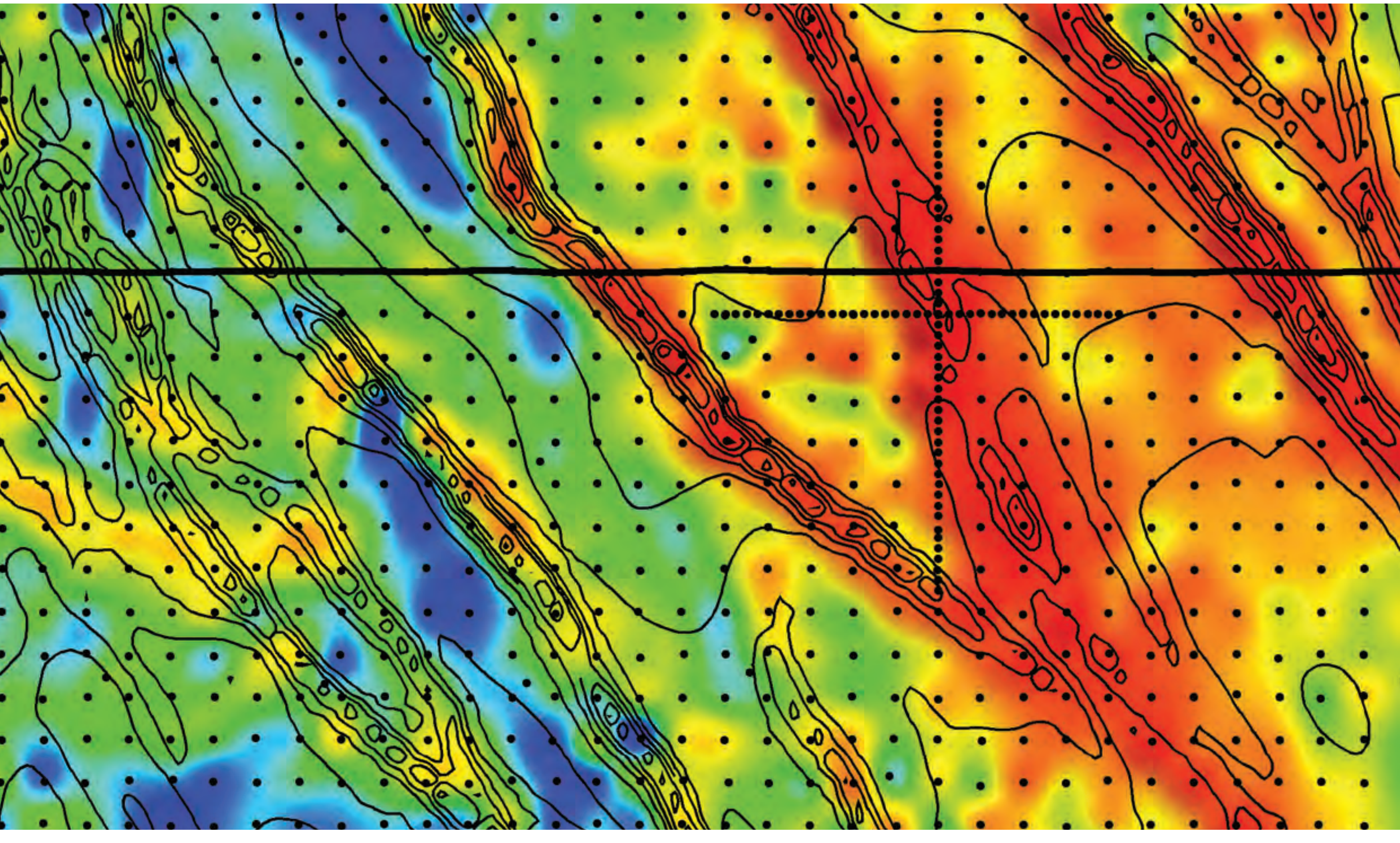
Exploration Magnetics

Theory and Practice



Editors: Phil Schmidt, James Austin, David Clark,
Keith Leslie, Mark Lackie and Clive Foss

Exploration
Magnetics

This book is dedicated to the memory of the late Professor Don Emerson, AM, PhD, who as a founding member of the Australian Society of Exploration Geophysicists, ASEG Past President, ASEG Gold Medal recipient, Co-Convenor of the ASEG's 1st Conference and Exhibition and former Editor of the ASEG's scholarly journal, Exploration Geophysics, *made extraordinary contributions to the profession of exploration geophysics in Australia over a career spanning six decades. For 28 years, Don was one of Australia's most eminent university teachers and researchers in exploration geophysics, mentoring many explorationists and researchers, as Head of Geophysics and finally as Head of Department of Geology and Geophysics, University of Sydney. After his university career, his passionate interest in petrophysical studies led to the establishment of Systems Exploration, which developed a comprehensive rock-properties testing facility, servicing the exploration and engineering industries. The Systems Exploration laboratory had extensive collaborations with CSIRO, particularly in the areas of palaeomagnetism, magnetic petrophysics and potential field methods.*

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Front cover: Vertical derivative of gravity image and magnetic (TMI) contours over Gairdner Dykes in the Gawler Craton of South Australia. Image by Clive Foss using data from the Geological Survey of South Australia (GSSA).

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CSIRO acknowledges the Traditional Owners of the lands that we live and work on across Australia and pays its respect to Elders past and present. CSIRO recognises that Aboriginal and Torres Strait Islander peoples have made and will continue to make extraordinary contributions to all aspects of Australian life including culture, economy and science. The use of Western science in this publication should not be interpreted as diminishing the knowledge of plants, animals and environment from Indigenous ecological knowledge systems.

May25_01

Foreword

It is indeed a privilege to introduce this latest earth science work of research and expertise from the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia's national science agency, with a global record of discoveries, innovations, inventions and leading-practice science in the mining and resources industries.

There is a clear line of sight between the economic importance of our nation's mineral resources industry and the opportunity that CSIRO has given to fostering a very deep dive into this practical collected research in exploration magnetics, both comprehensively underpinned by our national discovery-rich precompetitive magnetic datasets.

In 2024, the Australian Bureau of Statistics reported $3.95B of expenditure on mineral exploration across Australia. Successful exploration, leading to economic discovery, is fundamental to the nation's economy and the sustainability of Australia's mining industry, reported to have contributed a record $455B in export revenue in the 2022-23FY.

One of the key impediments to successful mineral exploration is the weathered cover sequence of rocks and sediments that conceals around 80% of Australia's prospective basement rocks. Using multiple geophysical methods along with geology and geochemistry has become fundamental in the undercover search for critical mineral resources, essential for Australia's industries and future economic prosperity.

Australia's world-leading precompetitive aeromagnetic coverage is a primary foundation dataset for the exploration industry in the analysis of prospectivity, optimum search parameters and project specific targeting. The challenge for magnetic exploration undercover is to extract the fullest understanding of the magnetic subsurface from the aerial survey measurement of total magnetic intensity.

As background for non-specialists and mineral explorers in international jurisdictions, it's relevant to reflect on the path of Australia as an early innovator and world leader in precompetitive geoscience and aerial magnetic surveying.

I had the pleasure in 2020 of working closely with author Doug Morrison on the production and publication of his book *Measuring Terrestrial Magnetism**, which recounts how the measurement of terrestrial magnetism has influenced the history of the world up until 1950.

In the 1940s there were major advances in magnetometry, and by the end of World War 2 the sensitivity of military magnetometers was rapidly improved. The mineral exploration industry applied these magnetometers to find new economic deposits of magnetic mineral ores. Countries including Australia, Canada and the United States directed their national geological survey departments to establish programs of major aerial magnetic surveying and mapping in the search for minerals and energy.

In 1945, Harold Raggatt, Director of the Australian Government Mineral Resources Survey, later Bureau of Mineral Resources (BMR), and his Chief Geophysicist, Jack Rayner, visited the American and Canadian geological surveys to investigate the potential for magnetic mapping of Australia from the air.

In the final chapter of his book, Morrison recounts the story of the BMR purchase in the late 1940s of two airborne magnetometers from the Royal Navy, which were significantly modified in Australia and installed in a DC3 aircraft in preparation for the first government magnetic aerial survey programs in the 1950s. In the following two decades, BMR first flew aeromagnetic and radiometric regional surveys across vast regions of northern Australia, and in collaboration with state and territory geological surveys began the systematic government regional magnetic mapping of known mineral domains and sedimentary basins with petroleum potential. In 1949, the first industry exploration aeromagnetic surveys were undertaken in Australia by major mining companies, including The Zinc Corporation, Broken Hill Proprietary Company Limited and Western Mining Corporation.

In the past six decades, the positive geoscience and funding collaboration of state, territory and federal geoscience agencies through successive government-funded exploration initiatives and joint national geophysical

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* Morrison WD (2020) *Measuring Terrestrial Magnetism: The Evolution of the Airborne Magnetometer and the First Anti-submarine and Aeromagnetic Survey Operations.* Australian Society of Exploration Geophysicists, Sydney.

mapping programs, covering every corner of Australia, has produced the world's best precompetitive high-resolution aeromagnetic datasets. Indeed, The Fraser Institute Annual Survey of Mining Companies over the past decade has regularly ranked Australia's prospectivity, underpinned by our free online national geoscience data, in the top five of all global jurisdictions.

Turning to *Exploration Magnetics*, this is a unique and complete advanced reference work for mineral explorers and specialist exploration geophysicists on all aspects of the theory and contemporary practice of magnetics. It covers the importance of analysing and understanding rock magnetic properties at the micro-scale through to the inversion/interpretation at exploration scale of magnetic source depth and configuration, induced and remanent magnetisation direction, continuously mapping subsurface magnetisation and contrasts in magnetisation properties.

Geoscientists with non-specialist experience in geophysics will nevertheless find some real exploration gems of wisdom in this work, including the extensive case study applications.

For the past four decades, Australia's aerial geophysical survey practitioners and contractors have continued to innovate, invent and refine their magnetic survey data acquisition systems, the majority delivering increasingly sensitive and ever lower noise levels in the final primary product – Total Magnetic Field maps and datasets.

We have known theoretically for many years that there is much more three-dimensional information that can be directly measured in the field, including total field gradiometry and even magnetic tensor gradiometry.

I refer to an excellent journal paper very much ahead of its time on magnetic interpretation by two authors of this book (Schmidt and Clark 2000[**]). This paper outlines compelling advantages for magnetic tensor gradiometry, noting the technical and instrumentational challenges at that time of operating SQUID technology in field environments.

In 2025, SQUID and field practical instrumentation has moved on, such that there are magnetic tensor gradiometry fixed wing and helicopter systems operating in North America and Southern Africa, but yet to be contracted for Australian survey operations. Sometime in the next few years, I hope that we will see the application of magnetic tensor gradiometry to our challenging and complex magnetic terrains under cover.

As a measure of the future-proof science in this book, I was delighted to see that estimation of magnetisation direction of a dipole source is covered in Chapter 7 for axial ratios of magnetic field components AND gradient tensor elements!

I am privileged to have had an association with all of the editors of this exceptional publication, each one recognised internationally and awarded as experts in this highly specialist area of exploration geophysics. Phil Schmidt and David Clark are both recipients of The Gold Medal of the Australian Society of Exploration Geophysicists (ASEG), the society's highest award for excellence in exploration geophysics. James Austin and his team are internationally recognised through their publications for the work on CSIRO's world-leading petrophysical rock property laboratory. Keith Leslie is also one of CSIRO's acknowledged inventors and experts in developing new geophysical systems, including magnetic surveying using the latest SQUID technology, an essential technology for the emerging area of magnetic tensor gradiometry. Clive Foss and Mark Lackie are widely recognised through their eminent publications as world experts in the practical analysis, interpretation and inversion of large minerals and environmental exploration magnetic datasets.

It is my view that this is an outstanding publication on the latest leading practice application of magnetisation and magnetic field studies to mineral exploration. This book is a must have for all practising exploration geophysicists, government geological surveys and other diverse users of geophysics for environmental, forensic and military applications and archaeology, as well as university earth science departments.

Congratulations to the editors and authors on your grand plan for producing this far-sighted work!

There is nothing else like this book. In the right hands, *Exploration Magnetics: Theory and Practice* will accelerate real breakthroughs in the search for Australia's next generation of critical mineral discoveries under cover.

Very Highly Commended,

[**] Schmidt PW, Clark DA (2000) Advantages of measuring the magnetic gradient tensor. ASEG *Preview*, April, pp. 20–26.

Ted Tyne
Former Director, Geological Survey NSW & Exploration NSW, Govt of New South Wales
Former Executive Director, Mineral Resources SA & PACE – Plan for Accelerating Exploration, Govt of South Australia
Founding Member, Past President & Honorary Member, Australian Society of Exploration Geophysicists (ASEG)

Dr Tyne has led a distinguished career in public geoscience programs in the NSW and SA Governments and the international airborne survey industry as well as in AMIRA geophysics research and teaching. He is known for his leadership of government-funded exploration initiatives, particularly high-resolution geophysical mapping surveys designed to stimulate exploration and bring forward new mineral discoveries. Ted has been directly responsible for initiating geoscience strategies and economic policies and delivering airborne geophysical projects, totalling more than 3.5 million line-kilometres of state and national precompetitive geophysical survey mapping, in partnership with Geoscience Australia, CSIRO and other state and territory geological surveys. In retirement, Ted continues to contribute to ASEG publications, symposia and conventions. (https://www.aseg.org.au/public/200/files/Ted%20Tyne%20Nov%202022a.pdf)

Contents

Preface

Geology is in large part a model-building science attempting to make the most of limited information to infer and extrapolate across large volumes of a sparsely or completely unsampled subsurface. This book investigates how subsurface models of magnetisation properties and distribution can be derived from magnetic field data.

An incorrect but nevertheless instructive statement is that 'the best geologist is the one who has seen the most rocks'. The basis for this statement is that no two examples of geological systems are identical and that geology is poorly predictable. The equivalent statement that 'the best magnetic field geophysicist is the one who has seen the most magnetic fields' is similarly untrue but conveys the same advantage of experience gained in every magnetic field investigation. Few published methods for magnetic field interpretation address irregular geological distribution of magnetisation or imperfections in magnetic field data. In consequence (and with notable exceptions) many academic publications have little meaningful impact in applied magnetic field studies. In this book we focus on the practical solution of problems and present extensive case study applications.

It is no accident that this book has originated from Australia. Australia has long been a leading supplier of metals to the world, and this forms a major pillar of the national economy. Discovery of future ore deposits beneath cover depends on remote sensing for which geophysics plays the key role. Australia has major advantages for mineral exploration. Necessarily, it has the geological endowment of resources to be discovered. It also has an excellent national coverage of FAIR (findable, accessible, interoperable and reusable) regional aeromagnetic data curated by Geoscience Australia and distributed by their GADDS (geophysical archive data delivery system) web utility. This regional data acquired mostly by Federal and State and Territory Governments, often as part of 'exploration initiative' programs, plays a critical role in the primary selection of areas for mineral exploration. Free availability of magnetic field data has been a key component in attracting mineral exploration to Australia and provides the data used throughout this book. CSIRO's palaeomagnetic and rock magnetic studies over many years are crucial in augmenting this magnetic field data to complete the circle of relationships between geology, mineralisation and the magnetic field.

Rocks are not expressly designed to optimise recording of the Earth's magnetic field or of processes such as mineralisation that they may have been subject to (the challenges of engineering a material to achieve that would be considerable). Ferromagnetism of rocks is of intricate complexity and is highly idiosyncratic, particularly for rocks within multi-phase mineral systems. The magnetisation of a rock is completely controlled by minerals that in most cases constitute only a few per cent or less of its volume, and the magnetisation of those minerals is in turn critically dependant on minor differences in chemistry, oxidation state and the size, shape and crystallographic imperfections of the mineral grains. Furthermore, recent advances in imaging ferromagnetism at ever smaller scales has revealed that fine-scale intergrowths play a more substantial role in rock magnetism than had formerly been widely appreciated. The palaeomagnetic and rock magnetism laboratory established by CSIRO in the 1970s has conducted leading research into the magnetisation of mineralised systems in all of Australia's major metallogenic provinces. This research has played a critical role in the exploration and development of Australia's largest mines and has promoted understanding of the considerable complexity of the magnetisation of mineral systems. Historical reports are available for download from the CSIRO potential fields team site (https://research.csiro.au/potential-fields).

The understandings gained from rock magnetic studies of known mineral systems across Australia are of great value in maximising recognition of similar as-yet-undiscovered systems beneath cover. For buried systems we lose the advantage of directly measured magnetisations and until samples for direct measurement of magnetisation are recovered from drilling we can only conduct poorly constrained inversion of magnetic field data. Substantial challenges of non-uniqueness in magnetic field inversion include lack of reliable analytic or statistical estimates of how distant a proposed solution may be from the truth. At present these limitations are insufficiently recognised and there is poorly justified acceptance of continuous, three-dimensional (voxel) inversion models of the subsurface. Only for 'brownfields' inversion in immediate proximity to existing mines and supported by extensive drilling constraints can space-filling magnetic field inversion models be developed with reasonable levels of confidence. A major suggestion we make repeatedly through this book, but that is only occasionally raised in published literature or scientific debate, is that the magnetic field is only informative at specific locations (that we term 'sweet-spots') determined by the subsurface geology and the magnetic field measurements. This message seems negative, but it is not. By isolating the most reliable information from a magnetic field inversion, that information and its higher reliability is highlighted and is not compromised by dilution with apparent information of little or no reliability.

Sweet-spots are predominantly due to the shallower magnetisations that produce field variations with sharp changes of curvature. The over-printed magnetic fields of deeper magnetisations are much poorer in this relatively diagnostic information. Space-filling voxel models distribute deeper magnetisations according to a predetermined expectation of 'depth functions' in the inversion algorithms. Many users of these models assume that the models are discoveries revealed by the inversion, but the depth distribution of magnetisation is as significantly determined by the inversion algorithm as it is by the ground. Alternative parametric models that we use extensively in this book are subject to equal if not greater discreditation if they are proposed to directly represent subsurface magnetisations. However, we use these models to recover their key statistics (parameters) that can be selectively presented as the most reliable information available from magnetic field inversion. Consider, for instance, a compact magnetisation for which the magnetic field cannot be distinguished from that of a homogeneous spherical magnetisation. Voxel inversions distribute the magnetisation across a cluster of neighbouring prisms, reporting a specific magnetisation in each voxel. A parametric model of homogeneous spherical magnetisation reports the horizontal and vertical coordinates of the centre of magnetisation, its mean strength and direction, and the radius of the sphere. The intensity of magnetisation and volume of the sphere can be multiplied to give the magnetic moment, and this should be considered the key estimate quantifying the magnetisation. Without independent knowledge of either the volume or intensity of magnetisation, no model specifying either value is justified. All acceptable models should, however, have a narrow range of magnetic moment values, common centres of magnetisation and common mean magnetisation directions. Inversions are better reported as a population of these reliable statistics, rather than as magnetisation or susceptibility values. Despite this, magnetic moments are rarely reported for models and few geoscientists are familiar with the units used or the values to expect.

The second section of this book (Chapters 5 to 15) focusses on recovery of source magnetisation direction from magnetic field data – a field to which CSIRO has made considerable contributions, including the PhD thesis and multiple publications of David Clark, and through industry collaborations (particularly with Encom Technology and more recently Tensor Research). For many years, magnetic field inversion was performed with a 'head in the sand' neglect of remanent magnetisation because of conceived difficulties in addressing the issue of an unknown magnetisation direction. Obvious expression of remanent magnetisation in magnetic field data is only recognised in specific cases where it has a similar or greater amplitude than the induced magnetisation and a significantly different direction. Nevertheless, remanent magnetisation is an intrinsic characteristic of ferromagnetism and is a significant contribution to all measured magnetic field variations sourced in crustal geology. The traditional measure of the relative strength of remanent to induced magnetisation (the Koenigsberger ratio or Q factor) is insufficient to determine recognition of remanent magnetisation in magnetic field data. Other factors that are significant are the departure of the remanent magnetisation direction from the local geomagnetic field direction, the spatial distribution of magnetisation, overlap of magnetic fields due to adjacent magnetisations and the measurement sampling of the field. The external static magnetic field expression of a magnetisation reveals only the total magnetisation that is the vector resultant of its induced and remanent components. Since approximately the start of this century, there has been a substantial transition from inversions that neglected remanent magnetisation to inversions that report supposed continuous subsurface distributions of magnetisation of varying direction. These complex models face the standard restriction of inversion, that matching the input field does not in itself justify the model. Geologists like and often ascribe significance to irregularities in such models because these irregularities are consistent with the expected geology, but it is specifically those details that are of lowest reliability. Wherever a simple, homogeneous model satisfactorily explains a set of magnetic field measurements, considerable independent justification is required to propose a more complex, inhomogeneous model. All models should, if possible, be reduced to their minimum key statistics.

A further factor repeatedly raised in the book (see Chapter 4 in particular) is the resurrection of what have become mostly archaic terms of ‘proximal’ and ‘distal’ to describe the declining information content of a magnetic field as it is measured further from a source magnetisation.

The concept of continuously mapping subsurface magnetisation follows from the apparently continuous mapping of the magnetic field imaged by magnetic field grids. These grid images are derived from a finite set of samples of the magnetic field and are not the continuous coverage they appear to be, with many grids much poorer representations of the true magnetic field than is commonly realised. Magnetic field grids generated from measurements at closer line spacing or at lower elevation can substantially revise perception of the underlying distribution of magnetisation. There is a theoretical ability to ‘downward continue’ a magnetic field grid from the measurement elevation to a lower elevation but this is rarely feasible because of sampling limitations, and the process does not create new information. Grids also support enhancement of data, such as computation of gradients (as widely used throughout this book). However, any use of enhancements must carefully consider limitations of the primary data because they are distorted by any insufficiencies in both the primary measurements and the gridding algorithm used. Quantitative analyses of the magnetic field should where possible be restricted to primary data measurements. As discussed in Chapters 2 and 3, estimation of depth to the top of magnetisation from grid data is particularly prone to error.

We take full responsibility for the work and views reported in this book but happily acknowledge input from interactions with colleagues both within the vibrant community of exploration geophysicists across Australia, well represented by the Australian Society of Exploration Geophysicists (ASEG), and internationally. We particularly wish to acknowledge the key roles played by the late Peter Milligan and Richard Lane of Geoscience Australia in enriching development of potential field geophysics in Australia.

Finally we would also like to acknowledge CSIRO’s Deep Earth Imaging Future Science Platform for supporting the publication of this book and the encouragement of Tim Munday to achieve this.

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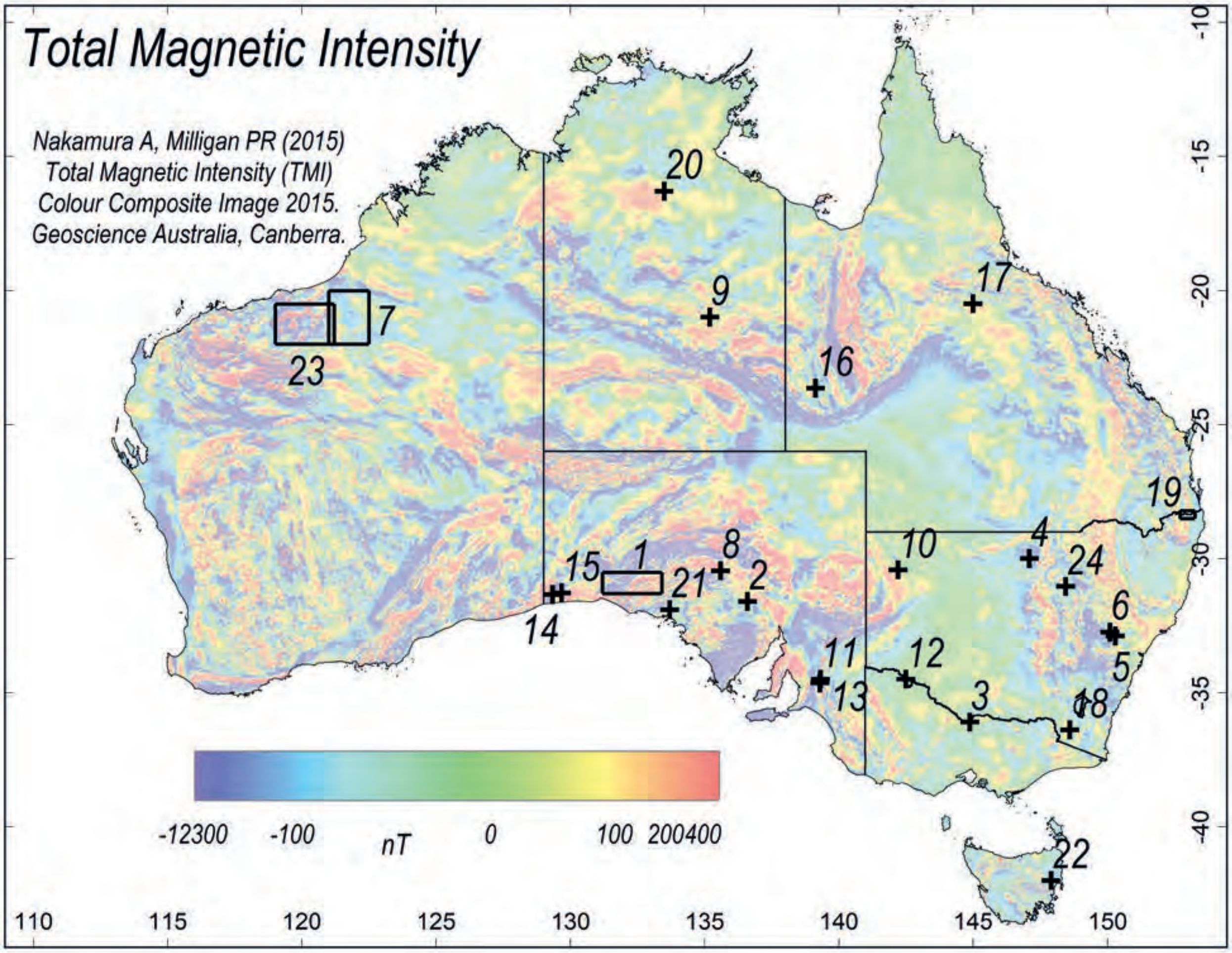
Map index

Australian study areas are shown on the map below, along with a table (opposite) listing corresponding chapter sections that include those studies.



Nakamura A, Milligan PR (2015)
Total Magnetic Intensity (TMI)
Colour Composite Image 2015.
Geoscience Australia, Canberra.

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