Introduction to geophysics—lecture notes. *Development corporation, Czech Republic*.
- Van Zijl, J.S.V. 1977. *A practical manual on the resistivity method*. National Physical Research Laboratory, CSIR.
- Van Zijl, J.S.V. 1986. *The Electromagnetic method*. South African Geophysical Association c/o BPI Geophysics, United States Hydrographic Office (U.S.H.O.)
- Van Zijl, J. .V. 1987. *A Practical manual on the resistivity method*. 2nd ed. Pretoria: National Physical Research Laboratory Council of Scientific and Industrial Research.
- Vozoff, K. 1972. The magnetotelluric method in the exploration of sedimentary basins. *Geophysics*, 37(1):98-141.
- Vozoff, K. 1990. Magnetotellurics: Principles and practice. *Proceedings of the Indian Academy of Sciences-Earth and Planetary Sciences*, 99(4):441-471.
- Wester, P., Merrey, D.J. & De Lange, M. 2003. Boundaries of consent: Stakeholder representation in river basin management in Mexico and South Africa. *World Development*,

31(5):797-812.

Zhdanov, M.S. 2010. Electromagnetic geophysics: Notes from the past and the road ahead. *Geophysics*, 75(5):75A49-75A66.

Zohdy, A.A., Eaton, G.P. & Mabey, D.R. 1974. Application of surface geophysics to ground-water investigations. United States Geological Survey (USGS)

APPENDICES

```

Project11 Schlumberger_1
5.00
11
7
Type of measurement (0=app.resistivity,1=resistance)
1
1198
2
0
4 0.00 0.00 15.00 0.00 5.00 0.00 10.00 0.00 2.32637
4 5.00 0.00 20.00 0.00 10.00 0.00 15.00 0.00 1.80039
4 0.00 0.00 25.00 0.00 10.00 0.00 15.00 0.00 0.844882
4 0.00 0.00 30.00 0.00 10.00 0.00 20.00 0.00 1.47944
4 5.00 0.00 30.00 0.00 15.00 0.00 20.00 0.00 0.944027
4 0.00 0.00 35.00 0.00 15.00 0.00 20.00 0.00 0.626495
4 10.00 0.00 25.00 0.00 15.00 0.00 20.00 0.00 2.19415
4 5.00 0.00 35.00 0.00 15.00 0.00 25.00 0.00 1.45767
4 5.00 0.00 40.00 0.00 20.00 0.00 25.00 0.00 0.545698

```

Appendix 1: The format (General Array) of the results for Traverse 2 as was extracted from the ABEM Terrameter LS 2 in the form of a data file. The whole document is not shown as 1198 measurements was taken during the roll-along survey.

As the data was interpolated using the Res2Dinv. the program, the data was formulated in a “General Array” format for the roll-along survey. The layout of the data is as follow:

MIXED.DAT file	Comments
Mixed array	Name of a survey line
1.0	Unit electrode spacing
11	Array type (11 for general array)
0	Array type, 0 non – specific
Type of measurement (0=app. Resistivity, 1=resistance)	Header
0	0 to indicate apparent resistivity
407	Number of data points
1	Type of x – location, 0 for the true horizontal distance

0	Flag for I.P. data, 0 for none (1 if present)
4 0.0 0.0 3.0 0.0 1.0 0.0 2.0 0.0 10.158	The format for each data point
4 1.0 0.0 4.0 0.0 2.0 0.0 3.0 0.0 10.168	"4" the number of electrodes used
4 2.0 0.0 5.0 0.0 3.0 0.0 4.0 0.0 10.184	X – and z – location of M1, M2, N1, N2
4 3.0 0.0 6.0 0.0 4.0 0.0 5.0 0.0 10.225	Apparent resistivity of the resistance value
4 4.0 0.0 7.0 0.0 5.0 0.0 6.0 0.0 10.337	
.....	Same format for all the other data points
0.0 0.0 0.0 0.0 0.0	Ends with a few zeros.

Appendix 2: For the Res2Dinv. Program to read data, it must be in the correct format. The user manual provides these formats for the different array types possible. For a roll along with survey, a normal "General Array" (Appendix 2) format must be used.

Appendix 3: The Grid report for the interpolation carried out for the results of the EM 34-3 (HD):

Gridding Report

Sat Oct 10 19:49:48 2020

Elapsed time for gridding: 0.01 seconds

Data Source

Source Data File Name: D:\Meesters\Veldwerk\Data\Surfer\Mag\Mag Data vir Surfer.xlsx (sheet 'EM(HD)')

X Column: A

Y Column: B

Z Column: C

Filtered Data Counts

Active Data: 70

Original Data: 70

Excluded Data: 0

Deleted Duplicates: 0

Retained Duplicates: 0

Artificial Data: 0

Superseded Data: 0

Exclusion Filtering

Exclusion Filter String: Not In Use

Duplicate Filtering

Duplicate Points to Keep: First
X Duplicate Tolerance: 1.6E-10
Y Duplicate Tolerance: 4.9E-10

No duplicate data were found.

Breakline Filtering

Breakline Filtering: Not In Use

Z Data Transform

Transformation method: Linear (use Z values directly)

No un-transformable data were found.

Data Counts

Active Data: 70

Univariate Statistics

	X	Y	Z
Count:	70	70	70
1%-tile:	26.95366	-26.671285	2.1
5%-tile:	26.95371	-26.671058	3.8
10%-tile:	26.95376	-26.670881	4.4
25%-tile:	26.953945	-26.670206	8
50%-tile:	26.954334	-26.669172	20.1

75%-tile:	26.95475	-26.668182	24.7
90%-tile:	26.954924	-26.667556	29.6
95%-tile:	26.954977	-26.667332	30.8
99%-tile:	26.955024	-26.66715	32
Minimum:	26.95366	-26.671285	2.1
Maximum:	26.95504	-26.6671	33.9
Mean:	26.9543422143	-26.6691601971	17.6342857143
Median:	26.9543425	-26.669151	20.15
Geometric Mean:	26.9543422109	N/A	14.2278100941
Harmonic Mean:	26.9543422076	N/A	10.4203649158
Root Mean Square:	26.9543422176	26.6691602247	20.000164285
Trim Mean (10%):	26.9543310317	-26.6691882349	17.4365079365
Interquartile Mean:	26.9543196	-26.6691877371	18.1
Midrange:	26.95435	-26.6691925	18
Winsorized Mean:	26.9543403429	-26.6691701829	17.5714285714
TriMean:	26.95434075	-26.669183	18.225
Variance:	1.83176518634e-07	1.4918078568e-06	90.328952381
Standard Deviation:	0.000427991259997	0.00122139586408	9.50415448007
Interquartile Range:	0.000805	0.002024	16.7
Range:	0.00138	0.004185	31.8
Mean Difference:	0.000496105590062	0.00142024356108	10.9127122153
Median Abs. Deviation:	0.000411	0.001056	8.25
Average Abs. Deviation:	0.000364614285714	0.00104916857143	8.36285714286
Quartile Dispersion:	1.493265604e-05	N/A	0.510703363914
Relative Mean Diff.:	1.84054051892e-05	N/A	0.618834944161
Standard Error:	5.11547398493e-05	0.000145984728008	1.13596373421
Coef. of Variation:	1.58783789489e-05	N/A	0.538958857424
Skewness:	0.0536425026655	-0.0106888564863	-0.16215686325
Kurtosis:	1.6765986748	1.76131076702	1.54994990033
Sum:	1886.803955	-1866.8412138	1234.4
Sum Absolute:	1886.803955	1866.8412138	1234.4
Sum Squares:	50857.559507	49787.0874964	28000.46
Mean Square:	726.536564385	711.244107091	400.006571429

Inter-Variable Covariance

	X	Y	Z
X:	1.8317652e-07	-1.3230932e-07	-0.00012933789
Y:	-1.3230932e-07	1.4918079e-06	0.0033502132
Z:	-0.00012933789	0.0033502132	90.328952

Inter-Variable Correlation

	X	Y	Z
X:	1.000	-0.253	-0.032
Y:	-0.253	1.000	0.289
Z:	-0.032	0.289	1.000

Inter-Variable Rank Correlation

	X	Y	Z
X:	1.000	-0.334	-0.083
Y:	-0.334	1.000	0.260
Z:	-0.083	0.260	1.000

Principal Component Analysis

PC1	PC2	PC3
-----	-----	-----

X:	-0.105828366237	-0.105828366237	0.994384411029
Y:	0.994384410341	0.994384410341	0.105828366217
Z:	-3.70322846832e-05	-3.70322846832e-05	0.105828366217

Lambda:	90.3289525054	1.38112232114e-06	1.69420699922e-07
---------	---------------	-------------------	-------------------

Planar Regression: $Z = AX + BY + C$

Fitted Parameters

	A	B	C
Parameter Value:	978.725007141	2332.54413946	35843.7388318
Standard Error:	2682.26639801	939.897218493	70271.2128011

Inter-Parameter Correlations

	A	B	C
A:	1.000	0.253	-0.939
B:	0.253	1.000	0.096
C:	-0.939	0.096	1.000

ANOVA Table

Source	df	Sum of Squares	Mean Square	F
Regression:	2	530.467447329	265.233723664	
	3.11644017403			
Residual:	67	5702.23026696	85.1079144322	
Total:	69	6232.69771429		

Coefficient of Multiple Determination (R^2):

0.0851104083089

Nearest Neighbor Statistics

	Separation	Delta Z
1%-tile:	0.000109178752509	0
5%-tile:	0.000156520414002	0.1
10%-tile:	0.000175647374021	0.2
25%-tile:	0.000177721692543	0.9
50%-tile:	0.000178630904379	1.9
75%-tile:	0.000180227633841	3.7
90%-tile:	0.000182701943064	5.2
95%-tile:	0.000183095603441	7.6
99%-tile:	0.000187771137289	10.4
Minimum:	0.000109178752509	0
Maximum:	0.000187771137289	10.4
Mean:	0.000176635426045	2.69428571429
Median:	0.000178674279399	1.95
Geometric Mean:	0.000176064877935	N/A
Harmonic Mean:	0.000175310841895	N/A
Root Mean Square:	0.000177071869186	3.62483497161
Trim Mean (10%):	0.000178528030225	2.39523809524
Interquartile Mean:	0.000178780366236	2.13714285714
Midrange:	0.000148474944899	5.2
Winsorized Mean:	0.000178907831659	2.37428571429
TriMean:	0.000178802783785	2.1
Variance:	1.56610414606e-10	5.96547412008
Standard Deviation:	1.25144082803e-05	2.44243200931
Interquartile Range:	2.50594129785e-06	2.8
Range:	7.85923847797e-05	10.4
Mean Difference:	7.63521563622e-06	2.57962732919
Median Abs. Deviation:	1.39091327511e-06	1.35
Average Abs. Deviation:	4.47411153603e-06	1.80857142857

Quartile Dispersion:	0.00700082696948	N/A
Relative Mean Diff.:	0.043225845501	0.957443865554
Standard Error:	1.49575788055e-06	0.291926461388
Coef. of Variation:	0.070848801741	0.906523015119
Skewness:	-4.55099255256	1.34331542674
Kurtosis:	24.3388585228	4.51792050003
Sum:	0.0123644798231	188.6
Sum Absolute:	0.0123644798231	188.6
Sum Squares:	2.19481127999e-06	919.76
Mean Square:	3.1354446857e-08	13.1394285714

Complete Spatial Randomness

Lambda:	12120582.4806
Clark and Evans:	1.22989929196
Skellam:	167.147753199

Gridding Rules

Gridding Method:	Kriging
Kriging Type:	Point

Polynomial Drift Order:	0
Kriging std. deviation grid:	no

Semi-Variogram Model

Component Type:	Linear
Anisotropy Angle:	0
Anisotropy Ratio:	1
Variogram Slope:	1

Search Parameters

No Search (use all data):	true
---------------------------	------

Output Grid

Grid File Name:	D:\Meesters\Veldwerk\Data\Surfer\Mag\Results\EM\EM(HD) vir Lyn 1,2 & 3.grd
Grid Size:	100 rows x 34 columns
Total Nodes:	3400
Filled Nodes:	2355
Blanked Nodes:	1045
Blank Value:	1.70141E+38

Grid Geometry

X Minimum:	26.95366
X Maximum:	26.95504
X Spacing:	4.1818181818214E-05
Y Minimum:	-26.671285
Y Maximum:	-26.6671
Y Spacing:	4.2272727272724E-05

Univariate Grid Statistics

Z	
Count:	2355
1%-tile:	3.36253279679
5%-tile:	4.5425463579
10%-tile:	5.72311938889
25%-tile:	10.02683579
50%-tile:	22.6305732274
75%-tile:	26.0811933547
90%-tile:	28.9283305214
95%-tile:	30.3400472263
99%-tile:	32.0163665437
Minimum:	2.50080897628
Maximum:	33.6792939642

Mean:	19.001939622
Median:	22.6305732274
Geometric Mean:	16.168951905
Harmonic Mean:	12.7966991521
Root Mean Square:	20.9541990812
Trim Mean (10%):	19.1489812363
Interquartile Mean:	20.4719472078
Midrange:	18.0900514703
Winsorized Mean:	18.9645578192
TriMean:	20.3422938999
Variance:	78.0378868439
Standard Deviation:	8.83390552609
Interquartile Range:	16.0543575648
Range:	31.178484988
Mean Difference:	9.96740016902
Median Abs. Deviation:	5.84095018301
Average Abs. Deviation:	7.61619286585
Quartile Dispersion:	0.444620156377
Relative Mean Diff.:	0.524546460376
Standard Error:	0.182036004516
Coef. of Variation:	0.464894937138
Skewness:	-0.392916962682
Kurtosis:	1.68695711485
Sum:	44749.5678099
Sum Absolute:	44749.5678099
Sum Squares:	1034029.77127
Mean Square:	439.078459136

Appendix 4: The Grid report for the interpolation carried out for the results of the EM 34-3 (VD):

Gridding Report

Sat Oct 10 20:01:23 2020

Elapsed time for gridding: 0.00 seconds

Data Source

Source Data File Name: D:\Meesters\Veldwerk\Data\Surfer\Mag\Mag Data vir Surfer.xlsx (sheet 'EM(VD)')

X Column: B

Y Column: C

Z Column: D

Filtered Data Counts

Active Data: 70

Original Data: 70

Excluded Data: 0

Deleted Duplicates: 0

Retained Duplicates: 0

Artificial Data: 0

Superseded Data: 0

Exclusion Filtering

Exclusion Filter String: Not In Use

Duplicate Filtering

Duplicate Points to Keep: First
X Duplicate Tolerance: 1.6E-10
Y Duplicate Tolerance: 4.9E-10

No duplicate data were found.

Breakline Filtering

Breakline Filtering: Not In Use

Z Data Transform

Transformation method: Linear (use Z values directly)

No untransformable data were found.

Data Counts

Active Data: 70

Univariate Statistics

	X	Y	Z
Count:	70	70	70
1%-tile:	26.95366	-26.671285	-13.6
5%-tile:	26.95371	-26.671058	-8.8
10%-tile:	26.95376	-26.670881	-7.4
25%-tile:	26.953945	-26.670206	-2.3
50%-tile:	26.954334	-26.669172	0.9

75%-tile:	26.95475	-26.668182	5.2
90%-tile:	26.954924	-26.667556	10.6
95%-tile:	26.954977	-26.667332	12.1
99%-tile:	26.955024	-26.66715	15.4
Minimum:	26.95366	-26.671285	-13.6
Maximum:	26.95504	-26.6671	19.3
Mean:	26.9543422143	-26.6691601971	1.66714285714
Median:	26.9543425	-26.669151	0.95
Geometric Mean:	26.9543422109	N/A	N/A
Harmonic Mean:	26.9543422076	N/A	N/A
Root Mean Square:	26.9543422176	26.6691602247	6.8214682123
Trim Mean (10%):	26.9543310317	-26.6691882349	1.3746031746
Interquartile Mean:	26.9543196	-26.6691877371	1.30857142857
Midrange:	26.95435	-26.6691925	2.85
Winsorized Mean:	26.9543403429	-26.6691701829	1.51714285714
TriMean:	26.95434075	-26.669183	1.175
Variance:	1.83176518634e-07	1.4918078568e-06	44.3871656315
Standard Deviation:	0.000427991259997	0.00122139586408	6.66236937069
Interquartile Range:	0.000805	0.002024	7.5
Range:	0.00138	0.004185	32.9
Mean Difference:	0.000496105590062	0.00142024356108	7.55374741201
Median Abs. Deviation:	0.000411	0.001056	4.2
Average Abs. Deviation:	0.000364614285714	0.00104916857143	5.18142857143
Quartile Dispersion:	1.493265604e-05	N/A	N/A
Relative Mean Diff.:	1.84054051892e-05	N/A	N/A
Standard Error:	5.11547398493e-05	0.000145984728008	0.79630544778
Coef. of Variation:	1.58783789489e-05	N/A	N/A
Skewness:	0.0536425026655	-0.0106888564863	0.232896534246
Kurtosis:	1.6765986748	1.76131076702	2.77325209628
Sum:	1886.803955	-1866.8412138	116.7
Sum Absolute:	1886.803955	1866.8412138	371.3
Sum Squares:	50857.559507	49787.0874964	3257.27
Mean Square:	726.536564385	711.244107091	46.5324285714

Inter-Variable Covariance

	X	Y	Z
X:	1.8317652e-07	-1.3230932e-07	0.00019989265
Y:	-1.3230932e-07	1.4918079e-06	0.00098392299
Z:	0.00019989265	0.00098392299	44.387166

Inter-Variable Correlation

	X	Y	Z
X:	1.000	-0.253	0.070
Y:	-0.253	1.000	0.121
Z:	0.070	0.121	1.000

Inter-Variable Rank Correlation

	X	Y	Z
X:	1.000	-0.334	0.094
Y:	-0.334	1.000	0.099
Z:	0.094	0.099	1.000

Principal Component Analysis

PC1	PC2	PC3
-----	-----	-----

X:	-0.10444239341	-0.10444239341	0.994530937899
Y:	0.994530937675	0.994530937675	0.104442393286
Z:	-2.15752596322e-05	-2.15752596322e-05	0.104442393286
Lambda:	44.3871656542	1.48435741783e-06	1.67916303612e-07

Planar Regression: $Z = AX + BY + C$

Fitted Parameters

	A	B	C
Parameter Value:	1674.95411595	808.103421296	-23594.1796933
Standard Error:	1940.58869663	680.004759987	50840.4092007

Inter-Parameter Correlations

	A	B	C
A:	1.000	0.253	-0.939
B:	0.253	1.000	0.096
C:	-0.939	0.096	1.000

ANOVA Table

Source	df	Sum of Squares	Mean Square	F
Regression:	2	77.9646562683	38.9823281342	
	0.875053583796			
Residual:	67	2984.7497723	44.5485040642	
Total:	69	3062.71442857		

Coefficient of Multiple Determination (R^2):

0.0254560645749

Nearest Neighbor Statistics

	Separation	Delta Z
1%-tile:	0.000109178752509	0.2
5%-tile:	0.000156520414002	0.2
10%-tile:	0.000175647374021	1
25%-tile:	0.000177721692543	1.8
50%-tile:	0.000178630904379	4.4
75%-tile:	0.000180227633841	6.6
90%-tile:	0.000182701943064	11
95%-tile:	0.000183095603441	14.2
99%-tile:	0.000187771137289	21.5
Minimum:	0.000109178752509	0.2
Maximum:	0.000187771137289	21.5
Mean:	0.000176635426045	5.32
Median:	0.000178674279399	4.5
Geometric Mean:	0.000176064877935	3.38240023679
Harmonic Mean:	0.000175310841895	1.56179749228
Root Mean Square:	0.000177071869186	7.12747200225
Trim Mean (10%):	0.000178528030225	4.68571428571
Interquartile Mean:	0.000178780366236	4.06857142857
Midrange:	0.000148474944899	10.85
Winsorized Mean:	0.000178907831659	4.85571428571
TriMean:	0.000178802783785	4.3
Variance:	1.56610414606e-10	22.8245217391
Standard Deviation:	1.25144082803e-05	4.77750162105
Interquartile Range:	2.50594129785e-06	4.8
Range:	7.85923847797e-05	21.3
Mean Difference:	7.63521563622e-06	4.92422360248
Median Abs. Deviation:	1.39091327511e-06	2.75
Average Abs. Deviation:	4.47411153603e-06	3.38571428571

Quartile Dispersion:	0.00700082696948	0.571428571429
Relative Mean Diff.:	0.043225845501	0.925605940317
Standard Error:	1.49575788055e-06	0.571020661862
Coef. of Variation:	0.070848801741	0.898026620498
Skewness:	-4.55099255256	1.5833457667
Kurtosis:	24.3388585228	5.56462801854
Sum:	0.0123644798231	372.4
Sum Absolute:	0.0123644798231	372.4
Sum Squares:	2.19481127999e-06	3556.06
Mean Square:	3.1354446857e-08	50.8008571429

Complete Spatial Randomness

Lambda:	12120582.4806
Clark and Evans:	1.22989929196
Skellam:	167.147753199

Gridding Rules

Gridding Method:	Kriging
Kriging Type:	Point

Polynomial Drift Order:	0
Kriging std. deviation grid:	no

Semi-Variogram Model

Component Type:	Linear
Anisotropy Angle:	0
Anisotropy Ratio:	1
Variogram Slope:	1

Search Parameters

No Search (use all data):	true
---------------------------	------

Output Grid

Grid File Name:	D:\Meesters\Veldwerk\Data\Surfer\Mag\Results\EM\EM(VD) vir Lyn 1,2 & 3.grd
Grid Size:	100 rows x 34 columns
Total Nodes:	3400
Filled Nodes:	2355
Blanked Nodes:	1045
Blank Value:	1.70141E+38

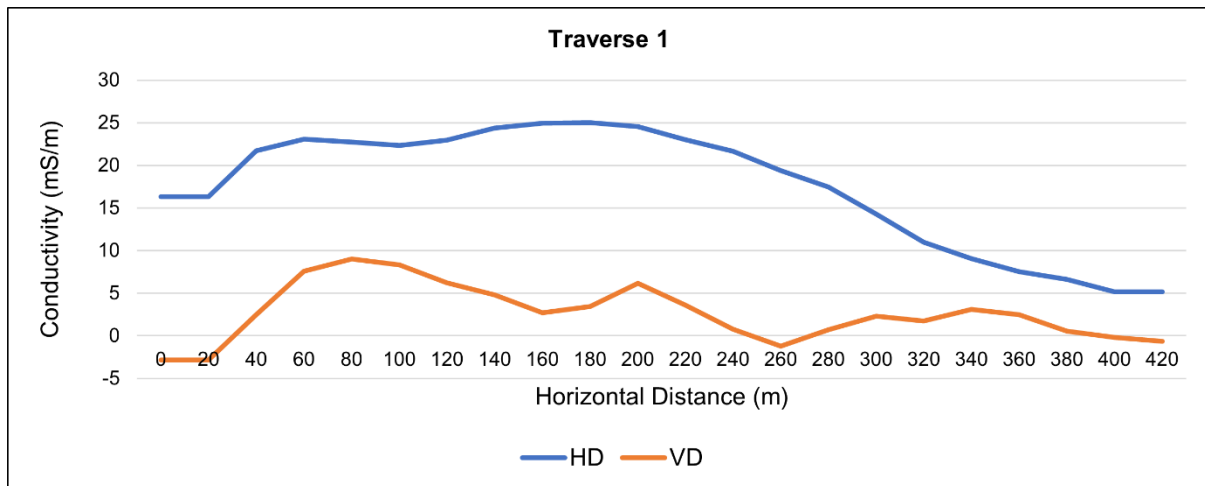
Grid Geometry

X Minimum:	26.95366
X Maximum:	26.95504
X Spacing:	4.1818181818214E-05
Y Minimum:	-26.671285
Y Maximum:	-26.6671
Y Spacing:	4.2272727272724E-05

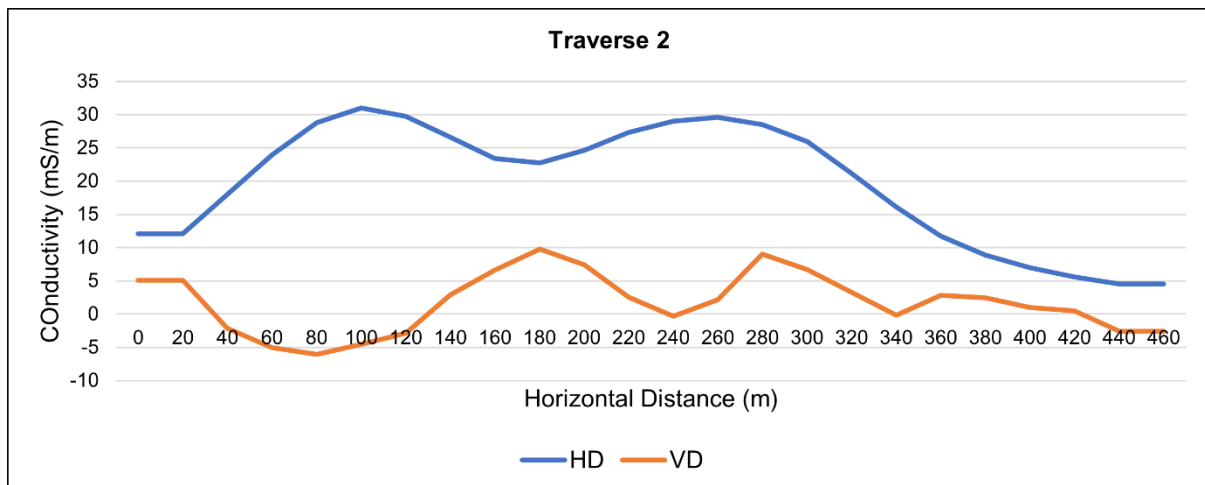
Univariate Grid Statistics

Z	
Count:	2355
1%-tile:	-8.82660717189
5%-tile:	-5.90754377453
10%-tile:	-3.95726902065
25%-tile:	-0.632627938729
50%-tile:	1.68906397537
75%-tile:	4.47196489729
90%-tile:	7.71567720335
95%-tile:	9.4404305383
99%-tile:	12.0354817107
Minimum:	-13.1483591146
Maximum:	14.5277569093

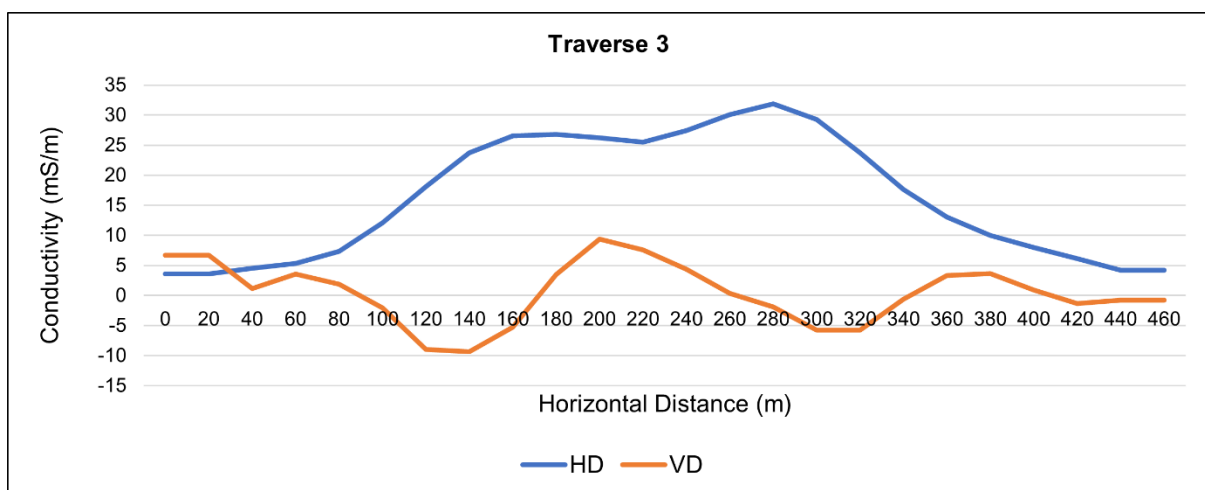
Mean:	1.82638481902
Median:	1.68906397537
Geometric Mean:	N/A
Harmonic Mean:	N/A
Root Mean Square:	4.75405762415
Trim Mean (10%):	1.84716387257
Interquartile Mean:	1.76119997222
Midrange:	0.68969889735
Winsorized Mean:	1.85379353974
TriMean:	1.80436622733
Variance:	19.2735664913
Standard Deviation:	4.39016702316
Interquartile Range:	5.10459283602
Range:	27.6761160238
Mean Difference:	4.90664482458
Median Abs. Deviation:	2.54579710432
Average Abs. Deviation:	3.39600369576
Quartile Dispersion:	N/A
Relative Mean Diff.:	N/A
Standard Error:	0.090466041514
Coef. of Variation:	N/A
Skewness:	-0.0480525226624
Kurtosis:	3.17664787441
Sum:	4301.13624879
Sum Absolute:	8707.32242882
Sum Squares:	53225.5054698
Mean Square:	22.6010638937



Appendix 5: 2D plot of the conductivity (mS/m) over horizontal distance as was measured by the EM 34-3 for Traverse 1.



Appendix 6: 2D plot of the conductivity (mS/m) over horizontal distance as was measured by the EM 34-3 for traverse 2.



Appendix 7: 2D plot of the conductivity (mS/m) over horizontal distance as was measured by the EM 34-3 Fore traverse 3.

Appendix 8: The Grid report for the interpolation carried out for the results of the Magnetometer (G5):

Gridding Report

Sat Oct 10 19:34:08 2020

Elapsed time for gridding: 0.02 seconds

Data Source

Source Data File Name: D:\Meesters\Veldwerk\Data\Surfer\Mag\Nuwe Mag.xlsx (sheet 'Sheet1')
X Column: B
Y Column: C
Z Column: D

Filtered Data Counts

Active Data: 162

Original Data: 162
Excluded Data: 0
Deleted Duplicates: 0
Retained Duplicates: 0
Artificial Data: 0
Superseded Data: 0

Exclusion Filtering

Exclusion Filter String: Not In Use

Duplicate Filtering

Duplicate Points to Keep: First
X Duplicate Tolerance: 2.4E-10
Y Duplicate Tolerance: 5.8E-10

No duplicate data were found.

Breakline Filtering

Breakline Filtering: Not In Use

Z Data Transform

Transformation method: Linear (use Z values directly)

No untransformable data were found.

Data Counts

Active Data: 162

Univariate Statistics

	X	Y	Z
Count:	162	162	162
1%-tile:	26.95366	-26.671956	27656.6
5%-tile:	26.95372	-26.671776	27687.27
10%-tile:	26.953787	-26.671508	27715.57
25%-tile:	26.953985	-26.670788	27796.53
50%-tile:	26.95437	-26.669617	28066.4
75%-tile:	26.954797	-26.668404	28235.33

90%-tile:	26.954991	-26.66764	28562.3
95%-tile:	26.955055	-26.667416	28809.4
99%-tile:	26.955111	-26.667191	29013.43
Minimum:	26.953089	-26.672045	27654.83
Maximum:	26.955128	-26.6671	29042.8
Mean:	26.9543831846	-26.6695821914	28084.8780864
Median:	26.954373	-26.669596	28068.885
Geometric Mean:	26.9543831808	N/A	28082.8081676
Harmonic Mean:	26.954383177	N/A	28080.7532131
Root Mean Square:	26.9543831884	26.6695822285	28086.9629945
Trim Mean (10%):	26.9543815786	-26.6695987172	28055.928
Interquartile Mean:	26.9543735667	-26.6696000988	28018.9474074
Midrange:	26.9541085	-26.6695725	28348.815
Winsorized Mean:	26.9543861475	-26.6695826543	28060.8465432
TriMean:	26.9543805	-26.6696065	28041.165
Variance:	2.05662293735e-07	1.9951561557e-06	117840.536204
Standard Deviation:	0.00045350004822	0.00141249996662	343.279093748
Interquartile Range:	0.000812	0.002384	438.8
Range:	0.002039	0.004945	1387.97
Mean Difference:	0.000522487991718	0.00163589394985	376.333062649
Median Abs. Deviation:	0.000409000000001	0.001214	264.245
Average Abs. Deviation:	0.000388493209876	0.00121633950617	266.620555556
Quartile Dispersion:	1.50624809145e-05	N/A	0.0078312588588
Relative Mean Diff.:	1.93841568601e-05	N/A	0.0133998467606
Standard Error:	3.56303288183e-05	0.000110976478314	26.970552781
Coef. of Variation:	1.68247236494e-05	N/A	0.0122229155737
Skewness:	-0.0550645265725	0.0102175335461	0.905443038399
Kurtosis:	1.96086025627	1.79736399369	3.17549896234
Sum:	4366.6100759	-4320.472315	4549750.25
Sum Absolute:	4366.6100759	4320.472315	4549750.25
Sum Squares:	117699.281237	115225.191832	127798153421
Mean Square:	726.538773065	711.266616244	788877490.255

Inter-Variable Covariance

	X	Y	Z
X:	2.0566229e-07	-1.8724718e-07	-0.0086779158
Y:	-1.8724718e-07	1.9951562e-06	0.17161302
Z:	-0.0086779158	0.17161302	117840.54

Inter-Variable Correlation

	X	Y	Z
X:	1.000	-0.292	-0.056
Y:	-0.292	1.000	0.354
Z:	-0.056	0.354	1.000

Inter-Variable Rank Correlation

	X	Y	Z
X:	1.000	-0.346	-0.084
Y:	-0.346	1.000	0.454
Z:	-0.084	0.454	1.000

Principal Component Analysis

PC1	PC2	PC3
-----	-----	-----

X:	-0.111251593454	-0.111251593454	0.993792273543
Y:	0.993792273542	0.993792273542	0.111251593454
Z:	-1.45546793347e-06	-1.45546793347e-06	0.111251593454

Lambda:	117840.536205	1.76478035004e-06	1.85476326909e-07
---------	---------------	-------------------	-------------------

Planar Regression: $Z = AX + BY + C$

Fitted Parameters

	A	B	C
Parameter Value:	39492.5742974	89721.2425635	1356414.95039
Standard Error:	58625.5011299	18822.4199771	1511725.36823

Inter-Parameter Correlations

	A	B	C
A:	1.000	0.292	-0.948
B:	0.292	1.000	0.027
C:	-0.948	0.027	1.000

ANOVA Table

Source	df	Sum of Squares	Mean Square	F
Regression:	2	2423793.79347	1211896.89673	
	11.6440298358			
Residual:	159	16548532.5354	104078.820978	
Total:	161	18972326.3289		

Coefficient of Multiple Determination (R^2):

0.127754169491

Nearest Neighbor Statistics

	Separation	Delta Z
1%-tile:	1.16619037889e-05	0
5%-tile:	8.08084154028e-05	0.540000000001
10%-tile:	8.64696478535e-05	3.54
25%-tile:	8.83628881357e-05	7.86
50%-tile:	8.93588272073e-05	14.07
75%-tile:	9.02718117688e-05	48.1
90%-tile:	9.05538513815e-05	144.9
95%-tile:	9.13509715341e-05	207.83
99%-tile:	0.000104759772814	312.86
Minimum:	1.16619037889e-05	0
Maximum:	0.000995354208312	384.37
Mean:	9.22825047684e-05	47.7916049383
Median:	8.93588272073e-05	14.07
Geometric Mean:	8.52660969733e-05	N/A
Harmonic Mean:	7.66617986096e-05	N/A
Root Mean Square:	0.000117336058733	89.59321664
Trim Mean (10%):	8.89741803086e-05	34.9059310345
Interquartile Mean:	8.91618690051e-05	17.8344444444
Midrange:	0.000503508056051	192.185
Winsorized Mean:	8.90372875461e-05	38.1730864198
TriMean:	8.93380885798e-05	21.025
Variance:	5.28430918523e-09	5778.57719492
Standard Deviation:	7.26932540559e-05	76.0169533389
Interquartile Range:	1.90892363314e-06	40.24
Range:	0.000983692304523	384.37
Mean Difference:	1.84049865973e-05	64.2636638295
Median Abs. Deviation:	9.95939071585e-07	7.865
Average Abs. Deviation:	9.61081069485e-06	40.0217283951
Quartile Dispersion:	0.0106861860218	N/A

Relative Mean Diff.:	0.199441775486	1.3446642755
Standard Error:	5.71132143216e-06	5.97245591012
Coef. of Variation:	0.787725194915	1.59059218532
Skewness:	11.7960748559	2.47914878409
Kurtosis:	147.067933041	8.97375060527
Sum:	0.0149497657725	7742.24
Sum Absolute:	0.0149497657725	7742.24
Sum Squares:	2.23037561001e-06	1300365.0038
Mean Square:	1.37677506791e-08	8026.9444679

Complete Spatial Randomness

Lambda:	16066877.8833
Clark and Evans:	0.739801343859
Skellam:	225.159029708

Gridding Rules

Gridding Method:	Kriging
Kriging Type:	Point

Polynomial Drift Order:	0
Kriging std. deviation grid:	no

Semi-Variogram Model

Component Type:	Linear
Anisotropy Angle:	0
Anisotropy Ratio:	1
Variogram Slope:	1

Search Parameters

No Search (use all data):	true
---------------------------	------

Output Grid

Grid File Name:	D:\Meesters\Veldwerk\Data\Surfer\Mag\Results\Mag vir Lyn 1, 2 & 3.grd
Grid Size:	100 rows x 42 columns
Total Nodes:	4200
Filled Nodes:	3061
Blanked Nodes:	1139
Blank Value:	1.70141E+38

Grid Geometry

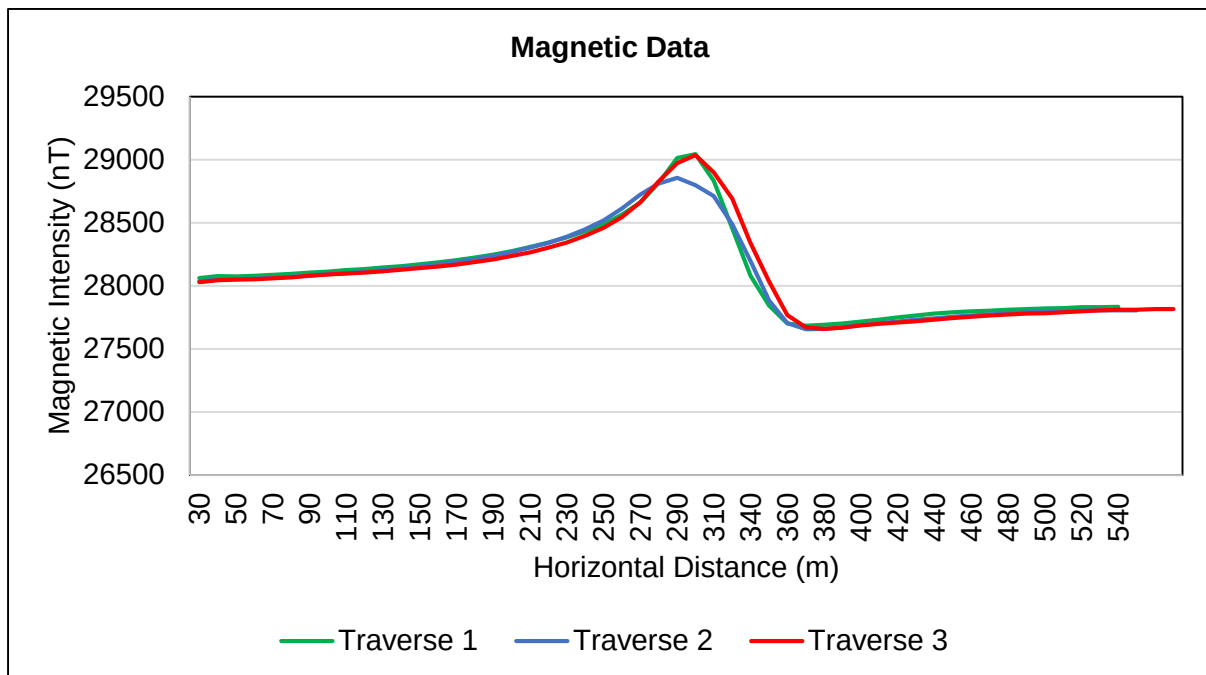
X Minimum:	26.953089
X Maximum:	26.955128
X Spacing:	4.9731707317071E-05
Y Minimum:	-26.672045
Y Maximum:	-26.6671
Y Spacing:	4.9949494949488E-05

Univariate Grid Statistics

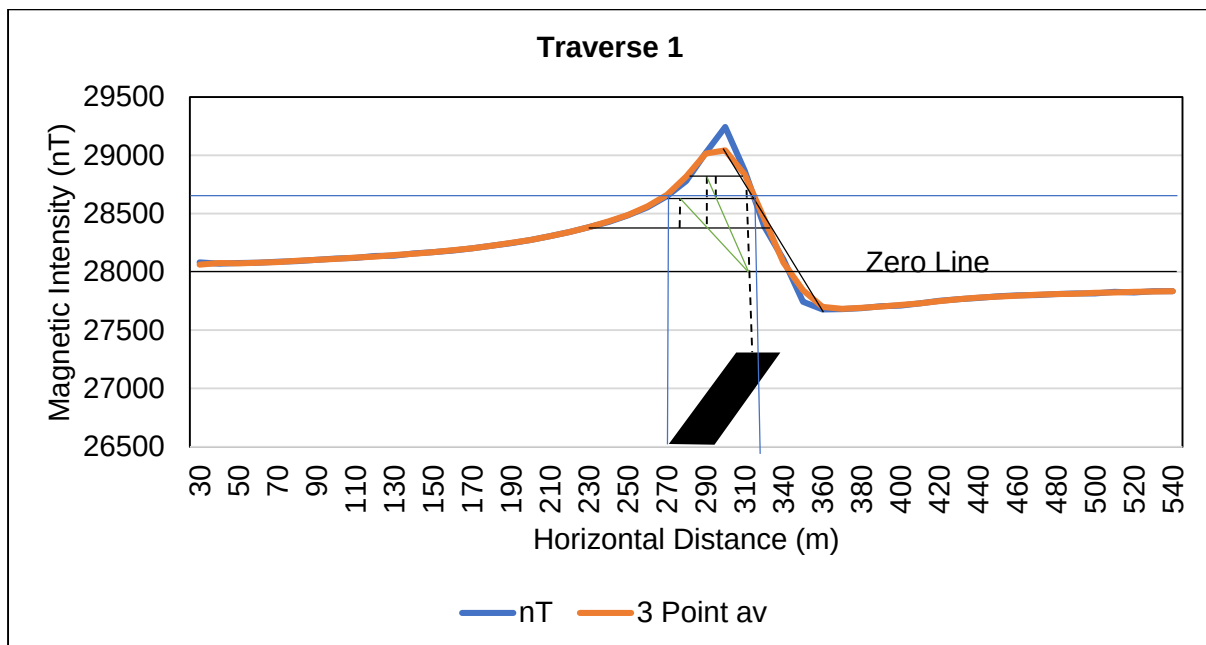
Z	
Count:	3061
1%-tile:	27640.5987363
5%-tile:	27693.5195339
10%-tile:	27736.4222306
25%-tile:	27797.3612806
50%-tile:	28057.3132672
75%-tile:	28256.5982639
90%-tile:	28571.0487884
95%-tile:	28732.5133627
99%-tile:	28886.327653
Minimum:	27624.0708785
Maximum:	29018.3641747
Mean:	28072.4025389

Median:	28057.3132672
Geometric Mean:	28070.5514509
Harmonic Mean:	28068.7111909
Root Mean Square:	28074.2644202
Trim Mean (10%):	28052.9626915
Interquartile Mean:	28007.1840541
Midrange:	28321.2175266
Winsorized Mean:	28060.0369766
TriMean:	28042.1465197
Variance:	104572.591836
Standard Deviation:	323.376857298
Interquartile Range:	459.236983263
Range:	1394.29329619
Mean Difference:	357.783530751
Median Abs. Deviation:	255.374892857
Average Abs. Deviation:	263.878618266
Quartile Dispersion:	0.00819276616665
Relative Mean Diff.:	0.0127450270868
Standard Error:	5.84490250373
Coef. of Variation:	0.0115193865879
Skewness:	0.778012394038
Kurtosis:	2.74934608937
Sum:	85929624.1717
Sum Absolute:	85929624.1717
Sum Squares:	2.4125709919e+12
Mean Square:	788164322.737

Appendix 9: 2D plot of the Magnetic intensity over horizontal distance as given by the G5 for all three traverses.



Appendix 10: 2D plot of the Magnetic intensity over horizontal distance as given by the G5 for all three traverses.



Appendix 11: Determination of the Zero Point of the dyke.