SUB-AUDIO MAGNETICS (SAM)

A High Resolution Geophysical Method for Simultaneously Mapping Electrical and Magnetic Properties of the Earth.

By

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A Thesis Submitted for the Degree of Doctor of Philosophy of the University of New England

Department of Geology and Geophysics

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DECLARATION

I certify that the substance of this thesis has not already been submitted for any degree and is not currently being submitted for any other degree or qualification.

I certify that any help received in preparing this thesis, and all sources used, have been acknowledged in this thesis.

M.K. Cattach

Armidale,
February, 1996.

DEDICATION

I am eternally grateful for the love and support of my family.

This thesis is dedicated to my parents, Keith and Elwyn, my sisters, Narelle, Carol, Roslyn, Lyndell and brothers, Colin, and Peter.

ABSTRACT

In recent times, there has been an accelerating trend in the exploration industry towards increased spatial resolution in geophysical surveys. Rapid development in computing technology and image processing techniques has meant that much finer detail is now being observed in the data and utilised, than was previously possible. However, geophysical surveys are often very labour-intensive and therefore, expensive. Consequently, there is a need to reduce the cost of acquiring high spatial resolution data.

Developments in digital electronics have resulted in significant improvements in geophysical instrumentation. Magnetic surveys, in particular, have benefited from the advent of continuous sampling magnetometers which have made high spatial resolution or "High Definition Magnetics" (HDM) surveys both logistically and economically feasible. A review of other geophysical methods revealed that improvements in survey efficiency have not been achieved across all geophysical techniques.

Higher precision data from the electrical techniques such as electrical resistivity (ER) and electrical induced polarisation (EIP) have resulted from real-time signal processing enhancements. However, significant increases in survey efficiency were found to be restricted due to the logistical constraint imposed by the need for grounded electrodes. Similarly, improvements in survey efficiency for the electromagnetic techniques, such as, magnetometric resistivity (MMR), magnetic induced polarisation (MIP) and SIROTEM, are limited by the time-consuming requirement to precisely orientate and level the sensor prior to taking a reading.

In recognition of the potential benefits of a cost-effective means of providing detailed electrical information, a high resolution method for acquiring parameters related to the electrical properties of the earth was proposed. The method employs electric current, typically in the sub-audio frequency range of 3-200 Hz, which is induced in the ground by either galvanic or electromagnetic means using a constant-current transmitter. The electromagnetic fields produced as a result of the transmitted current flow, as well as the Earth's spatially-varying magnetic field, are monitored with an optically-pumped total field magnetometer. The method was consequently entitled "Sub-Audio Magnetics" (SAM).

Spectral analysis of the magnetic field changes allows a suite of geophysical parameters to be derived. In order to differentiate the electrical measurements so obtained, from parameters recorded by conventional methods, new terminology was introduced. Where galvanic induction is used the properties measured include "Total Field MagnetoMetric Resistivity" (TFMMR) and "Total Field MagnetoMetric Induced Polarisation" (TFMMIP). The term "Total Field ElectroMagnetics" (TFEM) was adopted as the property measured during surveys which employ electromagnetic induction. Each of the parameters may be measured at close sample intervals while continuously traversing either on foot or in a ground or airborne vehicle. A significant benefit of the method in terms of survey efficiency, is the simultaneous acquisition of High Definition Magnetics (HDM).

In order to demonstrate the SAM concept, a series of feasibility trials using galvanic induction were conducted over known geology using a state-of-the-art, TM-4 caesium vapour magnetometer as the receiver. Analysis of the recorded waveforms confirmed the technical viability of the technique and enabled signal strengths to be quantified. Data reduction procedures were developed to correct the TFMMR data for the electromagnetic field due to current flowing in the wire feeding the electrodes as well as to perform normalisation for the expected response over a homogeneous half-space. The higher spatial resolution was found capable of providing significantly more diagnostic information than possible using conventional electrical or electromagnetic methods.

Deficiencies in the instrumentation used for the feasibility trials were addressed through the development of a TM-4 option card (the SAMCard) which featured:

- Measurement resolution of the order of 0.02 nT.
- A bandwidth of 500 Hz to prevent aliasing of the higher frequency components.
- Constant sample interval to enable waveform averaging and data processing.
- GPS synchronisation between the receiver and the transmitter to facilitate the detection of polarity reversals and to quantify phase lags from the transmitted signal.
- Separation of the spatially-varying field from the time-varying field due to the transmitted current.
- Sample intervals for the electromagnetic parameters of down to 2 m.

A series of field trials of the prototype SAMCard-enhanced TM-4 demonstrated that the simultaneous acquisition of HDM and TFMMR was readily achieved. However, characterisation of the much weaker TFMMIP response was not successful due to remaining deficiencies in instrument design. The results of the field trials enabled future development strategies for attaining TFMMIP information to be proposed.

The Sub-Audio Magnetics method is now being operated commercially for the acquisition of HDM and TFMMR. Exploration surveys have demonstrated the benefits both of multiple-property data sets and of high resolution for all parameters. In some situations, the TFMMR data were found to supplement the magnetics by providing consistent information which confirmed and extended the interpretation of the magnetics. In other cases, the TFMMR data exposed new, yet contrasting information which complemented the magnetics. The surveys highlighted the greater diagnostic power which can be derived from having multiple data sets as well as the interpretational bias which may result from too much dependence on a single data type.

Because of its inherent cost-efficiency and superior spatial resolution, Sub-Audio Magnetics has the potential to significantly enhance geophysical mapping for mineral exploration, archaeological investigation and environmental studies of salinity, industrial waste and chemical contamination in soils.

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TABLE OF CONTENTS

Declaration ii

Dedication iii

Abstract iv

Acknowledgements vi

Table of Contents viii

List of Figures xiii

List of Plates xiv

List of Tables xviii

List of Symbols xix

List of Acronyms xx

1 INTRODUCTION 1

1.1 An Endeavour to Increase the Spatial Resolution and Interpretability of Geophysical Surveys 1

1.2 Project Objectives 4

1.3 Achievements of the Research 6

1.4 Organisation of the Thesis 7

2 REVIEW OF RELEVANT CONTEMPORARY GEOPHYSICAL SURVEY METHODS 9

2.1 Introduction 9

2.2 State-of-the-Art High Definition Magnetics 10

2.2.1 Field Procedure 12

2.2.2 Instrumentation 13

2.3 Contemporary Galvanic Electrical Methods 14

2.3.1 Electrical Resistivity (ER) 14

2.3.1.1 Field Procedure 15

2.3.1.2 Instrumentation 17

2.3.1.3 Measured Parameters 19

2.3.2 The Electrical Induced Polarisation (EIP) Method 19

2.3.2.1 Field Procedure 20

2.3.2.2 Instrumentation 20

2.3.2.3 Measured Parameters 21

2.3.3 Magnetometric Resistivity (MMR) 25

2.3.3.1 Field Procedure 27

2.3.3.2 Instrumentation 28

2.3.3.3 Measured Parameters 29

2.3.3.4 Corrections 29

2.3.4 The Magnetic Induced Polarisation (MIP) Method 31
2.3.4.1 Field Procedure 32
2.3.4.2 Instrumentation 34
2.3.4.3 Measured Parameters 34
2.4 Comparison of the EIP and MIP Methods 35
2.5 Discussion 39

3 THE SUB-AUDIO MAGNETICS CONCEPT 40
3.1 Introduction 40
3.2 SubAudio Magnetics 42
3.2.1 Survey Speed 42
3.2.2 TFMMR / TFMMIP 43
3.3 Components of the SAM Signal 44
3.3.1 Calculation of the Primary Field 45
3.3.2 Calculation of the Normal Field 46
3.4 Determination of Total Field Corrections 47
3.5 Analytical Solutions for Total Field Magnetometric Resistivity (TFMMR) 52
3.6 Factors Affecting Data Quality 54
3.6.1 The Earth's Ambient Electromagnetic Field 54
3.6.2 Electromagnetic Induction (EM Coupling) 57

4 FEASIBILITY STUDIES: INSTRUMENTATION AND FIELD PROCEDURE 58
4.1 Introduction 58
4.2 The Geophysical Technology, Model TM-4 Caesium Vapour Magnetometer 59
4.2.1 The TM-4 Data Acquisition and Control Unit 59
4.2.2 Optically-Pumped Magnetometer Sensors 60
4.2.2.1 The Principle of Optical Pumping 62
4.2.2.2 The Phenomenon of Unequal Pumping 65
4.2.2.3 The Effect of Sensor Orientation 67
4.2.2.4 Performance Characteristics of Optically-pumped Magnetic Sensors 68
4.2.3 The TM-4 Frequency Counter 69
4.3 Transmitter - Zonge GGT-10 70
4.4 Base-Station Magnetometer - Geometrics G-856 70
4.5 Field Procedure 70

5 FEASIBILITY STUDIES: WAVEFORM INVESTIGATION AND DATA REDUCTION 75
5.1 Introduction 75
5.2 Parameters of the SAM Waveform 75
5.3 Investigation of the Recorded Waveforms 77
5.3.1 Waveform Types 77
5.3.2 The Effect of Superposition of $H_{Primary}$ and H_{Ge} 79
5.3.2.1 In-Phase Signals 79
5.3.2.2 Out-Of-Phase Signals 80

5.4 Data Reduction Procedures 82
5.4.1 Extraction of H_S and H_{Mod} fro n H_T 82
5.4.2 Correction of H_S for Temporal Variation 83
5.4.3 Extraction of TFMMR Inform ation 83
5.4.4 Correction for $H_{Primary}$ and H_{Normal} 84
5.4.5 Extraction of TFMMIP Paran eters 85
5.5 Data Quality 87
5.5.1 The Effect of High Frequency High Amplitude Noise Resulting from the Spatially-varying Magnetic Field 88
5.5.2 The Effect of EM Coupling 88
5.5.3 The Effect of Mains Power In erference 88
5.6 Discussion 89

6 FEASIBILITY STUDIES - FIELD RESULTS 92

6. Introduction 92
6.2 Feasibility Study #1 - Orlando Dep sit, Tennant Creek, Northern Territory 93
6.2.1 Location 93
6.2.2 Geological Setting 94
6.2.2.1 Form of the Mineralisati n 96
6.2.3 Prior Geophysics 98
6.2.3.1 Magnetics 98
6.2.3.2 Gradient Array Induced Polarisation (IP) 100
6.2.4 SAM Field Procedure 102
6.2.5 Results 104
6.2.5.1 Total Magnetic Intensity 104
6.2.5.2 Total Field Magnetometric Resistivity (TFMMR) 107
6.3 Feasibility Study #2 - Flying Docto Deposit. Broken Hill, New South Wales 111
6.3.1 Location 111
6.3.2 Geological Setting 112
6.3.2.1 Form of the Mineralisati n 115
6.3.3 Prior Geophysics 116
6.3.3.1 Induced Polarisation (IP / Resisti ity 116
6.3.3.2 Magnetic Induced Polari sation (MIP) 119
6.3.4 SAM Field Procedure 120
6.3.5 Results 122
6.3.5.1 Total Magnetic Intensity (TMI) 122
6.3.5.2 Total Field Magnetometric Resistivity (TFMMR) 122
6.4 Evaluation of the Feasibility Trials 125

7 DEVELOPMENT OF A PROTOTYPE SAM RECEIVER 126

7.1 Introduction 126
7.2 Specifications of a Sub-Audio Mag netics Receiver 127
7.2.1 Requirements for the Determi ation of the Spatially-varying Magnetic Field, H_S 127

7.2.2 Requirements for the Determination of the SAM Signal, H_{Mod} 127
7.3 The Approach Used 129
7.3.1 Total Magnetic Field Measurements 129
7.3.2 The SAM Measurements - The SAMCard 130
7.3.2.1 The Demodulation Circuit 130
7.3.2.2 Removal of Low Frequency Noise 130
7.3.2.3 Anti-Aliasing Filter 130
7.3.2.4 Mains Power Filters 132
7.3.2.5 Analogue to Digital Conversion 132
7.3.2.6 Transmitter - Receiver Synchronisation 132
7.4 TM-4 Enhancements 134
7.5 The SAM-XMT Transmitter Controller 137
7.6 The SAM Signal Simulator 139
7.7 Data Processing 141
7.7.1 Correction for the SAMCard Filter Response 142
7.7.2 Slope correction 144
7.7.3 Calculation of parameters 144
7.7.3.1 Corrections for TFMMR Parameters 144
7.7.3.2 Corrections for TFMMIP Parameters 145
7.7.4 Conclusion 146

8 FIELD TRIALS OF THE PROTOTYPE SAM RECEIVER 147

8.1 Introduction 147
8.2 SAM Case Study #1 - Taronga Tin Deposit, Emmaville, NSW 148
8.2.1 Location 148
8.2.2 Geological Setting 150
8.2.2.1 Form of the Mineralisation 153
8.2.3 Prior Geophysics 155
8.2.4 SAM Field Procedure 157
8.2.5 Results 159
8.2.5.1 Total Magnetic Intensity (TMI) 159
8.2.5.2 Total Field Magnetometric Resistivity (TFMMR) 161
8.2.5.3 Total Field Magnetometric Induced Polarisation (TFMMIP) 163
8.2.6 The Effect of Topography on Primary Field Corrections 165
8.2.7 Discussion 167
8.3 Case Study #2 - HYC Deposit, McArthur River, Northern Territory 169
8.3.1 Location 169
8.3.2 Geological Setting 170
8.3.2.1 Mineralisation 171
8.3.3 Prior Geophysics 172
8.3.4 SAM Field Procedure 175
8.3.5 Results 177

8.3.5.1 Total Magnetic Intensity (TMI) 177
8.3.5.2 Total Field Magnetometric Resistivity (TFMMR) 177
8.3.5.3 Total Field Magnetometric Induced Polarisation (TFMMIP) 180
8.3.6 Discussion 180
8.4 Case Study #3 - Homogeneous Half-Space, McArthur River, Northern Territory 182
8.4.1 Location 182
8.4.2 SAM Field Procedure 182
8.4.3 Results 184
8.4.3.1 Total Magnetic Intensity (TMI) 184
8.4.3.2 Total Field Magnetometric Resistivity (TFMMR) 184
8.4.4 Discussion 185
8.5 Conclusions 190
8.5.1 Assessment of the Prototype SAM Receiver for the Determination of Total Magnetic Intensity, TMI 190
8.5.2 Assessment of the Prototype SAM Receiver for the Determination of TFMMR and TFMMIP 190

9 EXPLORATION EXAMPLES 193
9.1 Introduction 193
9.2 Supplementary Data Sets 194
9.3 Complementary Data Sets 197
9.4 Discussion 201

10 PROJECT REVIEW, EVALUATION AND CONCLUSION 203
10.1 Introduction 203
10.2 Project Review 205
10.2.1 Stage 1 - Conceptual Development 205
10.2.2 Stage 2 - Field Tests Using Existing Instrumentation 207
10.2.3 Stage 3 - Instrument Development and Field-Testing 207
10.3 Recommendations for Future Development and Related Research 209
10.3.1 Proposed Further SAM Receiver Development 209
10.3.1.1 The "Intelligent" Frequency Counter 211
10.3.1.2 The Data Logger 212
10.3.2 Alternative Sensors 212
10.3.3 Field Procedure Modifications 213
10.3.4 Alternative Applications of SAM 214
10.3.5 Related Theoretical Research 214
10.4 Project Evaluation and Conclusions 214

References 219

Research Related Awards 227

LIST OF FIGURES

Figure 2-1. Common Resistivity Arrays (After Sumner, 1976) 18

Figure 2-2. The time domain IP waveforms showing the transmitted current waveform and the received voltage waveform. (After Sumner, 1979) 22

Figure 2-3. IP Frequency domain waveforms, showing a controlled, constant inducing current I being detected as voltages V_1 and V_2 where $V_1 < V_2$. (After Sumner, 1979) 22

Figure 2-4. Timing for the integration windows for a Scintrex IPR-12 IP receiver (After Scintrex, 1993b) 23

Figure 2-5. IP phase determination and vector components (After Sumner, 1976) 26

Figure 2-6. The *x*-component of the Normal magnetic field due to current flow between a pair of electrodes located on the y-axis and separated by a distance *L*. (After Edwards and Nabighian, 1991) 31

Figure 2-7. Typical MIP horseshoe array for reconnaissance surveying (After Seigel and Howland-Rose, 1990) 33

Figure 2-8. Typical MIP linear array for detailed surveying (After Seigel and Howland-Rose, 1990) 33

Figure 2-9. The EIP and MIP Energisation Process (After Howland-Rose, 1980) 37

Figure 2-10. The EIP and MIP Discharge of Induced Polarisation (After Howland-Rose, 1980) 37

Figure 3-1. Layout of a typical TFMMR / TFMMIP survey showing the ideal electrode positions and survey orientation relative to the direction of geological strike. Current electrode positions are C_1 and C_2 44

Figure 3-2. Ampere's Law - A current I passing through a length of conductor Δl creates a magnetising field $\Delta \mathbf{H}$ at a point P (Drawn from Telford *et al.*, 1990) 46

Figure 3-3. Elements of the Earth's magnetic field with respect to a local coordinate system 48

Figure 3-4. Projection of an applied field $\mathbf{F}_A$ onto a unit vector defining the direction of the Earth's magnetic field $\mathbf{F}_E$ 49

Figure 3-5. The theoretical Primary field ($H_{Primary}$) as measured with a total field magnetometer, resulting from current flowing through cables feeding grounded electrodes at positions C1 and C2 50

Figure 3-6. The theoretical Normal field (H_{Normal}) as measured with a total field magnetometer due to current flowing through a homogeneous earth 51

Figure 3-7. Geometry used to define a vertical fault model separating two media with different resistivities (After Fathianpour and Cattach, 1995) 52

Figure 3-8. Horizontal X, Y and vertical Z components of the anomalous magnetic field for the vertical fault model. Notice the relative magnitude of the -Z component compared to those of the horizontal component (After Fathianpour and Cattach, 1995) 53

Figure 3-9. Profiles showing the influence of the geomagnetic field inclination on TFMMR measurements for a fixed declination of 25° (After Fathianpour and Cattach, 1995) 53

Figure 3-10. Profiles showing the influence of the geomagnetic field declination on TFMMR measurements for a fixed inclination of 60° (After Fathianpour and Cattach, 1995) 54

Figure 3-11. Components of the electromagnetic noise spectrum (After Macnae *et al.*, 1984) 55

Figure 4-12. Caesium-vapour magnetometer schematic (After Dobrin, 1976) 64

Figure 4-13. Energy levels of the caesium-133 isotope showing Hyperfine splitting ("F") levels and Zeeman splitting ("m") levels (After Varian Associates of Canada, 1977) 64

Figure 4-14. (a) The spectrum of electron transitions between F = 4 Zeeman levels in an equilibrium caesium atom subject to an ambient magnetic field of 50000 nT. (b) The hyperfine

spectrum when subjected tc $\Delta m_F = +1$ pumping radiation. (c) The hyperfine spectrum when subjected to $\Delta m_F = -1$ pumping radiation. (After Meilleroux, 1969). 66

Figure 4-15. Operating orientations for the Scintrex CS-2 sensor showing both equatorial and polar dead zones (After Scintrex, 1993a). 67

Figure 5-1. A ten second time sample (15 m traverse length) illustrating the artificially induced modulation, H_{Mod}, superimposed on the spatially-varying magnetic field, H_S. 77

Figure 5-2. Examples of recorded waveforms for a one second time interval. (A) Typical square waves. (B) Spikes. (C) Square waves with spikes. 78

Figure 5-3. The effect of superposition of $H_{Primary}$ and H_G (8 Hz, 100% duty cycle) for in-phase signals. 80

Figure 5-4. The effect of superposition of $H_{Primary}$ and H_G (8 Hz, 100% duty cycle) with a phase lag of 50 mrad. 81

Figure 5-5. (A) A sample raw data profile H_T recorded over a conductor. The component signals were separated by digital filtering to produce: (B) The spatially-varying magnetic field data H_S, and (C) The SAM signal H_{Mod}. 82

Figure 5-6. (A) Peak amplitude of the SAM modulation H_{Pk} determined from the data in Figure 5-5. (B) The calculated Primary Field $H_{Primary}$. (C) The calculated Normal Field H_{Normal}. (D) The Normalised TFMMR data H_N. 84

Figure 5-7. Normalised Amplitude spectrum of a 1024 point SAM signal showing the fundamental frequency and the odd harmonics. The harmonics above the 11th have been folded back about the Nyquist frequency due to aliasing. 86

Figure 5-8. Relative amplitude of the 3rd harmonic and the fundamental frequency calculated from the data in Figure 5-5. 87

Figure 5-9. Recorded waveform showing 50 Hz mains power interference. 89

Figure 6-10. Orlando Location Plan (After Oates, 1993). 94

Figure 6-11. Orlando Regional Geology (After Foley *et al.*, 1995). 95

Figure 6-12. Orlando Local Geology Map (Drawn from Oates, 1993). 97

Figure 6-13. Orlando Geological Section - Line 700 mE (After Foley *et al.*, 1995). 98

Figure 6-14. Contours of the vertical component of the magnetic field in gammas (nT). Orlando Mine area (Drawn From McNeil, 1966). 99

Figure 6-15. Orlando Aeromagnetic Data (After Foley *et al.*, 1995). 99

Figure 6-16. Gradient Array IP contours (After Foley *et al.*, 1995). 101

Figure 6-17. Layout of the Survey Area showing the locations of electrodes C1, C2, C3 and C4 and current-bearing wire. 103

Figure 6-18. Orlando - Total Magnetic Intensity, H_S, with geological overlay. 105

Figure 6-19. Orlando - Total Magnetic Intensity, H_S - Reduced to the Pole. 106

Figure 6-20. Orlando - Normalised TFMMR, H_N with geological overlay. 109

Figure 6-21. Normalised TFMMR, H_N - Reduced to Pole. 110

Figure 6-22. Locality and Regional Setting for Broken Hill (After Stevens *et al.*, 1980). 111

Figure 6-23. Flying Doctor Geological Plan (Drawn From Larsen, 1993). 113

Figure 6-24. Flying Doctor Geological Sections (Drawn From Tyne, 1985). 114

Figure 6-25. Gradient Array Resistivity and Induced Polarisation Survey. Flying Doctor Prospect (After Tyne, 1987). 117

Figure 6-26. Dipole-dipole resistivity and IP profile - Line 25.25 S. Flying Doctor Prospect (After Tyne, 1987). 118

Figure 6-27. Time domain MIP response - Line 25.25 S (After Bishop, 1989). 119

Figure 6-28. Frequency domain MIP response - Line 25.25 S (After Bishop, 1989). 120

Figure 6-29. Layout of the Survey Area showing the location of the electrodes and current-bearing wire. 121

Figure 6-30. Flying Doctor - Total Magnetic Intensity, H_S with geological overlay. 123
Figure 6-31. Flying Doctor - Normalised TFMMR, H_N. 123
Figure 6-32. Flying Doctor TFMMR, H_N - Reduced to Pole. 124
Figure 6-33. Flying Doctor First Vertical Derivative of TFMMR, H_N - RTP. 124
Figure 7-1. Schematic of the SAMCard (After Bradbury, 1994a). 131
Figure 7-2. (A) Unstacked, 1024 point waveform recorded from the SAM signal simulator without SAM modulation, and (B) The amplitude spectrum of the waveform in (A) (After Bradbury, 1994a). 136
Figure 7-3. (A) Stacked, 1024 point waveform recorded from the SAM signal simulator without SAM modulation, showing the effect of 8x stacking, and (B) The amplitude spectrum of the waveform in (A) (After Bradbury, 1994a). 136
Figure 7-4. Larmor Signal Generator Schematic (After Bradbury, 1994b). 140
Figure 7-5. (A) Amplitude response, and (B) Phase response of the SAMCard (After Bradbury, 1994a). 142
Figure 7-6. (A) Typical SAMCard recording of a square wave produced by the SAM signal generator showing distortion due to the SAMCard's filter response, and (B) The result of correction of the recorded data by applying the compensation filter (After Bradbury, 1994a). 143
Figure 7-7. Diagram showing the phase relationship between $H_{Primary}$, H_G and H_{Mod}. 145
Figure 8-1. Taronga District Map (After Newmont Holdings Pty Ltd, 1982). 149
Figure 8-2. Taronga Tin Project Regional Geology (After Newmont Holdings Pty Ltd, 1982). 151
Figure 8-3. Taronga Tin Project District Geology (After Newmont Holdings Pty Ltd, 1982). 152
Figure 8-4. Taronga Southern Zone Mineralisation (Drawn From Newmont Holdings Pty Ltd, 1982). 154
Figure 8-5. Geological Cross Section - Line 3525 mN (Drawn From Newmont Holdings Pty Ltd, 1982). 155
Figure 8-6. Taronga - dipole-dipole array IP pseudosection from Line 3525N (Drawn From Cattach, 1985). 156
Figure 8-7. Schematic showing the layout of the electrodes and their feeding wires with respect to the survey area. 157
Figure 8-8. The location of the survey area and current-carrying wire with respect to topography. 158
Figure 8-9. Taronga - Total Magnetic Intensity, H_S. 160
Figure 8-10. Taronga - TMI - Upward continued to 25 m. 160
Figure 8-11. Taronga - Normalised TFMMR, H_N. 162
Figure 8-12. Taronga - Normalised TFMMR, H_N, Reduced to Pole. 162
Figure 8-13. Taronga - First Vertical Derivative of H_N - Reduced to Pole. 164
Figure 8-14. Taronga - Corrected Phase Response. 164
Figure 8-15. Diagram illustrating the effect of elevation on the strength and direction of the magnetic field due to current flowing in a long straight wire. 166
Figure 8-16. The difference in the Primary correction calculated with and without consideration of elevation. 168
Figure 8-17. TFMMR corrected for the Primary field with topographic correction. 168
Figure 8-18. Location and Geological Map of the Eastern Batten Trough in the McArthur River Area. Hatched area is surface projection of the HYC deposit. (After Logan *et al.* 1990). 170
Figure 8-19. Geological cross-sections looking north (Profile A-B) and looking west (Profile C-D) through the HYC deposit (After Logan *et al.* 1990). 171
Figure 8-20. Electrodes and cable configurations of the MIP survey over the HYC deposit (After Hishida *et al.*, 1993). 173
Figure 8-21. Normalised horizontal magnetic field (H_N) contours (%) for current flow parallel to strike over the HYC deposit (After Hishida *et al.*, 1993). 174

Figure 8-22. Relative Phase Shift (RPS) contours (°) for current flow parallel to strike over the HYC deposit (After Hishida *et al.*, 1993). 175
Figure 8-23. Schematic showing the layout of the electrodes and current carrying wire with respect to the survey area. 176
Figure 8-24. HYC - Total Magnetic Intensity, H_S. 179
Figure 8-25. HYC - Normalised TFMMR, H_N. 179
Figure 8-26. Schematic showing the layout of the electrodes with respect to the survey area. 183
Figure 8-27. Total Magnetic Intensity, H_S. 186
Figure 8-28. Homogeneous Half-Space - TMI, H_S - Upward Continued 20 m. 186
Figure 8-29. Homogeneous Half-Space - Peak amplitude of H_{Mod}, H_{Pk}. 187
Figure 8-30. Homogeneous Half-Space - Theoretical Primary field, $H_{Primary}$. 187
Figure 8-31. Homogeneous Half-Space - Ground field, H_G. 188
Figure 8-32. Homogeneous Half-Space - Theoretical Normal field, H_{Normal}. 188
Figure 8-33. Homogeneous Half-Space - Normalised TFMMR, H_N. 189
Figure 9-1. Archaean Gold Prospect: Grid A - Total Magnetic Intensity, H_S. 195
Figure 9-2. Archaean Gold Prospect: Grid A - Normalised TFMMR, H_N. 195
Figure 9-3. Archaean Gold Prospect: Grid B - Total Magnetic Intensity, H_S. 196
Figure 9-4. Archaean Gold Prospect: Grid B - Normalised TFMMR, H_N. 196
Figure 9-5. Cu/Au Prospect: Grid C - Total Magnetic Intensity, H_S. 198
Figure 9-6. Cu/Au Prospect: Grid C - Normalised TFMMR, H_N. 198
Figure 9-7. Cu/Au Prospect: Grid D - Total Magnetic Intensity, H_S. 200
Figure 9-8. Cu/Au Prospect: Grid D - Normalised TFMMR, H_N. 200
Figure 10-1. The proposed SAM Capable Magnetometer System - Design Concept. 210

LIST OF PLATES

Plate 4-1. The TM-4 magnetometer contro ler showing the in-built cotton-thread odometer. 61
Plate 4-2. The EG&G Geometrics G-822A caesium vapour magnetic sensor. 61
Plate 4-3. The Zonge GGT-10 IP/EM Tran smitter. 71
Plate 4-4. The Zonge XMT-16 Transmitter Controller. 71
Plate 4-5. The Kohler Motor-Generator and Zonge VR-1 Voltage Regulator. 72
Plate 4-6. The Zonge VR-1 Voltage Regulator. 72
Plate 4-7. The TM-4 magnetometer syste n in hand-held configuration showing a single Geometrics G-822A sensor. 74
Plate 7-8. The TM-4 based SAM Receiver showing the mounting position of the Trimble SVeeSix GPS Receiver. 138
Plate 7-9. The SAM controller incorporatin g the Trimble SVeeSix GPS Receiver. 138

LIST OF TABLES

Table 4-1. The TM-4 Controller Technical Specifications. (After Geophysical Technology Pty Ltd, 1990). 60

Table 4-2. TM-4 Frequency Counter specifications (20 MHz reference clock) at ambient magnetic field values of 50000 and 60000 nT (After Lee, 1987). 69

Table 5-1. The naming convention and symbols used to describe the components of the SAM waveform. 76

Table 7-1. Specifications of the SAM-XMT Transmitter Controller (After McCarthy, 1994). 137

Table 7-2. Specifications of the SAM Signal Simulator (After Bradbury, 1994b). 141

Table 10-1. Survey specifications and data acquisition rates for SAM, EIP and MIP. 216

Table 10-2. Data acquisition costs for SAM, EIP and MIP surveys. 217

LIST OF SYMBOLS

Greek Symbols

ρ	resistivity
ρ_a	apparent resistivity
β	phase angle
π	pi
η	Planck's constant

Roman Symbols

C_1, C_2	current electrodes
D	declination of earth's magnetic field
E	the Zeeman energy difference
$f_{Max(Spatial)}$	maximum spatial frequency in magnetic profile
$f_{Max(Time)}$	maximum time-varying frequency of spatial origin due to traverse speed
$\mathbf{F}_E$	unit vector defining direction of earth's magnetic field
G	geometric factor
h	height of sensor above ground
H_G	Ground magnetic field
H_{Mod}	Modulation in the magnetic field due to transmitted signal
H_N	Normal magnetic field
H_{Norm}	normalised magnetic field
H_P	primary magnetic field (analogous to V_P)
$H_{Primary}$	Primary magnetic field due to current flow in current-bearing wires
H_{Pk}	Peak amplitude of SAM modulation
H_S	spatially-varying magnetic field
H_T	total magnetic field
I	inclination of Earth's magnetic field
I	current
I_P	primary current
M	chargeability
M_i	ith chargeability integration window
P_1, P_2	potential electrodes
t_1, t_2	times at beginning and end of integration window
V	velocity
V	voltage
V_P	primary voltage
V_t	voltage at time t
X_E, Y_E, Z_E	x,y,z-components of unit vector defining the earth's magnetic field

LIST OF ACRONYMS

AC	Alternating Current
AFMAG	Audio Frequency MAGnetics
AMT	Audio MagnetoTellurics
ASEG	Australian Society of Exploration Geophysicists
CSAMT	Controlled Source Audio MagnetoTellurics
DC	Direct Current
DHMMR	Downhole MagnetoMetric Resistivity
EIP	Electrical Induced Polarisation
ELF	Extremely Low Frequency
EM	ElectroMagnetic
ER	Electrical Resistivity
FE	Frequency Effect
GPS	Global Positioning System
GRI	Geophysical Research Institute
HDM	High Definition Magnetics
IP	Induced Polarisation
MIP	Magnetic Induced Polarisation
MMR	MagnetoMetric Resistivity
MT	MagnetoTellurics
PFE	Percent Frequency Effect
RF	Radio Frequency
RPS	Relative Phase Shift
SAM	Sub-Audio Magnetics
SP	Self Potentia
TFEM	Total Field ElectroMagnetics
TFMMIP	Total Field MagnetoMetric Induced Polarisation
TFMMR	Total Field MagnetoMetric Resistivity
TMI	Total Magnetic Intensity