MAGNETIC AND GRAVITY INTERPRETATION
OF AN AREA OF
PRECAMBRIAN SEDIMENTS IN AUSTRALIA

by

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A thesis submitted to the University of Adelaide
in fulfilment of the requirements
for the degree of Doctor of Philosophy

September, 1972

This thesis contains no material which has been accepted for the award of any other degree or diploma in any University. To the best of the author's knowledge and belief, the thesis contains no material previously published or written by another person, except when due reference is made in the text.

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ABSTRACT

The interpretation of aeromagnetic and ground magnetic surveys made over Adelaide System sediments in the Adelaide Geosyncline (South Australia) shows that long linear magnetic anomalies are caused by magnetic sedimentary beds. Of the 14 magnetic beds recognized in the Wilpena, Umberatana and Burra rock groups near Orroroo, only one is an iron formation; the others lie within shales, slates, quartzites and tillites. The magnetic beds have the form of thin sheets conformable with the sedimentary layering. These magnetic sheets are interbedded with non-magnetic layers forming beds which have a total thickness of up to 300 metres. Individual sheets are weathered to depths of up to 200 metres. The beds are usually magnetized in a direction close to the geological layering. Remanent magnetism is usually a more important contributor to the magnetic anomalies than the magnetic susceptibility. Interpretation of the anomalies indicates that in the Lower Tapley Hill magnetic bed, a component of remanent magnetism acquired before folding lies in a direction of 135° east of north, and is close to the geological layering; the direction of the pre-folding component of remanence was deduced by a study of vertical field anomalies around anticlinal structures. The strength of magnetization of the most strongly magnetic beds is about 10^{-3} c.g.s. units.

While most of the shallow source magnetic anomalies observed over the Adelaide Geosyncline are caused by magnetic beds within Adelaide System sediments, there are some which are caused by other sources. Basic igneous rocks within diapirs are magnetic. With the wide spacing (1.6 kilometres) of aeromagnetic flight lines it is difficult to recognize anomalies which might be caused by small unrecognized or unexposed igneous bodies. A weak aeromagnetic anomaly (4 gammas) was recorded over small carbonatite dykes in the Walloway Diapir.

Most of the anomalies over plains of Quaternary sediments are probably produced by variations in thickness of the magnetic part of the sediments, but susceptibility changes within the sediments may also be important. The magnetic susceptibility of the Quaternary sediments is about 1,000 x 10^{-6} c.g.s. units at one locality.

The magnetic pattern also shows various broad anomalies and lineaments which are probably caused by deep magnetic bodies below the Adelaide System sediments.

It appears that the average density of Adelaide System sediments and older basement rocks is approximately the same; thus the regional Bouguer anomaly data do not give information on the depth to the floor of the Adelaide Geosyncline. Negative gravity anomalies with an amplitude of 20-40 milligals indicate that low density granite batholiths of considerable size and depth extent occur in the Mt. Painter area, near Glenorchy Homestead, and in the area of the Anabama Granite. There are various long gravity gradients which may be caused by density changes in the basement below the Adelaide System sediments.

Comments which clarify various points raised during examination of the thesis are included as Appendix A7.

ACKNOWLEDGEMENTS

The work for the thesis was carried out at the Department of Economic Geology of the University of Adelaide while the author was in receipt of a Commonwealth Post Graduate Award. The author acknowledges with pleasure the stimulating supervision given by Professor D. M. Boyd during the research. Various geologist colleagues at the University provided valuable assistance with the work. The author is particularly grateful for help by Dr. V. Gostin and Mr. J. Sumartojo of the Department of Geology and Mineralogy, and Dr. R. Both and Mr. J. Barry of the Department of Economic Geology.

The author thanks the Director of the South Australian Department of Mines for allowing access to original aeromagnetic flight charts and other unpublished data for the research project, and for providing office space in which to study the material. Officers of the Department of Mines gave valuable assistance; in particular, thanks are expressed to Mr. G. Whitten, Mr. D. McPharlin, Mr. R. Gerdes and Mr. B. Milton.

During the research work the author was on leave without pay from the Bureau of Mineral Resources, Canberra. The author thanks the Director of the Bureau for providing the data from the 1970 regional Helicopter Gravity Survey of the eastern part of South Australia, and for allowing access to other unpublished material. The author is particularly grateful for the assistance and advice given by Mr. F. Brown in preparing a report on the gravity work for the Bureau, and for the drafting by Mr. R. Sandford in connection with the gravity work.

While the research project was essentially geophysical, it was necessary to investigate the mineralogy of various rock samples.

The author gratefully acknowledges the help given by Mr. W. Mussared in preparing thin and polished thin sections, and the mineragraphic work by Dr. A. Whittle, Dr. R. Both and Mr. J. Barry.

Various mineral exploration companies assisted with the work by providing drill hole material, and allowing access to unpublished geophysical information from various areas. Although the geophysical data (mainly magnetics) are not discussed in the text of the thesis, it provided valuable checks on the conclusions drawn from the author's work. The author particularly thanks Mr. I. Haddow of R.M.C. Minerals, and Mr. K. Price of Minerals, Mining and Metallurgy Ltd. for drilling percussion holes at three localities of interest. The author acknowledges the assistance of Mines Exploration Pty. Ltd. and R.M.C. Minerals for providing field hands to assist on ground magnetometer surveys in the Orroroo area. The author acknowledges the help by Mr. D. Christie of Broken Hill South Pty. Ltd. in giving access to geophysical data from ground magnetometer surveys north of Waukaringa. The author acknowledges the assistance by Mr. D. Colchester and Mr. J. Stracke of Stockdale Prospecting Ltd. in allowing the author to examine kimberlite dykes and plugs in the Terowie area, and for allowing access to an unpublished paper on the kimberlites in the area.

The drafting of some of the diagrams for the thesis was done by the author. The author acknowledges the work by Mr. R. Cammell of the Department of Economic Geology, Miss A. Hockey and Mr. R. Sandford of the Bureau of Mineral Resources, who between them drafted approximately two-thirds of the diagrams. Mr. R. Sprod of the Department of Economic Geology did most of the photographic work on the diagrams and his help is gratefully acknowledged. The author acknowledges the help by his wife, Marilyn Tucker, Miss G. Harper and Miss K. Duncan, who typed drafts of the thesis and other work during the research work. Mrs. H. Ball of the Department of Economic Geology typed the thesis and ran off the copies; her help on this exacting task and other assistance she gave during the course of the work is gratefully acknowledged.

PUBLICATIONS

Two papers were completed during the research work.

1. "Reconnaissance Helicopter Gravity Survey in the Flinders Ranges, South Australia 1970" by D. H. Tucker and F. W. Brown. Bur. Miner. Resour. Aust. Rec. (unpublished).

This document is the author's interpretation of the helicopter gravity survey flown by the Bureau of Mineral Resources for the South Australian Department of Mines. When the author commenced research for the thesis in March, 1969, he asked the Director of the Bureau for access to the gravity survey data as soon as it was available; the Director agreed on condition that an official document be written which included interpretative work for the thesis. The main lines of investigation were the problem of densities and the problem of gravity lows associated with granite bodies. However, other lines of study such as the relation of regional gravity trends and lineaments to the location of mineral occurrences, were also pursued because the author considered these of importance in an interpretation of regional gravity data in an area regarded as a mineral province.

The interpretative work in the official document is solely that of the author except for the two appendices 1 and 2 which were written by Mr. F. W. Brown of the Bureau.

2. "Lamprophyric intrusions of probable carbonatitic affinity from South Australia" by D. H. Tucker and K. D. Collerson. Geol. Soc. of Aust. (accepted for publication, May, 1972).

In the course of study of the aeromagnetic data for the ORROROO 1:250,000 sheet the author was interested in magnetic anomalies which were apparently unrelated to the magnetic Adelaide System sediments. It was while measuring the densities of hand specimens collected during geological mapping of ORROROO by Binks (1968), that the author recognized that one rock which came from an area already selected by the author as a possible area of igneous intrusions, resembled kimberlite. The significance of the sample had not previously been recognized. Subsequent field studies by the author and Mr. K. Collerson (petrologist) in the area where the original specimen had been collected (Walloway Diapir) located five dykes and two plugs of primary carbonate rocks in an area some 500 by 200 metres in size.

The detailed petrography and geochemistry of the rocks from the various intrusive bodies were investigated by Collerson; the author carried out a study of the magnetics of the area. A joint paper was written on the intrusives.

TERMINOLOGY AND GEOPHYSICAL UNITS

Terminology

SADM - South Australian Department of Mines

BMR - Bureau of Mineral Resources (Geology and Geophysics)

The Department of National Mapping has divided Australia into 1:250,000 areas, 1° latitude high by 1.5° longitude wide. These areas have been given official names, and in the thesis are referred to in capital letters, e.g. ORROROO. Geographical place names are referred in lower case, e.g. Orroroo.

Units

For work with magnetic anomalies, the unrationalized c.g.s. system of units is used together with the usual subdivision of the intensity of the magnetic field (Oersteds) into gammas (Chiswell & Grigg, 1971). Thus 1 Oersted = 10^5 gammas. Volume magnetic susceptibilities are quoted as having "c.g.s. units"; it would be acceptable to use the alternative notation "e.m.u./cm^3". Intensities of magnetization are referred to in c.g.s. units. Lengths are mostly scaled in metres (m) or kilometres (km). This does not conflict with the use of c.g.s. units, because in standard formulae for magnetic anomalies due to bodies of various shapes (e.g. Gay, 1963), the dimensions of length, which describe the depth and width of the bodies, cancel out.

For work with gravity anomalies, the standard subdivision of the acceleration due to gravity, the milligal (mg), is used. Thus 10^3 mg = 1 gall = 1 cm/sec^2.

Volume I

Chapter 1

FRAMEWORK OF THE PROBLEMS

1.1 Introduction to the thesis work

This thesis presents an interpretation for some of the special features evident in regional aeromagnetic data and Bouguer gravity data from an area of Precambrian sedimentary strata in eastern South Australia. As yet, very little detailed work of the kind discussed in the thesis has been done on the regional geophysical data for Precambrian areas of Australia or other parts of the world. It is hoped that the thesis will stimulate other research, both geological and geophysical, in the thesis area and other areas of Precambrian metasediments in Australia (Fig. 1.1).

Most of Australia has now been surveyed with both aeromagnetics and Bouguer gravity networks either by or on behalf of the Bureau of Mineral Resources (BMR). The primary purpose of most of the work has been to delineate sedimentary basins prospective for oil and to this end the data have been very useful. In the course of the work great areas of Proterozoic and Archaean rocks have been surveyed (e.g. the Kalgoorlie area where banded iron formations are strongly magnetic), but for these areas no detailed interpretation has been published. The main problem is that to interpret all of the available data would take a great number of geophysicists a great deal of time. For example, there are more than two million line miles of aeromagnetic charts, and to carry out a line by line analysis of this in conjunction with brief geological studies would take about 300 man years. Reporting on regional surveys is usually undertaken by the BMR, and so far, the reports have mainly been very brief and point out some of the most important features.

In some areas of particular interest, extensive ground follow-up studies have been carried out by government agencies and published, e.g. Tennant Creek (Daly, 1957), Savage River (Eadie, 1970). In addition, mineral exploration companies have worked in many areas of interest. This work is unpublished and is not available.

Because of the current interest in mineral exploration of the Precambrian shield areas of Australia, it is timely to present a study of some special features of interest in the geophysical data for an area where the geology is fairly well known. It is to be hoped that similar work will soon be carried out in areas where the geology is not well known, because it is clear that much useful information is available in the geophysical data.

The area chosen for study in this thesis is the Adelaide Geosyncline (Fig. 2), an area where the stratigraphic succession for sediments of Upper Proterozoic age (Adelaide System sediments) is established, and the geology is fairly well known. Figure 1.2 shows the location of the Adelaide Geosyncline in South Australia and illustrates the geology of the area. Figures 1.3 and 1.4 show the Bouguer anomalies and aeromagnetic anomalies over the area of greatest interest in the thesis.

The problems to be studied are

1. magnetic anomalies which are caused by near surface sources associated with Adelaide System sediments, and
2. Bouguer anomaly lows which appear to be related to granites.

There are special difficulties in interpreting regional geophysical data. The first is the enormity of the task of studying all recorded anomalies. The second is the problem of obtaining suitable drill core material.

For the thesis research on magnetic anomalies, special attention was given to the ORROROO sheet, an area of about 15,000 sq km, for which detailed geology maps and the most recent aeromagnetic survey data were available (Figs. 1.5 & 1.6 in the pocket of Vol. 2). Apart from the factor of quality of the data for ORROROO, the area was selected for detailed work because it appeared that a change in magnetic properties of Adelaide System sediments occurs across the area. In the regional Bouguer anomaly data, a few special anomalies were selected for study.

During the course of the research, a general investigation of the geophysics was carried out for the entire Adelaide Geosyncline. At the outset it was hoped that many aspects of the geophysics could be fully pursued, and that an appraisal could be given for the whole area. It was found that this was far too ambitious a project for one Ph.D. As various avenues of research were followed it became evident that they in themselves could be the subjects of further M.Sc. or Ph.D. researches.

For example, the aeromagnetic and Bouguer gravity maps show evidence of a fracture pattern in the basement of the Adelaide Geosyncline. Deep source magnetic and gravity anomalies are truncated or are displaced along distinct lineaments. Other anomalies line up into distinct lineaments. Features like these have been qualitatively interpreted by Gay (1972) as indicative of basement faults. To quantitatively interpret the anomalies for basement structures is very difficult and is a major project. Thomson (1965) considers that mineral occurrences in the Adelaide Geosyncline form lineaments indicating that deep fracturing controlled the emplacement of minerals into the Adelaidean sediments. Clearly a full investigation of the basement fracturing would be valuable in the area.

A second example, which comes from the author's work, is that the geosynclinal sediments are often deeply magnetically weathered; as yet geological and geophysical studies have been confined to the weathered zone. It would be of interest to work with fresh rock samples to compare the geophysical and geological properties with results from the weathered material. The author's work with magnetic anomalies due to shallow sources is the first to use geophysics to put a quantitative estimate on depth of weathering of Proterozoic aged strata in the Adelaide Geosyncline. However, the major problem in following the investigation to a full conclusion is that there is little drill core available from below the weathered zone. Most material comes from percussion holes which do not exceed about 100 m in depth. The holes are located in the zone of enrichment of interest in mineral exploration. Clearly an investigation of the kind suggested above would be of value in the area, but its success rests with being able to obtain fresh cores for study. This is beyond the resources of the University of Adelaide and would have to be carried out in close cooperation with mineral exploration companies. The author approached 35 companies active in the Adelaide Geosyncline, and although they all offered some help, none was prepared to drill deep holes for pure research purposes.

1.2 Geology of the Adelaide Geosyncline

1.2.1 General geology

The name 'Adelaide Geosyncline' was given by Sprigg (1952) to an area of fold mountains which consist predominantly of sediments of Upper Proterozoic age and to a lesser extent of sediments of Cambrian age. Figure 1.2 shows the general geology of the Adelaide Geosyncline.

The mountains include the Willouran Ranges in the north-west, the Flinders Ranges in the north and central areas, the Olary Ranges in the east near the Willyama Block, and the Mt. Lofty Ranges in the south of the geosyncline. Most of the exposure has low relief with gently undulating hills rarely exceeding 200 m above sea level. The highest peaks reach 700 m in the Northern Flinders Ranges and the Mt. Lofty Ranges.

The geology of the area has been discussed by Thomson (1970) and Parkin (1969) who have also summarised the work by previous authors. The Adelaide Geosyncline forms a north/south belt of relatively unaltered sediments, flanked by blocks of older crystalline and metasedimentary strata of the Gawler Platform in the west and the Willyama Block in the east. The older strata are of Lower Proterozoic and Archaean age, and consist of granite gneisses, granulites and metasediments, together with acid intrusives and extrusives of considerable size. Small inliers of this material occur in the north, in the Mt. Painter Block, and in the south, in the Mt. Lofty Ranges. The Gawler Range Volcanics have been dated by Compston et al. (1966) at 1535 ± 25 m.y., and this is thought to indicate the youngest major tectonic event on the Gawler Platform (Thomson, op. cit.).

The name 'Adelaidean' has been given to the time interval in which 'Adelaide System' strata, the main material in the Adelaide Geosyncline, were deposited. Adelaidean time extends from the base of the Cambrian at about 560 m.y., back to approximately 1400 m.y. (Parkin, 1969, p.49). Sedimentation continued at least until Middle Cambrian time when the Adelaide Geosyncline underwent orogenesis and mild metamorphism which continued until early Ordovician time. The youngest reliable date for the orogenic event is 473 m.y. for the Anabama Granite, which intrudes sediments of Adelaidean age south-east of the Willyama Block.

1.2.2 Stratigraphy

The stratigraphy of Adelaidean and Cambrian aged sediments has been discussed by Parkin (1969, Chapters 2 and 3). The most recent stratigraphic subdivision which is now in common usage is that proposed by Thomson et al. (1964), and later slightly modified by Thomson (1966) and Forbes (1971). Figure 1.7 summarises time and rock terms used in the Adelaide Geosyncline and adjoining areas. Further details of the stratigraphy are discussed in Chapters 3 and 4.

The total stratigraphic thickness of Adelaide System sediments in the Adelaide Geosyncline is believed to be about 20 km (Parkin, 1969, page 81). The sediments are mainly shallow water marine detrital strata except for one volcanic bed (the Wooltana Volcanics) which occurs locally around the Mt. Painter Block. Dominant rock types are clean washed sandstones (quartzites), red, green and grey shales, and siltstones and carbonates. Two tillitic formations are recognized in the section, the Sturt Tillite being of widespread distribution and occasionally containing ironstone horizons and the Yeralina Subgroup being of local distribution. The total stratigraphic thickness of Cambrian sediments exceeds 15 km in the south of the geosyncline. However, in the north it is much less. Cambrian strata are known to underlie other Palaeozoic and Mesozoic strata in the sedimentary basins flanking the geosyncline (Fig. 1.2). The lithology of Cambrian strata is similar to that of Adelaidean strata and will not be discussed in the thesis.

One problem in mapping in areas of stratigraphic changes in Precambrian sediments is the inherent lack of fossils and the consequent lack of satisfactory time lines. In the Adelaide Geosyncline, time significance is associated with ubiquitous formations. For example, the Sturt Tillite consistently underlies, and the Nuccaleena Dolomite overlies, the Farina and Yeraline Subgroups in which facies changes are recognized. Daily (1963) pointed out the general lack of recognized fossils in the Precambrian section; until dates are applied the markers should strictly be considered lithostratigraphic rather than stratigraphic markers. The application of the term 'stratigraphic markers' as used by the South Australian Department of Mines (SADM) is used in the thesis.

1.2.3 Igneous intrusions in the Adelaide Geosyncline

Igneous activity was not common in the area during deposition of the Adelaide System sediments.

The Wooltana Volcanics which lie near the base of the Adelaidean succession are known only locally around the Mt. Painter Block. These may be equivalent in age to the Roopena Volcanics which outcrop in an area of about 10 sq km on the west side of the Flinders Ranges, although neither stratigraphic nor radiometric evidence has proved it. Unless some of the sediments in the 20 km or so of Adelaidean succession are unrecognized lavas or tuffs, the Wooltana Volcanics are the only undoubted igneous material of Adelaidean age.

Extrusive igneous rocks occur at the base of the Cambrian succession. These are the basic Truro Volcanics on the east side of the Mt. Lofty Ranges; they outcrop over an area of about 10 sq km and are up to 600 m thick. The lavas lie unconformably on Adelaidean strata which were previously gently folded and eroded. The extent of the volcanics to the east under Palaeozoic and younger sediments of the Murray Basin is unknown.

Except for the south of the geosyncline, east of Adelaide, geological maps published by the SADM show few large igneous bodies emplaced in Adelaide System or younger sediments.

The largest intrusive known in the whole area is the Anabama Granite, 40 km to the south-west of the Willyama Block. This granite body is recognized in the field as a number of outcrops of the order of 2 km across on the southern limb of an anticline of Adelaidean sediments. The exposed granites lie within an area 50 km long by about 15 km wide. Mirams (1961) suggested that the individual outcrops coalesced at depth into a batholith. East of Adelaide, in the area of strongest metamorphism of the geosynclinal deposits (Fig. 1.2), numerous small pegmatite dykes or granites some 0.5-5 km in length are known. Some of these were emplaced in Adelaide System sediments but most are within Cambrian aged strata.

In the central and northern parts of the geosyncline, which are of most interest in the thesis, intrusives are usually very small and are often associated with areas of diapiric breccia (Dalgarno & Johnson, 1965).

Basic rocks, chiefly dolerites, are frequently found in the breccia (Coats, 1964). Usually the basics are dykes a few metres long or small plugs; these were intruded during and after emplacement of the breccia.

Two areas of diorites are known. In the southern part of the Paratoo Diapir, diorites up to 2 sq km in area intrude diapiric breccia and the enclosing Adelaidean formations over an area of about 10 sq km. The contact relationships of the Paratoo diorites have been discussed by Binks (1971). 45 km to the south of Paratoo, diorites are recognized near Bendigo Homestead (Mirams, 1964). The contact relationships of these are not known, but the SADM is drilling in the area and more should be known before long.

1.2.4 Structure and metamorphism

The form of the Adelaide Geosyncline as considered by Thomson (1970) is shown on Figure 1.8. Thomson's map was compiled from geological and magnetic interpretations and shows basement form lines and important structural features for the area.

The orogeny which terminated Cambrian sedimentation in the Adelaide Geosyncline produced most of the present structure of the area. This event has been discussed by Parkin (1969, Chapters 2 and 3) and Offler and Fleming (1968) who have also summarised earlier work.

There is a range of intensity of deformation and metamorphism within the Adelaide Geosyncline (Fig. 1.2). Deformation is strongest in the Olary Ranges and extends south into the northern Mt. Lofty Ranges. Folds are linear and arcuate. Biotite grade of metamorphism is attained and slaty cleavage is common (Preiss; Offler & Fleming, op. cit.; Binks, 1971). This area corresponds to the area of strongly magnetic sediments which is discussed later. To the north-west, in the Central Flinders Ranges, folds are less intense and commonly form open domes and basins. Dips are usually less than 45^{0} and slaty cleavage is absent. In this area magnetism of sediments is weak. In the Northern Flinders Ranges deformation is strong and once again sediments are often strongly magnetic. While, to be strictly correct, the strata of Adelaidean age should be referred to as 'metasediments', in the literature on the Adelaide Geosyncline they are called 'sediments', and this latter terminology is used in the thesis.

1.3 Framework of the geophysical problems studied

A feature of special interest is that the great thickness of strongly folded Adelaidean sediments contains very few volcanics. In the Adelaide Geosyncline volcanics are only locally recognized near the base of the succession; these are conformable with the sediments and their total thickness does not exceed 2 km. However, although only one volcanic bed is known, the Adelaidean strata are magnetic and the contour maps indicate that linear magnetic anomalies closely follow the geological layering (Tipper & Finney, 1966) at several levels in the stratigraphic succession. Figure 1.4 shows some of the magnetic features important to the thesis and in particular indicates the widespread extent of linear anomalies associated with Adelaidean strata.

In addition to the linear magnetic anomalies attributable to sediments, there are very broad anomalies which appear to come from very deep sources possibly below the Adelaidean sediments. These are most prominent in areas where the magnetic effect of sediments is weak, but even where the sediments are strongly magnetic, superimposed broad anomalies are evident. BMR reporters, Tipper and Finney (1966), Young and Gerdes (1966), and Milsom (1965), have stated that most of the broad anomalies come from deep within or below the Adelaidean strata and have estimated depths to basement for the Adelaide Geosyncline. Their work has been confined to areas where sediments are only weakly magnetic. It is necessary to consider the strongly magnetic sediments in detail to establish whether it is a valid procedure to interpret broad magnetic anomalies in these areas for depths to basement.

Another feature of interest in the Adelaide Geosyncline is that very few igneous intrusive bodies more than a few metres across are recognized. However, the magnetic and gravity maps show many nearly circular anomalies which might be caused by unrecognized intrusive sources close to the surface. Tipper and Finney (1966) and Bennett (1968) stated that the magnetic anomalies attributable to intrusives may also indicate the presence of unrecognized or buried diapiric structures in the area. Small intrusive dolerites and other basics are recognized in most of the diapirs in the Adelaide Geosyncline (Dalgarno & Johnson, 1965; Coats, 1964). As yet no one has published confirmatory evidence that the small circular anomalies are caused by either diapirs or intrusives.

While geological and aeromagnetic studies have contributed to the understanding of the shape and depth to basement of the Adelaide Geosyncline, the gravity data have not yet been fully assessed to find whether a useful contribution can be made to the problem. Figure 1.3 shows the Bouguer gravity contour map and the geology for the area of most importance to the thesis. The most prominent anomalies are lows. In the east the lows are associated with granites. In the west the two prominent lows are elongate features lying approximately along longitude 138°. These have an unknown source but appear to be due to very deep density contrasts.

Regional geophysical maps can be expected to delineate the large-scale features of an area and BMR reporters, including the author, have done this for most of the Adelaide Geosyncline. Therefore it is now of special importance to work in detail over some of the best defined anomalies in the area to find what they mean and to show how much can be derived from the regional geophysical data. To do this has been the main purpose of the thesis research.

Three specific problems are discussed in the thesis. These are:

1. Do the linear magnetic anomalies over Adelaide System sediments indicate the presence of conformable magnetic beds, and what special characteristics of the beds can be revealed by magnetic interpretation?

2. Can anomalies be selected from the aeromagnetics which are likely to be caused by unrecognized or unexposed intrusive bodies in areas of Adelaide System sediments?

3. What interpretation can be made for the Bouguer gravity lows on the east side of the Adelaide Geosyncline?

Chapter 2

SCOPE OF THE THESIS

2.1 Scope

The scope of geophysical studies of geological problems can be extremely wide. For example, if it is known that a rock body is magnetic, then magnetic anomalies can be interpreted to give information on the body's shape, size, depth and magnetization. If suitable rock samples are available then magnetic properties can be directly measured. Magnetic minerals causing the rock's magnetism can be identified and the special details of the rock mineralogy and petrography can be revealed by microscopic work. There is scope for several years' work on a single magnetic body.

For the thesis research it was decided that the main emphasis should be placed on a preliminary investigation of magnetic and gravity anomalies in a large area rather than on the detailed analysis of one or two special problems in a small area. While the latter approach would have been possible, it was considered that for the area studied, the former approach would have the advantage of providing new information of wide appeal to geologists, and furthermore, would lay the groundwork for more detailed geophysical investigations in the future.

After 18 months' work it was considered that one particular sedimentary formation (the Tapley Hill Formation) was of special interest because it contains a magnetic zone which can be traced for hundreds of kilometres along strike. It was considered that a study of fresh and magnetically weathered rock could provide information of application to other magnetic problems in the area. Thus at that stage of the work, the research nearly became oriented to the lines of palaeomagnetic research. The problem was to get magnetically fresh rock samples from a deeply weathered formation. Because suitable material was unavailable and an appeal for new drill holes met with limited success, this line of research was abandoned. Information on the magnetic properties of the formation was obtained from the magnetic anomalies.

When the author left the BMR to undertake Ph.D. research, it was agreed that when the BMR completed its regional helicopter gravity survey of the Adelaide Geosyncline, he would have the first opportunity of interpreting the data. It was agreed that if the offer was accepted, then the author would write an interpretative report for the BMR. The report was written. It is currently being edited by the BMR and will shortly appear in the unpublished 'Record Series' (under joint authors, Tucker & Brown) and will later be published in the 'Report Series'. Only part of the work included in the 'Record' is presented in the thesis.

Wherever possible the author made use of the University of Adelaide's CDC 6400 computer to assist with interpretations. A list of the programs and their functions is included as Appendix A5. All programs, with the exception of one to find the gravity or magnetic anomaly due to a body of arbitrary shape, were written by the author. No new special interpretative technique was devised because it appeared that there was a sufficient framework of techniques available within published literature.

2.2 The data studied

Figure 2.1 shows an index map to 1:250,000 sheets of eastern South Australia. Each sheet is 1.5° longitude wide, and 1° latitude high. In the thesis, 1:250,000 sheets are referred to in capital letters; place names are referred to in lower case. The figure also shows the localities of ground magnetometer surveys and drill holes from which material was tested for magnetic susceptibility or density. Drill holes are listed in Appendix A1; ground magnetometer traverses are listed in Appendix A3.

Published and unpublished SADM geological, aeromagnetic and Bouguer gravity maps (7 km grid) for the area shown on Figure 2.1 were studied in the course of the research. Most of these maps are at a scale of 1:250,000. The SADM 1:47,520 geological maps were used during detailed work on ORROROO.

The flight charts for ORROROO were examined in detail. For this area, and for most of the area shown on Figure 2.1, aeromagnetic surveys were flown on east/west lines, one mile apart (1.6 km) at a continuous ground clearance of 500 feet (150 m). Flight paths were recovered by the SADM from the flight strip film and 1:63,360 photo mosaics.

2.3 Magnetic data

The ORROROO sheet was chosen for detailed study of the magnetics, where geological mapping by the SADM (Binks, 1968) was of an exceptionally high standard, and where the most recent low-level aeromagnetic survey had been conducted, and the contour map clearly shows many of the sedimentary formations are magnetic. Binks' map of ORROROO and the SADM total field aeromagnetic contour map are in the pocket at the back of the thesis (Figs. 1.5 & 1.6).

Other parts of the Adelaide Geosyncline are less well suited for detailed study, because either the available geology maps or aeromagnetic data are not of as high a quality as for ORROROO. For example, on BURRA (Mirams, 1964) the geology map is extremely generalized and needs several changes in the naming and subdivision of formations. In addition the aeromagnetic contour map of the area is contoured at 50 gammas and shows little detail of any but the most strongly magnetic strata. On PARACHILNA (Dalgarno & Johnson, 1966), the geology map is of high quality but the sediments are only weakly magnetic. On COPLEY, although an exceptionally high quality unpublished SADM geological map is available and the sediments are magnetic, the flight line direction is very often parallel to strike.

The author's method of investigation was to carry out a line by line study of the aeromagnetic flight charts and then examine particularly interesting features with a ground magnetometer. Clearly to follow up all aeromagnetic anomalies with a ground magnetometer would be an enormous task and this was not attempted. Rather, a suite of representative features was followed up. It was considered that a study of the most strongly magnetic features would reveal data applicable to the less well defined weakly magnetic features. Trial field surveys where aeromagnetic anomalies are weak (e.g. 50 gammas or less), were disappointing because good anomalies for detailed interpretation were seldom found.

Although most ground work was on ORROROO, surveys were also conducted at localities as far south as BARKER and as far north as COPLEY. It was considered necessary to do this to be sure that the particular magnetic beds identified on ORROROO were not just confined to that area.

A limitation to the magnetic interpretation was imposed by the lack of suitable drill core for the measurement of rock properties. Thus as yet, various models proposed to account for magnetic anomalies are untested by drilling. Because of the problem of obtaining fresh rock, little mineragraphic and no palaeomagnetic work was carried out. It was considered that little could be learnt until suitable drill core is available for study.

2.4 Gravity data

Unlike aeromagnetic data which show great detail along flight lines, regional gravity data have little detail over small-scale structures. It is a far coarser geophysical tool than aeromagnetics. As a result, the minimum size of features which can be studied without resort to detailed ground work is large, with dimensions being approximately four times the grid spacing. At the outset of the research it was decided that no detailed gravity surveys would be carried out. This was mainly because the University of Adelaide does not own a gravimeter, but also because the work would have taken too long. In accordance with this, the place of the regional Bouguer gravity interpretation in the thesis is to provide information on large-scale features.

The area chosen for discussion is centred on the ORROROO sheet and includes a total of 15 surrounding sheets (Fig. 1.3). However, discussion is mainly limited to the areas of Adelaidean outcrop east of longitude 138° because other students are working west of this line. While the author could have confined study to the magnetics alone, it was considered beneficial to work concurrently on the magnetics and gravity because this would allow as wide a range of information as possible to be available for future workers. In addition, a combined study often reveals features which, with one method alone, might go unnoticed.

The major limitation to the gravity work (apart from the station spacing) was the problem of densities. This always confronts gravity interpreters and is not easily overcome without extensive work. This is particularly so where density contrasts between rock units of interest are low. The problem of obtaining representative rock densities for various units became more apparent as the work proceeded; as mentioned earlier, there is little drill core available. In addition most of it comes from geologically disturbed areas. While reasonable lengths were taken to obtain densities representative of various rock units, the results are largely disappointing. The results serve to illustrate just how much work is necessary to obtain adequate density data. In accordance with this problem, the density contrasts necessary to explain the various anomalies discussed in the thesis, are sometimes assumed.

2.5 Appendices

Appendices of data important to the thesis are included in Volume 2. Bulky material, for example the ground magnetometer profiles, has been omitted. Magnetic susceptibilities are presented in drill log or histogram form rather than as tables. Listings of computer programs have been omitted. A dossier of ground magnetometer profiles, and computer listings are held in the Department of Economic Geology, University of Adelaide.

One appendix gives details of the author's use of the magnetic method in the interpretation of anomalies due to dipping tabular bodies of infinite strike length and depth extent. While this information is essentially a reiteration of published material, it is included because several colleagues indicated it would be of interest to them to have details of methods especially applicable to the thesis area.

Appendix A7 contains comments which clarify points raised during examination of the thesis.

2.6 Presentation

The interpretative work in the thesis is presented in three parts. Part A deals with the magnetic response of Adelaidean sediments. Part B discusses the magnetic anomalies likely to be caused by other sources. Part C deals with interpretation of the Bouguer gravity field.

Wherever possible, maps in the thesis have been kept to the minimum practical size, and conform to metric scales currently in use in Australia. The presentation of geophysical data in juxtaposition with geological data is a major problem. For the thesis, maps have been simplified and generalized as much as possible without losing important details. In some cases overlays have been used. Overlays used in the figures were sometimes drawn from maps on a different projection from the base diagrams. They have been photographically adjusted to conform as closely as possible with the base diagrams.

PART A

Magnetic anomalies caused by Adelaide System sediments

Chapter 3

AEROMAGNETIC STUDY OF ORRORO0

3.1 Introduction

Linear magnetic anomalies have been observed over metamorphosed sedimentary strata in many parts of the world. Sometimes the anomalies are caused by beds of ironstone or iron formations and the aeromagnetic or ground magnetic methods are used in an initial discovery role or to map extensions of known mineralization. Good examples of magnetic iron formations are those of the Lake Superior district (Bath, 1962; Leney, 1966). Volcanics are commonly magnetic and produce prominent linear magnetic anomalies when interlayered with sediments. However, quite often slates and shales are magnetic and produce prominent linear magnetic anomalies, e.g. in the Witwatersrand area (Roux, 1967) and Nova Scotia (McGrath, 1970).

A vast quantity of aeromagnetic data has been collected in Australia by government agencies and it is clear that Precambrian strata are sometimes magnetic, and that anomalies often follow geological layering. Some of the Adelaide System sediments in the Adelaide Geosyncline are magnetic (Tipper & Finney, 1966), and there is almost a complete absence of volcanics, although some ironstones are known. Upper and Lower Proterozoic strata on the north side of the Amadeus Basin are often closely followed by aeromagnetic anomalies (Young & Shelley, 1966). Shelley (1969) suggested that linear anomalies in the Daly River area are caused either by volcanics or the sedimentary strata with which they interlayer. Dockery and Tipper (1965) reported that some of the Proterozoic metasediments in the Mount Isa area are magnetic.

The primary purpose of the regional aeromagnetic surveys in Australia has so far been to delineate sedimentary basins and there is little published information on the Precambrian shield areas.

The interpretation of ground magnetometer surveys appears to be at a similar state to the airborne work. From the limited published material it appears that beyond a mapping role, the magnetic interpretation has usually been dropped at an early stage.

In Australia no detailed line by line analysis of aeromagnetic flight charts over magnetic sediments has been published and it is unlikely that such an analysis has been attempted for a large area. One reason for this is that a great deal of time is required. Another is that few suitable areas in Australia have detailed geological maps available, and therefore the conclusions to be drawn from a detailed study of the aeromagnetics are limited. However, where geological information is scarce the aeromagnetics may be the only data available and can be used to give a very generalized outline of important features of the geology. Therefore it is important that eventually all aeromagnetic data for Australia should be studied.

To fill in the gap in the knowledge of the magnetic response of Adelaide System sediments, the author studied an area where both detailed geological maps and high quality aeromagnetic data are available. The area is the ORROROO 1:250,000 map sheet in South Australia which covers steeply dipping strata of Adelaidean age. ORROROO is particularly interesting because in one part there are numerous strong linear anomalies (e.g. 100 gammas or more) from shallow sources, while in the other there are only a few weak linear anomalies. Moreover, the geological mapping by Binks (1968) shows that stratigraphic changes and a change in metamorphic grade occurs between the strong and weak magnetic response parts of the sheet (Binks, 1971).

Tipper and Finney (1966), in an unpublished BMR report, briefly discussed the aeromagnetic data for ORROROO and PARACHILNA and concluded that there are at least three strongly magnetic sedimentary units, the Holowilena Ironstone, the Tindelpina Shale Member and the Wilpena Group. They noted that numerous weak anomalies occur which are usually difficult to trace between flight lines.

On close analysis it was found that the weak anomalies can be traced between flight lines and that these, like the strong anomalies, usually fall over particular formations. In this chapter the results are presented for the detailed study of the ORROROO flight charts. Linear magnetic anomalies are correlated with mapped Adelaide System sedimentary strata and the positions of the main magnetic beds in the stratigraphic column are established. Broad magnetic anomalies, possibly due to a deep magnetic basement below the Adelaidean strata, are not discussed in this chapter.

3.2 Recording details of the ORROROO aeromagnetic survey

The ORROROO total field aeromagnetic survey was flown with an MSF-3 fluxgate magnetometer in a stinger installation in a DC-3 aircraft. Magnetic data were recorded with a chart recorder which had a full-scale deflection of 500 gammas (50 gammas/inch). Horizontal scale on the charts was approximately 1:50,000 and was dependent on the aircraft speed. The flight path was recorded with 35 mm strip film and was recovered by the SADM by plotting every tenth photo centre on 1:63,360 scale photo mosaics; the plotted centres were located about 0.6 km apart. Subsequent to this the path was also plotted by the SADM on 1:47,520 base maps which are 0.5° of longitude wide and 0.25° of latitude high. These are referred to hereafter as flight path maps.

The altitude of the aircraft was nominally 150 m above ground level, flight lines ran east/west, and were spaced nominally at 1 mile (1.6 km). Because the survey was not specifically designed to obtain high resolution data, the altitude was not closely controlled and variations between 100 m and 300 m were common. Most of the hills in the ORROROO area are gently rounded with peaks less than 100 m above the lowlands. However, in the far west of the area the topography is rugged and slopes of 30° reaching 200 m are not uncommon and here the altitude varied significantly from 150 m.

3.3 Topographic effects and flying noise

To establish the lower limit of detectability of anomalies caused by susceptibility contrasts within near surface material, it is important to consider topographic effects and the pseudo-anomalies resulting from them.

The problem has been considered for ground work by Gupta and Fitzpatrick (1971) who showed that strong anomalies can be produced across cliffs in magnetic material, e.g. a ground traverse across a 7.5 m cliff in material with magnetic susceptibility $k = 2,000 \times 10^{-6}$ c.g.s. units gives an asymmetric* anomaly of about ± 300 gammas. Even quite low susceptibility material will produce significant ground anomalies; for the case above, if $k = 50 \times 10^{-6}$ c.g.s. units, amplitude = ± 7.5 gammas.

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* In the thesis magnetic anomalies which consist of two associated peaks will be referred to as 'asymmetric anomalies'. Thus an asymmetric anomaly has a positive peak and an associated negative peak.

Susceptibility data (Appendix A2) indicate that the background susceptibility of Adelaidean rocks in the ORROROO area is probably less than 100 x 10^{-6} c.g.s. units. Small topographic features like the cliff discussed above will have a negligible effect at an altitude of 150 m. However, large hills can be expected to produce significant anomalies on aeromagnetic charts even for weakly magnetic rocks. The theoretical anomalies produced by several idealized structures are indicated on Table 3.1.

Table 3.1

Magnetic anomalies produced by topography

Ground Feature	Height	Aircraft Altitude above Base of Feature (m)	Amplitude max-min (gammas)	Half-width (m)
Long North/South Ridge*	50	150	4.0	280
"	50	250	1.9	360
"	100	150	10.6	220
"	100	250	4.5	320

* Anomalies calculated for features of infinite length and triangular cross section with a base width of 550 m and susceptibility 100 x 10^{-6} c.g.s. units.

Table 3.1 shows that an aircraft passing 50 m above a north/south ridge 100 m high and 550 m wide at the base, can record a total field anomaly in excess of 10 gammas if the rock has susceptibility 100 x 10^{-6} c.g.s. units. This is an extreme case because usually the aircraft gains altitude before reaching a steep hill to avoid dangerous air currents and avoid stalling. In the ORROROO aeromagnetic survey, high hills were usually cleared by at least 150 m. Thus the maximum anomaly amplitude expected is less than 5 gammas if the susceptibility is 100×10^{-6} c.g.s. units. In the western part of ORROROO in areas of steep topography, anomalies possibly attributable to topographic effects are usually less than 2 gammas in amplitude. This indicates that the background susceptibility may be less than 50×10^{-6} c.g.s. units. In the eastern part of ORROROO where the magnetic response of some sediments is strong, it is probable that the background susceptibility is less than 100×10^{-6} c.g.s. units.

Over the entire survey area the flight charts show a ripple with an envelope of up to ± 2 gammas which can probably be attributed to variations in aircraft heading, and electrical noise of equipment on board. The ripple usually has a sharp leading or trailing edge and half-width of less than 500 m.

For this chapter the lower limit for the detection of genuine anomalies (i.e. caused by susceptibility contrasts at or below ground level) is taken as ± 5 gammas above background.

3.4 Method of study and positioning of sources

All anomalies greater than 2 gammas in amplitude and with half-widths or slopes indicative of sources close to the surface were selected from the aeromagnetic data. Figure 3.1 illustrates how the data were interpreted. A regional level was drawn along each flight profile, and the peak amplitudes and positions of anomalies above or below this were noted. Figure 3.1(a) illustrates the interpretation procedure and Figure 3.1(b) shows how, if the true base level for the profile is unknown, an erroneous interpretation may be made.

The positions of peaks of anomalies on the flight charts were plotted on 1:47,520 base maps which overlay the SADM flight path maps (see Fig. 3.1(c)). For nearly symmetrical anomalies a small arrow indicating the sign and the amplitude was marked at the interpreted position of each source. Asymmetric anomalies were indicated by two arrows connected with a dashed line to indicate the relationship between the positive and negative peaks. From this the approximate source positions were located. Anomalies with the characteristic shape due to sources with limited depth extent were indicated on the maps. Anomalies particularly suited to the calculation of a source depth were given a special symbol (e.g. double or triple shafted arrow on Fig. 3.1(c)).

Estimation of the position of a magnetic source from its corresponding magnetic anomaly is subject to error. Gross errors occur if anomalies in the magnetometer chart are interpreted as two minima (corresponding to two separated bodies) when they should be interpreted as a single maximum (corresponding to a single body), or vice versa (Fig. 3.1(b)). A few cases of this kind were observed and were picked up by the fact that the two different interpretations were sometimes made on adjacent lines. Where observed, the data were reinterpreted to give consistency on adjacent lines. The accuracy of an interpreter's geographic positioning of magnetic sources from magnetometer charts is usually in the range ± 50 m for well defined anomalies and up to ± 150 m or more for partly resolved or asymmetric anomalies.

Because 'broad' anomalies caused either by deep or very broad magnetic bodies are not discussed in this chapter, no qualification (e.g. narrow or sharp) is needed in the following discussion. The top surface of all magnetic bodies discussed lies within 300 m of the ground surface.

The base maps of magnetic source positions were overlain on the SADM 1:47,520 geology base sheets which were compiled by the SADM during mapping of the ORROROO area.

3.5 Interpretation of the magnetometer data

Figure 3.2 shows an overlay of the positions of shallow magnetic sources on a generalized geology map of ORROROO; each source has a number corresponding to the amplitude of response. Table 3.2 shows the amplitude ranges corresponding to the numbers and how many anomalies lie in each range.

Table 3.2

Amplitude Number	Amplitude Range (gammas)	No. of Anomalies	Descriptive Term
1	5-20	1965	weak
2	21-100	479	medium
3	101-400	187	strong
4	401+	25	

Most anomalies are weak and these are fairly evenly distributed over the area. About one-third of all anomalies are in the medium and strong amplitude ranges, and most of these are confined to the south-east part of ORROROO.

There is a marked correlation of the linear trend of magnetic anomalies with the trends of sedimentary bedding over the whole amplitude range of anomalies considered (5 to 1,500 gammas). In general, there is continuity of magnetic sources between adjacent flight lines where the flight lines both cross the same sedimentary formation. However, some anomalies are not associated with the sediments and are caused by other sources (discussed in Chapter 6). In this chapter only anomalies correlatable with Adelaidean sediments are discussed.

3.5.1 Character of anomalies and sources for Adelaidean sediments

To illustrate the character of the total field magnetic anomalies over the Adelaide System sediments two adjacent flight charts are reproduced on Figure 3.3 above the corresponding geological sections. Anomalies are recorded over the same formations on both limbs of the synclines but their amplitudes are usually unequal and some are of negative sign. These are common features over the whole ORROROO sheet and are probably due to the combined effects of variations in source dimensions, depth of weathering, magnetic mineral content and remanent magnetization. Anomalies over north/south striking strata are often symmetrical in shape and therefore are particularly simple to interpret for source position, dimensions and depth. Many of the anomalies are of the partly resolved kind (see Fig. 3.3), and it is often difficult to distinguish between the case of two or more magnetic sources separated by weakly magnetic material, and concentrations of magnetic material in a broad magnetic zone. The key to distinguishing these two distinctly different phenomena often comes from a profile further along strike where anomalies are better resolved.

The sources of the linear magnetic anomalies over Adelaidean sediments are steeply dipping tabular bodies of considerable strike length and depth extent, and are approximately conformable with sedimentary layering.

This is supported by:

1. The linear continuity of anomalies at corresponding stratigraphic positions on adjacent flight lines.

2. The correspondence of anomaly shapes with the theoretical shapes expected over infinite tabular bodies. Anomalies with shape attributable to bodies of limited depth extent are rare.

Interpretation of some of the best resolved aeromagnetic anomalies using the methods of Gay (1963), Koulomzine et al. (1970) and others, indicated that the apical width of the tabular bodies is usually less than 300 m. This was confirmed by ground studies (Chapter 4). This estimate puts an upper limit on the thickness of the bodies because as dips become very steep the thickness approaches the apical width. Depth estimates to the top surface of sources usually do not exceed 200 m below ground level.

Because the tabular bodies correlate closely with the stratigraphy, they can be called magnetic beds and this terminology will be adhered to hereafter. A 'magnetic bed' is a geophysical rather than geological feature. Its dimensions largely depend on the altitude of observation with the magnetometer. Magnetic beds closer together than about twice the altitude of the aircraft above cannot be resolved from the corresponding magnetic anomalies. Therefore (and as ground work in Chapter 4 shows) single magnetic beds interpreted from the aeromagnetic charts may be composed of two or more thin magnetic horizons interlayered with weakly magnetic material. Although a magnetic bed is a geophysical feature, it has geological significance in that it indicates the presence of an anomalous amount of magnetic minerals. The presence, or absence of magnetic minerals may be associated with other special geological phenomena, including mineral composition, grain size, and oxidation state. Because the magnetic beds lie within sedimentary strata but have their top surface below ground level, it is evident that magnetic minerals in the near surface part of the sediments have been weathered out.

Because anomalies change significantly in amplitude and shape over distances of as little as 10 km, the beds are not homogeneous over a great strike length. While amplitude variations can be attributed to variations in depth of weathering, source width or magnetic mineral content, it is usually difficult to be sure which mechanism is most important. A small change in depth of weathering (e.g. 10%) cannot be distinguished from a small change in source thickness or magnetic mineral content. Experience indicates that changes in depth of weathering are less important than changes in source width and magnetic mineral content, in controlling the amplitude of response of the magnetic beds.

Interpretation of individual anomalies indicates that remanent magnetism is important in the area. Anomalies are commonly not of the shape expected if inductive magnetism acts alone and in some cases, particularly over the lower part of the Tapley Hill Formation, the influence of remanent magnetism is far greater than induction. The problem of remanent magnetism is discussed in Chapter 5.

3.5.2 Correlation of magnetic sources with stratigraphy

In correlating aeromagnetic anomalies with geology, reliance is placed on the accuracy of plots of the aircraft flight path, the accuracy of the geological maps and the accuracy of the interpreter in locating the source positions from the anomalies. For ORROROO the photo positioning and geological data are of a high standard and there are few problems here. The main problem lies with the character of the magnetic beds. Because they are often weathered to 100 m or more, the position interpreted from the magnetometer charts will lie on the down-dip side of the outcrop. While this migration is not large for very steep dips, for low dips of the order of 30°, the migration can be 200 m or more, depending on the depth of weathering. Most of the mapped formations on ORROROO are 500 m or more thick and there is little problem in deciding whether or not magnetic beds lie within them. However, to find the precise stratigraphic position requires ground magnetometer work. The precise locations of some sources in the stratigraphic column are discussed in Chapter 4.

In correlating the magnetics and geology, maps at a scale of 1:47,520 were used. Figure 3.4 shows the magnetic beds traced on ORROROO from aeromagnetic anomalies of 5 gammas or more in amplitude. The map was prepared after ground work had been carried out. The magnetic beds are shown on Figure 3.4 as discontinuous lines, often terminating where flight lines are nearly parallel to the geological strike (e.g. around the noses of fold structures). This illustrates a limitation of mapping with the magnetic method. A flight line must cross a magnetic bed to allow its geographical position to be determined from the anomalies. Where several magnetic beds lie close together the individual anomalies often merge around the noses of folds. Thus in these areas, although the anomalies indicate a magnetic zone, the individual beds cannot be traced. A new survey with flight lines running north/south would help to complete the mapping in problem areas. Only where sources can be traced between three or more adjacent flight lines is a bed marked in. Often anomalies with lower amplitude than 5 gammas can be traced further along strike. In other cases anomalies sometimes occur at corresponding stratigraphic positions several flight lines apart. These are not considered. The positions of magnetic beds in the Adelaidean section are shown on Figure 3.5.

The magnetic response of Adelaidean sediments changes across a line drawn from about longitude 138°30', latitude 33° to longitude 139°, latitude 32° (see Fig. 3.4). The area in the east of ORROROO will be referred to as Area A and in the west as Area B. The following differences occur:

1. More anomalies are recorded in Area A than Area B.
2. 14 magnetic beds are recognized in Area A and only 10 in Area B.
3. The amplitude of anomalies is often 100 gammas or more in Area A, while it is usually less than 10 gammas in Area B.
4. Magnetic beds can often be traced continuously along strike of outcrop for more than 30 km in Area A, while in Area B they can rarely be traced for more than 10 km.

Binks (1968, 1971) reported differences in the geology of the eastern and western parts of ORROROO. The differences occur in

1. stratigraphy, and
2. metamorphic grade.

The changes in stratigraphy are shown on Figure 3.5. Features of special interest are that the siltstones of the Wilpena Group are red in Area B and green in Area A, and that the sedimentary iron content of the Yudnamutana Subgroup increases from west to east. Binks (1971) noted that although the rocks of the ORROROO area are essentially unaffected by metamorphism, low grade metamorphism (biotite, chlorite, sericite) has taken place in the Adelaidean rocks in the east. He supported Tipper and Finney (1966) who considered that the high magnetic response in the east of ORROROO was probably due to metamorphism of the sediments.

3.5.3 Position of magnetic beds in the stratigraphic column

Rocks of the Adelaide System have been grouped into four major units (Thomson et al., 1964) named the Wilpena Group, Umberatana Group (includes the Yeralina Subgroup, the Farina Subgroup and the Yudnamutana Subgroup), Burra Group and Callanna Beds, and these are convenient subdivisions for the discussion below (see Fig. 3.5). The Callanna Beds are omitted from it because their aeromagnetic response is weak and their stratigraphy is not well established on ORROROO. For the following discussion of stratigraphic positions it may be helpful to refer to the published ORROROO geological map (Fig. 1.5).

3.5.3.1 Burra Group

Two magnetic beds were recognized in Area A and these lie in the Minburra Quartzite and near the top of the Cradock Quartzite. The magnetic bed within the Minburra Quartzite is the more extensive of these; it has the strongest response (100 gammas) in the north-east of Area A near Waukaringa. This local increase in response is also evident in magnetic beds in the Holowilena Ironstone and the lower part of the Tapley Hill Formation of the Umberatana Group.

In Area B, three magnetic beds occur: at the base of the Belair Subgroup, within the Minburra Quartzite, and within the Cradock Quartzite.

As in Area A, the Minburra Quartzite magnetic bed is the most extensive and easily traced bed.

3.5.3.2 Umberatana Group

Yudnamutana Subgroup

On ORROROO this subgroup mainly consists of the Appila Tillite which contains the Holowilena Ironstone in the north-east of the area.

There is a single discontinuous magnetic bed near the subgroup's base, which correlates with the Holowilena Ironstone where it is mapped. The highly magnetic Holowilena Ironstone which contains hematite and magnetite (Binks, 1971; also discussed in Appendix A4) is mapped over a strike length of about 25 km in the north-east of Area A. It produces anomalies with amplitudes of up to 1,500 gammas; however, they fade to about 10 gammas no more than 15 km to the south and west along strike from the mapped outcrop. The anomalies strengthen locally in central ORROROO and then fade out once again towards the west.

Where the Holowilena Ironstone is mapped on the north side of the Oopina Anticline (10 km north of Waukaringa), dips of bedding are mainly to the north and north-east, and here the corresponding magnetic anomalies are chiefly of positive sign. However, on the southern side of the anticline (6 km north-west of Waukaringa), where the Yudnamutana Subgroup dips south, and where magnetic interpretation indicates that remnants of the Holowilena Ironstone occur, the sign of anomalies is negative. From this sign change it is evident that the response of the Holowilena Ironstone is a function of geological dip. The magnetic bed appears to preserve an element of remanent magnetization acquired before folding occurred.

Farina Subgroup and Yeralina Subgroup

Five magnetic beds occur in Area A and four in Area B. The magnetic beds in Area A lie close to the base of the Tapley Hill Formation (mapped as the Tindelpina Shale Member), within the Tapley Hill Formation, at the boundary between the Tapley Hill Formation and Tarcowie Siltstone, at the boundary between the Tarcowie Siltstone and Waukaringa Siltstone Member and within the Yeralina Subgroup. A bed was recognized within the Tarcowie Siltstone where the Waukaringa Siltstone was not mapped. Possibly this is equivalent to the one between the Waukaringa Siltstone Member and the Tarcowie Siltstone.

In Area B magnetic beds were found close to the base of the Tapley Hill Formation (Tindelpina Shale Member), within the Tapley Hill Formation, close to the boundary between the Upper and Lower Willochra Formations and within the Upper Willochra Formation. In Area B, very weak magnetic anomalies (less than 5 gammas sometimes) not easily traced between flight lines, lie close to the boundary of the Tapley Hill Formation and Uroonda Siltstone Member, within the Etina Formation and the Elatina Formation. These might be caused by very weakly magnetic beds.

The position of magnetic beds in the stratigraphic column for the Farina and Yeralina Subgroups suggests continuity through the stratigraphic changes in the ORROROO area.

The strongest and most extensive anomaly in these two subgroups is associated with the Tindelpina Shale Member which is an extensive marker in the Adelaide Geosyncline; this is a pyritic carbonaceous shale about 60 m thick at the type locality on COPLEY. Binks (1971) states that the Tindelpina Shale contains minor pyrrhotite. There are no published analyses for ORROROO to support this. Tipper and Finney (1966), who recognized that the anomaly was partly caused by remanent magnetism, assumed that the source of the magnetism was pyrrhotite occurring with the pyrite in the shales. While acknowledging that pyrrhotite could be very strongly remanently magnetized, it would probably require 5% or more to produce aeromagnetic anomalies of up to 500 gammas over a bed which is about 100 m thick and magnetically weathered to about 100 m below the surface. It is doubtful that pyrrhotite is the magnetic mineral responsible for the anomalies. Ground work (discussed in Chapter 4) showed that the magnetic bed is much thicker than the zone of the stratigraphic column recognized as the Tindelpina Shale Member. In the field on ORROROO the member is often difficult to recognize and as yet there has been no drilling to define its thickness.

It is clear from this case that there are problems in associating the geophysically located magnetic bed with a geological bed. It is considered that at this time the position of the magnetic bed discussed above should be described as 'near the base of the Tapley Hill Formation'. In Chapters 4 and 5 the magnetic bed is referred to as the 'Lower Tapley Hill magnetic bed'.

3.5.3.3 Wilpena Group

Six magnetic beds recognized in Area A are as follows: four within the Ulupa Siltstone and one within the Bunyeroo Formation and the Wonoka Formation. The lowest bed lies near the base of the Ulupa Siltstone, just above the Nuccaleena Formation.

Three magnetic beds recognized in Area B are located as follows:

one within the A.B.C. Range Quartzite, one within the Brachina Formation and one between these two formations. It is not known whether any of the four magnetic beds within the Ulupa Siltstone in Area A correlate with the magnetic beds of Area B.

The most strongly magnetic bed in Area A has anomalies up to 600 gammas on the western limb of the Dawson Syncline (20 km north-north-east of Peterborough), while on the eastern limb 10 km away, the corresponding anomalies are of the order of 100 gammas in amplitude. These amplitude changes may be due to an element of remanent magnetization. The response of the equivalent magnetic bed drops from about 100 gammas to 20 gammas across other synclines to the east and north-east of the Dawson Syncline. These amplitude changes may be due to changes in magnetic mineral content of the magnetic bed or perhaps to an influence of remanent magnetism which is a function of geological dip.

3.6 Magnetization of beds

Because remanent magnetization is important in the magnetic beds of the ORROROO area, the susceptibility cannot be calculated directly from aeromagnetic profiles. Rather, the effective magnetization (J') or the effective magnetic susceptibility (ke) are the parameters which can be estimated (e.g. by the equations of Gay, 1963). The effective magnetic susceptibility is the susceptibility which is required to produce the observed magnetic anomaly if the source is inductively magnetized by the earth's field. The susceptibility of country rock enclosing the magnetic beds is assumed to be zero. In the field area the earth's field has an intensity of 59,000 gammas, and is directed upwards at an inclination of 65° to the horizontal. A minimum estimate of ke can be made from the magnetic anomalies if the source body is given the minimum possible depth below surface and the maximum width. A maximum estimate can be made if the source body is given a maximum depth and a minimum thickness. To illustrate the order of effective susceptibility required to produce the observed anomalies, minimum and maximum estimates corresponding to several aeromagnetic anomaly amplitudes are shown on Table 3.3. These are for magnetic beds assumed to be magnetically homogeneous, 300 m or 50 m thick, and magnetic at the surface or 150 m below the surface.

Table 3.3

Estimates of Effective Magnetic Susceptibility
from Aeromagnetic Anomalies

Total field anomaly amplitude at 150 m above ground level	ke* (min) c.g.s. units (w = 300 m z = 0 m)	ke* (max) c.g.s. units (w = 50 m z = 150 m)	Example stratigraphic positions of magnetic beds
10 gammas	50×10^{-6}	700×10^{-6}	Wonoka Formation
100 "	500 "	7,000 "	Upper Ulupa Siltstone
500 "	2,500 "	35,000 "	Lower Tapley Hill Formation
1,500 "	7,500 "	105,000 "	Holowilena Ironstone

* Estimates for north/south striking, infinite tabular bodies dipping vertically. w = apical width, z = depth below ground level.

These estimates indicate that some of the beds are very strongly magnetized. However, they are of little value for the direct comparison of various beds because for most beds the precise thickness is unknown. The thickness and magnetization of particular beds is discussed in Chapters 4 and 5.

3.7 Discussion

On ORROROO, linear aeromagnetic anomalies often 20 km or more long, are caused by magnetic beds conformable with the stratigraphic layering of Adelaide System sediments. The beds are no more than 300 m thick and lie within weakly magnetic strata which probably have a magnetic susceptibility of less than 100 x 10^{-6} c.g.s. units. From the available geological evidence, none of the magnetic beds are volcanics, and only one is correlated with an iron formation; their occurrence indicates an increase of magnetic mineral content over small intervals of the stratigraphic succession.

Because some of the beds are remanently magnetized it is not possible to estimate magnetic susceptibility from the aeromagnetic data. Moreover, in consequence, it is not meaningful to use the empirical relationships of magnetic susceptibility and magnetic mineral content such as those in Grant and West (1965, pp.267,268) to estimate the amount of magnetic minerals present in the beds. Except for the Holowilena Ironstone magnetic bed and the most strongly magnetic bed within the Ulupa Siltstone where magnetite is recognized (Appendix A4), the magnetic minerals causing the anomalies are unknown as yet. Adelaidean sediments often contain a few percent of pyrite, either at the surface or in bore core, and it is possible that a small amount of pyrrhotite coexists with the pyrite at depth and contributes to the magnetic response.

The magnetic response of shales of the Witwatersrand System in the Republic of South Africa is comparable with that of Adelaidean sediments. Here the magnetic mineral is magnetite (Roux, 1967). It is likely that magnetite is the dominant magnetic mineral in Adelaidean sediments and in most of the magnetic beds probably does not exceed about 1%.

Ground magnetometer work is necessary to provide detail of the form of the magnetic beds, particularly to find whether each consists of several thin magnetic sheets as can be expected in well laminated sediments. In addition ground work can provide a more accurate estimate of total bed thickness than is possible with aeromagnetic profiles.

Studies of ground magnetometer profiles to find more about the form of the magnetic beds and the influence of remanent magnetism are presented in Chapters 4 and 5.

ORROROO can be roughly divided into two areas. In the eastern area (Area A) magnetic response of the sediments is higher than in the western area (Area B). While the difference can be attributed to a difference in magnetic iron content of magnetic beds in the two areas, from the magnetometer data it is not possible to conclude whether this is related to a difference in total iron content of the sediments. Binks (1971) has stated that the total iron content of the Yudnamutana Subgroup increases from east to west; possibly the same is true for other parts of the section. Binks (op. cit.) has reported that metamorphic grade increases from west to east on ORROROO and this corresponds to weak magnetic response in Area B and strong response in Area A. Unpublished work by Brotherton (Honours thesis, 1967, University of Adelaide) compared the metamorphic grade and iron mineralogy and geochemistry of stratigraphically equivalent Wilpena Group rocks at two areas on BARKER. He found that the weakly metamorphosed red shales and siltstones near Sellicks Hill contained more hematite than magnetite (average of three samples; Fe_2O_3 = 3.32% by weight, FeO = 1.95% by weight), while in the grey-green phyllites near Delamere the opposite occurs (average of three samples; Fe_2O_3 = 4.22% by weight, FeO = 4.15% by weight). Brotherton attributed the development of magnetite to metamorphic processes. The aeromagnetic contour map over the BARKER area shows very weak anomalies over the rocks of Sellicks Hill, while near Delamere anomalies exceed 200 gammas in amplitude. It appears that the most important factor controlling the magnetic response of the sediments is probably metamorphism. There is no evidence that magnetite occurs as detrital material. However, this possibility should not be overlooked.

To resolve the problem of the relationship between magnetic iron content and total iron content of the Adelaidean sediments requires mineragraphic study of rock samples. However, a further problem is presented. The magnetic beds are often magnetically weathered up to 200 m below the surface. Thus deep drilling is required to obtain truly fresh rock for study.

One of the potentially most useful features brought out by interpretation of the aeromagnetics of ORROROO is that the magnetic beds can be traced for long strike lengths and appear to continue through lithologically different but stratigraphically equivalent rock units, particularly in the Umberatana Group. Some of the beds may be useful as stratigraphic markers although only ten magnetic beds were recognized in Area B while 14 were recognized in Area A. The reason for the difference in numbers is not clear and only in the case of the Holowilena Ironstone magnetic bed in the Yudnamutana Subgroup is there direct geological evidence for a magnetic bed to lense out to the west. A great deal of further work is required to resolve whether all the magnetic beds are always present in the stratigraphic succession, which would be of great interest to stratigraphers. The major problem is that the response of the beds in Area B is much weaker than in Area A. It is doubtful if further work with aeromagnetics on ORROROO will add much to the picture already established for the area. To detect magnetic beds with weak aeromagnetic response requires ground magnetometer work but even this has associated problems. Ground profiles show the presence of a strong surface noise component which tends to mask the influence of weakly magnetic beds, particularly if they are weathered to a considerable distance below the surface. The influence of noise is discussed further in Chapter 4.

A study of the contour maps for other parts of the Adelaide Geosyncline indicated that the detailed picture established for ORROROO is probably not a local feature. For example, the magnetic bed near the base of the Tapley Hill Formation can often be traced on COPLEY in the north and ADELAIDE in the south. One or two magnetic beds can often be traced in the Wilpena Group as far south as BARKER.

Chapter 4

DETAILS OF MAGNETIC BEDS REVEALED BY GROUND SURVEYS

4.1 Introduction

While aeromagnetic interpretation can give an approximate position of a magnetic body to within about 50 m, ground magnetometer surveys are essential to locate sources accurately. As ground work provides more detail of anomalies than is possible with airborne work, the results are of great value if dimension parameters to describe the sources are desired. Ground work is particularly important where sources are thin or small in extent.

The use of the aeromagnetic method to provide data for huge areas since the 1940's has overshadowed the more mundane use of magnetometers on the ground, and the literature clearly reflects this. Publications on the use of the ground magnetometer and the special problems in interpretation are rare, and most attention is given to airborne work. The major problem of ground work is the almost overwhelming detail which can be gathered, and in this respect the use of airborne methods for the study of shallow sources has the outstanding advantage of simplifying the data. Some of the problems in the interpretation of ground magnetic data are discussed in this chapter.

There are few recent published reports on ground magnetometer surveys across Precambrian metasediments; most of these discuss iron formations or intrusives (e.g. Eadie, 1970; Webb, 1966; Leney, 1966; Strangway, 1965). Some of the earliest work on extensive magnetic beds was done by Krahman (1936) in the Witwatersrand area of the Transvaal; it was found that magnetic shales of the Witwatersrand System could be traced under younger cover by the magnetic method and used as stratigraphic markers in the search for gold bearing beds (summary in Roux, 1967). At that time most attention was given to finding the geographical position and depth of magnetic material, rather than detailing the precise form of the sources. In recent years interpretation techniques have become increasingly sophisticated and we can now expect to derive special details of the form of magnetic strata from their anomalies.

Ground magnetometer surveys across Adelaide System sediments were carried out at numerous localities in the Adelaide Geosyncline, both to accurately locate sources and to provide detailed data for the estimation of parameters of the magnetic beds. Ideally magnetometer lines across linear bodies are best if run normal to strike of outcrop. It was not always practical to follow this rule. For interpretation processes, profiles from magnetometer lines oblique to geological strike were contracted in length to appear as if they were taken normal to strike. Details of the survey procedure are included in Appendix A3. A total of 120 lines (totalling 250 km in length) were put in; some of these were isolated reconnaissance lines and others were close together and parallel to provide local detail. Most ground lines were more than 2 km long with station spacings of 7.5 m (25 feet) or more. Localities were chosen on the basis of the quality of the aeromagnetic anomalies and exposure in the area. Although there are numerous roads in the thesis area, magnetometer lines were not usually put in on them, because experience showed that man-made magnetic sources are often present.

Preliminary ground surveys in areas of strong and weak aeromagnetic anomalies indicated, as was expected, that the best defined anomalies were found where the aeromagnetic anomalies werestrongest. For this reason effort was concentrated on beds which had strong aeromagnetic anomalies (e.g. 100 gammas or more). The ground work was mainly confined to the eastern part of ORROROO. However, reconnaissance lines were put in, both in the west of ORROROO and in other areas of the geosyncline (see Figs. 2.1 & 4.4). Most work was performed across the Lower Tapley Hill magnetic bed because it is the most extensive magnetic bed in the geosyncline and preliminary investigations indicated that general conclusions on the nature of this bed are applicable to others.

In this chapter interpretations of six selected ground magnetometer profiles from ORROROO are shown to illustrate features of magnetic beds. Others not included in the thesis show similar features and the conclusions drawn for the six profiles are not restricted to a few isolated localities.

4.2 Character of vertical field ground anomalies over Adelaide System sediments

All profiles discussed in this chapter were obtained with a vertical field fluxgate magnetometer. The sign convention conforms to that in Gay (1963); an induced vertical field anomaly over a vertical rod at the south magnetic pole is of negative sign (a total field anomaly is of positive sign).

The ground magnetometer profiles across steeply dipping Adelaide System sediments show the presence of broad symmetrical or nearly symmetrical anomalies with half-widths of 500 m or less (attributable to deep magnetic sources), together with superimposed narrow anomalies (attributable to near surface magnetic material). Figures 4.1, 4.3 and 4.4 illustrate the form of the anomalies. The anomalies evident on aeromagnetic charts and of primary interest in the ground work are the broad anomalies; the narrow anomalies can be considered to be a noise which rapidly decreases in amplitude with increasing altitude. Noise is considered in detail in section 4.3 of this chapter.

The broad anomalies usually have two or more main peaks, indicating that two or more sources contribute; in only a limited number of cases were single well isolated broad anomalies found. They often closely approximate the shape of theoretical anomalies across steeply dipping thin tabular bodies (cf. Gay, 1963). Broad anomalies are usually essentially similar in shape over distances of 10 km or more along strike. However, details often change over distances of as little as 500 m. For example, an anomaly which shows several partly resolved peaks at one location may have only one or two peaks at another. This sort of change can be attributed to an increase in depth or lensing out of the sources. It appears valid to interpret the anomalies as due to steeply dipping tabular bodies of considerable strike and depth extent.

The vertical field anomalies are usually symmetrical or nearly symmetrical in shape, even for east/west striking north dipping beds. This indicates that magnetization is close to geological layering. If beds are inductively magnetized by the earth's field, it would be expected that vertical field anomalies would be of symmetrical shape over south dipping east/west striking magnetic beds, and of asymmetrical shape over north dipping beds. Few asymmetric anomalies were recorded. The theoretical vertical field anomalies over tabular bodies magnetized in the plane of bedding will be symmetrical, independent of their strike or dip. In the main, this condition appears to exist for most of the magnetic beds. There are two phenomena which can independently account for magnetization always lying close to the plane of bedding. These are 1. demagnetization effects associated with material of very high susceptibility, and

2. strong remanent magnetization in a direction close to the plane of bedding.

Because anomalies are often of opposite sign to that expected if inductive magnetization acted alone, it appears that remanent magnetism is more important than demagnetization effects.

After preliminary field trials it was found that a station spacing of 15 or 30 m usually provided sufficient detail of the broad anomalies to allow quantitative interpretation. However, closer stations, e.g. 7.5 m or less, were often necessary across peaks and turning points of the anomalies to give full definition.

On the basis of the tabular body model the broad magnetic anomalies can be interpreted to give depth estimates of 50-100 m or more. It is shown in section 4.6 that the upper surface of magnetic beds is quite complex in shape.

4.3 Noise

The major problem in the interpretation of the ground data is the presence of magnetic noise on the profiles. All magnetometer profiles across the Precambrian strata, and for that matter younger cover rocks, show the presence of broad anomalies up to 500 gammas or more in amplitude, attributable to sources up to 100-200 m below the surface, together with a superimposed noise component attributable to sources within about 5 m of the surface.

The noise component appears on the ground profiles as sharp spikes, commonly of an amplitude up to ± 20 gammas, and occasionally of ± 100 gammas or more. Usually the spikes lie between three stations (grid 7.5 m or more) and measurements 1 m apart or less are required to provide detail of their shape.

Repeat readings at different times were made along two traverses to allow estimation of instrument reading errors. Figure 4.1(a) shows a vertical field profile from the thesis area which was read on two consecutive days. To allow comparison of the two results a static difference of about 50 gammas in background level has been included. The envelope of differences between the readings is about 10-20 gammas wide. A few differences lie outside this range, possibly because the exact position occupied on the first reading was not occupied on the second. Thus the reading accuracy of the magnetometer is between ± 5 and ± 10 gammas. Therefore some of the low amplitude noise spikes on field profiles can be attributed to reading errors. However, the noise is often of higher amplitude than can be attributed to reading errors and much of it must be due to the influence of magnetic material at ground level or below. Because the sign of the spikes is often opposite to that expected if inductive magnetism acted alone, it is evident that the sources are often remanently magnetized.

Detailed measurements across some of the spikes indicated that the sources often have limited strike extent (5 m or less) and appear to be random in their occurrence. However, sometimes the spikes are apparently associated in some way with deep magnetic beds. For example, there is often a strong burst of noise on the geological up-dip side of a deep magnetic bed. Figure 4.1(b) shows an example of this and illustrates the use of the term 'up-dip'. The high amplitude spikes labelled (1) lie on the up-dip side of a broad anomaly which is due to magnetic beds in the lower part of the Tapley Hill Formation.

The noise bursts can often be traced along strike for 500 m or more, and in this situation it is often possible to trace individual spikes along strike for a considerable distance. Where noise bursts are associated with deep magnetic beds, the sign of individual spikes is often the same as that of the anomaly due to the deep sources. It is possible that some of the noise is due to very thin near surface remnants or derivations of the deeper magnetic sources. Magnetic minerals present in the remnants would presumably be the same as at depth. For situations where there is no evidence of associated magnetic material at depth, some other mechanism, probably an influence of weathering, may act to concentrate magnetic minerals near the surface. Alternatively, some of the near surface rocks may preserve small lenses or pods of magnetic minerals which have been unaffected by weathering processes. This may be the case in the following example.

Seven percussion holes were drilled in the Appila Tillite 12 km south-west of Waukaringa to test three anomalies which were classified as noise (see Appendix A2 - Ajax Holes 1 to 7). The highest amplitude recorded was 1,500 gammas positive. The sign of the anomalies was the same as recorded over the Lower Tapley Hill magnetic bed, some 100 m higher in the section. Interpretation of detailed magnetometer profiles indicated that two of the sources lay no more than 3 m below the surface. There was no evidence of a large deep source below them. The anomalies are caused primarily by remanent magnetism and so susceptibility measurements on cuttings are of limited value. It was expected that material of high susceptibility (with associated strong remanence) would be penetrated. It was not. The recorded susceptibilities were all below 200 x 10^{-6} c.g.s. units. In most holes, susceptibilities drop by one half in the top 3 m and rise to a background level of about

100×10^{-6} c.g.s. units at 5-10 m. Approximately 1.5% pyrrhotite was found in two samples of cuttings magnetically separated (Appendix A2, Samples OR60 & OR62). It appears that the drill holes missed the targets. A brick-sized block of surface rock tested with a magnetometer for remanent magnetization produced no useful results. No sulphide was visible in the rock. It contained about 1% limonite pseudomorphs after pyrite. It is probable that strong remanent magnetization of unexposed pyrrhotite-bearing rock caused the magnetic anomalies.

The randomly occurring component of noise is present on all ground profiles for the Adelaide Geosyncline whether they are from areas of exposed Adelaidean strata or thick younger rocks (e.g. Quaternary). An example of this kind of noise can be seen on Figure 4.1(b) in the vicinity of spikes labelled (2). Usually the spikes cannot be attributed to magnetic rocks at the surface; surface rocks are usually only weakly magnetic. Magnetic susceptibility tests on drill hole cuttings and other samples (Appendix A2) from both Adelaidean and younger strata indicate that a zone of enrichment of magnetic minerals about 2-5 m thick often lies at or close below the surface. In this zone susceptibilities in the range 200-400 $\times 10^{-6}$ c.g.s. units are often found in Adelaide System sediments; just below the magnetically enriched zone susceptibilities are usually about 100×10^{-6} c.g.s. units or less. Cook and Carts (1962) measured susceptibilities of residual soils in the U.S.A. and Panama, and concluded that magnetic minerals often form in place near the surface, viz. maghemite, and contribute substantially to the observed magnetism of the soils. It is probable that the same mechanism is important in the rocks of the Adelaide Geosyncline. Inductive magnetization of near surface concentrations of magnetic minerals probably causes some of the magnetic noise. Although no direct measurements were made of the natural remanent magnetism (NRM) of magnetic material causing the noise spikes in the Adelaide Geosyncline, it is evident from the magnetic interpretations that material close to the surface exhibits an appreciable magnetic remanence. Possibly chemical remanent magnetism (CRM) and viscous remanent magnetism (VRM) are important (Irving, 1964, pp.28-34).

4.4 Magnetic susceptibility measurements on Adelaide System rocks

The volume magnetic susceptibility of Adelaide System rocks was measured with two susceptibility bridges. The detailed results of measurements are included in Appendix A2.

Obtaining fresh rock for measuring the susceptibility of magnetic beds was a problem. While the cores or cuttings from many drill holes in the Adelaide Geosyncline are held in the SADM corestore, they are of limited use for magnetic interpretation. There are two reasons for this. Firstly, the drill holes put down in the past by exploration companies have not been to test the sources of magnetic anomalies, and secondly they are usually of limited depth (less than 200 m) and are often in geologically disturbed areas where the weathering depth is likely to exceed that in less disturbed areas.

To the author's knowledge only one bed which often has associated magnetic anomalies has been drilled (near the base of the Tapley Hill Formation). However, the drill holes were not sited to give information on magnetic sources; rather they were placed to test for copper mineralization which often occurs at this level (associated with the Tindelpina Shale Member). Mapping by the SADM indicates that the

Tindelpina Shale Member lies at the base of the Tapley Hill Formation at the localities of the five cores tested. The holes did not exceed 200 m in depth and the susceptibilities recorded were usually less than 100 x 10^{-6} c.g.s. units. In all of the cores, fresh pyrite was present below about 50 m and this may indicate that the rocks are magnetically fresh at these depths. However, there was no indication of a high susceptibility zone below the depth of oxidation of pyrite. Magnetic response in the areas of the drill holes was very weak. Thus at the localities of the drill holes the Lower Tapley Hill magnetic bed either does not occur, or is very weakly magnetized.

The magnetic interpretation indicated that magnetic beds are usually weathered to a considerable distance below the surface. Thus it was to be expected that susceptibility measurements on surface rock samples would be of limited value. This was found to be the case and of the 100 samples tested, high values were obtained only for a few samples of Holowilena Ironstone and Ulupa Siltstone. For the Ulupa Siltstone there is a weak grouping of susceptibilities around 50 x 10^{-6} c.g.s. units and 1,000 x 10^{-6} c.g.s. units. Of the 31 samples tested nine have susceptibilities between 1,000 x 10^{-6} and 30,000 x 10^{-6} c.g.s. units. Four samples of Holowilena Ironstone were tested and their susceptibilities lie in the range 100-58,000 x 10^{-6} c.g.s. units. Magnetite altering to martite was recognized in the Ulupa Siltstone and Holowilena Ironstone (see Appendix A4).

From the available direct measurement data it appears that the susceptibility of magnetically weathered Adelaidean rocks is usually low, and is probably less than 100 x 10^{-6} c.g.s. units except within a few metres of the surface where in some places it is known that the susceptibility is 300 x 10^{-6} c.g.s. units or more. It appears that the susceptibility of material in the magnetic beds could be quite high. If measurements on the Ulupa Siltstone and Holowilena Ironstone are taken as a guide, susceptibilities of the components of some magnetic beds lie in the range 30,000-60,000 x 10^{-6} c.g.s. units. However, there is evidence that magnetic beds contain strongly magnetic and weakly magnetic layers. Thus to assign an average susceptibility to a bed is not possible from the available direct measurement data.

McGrath (1970) reported susceptibility measurements on surface samples and drill cores from the Halifax Formation in Nova Scotia. The aeromagnetic response of these slates is very similar to that observed over the Adelaidean strata. McGrath considers that the magnetic effect of the Halifax Slates is primarily caused by pyrrhotite ($k < 300 \times 10^{-6}$ c.g.s. units), but that within the more highly metamorphosed contact aureoles surrounding intrusive granites, magnetite is the main magnetic mineral ($1,000 \times 10^{-6} < k < 6,500 \times 10^{-6}$ c.g.s. units). Possibly his susceptibility range for magnetite rocks applies to some of the strongly magnetic beds in Adelaide System sediments.

4.5 Method of interpretation and problems

Interpretation schemes for magnetic anomalies have become increasingly sophisticated in recent years and there is a range of powerful methods available, particularly for anomalies due to steeply dipping infinitely long tabular bodies (e.g. Peters, 1949; Smellie, 1956; Hutchison, 1958; Hall, 1959; Bruckshaw & Kunaratnam, 1963; Gay, 1963; Powell, 1967; McGrath & Hood, 1970; Koulomzine et al. 1970). Anomalies of interest can be enhanced by linear filtering or continuation methods (e.g. Henderson, 1960; Zurflueh, 1967;

Naidu, 1968). A well defined magnetic anomaly which is close to the theoretical shape expected for an infinitely long dipping tabular body, can be analysed to yield source dimensions, depth and strength of magnetization within error bounds of about ± 10%.

Of the published interpretation methods, the curve matching methods (e.g. Gay, 1963), which require fitting of an entire theoretical anomaly to the field anomaly, were found the most useful in the Adelaide Geosyncline. However, it must be acknowledged that if an anomaly observed in the field closely approximates the theoretical shape of a tabular body anomaly, then other simpler interpretation methods (e.g. Peters, 1949) will give closely similar results. The particular advantage of a curve matching method is that it can often be successfully applied to noisy data. However, to be most effective, the influence of noise must be assessed, particularly above the half amplitude points of the anomaly. In many instances, particularly for anomalies of 100 gammas or more in amplitude, the general form of the anomaly can be seen. The interpretation method applied by the author was to choose an initial profile from Gay's set of standard curves which had the same shape as the field profile and then make successive adjustments to the corresponding model until the theoretical profile closely fitted the field profile. Theoretical anomalies were produced by computer. Adjustments were made by trial and error rather than by a computerized iterative method such as that of McGrath and Hood (1970). Usually about five adjustments were necessary.

For all profiles interpreted in this chapter the geological dip of Adelaidean sediments was measured in the field. It was found that in most cases the theoretical anomaly expected if inductive magnetism acted alone did not match the field profiles. It is considered that remanent magnetism is an important contributor to nearly all anomalies studied. Gay (1963) stated that his method was just as effective for finding depth and width of remanently magnetized tabular bodies as for inductively magnetized bodies. The essential quantities derived are depth and apical width (i.e. width of the flat top surface of the tabular body); because geological dip was measured in the field, so thickness and strength and direction of magnetization could be derived.

The influence of noise is a problem particularly for low amplitude anomalies (e.g. 50 gammas or less) because it often completely masks the parts of the curve most necessary for quantitative interpretation. Linear filtering techniques (Henderson, 1960; Naidu, 1968) were applied to remove the noise from several low amplitude problem anomalies. After trial runs with various filters it was found that the resultant smoothed profiles did not clearly show one of the most important features evident in most of the best unfiltered data; it is often evident in well defined high amplitude anomalies that two or more tabular sources at different depths are present. Filtering tends to destroy evidence of the shallowest sources. In addition, linear filtering is strictly applicable to cases of random noise; quite often over important parts of anomalies the noise is not random and shows a preferential sign which is the same as for the broad anomalies. Because of these factors it was decided that most benefit would come from a study of well defined, unfiltered strong anomalies which were least influenced by noise.

The technique of downward continuation (Henderson, op. cit.) was applied to several anomalies to gain more information on the contributing sources. Noise was removed by hand or by linear filtering and the resultant profile was then continued. The method was found to be very sensitive to the filter used; any small irregularities due to near surface noise tended to become over emphasized by the continuation process. Thus several trial runs and successive smoothings were necessary before a successful continuation was achieved, which only enhanced anomalies due to deep sources. Because of the problem of noise, it is considered that downward continuation is not a particularly useful technique for the study of anomalies due to sediments in the Adelaide Geosyncline.

It is difficult to assess the influence of demagnetization effects in the area. Demagnetization becomes important in magnetic interpretation if the susceptibility of source rocks is about 0.1 c.g.s. units or more (Gay, 1963). Because the magnetic method cannot resolve several closely spaced sources at a depth much in excess of their separation, it is usually difficult to decide whether the source of an anomaly is a single thick magnetic bed, or several close, very strongly magnetized thin beds. In the latter case demagnetization effects might be important. However, if the susceptibility measurements in the area are taken as a guide, demagnetization effects can be neglected.

Another problem of interpretation is that of separating the effects of induced magnetism and remanent magnetism of beds where both are important. Methods such as those of Hall (1959), Gay (1963) and Powell (1965) allow rapid estimation of magnetization inclination if the geological dip is known to within about $\pm 10^{\circ}$ (as is usually the case for Adelaide System sediments). The strength of apparent magnetization (J') can also be estimated if the geological dip is known. For a single long magnetic bed, where inductive and remanent magnetism are both important, it is not possible with magnetic interpretation to find the true direction and intensity of magnetization (J). In general J is greater than or equal to J'. Susceptibility data allow estimation of the individual effects of induced magnetization and remanent magnetism in the plane normal to strike of the bed (i.e. apparent remanent magnetization). Unless susceptibility of the bed is known no accurate estimate of the apparent strength of remanent magnetization can be made. Reliable susceptibility data were not available for the magnetic beds in the Adelaide Geosyncline; therefore the author's work was confined to estimation of the strength and direction of apparent magnetization, except for the Lower Tapley Hill magnetic bed where special geological circumstances permitted an approximate estimation of the strength of remanent magnetization (discussed in Chapter 5).

A method for finding the intensity and direction of apparent magnetization (J') by use of Gay's (1963) method is outlined in Appendix A6. In the thesis c.g.s. units are used. Therefore if a magnetic rock of susceptibility k (c.g.s. units) is inductively magnetized by the earth's field (0.59 Oersteds), the magnetization J is equal to 0.59 x k c.g.s. units.

4.6 Characteristics of magnetic beds as indicated by interpretation of ground data

Most ground work was carried out across the Lower Tapley Hill magnetic bed and the following discussion is mainly of anomalies associated with this bed. The ground magnetic anomalies are often 200 gammas or more in amplitude, and the problem of noise is less than over beds with weak response. It is considered that interpretation of the magnetic anomalies associated with this bed can yield information applicable to other magnetic beds in the Adelaide Geosyncline. While ground lines were run across many of the magnetic beds, only the Holowilena Ironstone is discussed apart from the Lower Tapley Hill magnetic bed. Figure 4.4(d) shows the locality of field lines on ORROROO and indicates those discussed in this chapter.

4.6.1 Presentation of interpreted magnetometer profiles

Presentation of interpreted magnetic anomalies is a problem. Some authors show the field profile and theoretical anomaly in juxtaposition, others separate the two. Because the field profiles have important details which would be obscured by the juxtaposition presentation, for this thesis it was decided to separate the profiles. The individual anomalies interpreted are drawn at various horizontal and vertical scales so that they all have about the same width and height (Figs. 4.3 & 4.4).

The figures illustrating the interpretation of magnetic anomalies show the corrected field profiles on an arbitrary base level, above the calculated theoretical profiles, the models, and the geology. The base level for the theoretical profiles is common with the ground surface for the models. The horizontal axes and vertical axes below ground level are scaled in metres, while above ground level the axes are scaled in gammas. The inset clocks show the direction of To', the orientation of the effective total magnetic field (cf. Gay, 1963), and the direction of J', the interpreted apparent magnetization responsible for the magnetic anomalies. It will be seen that in most cases the direction of J' is quite different from To'. The theoretical anomalies were calculated with a grid interval appropriate to give a clear picture.

The grid interval is indicated near each of the theoretical profiles.

4.6.2 Geology of the lower part of the Tapley Hill Formation

Thomson et al. (1964) described the Tindelpina Shale Member of the Tapley Hill Formation as a black carbonaceous pyritic shale about 200 ft (60 m) thick which frequently contains thin interbeds of carbonate. The bed is a marker unit which persists over the whole of the Adelaide Geosyncline except for rare 'pinch-outs' due to local erosion (Parkin, 1969, Chapter 2). It lies at the base of the Tapley Hill Formation which is a silty unit, and lies immediately above the Yudnamutana Subgroup, which on ORROROO mainly consists of the Appila Tillite, a glacial quartzite unit. From the author's experience, the true thickness of the Tindelpina Shale Member is often hard to ascertain in the field because both it and the lower part of the Tapley Hill Formation often do not outcrop and are thinly covered by soil. The Appila Tillite usually forms prominent ridges which can be easily traced both on aerial photographs and on the ground.

Figure 4.2 shows a stratigraphic column for the Tindelpina Shale Member in the north-east of ORROROO, compiled by the author with the help of two geologists of the University of Adelaide, Dr. V. Gostin and Mr. J. Sumartojo. Binks (1971) stated that the Tindelpina Shale contains minor pyrrhotite; in the area studied by the author no pyrrhotite was observed. The main indication of sulphides in the area studied is the presence of limonite pseudomorphs after pyrite in the surface rocks. In rare cases limonite octahedra after magnetite are present. The presence of these octahedra is some of the strongest evidence available from geological studies that the Tindelpina Shale Member contains strongly magnetic minerals. In addition magnetic separation of cuttings from a drill hole into the shale at the Southern Cross Mine on COPLEY revealed a trace quantity (0.01%) of magnetite (Appendix A4, Sample C063). The evidence from the magnetometer data is that probably 1% or more of magnetite exists below the depth of magnetic weathering.

4.6.3 Interpreted vertical field magnetometer profiles across the Lower Tapley Hill magnetic bed

4.6.3.1 Profile 68

This profile (Fig. 4.3(b)) is perhaps the key to the shape of anomalies due to magnetic sedimentary beds in the area. It shows a broad, nearly symmetrical anomaly (1) together with a narrower anomaly (2) on the up-dip side and numerous noise peaks (e.g. 3,4,5), most of which have the same sign as the broad anomaly. Many of the ground profiles are very similar to Profile 68. A model and the corresponding theoretical anomaly are shown below the field profile. The model which accounts for the anomalies consists of a body with an apical width of 180 m at a depth of 180 m, out of which extends a body with an apical width of 30 m at a depth of 30 m. An alternative model for the deeper of the two bodies would be several thin closely spaced magnetic sheets. However, it is not possible to resolve them. Because the anomaly sign is opposite to that expected if inductive magnetism acted alone, it is apparent that the source is remanently magnetized. As the anomalies are symmetrical, the magnetization must lie close to the plane of bedding. Magnetization in the dip plane for the model (i.e. the plane normal to the trace of outcrop) is $J' = 2.6 \times 10^{-3}$ c.g.s. units.

The model probably approximates the form of the magnetic beds. At this locality it appears that magnetic minerals are weathered to a depth of 180 m except in a thin bed which extends closer to the surface.

The noise peak (3) on the down-dip side of the broad anomaly may be caused by a very thin magnetic bed at a depth of 6 m. A narrow anomaly or noise peak often occurs at this position on the other profiles across the lower part of the Tapley Hill Formation. Where it is absent it is probable that the thin source bed is deeply weathered. Peaks (4) and (5) may have a similar source to that suggested for peak (3).

4.6.3.2 Profile 76S

This profile (Fig. 4.3(a)) shows two partly resolved anomalies (1,2) which make up a broad anomaly. The peak of anomaly (2) is disguised by noise. The peak of anomaly (1) is sharper than expected for a single flat topped source. A three body model was constructed to account for anomalies (1) and (2). The major contribution to the theoretical anomaly comes from two deep sources (apical width 60 m, depth 120 m, and apical width 55 m, depth 110 m). The sharp peak of anomaly (1) is not fully understood and modelling to account for it is difficult. Modelling with a third source (depth 30 m) partly accounts for the sharp peak.

Anomalies appear to be symmetrical and the sign is opposite to that expected if inductive magnetism acted alone. Therefore the sources are remanently magnetized and magnetization lies close to the plane of bedding. An estimate of magnetization in the dip plane for the model is $J' = 4.0 \times 10^{-3}$ c.g.s. units.

The model probably approximates the form of magnetic beds at the locality. It appears that the beds are weathered to a depth of 110-120 m except for one or more very thin beds which extend closer to the surface.

4.6.3.3 Profile 74

This profile (Fig. 4.3(c)) shows a broad anomaly with a peak rather too sharp for the source to be a single, thick, flat topped body. The anomaly is similar to anomaly (1) on Profile 76S. A two body model can account for the anomaly. This consists of one body with an apical width of 105 m and a depth of 55 m and another with an apical width of 10 m at a depth of 23 m. The depth and dimensions of the thin source are very approximate because the residual anomaly separated from the main peak for this profile is subject to considerable error. However, the model shows the same form as those for Profiles 76S and 68. An alternative model which would equally well account for the anomaly on Profile 74 consists of several thin, closely spaced sources. Yet another consists of a thick body with a triangular top surface rather than a flat surface.

The model probably approximates the general form of magnetic beds at the locality.

The anomaly is symmetrical and is opposite in sign to that expected if induction acted alone. Therefore the source is remanently magnetized in a direction close to the plane of bedding. An estimate of magnetization in the dip plane of the model is $J' = 0.9 \times 10^{-3}$ c.g.s. units.

4.6.3.4 Profile 115

This profile (Fig. 4.3(d)) shows a broad anomaly (1) and a poorly defined broad anomaly (2) on the left side. Noise is random and can be filtered off in this case. Because anomaly (2) is not well defined even after filtering and downward continuation, the model constructed only accounts for anomaly (1). The model consists of a single thick source with an apical width of 160 m and a depth of 80 m. Downward continuation indicated that a two body model would also explain anomaly (1). The width of the single body model is based on the results of continuation.

Anomaly (1) is symmetrical and opposite in sign to that expected if inductive magnetism acted alone. Therefore the source is remanently magnetized and the direction of magnetization lies close to the plane of bedding. An estimate of magnetization in the dip plane of the model is J' = 0.25 x 10^{-3} c.g.s. units. If a two body model is used to account for anomaly (1), the magnetization is approximately four times this value.

The model probably approximates the general form of magnetic beds at the locality. It appears that the beds are magnetically weathered to a depth of about 80 m.

4.6.4 Discussion of the Lower Tapley Hill magnetic bed

There is evidence that the Lower Tapley Hill magnetic bed revealed by aeromagnetic interpretation consists of two or more thin magnetic beds within a zone 250 m wide. The lowest of these lies in the Tindelpina Shale Member (see Fig. 4.3). Thus the whole of the 250 m thick magnetic zone does not exactly correspond with the Tindelpina Shale Member as defined by Thomson et al. (1964). Interpretation of magnetic anomalies indicates that the upper part of the bed is magnetic at a depth of about 80-200 m below the surface.

Because of the great depth of magnetic weathering of the beds it is not possible to resolve the fine details fully with the magnetic method. Drilling will be required to find whether the magnetic source consists of a single thick bed weathered to give the appearance of several thin sheets or whether the source is made up of several thin sheets weathered to various depths.

Until fresh rock is available for study the problem of whether the mineral causing the magnetic anomalies is magnetite or pyrrhotite cannot be resolved. The available evidence indicates that magnetite is present but the quantity is difficult to ascertain. Empirical relationships between magnetic susceptibility and magnetite content (Grant & West, 1965, pp.367,368) are not directly applicable because the beds are remanently magnetized. If the 250 m thick magnetic zone discussed above is treated as a single thick bed (cf. interpretations of Profiles 115 & 68), the equivalent magnetic susceptibility is 400-4,000 × 10^{-6} c.g.s. units. If treated as several thin beds (cf. interpretation of Profile 76S), the susceptibility of individual beds may be 8,000 × 10^{-6} c.g.s. units or higher. It is likely that the ratio of remanent magnetism to induced magnetization is two or more (see Chapter 5). Therefore the true susceptibility is probably less than half the equivalent susceptibility, e.g. about 200-2,000 × 10^{-6} c.g.s. units. From the relations in Grant and West (op. cit.) the quantity of magnetite present in the Lower Tapley Hill magnetic bed could be 0.1-1.0%.

The quantity of pyrrhotite required to produce susceptibilities in the range 200-2,000 × 10^{-6} c.g.s. units would be 1-10% or more (Jakosky, 1950, p.154). Although it is possible that pyrrhotite contributes to the magnetic response of the Tindelpina Shale, it is more likely that a small quantity of magnetite causes the anomalies.

4.6.5 Geology of the Holowilena Ironstone

The Holowilena Ironstone is described by Thomson et al. (1964) from PARACHILNA as a hematite siltstone, with lenses of dolomite and greywacke, with glacial erratics, totalling 400 ft (120 m) thick. A bed of hematite and magnetite siltstone which can be traced for 20 km near the base of the Yudnamutana Subgroup in the north-east corner of ORROROO is considered by Binks (1971) to be equivalent to the Holowilena Ironstone on PARACHILNA. Measurements on the ground by the author indicate that in the north-east of ORROROO the Holowilena Ironstone is less than 50 m thick and that of this thickness more than half consists of interbedded siltstones. A mineralogical study of two small samples containing 50% iron oxides by volume (Appendix A2) indicated that magnetite is altering to martite. The susceptibilities measured for the samples (0.011-0.058 c.g.s. units) are probably one-half those of unaltered equivalent rock at depth. Two other samples gave the values 100×10^{-6} and 400×10^{-6} c.g.s. units for susceptibility. Although heavily stained, these samples contained less than 10% iron oxides.

4.6.6 Interpreted magnetometer profiles across the Holowilena Ironstone

4.6.6.1 Profile 121

Profile 121 (Fig. 4.4(a)) was taken across boldly outcropping Holowilena Ironstone. The complexity of the magnetic anomalies is typical of that expected over a dipping layered tabular source which is magnetic at the surface. On Figure 4.4(a) the zone over which ironstone crops out is indicated by a heavy line. This part of the profile was re-read at 1 metre intervals to provide detail of the anomalies 1, 2 and 3, but the detailed profile is not included here. The detailed work showed that magnetic anomalies are displaced towards the down-dip side of magnetic outcrops. Thus although surface rocks are strongly magnetic, material below the surface is even more strongly magnetic.

The model which accounts for the field profile consists of three tabular bodies with apical widths of 2 m at depths of 3 m, 3 m and 6 m (for anomalies 1, 2 and 3 respectively) and a thicker body with an apical width of 48 m at a depth of 24 m. It was found that the model could be built up assuming the sources are influenced by inductive magnetism acting alone. Figure 4.4(a) indicates that the direction of magnetization is almost normal to the plane of bedding of the sources. An estimate of the intensity of apparent magnetization of the thick body in the model is J' = 0.03 c.g.s. units, corresponding to a magnetic susceptibility of 0.058 c.g.s. units. The correspondence of this value with a measured susceptibility is coincidental. At this locality it appears that the rocks preserve a strong component of remanent magnetization which lies close to the plane of bedding. Because it also lies close to horizontal (Appendix A2, Sample AAH1) the remanent magnetism has little effect on the anomalies.

While it is considered that the model approximates the form of magnetic beds associated with the Holowilena Ironstone at the locality, from the magnetometer data it is not possible to resolve whether the source of anomaly (4) is a single thick body as shown on Figure 4.4(a) or whether it is a multi-layered body.

4.6.6.2 Profile 126

This profile (Fig. 4.4(b)) shows a broad anomaly (1) with a narrow anomaly (2) on the up-dip side. Anomaly (2) lies close to an outcropping ironstone bed 2 m thick. However, as for the case of Profile 121, the anomaly lies on the down-dip side of the outcrop. Because the anomalies are not of the shape expected if inductive magnetism acted alone it is evident that remanent magnetism is important. The model constructed to account for anomalies (1) and (2) consists of a tabular body with an apical width of 23 m at a depth of 23 m and a tabular body with an apical width of 4.5 m at a depth of 4.5 m. An estimate of magnetization in the dip plane of the thick bed of the model is $J' = 0.1$ c.g.s. units.

4.6.7 Discussion of magnetic beds associated with the Holowilena Ironstone

The magnetic data indicate that magnetic beds in a total thickness of 60 m are associated with the Holowilena Ironstone. Some of these beds are probably very thin and come close to the surface, but the top of the thickest bed lies about 23 m below the surface. Both of the interpretations indicate that a thick magnetic bed overlies one or more thin beds. Some of the thin beds are magnetic at the surface but pass down-dip into even more strongly magnetic material. There are no distinctive ironstone beds exposed at the surface which correspond to the strongly magnetic bed at 23 m depth.

To the south-west of the area where Profiles 121 and 126 were taken the vertical field anomalies at the equivalent position to the Holowilena Ironstone are positive. Here the beds dip to the south rather than to the north and north-east as in the vicinity of Profiles

121 and 126. Thus the sign of anomalies is a function of geological dip (see Chapter 5 for discussion of this feature in connection with the Lower Tapley Hill magnetic bed), and it is probable that the ratio of remanent to induced magnetization is up to two or more. The susceptibility of the magnetic bed is close to 0.06 c.g.s. units. This susceptibility could be caused by approximately 20% magnetite in sedimentary rocks (Grant & West, 1965, p.368).

4.7 Discussion of magnetic beds

The single magnetic beds indicated by interpretation of the aeromagnetic data can often be resolved into several beds by use of ground magnetics. Thus each magnetic bed predicted from aeromagnetics probably consists of a zone of thin strongly magnetic beds separated by less strongly magnetic material. The total thickness of the Lower Tapley Hill magnetic bed is about 250 m. From other studies (not presented in the thesis) of ground anomalies associated with the Ulupa Siltstone, it appears that 250-300 m is usually the maximum thickness of the zones of magnetic strata.

Ground magnetic anomalies over Adelaidean sediments have a very characteristic shape. They have a broad component attributable to deep magnetic material and a complex arrangement of sharp anomalies on the up-dip side of the broad anomaly, attributable to remnants of the deep material.

The depth of magnetic weathering is variable both within each zone of beds and along strike. It appears that 200 m is about the maximum depth of weathering, although it is a common feature that various thin beds are only weathered to depths of from 5-30 m or less.

Often the shallow weathered beds appear to extend up from a deeper thick magnetic bed. This feature has a close parallel with the way in which rocks break down near the surface; resistant strata outcrop, less resistant strata decompose to great depths. In the areas studied there is a little evidence to correlate mechanical breakdown with magnetic weathering in the case of the Holowilena Ironstone magnetic bed, and the Ulupa Siltstone magnetic bed (the bed with 600 gamma aeromagnetic anomalies - Fig. 3.5).

In all of the ground studies over magnetic beds there were no magnetic anomalies which could be unequivocally due to inductive magnetism acting alone. Rather, it appears that in general, remanent magnetism is more important. Because remanent magnetization is important and magnetic beds are interlayered with weakly magnetic material, estimates of susceptibility from magnetic interpretation are subject to great errors, possibly 100% or more. However, it appears that the magnetic susceptibility of magnetic beds is probably 1,000 x 10^{-6} c.g.s. units or more above the background susceptibility.

Chapter 5

REMANENT MAGNETISM OF THE LOWER TAPLEY HILL MAGNETIC BED

5.1 Introduction

The most widespread and consistently occurring magnetic bed in the Adelaide Geosyncline is the one near the base of the Tapley Hill Formation. For ease of discussion in this chapter the magnetic bed will be referred to as the Lower Tapley Hill magnetic bed. It is for this magnetic bed that Tipper and Finney (1966) suggested that an element of remanent magnetization was acquired prior to folding, such that the observed magnetic anomalies are a function of geological dip. They suggested that the proposed pre-folding component of remanent magnetism lies close to the plane of bedding. With such an arrangement, reversals in sign of anomalies across folds are to be expected. Interpretation of total field aeromagnetic contour maps over the whole area of the Adelaide Geosyncline indicates that it is a common feature that anomalies over the magnetic bed on adjacent limbs of fold structures are either opposite in sign or of different amplitude (Figs. 5.1 & 5.2).

From a detailed analysis of aeromagnetic flight charts and ground magnetometer profiles on ORROROO it was found that reversals in sign of anomalies over magnetic beds occur at several positions in the stratigraphic column. Most of the reversals recognized have the same sense as the reversals over the Lower Tapley Hill magnetic bed, viz. Holowilena Ironstone magnetic bed, magnetic bed between the Tarcowie Siltstone and Waukaringa Siltstone. Thus total field anomalies over beds dipping to the north, north-west or west are often of positive sign, while beds dipping south, south-east or east are often of negative sign. A similar sign relationship holds for vertical field anomalies. Vertical field anomalies over beds dipping to the north, north-west or west are often of negative sign, and over beds dipping to the south, south-east or east, are often of positive sign. Moreover, it is usual that the vertical field anomalies are symmetrical or nearly symmetrical independent of geological dip which is indicative of the magnetization lying close to the plane of bedding.

To learn more about the suggested pre-folding component of remanence, detailed ground magnetometer lines were run on two plunging fold structures south-west of Waukaringa (see Fig. 5.2) where it appeared likely that both the direction and inclination of the remanent magnetism associated with the Lower Tapley Hill magnetic bed could be determined from the anomalies. The ground work was concentrated in an area where anomalies change sign across fold structures, rather than where the anomalies have the same sign but different amplitude. It was expected that a ground study near the zone of sign change of anomalies would give information on the azimuth of the remanent magnetization. The basis of the interpretation is outlined in section 5.3. The author has seen no report in the literature in which both the inclination and azimuth of a pre-folding component of remanent magnetization relative to the plane of bedding of sediments have been derived from magnetic anomalies by the method discussed in this chapter. Reported work is often similar to that discussed in Chapter 4 where the component of magnetization in the dip plane is found (e.g. Bath, 1962).

The work done has a parallel in Graham's tests for stability of natural remanent magnetism (NRM). Graham (1949) stated that one of the best tests for stability of NRM is to find whether results of palaeomagnetic tests from two limbs of a fold give the same remanent vector orientation when the fold is mathematically unfolded. Another test for stability comes from the self consistency of palaeomagnetic results over a wide area. Because the interpretation of magnetic anomalies indicates that Adelaidean sediments are deeply weathered, and because palaeomagnetic testing on surface rocks in the Adelaide Geosyncline by Briden (1965, 1967) had disappointing results, it was decided to confine the study of remanence to large magnetic anomalies.

5.2 Previous palaeomagnetic work on Adelaide System sediments

Briden (1964, 1967) discussed results of palaeomagnetic tests on surface samples and drill cores from several sites in the Adelaide Geosyncline. He collected samples from areas where he considered that metamorphism has been weak; subsequent study by the author indicates that the beds tested do not produce observable anomalies on the aeromagnetic maps in the area tested. Thus the rocks sampled may be classified as weakly magnetic in comparison to the magnetic beds discussed in Chapters 3 and 4 of this thesis.

Briden (op. cit.) found it difficult to isolate a primary component of NRM. Samples from the upper part of the Adelaidean, viz. Wilpena Group, and the overlying Cambrian sediments have NRM consistent with a Mesozoic or early Tertiary age. He suggested that the dominant NRM is a secondary magnetization which probably results from a surface effect or metamorphic effect.

It is to be expected that in the parts of the Adelaide Geosyncline where metamorphism has been strong the main NRM detected will be a secondary component. Therefore it is unlikely that a primary component acquired at the time of deposition of the Adelaidean sediments will be detected. Nevertheless, any information about a pre-folding component of remanence for Adelaidean sediments is still of interest.

5.3 Basis of interpretation

The influence of remanent magnetism on magnetic anomalies over dipping tabular magnetic bodies is well known and interpretive schemes have been devised to account for it (e.g. Sutton & Mumme, 1957; Hall, 1959; Gay, 1963; Powell, 1965; Koulomzine et al., 1970).

Consider the case of strong remanent magnetism acting on a long uniformly magnetized thin magnetic bed of constant thickness and depth of weathering, and such that the direction of remanence lies in the plane of bedding. For the following discussion it is assumed that the effect of inductive magnetism is negligible. The amplitude and sign of vertical field magnetic anomalies over the dipping bed are dependent on the magnitude of the component of the remanent magnetization in the dip direction, i.e. the apparent magnetization. This component is the only one important in producing vertical field anomalies over the bed. Thus if the component in the dip direction is zero, so the anomalies are zero, and if the component in the dip direction is maximum, then the anomalies are a maximum, with the sign dependent on whether the vector direction is up-dip or down-dip. Following the convention that the earth's field lines point upwards in the southern hemisphere and downwards in the northern hemisphere (cf. Gay, 1963), then with the vertical field magnetometer, negative anomalies are recorded over the remanently magnetized bed if the vector direction is up-dip, i.e. pointing up out of the ground. When the vector points down-dip vertical field anomalies are of positive sign.

Total field anomalies measured in areas other than at the poles will not in general be symmetrical over a bed magnetized in the plane of bedding. In the southern hemisphere, over steeply dipping beds, the anomalies will be mainly positive if the vector is up-dip, and mainly negative if down-dip.

If the remanently magnetized bed discussed above occurs in a peneplaned dome structure, then by measuring the amplitude and sign of anomalies around the structure the direction of the remanent vector can be deduced. Taking the case of anomalies changing sign along strike from positive, through zero amplitude, to negative, then where the anomaly amplitude is zero the remanent vector points along the geological strike towards the region where anomalies are of negative sign. For a thin magnetic bed with a constant depth of weathering and strength of remanent magnetization, anomaly amplitudes plotted against strike direction around a closed structure will closely fit a sinusoid. The area under the anomalies will also closely fit a sinusoid. Amplitudes and areas under anomalies are independent of the geological dip of the bed.

For two or more identical thin magnetic beds arranged parallel and close together (in the structure discussed above), and which produce partly resolved anomalies, the sum amplitude will depend on the geological dip, because with low dip the top surface of the beds are further apart than with steep dip. Thus the anomalies will be better resolved when the geological dip is low. However, the total area under the anomalies is independent of dip and will closely fit a sinusoid if plotted against strike direction around the closed structure. If the magnetic beds have finite thickness, then anomaly amplitudes are further dependent on dip because the magnetic charge density on the top surface is decreased as the apical width increases. However, once again the area under the curves plotted against strike direction should lie close to a sinusoid.

If the remanent magnetic vector is oblique to the bedding plane, then the interpretation problem to find the vector direction is more complex but still soluble. In this case the shape of the anomalies will not usually be symmetrical as for the simple case discussed above.

Interpretation problems arise if inductive magnetism is important and if a second component of remanent magnetism has been acquired in a direction other than the plane of bedding since folding occurred. To fully account for these influences would be impossible without taking measurements on oriented samples with palaeomagnetic apparatus. However, if the influence of the second component of remanence or inductive magnetism is not too strong, as appears to be the case for the area studied, simple approximations can be made to account for them and the detailed study of rock specimens can be avoided.

5.4 Interpretation of ground surveys in the Waukaringa area

Figure 5.3 shows the vertical field anomalies over the Lower Tapley Hill magnetic bed on two adjacent noses of a plunging anticlinal structure near Waukaringa. The profiles show the noisy field data rather than smoothed idealized anomalies, to illustrate that at the outset there is a problem in interpreting the data. The anomalies change sign from positive where beds dip southwards, to negative where beds dip northwards. The influence of inductive magnetism appears to be very much less than remanent magnetism. If the contribution of induction was important, the anomalies over south dipping beds (positive anomalies) could be expected to be of lower amplitude than over north dipping beds (negative anomalies), when considered in combination with the influence of remanence with constant azimuth in the plane of bedding. However the opposite occurs. The positive anomalies are of higher amplitude than the negative anomalies. The strongest of the positive anomalies, viz. Profiles 65S, 68, 69, 44S and 64S, are nearly symmetrical in shape and this indicates that magnetism is close to the plane of bedding (probably within ± 10^{o}). The negative anomalies are more complex and their shapes are more strongly influenced by noise, but in this area and other parts of the Adelaide Geosyncline they show strong influence of a component of magnetization close to the plane of bedding, viz. Profiles 60N, 62 and 65N. It is considered that the influence of inductive magnetism can be neglected in interpretation of the anomalies.

While interpretation of a simple theoretical case like that outlined in section 5.3 is straightforward, interpretation of the field data is not.

For the particular application of interpretation required in this chapter, perhaps the most difficult problem was that of accurately mapping the magnetic beds. The most important factor required to determine the direction of remanent magnetization is the strike of the magnetic bed near the point of sign change of the anomalies. It was near this region that the complexity of the anomalies largely prevented accurate mapping. It was necessary to interpolate from where anomalies were well defined into the region where they were not. Uncertainties in the depth of magnetic weathering, bed thickness and strength of magnetization made interpolation difficult. Some guidance was taken from tracing outcropping beds.

It is considered that the main features of the field profiles can be explained by considering a pre-folding component of remanence in the plane of bedding together with a second component which has had an approximately equal influence both on the positive and negative anomalies. This second component appears to be directed downwards close to layering in the magnetic beds. The basis for proposing the existence of this second component of remanence with such special directional properties comes partly from the ground work in this and other areas, and partly from the picture provided by the aeromagnetic coverage (discussed further in section 5.6). Where dips are low around the noses of the anticlinal structures, the anomalies show evidence of two parallel sources. Thus in this area the Lower Tapley Hill magnetic bed appears to contain two magnetic beds (cf. Chapter 4). For analysis of the remanent vector direction the magnetic sources were assumed to lie in a single thick magnetic zone (see Fig. 5.3). Furthermore the beds were assumed to be weathered to the same depth, both within the zone and along strike (depth of weathering estimates from the best anomalies lie in the range 100-200 m).

Figure 5.4 shows amplitude and areas of hand smoothed anomalies plotted against geographic strike direction of the magnetic beds. Data from both structures are combined on the one plot. Sine curves have been fitted by hand to this data. It is considered that the azimuth of the pre-folding plane of bedding component of remanent magnetism is given by the zero amplitude and area points on the sine curves (dashed base line). The adjustment of base level to zero accounts for the proposed second component of remanence. It is estimated that the declination of the pre-folding plane of bedding component of remanent magnetism is 135^{0} geographic. The error bounds are probably about $\pm 20^{0}$. Thus in the unfolded beds a linear rod oriented in a direction of 135^{0} would have north magnetic poles on its south-eastern end.

Fold patterns in the southern part of the Adelaide Geosyncline show concavity south-eastwards, indicating that tectonic stresses acted from this direction. In view of this, the folding may have migrated the direction of pre-folding remanent magnetism from about 120^{0} (geographic) to its presently calculated direction of 135^{0} (geographic).

5.5 Strength of magnetization

An estimate of the strength of magnetization in the Lower Tapley Hill magnetic bed can be made from the vertical field magnetometer profiles in the Waukaringa area. Because the amplitude and sign of anomalies change across anticlinal structures, it is necessary to consider profiles over both north and south dipping beds. Two profiles are considered, 68 and 60N on Figure 5.3. The anomaly on Profile 68 is discussed in Chapter 4 and the estimate of strength of magnetization is $J' = 2.6 \times 10^{-3}$ c.g.s. units, directed down-dip. The best defined positive anomaly on Figure 5.3 is on Profile 60N and this appears to be the partial resolution of anomalies due to two or more thin parallel beds over a total apical width of 170 m. Each of these probably lies at a depth of about 45 m. An estimate of magnetization for a single thick bed made after continuing the partly resolved anomaly to 135 m is $J' = 0.6$ c.g.s. units. Here the distance from source to magnetometer is the same as for the source of the anomaly on Profile 68.

Because of the widespread occurrence and similarity of magnetic anomalies over the Lower Tapley Hill magnetic bed both in the locality of ground lines discussed in this chapter, and other parts of the Adelaide Geosyncline, it is reasonable to assume that the overall thickness of the bed is fairly constant. In support of this the interpreted total thicknesses of the magnetic beds on Profiles 68 and 60N are approximately the same. Therefore we can use the interpreted strengths of magnetization from Profiles 68 and 60N to give an approximate estimate of the strength of the components of magnetization acquired before and after folding (viz. J1 and J2 respectively) in the Waukaringa area.

Thus $$J1 + J2 = 2.6 \times 10^{-3} \text{ c.g.s. units}$$
$$-J1 + J2 = 0.6 \times 10^{-3} \text{ c.g.s. units}$$

And $$J1 = 1.0 \times 10^{-3} \text{ c.g.s. units}$$
$$J2 = 1.6 \times 10^{-3} \text{ c.g.s. units}$$

Thus in the Waukaringa area the pre-folding component of remanent magnetization has an intensity of 1.0×10^{-3} c.g.s. units and the post-folding component has an intensity of 1.6×10^{-3} c.g.s. units. These figures apply for a model assumed to consist of a single magnetic bed about 200 m thick. In view of the discussion in section 5.6 it is to be expected that the strength and ratio of the two components of remanence will be different at different localities. However, the estimate made above serves to establish the order of size of the magnetization.

5.6 Interpretation of the total field aeromagnetic anomaly map

The map of total field aeromagnetic anomalies (Fig. 5.1) shows three main sets of characteristic areas (see Fig. 5.2):

Characteristic 1

Areas where south or east dipping beds have negative anomalies and adjacent north or west dipping beds have positive anomalies of lower amplitude (considered previously in this chapter).

Characteristic 2

Areas where south or east dipping beds have negative anomalies of higher amplitude than over adjacent north or west dipping beds.

Characteristic 3

Areas where east and west dipping beds have positive anomalies but the amplitude over west dipping beds usually exceeds that over east dipping beds.

Vertical field ground magnetometer work in areas showing these characteristics produced symmetrical or nearly symmetrical anomalies indicative of magnetization close to the plane of bedding.

The main features can be qualitatively explained on the basis of three factors:

(1) A component of remanent magnetism close to the plane of bedding and of constant azimuth, produced before folding.

(2) A component of remanent magnetism close to the plane of bedding produced after folding and directed down-dip.

(3) Inductive magnetism and/or a third component of remanence directed upwards (probably close to the plane of bedding).

Factor (1) produces negative total field anomalies over east or south dipping beds and positive anomalies over west or north dipping beds. Factor (2) produces anomalies of negative sign and factor (3) produces anomalies of mainly positive sign. If amplitudes A(1), A(2) and A(3) are assigned to the total field anomalies produced by the three factors, then the three main sets of characteristics can be explained as follows:

Characteristic 1

$A(1) > A(2) > A(3)$

Characteristic 2

$A(2) > A(1) > A(3)$

Characteristic 3

$A(3) > A(1) > A(2)$

The possible geological implications of this interpretation are manifold.

The time of acquisition of the interpreted pre-folding component of remanence is not known. The main folding in the Adelaide Geosyncline occurred during the Lower Ordovician (Parkin, 1969, p.106). Therefore the pre-folding component of remanence must have been acquired in the Lower Ordovician or before. The palaeomagnetic data for Australia are incomplete for times before Ordovician (e.g. see Irving, 1964). It is quite possible that the remanence results from a 'moderate temperature viscous remanent magnetization' acquired when the beds were deeply buried beneath a thick sedimentary pile (cf. Irving & Opdyke, 1965). A thermal mechanism appears more likely than a mechanical one, e.g. Detrital Remanent Magnetism (cf. Nagata, 1962), because the pre-folding remanence associated with the Lower Tapley Hill magnetic bed also appears to be associated with other beds in the Umberatana Group, viz. near the boundary of the Waukaringa Siltstone and the Tarcowie Siltstone, and the Holowilena Ironstone. Thus a similar effect is observed over a total stratigraphic thickness of at least 2 km. Whatever the mechanism of acquisition, the pre-folding component has survived metamorphism associated with the Ordovician orogeny.

The proposed second component of remanent magnetism is of special interest because, like the first, it appears to lie close to the plane of bedding. If the second component was acquired during or after folding, then the ancient magnetic field would probably have had to be near vertical. It is conceivable that the magnetic minerals in the Lower Tapley Hill magnetic bed are of a platy nature and lie parallel to bedding planes such that the magnetic susceptibility is anisotropic and is maximum in the bedding planes; the inclination of TRM in such an arrangement will tend to lie close to the plane of maximum susceptibility (Irving, 1964, p.35). Magnetite, magnetically separated from cuttings of Tindelpina Shale (Appendix A4, Sample C063) was of a platy nature which gives support to this suggestion.

On the basis that remanent magnetism is due to thermal effects before, during and possibly after folding, it is possible to suggest a migratory or time-varying habit to the centres of heating. Areas where the pre-folding component of remanence is low (e.g. Characteristics 2 & 3 on Fig. 5.2) may have been heated longer after folding than areas where it is well preserved (e.g. Characteristic 1). Alternatively, where pre-folding remanence is low, heating may have been low before folding.

It is possible that the observed differences in aeromagnetic response are associated in some way with differences in magnetic minerals and grain size.

5.7 Discussion

The particular method used in this chapter to derive a direction for the pre-folding component of remanent magnetism probably has limited application. Suitably magnetized beds in structures suitable for interpretation are probably fairly rare, although in the Adelaide Geosyncline the method could probably be successfully applied at various localities to test both the Lower Tapley Hill magnetic bed and others. Perhaps the most important aspect of the work is that magnetic interpretation in the Adelaide Geosyncline can give new information on remanently magnetized beds which are strongly weathered near the surface. The information is of bulk properties of a thick magnetic bed (e.g. 200-300 m) inaccessible without drilling.

It appears that:

1. The Lower Tapley Hill magnetic bed, a feature some 250 m thick, is remanently magnetized near the plane of bedding.
2. The plane of bedding remanence was acquired in at least two stages, one before folding and one (or more) after folding.
3. The pre-folding component of magnetism has an azimuth of 135° (geographic) near Waukaringa; this figure is probably valid as far north as Mt. Painter (COPLEY) and almost as far south as Adelaide (ADELAIDE).
4. The strength of pre-folding and post-folding remanence near Waukaringa is 1.0×10^{-3} and 1.6×10^{-3} c.g.s. units.

5. In some areas the second component is markedly stronger than the first (viz. Area 2, Fig. 5.2).

6. In one area the influence of inductive magnetism or a third component of remanence is evident (viz. Area 3, Fig. 5.2).

PART B

Magnetic anomalies not caused by Adelaide System sediments

Chapter 6

ANOMALIES NOT DUE TO ADELAIDEAN SEDIMENTS

6.1 Introduction

An interpretation of the magnetic response of shallow sources in the Adelaide Geosyncline would not be complete without considering some of the less commonly observed features which, although difficult to interpret, and not fully understood by the author, are important to the overall picture. While most aeromagnetic anomalies are probably caused by magnetic Adelaide System sediments, there are others which differ in character and may be caused by intrusives or other bodies. It is these anomalies which are discussed in this chapter.

A special feature of the Adelaide Geosyncline is that few large igneous bodies have been found within Adelaide System sediments. The largest body known is the Anabama Granite (on OLARY) which is 40 km long: the second largest is a body of melaphyre and diabase 6 km across in the Oraparinna Diapir on PARACHILNA (Johns, 1972). Diorites 2 km across are mapped in the Paratoo Diapir on ORROROO (Binks, 1968) and near Bendigo Homestead on BURRA (Mirams, 1964). There are few published reports which discuss intrusives in the area; most attention has been given to Adelaidean sediments.

There are 30 or more breccia structures in the Adelaide Geosyncline which Dalgarno and Johnson (1965), Binks (1971) and others consider to be diapirs. The breccia consists of sedimentary material which was probably derived from some of the lowest members of the Adelaide System (Coats, 1964; Binks, op. cit.). Within the breccia small basic intrusive plugs and dykes, a few metres across, are often found.

Usually these are dolerites, but in the Walloway Diapir (ORROROO) small plugs and dykes of carbonatitic rocks are recorded (Tucker & Collerson, in press). Some diapirs have associated magnetic anomalies, and on this basis Tipper and Finney (1966) and Bennett (1968), predicted the locations of a total of eight unrecognized diapirs from a combined study of aeromagnetic and geology maps for ORROROO and PARACHILNA. Their predictions have not yet been confirmed.

Away from the diapirs most recognized intrusives are small. On BURRA, Colchester (in press) reports that 24 dykes and seven plugs of micaceous kimberlite are known about 25 km east of Terowie. The dykes are from 20 cm to 2 m across and are up to 400 m long. The largest plugs are about 100 m across. It is only in the southern part of the Adelaide Geosyncline where metamorphism has been strongest, that intrusive bodies of a few kilometres in length are fairly common. For example, on ADELAIDE about 50 pegmatite and dolerite dykes more than 2 km long are shown.

On the basis of the known geology it appears that unrecognized igneous bodies to be expected in the northern part of the Adelaide Geosyncline are probably quite small and will not exceed 100-500 m across. It is to be expected that magnetic bodies of this size are difficult targets to recognize with regional aeromagnetic surveys of the area because of the predominance of magnetic sediments.

While the contour maps for the Adelaide Geosyncline show several strong circular anomalies of 100 gammas or more which may be caused by large igneous intrusive bodies which lie near the surface, it is clear that a careful study of flight charts and the known geology is required to recognize anomalies which might be caused by small bodies. While the flight line spacing of 1 mile (1.6 km) for surveys in the area is too wide to be sure that all magnetic bodies capable of producing observable aeromagnetic anomalies at 150 m altitude were crossed, the data are suitable for a preliminary study.

The aeromagnetic records for ORROROO were studied in detail. Numerous anomalies were found which appear out of character with the response of Adelaide System sediments. Most of them lie over the plains of Quaternary sediments and appear to come from sources within or beneath the flat lying strata. The amplitudes of most of these anomalies are less than 20 gammas.

It was beyond the resources of the University of Adelaide to provide drills to test the sources. One exploration company, Minerals, Mining and Metallurgy Ltd., provided help on the problem and drilled six holes into the Quaternary sediments of the Walloway Plain to test whether a 40 gamma aeromagnetic anomaly was caused by the sediments.

6.2 The anomalies

For the study of magnetic sediments 5 gammas was taken as the lowest significant aeromagnetic anomaly amplitude. As discussed in Chapter 3, there were many anomalies of less than 5 gammas picked from the flight charts; they were not considered significant because they might be caused by variations of aircraft altitude or by topography. For the same reason, for the work discussed in this chapter 5 gammas was taken as the lowest significant anomaly amplitude.

The 1:47,520 scale base maps of interpreted shallow source magnetic anomalies were studied in conjunction with the geological maps. Selection of special features in Area A of ORROROO is a problem because the pattern is dominated by anomalies due to magnetic beds. However, in Area B the response of Adelaide System sediments is weak and isolated or cross cutting features are more easily detected. Those of particular interest are shown on Figure 6.1. Some of the features have been recognized previously by Tipper and Finney (1966) and Bennett (1968); these are indicated on Figure 6.1 by a T or a B.

Four types of features were recognized in the data for ORROROO. These are:

1. Linear anomalies transverse to strike of exposed Adelaide System sediments.
2. Anomalies observed on one or two flight lines and therefore of unknown or uncertain strike direction and extent.
3. Anomalies clustered in small groups in areas 5 km or more across.
4. Linear zones about 2 km wide which can be traced across Adelaidean and younger sediments, and in which there are none or very few anomalies.

The method of selection of these features is discussed below.

6.2.1 Type 1 - linear anomalies

Figure 6.2 shows two examples of cross cutting magnetic features (heavy lines) near the town of Orroroo. The southern-most of the two lies over the boundary between Quaternary strata and the Adelaidean. The northern-most lies over Quaternary strata and is approximately parallel to the boundary with the Adelaidean. Man-made features are shown on the map to illustrate that they are not important. Most of the linear features recognized in the area lie close to the boundary between Adelaidean and Quaternary strata. The anomalies are usually of the asymmetric kind with the positive limb on the northern side. The amplitude is usually less than 40 gammas.

6.2.2 Type 2 - isolated anomalies

To illustrate the problem of selection of isolated anomalies unlikely to be caused by Adelaidean strata, one seemingly isolated anomaly is indicated on Figure 6.2 by a bold arrow. The map to the south shows that anomalies occur at a corresponding stratigraphic position further along strike. Thus the arrowed anomaly is almost certainly caused by a magnetic sedimentary bed. Over areas of Adelaidean outcrop (undisturbed by diapirs), no isolated anomalies with amplitudes of 5 gammas or more were found, which were clearly not caused by the sediments. In all cases an apparently isolated anomaly on one flight line lay at a position which further along strike (perhaps 3-5 km) had corresponding anomalies at the same stratigraphic level.

In areas of Quaternary cover the lack of geological control makes the problem of selection of isolated anomalies even more difficult. In addition there is evidence that the Quaternary material is strongly magnetic and produces aeromagnetic anomalies of 20 gammas or more. For this reason only the strongest of the isolated kind of anomalies over Quaternary sediments were selected. Three features of this kind are shown on Figure 6.1. Two of them lie in areas where the geological maps indicate zones of disturbance and the third lies near the northern end of a Type 1 feature.

6.2.3 Type 3 - groups of anomalies

Numerous anomalies with amplitudes usually less than 20 gammas are recorded over plains of Quaternary sediments and do not appear to follow the linear trends which might be expected if the underlying strata have a trend and response similar to the surrounding Adelaidean rocks (see Fig. 3.2). In Area B there are more anomalies over the plains than over the surrounding Adelaidean strata. Although some of them lie in quite well defined groups, it is difficult to establish trend directions. Figure 6.1 shows three of the best isolated groups in which four or more anomalies of 20 gammas or more in amplitude were recorded.

6.2.4 Type 4 - non-magnetic zones

On any map of randomly distributed points there will always be a few short line-ups which can be selected. A map of plotted points such as Figure 3.2 combines both random and systematic data. From this sort of data it is to be expected that linear zones can be selected which are oblique to the general geological trends. This appears to be the case for Figure 3.2. Numerous non-magnetic zones oblique to the geological strike are evident between four or five flight lines.

While it is probable that some of these zones result purely from the statistics of the data, it is possible that some are due to unmapped geological features.

For control in the interpretation of the anomalies described in this section, three lines of research were followed. Magnetic anomalies over diapirs, dyke swarms and Quaternary sediments were investigated. The results of the investigations are presented in the following three sections.

6.3 Magnetic anomalies over diapirs

Figure 6.3 shows the locations of areas of diapiric breccia on ORROROO and indicates the position and amplitude of magnetic anomalies. In view of the discovery of magnetic carbonatites in the northern end of the Walloway Diapir, which have an associated aeromagnetic anomaly of 4 gammas (Tucker & Collerson, in press), the amplitude significance level was reduced to ± 3 gammas for diapirs. Table 6.1 shows the maximum amplitude of anomalies over the breccia which can be attributable to near surface sources. The table also indicates the structures in which intrusive rocks have been reported (Binks, op. cit.; Tucker & Collerson, in press).

Table 6.1

Amplitude of Aeromagnetic Anomalies over Diapirs on ORROROO

Number	Name	Maximum anomaly amplitude	Intrusive rocks known in the breccia
1	Worumba	12	dolerites and basalts
2	Worumba	4	?
3	Worumba	-	?
4	-	-	?
5	Wirreanda	-	?
6	Wirreanda	-	?
7	-	-	?
8	-	-	?
9	-	7	?
10	-	-	?
11	Round Hill (informal)	30	?
12	Yanyarrie	3	?
13	Carrieton	-5	?
14	Great Gladstone	-	quartz microdiorite
15	Oladdie	-	?
16	Coomooroo	16	?
17	Walloway	-4	carbonatites
18	Melrose	13	dolerites, quartz porphyries & aplites
19	Baratta	7 (100)*	?
20	Paratoo	400	diorite
21	Mt. Grainger	-10 (-90)*	diorite
22	Bulininnie	-	?
23	Oodlawirra	(140)*	?

* Amplitude in brackets is that of magnetic anomalies very close to breccia zones and probably due to magnetic bodies associated with the diapirs.

The magnetic response of most diapirs on ORROROO is weak (less than 20 gammas) and over many, no anomalies were recorded. The strongest response (400 gammas) over the Paratoo Diapir, is attributed to large plugs of magnetic diorite. Weak anomalies (10 gammas) over the Mt. Grainger Diapir are associated with dykes of diorite. The Round Hill Diapir (informal name), has associated anomalies (up to 30 gammas) which delineate a linear feature trending north-east in the southern-most part of the structure. While the Baratta, Mt. Grainger and Oodlawirra Diapirs have weak or negligible response over their outcrop, strong anomalies are closely associated with them, e.g. a 100 gamma linear anomaly lies within 0.5 km of the west side of Baratta, a 90 gamma linear anomaly lies within 0.5 km of the east side of Mt. Grainger and a 140 gamma linear anomaly lies within 0.5 km of the east side of the Oodlawirra Diapir. The source of the strong anomalies is not known except for the Paratoo Diapir. Interpretation of the aeromagnetic anomalies indicates that the source rocks have a magnetic susceptibility of $1,000-3,000 \times 10^{-6}$ c.g.s. units comparable with that for dolerite or gabbro.

Reconnaissance ground magnetometer surveys across the Walloway Diapir (ORROROO) and the Mt. Coffin Diapir (COPLEY) showed that only igneous intrusive bodies are strongly magnetic. The brecciated sediments are very weakly magnetic.

Binks (1971) states that the crush breccia was probably derived from the lowest members of the Adelaidean sediments, viz. Callanna Beds; over the areas of outcrop of relatively undeformed Callanna Beds away from the diapirs, the magnetic response is very weak and on ORROROO aeromagnetic anomalies do not exceed 10 gammas in amplitude.

The available evidence indicates that most of the aeromagnetic anomalies associated with diapirs are caused by igneous intrusive rocks. This generalization applies not only to ORROROO, but to other parts of the Adelaide Geosyncline as well. For example, on PARACHILNA strong aeromagnetic anomalies (200 gammas in amplitude) recorded over the Enorama, Blinman and Oraparinna Diapirs, lie over a variety of igneous rocks, including melaphyres, dolerites and gabbro. Similarly in the Spalding Diapir on BURRA, strong anomalies lie over basic plugs and dykes.

On ORROROO the four most strongly magnetic diapirs lie in Area A where the Adelaide System sediments are strongly magnetic. Although the cause of this association is not understood it is possible that if the magnetism of sediments primarily results from metamorphic effects, then the magnetic components of these diapirs may also be a product of the same metamorphic event.

6.4 Magnetic response of dyke swarms

There are three dyke swarms of importance to the interpretation of magnetic anomalies in the ORROROO area. These are the Eyre Peninsula dykes, the Walloway Diapir carbonatites and the Terowie kimberlites.

One of these, the Eyre Peninsula dyke swarm (Fig. 1.4), has been recognized only on the Gawler Platform, but if it was continuous across the Adelaide Geosyncline it would extend across the south-western half of ORROROO. The existence of the dykes is inferred from aeromagnetic interpretation; no outcrop of igneous material associated with the anomalies has ever been reported. Because it was considered possible that some of the linear cross cutting anomalies within the geosyncline may be an extension of the Eyre Peninsula dyke swarm, a study was made on the Eyre Peninsula to learn more about them and in particular to find whether they intrude Adelaidean strata. The problem of age was not resolved. Reconnaissance ground surveys were carried out 12 km north of Hesso, 11 km west of Yudnapinna and 25 km west of Woomera in areas where the aeromagnetic contour maps showed north/west trending linear anomalies cut across areas of flat lying Adelaidean strata. A total of seven ground lines were read at the three localities.

Whereas the aeromagnetic interpretation indicated that near Hesso and Woomera the depth to sources was in the range 0-300 m, interpretation of the ground data gave depths in the range 90-180 m. In the Hesso area (Fig. 6.4) a search for remnants of igneous rocks in a water course, which from interpretation of the magnetic anomalies is coincident with the dykes for 7 km, revealed nothing. The ground work showed that a single dyke interpreted from aeromagnetic data could be resolved into three thin bodies over a total width of 1,200 m. Each body is probably between 10 and 100 m wide which puts magnetic susceptibility estimates in the range 1,200-12,000 x 10^{-6} c.g.s. units. These values are consistent with the susceptibility of dolerite. The higher estimate is consistent with a susceptibility measured for a dolerite dyke near Whyalla (Boyd, pers. comm.). Because no outcrop of the magnetic material was found within Adelaide System sediments, as yet there is no direct evidence that the dykes intrude Adelaidean material. Moreover there are no drill holes close to the field area studied which can give definite information that the flat lying Adelaidean strata are thicker than the 90 m depth estimate to the top of the dykes made from magnetic data. The problem is not fully resolved; the author considers that the Eyre Peninsula dykes intrude the Adelaidean sediments on the Gawler Platform.

Although anomalies with amplitude comparable with those delineating the Eyre Peninsula dyke swarm do not extend across the Adelaide Geosyncline, there are indications in the geology that fractures extend south-east across ORROROO and BURRA. Thomson (1965) noted that mineral occurrences frequently lie on north/west trends and suggested the presence of deep fractures in the basement of the geosyncline. The locations of seismic epicentres show trends in the north-west direction (Stewart & Mount, 1972) across the Adelaide Geosyncline.

The Walloway Diapir carbonatites and the Terowie kimberlites are post-Adelaidean features. Within the north end of the Walloway Diapir five dykes and two plugs of lamprophyric rocks of kimberlitic and carbonatitic affinity were found within the diapiric breccia. The largest dyke is $1\frac{1}{2}$ m thick and 150 m long, and the plugs are at least 5 m across. The intrusions form a ring structure about 500 m long by 200 m across. 1 km to the south of the intrusions recognized by the author, the exploration lease holders, Electrolytic Zinc Co. of Australasia Ltd., found a dyke of similar material cutting out of the diapir into Adelaidean sediments (Horne, pers. comm.). Magnetic susceptibility measurements on four small samples from different bodies gave values in the range 700-7,000 x 10^{-6} c.g.s. units. Vertical field ground magnetometer profiles across the northern end of the Walloway Diapir showed little departure from a background level except when nearly directly over the exposed dykes and plugs, which indicates the rocks are magnetic at the surface. Anomalies ranged in amplitude from 100 to 6,000 gammas. The longest dyke produced a symmetrical

6,000 gamma positive vertical field anomaly. The sign was opposite to that expected if inductive magnetism acts alone and thus the body must be remanently magnetized.

A single flight line of the ORROROO aeromagnetic survey passed over the carbonatites at 150 m and recorded a total field anomaly of 4 gammas negative; it appears that this was caused by the long remanently magnetized dyke. If the line had passed directly over this body, then a total field anomaly of about 25 gammas negative would be expected. The ground magnetic anomalies and susceptibilities conform closely with those of kimberlite pipes and dykes in Yukatia in the U.S.S.R. and in South Africa, which are discussed by Gerryts (1967).

The Terowie kimberlites intrude Adelaidean sediments of the Umberatana and Burra Groups, and show a preference for locations in anticlinal structures. The strike of the dykes does not appear to be influenced by existing rock structures although several do occur in a fault (Colchester, in press). Overall, the strike directions of the dykes show a preference for the north-west direction.

The kimberlites are known to be magnetic (Colchester, pers. comm.), but as yet the only susceptibility value known is 3,000 x 10^{-6} c.g.s. units which was obtained by the author for a single specimen of one dyke. The BURRA aeromagnetic map shows little useful data over the Terowie kimberlite field, probably because the contour interval is 50 gammas. It also appears that the flight lines did not pass directly over the largest and most magnetic bodies. However, the contours do show weak fluctuations in the area which may indicate that the maximum aeromagnetic response is less than 50 gammas. Because the precise positions of the individual kimberlites are not known, the original flight charts for the area were not examined.

If the magnetic susceptibilities conform to the range 100-6,000 x 10^{-6} c.g.s. units for Russian kimberlites (Gerryts, 1967), then the largest dyke could produce a total field aeromagnetic anomaly of 10 gammas at 150 m altitude. The large plugs, which are more than 100 m across, could produce aeromagnetic anomalies of more than 100 gammas.

6.5 Magnetic response of Quaternary sediments

Magnetic susceptibility measurements on percussion drill cuttings from six drill holes in the Quaternary sediments of the Walloway Plain gave surprisingly high values. These are shown fully in Appendix A2 and are summarised on Table 6.2.

Table 6.2

Magnetic Susceptibility of Walloway Plain Sediments

Depth	Volume Susceptibility*	Age
0-5 metres	700 x 10^{-6} c.g.s. units	Quaternary
5-20 "	350 "	"
20-30* "	2,400 "	"
30-33 "	60 "	(?) Adelaidean
Average 0-30 m	1,090 x 10^{-6} c.g.s. units	

* One sample in this interval contained approximately 1% maghemite.

Aeromagnetic interpretation indicated that a north/south trending 40 gamma linear anomaly on the west side of the Walloway Plain could be caused by a steeply dipping tabular body at a depth of 0-50 m. Four vertical field ground magnetometer profiles were read across the feature at one locality (arrowed and numbered 1 on Fig. 6.1)

Anomalies were up to 140 gammas in amplitude and were very noisy; an anomaly approximating the theoretical shape expected over an ideal dipping tabular body was located on only one of the four lines. The lines were 1 km long and 150-200 m apart. A depth estimate made for the best line using a dipping tabular body model was 60 m. The drill made available to test the magnetic anomaly had a depth capacity of 33 m. Because of this, the pattern of drill holes was designed to test whether the Quaternary strata themselves caused the magnetic anomalies. The six holes drilled were sited 15 m apart in line to cover the central part of the interpreted asymmetrical anomaly.

While the drilling results do not rule out the possibility that a thin dipping tabular source below the Quaternary strata causes the anomalies, they indicate that susceptibility contrasts within the Quaternary sediments may be important. As shown on Table 6.2, susceptibilities are high from the surface to 30 m. Although the areal distribution of the strongly magnetic material is unknown, it is possible that in the vicinity of the drill holes it forms a narrow linear north trending zone (e.g. bounded by basement faults). A theoretical anomaly across a north trending, 200 m wide, flat ribbon of material with susceptibility contrast 2,000 x 10^{-6} c.g.s. units, depth 170 m (corresponding to aircraft altitude above the source) and thickness 10 m, is symmetrical and has a maximum total field amplitude of 9 gammas. This is 31 gammas less than the observed aeromagnetic anomaly. Furthermore, the theoretical anomaly is symmetrical whereas the observed aeromagnetic anomalies are asymmetric. It is possible that the Quaternary sediments are remanently magnetized. This could account for both the high amplitude (40 gammas) and the shape of the aeromagnetic anomalies.

The average magnetic susceptibility of the Quaternary sediments at locality 1 discussed above is 1,090 x 10^{-6} c.g.s. units. Theoretical total field anomalies computed across the north/south edge of a 30 m thick flat sheet (i.e. a sheet extending east across the Walloway Plain) are asymmetric and have an amplitude of 25 gammas at an altitude of 150 m. While the amplitude and shape of the computed theoretical anomaly is similar to that of the observed aeromagnetic anomalies, a theoretical vertical field anomaly computed at ground level is quite different from the field results. The amplitude and gradients of the theoretical anomaly exceed those of the observed ground anomaly. Thus the problem of finding the source of the linear aeromagnetic anomaly on the west side of the Walloway Plain is not solved. Nevertheless, because the magnetic susceptibility of Quaternary sediments is so high it is evident that changes in thickness or distribution of the magnetic material could produce aeromagnetic anomalies of 25 gammas (or more if the material is thicker than 30 m). It is to be expected that faults in the basement with a throw of 10 m or more will show up in the aeromagnetic data. Similarly, valleys or other depressions in the basement can be expected to produce observable aeromagnetic anomalies.

Magnetic separations were made with a hand magnet for two samples of cuttings (Appendix A4, Samples OR58 & OR59). One sample with a susceptibility of 3,500 x 10^{-6} c.g.s. units contained 10% (by weight) strongly magnetic material. One tenth of the magnetic portion consisted or maghemite and most of the remainder consisted of microcrystalline goethite, earthy clay limonite and colloform limonite. Maghemite has a susceptibility close to that of magnetite (Lindsley et al., 1966), but the other minerals normally have very low susceptibilities. It is probable that the observed susceptibility of the sample is due almost entirely to the maghemite. It was observed that when the magnetic grains were shaken on a piece of paper they grouped together into an aggregate; probably all grains including the maghemite are strongly remanently magnetized, which accounts for the fact that they are strongly attracted to a hand magnet.

6.6 Interpretation of the aeromagnetic anomalies on ORROROO

The following interpretation is given for the features shown on Figure 6.1.

6.6.1 Type 1 - linear anomalies

It is probable that most of the features around the borders of the Willochra and Walloway Plainsare caused by the magnetic Quaternary sediments thickening across small basement ridges. However at the one test site (numbered 1 on Fig. 6.1) the results are equivocal for both an intrusive source and a Quaternary sediment source. Until further drilling tests are carried out, the problem will not be resolved. There are few Type 1 features which are unlikely to be caused by the Quaternary sediments. These are listed below:

1. The 20 gamma feature extending south-west from the Baratta Diapir appears to be closely associated with the diapir. An igneous intrusive source is suggested.
2. The 500 gamma feature 13 km west of the Baratta Diapir lies in the core of an anticline which may contain a diapir (Binks, 1971). In the Adelaide Geosyncline, diapirs are preferentially located in anticlinal structures. An igneous intrusive source is suggested.

3. The 10 gamma feature 22 km west of the Mt. Grainger Diapir lies in the core of an anticlinal structure. An igneous source possibly associated with diapirism is suggested.

4. The 10 gamma feature 5 km south of the Round Hill Diapir may be an extension of the 30 gamma feature within the diapir. An intrusive source, possibly with an associated south-west extension of the diapir under Quaternary sediments is suggested.

5. The 50 gamma feature close to the small areas of diapiric breccia in the south-west corner of ORROROO may be due to intrusives associated with the diapir.

6. The 15 gamma feature extending south-west from near the Oodlawirra Diapir closely follows a fault inferred by Binks (1968). While there is a possibility that strongly magnetic Adelaidean sediments are the source, an intrusive source is more likely.

7. The 10 gamma feature which trends south-east across the Koonamore Plain and appears to be associated with a 10 gamma feature cutting across Adelaidean sediments is a problem. The 1:63,360 photo mosaics show no corresponding lineament over the Adelaidean outcrop. Moreover, a search on the ground near the northern end of the feature over Adelaidean outcrop revealed nothing. While the two features might be caused by a very thin intrusive (e.g. 10 m thick or less) it is possible that they result from a fortuitous line-up of magnetic anomalies due to Adelaide System sediments.

6.6.2 Type 2 - isolated anomalies

One of the three features of special interest was tested with a ground magnetometer (numbered 2 on Fig. 6.1). A combined interpretation of the aeromagnetic data and ground data from two east/west lines

0.8 km apart across the anomaly indicated that the source might be a plug 200 m across at a depth of 180 m. An estimate of susceptibility made from the 1,100 gamma vertical field anomaly on one line (assuming inductive magnetism acts alone) is 5,500 x 10^{-6} c.g.s. units. This value is consistent with that for a basic or ultrabasic intrusive source (e.g. gabbro or kimberlite). A search in creeks in the area revealed no igneous rocks; the creeks are about 3 m deep and only rarely are Adelaidean sediments exposed in them. It appears that the source will only be revealed by drilling through the Quaternary sediments which cover the area.

It is probable that the two Type 2 features shown near the south-east and north-east sides of Figure 6.1 are caused by intrusive plugs. Because of the proximity of the feature on the south-east side to an area of diapiric breccia and the Paratoo and Bendigo diorites, it is suggested that the source may be a diorite associated with a diapir. However, the possibility that the source might be a large kimberlite should not be overlooked.

6.6.3 Type 3 - groups of anomalies

None of the three features shown on Figure 6.1 was tested on the ground. Tipper and Finney (1966) suggested that the 20 gamma feature to the north of the Walloway Plain was associated with a buried diapir. While the possibility that a diapir exists in the area cannot be confirmed without drilling, the author considers that the magnetic sources lie within the Quaternary sediments. The anomalies may be caused by variations in thickness of the magnetic components of the Quaternary sediments, possibly due to basement topography. The two features selected on the Willochra Plain may also be caused by the Quaternary sediments.

6.6.4 Type 4 - non-magnetic zones

While the non-magnetic zones selected on Figure 6.1 might be due to the statistics of the data, there is a possibility that they indicate subtle geological features. For example, along a zone of small faults it could be expected that the depth of magnetic weathering is greater than in non-faulted areas. Along such a zone the amplitude of response of sediments could be reduced, thus giving an apparently non-magnetic zone. A feature of special interest is that four of the zones lie close to a line between the north end of the Walloway Diapir (in which carbonatites occur) and the area on BURRA where kimberlites occur. It is possible that the zones are in some way associated with the intrusives. These lineaments defined by the four zones have a trend direction parallel to that of the Eyre Peninsula dykes. It is possible that the non-magnetic zones define a deep fracture which is associated with the dykes.

6.7 Discussion

The work done on non-Adelaidean magnetic sources is of a preliminary nature, and the conclusions drawn are tentative. However, several important points can be made.

Firstly, the Quaternary sediments can be strongly magnetic and can cause aeromagnetic anomalies of 20 gammas or more. Secondly, the size of intrusives to be expected in the area is very small. Thus regional surveys of the kind carried out so far in the Adelaide Geosyncline are unlikely to locate many magnetic intrusive bodies, and interpretation of the widely spaced lines will be difficult. A detailed survey with flight lines possibly 0.4 km apart or less at as low an altitude as possible is required. Thirdly, many diapirs have associated magnetic anomalies due to near surface sources. It appears that igneous intrusive bodies are most important in producing the anomalies. Fourthly, it is evident that a study of original flight charts combined with study of the geology is necessary to isolate anomalies which might be due to intrusives. The magnetic anomalies due to Adelaide System sediments dominate the pattern and make selection of non-Adelaidean sources very difficult.

PART C

Bouguer gravity anomalies associated with granites

Chapter 7

GENERAL ASPECTS OF BOUGUER AND MAGNETIC ANOMALIES

7.1 Introduction

The regional helicopter survey Bouguer gravity maps for the Adelaide Geosyncline were studied during the course of the thesis research. A map of the area considered is shown on Figure 1.7. Data were collected on a 7 km square grid oriented north/south.

The techniques of interpretation of Bouguer anomalies are discussed in various text books (e.g. Jakosky, 1950; Grant & West, 1965; Parasnis, 1966) and other publications. In any geophysical study it is important to assess what can be derived from the data. Regional helicopter gravity surveys have been completed over most of Australia and in the course of the work both sedimentary basins prospective for oil, and Precambrian shield areas have been surveyed on grids ranging from 7 to 15 km. The primary purpose of the work has been to delineate major structures and to provide data suitable for estimation of thickness of sediments in the Palaeozoic and younger basins. Most of the reports on regional surveys are unpublished as yet and are held by the BMR. There are a few published reports in the BMR's Report Series and Petroleum Search Subsidy Act Series, but these are mainly qualitative, and little quantitative material is available. In particular, there is little published quantitative information on Precambrian shield surveys. It is Precambrian shield areas rather than young sedimentary basins which are of concern in this thesis.

To help in assessing what could be expected from the data for the Adelaide Geosyncline the literature was studied both for Australia and other areas. In general, reports are of two kinds; qualitative accounts for large areas (e.g. Kane et al., 1972) and quantitative interpretations of individual anomalies in small areas (e.g. Watts, 1972; Healey, 1966; Mabey, 1966). The place of regional studies is to establish large-scale features and delineate areas where detailed work can be of help in understanding the geology. For a regional study to be most rewarding, additional information such as detailed gravity lines, seismic depth estimates, drill hole data, density data and geological data are necessary. Clearly a geophysical interpretation must be tied to the known geology as closely as possible. However, regional surveys can be expected to delineate special features which are unrecognized in geological mapping, and in areas where the geology is not well known they can be expected to give a very generalized picture of the geology, especially if aeromagnetic maps are studied along with the gravity maps.

To interpret the individual anomalies quantitatively from an area is difficult; each anomaly needs an individual approach. The main problem in shield areas is that density data are usually scarce and to sample adequately is difficult. Often the density contrast between various units is low (Smithson, 1971). In addition, variations in metamorphic grade and geological complexity can produce changes in density of a unit and therefore it is difficult to assign an average density applicable over a wide area. Another problem specific to regional data is that because of the wide station spacing, anomalies are often only poorly defined. This problem, coupled with a lack of density data or other helpful information, makes quantitative interpretation of some anomalies impossible.

Before commencing interpretation of the most recent helicopter

Bouguer anomaly data collected by the BMR (COPLEY, PARACHILNA, ORROROO, OLARY and parts of CALLABONNA, FROME, CURNAMONA, CHOWILLA and PORT AUGUSTA, see Fig. 1.3), it was agreed that in exchange for the author having first access to the new data, he would write a report on his findings for the BMR. The work was to be first compiled as an internal Record for the BMR and in time it was to be published as one of the BMR's Report Series. The BMR Record has been prepared (Tucker & Brown, 1972). Mr. F. W. Brown of the BMR was co-author for the report; he assisted in editing, and the preparation of figures, and in addition wrote appendices on the statistics of the survey.

For any gravity interpretation it is of help to have data from surrounding areas. Bouguer anomaly maps are available for areas adjoining the west, south and north sides of the area shown on Figure 1.3, but not for the east side. The area shown includes areas of Precambrian rocks and Palaeozoic basins. For the BMR Record the author made a basic interpretation (mostly qualitative) of the whole area shown on Figure 1.3 and discussed in detail the gravity lows which appear to be associated with granite bodies. Because much of the area covers a mineral province (the Adelaide Geosyncline) an attempt was made to find associations between gravity features and mapped mineral occurrences. The association between some gravity lineaments and the location of seismic epicentres were noted.

For the thesis it was decided that two problems of the gravity work were most important. The first was the fundamental problem of obtaining density data. The second problem was that of interpreting some of the gravity minima where the geological and geophysical maps indicate that the source rocks are probably exposed or close to the surface. The two problems are discussed in Chapters 8 and 9.

The area in which quantitative analyses were performed lies east of longitude 138°. Others are working in the area to the west of this line (Gerdes, M.Sc. student) and so for the thesis (and the BMR Record) little detailed analysis was performed in the west.

In the following sections of this chapter various general aspects of the Bouguer anomaly data for the thesis area are discussed, and in addition various general comments are made about the basement of the Adelaide Geosyncline, and the basins of Palaeozoic sediments on the east side of the geosyncline. A discussion of the basement is important to the interpretation of gravity lows presented in Chapter 9.

7.2 Presentation of the Bouguer anomaly map

The bouguer anomaly map (Fig. 1.3) was prepared by the BMR from 1:250,000 maps contoured at 5 mg. Data were reduced to mean sea level at Adelaide. The Bouguer densities used in the reduction vary from place to place. In the north of the area 1.9 g/cm^3 was used for basinal areas of predominantly Palaeozoic and younger strata. In the south-east corner 2.2 g/cm^3 was used for an area of similar strata. For most of the area covering Precambrian rocks 2.67 g/cm^3 was used. The boundary between areas reduced with different Bouguer densities is marked with a double line. The contours have not been adjusted to match at the survey boundaries.

Inaccuracies in the Bouguer densities used for reduction of data over the young basins are not of great importance because the elevation of most stations is only a few metres above mean sea level. However, for the areas of Precambrian rocks the Bouguer densities are of more importance because the elevation of some of the stations is several hundred metres above sea level. Work to derive an estimate of average density for Adelaidean and pre-Adelaidean rocks is discussed in Chapter 8. From this it seems that the Bouguer density of 2.67 g/cm^3 used in the reduction is probably low by about 0.06 g/cm^3. Over most of the Adelaide Geosyncline elevations do not exceed 700 m above sea level. If a Bouguer density of 2.73 g/cm^3 was used instead of 2.67 g/cm^3, then the Bouguer gravity at some of the highest stations would be 1-2 mg less than shown on Figure 1. It is considered that errors in the Bouguer gravity values due to an incorrect choice of Bouguer density are of little consequence over most of the areas of Precambrian rocks.

7.3 General considerations of the Bouguer anomalies in the thesis area

Some of the Bouguer anomalies in the thesis area were briefly discussed in Chapter 1. Figure 1.3 shows a composite map of Bouguer anomalies and geology.

The most prominent anomalies lie close to the margins of the Adelaide Geosyncline (refer Fig. 1.3) and most of these are lows. The background level over much of the area is 0-10 mg. A low reaching -40 mg lies close to Lake Callabonna; a low reaching -45 mg lies near Curnamona Homestead; a low reaching -40 mg lies south of Olary. On the western side a low reaching -35 mg lies over the Willouran Ranges, and a low reaching -40 mg lies over the western part of PARACHILNA, ORROROO and BURRA. Within the latter anomaly an intense localized low reaching -50 mg lies in the north-west corner of BURRA. Over the central part of the geosyncline the gravity anomalies are very broad and do not depart much from 0 mg. Over the pre-Adelaidean rocks of the Gawler Platform the pattern is complex and localized residual anomalies of up to ± 20 mg occur. The background level for this area is about 0 mg. Over the thin flat lying Adelaidean and Cambrian strata on ANDAMOOKA and TORRENS the pattern is complex and highs and lows reach ± 10 mg or more above a background level of about -10 mg.

While the gravity pattern shows a loose correspondence with the geology, when considered in detail most of it is difficult to interpret. For example, the gradient on the western side of the long low near the edge of PARACHILNA, ORROROO and BURRA, corresponds with faults (mapped and inferred) which Thomson (1970) considers make up a single feature called the Torrens Lineament. However, on the geological maps there appears to be no corresponding fault system in the Adelaidean material along the gradient on the eastern side of the low. The aeromagnetic pattern in the area of the gravity low is almost featureless; therefore, depth to magnetic basement estimates are unreliable. Geological evidence (Thomson, op. cit.) indicates that the Adelaidean material may be less than 10 km thick. Detailed interpretation of the gradients around the low is prevented by the wide station spacing (7 km). Elementary interpretation of the gradients using a step model (Bancroft, 1960) indicates that the depth to the low density body is no more than 11 km. It appears that it lies in strata below the Adelaidean sedimentary pile. However, the low may indicate a great thickening of low density components of the Adelaidean rocks.

A gravity low similar to the one discussed above lies over the Willouran Ranges. The geology in this area is not well known, but depth estimates from aeromagnetic data indicate that the magnetic basement (probably pre-Adelaidean) may be no more than 4 km below the surface. Elementary interpretation of the gradients of the gravity low using a step model (Bancroft, op. cit.) indicates that the depth to the source is no more than 12 km. It appears likely that the low density body lies in strata below the Adelaidean. However, as yet it cannot be discounted that the low is caused by great thickening of low density Adelaidean rocks.

It is to be hoped that work in progress at the University of Adelaide will help resolve the problem of the gravity lows on the western side of the Adelaide Geosyncline.

In Chapter 9, some of the best defined localized gravity lows on the eastern side of the geosyncline are discussed. It seems most likely that all of these features are caused by granitic bodies.

7.4 Basement of the Adelaide Geosyncline

Information on the nature of the basement underlying the Adelaidean sediments is accumulating but there is much to be done before it is fully understood.

Seismic evidence (Stewart, in press) indicates that there is virtually no velocity gradient with depth within and below the Adelaide Geosyncline down to the bottom of the crust at 38 km. This is an unusual phenomenon and may indicate either that the Adelaide System sediments and the underlying material are closely similar in average composition and therefore have the same seismic velocity, or that the Adelaidean strata persist to the bottom of the crust. The former suggestion is supported by the fact that the highest crustal velocity recorded in the pre-Adelaidean rocks of the Gawler Platform, 6.3 km/sec (Doyle & Everingham, 1964), is nearly identical with the velocity in Adelaidean sediments, 6.25 km/sec (Stewart, op. cit.).

Measured stratigraphic thicknesses (in Parkin, 1969; Thomson et al., 1964) for the various Adelaide System sedimentary units total 18 km or more in the central and northern parts of the Adelaide Geosyncline. The total stratigraphic thickness of Cambrian units exposed in the northern part of the geosyncline is at least 4 km. Thus at the cessation of deposition the total sediment thickness may have been in excess of 22 km, but probably much less than the present crustal thickness. Because of the complexity of structures produced by orogenesis it is impossible from geological evidence alone to accurately estimate the thickness of the Adelaidean Unit. Thomson (1970) made estimates from stratigraphic thicknesses observed on the limbs of fold structures assumed to be concentrically folded. His map is shown on Figure 1.8. He estimated that the depth to the basement was in excess of 10 km near the north/south axis of the geosyncline. The author made six depth estimates on ORROROO and PARACHILNA across suitable fold structures assuming concentric folding and arrived at values of about 10 km in agreement with Thomson. However, not all of the Adelaidean section is exposed and this was not allowed for. Thus 10 km is probably a minimum estimate of depth to basement.

Geological evidence that a basement of rocks dissimilar or older than the Adelaidean sediments exists near the deepest part of the geosyncline comes from diapirs. While diapiric breccia often closely resembles the lowest units of the Adelaidean, it usually contains acid and basic rocks of igneous origin, some of which may have been torn from the basement (cf. Coats, 1964). No comparative study has ever been made of the igneous rocks in all the diapirs and those found on surrounding basement areas, e.g. Gawler Platform and Willyama Block. Thus as yet it cannot be said from geological evidence that the basement of the Adelaide Geosyncline is or is not similar to these areas.

The Bouguer gravity contour map does not help much in a study of the basement of the Adelaide Geosyncline. The Bouguer anomalies are weak over most of the area of Adelaidean outcrop and do not depart much from 0 mg. In Chapter 8 it is shown that there is little or no difference between the average density of the Adelaidean strata and the average density of pre-Adelaidean strata. It appears that for interpretation of the gravity data the Adelaide Geosyncline cannot be modelled as a simple basin of low density material on a dense basement. Furthermore, from the discussion of anomalies in section 7.2 of this chapter, it appears that more work is required to resolve whether the low density sources of the two major lows on the western side of the geosyncline lie within the basement under the Adelaide System sediments or within the sediments themselves.

Quantitative information about the depth to basement and its probable composition comes from magnetic data although at this time much still remains to be done. An aeromagnetic map and geological map of the area are shown on Figure 1.4. Various BMR reporters (Tipper & Finney, 1966; Young & Gerdes, 1966; and others) consider that broad magnetic anomalies over the Adelaide Geosyncline come from magnetic sources below (or possibly within) the Adelaidean sedimentary fill. Most of their depth estimates (Fig. 7.1) were made for well defined anomalies marginal to the north/south axis of the Adelaide Geosyncline in areas where Adelaide System sediments are only weakly magnetic at the surface. Anomalies near the deepest part of the geosyncline as postulated by Thomson (1970) are poorly defined, indicative of a great depth to magnetic basement or a weakly magnetic basement. The few estimates on PARACHILNA and ORROROO near the axis of the geosyncline are for poorly defined anomalies and do not exceed 10 km. Although from these it might appear that we can say that the magnetic basement of the Adelaide Geosyncline lies at 10 km or less near the deepest part, preliminary interpretations by the author of some of the low amplitude broad anomalies give depths of 15 km or more, particularly in the areas of strongly magnetic sediments. The author considers that the data need restudying both in areas already covered by BMR reporters, and where depth to basement estimates have not been made, paying particular attention to the recognition of intrabasement and suprabasement features. The author's study of the magnetic response of the Adelaide System sediments has laid the groundwork for further interpretation of the deep source magnetics of the Adelaide Geosyncline. It is unlikely that susceptibility contrasts within the sediments themselves cause broad anomalies in areas where the aeromagnetic response due to the near surface material is weak, i.e. over most of the northern part of the Adelaide Geosyncline. The average susceptibility of the sediments is probably less than 100×10^{-6} c.g.s. units in this area. In the area of strongly magnetic sedimentary beds in the south-east of the geosyncline, broad anomalies (e.g. with half-widths of about 20 km) are probably due to the combined effects of unexposed structures of magnetic sediments, and other deep sources. Depth estimates in this area can give minimum and maximum estimates of thickness of the Adelaidean material.

It is a general feature of the magnetic pattern that over exposed strongly folded Adelaidean strata, viz. east of longitude 138°, the magnetic anomalies attributable to deep sources are very weak, while over essentially unfolded Adelaidean strata, viz. west of longitude 138°, the anomalies attributable to deep sources are very strong and clearly come from shallower sources than in the area of strong folding (see Figs. 1.4 & 7.1). The pattern over flat lying Adelaidean strata on the Gawler Platform resembles that over the Willyama Block and other parts of the Gawler Platform, as does the pattern between the Mt. Painter Block and the Willyama Block. It appears most likely that the deep magnetic basement in these two areas consists of pre-Adelaidean rocks similar to, or the same as some of those of the Willyama Block and Gawler Platform. In the area of strong folding in the Adelaide Geosyncline, the magnetic pattern indicates a deeply depressed basement. However, as yet it is not possible to say whether the magnetic basement is similar to the pre-Adelaidean strata surrounding the geosyncline or not. Analysis of the individual anomalies to determine block sizes and susceptibilities may help on this problem.

7.5 Basement of the Frome Embayment and Murray Basin

The aeromagnetic maps give information on the strata comprising the basement underlying flat lying Quaternary and Palaeozoic sediments. Two areas of particular interest are the northern part of the Murray Basin and the Frome Embayment (Fig. 1.4). Both areas are prospective for oil and are currently being explored with seismic surveys and drill holes. Permian aged sands are the main strata of interest. Most published drill hole information is for the Murray Basin (Parkin, 1969, p.178).

None of the drill holes (maximum depth 300 m) in the northern part of the Murray Basin has penetrated strata older than Quaternary in age, although 15 km to the south of CHOWILLA, the Renmark Bore bottomed in Permian sands at 4,018 ft (1,200 m). Drill holes further south bottomed in schists and phyllites, and Thomson (1970) and others equate it with the metamorphosed Kanmantoo Group in the Mt. Lofty Ranges. For example, one of these drill holes is the Pinnaroo Bore, 100 km south of CHOWILLA, which bottomed at 1,280 ft (390 m) in schists and phyllites. Others further south bottomed in similar material. Thomson (op. cit.) considers that the Kanmantoo Group underlies much of the Murray Basin and may reach a total thickness similar to its observed stratigraphic thickness in the Mt. Lofty Ranges (about 20 km). Aeromagnetic maps show that some of the Kanmantoo Group rocks have a response similar to strongly magnetic Adelaide System sediments. For example, the Nairne Pyrite Member produces prominent linear aeromagnetic anomalies.

In the northern part of the Murray Basin shown on Figure 1.4 the aeromagnetic pattern is similar to that over strongly magnetic Adelaide System sediments. Anomalies are linear and follow a general arcuate trend which closely parallels the outcrop on the eastern side of the Flinders Ranges on BURRA, ORROROO and OLARY. Although it is most probable that the magnetic anomalies arise from magnetic Adelaidean sedimentary beds at depths up to about 1 km below the surface, it should not be overlooked that some might be caused by Kanmantoo Group metasediments. Because the magnetic pattern is closely similar to that over outcrop of Adelaidean material, it is clear that the magnetic beds are folded and have been peneplaned before deposition of the Murray Basin sediments. The magnetic pattern indicates that folds are elongate in the north-east direction.

Unpublished data from drill holes around Lake Frome by the Delhi-Santos group show that strata of Middle Cambrian age occur at a depth of about 600 m. No drill holes have penetrated the Adelaidean or pre-Adelaidean. It has been suggested by Thomson (1970) that in the area of the Frome Embayment the pre-Adelaidean basement may lie at a depth of 10 km or more below the surface. The author disagrees with this view in the light of geophysical data. The aeromagnetic maps for the Frome Embayment show a complex pattern of circular anomalies similar to that over the Willyama Block. Anomalies are circular, sometimes falling in north/south lines. Depth estimates from the most prominent deep source anomalies by BMR authors are usually in the range 1-6 km with the deepest lying close to the eastern side of the Flinders Ranges (Fig. 7.1). It is probable that the magnetic basement under the Frome Embayment lies at a depth of 1-6 km and consists of pre-Adelaidean material similar to that on the Willyama Block. It is most unlikely that the magnetic basement consists of Adelaide System sediments. The outcropping Adelaidean to the west of the Frome Embayment on PARACHILNA and the southern part of COPLEY is very weakly magnetic and if Adelaidean strata do occur in the FROME and CURNAMONA areas beneath Palaeozoic and Quaternary strata, it is unlikely to produce the observed magnetic anomalies.

The aeromagnetic pattern in the west of FROME shows a circular feature about 75 km across (Fig. 1.4). The anomaly has steep gradients defining its boundaries and encloses localized anomalies, some of which have north/south alignment. The Bouguer gravity map shows a broad low (residual, -10 mg) over the area of the magnetic anomaly. While the low might be caused by a thickening of low density sediments, it could indicate the presence of a low density basement. It is probable that the source of the circular magnetic feature lies within pre-Adelaidean material. The basement rocks may be of granitic composition.

Chapter 8

DISCUSSION OF DENSITY DATA FOR THE ADELAIDE GEOSYNCLINE

8.1 Introduction

A problem which must be faced in any interpretation of Bouguer gravity data is that of estimating representative densities of rock units and density contrasts between rock units in the area. In a metamorphic area like the Adelaide Geosyncline and its surroundings, the problem is perhaps most acute because the density contrast between various lithologies of interest can be expected to be low. For the case of basins of Palaeozoic or younger sediments within a metamorphic environment often the problem of densities is not as bad because the density contrast between the basement and sediments is likely to be high (possibly 0.30 g/cm^3 or more). In this situation a small error (say 0.05 g/cm^3) in a density estimate will probably not seriously influence the results of interpretation of the gravity data. However, in a metamorphic terrain an error of 0.05 g/cm^3 might be larger than the density contrast sought. While there are values published for different lithologies from various areas throughout the world (Grant & West, 1965, p.199; Smithson, 1971), it is essential in a new area to make new measurements.

At the outset of work on the regional Bouguer gravity data for the Adelaide Geosyncline, the author looked at the problem of estimating average densities for rocks in the area. It was found that the problems are manifold. There is practically no published density data for the area. Very few drill cores have been logged for densities either within the geosyncline or the surrounding areas. Moreover, the available published and unpublished data are usually from geologically disturbed areas of economic interest. As work proceeded on what was originally considered to be a fairly elementary problem, it was found that it was extremely difficult to produce meaningful density data. It became clear why in many papers on interpretations of Bouguer anomalies any reference to density measurements on rocks is made in an almost guarded fashion.

In this chapter the results of the author's work on density are presented. Problems which arose and which will probably be of interest to future workers in the area are discussed. The author's work has done little more than expose the tip of the iceberg.

8.2 Classification of rock types

The geology of South Australia has been discussed by SADM geologists in Parkin (1969). The rocks important in the interpretation of the regional Bouguer gravity data over the Adelaide Geosyncline can be discussed under three broad classifications. These are: Adelaidean and Cambrian sediments, pre-Adelaidean crystalline basement rocks and post-Adelaidean igneous intrusives. These are considered in turn below.

8.2.1 Adelaidean and Cambrian sediments

In the Adelaide Geosyncline these sediments mainly consist of four lithologies:

1. Carbonates (dolomites, limestones and intermediate members), e.g. the Nuccaleena Dolomite.
2. Siltstones (e.g. Tapley Hill Formation) and calcareous siltstones (e.g. Wonoka Formation).
3. Shales (argillaceous rocks), e.g. the Tindelpina Shale Member.

4. Quartzites (includes continental tillites in the Adelaidean stratigraphic succession, but not in the Cambrian), e.g. the Appila Tillite.

The stratigraphic columns for the published SADM geological maps of the Adelaide Geosyncline show that repetition of formations of similar overall lithology occurs in distances of about 0.5-3 km.

The contour maps of Bouguer gravity anomalies indicate that the mixing of the various sedimentary lithologies by folding processes has been quite effective. There are few areas where the contours closely follow the outcrop of a particular formation. One of these is in the south-west corner of PARACHILNA (Cambrian limestones). It appears that even though it can be expected that there are density differences between units of different lithology, in general they have been mixed so that from the point of view of a regional Bouguer gravity survey, they can be considered as a single geological unit. Cambrian material does not outcrop widely in the northern part of the geosyncline. Furthermore, the lithologies of Cambrian sediments are similar to those of Adelaidean sediments (see Parkin, 1969). Therefore, for the discussion of densities which follows in this chapter no distinction is drawn between Cambrian and Adelaidean strata. For the discussion of densities the slab of material consisting of folded Adelaidean and Cambrian sediments will be referred to as the 'Adelaidean Unit'.

8.2.2 Pre-Adelaidean metamorphic basement rocks

Other than for the Mt. Painter Block (Coats & Blissett, 1971) too little is known of the pre-Adelaidean rocks to classify them into the numerous lithologies expected in metamorphic terrains. Being guided by published and unpublished SADM maps and reports on the metamorphic basement areas, it appears that most of the rocks fall into two broad classifications.

1. Metasediments (includes schists, gneisses, sandy metasediments, quartzites and local iron formations).
2. Extrusive and intrusive acid igneous and related rocks, e.g. the Gawler Range Volcanics, granites of the Mt. Painter Block.

From the Bouguer gravity anomaly maps it is evident that the density of pre-Adelaidean rocks changes from place to place. For example, over the south-east side of the Willyama Block, the Bouguer anomalies are positive (15 mg with Bouguer density = 2.67), whereas over the north-west side, the Bouguer anomalies are negative (-15 mg with Bouguer density = 2.67). Similarly, over the Gawler Platform both positive and negative Bouguer anomalies are recorded.

8.2.3 Post-Adelaidean igneous intrusives

Most of the large igneous intrusives into Adelaidean sedimentary strata are acidic and can be loosely classified as granites (e.g. the Anabama Granite).

8.3 Measurement of density of rocks

There are several qualifications of the term 'density'. It is important to distinguish between them (cf. Grant & West, 1965, p.192). They are Bulk Density which is the volume density of specimens of macroscopic size, and Grain Density which is the density of the actual rock forming minerals. Bulk density can be subdivided into dry and wet bulk density. Dry bulk density is the volume density of a dessicated rock, while wet bulk density is the density of a rock fully impregnated with water. For highly porous sediments the difference between wet and dry densities can be 30% or more (Hedberg, 1936). For fresh crystalline or metamorphic rocks the difference is probably less than 3% (Woollard, 1959). In gravity interpretation it is usual to use wet bulk densities to establish density contrasts, although if the body of interest lies above the water table, dry bulk densities would have to be used. It appears that a further qualification of the term density is required when unweathered rocks deep below the surface are considered. The term 'true bulk density' or 'true density' is probably appropriate. If we consider a geological formation which extends from the surface to great depth, the progression of names to describe the density of the rock in place are dry bulk density, wet bulk density and true bulk density. A wet bulk density is appropriate for a rock below the water table but within the weathered zone, whereas below the weathered zone the rock is likely to be less porous and thus the term 'true density' should be applied.

If depth estimates made from magnetic anomalies over sedimentary beds can be taken as a guide, then the depth to fresh rock in the Adelaide Geosyncline is probably 100-200 m or more. The water level in three abandoned mine shafts on ORROROO, namely the Waukaringa Mine (north-east), the Ajax Mine (north-east) and the Spring Creek Mine (south-west) was 20-30 m below the surface. It is probable that the water table in most of the area of Adelaidean and pre-Adelaidean rocks considered in the gravity interpretation lies about 20-30 m below the surface. Thus for rocks in place the various densities can be assigned as follows:

1.	0-30 m	dry bulk density
2.	30-200 m	wet bulk density
3.	200 m$^+$	true density

For interpretation of regional Bouguer gravity anomalies, such as those found over granite batholiths, estimates of true bulk density are required.

There are various direct and indirect methods with which to estimate the density or density contrast between rock units. These are described fully in geophysical texts (e.g. Grant & West, 1965; Parasnis, 1966). Two main methods were used by the author; the water displacement method (sometimes referred to as Archimedes Method) and 'density profiling'.

Dry bulk densities of dry surface rock samples and drill core samples weighing about 200 g were measured by the water displacement method with a Mettler 1,000 g balance (reading accuracy of 0.01 g). Rocks were weighed in air and then suspended in a beaker of tap water by a thin cotton thread. The operation was done quickly so that water had little time to soak in. If any samples bubbled they were discarded. The value found by this method is the specific gravity of the rock. If the density of water used is 1 g/cm^3 then the specific gravity is equal to bulk density. For the thesis specific gravity and density are assumed to be the same.

An approximate estimate of true density was obtained for the Adelaidean Unit by use of the 'density profiling' method which was described by Nettleton (1939). Linsser (1965) has discussed some of the problems of the method and shown how in suitable areas a grid of points, rather than individual profiles, can be analysed to give a better estimate of the average density of rock. For the thesis an individual profile approach was used. With this method Bouguer gravity anomalies are calculated across high hills for various assumed Bouguer densities. The Bouguer density for the anomaly which shows least influence of topography is approximately the density of rock composing the hill, provided the density of rock in the area is fairly constant. To give best results rocks must be of constant density. For sedimentary material best results should be found where the sediments are flat lying. In these cases density profiling will give an average density. The method should be valid on a regional scale for Bouguer anomalies across mountain ranges provided the condition of constant rock density is satisfied. This appears to be the case for the Adelaide Geosyncline. A great thickness of sedimentary strata of various lithologies has been folded and effectively mixed so far as the regional gravity is concerned. Particularly in the northern part of the geosyncline where some peaks in the Flinders Ranges reach to 700 m or more above the surrounding plains, there is a marked correlation between topography and Bouguer anomalies.

Because there is seismic P wave velocity data available from earthquake and atomic explosion studies for the rocks of the Gawler Platform and Adelaide Geosyncline, an attempt was made to use the empirical relationships between velocity and rock density (e.g. Woollard, 1959). Because the velocity versus density curves published by various authors give quite different density values for the one velocity, it appears that the method is of limited use in the area. However, the seismic data give supporting evidence that the average density of pre-Adelaidean and Adelaidean rocks is the same.

There is no locality in the Adelaide Geosyncline where the density of the Adelaidean Unit can be estimated from a combined study of known basement depth and Bouguer gravity anomalies over faults. In the regional Bouguer anomaly data, gradients on probable faults are not well defined, and there are no deep drill holes through the Adelaidean Unit.

8.4 Problems of estimating average density

In the author's work three main problems were encountered, namely the problem of collecting an adequate number of rock samples to be representative of rock lithologies of interest, the problem of porosity of rocks and the problem of density changing with depth. These are discussed below.

8.4.1 Sampling

From a survey of the literature it is evident that if gravity interpreters collect any surface rock samples at all, then they usually collect between one and twenty from each unit of interest.

The author collected a total of 186 fist sized surface rock samples of various lithologies from various parts of the Adelaide Geosyncline. Some (110) were collected during the work on magnetic sediments; others (43) came from the collection accumulated by Mr. P. Binks of the SADM during mapping of ORROROO, and others (33) from the collection of Mr. J. Sumartojo of the University of Adelaide. Because in the Adelaidean succession, a rock of a particular lithology (e.g. siltstone) from a particular formation is usually indistinguishable in hand specimen from a rock of the same lithology in another formation, there is no advantage in the author's work in showing exactly where each sample came from. Most of the sedimentary rocks came from ORROROO (150). Usually between one and five samples were collected at each locality; localities were often 5-20 km apart. To give adequate information on the 20 km or more of section of Adelaidean and Cambrian sediments would probably require thousands of fresh samples. From the great variability of density of rocks of the same lithology it is clear that the author's rock samples fall far short of being a representative sample (Fig. 8.2). However, they do provide a starting point on the problem.

8.4.2 Porosity

Surface rocks are commonly more porous than at depth and a correction for this is necessary to estimate the true density of fresh rock in place. Hedberg (1936) has shown that even in well compacted rocks there can be a difference of 10% or more between dry bulk densities and wet bulk densities. Metamorphic rocks can have a high porosity, due to development of fractures and the effects of solutions (Leversen, 1954, p.71). For porosity corrections to be meaningful in density studies, a comparison must be made between fresh and weathered rocks, otherwise it is difficult to assess whether the pores are filled by solids or fluids at depth. Parasnis (1952) made a study of rock densities in the English Midlands and considered the problem of porosity. He used density profiling and measurements on surface rock samples. His results of average density using these methods were almost identical. He considered that because it is usually not known to what extent surface rocks contain water, the best assumption that can be made is that the true density lies somewhere between the density of saturated and dry rock specimens. The author considers that while this assumption is quite valid for the top few tens of metres or even hundreds of metres of rocks in the weathered zone, it is not valid when an attempt is made to estimate the true density of unweathered material from considerations on surface rocks. For this case we must consider what solid material has been leached from the rocks by weathering processes (thus increasing the porosity). Even a wet bulk density of a surface specimen is likely to be considerably less than the true bulk density of fresh material. To assess the importance of porosity and the effects of leaching on measurements on surface rocks, the following equation was used:

$$\rho = \rho_0 + \rho_1 \frac{V_1}{V} + \rho_2 \frac{V_2}{V}$$

where ρ is the true bulk density of a fresh unweathered rock in place, with volume V,

ρ_0 is the dry bulk density measured for the equivalent weathered rock, e.g. by water displacement method,

ρ_1 is the density of fluid (liquid and gas) normally present with the volume V_1 in the fresh rock,

and ρ_2 is the grain density of solid filling with volume V_2 leached from the fresh rock and now replaced by voids in the dry weathered rock.

This equation is valid if it is assumed that V is constant.

Wet bulk density (ρ_1 is the density of pure water) of a weathered rock is given by

$$\rho_{wet} = \rho_0 + \frac{V_1 + V_2}{V}$$

and in general

$$\rho > \rho_{wet}$$

Table 7.1 shows that the true density of a fresh rock in place is likely to be significantly higher than the dry bulk density measured for a surface sample even if only a small porosity (3%) is taken into account.

Table 7.1

Effect of Porosity Corrections on Dry Bulk Densities

ρ_0 (dry) g/cm^3	$\frac{V_1}{V}$	ρ_1* g/cm^3	$\frac{V_2}{V}$	ρ_2 g/cm^3	ρ (true) g/cm^3
2.65	0.03	1.0	0	-	2.68**
2.65	0.02	1.0	0.01	2.6 (silicates)	2.70
2.65	0.02	1.0	0.01	5.0 (iron oxides sulphides)	2.72
2.65	0.01	1.0	0.02	2.6	2.71
2.65	0.01	1.0	0.02	5.0	2.76

* Density of water

** 2.68 g/cm^3 is also the wet bulk density.

Usually it is not known what material has been leached from a rock. Therefore to estimate the true density from studies of surface rocks is probably an almost impossible task. However, it is clear that density measurements on dry or saturated surface rocks, will give lower estimates of the true density of unweathered rocks in place.

8.4.3 Density changes with depth

It is well established from drill hole studies that for the top few kilometres of the crust, rocks of a particular lithology increase in density with depth below the surface (e.g. Athy, 1930). A general increase in dry bulk density of the Anabama Granite with depth is evident in the author's data from drill hole DDH AN2 (Fig. 8.5). This may be attributable to weathering processes. Woollard (1959) states that experimental evidence shows that for crystalline rocks collected at the surface, a density change due to the elimination of an initial porosity of 3% (or less) by pressure, can be exactly offset by thermal expansion at great depth. The problem is very complex and much work remains to be done. Within the scope of present knowledge it appears that a density contrast established from studies of surface rocks or drill hole samples is probably valid at the depths of interest in regional Bouguer gravity surveys (e.g. 5-10 km).

8.5 Density data for Adelaide System sediments

Because there is so little data available on the density of rocks of the Adelaide Geosyncline and surrounding areas this will not be discussed separately from the author's work.

8.5.1 Direct measurements

Mumme (1961) measured bulk densities of surface samples of diapiric breccia and Adelaide System sediments in and around the Blinman Diapir (PARACHILNA). He concluded that for the purposes of interpretation of his detailed Bouguer gravity survey, the average bulk density of the breccia near the surface was 2.40-2.50 g/cm^3 and the average bulk density of Adelaide System sediments enclosing the breccia was 2.62 g/cm^3. He did not state the statistics of the sample.

The results of drilling of the Lyndhurst Diapir (COPLEY) indicated that the dry bulk density of samples of diapiric breccia lies within a wide range, 2.05-2.85 g/cm^3 (Fig. 8.1). Although diapiric breccia is predominantly composed of distorted and fractured sedimentary strata from the lowest members of the Adelaidean Unit (the Callanna Beds), from the available data it is inappropriate to assign a mean density to these units. Relatively undisturbed Adelaidean sediments were penetrated by the drill holes. Below 50 ft (15 m) siltstones and shales of the Tapley Hill Formation have dry specific gravities (dry bulk densities) in the range 2.35-2.72 g/cm^3 (arithmetic mean 2.49 g/cm^3). Copper-mineralized and barren tillite have dry bulk densities in the range 2.42-2.85 g/cm^3. Without examining the core samples in detail the results from the Lyndhurst Diapir are of limited value on a regional scale. However, the logs on Figure 8.1 serve to illustrate the variability of density of rocks in the area. For drill hole DDH LYD5 the densities of very near surface rocks within the one stratigraphic unit (Tapley Hill Formation) are significantly lower than at depth.

Figure 8.2 shows histograms of the results of the author's measurements of dry bulk density of Adelaide System sediments. The histograms (particularly B and C) all show a wide range of values which is probably indicative of variations of mineralogical composition and porosity. Estimates were made of the mean and the mode of each distribution. For histograms B and C the distributions are distinctly skewed. For carbonates and quartzites the mean is very close to the mode while for siltstones and shales the mean and the mode are widely separated. It is considered that the low density tails of siltstones and shales may be attributable to weathering and higher porosity for those samples, and that the dry bulk density of solid specimens lies close to the mode rather than to the mean of distributions. Table 8.2 summarises the results.

An estimate of the average density of the Adelaidean sedimentary section taken as a single unit composed of the four main lithologies is shown on Table 8.3. Densities of each lithologic unit have been

Table 8.2

Density of Adelaidean Surface Samples

Lithology	No. of Samples	Dry Density Mean (g/cm3)	Standard Deviation	Range (g/cm3)	Estimated 80% Confidence Limits (g/cm3)	Dry Density Mode (g/cm3)
Carbonates	21	2.76	0.07	2.65-2.88	2.68-2.85	2.78
Siltstones & calcareous siltstones	47	2.63	0.12	2.31-2.82	2.60-2.80	2.72
Shales	38	2.58	0.15	2.18-2.81	2.60-2.80	2.68
Quartzites	15	2.63	0.05	2.54-2.72	2.55-2.70	2.62

weighted according to their approximate percentage (by thickness of section). The percentages were calculated by R. Coats (pers. comm.) of the SADM, from his measurements during geological mapping of COPLEY. The estimates can probably be taken as a guide to other parts of the Adelaide Geosyncline.

Table 8.3

Density of the Adelaidean Unit from Surface Samples

Lithology	Estimated %* of Section	Dry Density Mode (g/cm^3)
Carbonates	7.5	2.78
Siltstones & Calcareous Siltstones	39.0	2.72
Shales	9.5	2.68
Quartzites	44.0	2.62
Weighted Mean	Density	2.68 g/cm^3

* Approximate percentages for COPLEY.

The data give an average dry bulk density of 2.68 g/cm^3 when the modes of the distributions on Figure 8.2 are used. Three siltstone samples were soaked in water for one week and then the wet bulk densities were determined. The increase averaged 0.03 g/cm^3 for the three samples. This indicates that about 3% of the dry rock is occupied by voids. If all the rocks have an average porosity of 3% or more, then the true bulk density (or true density) of the Adelaidean Unit would be 2.71 g/cm^3 or more. It is considered that 2.68 g/cm^3 is a lower estimate of the average true density of the Adelaidean Unit.

8.5.2 Indirect measurements

Density profiles were drawn for 13 east/west lines of Bouguer anomaly data from the 1970 helicopter gravity survey (Fig. 8.3). The original stations are not specially marked on the profiles; they lie at the intersection of straight line segments. Bouguer anomalies were calculated for six Bouguer densities (2.0, 2.2, 2.4, 2.6, 2.8 and 3.0 g/cm^3) and on the original plots from which Figure 8.3 was drawn, anomalies were estimated for 2.5, 2.7 and 2.9 g/cm^3.

The data are not ideally suited for correlation analysis by computer and were interpreted by eye; each set of profiles has its own peculiarities. For example, on Profiles A and B (Fig. 8.3) a strong low lies close to the region of highest topography and cannot be removed by reasonable changes in Bouguer density. The low lies over granites of the Mt. Painter Block. On Profile L, the Bouguer anomalies just to the west of the area of highest topography show a strong low which appears to be associated with the Quaternary sediments of the Willochra Plain. Thus not all of the density profiles are suitable to yield an estimate of density of the Adelaidean Unit. Six are considered unsuitable.

On most of the density profiles only a small part of the total length is useful. For example, on Profile D a section about 40 km long across the highest peak shows a change from a loose correlation with the topography at a Bouguer density of 2.60 g/cm^3 or less, to anti-correlation at 2.80 g/cm^3 or more (2.70 g/cm^3 was selected as the 'best' Bouguer density). Reversals of correlation between peaks and anomalies defined by three stations are common in the data (see Profile D, the highest peak, Profile I near 220 km). 25 of these were selected from the profiles; the appropriate Bouguer densities ranged between 2.2 and 3.0 g/cm^3; a histogram of the values was fairly flat but showed a broad peak in the range 2.5-2.9 g/cm^3 (class interval 0.2 g/cm^3). It is considered that while the 'three point' reversals are probably useful to give a local average density, there is an advantage in using as great a length of profile as possible to arrive at a regional average Bouguer density.

Results of density profiling over distances of 30-40 km or more are summarised on Table 8.4. The table shows the Bouguer density chosen and the probable range of error. An average of densities is 2.73 g/cm^3. This is assumed to be an average for the Adelaidean Unit (Table 8.4). The method used is very subjective, but two repeat estimates made one month and two months after the original study gave almost the same result for each profile.

It is considered that the average density found by the method is close to the average true density of the Adelaidean Unit.

Earthquake data for South Australia (Table 8.5) indicate that for rocks in the Adelaide Geosyncline the seismic P wave velocity is 6.25 (± 0.03) km/sec; furthermore, there appears to be virtually no velocity gradient from near the surface to the bottom of the crust at 38 km (Stewart, 1972). Seismic data from the Maralinga atomic tests 500 km west of the Adelaide Geosyncline indicate that the P wave velocity of some of the rocks of the Gawler Platform is 6.3 km/sec (Doyle & Everingham, 1964). The error bounds of the velocity for the Gawler Platform were not stated, but the difference in velocities for the two areas are probably within the limits of experimental error. Thus it appears that on the basis of seismic P wave velocity, some strata in the two areas are indistinguishable.

Table 8.4

Density of the Adelaidean Unit from Density Profiling

Profile	Latitude	Bouguer Density (g/cm^3)	Density Range
A	30° 4'	2.70	2.60-2.80
B	30°15'	n.e.	-
C	30°31'	n.e.	-
D	30°46'	2.70	2.60-2.80
E	31° 2'	3.00	2.90-3.10
F	31°14'	n.e.	-
G	31°29'	2.70	2.60-2.80
H	31°45'	2.60	2.50-2,70
I	32° 0'	2.60	2.50-2.70
J	32°16'	2.80	2.70-2.90
K	32°31'	n.e.	-
L	32°47'	n.e.	-
M	32°58'	n.e.	-

Mean density = 2.73 g/cm^3

SD = 0.1

n.e = no estimate made because profiles are unsuitable

Table 8.5

Density Estimates from Seismic P Wave Data

Area	Crustal Thickness (km)	Velocity km/sec	Density (g/cm^3)		
			A	B	C
Adelaide Geosyncline	38	6.25 ± .03	2.75	2.86	2.70
Gawler Platform	38	6.30 ± ?	2.77	2.89	2.72

A. Velocity to density conversion using data from Nafe and Drake (*in* Grant & West, 1965, p.200). For rocks of many lithologies under surface conditions.

B. Velocity to density conversion using data from Woollard (1959, p.1530). For crystalline rocks under surface conditions.

C. Velocity to density conversion using data from Woollard (1959). For rocks at a depth of 8 km or greater.

The seismic P wave to density conversions using published data give equivocal results (Table 8.5); any of the obtained values might be a valid estimate of the average density of Adelaide System sediments.

The lack of a crustal velocity gradient in the area of the Adelaide Geosyncline may indicate that the crustal material has a constant density as if composed entirely of Adelaide System sediments. However, the experimental work of Birch (1958) on crystalline rocks indicates that different rock types under different pressure conditions can have the same velocity but a different density. Thus it does not necessarily follow that constant crustal velocity implies constant crustal density.

8.6 Density data for pre-Adelaidean rocks

Density data for the pre-Adelaidean rocks in South Australia are scarce. The author was only able to find a limited amount of data for drill core from the Middleback Range area of the Gawler Platform (Taylor, 1962, 1964; Gunn, 1967) and the Broken Hill Mines area of the Willyama Block (Broken Hill South Pty. Ltd., Russell, pers. comm.). In view of the problems encountered in the study of Adelaide System sediments it was considered that a major sampling program and analysis would be beyond the scope of the thesis. In this section the available data and the limited amount of work performed by the author are discussed.

8.6.1 Direct measurements

Taylor (op. cit.) summarised the results of density tests by the Broken Hill Proprietary Company Ltd. (BHP) and the SADM on drill core from the Middleback Range area. The work was undertaken to establish density contrasts between iron ore rocks and barren metasediments. He considered that for the purposes of gravity interpretation in the area the important average densities are:

1.	jaspilite and magnetite rocks	3.3 g/cm^3,
2.	hematite scree and ore rocks	4.0 g/cm^3,
3.	all other rocks	2.7 g/cm^3.

He showed ranges of densities for schists (2.4-2.6 g/cm^3), gneiss (2.4-3.0 g/cm^3), amphibolite (2.7-3.0 g/cm^3) and the ore rocks, but did not state sampling statistics or means for the individual lithologies. The density ranges above conform quite well with other published data (e.g. Smithson, 1971). However, to be of general application in estimating an average density of Gawler Platform rocks, means to two decimal places are required. Gunn (op. cit.) measured the density of 123 surface and core samples of country rock and ore types and agreed with Taylor's conclusions. However, once again the data are unsuitable for the purposes of generalizing for the whole Gawler Platform.

The author measured the dry bulk density of four solid surface samples of Gawler Range Porphyry, an extrusive unit which crops out over an area of 40,000 sq km, and is in places accompanied by Bouguer anomaly lows. Two samples of flow banded rhyolite from two localities have dry densities of 2.47 and 2.48 g/cm^3. Two samples of massive felspar porphyry from two localities have dry densities of 2.58 and 2.60 g/cm^3. These measurements are the only available data for acid igneous rocks of the Gawler Platform. It appears that the Gawler Range Porphyry is a low density unit.

The Broken Hill results (Russell, pers. comm.) for selected samples from drill holes up to 850 m deep are summarised on Figure 8.4. Biotite and sericite schists have dry bulk densities in the range 2.66-2.77 g/cm^3 (9 samples, mean 2.71 g/cm^3, SD 0.03, mode 2.72 g/cm^3). Garnetiferous schists have densities in the range 2.67-3.15 g/cm^3 (16 samples, mean 2.88 g/cm^3, SD 0.14, mode 2.88 g/cm^3).

8.6.2 Indirect measurements

The results of seismic studies (Doyle & Everingham, 1964) from the atomic bomb explosions at Maralinga, South Australia indicated that the main P wave crustal velocity on the Gawler Platform is 6.3 km/sec (Table 8.5). While the P wave to density conversions shown on Table 8.5 give equivocal results it is of importance that the actual velocity recorded is close to that for the Adelaidean Unit. It is possible that the density of much of the Gawler Platform strata (probably the metasediments) is close to that for the Adelaidean Unit. Unlike the case for the Adelaide Geosyncline area, several seismic velocities were recorded by Doyle and Everingham (op. cit.) for the Gawler Platform. It is likely that these are associated with significant lithological changes with depth.

Contrasts between most Adelaidean and pre-Adelaidean rocks are not well defined in the Bouguer gravity data. For example, on the south-west side of the Willyama Block there is not a well defined gradient parallel to the contact zone (see Fig. 1.3). Rather, the contours lie almost at right-angles to the contact and might be interpreted to show a change of density within the Willyama Block strata.

The contact relationships between Adelaidean and pre-Adelaidean strata are best known around the Mt. Painter Block (Coats & Blissett, 1971). The Bouguer anomaly map shows a 20 mg low over the basement inlier which is probably caused by a low density body within it rather than by a density contrast between the metasediments of the Adelaidean and pre-Adelaidean. This area is discussed further in Chapter 9.

8.7 Density data for post-Adelaidean igneous intrusives

There is no published data available on the densities of material composing the various granite bodies known in South Australia.

Measurements of dry bulk density were made on 194 samples of drill core from three holes into the Anabama Granite (drill logs in Hosking, 1970), the deepest of which reached 143 m (469 ft) below the surface. The locations of the drill holes are shown on Figure 9.3. Samples of approximately 150 g in weight were taken at a regular interval over the length of each core (10 feet in two cores and 5 feet in the third); the samples were all of solid appearance, but above 20 m some contained holes up to 2 mm across. Drill logs showing the lithology (generalized after Hosking, op. cit.) and density of samples are shown on Figure 8.5; a histogram of the densities is shown on Figure 8.4. Density values for each core become less scattered below 30 m; for core from holes AN2 and AN3, 30 m corresponds to a vertical depth of 21 m, while for hole AN1 it is the actual depth below the surface.

Table 8.6 shows the arithmetic mean density for samples below 30 m from each of the cores.

When rounded to two significant figures the means for the three cores lie in the range 2.61-2.66 g/cm^3, and the mean for all cores is

Table 8.6

Dry Bulk Density of Anabama Granite Drill Core

Drill Hole	No. of Samples	Density g/cm^3	Standard Deviation
DDH AN1	36	2.655	0.09
DDH AN2	89	2.661	0.08
DDH AN3	42	2.614	0.09
All	167	2.647	0.09

2.65 g/cm^3. 80% of the density values for samples below 30 m lie in the range 2.52-2.76 g/cm^3. The mode of the distribution for all samples lies close to 2.67 g/cm^3.

The density values tend to increase with depth below the surface for each of the cores. The effect is most marked in the log for DDH AN2 (see Fig. 7.5). For this core a straight line through the scattered values obeys the formula,

$$\text{dry density} = 2.54 + d \times 8.8 \times 10^{-4} \text{ g/cm}^3 \quad (30 < l < 182 \text{ m})$$

where d = core length in metres.

If d is converted to z, the vertical depth below the surface, the formula becomes,

$$\text{dry density} = 2.54 + z \times 1.25 \times 10^{-4} \text{ g/cm}^3 \quad (21 < z < 130 \text{ m})$$

If the linear increase of density with depth can be attributed to lessening of weathering effects with increasing depth, then it is likely that the true bulk density of unweathered, solid granite is no less than 2.65 g/cm^3 and probably close to 2.70 g/cm^3. Thus from this core, 2.65 g/cm^3 is a minimum estimate of the true bulk density. The reason why the density mean for DDH AN3 is about 0.05 g/cm^3 less than the other cores is not known; it may be an influence of lithology or weathering. From this core 2.61 g/cm^3 is a minimum estimate of true density.

The mean density estimates for each core, and for all cores from the Anabama Granite, compare closely with published figures for granites. For example, Jakosky (1950, p.264) gives the normal range as 2.52-2.81 g/cm^3, and the mean as 2.67 g/cm^3. The fact that the means for each core are different exemplifies the necessity to take as many observations from as wide an area as possible if a reasonably representative density estimate is to be derived for a rock unit.

Because there is no drill core available from other granite bodies in the area, it was decided that a major surface sampling program would be needed to yield even minimally useful results. Therefore, for the purposes of gravity interpretation in the thesis granites are assumed to have a true density of 2.61-2.65 g/cm^3. It is accepted that their true densities may be significantly higher or lower than these values.

8.8 Conclusions

The problem of finding densities of rock units and contrasts between units in the Adelaide Geosyncline and surrounding areas is far from solved. However, several useful points can be made for interpretation of the regional Bouguer anomalies.

1. The Adelaidean and Cambrian sedimentary strata in the Adelaide Geosyncline, if considered as a single geological unit, have an average true density of at least 2.68 g/cm^3 and possibly up to

2.73 g/cm^3 or more. This conforms with current thinking on the average density for the upper crust (Smithson, 1971).

2. At least part of the crust in the areas of pre-Adelaidean rocks consists of strata similar to the Adelaidean on the basis of density.

3. The extrusive Gawler Range Porphyry on the Gawler Platform may have a true density as low as 2.50-2.60 g/cm^3.

4. The intrusive Anabama Granite has a true bulk density of at least 2.61-2.65 g/cm^3 and possibly as much as 2.70 g/cm^3. Other granites probably have a similar density.

5. The important density contrast for the interpretation of Bouguer gravity lows appears to be between acid igneous rocks and all others (metasediments). If the Anabama Granite is taken as a guide, intrusive granites can be expected to be 0.05-0.10 g/cm^3 less dense than enclosing metasediments.

The study of surface samples of Adelaidean strata indicates that rocks of various lithologies have significantly different densities. The classification of rock types by the author was very approximate. The rocks were all weathered. It would be of interest to collect samples of core from the various drill holes in the Adelaide Geosyncline, accurately classify them by microscopic studies, assess the porosity and what minerals have been removed by leaching, and then re-estimate the average true density for the individual lithologies and the Adelaidean Unit. Such work could provide more reliable density data for detailed gravity work, and perhaps provide a stimulus for work in other areas where very low density contrasts exist between units of interest. Furthermore, it could provide useful information on the problem of whether a density contrast established by study of surface rocks is also valid at depth.

Chapter 9

INTERPRETATION OF GRAVITY LOWS ASSOCIATED WITH GRANITES

9.1 Introduction

The study of the geology of granite bodies in the Adelaide Geosyncline and surrounding areas has been summarised by Parkin (1969). Work in other parts of the world has shown that where Bouguer anomaly lows are associated with granites information on the size and shape of exposed granites can be obtained (e.g. Bott & Smithson, 1967) and in some instances can be used to predict the occurrence of large unexposed bodies (e.g. Bott & Masson-Smith, 1957).

In the area of main interest in the thesis (Figs. 1.3 & 9.1) three areas of granitic rocks have associated gravity lows. Anomaly 5 lies over granites in part of the Mt. Painter Block, part of Anomaly 11 lies over granitic rocks in the north side of the Willyama Block, and Anomaly 14 lies over the Anabama Granite. It is to be expected that quantitative interpretation of the Bouguer anomalies can yield new information on these areas. Other gravity lows (see Fig. 9.1) in the area, Anomalies 2, 12 and 21, which may also be caused by unexposed granites, were not studied in detail. Anomaly 21 is being studied by another worker; Anomaly 2 is under investigation by the SADM; Anomaly 12 is not well defined by the regional gravity data.

A special problem with the regional gravity data is that along any single line across the gravity lows there are too few stations to fully define profiles suitable for detailed analysis. It was found that by averaging values in a wide strip across the anomalies reasonably well defined profiles can be produced. A second problem common to all gravity interpretations is that of obtaining density data. The author's work on the problem is discussed in Chapter 8.

9.2 Method of interpretation of gravity lows

9.2.1 General considerations

The study of batholiths with the gravity method has been discussed by Bott (1955, 1962); Bott and Smith (1958); Skeels (1963); Grant & West (1965); Bott & Smithson (1967) and Jacoby (1970) who establish the methods of attack for solving two major problems, firstly whether a gravity anomaly is caused by a thickening of sediments or an unexposed batholith and secondly, how to establish the probable depth extent of the body. The approach used in gravity interpretation of anomalies possibly due to plutons is largely a 'cut and try' method. The first step is to propose a reasonable model and density contrast based on the available geological and geophysical evidence. The volume of the model should be such that the mass deficiency is approximately that established by integration over the whole anomaly. Then the theoretical anomaly of the model (usually a profile) is compared with the observed anomaly and the model is successively modified until a good fit is achieved. If little useful geological or geophysical data are available the problems are manifold.

The determination of the density contrast presents problems. Experience has shown (e.g. Bott & Smithson, op.cit; and the work of the author) that granites are often less dense than the country rocks in which they are emplaced. Density measurements on rock samples can give a guide to the contrast between granite and country rocks. Density measurements on the rocks usually establish density contrasts in the range -0.05 to -0.18 g/cm^3 (Bott & Smithson, op. cit.). Interpretation of the anomalies using simple shapes can establish reasonable maximum and minimum values for density contrast.

Determination of the depth extent of the body is relative to the problem of density contrast. Elementary interpretation using a simple model with reasonable assumed maximum and minimum density contrasts, can establish the minimum and maximum depth to the bottom of a body with regard to the density contrast. There is no way of assessing whether an established density contrast is valid for the whole geological body unless it is drilled. Thus a 'cut and try' model postulated must be regarded as a model for density contrast which probably approximates the shape of the body.

9.2.2 Accuracy of data

The 1970 BMR helicopter gravity and elevation data used in the thesis were established using the cell method of traversing described by Hastie and Walker (1962). Gravimeters used were a Worden 274 (factor 0.09177 mg/div) and a Worden 708 (factor 0.08330 mg/div). Elevations of stations above mean sea level were obtained by the two-barometer technique. One barometer continuously recorded barometric pressure at a base station; the other measured pressure at the gravity stations. The Bouguer anomaly values were computed on the CYBER 73 computer at Monash University, Melbourne. Statistical tests (Tucker & Brown, 1972) indicate that standard deviation for the elevation in the adjusted data was less than 2 m (corresponding to 0.13 mg). The maximum recorded departure of elevation from the reduced level was 7.7 m (corresponding to .51 mg). The adjustment in gravity values before correcting for elevation was usually less than 0.11 mg. Perhaps the most important factor to assess is the difference in Bouguer anomaly values between the highest and lowest stations in the area if an incorrect Bouguer density is used in reduction (Table 9.1).

Table 9.1

Absolute Errors in Bouguer Anomalies

Anomaly	Elevation above Mean Sea Level		Average Elevation	Bouguer Anomaly*
	max	min		
5	679 m	242 m	400 m	1.4 mg
11	331 m	62 m	150 m	0.8 mg
14	424 m	160 m	300 m	0.8 mg

* Difference in Bouguer anomaly between highest and lowest stations for 0.1 g/cm^3 error in Bouguer density.

Table 9.1 shows that the difference between Bouguer anomalies at the highest and lowest stations is less than 1.5 mg in the area of anomalies interpreted quantitatively in the thesis, if the Bouguer densities used in reduction of the data are within 0.1 g/cm^3 of the correct values. For the reduction of data for quantitative interpretation, 2.67 g/cm^3 was used in the area of Anomalies 5 and 14 (mainly Adelaidean sediments, pre-Adelaidean sediments and granites) and 2.2 g/cm^3 was used in the area of Anomaly 11 (mainly Quaternary to Upper Palaeozoic sediments above sea level).

It is considered that the chosen Bouguer densities are within 0.1 g/cm^3 of the average near surface rock densities. Errors at any station due to either observation or incorrect choice of Bouguer density are usually less than ± 1.0 mg. Errors of this size are likely to have little influence on the interpretation of anomalies of 20 mg or more. Although the Bouguer gravity anomalies have been reduced to sea level, for interpretation of the regional data and production of models there is no serious error in assuming the ground surface flat at the average elevations indicated on Table 9.1.

9.2.3 Calculation of excess mass and maximum density contrast

Mass deficiency (hereafter referred to as excess mass) was calculated from the three Anomalies 5, 11 and 14 using the integration method described in Grant and West (1965, Chapter 10). The method includes a tail correction for the area beyond the limits of integration. A hand smoothed contour map was drawn for each anomaly. The data were regridded at 3.7 km for Anomaly 5 and 7 km for Anomalies 11 and 14 and then the excess mass was calculated by integration with a computer. Mass estimates are usually low because there is a tendency to underestimate the regional for an anomaly.

Estimates of excess mass for the three anomalies are shown on Table 9.2. The minimum estimates were obtained by underestimating, and the maximum estimates by overestimating the regional.

Table 9.2

Anomaly	Excess Mass (grams)		Density Contrast (g/cm^3)
	min	max	min
5	-2.1×10^{17}	-2.9×10^{17}	-0.07
11	-1.8×10^{18}	-2.5×10^{18}	-0.05
14	-2.0×10^{18}	-2.6×10^{18}	-0.08

Minimum density contrasts for the bodies causing the anomalies were estimated on the assumption that the sources are rectangular parallelepipeds, with width defined by half amplitude points of the anomalies. The upper surface was assumed to be exposed, and the depth to the bottom surface was taken as 38 km (crust thickness). The theoretical anomalies were wider near the peak and the base than the observed anomalies.

9.2.4 Production of profiles

Profiles drawn to connect values on any line at right-angles to the long axis of anomalies in the regional data usually differ in detail from those adjacent. Therefore there is an advantage in averaging the values in a reasonably wide strip across the centre of the anomalies. The method used was to project all values in a strip 15-20 km wide onto a line, and then replot and draw a smooth curve through the slightly scattered data. The profiles were continued far enough to allow a reasonable assessment of the regional Bouguer gravity anomaly in each case.

Figure 9.2 shows the Bouguer anomalies used for model studies in this chapter. Generalized geological sections are shown.

9.2.5 Modelling

The main modelling work was carried out with a computer program based on the method of Talwani (1965) and written by Mr. J. Trethewie of Austral Exploration Services, Adelaide. The program calculates the gravity anomaly for an arbitrarily shaped three dimensional solid body. The accuracy of the program was checked by computing the anomaly due to a sphere and comparing the values with those calculated by hand using the simple sphere formula (Grant & West, 1965, p.293). Values compared almost exactly. Values computed with the program were 0.3% lower near the peak than those calculated by hand. The discrepancy arose because with the computer test, the spherical shape was approximated by nine horizontal circles and the curved surface between the circles was lost. For the sphere model, the program assumes the solid body between any two circles is a truncated cone.

As is discussed later, several reasonable density contrasts were tried for various models. From an initial model based on geological and geophysical considerations, and with an excess mass close to that calculated for the anomaly, successive alterations (holding excess mass constant) were made until a reasonably good fit to the observed profile was achieved.

Because the problem of densities is not fully solved, and it is possible that the models (on the basis of density contrast) should be based on a basin shape, the iterative method of Bott (1960) was tried for Anomalies 11 and 14. The results for Anomaly 14 are discussed later.

9.3 Bouguer Anomaly 14 - the Anabama Granite

The peak of Anomaly 14 lies over an area of scattered granite outcrops (Fig. 9.3) which Mirams (1961) considers are the surface exposure of a large granite pluton or batholith (Parkin, 1969, p.34) has drawn a cross section across the granite and Adelaidean strata in the area. The geology of the area has not been mapped in detail. The SADM unpublished photo-interpreted OLARY sheet shows granite outcrops in an area some 50 km by 12 km. A generalized geological cross section based on the SADM mapping is shown on Figure 9.2. The exact position of the granite boundaries is hidden by alluvium.

On Figure 9.3 most of the granite outcrops lie inside two parallel ridges of magnetic Yudnamutana Subgroup strata (Adelaidean). To the south-east along line AA' the cover rocks are Cainozoic and Mesozoic sediments of the Murray Basin. Mirams (op. cit.) discussed the field relationship of the granite. He noted that remnants of altered Adelaide System sediments occur within the granite and considers this indicates the proximity of the roof of the granite mass. He stated that the predominant intrusive rock type is a medium to coarse grained unstressed granite.

The aeromagnetic contour map of OLARY shows that the Yudnamutana Subgroup and other Adelaidean strata contain strongly magnetic beds. The granite is not strongly magnetic. Aeromagnetic contours at 1,000 gamma intervals are superimposed on the geology (Fig. 9.3). It is evident that magnetic Adelaidean material lies beneath some of the alluvium within the general frame of Adelaidean outcrop which defines the limits of most of the largest granite outcrops. This supports Mirams' (op. cit.) impression that the observed granites lie near the roof of a large body. To the south-east of the granite in the vicinity of A' on Figure 9.3 the aeromagnetic data indicate that magnetic strata (probably Adelaidean) lie at a depth of 0.5-1 km beneath a cover of non-magnetic Cainozoic and Mesozoic strata.

There is little doubt that Bouguer Anomaly 14 is caused by a large granite batholith. Three dimensional models were constructed to account for the gravity anomaly.

9.3.1 Profiles

A profile was drawn normal to the long axis of the gravity contours (AA' on Fig. 9.3) using the averaging method described earlier. A sloping linear regional appears to be appropriate for the area (Fig. 9.4).

A small adjustment in either level or slope of the regional makes little difference to the batholith models produced. The original and adjusted profiles are steeper on the south-east side than the north-west side.

9.3.2 Density contrast

In Chapter 8 it was established that the minimum density contrast between the Anabama Granite and the Adelaidean Unit most probably lies in the range 0.07-0.12 g/cm^3. Estimates of minimum and maximum density contrast from trial models indicated the range 0.08-0.19 g/cm^3. The value 0.10 g/cm^3 was adopted.

9.3.3 Models

A model constructed with the 3D model program to account for Bouguer Anomaly 14 is shown on Figure 9.4 (Model 1). The initial block was an equilateral trapezoid with side slope 60^0 and with surface width 11 km. This width includes most of the granite outcrops between the ridges of Yudnamutana Subgroup rocks (Fig. 9.3). A length of 45 km was adopted. On Figure 9.2 the north-east and south-west ends of the block corresponding to this length lie between the -30 and -35 mg contours. Six successive adjustments of the block resulted in the model shown on Figure 9.4. To obtain a good fit near the minimum of the anomaly it was necessary to put the top of the block 0.2 km below ground level. This does not necessarily imply that the corresponding geological body, i.e. the granite, does not reach the surface. Further small adjustments to the model, for example, a slight reduction in width, could take the block to the surface. As the model stands it was necessary to reduce the width of the top of the block to less than the original 11 km. The depth to the base of the low density block lies at 23 km. This is more than double the depth of granite batholiths discussed by Bott and Smithson (1967). Preliminary modelling with a density contrast of 0.20 g/cm^3 indicated that even with this high contrast the bottom of a trapezoidal block would have to lie at no less than 15 km. Variable density modelling was tried but abandoned. On the basis of the available density data variable density modelling is not warranted.

Because there is a weak possibility that in this area the granite and the Adelaidean Unit have essentially the same average density and both overlie a much denser basement, models were constructed with Bott's (1960) iterative method for basins. Even with a different choice of regional than that used for the models, the models (Fig. 9.4) seem totally unreasonable. For example, on the north-west side of the granites Models 2 and 3 suggest the depth to basement is about 3 km. The OLARY geological map shows that some of the youngest Adelaidean strata occur in this area. Because older units (viz. Yudnamutana Subgroup and others) also occur in the area, it is likely that the Adelaidean Unit is up to 10 km thick on the north-west side of the Anabama Granite.

9.3.4 Conclusion

On the assumption that the Anabama Granite is 0.1 g/cm^3 less dense than both the Adelaidean Unit and any underlying pre-Adelaidean strata in the area, the batholith Model 1 is proposed as approximating the shape of the body. The model appears to extend to a depth of 23 km. This depth differs from published work on other granites which suggest 10 km as a reasonable depth extent. However, because the gravity anomaly extends so far to the north-west and south-east of the known granite outcrops, it is quite likely that the density contrast (and the granite) does extend to great depth. An alternative model to that proposed would probably require a laccolith which thins towards the edges and has a substantially higher density contrast (0.20 g/cm^3 or above).

On the basis of the model approximating the shape of the Anabama Granite, it appears that several of the outcrops of granite shown on Figure 9.3 are small apophoses from the main body. One of these lies 15 km north of Anabama Hill (the drill holes on the figure are located on Anabama Hill). The width of the near surface part of the body is indicated on Figure 9.3.

9.4 Bouguer Anomaly 11 - Glenorchy area

While the peak of Bouguer Anomaly 11 (Fig. 9.6) lies over an area of Palaeozoic to Recent aged sediments of the Frome Embayment, much of the southern part of the anomaly lies over granitic rocks of pre-Adelaidean age (Willyama Complex). The gravity anomaly is closely coincident with the granitic material.

Figure 9.6 shows a simplified geological sketch map of the area taken from the unpublished SADM maps of CURNAMONA and OLARY, together with the Bouguer anomaly contours and aeromagnetic contours. Published SADM 1:63,360 geological maps of Glenorchy (lat. 31°45'-32°00', long. 139°30'-140°00') and Plumbago (lat. 32°00'-32°15', long. 139°30'-140°00') show that pre-Adelaidean strata are predominantly of granitic composition. For example, within the -25 mg gravity contour, rocks mainly consist of anatectic granites, adamellites, migmatites, granite gneisses and various undifferentiated granitized terrains. Radiometric dating data from various authors for rocks in the Crockers Well uranium mine area (10 km south of Glenorchy Homestead) have been reinterpreted by

Cooper (1972, in press). He considers the date of mineralization to be 1705 m.y., followed by regional metamorphism of 513 m.y. From this it can be inferred that the age of rocks in the area may be 1705 m.y. or more. The published and unpublished maps indicate that outside the -25 mg gravity contour (30 km to the east and south-east of Glenorchy), pre-Adelaidean rocks include both granitic material and layered metasediments. The available information indicates that granitic material near the southern part of Bouguer Anomaly 11 is all very old and was emplaced before Adelaidean times. The Adelaidean rocks (mainly Umberatana Group slates, siltstones, quartzites and dolomites) appear to have been deposited on the granites.

On Figure 9.2 a profile is shown along latitude 32^0 crossing the southern part of the anomaly. The anomaly has a broad peak and steep gradients typical of the response expected over a flat topped low density block of limited depth extent, at or near the surface. From this and the available geological information it appears that the gravity anomaly is caused by pre-Adelaidean granitic rocks, which are exposed in the south and extend to the north under Recent and other cover rocks. It is unlikely that low density cover rocks contribute much to the anomaly.

Figure 9.6 shows the outline of a proposed low density block responsible for the gravity anomaly. The limits of the block were defined on geological and geophysical grounds. The southern part encloses the bulk of the mapped granitic rocks. In the area of Recent cover, the eastern and western margins were defined from the aeromagnetic pattern and general aspects of the gravity anomaly. There appears to be a correspondence between the gravity anomaly and the aeromagnetic pattern, although it is not easy to exactly define what the correspondence means. South of line AA' on Figure 9.6, there are more strong localized anomalies inside the dashed boundary than outside it. These anomalies are probably caused by sources at a depth of 1 km or less. There is a general rise of about 200 gammas in the background level of magnetic anomalies over the area enclosed by the -30 mg gravity contour. Over the northern part of the gravity anomaly there are few strong localized magnetic anomalies, which may indicate a composition change in the magnetic basement, or an increase in depth to the strongly magnetic material (see Fig. 9.6). The existence of strongly magnetic material at shallow depths near the minimum of the gravity anomaly rules out the possibility that there is a great thickness of low density sediments which contribute to the anomaly north of the area of outcropping pre-Adelaidean material. The magnetic basement almost certainly consists of pre-Adelaidean material. Over exposed pre-Adelaidean material, strong anomalies often correlate with amphibolite dykes, and metasedimentary rocks. It appears that the source of the gravity anomaly is a block of low density granitic material which is generally weakly magnetic but contains some local strongly magnetic components.

Models were constructed on the basis that the gravity anomaly is caused by a batholith of low density granitic material.

9.4.1 Profiles

The Bouguer density chosen for reduction of the data was 2.2 g/cm^3. A profile was drawn normal to the long axis of the gravity contours (AA' on Fig. 9.6) using the averaging method described earlier. Data points on the east side define a fairly definite curve; on the west side there is a considerable scatter (Fig. 9.2).

9.4.2 Density contrast

No direct measurements of density contrast between granitic rocks and other material in the Glenorchy area are available. Estimates of minimum and maximum density contrast from trial models indicated the range 0.05-0.15 g/cm^3. The value 0.07 g/cm^3 was adopted as a minimum density contrast for modelling.

9.4.3 Models

A model constructed with the 3D model program to account for Anomaly 11 is shown on Figure 9.7 (Model 1). The initial block had a width of 25 km (indicated on Fig. 9.6), a length of 60 km and vertical sides. The upper surface was assumed flat and lying at a depth of 1 km as indicated by depth to magnetic basement estimates along line AA'. Excess mass was held constant at -2.5 x 10^{18} g during the model adjustment procedure. Five adjustments resulted in the model shown. As for the modelling on Anomaly 14, a high value was obtained for the depth to the bottom of the low density block (26 km). It was necessary to round the top surface of the block to account for the anomaly.

A second trial model (not shown as a figure) was constructed for a higher density contrast (0.13 g/cm^3) initially using the same block width as for Model 1. It was found that the shape of the top surface was little different than for Model 1 but the depth extent had to be substantially reduced and the width had to be considerably increased to account for the wide flanks of the anomaly.

A third trial model was constructed for a different choice of regional level (Fig. 9.8, Model 3). The low density block (contrast 0.09 g/cm^3) is slightly wider than Model 1 and the shape of the top surface is essentially the same. However, the depth extent (13 km) is considerably less. Clearly the correct choice of regional is critical in determining depth extent.

9.4.4 Conclusions

Anomaly 11 is caused by low density rock which is probably a granitic intrusion of pre-Adelaidean age. Model 3 is favoured. Granites exposed in the vicinity of Glenorchy Homestead are probably part of the body; it continues under cover to the north.

From the modelling it appears that beneath the area of Recent cover, the top part of the body is rounded as if unchanged by erosion before deposition of the sedimentary cover. If the model is an indication of the shape of the unexposed granite body, then it is not easy to explain why depth estimates to magnetic basement (if assumed to be the granite or included metasediments) do not substantially increase towards the edges of the body. Close to AA' on Figure 9.6 magnetic depth estimates range from 0.5-1.0 km near the centre, to 1-2 km near the edges of the low density block. Gravity modelling indicates 0.8 km near the centre and 6 km near the edges. To account for this discrepancy is important because magnetic anomalies were initially used to define part of the boundary of the low density block, particularly the east side. Three explanations are suggested. First, the strong magnetic anomalies are caused by small plug-like magnetic bodies emplaced after the general large mass. The edge of a granite is a favourable site for later intrusions. Some of the small plugs could extend up into overlying metasediments. Depth estimates from aeromagnetic anomalies associated with the plugs do not appear to give a valid depth estimate to the main body. Second, the strong anomalies are a result of metamorphic effects on overlying material, possibly associated with emplacement of the granite. For this situation depth estimates from the strong anomalies probably give the depth to magnetic components of the metasediments. Third, part of the upper part of the batholith is of higher density than the main body and does not contribute to the gravity anomaly. Depth estimates from the strong anomalies give the true depth to the top of the body. Of these explanations the first is favoured.

9.5 Bouguer Anomaly 5 - Mt. Painter area

Gravity Anomaly 5 lies over the southernmost part of the Mt. Painter Block. The area has been geologically mapped by the SADM and the geology discussed by Coats and Blissett (1971). The geology and Bouguer anomaly contours are shown on Figure 9.9 and a cross section is shown on Figure 9.2. Coats and Blissett think that the pre-Adelaidean Older Granite Suite (mainly rapakivi-like granite and granite porphyry) and Radium Creek Metamorphics (phyllite, schist and quartzite) are domed into an anticline and that this has been later intruded by the Mudnawatana Granite (granodiorite), and various pegmatites. They consider that the Older Granite Suite is a laccolith and the Mudnawatana Granite is a plug. They consider that pegmatites south-west of the main outcrop of the Mudnawatana Granite are related to it and may be derived from a large unexposed body.

Adelaide System sediments dip outwards from the basement inlier. Boulders of the Older Granite Suite rocks are found in the basal conglomerate of the Callanna Beds in the oldest of the Adelaidean sediments, indicating that at least part of the Mt. Painter Block was above sea level during Adelaidean sedimentation. Various phases of movement have occurred, the last of which was probably in the Cainozoic.

The gravity anomaly covers only a small part of the exposures of granites in the Mt. Painter Block. This may indicate that some are thicker than others or that some of the granites are of lower density than others. While it is almost certain that the gravity anomaly is caused by a granitic mass, from the available data it is not easy to find which unit is the source. As can be seen on Figure 9.9, the gravity stations are sparse, and the averaging method applied reasonably successfully to Anomalies 11 and 14 does not define the shape of the anomaly satisfactorily. Furthermore, there is no density data available for the granites in the area. Two geologically acceptable models were constructed which can account for the anomaly as defined by the data.

9.5.1 Profiles

A profile was drawn normal to the long axis of the gravity anomaly. Gravity values were averaged for a strip 15 km wide about AA' (Fig. 9.2). The regional level is critical for the anomaly and a difference of one or two milligals has a strong influence on the models.

9.5.2 Density contrast

There are no direct density measurements available for rocks in the area. Estimates of minimum and maximum density contrast from preliminary studies of the gravity anomaly indicated the range 0.07-0.20 g/cm^3. The value 0.10 g/cm^3 was adopted for a batholith model and the value 0.14 g/cm^3 was adopted for a laccolith model.

9.5.3 Models

The two models constructed with the 3D modelling program are shown on Figures 9.10 and 9.11.

Model 1 was constructed for a residual anomaly with the minimum acceptable cut off on its flanks. The presumption was that the elliptically shaped core of pre-Adelaidean rocks (Older Granite Suite and

Radium Creek Metamorphics on Fig. 9.9) approximately defines the outline of the low density mass. The model derived after five adjustments from an initial flat slab, has the shape of half an ellipsoid of revolution. The theoretical anomaly is too wide near the peak and too narrow near the base to account for the field anomaly, but as the field anomaly is not well defined the fit is considered acceptable.

Model 2 was constructed for a residual anomaly with the maximum acceptable regional level. The presumption was that a low density batholith with near surface width equal to that of the exposed Mudnawatana Granite 20 km north-east of Mt. Painter extends beneath the surface along the axis of the gravity low. Four adjustments to an initial vertical block 15 km thick resulted in the model shown on Figure 9.11.

9.5.4 Conclusions

Without density data for the area and a better defined field profile it is difficult to select the more reasonable model.

Model 1 is geologically acceptable if it is assumed that the Radium Creek Metamorphics (probably dense strata) are thin and that the Older Granite Suite lies beneath them on the south-east side of the basement inlier, and is a low density unit. North of the area shown on Figure 9.9 an equally extensive area of Older Granite Suite rocks have negligible associated gravity anomalies. While it is possible that the Older Granite Suite rocks, extending north-east from the gravity low, are thin thus giving little gravity response, from the mapping in the area this seems unlikely. It is possible that there is a significant density difference between the granites in the two areas.

The batholith model (Model 2) is favoured for the source of the gravity low. While the model may be geologically valid, the identity of the low density rock unit is not established. The large exposure of Mudnawatana Granite near the north-east end of the gravity low is accompanied only by minor flexures in the contours. The data are inadequate to be certain that this is part of the top of the proposed batholith. It is possible that the exposure is thin, thus causing little response.

Detailed gravity lines and density measurements on rocks in the area will be necessary to resolve the problem.

9.6 Notes on Anomaly 2

Anomaly 2 is an intense gravity low similar in area, shape and amplitude to Anomalies 11 and 14. It lies over an area of Recent to Palaeozoic aged sediments of the Great Artesian Basin. Lonsdale and Ingall (1965), in an unpublished qualitative report on a Bouguer gravity survey of much of the north-east of South Australia, considered that the anomaly might be caused either by a thickening of Palaeozoic sediments in a deep localized basin or by a low density batholith, possibly of granitic composition. The author favours the latter suggestion based on the following information.

1. The aeromagnetic contour map for the area shows three strong magnetic highs on the east and north sides of the gravity anomaly in the area of steepest gravity gradients (refer Figs. 1.4 & 9.1). The peaks of the magnetic highs lie inside the -15 mg gravity contour (the regional level for the gravity anomaly is close to 0 mg). Preliminary depth estimates indicate that depth to the sources is no more than 2 km.

2. Seismic data (Parkin, 1969, page 157) indicate the depth to the Cadna-owie Formation (Cretaceous) is less than 600 m in the area. Cross sections based on drilling in the Moomba-Gidgealpa gas fields 100 km to the north of the gravity anomaly indicate that the maximum thickness of pre-Cretaceous/post-Cambrian strata is about 3 km (Parkin, 1969, page 145).

3. The gravity anomaly is of the flat topped variety with gradients steeper near the peak than the base of the anomaly. The rate of change of gradient is higher on the inside than the outside of the anomaly. This is indicative of the low density body having sides which slope outwards.

While it is dangerous to extrapolate the observed thickness of known low density sediments for 100 km, it is likely that in the area of the gravity anomaly the overburden thickness is no more than that indicated for the gas field area. This is supported by the depth estimates to magnetic basement (probably to pre-Adelaidean strata) in the area. To account for the gravity anomaly, a thickness of 10 km or more of low density post-Cambrian sediments would be required near the centre of the low.

It appears that Anomaly 2 is caused by a low density batholith, with sides sloping outwards. The magnetic anomalies appear to be associated with the proposed body and could be due to a contact metamorphic effect. The batholith is probably largely composed of non-magnetic material. It is likely to be of granitic composition.

9.7. Discussion

Of the anomalies quantitatively interpreted in this chapter, only Anomalies 11 and 14 are sufficiently well defined by the regional data to be reasonably certain of the shape of the sources. Further field work is required on Anomaly 5.

Anomalies 11 and 14, and possibly Anomaly 5, are probably caused by batholiths of considerable size and depth extent. If the density contrasts chosen for the modelling are close to the true values and exist throughout the granitic bodies, then it appears that the depth to the bottom of the Anabama Granite batholith is 23 km, to the bottom of the Glenorchy batholith is 13 km and to the bottom of the Mt. Painter batholith is 13 km.

It is likely that Anomaly 2 is caused by an unexposed low density batholith probably of granitic composition.

Chapter 10

CONCLUSION

The main aims of the thesis have been to discuss magnetic anomalies which are caused by near surface sources associated with Adelaide System sediments, and Bouguer anomaly lows associated with granite bodies. The research produced important new geophysical information on the Adelaide Geosyncline; to find the full significance of the geophysical results requires further geological studies.

New information was found on Precambrian sedimentary beds in the Adelaide Geosyncline. To the author's knowledge no equivalently detailed information has been published for other areas of Precambrian sediments in Australia. Thus the results are important not only for the Adelaide Geosyncline, but also for other similar areas, because they serve as an example of what can be done. It is now known that magnetic beds occur at discrete levels in the stratigraphic succession of Adelaide System sediments, and some of the special properties of the beds are known. However, the geological significance of the magnetic beds is still not fully understood, and it is to be hoped that geologists will take up the problem. Future studies of the Adelaidean stratigraphy cannot ignore investigation of the iron minerals.

In the area of the Adelaide Geosyncline, it was found that sediments in Cainozoic basins within the mountain ranges are strongly magnetic. The geological significance of the concentration of iron minerals in these strata is yet to be established.

Interpretation of the existing aeromagnetic data with a view to finding magnetic intrusives is very difficult. This is mainly because of the likely small size of the bodies, but also because of the dominating influence of anomalies due to magnetic Adelaide System beds and magnetic Cainozoic sediments. However, it is known that various small intrusive bodies, viz. the Walloway Diapir carbonatites, are magnetic. Thus, despite the difficulties of detecting small intrusives, the magnetic method must be considered as a useful primary tool for future exploration in the area. Surveys to find small intrusives in areas of magnetic sediments will require a closer line spacing and lower ground clearance than the existing data.

The value of detailed study of original aeromagnetic flight charts, and ground follow-up work, is demonstrated by the thesis. To get the full benefits of the available geophysical data for other areas requires similarly detailed analysis; a study of contour maps of total magnetic intensity is not enough.

Interpretation of Bouguer anomaly lows on the east side of the Adelaide Geosyncline produced new information on areas of granites. Despite possible criticisms on geological grounds of the geophysical models produced in the research work, the important feature is that the gravity lows are caused by large low density rock masses of batholithic form and not bodies of limited depth extent. For example, previous geological studies in the Mt. Painter area have indicated that most of the granites in the area are thin sheets: the gravity results indicate that a low density mass of considerable depth extent occurs in the core of the southern part of the Mt. Painter Block. Future work on the geology of the Mt. Painter area, the Anabama Granite and the Glenorchy area must take the geophysical information into account.

Difficulties were found in estimating the average density of rock bodies. This was particularly true for ones as lithologically complex as the Adelaide System sediments, but was also the case for bodies of essentially one lithology, viz. granite. Although the gravity data yielded useful information in areas of granites, it does not appear to be of help on the problem of finding the thickness of Adelaide System sediments in the Adelaide Geosyncline.

Although not discussed in detail in the thesis, the long gravity gradients, and deep source magnetic anomaly lineaments, are features important to an overall understanding of the Adelaide Geosyncline. In other parts of the world, lineaments on gravity and magnetic maps have been found to have special associations with mineral provinces. Future studies of the regional geology of the Adelaide Geosyncline must take these features into account.

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