A gravity study of northern Botswana: a new perspective and its implications for regional geology

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A gravity study of northern Botswana: a new perspective and its implication for regional geology

by

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Abstract

A gravity survey in 1998-1999 were collected that filled in existing holes in data coverage of the 1972-1973 survey of northern Botswana. Improvements in data quality associated with precise positioning using differential GPS have lead to significant improvements in the quality of gravity data which result in the better definition of the regional geology. The colour composite map of apparent physical property can be calculated by combining the apparent density map and the apparent magnetic susceptibility map, after both map have been generated by specific calculation filters. The geological boundary has been visually interpreted from the colour composite map. Not only the interpreted boundary reveals more features than the features in the existing geological map, but also the comparison between old data and new data from the two dimensional spectrum analysis has shown the superiority of the new data set.
Acknowledgements

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# Table of content

Abstract .................................................................................................................................................. i
Acknowledgements .................................................................................................................................. ii
Table of content ..................................................................................................................................... iii
List of figures .......................................................................................................................................... v
List of tables .......................................................................................................................................... ii
1. Introduction ....................................................................................................................................... 1
   1.1. RESEARCH QUESTIONS ................................................................................................................ 1
   1.2. BACKGROUND................................................................................................................................ 1
   1.3. LOCATION ....................................................................................................................................... 3
   1.4. PROBLEM STATEMENT .................................................................................................................... 3
   1.5. TECTONIC AND GEOLOGICAL SETTING IN NORTHERN BOTSWANA ........................................... 3
       1.5.1. Precambrian basement complex ............................................................................................. 3
       1.5.2. Limpopo Mobile Belt ............................................................................................................. 6
   1.6. RESEARCH OBJECTIVES ............................................................................................................... 6
   1.7. RESEARCH METHODOLOGY ......................................................................................................... 7
   1.6. STRUCTURE OF THE THESIS ....................................................................................................... 7
2. Background to gravity surveys ........................................................................................................... 9
   2.1. STATION DISTRIBUTION ............................................................................................................... 9
   2.2. GRAVITY DATA REDUCTION OF 1998-1999 SURVEY .................................................................. 9
   2.3. THE BOUGUER ANOMALY PATTERN ............................................................................................. 10
   2.4. A COMPARISON OF 1973 AND 1999 GRAVITY SURVEY RESULT ................................................ 14
   2.5. SUMMARY AND DISCUSSIONS ...................................................................................................... 20
3. Grid data analysis and Image processing ............................................................................................ 22
   3.1. AMMP GRID DATA ....................................................................................................................... 22
   3.2. GRID DATA QUALITY AND DATA GRIDDING ............................................................................ 22
   3.3. SPECTRAL ANALYSIS .................................................................................................................... 24
       3.3.1. 2-D power spectrum ................................................................................................................ 24
   3.4. RADIALY AVERAGED SPECTRUM ................................................................................................. 28
   3.5. ENHANCEMENT OF REGIONAL-RESIDUAL FEATURES ................................................................. 32
       3.5.1. First vertical derivative ....................................................................................................... 32
       3.5.2. Shaded relief image .............................................................................................................. 32
   3.6. SUMMARY AND DISCUSSION ....................................................................................................... 35
4. Apparent physical property map ......................................................................................................... 37
   4.1. INTRODUCTION ............................................................................................................................. 37
   4.2. ROCK PROPERTY DATA ............................................................................................................... 37
   4.3. DATA PRESENTATION .................................................................................................................... 39
       4.3.1. Colour composite scheme .................................................................................................... 39
       4.3.2. Apparent magnetic susceptibility map ............................................................................... 39
       4.3.3. Apparent density map ....................................................................................................... 44
   4.4. LIMITATIONS ............................................................................................................................... 44
   4.5. COMPARISON WITH GEOLOGY ................................................................................................... 46
   4.6. THE FINAL INTERPRETATION MAP ............................................................................................. 51
   4.7. SUMMARY AND DISCUSSIONS ..................................................................................................... 51
5. Discussion .......................................................................................................................................... 54
6. Conclusion and Recommendation ...................................................................................................... 55
List of figures

Figure 1.1 Gravity data locations of Botswana from various sources. The recent gravity survey is outlined by the polygon over almost all the northern part of Botswana..............................2

Figure 1.2 Various published attempts at a generalized tectonic framework of southern Africa........5

Figure 1.3 An overview of surface and general rock type in Botswana...........................................6

Figure 1.4 Operation flow chart of the research ..............................................................................8

Figure 2.1 (a) An elevation map obtained from the recent gravity survey shows remarkable number of geomorphological features in the study area, indicating a northeast-southwest trending across the Okavango delta (b) Bouguer anomaly map of 1998-1999 survey........................................11

Figure 2.2 (a) 1998-1999 Bouguer anomaly map with contour interval 2 mGal (b) The classified zones of (a) which are described in Table 2.2 (b).............................................................................13

Figure 2.3 (a) 1998-1999 Bouguer anomaly map (b) 1972-1973 Bouguer anomaly map. Their gravity stations distribution are also displayed in each map...........................................................................16

Figure 2.4 (a) Data distribution comparison between the 1972-1973 (x) and 1998-1999 (+) gravity survey. (b) The subtracted grid results between 1972-1973 gravity grid and 1998-1999 gravity grid give the anomaly value in range between –37 mGal to +24 mGal...........................................17

Figure 2.5 Conceptual diagram of grid survey design .......................................................................19

Figure 2.6 The overlaying of Bouguer contour (CI= 5 mGal) on geological map of northern Botswana (modified after Botswana Geology Map, 2000).........................................................21

Figure 3.1 AMMP grid data coverage of the study area...................................................................23

Figure 3.2 Coordinate axes in the space and frequency domains showing the two dimensional continuous function and its continuous spectrum. .............................................................25

Figure 3.3 Different gravity data distribution from various data sets ..............................................26

Figure 3.4 2-D power spectrum from different potential field data sets.........................................27

Figure 3.5 2-D power spectrum of the 1998-1999 gravity survey ..................................................29

Figure 3.6 The map shows the subtracted gridding results............................................................30

Figure 3.7 Radially averaged spectrum from various geophysical data sets over the study area.....31

Figure 3.8 Gravity lineament interpretation reveals more clearly the presence of lineament patterns 33

Figure 3.9 Radially averaged spectrum from various geophysical data sets over the study area. ......31

Figure 3.10 Subtracting the 1972-1973 grid from the 1998-1999 grid gives the anomaly value in range between –37 mGal to +24 mGal..........................................................17

Figure 4.1 The bivariate distribution of magnetic susceptibilities plot..............................................38

Figure 4.2 Colour scheme for generating apparent physical property map (a) described colour for apparent magnetic susceptibility (b) described colour for apparent density (c) colour composite of apparent physical property map.................................................................40

Figure 4.3 (a) The filtered map after applying low pass filter to AMMP grid data with low pass wave number cut-off = 0.00002 cycles/m (b) Its radially average spectrum was changed and coincided with the radially averaged spectrum of gravity.........................................................................41

Figure 4.4 Calculated apparent physical property maps.................................................................43

Figure 4.5 Calculated apparent density map..................................................................................45
Figure 4.6 A final apparent physical property map combined colour composite map from apparent
density and apparent magnetic susceptibility. The study area consists mostly of high magnetic
susceptibility (colour in blue-magenta-red) with varying in density materials.........................46
Figure 4.7 Outline of rock unit over the study area classified by group....................................47
Figure 4.8 Final apparent physical property map ......................................................................48
Figure 4.9 (a) Yellow colour consists mainly of rock unit RB which is bordered by rock unit QM to
the west and rock unit WC to the right respectively. .................................................................50
Figure 4.10 Final interpretation map showing regional geology over the study area. The gravity
lineament interpretation obtained from figure 3.8 (b) are superimposed on the map. The green
dash colour represents the assumption of a dolerite dyke occurred in this zone .......................52
Figure 4.11 Regional geology over the study area (Thomas, et. al., 1993) overlain by the final
apparent physical property map.. .............................................................................................53
List of tables

Table 1.1  Major pre-Karoo tectonic terranes and major mafic complexes as a reference to Figure 1.2 c (modified after Key and Ayres, 2000)........................................................................................................................................5
Table 2.1  Grid projection specifications .................................................................................................................10
Table 2.2  Descriptions of Bouguer anomaly zone based on gravity pattern..............................................................12
Table 2.3  The range of densities of major rock groups in Botswana (modified after McMullan et al., 1995).............................................................................................................................................14
Table 2.4  Improvement features obtained in the 1998-1999 gravity survey..............................................................15
Table 2.5  The summary statistics of the Bouguer anomaly and elevation values for all stations of gravity surveys in Botswana........................................................................................................................................18
Table 2.6  Calculated spacing ratio results between the two surveys, Spacing ratio= Area / (No. stations) × (Spacing)^2 . ................................................................................................................................................19
1. Introduction

1.1. Research questions

The research deals with the northern portion of Botswana as outlined by the gravity survey carried out in 1998-1999 (Figure 1.1). The main objective is to use these gravity data to improve geological interpretation in the region. Answers to the following research questions were sought:

- What is the subsurface structure of the basement in the study area?
- What is its relation to known geology?

1.2. Background

Geophysical techniques measure physical phenomena to provide information about the properties of the earth. The measurements are usually defined in terms of anomalies relative to a background. The gravity method of geophysical surveys involves measuring the earth’s gravitational field at specific locations on the earth’s surface to determine the location of subsurface density variations which are caused by some rocks having a greater or lesser density than others. The main objective of the new regional gravity survey in the study area was to improve the geological understanding of a region almost totally devoid of basement outcrop.

Gravity station locations are, in general, irregularly distributed mainly due to the access problem. This inevitably results in interpolation errors in the computation of a regular grid from the random data point distribution. To understand the limitations of gravity data, the affect of spatial data distribution on accuracy and resolution must be fully understood.

A gravity survey carried out in 1972-1973 (Reeves and Hutchins, 1976) gave an overall density of 37 gravity stations per 100 kilometer square for the country of Botswana as a whole. Most of the data were obtained along the available tracks with an accuracy of $\pm 1$ km in latitude, $\pm 5$ m in altitude, and $\pm 0.05$ mGal in gravity measurement respectively. However, areas of total land inaccessibility in the north of the country and of limited accessibility in other areas were not fully covered.

In subsequent years, the data distribution has been much improved, except in northern part of the country. A detailed gravity survey was carried out over almost all of northern Botswana during 1998-1999 (Poseidon Geophysics, 1999). Improvements in data quality associated with precise positioning using differential GPS have led to significant improvements in the quality of gravity data coverage. A total of 4003 gravity stations on a 7.5 km grid were established with an accuracy of better than $\pm 10$ m in position, $\pm 0.15$ m in altitude, and $\pm 0.03$ mGal in gravity measurement.
Figure 1.1 Gravity data locations of Botswana from various sources. The recent gravity survey is outlined by the polygon over almost all the northern part of Botswana. The geographical boundaries of the study area are defined between the following coordinates: 20°59' E and 27°43' E longitude and 17°50' S and 22°34' S latitude. The gravity obtained in 1972-1973 is represented by cross symbols.
1.3. Location

The research deals with the northern portion of Botswana. The country is land-locked in the center of the Southern African plateau and shares its borders with Zimbabwe, South Africa, Namibia and Zambia. Much of the country is flat and the mean altitude above sea level is approximately 1000 meters (Thomas and Shaw, 1991).

1.4. Problem statement

Some preliminary geophysical data of Botswana has already been used with encouraging results (McMullan et al., 1995; Poseidon Geophysics, 1999) but more extensive surveys are an absolute necessity. The geophysical data has served to improve the knowledge of the geological structure which could result in the better understanding of the regional geology and hence its mineral potential.

So far, no comprehensive study of all available information has been undertaken that would enable a regional analysis of the gravity survey for the structural and stratigraphical framework of northern Botswana. The data distribution of the recent gravity survey is considered generally good. Considering its accuracy in both position and gravity, areas where the gravity field was previous under sampled have been improved.

1.5. Tectonic and geological setting in northern Botswana

Botswana's geological framework is characterised by considerable diversity and complexity both of which are imperfectly understood. The country contains significant elements of the major tectonic, magmatic, metamorphic and sedimentary terranes present in southern African. The geological record spans from the Archaean to Recent and virtually all the rocks within Botswana have continuity or correlatives with those in neighbouring countries (Figure 1.2).

Parts of the continent stabilised during the Archaean through a series of complex tectonic, magmatic, sedimentary and metamorphic events. The Zimbabwean and Kaapvaal Cratons are characterised by granite and greenstone rock formations. They are separated by the Proterozoic Limpopo Mobile Belt (Key and Ayres, 2000). Major crustal sedimentation took place at the beginning of the Proterozoic. In the Paleozoic and Mesozoic, further deposition of sediments took place. Widespread and vast outpouring of continental basaltic magma also occurred at 180±2 Ma (Reeves, 2000). A summary of major tectonic terranes and major mafic complexes of northern Botswana are presented in Table 1.1.

1.5.1. Precambrian basement complex

Surface exposures of Precambrian rocks are limited. Though the precise stratigraphical affinities are often doubtful, the Precambrian geology in the study area can be considered to comprise two areas of basement of platform rocks which are the eastern zone of very ancient Archean cratonic rocks and the northwestern zone of Proterozoic rocks. They are separated by the southwest-northeast trending part of the Kalahari suture zone. It is a major bounding fault on the southeast side of the northwest Botswana rift. However, the nature and location of the original northwestern margin of the rift is unknown due to the effects of the younger Damaran orogenesis (Thomas and Shaw, 1991, Key and Ayres, 2000).
a) Crustal architecture of southern Africa.

b) The major Precambrian tectonic terranes of southern Africa.

c) The major pre-Karoo tectonic terranes and major mafic complexes in Botswana (see Table 1.1 for index)
Figure 1.2 Various published attempts at a generalized tectonic framework of southern Africa
(a) Thomas et al., 1993 (b) and (c) Key and Ayres, 2000.

The Kalahari suture zone is part of the Paleoproterozoic Kheis belt that extends from South Africa to southern Botswana. It eventually continues to the northeast and extends into the Magondi belt of western Zimbabwe. The most significant downthrow along this zone appears to have taken place during the Neoproterozoic and earliest Paleozoic times as there is a major basin of these ages to its west. The Passarge basin is infilled with Neoproterozoic Ghanzi group strata with a total thickness of about 10 km (Key and Ayres, 2000). To the northwest of the Damaran belt there is a terrane with a pronounced north-northwest to north trending based on the detailed airborne magnetic data from Ngamiland. It is possible that these features, which are due to folded metasedimentary rocks, form a cover sequence over the southern tip of the Archean Congo craton (Key and Ayres, 2000)

Table 1.1 Major pre-Karoo tectonic terranes and major mafic complexes as a reference to Figure 1.2 (modified after Key and Ayres, 2000)

<table>
<thead>
<tr>
<th>Period</th>
<th>Geological representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neoproterozoic</td>
<td>9a, Passarge basin</td>
</tr>
<tr>
<td></td>
<td>8, Kihabe complex</td>
</tr>
<tr>
<td></td>
<td>7a, Kwando complex</td>
</tr>
<tr>
<td></td>
<td>7, Ghanzi-Chobe belt</td>
</tr>
<tr>
<td>Mesoproterozoic</td>
<td>6, NW Botswana belt</td>
</tr>
<tr>
<td>Paleoproterozoic terrane</td>
<td>5b, Gweta belt/Magondi belt</td>
</tr>
<tr>
<td></td>
<td>5a, Mahalapye belt</td>
</tr>
<tr>
<td>Achean terrane</td>
<td>4, Congo craton</td>
</tr>
<tr>
<td></td>
<td>2/3, Plate boundary zone between Limpopo belt and Zimbabwe craton</td>
</tr>
<tr>
<td></td>
<td>3, Limpopo belt</td>
</tr>
<tr>
<td></td>
<td>2, Zimbabwe craton</td>
</tr>
<tr>
<td></td>
<td>1, Kaavaal craton</td>
</tr>
<tr>
<td>unknown</td>
<td>R, Rakops</td>
</tr>
</tbody>
</table>

Parts of Archean geology of the Zimbabwe Craton, and less extensively, the Kaapvaal craton lying in the east of the study area are made up of a number of rock units. There appears to be a gross stratigraphy with a sequence of migmatites and associated porphyritic granites underlying the Tati-Vumba greenstone belts that are in turn overlain by layered gneisses. The Matsitama greenstone belt and the surrounding granitoid rocks are Archean in age and placed within the western zone of the Limpopo belt (Aldiss, 1991). The northern margin of the Kaapvaal craton in Botswana is partly defined by the Paleoproterozoic Mahalapye complex, a magmatic complex whose trends are inherited from the gneissic country rocks of the southern marginal zone of the Limpopo Mobile Belt (Key and Ayres, 2000)
1.5.2 Limpopo Mobile Belt

The Limpopo Mobile Belt is a northeast-southwest-trending zone of originally thickened Archean crust. The belt is situated between the Zimbabwean craton to the north and the Kaapvaal Craton to the south. It is made up of four distinct domains (Key and Ayres, 2000). These domains are a western, northern marginal, central and southern marginal zone. The lithological units are essentially the same lithologies as identified on the Zimbabwe craton. However, the northern marginal zone does not extend into Botswana. Within the mobile belt, all the differentiated lithologies are intensely deformed with their distribution reflecting the principal structural trends (Majaule, et. al., 2001; Key and Ayres, 2000). An overview of general rock types in Botswana is illustrated in Figure 1.3

1.6 Research objectives

2. To interpret anomalies as a result of the presence of geological structure.
3. To determine the geometry of geological contacts at depth.
4. Joint interpretation of gravity and aeromagnetic data of similar resolution and the identifications of rock units from the two different rock properties, namely, density, and magnetisation.

1.7 Research methodology

The procedures adopted are summarised as the following (Figure 1.4)

1. Review relevant published scientific research literature on both the geological framework of the study area and geophysical techniques in general and then finalize research plans such that it builds upon prior knowledge.
2. Analyse the data: Geosoft OASIS® is used for gravity and aeromagnetic data analysis especially in performing the FFT on the data set; ILWIS® and ArcView® are used for interchanging different data formats; and Grapher® is used for statistical data analysis.
3. Create Bouguer anomaly maps from different gravity data sets and make recommendations on the effect of data distribution on the gridding.
4. Use enhancement techniques, e.g. shaded relief, to extract features of the dominant structure/lineament trends from Bouguer anomaly map. Confirm new findings by comparison with existing geological map (Botswana Geology Map, 2000).
5. To estimate the depth distribution of the gravity sources from the radially averaged power spectrum and diagnostic the data quality from 2-D power spectrum (Billings and Richards, 2000). In order to get the most beneficial interpretation, aeromagnetic data coverage of the study area with a similar grid resolution will be introduced and studied at this stage.
6. Use the grid colour composite method to present the apparent density and magnetic susceptibility data in one map. A colour table will be attached to each of the two data sets and assigned by varying colours with respect to the calculated physical properties value in each map. The combination of these colours from two derived maps will give new colour categories and the possibility of physical property mapping which might correspond to a geological map (Everaerts, 1990).
7. Qualitative Interpretation of all results.

1.6 Structure of the thesis

The thesis comprises six interrelated chapters. The following is a description of the chapter contents. Chapter 1 is an introduction to the study program, and give a summary of the tectonic and geological setting of the study area.

Chapter 2 Comments on different gravity surveys between 1972-1973 gravity data and the recent data are described.

Chapter 3 combines analysis of Bouguer anomaly and total magnetic intensity by using the radially average spectrum and 2-D power spectrum techniques. The gridding analysis is described in detail.

Chapter 4 introduces the grid color composite techniques and the results of its mapping and analyzing the pattern of apparent physical property map, new geological map with respect to basement geology over the study area is presented.

Chapter 5, discussion of all results.

In Chapter 6, general conclusions and recommendations are presented.
Figure 1.4 Operation flow chart of the research
2. Background to gravity surveys

2.1. Station distribution

A field survey was undertaken during 1998-1999 to fill gaps in existing gravity data coverage in almost all northern part of Botswana. Locations were determined using dual-frequency Global Positioning System (GPS) units and differential measurements. The 4002 new gravity data points of the study area at stations on an approximately 7.5 km grid were compared with previously collected data in 1972-1973 gravity survey to check the integrity of the new data and to develop a better regional view of the regional geology in this region.

A gravity survey obtained in 1972-1973 (Reeves and Hutchins, 1976) gave an overall density of 37 gravity stations per 100 km² for the country of Botswana as a whole. Most of the data were collected along the available tracks with an evenly spaced about 10 km apart. However, areas of total land inaccessibility in the north of the country, and of limited accessibility in other areas were not fully covered.

The broad scale surveying of the country with an observation spacing of 7 to 10 km could be justified by the need to define the tectonic structure of the continent and to determine the size and extent of the major tectonic units. Surveys designed to solve geological problems should contain sections of various station spacing. Gravity survey should take into consideration some parameters that affect the accuracy and resolution of gravity, for example, the interpolation of the gravity field between stations and geological noise due to near surface density variations and deep regional discontinuities. The size and depth of the target bodies will determine the optimum observation spacing for the gravity survey. Sampling theory indicates that the observation spacing should be closer than half the wavelength of the anomaly (Telford et al., 1990).

2.2. Gravity data reduction of 1998-1999 survey

The observed gravity reading is corrected for instrument drift, tidal effects, latitude, and heights. Field procedures for monitoring the accuracy of corrected observed gravity reading were systematically repeated over the duration of the survey. GPS measurements and gravity observations were reduced to the World Geodetic System 1984 (WGS84) datum and transformed to the Clarke 1880 (Modified) datum. Bouguer gravity anomalies were calculated using the 1967 International Gravity Formula using a mean crustal rock density of 2.67 g/cc (Poseidon Geophysics, 1999);

Theoretical Gravity (GRS67): \( g = 978 \, 031.846 \left( 1 + 0.005 \, 278 \, 895 \, \sin^2 \phi + 0.000 \, 023 \, 462 \, \sin^4 \phi \right) \) mGal

Free Air Gravity \( g_{FA} = g_{OBS} - g + 0.3086h \) mGal

Bouguer Gravity \( g_B = g_{OBS} - g + 0.3086h - 0.04192 \rho h \) mGal

where : \( g_{OBS} \) is observed gravity, \( \phi \) is latitude, \( h \) is height (m), and \( \rho \) is density (t/m³)
The reduced data is interpolated to a square grid using a minimum curvature algorithm. A grid cell size of 2.5 km was used to create a spatial map display of the gravity data. Although the terrain of Botswana is comparatively flat, there are some areas in the eastern part of the country which exhibit considerable relief (Figure 2.1). The Kalahari and Karoo escarpment north of Serowe was selected to estimate the magnitude of the terrain correction. In this area the elevation drops from 1230 m to about 970 m in a distance of approximately 22 km. Using the standard Hammer Chart, the total terrain correction for perhaps the highest relief area in Botswana is less than 0.001 mGal. Therefore no terrain corrections were applied to the gravity data acquired during the regional survey of northern Botswana (Poseidon Geophysics, 1999). The parameters for generating maps are listed in Table 2.1.

<table>
<thead>
<tr>
<th>Ellipsoid</th>
<th>Clarke 1880 (Arc)</th>
<th>Projection : Transverse Mercator (UTM zone 34)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equatorial Radius</td>
<td>(a=6,378,249.1)</td>
<td>Central Meridian</td>
</tr>
<tr>
<td>Polar radius</td>
<td>(b=6,356,514.9)</td>
<td>21° East</td>
</tr>
<tr>
<td>Ellipticity</td>
<td>(e=0.08248326)</td>
<td>Base Parallel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0° (Equator)</td>
</tr>
<tr>
<td>False Easting</td>
<td>500,000 m</td>
<td>False Northing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10,000,000 m</td>
</tr>
</tbody>
</table>

The spacing between the samples may be adequate to record large wavelengths, but it may not be close enough to record short wavelengths. Only wavelengths which are longer than twice the sampling interval can be reliably recorded (Macleod, 1986). This spatial frequency is called the Nyquist frequency. If the frequencies in the sampled field are greater than the Nyquist frequency, then they cannot be reliably recorded. Errors will be introduced in frequencies lower than the Nyquist frequency by a process called aliasing. In the study, all maps were generated with a grid cell size of 2.5 km. In this case 1/3rd of the station interval was used (7.5/3=2.5 km). The observed values at each stations were interpolated to a square grid using a minimum curvature algorithm routine. The gridding algorithm calculates grid points weighted on a nearest neighbour search pattern, which expands to a maximum of eight times the grid cell size (20 km). If no observation points are within the search radius, no grid value is calculated for that point. Blanking distance of 50 km was also decided to fill in the gap area on the map. This parameter should be set to just greater than the maximum sampling interval through which interpolation is desired.

### 2.3. The Bouguer anomaly pattern

The dominant characteristic of the gravity map (Figure 2.2 a) is the elongate or linear aspect of the anomalies which run in a northeast-southwest trend. In many regions, anomalies of similar trend from patterns that characterize the area. In the northwest part of the study area, a distinct feature is a continuous narrow high that nearly encircles the area on the NW part of the map to the others. In much of the central part of the study area the anomaly trends and shapes are variable, but they form
Figure 2.1 (a) An elevation map obtained from the recent gravity survey shows remarkable number of geomorphological features in the study area, indicating a northeast-southwest trending across the Okavango delta. (b) Bouguer anomaly map of 1998-1999 survey.
consistent patterns. The most prominent of these patterns over the region are the linear lows and highs that trend in northeast-southwest. A most notable feature in the easternmost portion is a clear strong anomaly, the pattern is considered to be a trending in WNW-ESE direction with a width of about 5 km and length of about 8 km. Description of the anomaly patterns of the study have been compiled in table 2.1

**Table 2.2** Descriptions of Bouguer anomaly zone based on gravity pattern

<table>
<thead>
<tr>
<th>Zone</th>
<th>Anomaly characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Most dominant pattern of map; generally WNW-ESE continuous trending, probably include several tectonic events, three region of strong amplitude are indicated in this zone</td>
</tr>
<tr>
<td>B</td>
<td>The outstanding features with northerly continuous trend of high amplitude lying between zone A and zone C, high amplitude anomalies are also marked in this zone</td>
</tr>
<tr>
<td>C</td>
<td>Zone of broad northerly trending; alternating moderate to low amplitude</td>
</tr>
<tr>
<td>D</td>
<td>No notable dominant trend, broad anomalies of low amplitude, anomalies broader than those in zone C</td>
</tr>
<tr>
<td>E</td>
<td>Broad anomalies of moderate; trending is indicated NE-SW</td>
</tr>
<tr>
<td>F</td>
<td>Zone of broad, irregular shaped anomalies of diverse trend with moderate amplitude, overprinted by pattern of many small anomalies</td>
</tr>
<tr>
<td>G</td>
<td>Zone dominated by broad, irregular shaped anomalies of generally NE-SW trend, moderate to high amplitude, include a small zone of almost circular pattern with low amplitude</td>
</tr>
<tr>
<td>H</td>
<td>Narrow anomalies of low amplitude with dominant NE-SW trend</td>
</tr>
<tr>
<td>I</td>
<td>Zone of broad, irregular shaped anomalies of generally NW-SE trend</td>
</tr>
<tr>
<td>J</td>
<td>Large, irregular zone with diversity of anomaly amplitude with general NW-SE trend, probably include several sub-zones</td>
</tr>
<tr>
<td>K</td>
<td>Small zone of low to moderate amplitude situated on the north</td>
</tr>
<tr>
<td>L</td>
<td>Zone of broad anomaly located on the most eastern part, moderate amplitude, smooth intensity, trending is not clearly identified, two zone of low and high amplitude are included</td>
</tr>
<tr>
<td>M</td>
<td>Small zone of moderate to high amplitude connected to zone L</td>
</tr>
</tbody>
</table>

The overall range of Bouguer anomaly in northern Botswana is -154 to -64 mGal, all negative. The major rock groups in Botswana have varying densities ranging from Kalahari beds with a density of 2.26 g/cm³ to Archean basement with densities in excess of 3.00 g/cm³.

Typical rock densities are available from a variety of sources. The maximum density contrast between adjacent sedimentary formation is generally less than 0.25 g/cm³, between igneous rocks it can be as much as 1.4 g/cm³, while for metamorphic rocks it is 1.2 g/cm³ (Keating, 1995). According to the densities of major rock groups in Botswana (table 2.3), distinct Bouguer anomaly maximum in the study area is caused by greenstones that associated with Archaean basement which is located on the eastern part of the study area. Small areas of Bouguer anomaly minima, such in zone G and F, are probably caused by intrusive rocks such as granite.
Figure 2.2 (a) 1998-1999 Bouguer anomaly map with contour interval 2 mGal (b) The classified zones of (a) which are described in Table 2.2 (b)
Table 2.3 The range of densities of major rock groups in Botswana (modified after McMullan et al., 1995)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Range g/cm³</th>
<th>Average g/cm³</th>
<th>Standard deviation</th>
<th>No. of points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalahari beds</td>
<td>1.82-2.53</td>
<td>2.26</td>
<td>0.227</td>
<td>10</td>
</tr>
<tr>
<td>Stormberg basalts</td>
<td>2.23-2.86</td>
<td>2.62</td>
<td>0.140</td>
<td>76</td>
</tr>
<tr>
<td>Dolerite</td>
<td>2.75-2.88</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Waterberg</td>
<td>2.70</td>
<td>-</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>Ghanzi Group</td>
<td>2.57-2.69</td>
<td>2.64</td>
<td>0.054</td>
<td>54</td>
</tr>
<tr>
<td>Toteng diabase</td>
<td>2.75-3.02</td>
<td>2.95</td>
<td>0.069</td>
<td>12</td>
</tr>
<tr>
<td>Kgwebe porphyry</td>
<td>2.63-3.02</td>
<td>2.76</td>
<td>0.182</td>
<td>11</td>
</tr>
<tr>
<td>Tati schist belt</td>
<td>2.65-2.96</td>
<td>2.77</td>
<td>0.149</td>
<td>12</td>
</tr>
<tr>
<td>Precambrian metamafics</td>
<td>2.71-3.08</td>
<td>-</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Precambrian gneiss</td>
<td>2.64-2.65</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Karoo clastic sediments</td>
<td>1.90-2.64</td>
<td>2.40</td>
<td>0.19</td>
<td>203</td>
</tr>
<tr>
<td>Proterozoic basement</td>
<td>2.48-2.93</td>
<td>2.72</td>
<td>0.112</td>
<td>19</td>
</tr>
<tr>
<td>Archaean basement</td>
<td>2.54-3.14</td>
<td>-</td>
<td>-</td>
<td>280</td>
</tr>
</tbody>
</table>

In the geologically better-known eastern parts of Botswana the denser rock of the isolated greenstone belts produce local positive anomalies (Reeves and Hutchins, 1976). They are characterized by a layered heterogeneous assemblage of metasedimentary and metavolcanic rocks. The Matsitama anomaly extends westwards from the area of Precambrian outcrop to an area where basement rocks are concealed by Karoo and Kalahari sediments.

The gravity high of particular interest is the large body that is located on the easternmost portion of zone A. It is probably indicates the continuity of the Matsitama greenstone belt into Botswana as remarked by Reeves (1976). An overall of zone A, when traced weswards into Botswana, dies out near Maun around the Okavango area. This Bouguer anomaly pattern seems to be consistent with the termination of the Mobile belt rather than an extension westwards to intersect the Damaran belt.

In the central part of study area a number of features on the Bouguer anomaly map with NE-SW trend seems to characterize the central basin. Their western and eastern limits may possibly be defined by zone B and eastern part of zone A respectively.

2.4. A comparison of 1973 and 1999 gravity survey result

The 1973 and 1999 reduced gravity values and elevation heights are shown in Table 2.4. It can be seen from the table that an accuracy in positions and elevation heights has being improved in 1999 gravity data. The accuracy of differential GPS used in this survey is to ±100 m horizontal and ±0.15 m vertical, which is sufficient for the sensitivity of gravity instrument.
Figure 2.3 is presenting the comparison between Bouguer anomaly map obtained from 1998-1999 survey and 1972-1973 gravity survey respectively. Circled area 1 and 5 on the maps represent similar pattern as observed in both gravity maps (table 2.4). Theses pattern reflect the responding of long wavelength in the study area. The width of theses anomaly are greater than 100 km. However, there are a number of improvement features have been better defined by the 1998-1999 gravity survey over the previous survey in 1972-1973. Shapes of the anomaly obtained in 1972-1973 are generally limited by their gravity station patterns, for example, anomaly pattern represented in area 3 is in good agreement with their orientation along the gravity stations trend.

**Table 2.4 Improvement features obtained in the 1998-1999 gravity survey**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High amplitude, irregular shape</td>
<td>High amplitude, irregular shape</td>
</tr>
<tr>
<td>2</td>
<td>Low amplitude, not clearly identified</td>
<td>Low magnitude showing NW-SE trend</td>
</tr>
<tr>
<td></td>
<td>trending</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Two elongated bodies</td>
<td>Irregular shaped anomalies of diverse trend</td>
</tr>
<tr>
<td>4</td>
<td>High amplitude, circular in shape</td>
<td>Continuous high amplitude trend across NW part</td>
</tr>
<tr>
<td>5</td>
<td>Broad anomalies of low amplitude</td>
<td>Broad anomalies of low amplitude</td>
</tr>
<tr>
<td>6</td>
<td>Circular in shape</td>
<td>Irregular shaped anomalies of generally NE-SW trend</td>
</tr>
<tr>
<td>7</td>
<td>High amplitude, circular in shape</td>
<td>Lack of data, however, trending show NE-SW</td>
</tr>
</tbody>
</table>

Gravity data contain broad information, each reading includes the effects due to both deep and shallow sources which produce a response at point of measurement. By subtracting 1998-1999 grid data from 1972-1973 gravity grid, the grid result show information with close to the responses of the shallow sources and can also imply area that lack of information from the previous data set but has being improved in the 1998-1999 gravity survey. The differences between the two Bouguer anomaly maps are illustrated in Figure 2.4 (b)
Figure 2.3 (a) 1998-1999 Bouguer anomaly map (b) 1972-1973 Bouguer anomaly map. Their gravity stations distribution are also displayed in each map.
Figure 2.4 (a) Data distribution comparison between the 1972-1973 (x) and 1998-1999 (+) gravity survey. (b) The subtracted grid results between 1972-1973 gravity grid and 1998-1999 gravity grid give the anomaly value in range between –37 mGal to +24 mGal.
Table 2.5 The summary statistics of the Bouguer anomaly and elevation values for all stations of gravity surveys in Botswana.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of stations</td>
<td>890</td>
<td>4002</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latitude</td>
<td>±1 km</td>
<td>Better than ±10 m</td>
</tr>
<tr>
<td>Altitude</td>
<td>±5 m</td>
<td>±0.15 m</td>
</tr>
<tr>
<td>Gravity reading</td>
<td>±0.05 mGgal</td>
<td>±0.03 mGal</td>
</tr>
<tr>
<td><strong>Gravity (mGgal)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>-151.80</td>
<td>-154.35</td>
</tr>
<tr>
<td>Maximum</td>
<td>-64.90</td>
<td>-63.52</td>
</tr>
<tr>
<td>Mean</td>
<td>-107.59</td>
<td>-110.53</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>14.04</td>
<td>14.49</td>
</tr>
<tr>
<td><strong>Elevation (m)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>876.7</td>
<td>900.94</td>
</tr>
<tr>
<td>Maximum</td>
<td>1307.7</td>
<td>1352.95</td>
</tr>
<tr>
<td>Mean</td>
<td>991.8</td>
<td>998.84</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>76.7</td>
<td>74.42</td>
</tr>
</tbody>
</table>

**the gravity stations in study area which cover almost all northern part of the country.**

The significance feature presented on the western part of the map (Figure 2.4 a) looks like pattern in Bouguer gravity map obtained in 1998-1999 survey. The subtracted grid result shows similar patterns as in the 1998-1999 gravity map. These patterns seem to be the features that being enhanced by new gravity data set.

The error is small in area of high density data and maximum in area that lack of measurements. The map shows the maximum anomaly that may have gone undetected by this particular set of gravity stations.

In regional surveys, observation density or station spacing is often calculated from the area to be covered divided by the number of stations that can be afforded. When planning the station spacing, consideration should be given to the existing anomaly pattern.

The benefit of grid survey can be seen from Figure 2.5. The effective width of the body that can be detected from the diagram is 3.75 km (7.5 km × sin [30°]) This value is equal to half of the station spacing (7.5/2= 3.75 km). Therefore, with adequate data sampling grid in 1998-1999 gravity survey it can define shape of anomaly to be better than that in 1972-1973 gravity survey. However, surveys designed to solve geological problems should contain sections of various station spacing. If we are looking for a circular body then the station spacing should be critical not the orientation of the survey.
Figure 2.5 Conceptual diagram of grid survey design

It is notably to pay attention in the data distribution differences (Figure 2.4 b) of these two gravity surveys in terms of spacing ratio. Generally, the task of carrying out a gravity survey is to decide the survey plan and get the best value from each observation point and try to maintain a spacing ratio of 1. This value is calculated based on square grid format (Barritt and Reeves, 1997). The calculation of the spacing ratio over the study area in northern Botswana from the two surveys are presented in Table 2.5.

Table 2.6 Calculated spacing ratio results between the two surveys, Spacing ratio = Area / (No. stations) × (Spacing)^2.

<table>
<thead>
<tr>
<th>Gravity survey</th>
<th>Area (km)^2</th>
<th>No. stations</th>
<th>Station spacing (km)</th>
<th>Spacing ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972-1973</td>
<td>377175</td>
<td>890</td>
<td>10</td>
<td>4.2</td>
</tr>
<tr>
<td>1998-1999</td>
<td>377175</td>
<td>4002</td>
<td>7.5</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Typically, a network of gravity observation stations is far from the ideal square grid format, however, the 1972-1973 gravity survey provides a compromise survey with evenly spaced data but there are still lack of data coverage with a great distance especially in the western and upper central part of the study area. It is clearly to see that spacing ratio within the same area, 1998-1999 gravity survey gives better spacing ratio than the previous survey.
2.5. Summary and Discussions

In this study, large scale features are of the most interest to distinguish the boundaries of various terranes.

1. The anomaly was not closely defined by the widely spaced of 1972-1973 gravity survey but the presence of a significant anomaly is indisputable present in the 1998-1999 gravity survey. Improvements in data quality associated with precise positioning using differential GPS have lead to improvements in the quality of gravity data. The gravity survey in 1998-1999 provides better details of shorter wavelength features and also defines Bouguer anomaly pattern better than that presented in the 1972-1973 gravity survey, such as Bouguer anomaly zone B and zone J in figure 2.2

2. General rock types over the study are shown on the map (Figure 2.6). To the east is an area of metamorphic rocks. Most of the oldest rocks are exposed in this area where two Archean terranes are recognised; Zimbabwe craton and western part of Limpopo mobile belt. In the northwest is an area of complex geology consisting of metamorphic, igneous, and sedimentary rock. Apart from that Karoo basalt is interpreted to cover most of middle part of the map. The study has revealed a number of features beneath the extensive Karoo sediment such as A, F and B. It also indicated that Archean greenstone rocks which are exposed in the eastern part of the study area extend westward beneath the Karoo sediments.

3. A set of anomaly characteristics have been used based on those described in the previous section to delineate the crust into a series of zones. The first and most important characteristics is trend, because it indicates the direction of density discontinuities, which should be controlled by lithology. Subsequently is a combination of anomaly wavelength and relative anomaly amplitude, which indicates lateral extent of source and some combination of density contrast. Consequently is anomaly scatter or noise which indicates lack of large uniform sources of singular density. The major structural feature in Bouguer anomaly map is lying in NE-SW direction as appeared in geological map.
Figure 0.1 The overlaying of Bouguer contour (CI= 5 mGal) on geological map of northern Botswana (modified after Botswana Geology Map, 2000). As can be observed from the geological map the 1998-1999 gravity survey reveals interesting features beneath the extensive cover of Karoo sediments. As an instance, from right to left across the map parts of zone A are located on the exposed Archaean outcrop indicating its extension into Botswana. While zone F indicates anomalous body underlain the Karoo basalt in the middle of the map defined by irregular shape. The prominent arcuate feature of zone B occurs along the western part of the study area.
3. Grid data analysis and Image processing

3.1. AMMP grid data

Typically the product used for interpretation is the gridded image. Many gridded images of geophysical data include artefacts of anomalies. This distorts the anomaly shapes and patterns used to interpret the data as well as introducing (or removing) power at frequencies, which may be important for further processing. Some of the features may be due to poor data quality, inappropriate choice of survey parameters, poor gridding algorithms or inappropriate choice of the parameters used by the gridding algorithm (Billings and Richards, 2000).

The African Magnetic Mapping Project (AMMP) grid data which is available at a 1.0 km grid cell size and a 1.0 km terrain clearance (Barritt, 1993) was resampled to 2.5 km grid to make comparisons with similar grid cell size to Bouguer anomaly map. Figure 3.1 shows the magnetic data coverage of the study area in the AMMP data set. There is a swarm of closely spaced dykes, named the post-Karoo dyke swarm, crossing the study area on a strike of approximately N110°E (Reeves, 1978). These magnetic data revealed the post-Karoo dyke swarm. The known geological information shows that the rock type of these dykes is dolerite and the depth of these dykes is about 100 m, as the base of the Kalahari sand cover.

Notice on figure 3.1, although the character of the gravity map is somewhat different from the magnetic map but there are some excellent correlations between the magnetic and gravity maps, for example the prominent pattern of gravity zone B (figure 2.2) which moderate to high magnitude coincides with continuous pattern of low to moderate intensity magnetic. The circular shape of low density contrast zone G (figure 2.2) match with the outline of high magnetic intensity. However, most part on magnetic map are obscured by high intensity of the swarm dyke such as the distinct gravity pattern zone A (figure 2.2) located in the eastern part of the map.

3.2. Grid data quality and data gridding

The fast Fourier transform (FFT) suggest itself for quality control because it converts the grid from spatial domain to the frequency domain where certain problems within the data become more obvious. Grid distortion caused by differing sampling density would result in an elongated power spectrum. (Billings and Richards, 2000)

The initial aim of this section was to begin to establish some guidelines to help ensure the best possible quality of gridded data, and to investigate and document the possible use of the two dimensional FFT as a tool for diagnosing problems in gridded datasets. Fourier transforms are usually displayed as 2-D
Figure 3.1 AMMP grid data coverage of the study area. Notice the prominent pattern of the swarm of dykes run across the study area with the strike of 110° degree. The colour image generated from an artificial illumination source azimuth 45 degree and inclination 45 degree respectively. The Bouguer anomaly with contour interval of 10 mGal are overlain on the magnetic image.

Power spectra with a logarithmic scale applied to the data. The power spectrum reflects the strength of the sine and cosine components at each frequency. The reason it is displayed with a logarithmic scale is that there is a huge variation in the amplitudes of the different spectral components.

The FFT estimates Fourier components between zero frequency and the Nyquist limit imposed by the grid cell size. In the data sets used here, the maximum frequency is 0.2 cycle/km (spatial wavelength 5 km) corresponding to a pixel size of 2.5 km.

The term aliasing and Nyquist frequency are often used to describe problems and limitations in gridded data sets. The Nyquist frequency is the highest frequency (shortest wavelength) that is possible to measure given a fixed sample interval. It is defined by the expression (Clement, 1972; Billings and Richards, 2000; Geosoft, 1998);
\[ N = \frac{1}{(2\Delta x)} \] where \( \Delta x \) is the sample interval

Aliasing results when the actual data that is being sampled contains significant information that has a short wavelength (higher frequency) than the Nyquist. An important problem with aliasing phenomena is that you often cannot see the aliasing because it can be hidden by the chance locations of the samples. Inversely, the chance locations of samples can give the appearance of much longer wavelength features than really exist. (Macleod, 1986; Geosoft, 1998)

The Nyquist frequency and the effects of aliasing must be considered at a number of stages in the creation and use of gridded data;

1. The design of surveys should take into account the expected spatial size of information that is measured, and the detail required for the data to be useful. Note that because of aliasing, it may be necessary to sample to a higher density than is required for the interpretation of the data to remove aliased noise from data as part of the gridding process.
2. Pre-gridding filter should be applied to data to remove wavelengths that may be aliased at the chosen grid cells size.
3. The grid cell size must be chosen to sample the required detail in the data.

The program first estimates grid values at the nodes of a coarse grid (usually 8 times the final grid cell size). This estimate is based upon the inverse distance average of the actual data within a specified search radius (weighted average where weight coefficients are calculated from 1/distance from node). If there is no data within that radius, the average of all data points in the grid is used. The same process is then repeated using the coarse grid as the starting surface. This procedure is iterated until the minimum curvature surface is fitted at the final grid cell size. A very important parameter in the process is the number of iterations used to fit the surface at each step. The greater the number of iterations, the closer the final surface will be to a true minimum curvature surface (Geosoft, 2000).

According to the Nyquist theorem, gridded data set are limited in the detail of information that they contain by the Nyquist frequency, i.e. \( 1/(2*(\text{grid cell size})) \), and original survey data is limited in the detail of information that has been measured by \( 1/(2*(\text{station interval})) \). Therefore any information at wavenumbers between 0.0625 cycle/km (data) and 0.2 cycle/km (grid) is ambiguous and is created by interpolation.

### 3.3. Spectral Analysis

Fourier spectral analysis in recent year has become a widely utilized tool for the processing and interpretation of potential field data. Both 2-D power spectrum and radially average power spectrum of all geophysical data sets over the study area with the grid cell size of 2.5 km were calculated and analysed.

#### 3.3.1. 2-D power spectrum

In the analysis of two-dimensional data, frequencies aliasing must be considered when working with sampled data. It is advantageous to consider aliasing in terms of the overlap of the repeating spectra inherent in the finite Fourier transform (Clement, 1972). Figure 3.2 shows the basic principle of two
dimensional plotting between two domains in Fourier transform pairs, space domain and frequency domain. The linear pattern occurred in the space domain will be presented in frequency domain with phase shift $\pi/2$ (Clement, 1972; Zhou, 1992).

Figure 3.2 Coordinate axes in the space and frequency domains showing the two dimensional continuous function and its continuous spectrum with the double arrow indicates a Fourier transform pair (modified after Clement, 1972).

To discover the grid data quality of all gravity and magnetic data sets over the study area with particularly to make comparison with the 1998-1999 gravity survey, the 2-D power spectrum was then analysed. The maximum frequencies represented in the Fourier domain are determined by the spatial grid cells size ($\Delta x$, $\Delta y$) through the Nyquist relationship ($1/2\Delta x$, $1/2\Delta y$). Any frequencies higher than these will be aliased (folded) back into the lower frequency part of the spectrum (Macleod, 1986; Geosoft, 1998). Estimating values at places where there are no observations available requires interpolation from the known observations. However, the control becomes weak when estimates are made at point distant from actual observations, as in the case of the 1972-1973 gravity survey.

The power spectrum has been stretched pink colours correspond to regions of high power, grading through red, yellow, green and then to blue, which represents the lowest power. The very centre of the
Figure 3.3 Different gravity data distribution from various data sets (a) 4,002 gravity stations with 7.5 km spaced grid (b) the 1972-1973 gravity survey with 10 km spacing. The study area is outlined by the polygon.
Figure 3.4 2-D power spectrum from different potential field data sets. The aliasing features have been occurred in (a) and (b) because parts of the country carried out in more detailed spacing (less than 2.5 km grid) (c) AMMP grid data and (d) 1998-1999 gravity data
frequency spectrum represents the average value in the image, frequencies gradually increase as moving away from the centre of the frequency spectrum.

Gravity data of different data sets are shown in Figure 3.3. Two dimensional power spectrum in Figure 3.4 (a) and (b), were generated from 1972-1973 gravity survey. Artefacts are clearly visible in both figures, these features could be artefact due to unevenly distance between gravity station and also due to shorter wavelength that aliasing in the spectrum interpolation and gridding of the algorithm used to generate the FFT transform. The artefacts do not appear in the 1998-1999 grid over the study area in Figure 3.4 (d).

The 2-D power spectrum of magnetic data in figure 3.4 (c) shows a characteristic that manifests itself as a concentration of power along the horizontal frequency axis. Notice that the power spectrum is elongated in the vertical direction which corresponds to the direction of the survey lines. This indicates that there is a lot of power and hence a lot of structure in the image in the vertical direction and reflects the dense along-line sampling. The other feature to note in the power spectrum is the northeast to southwest trending concentrations of power. These correspond to the southeast to northwest trending geological features, dyke swarm, which is not easily seen in Bouguer anomaly (Figure 3.4 d).

There is also another feature in northwest to southeast trending presented in the power spectrum map. It is notably that the magnetic provide strong feature in two dimensional power spectrum map than that presented in gravity.

Apart from minimum curvature gridding, bi-directional gridding is a preferred method for handling line data which is used often in aeromagnetic data, as in AMMP magnetic data, because it has the ability to enhance trends that cross the line direction. Each line of data is first interpolated to determine the data value at the intersection of grid lines, and then each grid line is interpolated to the final nodes of the grid. The result is that even narrow features that continue from lie to line are interpolated correctly. Also, by taking advantage of the fact that line data is already ordered, bi-directional gridding algorithm is faster than minimum curvature techniques (Geosoft, 1998).

Bi-directional gridding assumes that the survey lines are perpendicular to the geological strikes of the survey area. If this assumption is not met, the gridding leads to erratic interpolation in the direction across survey lines. Bi-directional gridding can also allow the gridding direction to be perpendicular to one, but only one, geological strike (Zhou, 1992). The bi-directional gridding was carried out in this study on the recent gravity data by creating an arbitrary survey line running from south to north (figure 3.5 c). Attempts have been tried to find out the difference between the two different gridding methods on same gravity data, 1998-1999 gravity data set as illustrated in Figure 3.6. The result shows higher different in NE-SW direction.

### 3.4. Radially averaged spectrum

Significant insights into the internal earth structure have been obtained from its gravity and magnetic fields, which reflect the way in which density and magnetization are distributed. Since such fields arise from the superposition of a large number of sources of variable size, they can appear similar over
Figure 3.5 2-D power spectrum of the 1998-1999 gravity survey (a) Bi-directional gridding (b) Minimum curvature gridding and (c) An arbitrary line direction in N-S
Figure 3.6 The map shows the subtracted gridding results which have values in range between –5.83 mGal to 4.10 mGal. (b) 2-D power spectrum of the gridding in (a) shows trending in NE-SW and less in WNW-ESE trending.
Figure 3.7 Radially averaged spectrum from various geophysical data sets over the study area. (a) The 1998-1999 gravity survey (b) Notice on the wavenumber between, approximately, 0.012 cycles/km and 0.053 cycles/km have been improved by the 1998-1999 gravity survey. However, according to the spacing grid of 7.5 km of recent gravity survey (1/7.5=0.067 cycles/km), any information of the wavenumber lying between 0.067 cycles/km and 0.2 cycles/km are ambiguous and created by interpolation.
many spatial scales. There is a fundamental relationship between wavenumber and depth (Spector and Grant, 1970; Nnang, et al., 2000) that can be used to separate the regional field from the residual field.

The 2D power spectrum is often converted to a radially averaged power spectrum for ease of presentation. The result is a one dimensional plot, starting with zero spatial frequency, and increasing to the Nyquist frequency (Figure 3.7). Each point is the average of all points lying on the circle with constant frequency. The results were used for the design of the regional-residual filter and the calculation of the depth to the top of a statistical ensemble of potential sources. The slope of the graph in the low frequency part of the curve represents the regional component of the field while the slope of the high frequency part represents the residual component produced by more shallow source. The application of the techniques of this section has helped to define some of the structural boundaries seen in the gravity magnetic data. The depth (h) to statistical ensemble of sources is determined by the following expression: $h = -\text{slope of power} / (4\pi)$ (Spector and Grant, 1970; Macleod, 1986).

It is of note that the boundary defined by the recent gravity data coincides with 1972-1973 gravity survey at high wavenumber. Improvement of new gravity over the previous survey was marked between 0.012 cycle/km to 0.053 cycle/km which respond to depth at 90 km and 18 km respectively. The energy of AMMP magnetic data is higher than that of gravity about the degree of power 2 (log scale) and increasing toward high wave number.

### 3.5. Enhancement of regional-residual features

Certain trends or features may be difficult to see because of the complexity of the map. If we are interested in analyzing local features in the gravity field, broad scale regional features may be distorting the picture. If we are only interested in deep seated features, the near surface anomalies may obscure them. By either isolating or enhancing portions of the gravity field, analysis may be simplified. It is desirable to filter the data in a way that will isolate or enhance certain features.

#### 3.5.1. First vertical derivative

Derivative filters play a role in gravity and magnetic interpretation because they isolate contacts over which the field can be expected to change rapidly and therefore to have large values for its derivatives. More specifically, in this case the analysis yielding the contact parameters involves both the vertical and the horizontal derivatives. The first vertical derivative emphasizes the shallow component of the source geology while still leaving some middle wavelengths and eliminating very long wavelengths.

The edges of anomalies become sharper or clearer if derivative operators are applied to the data. For example, the first vertical derivative of gravity map shown in Figure 3.8 enhances the signatures of the border fault N-S trending along Nata. The evidence of lineaments, NE-SW trending, become more clearly on the central of the study area.

#### 3.5.2. Shaded relief image

Digital enhancement of images for visual interpretation is based on two important attributes of the psychophysiology of human vision which can be considered as having two modes; achromatic vision, based on the grey tones in a black and white picture, and chromatic, or colour vision. Potential field
Figure 3.8 Gravity lineament interpretation reveals more clearly the presence of lineament patterns which are not clearly seen in the Bouguer anomaly map. Notice the NE-SW lineament sets are truncated by long arcuate pattern located on the western portion of the study area.
Figure 3.9 Shaded relief image maps with illumination inclination 25° and declination 10° CCW from the North enhance a number of lineaments to become more clearer (a) AMMP grid data and (b) Bouguer anomaly map.
anomalies can be made to appear 3-D by calculating the first horizontal derivative in the direction of illumination of interest. Gridded data is treated as a topographic surface and its apparent reflectance calculated for an illumination source at an assumed azimuth and inclination.

Apparent reflectance is dependent on the angular relationship between the slope of the anomalies and the illumination direction. It is maximum when the illumination direction is perpendicular to the surface slope. Therefore, a curvilinear feature has maximum reflectance when it is illuminated normal to its strike and least reflectance when the illumination direction is along strike.

Grid data is treated as a topographic surface and its apparent reflectance calculated for an illumination source at an assumed azimuth and inclination. Since regional bodies produce low local gradient anomaly, reflectance of these anomalies are low while anomalies due to shallow sources have steep gradients. This is how anomalies due to shallow sources are enhanced and regional anomalies are suppressed.

The complimentary shaded relief map compiled with an arbitrary illumination source is illustrated in Figure 3.9. Northwest-trending features are all enhanced in this map. An interesting, roughly circular feature is clearly evident straddling the western boundary of the study area.

3.6. Summary and Discussion

In this chapter, the gridding analysis illustrates the important information to be taken account of in data quality. Linear structures are often the objects to be interpreted with priority. This is because they are often formed in association with faults or contact or tectonic feature in geological mapping. Therefore studying linear anomalies play an important role in geological interpretation of geophysical map. Any predominantly linear trending may be observed from its power spectrum map where the spectral energy is elongated in the direction corresponding to its spatial orientation.

1. An atlas of power spectra started as new surveys for data quality are analysed. The examples in this chapter provide comparison between the old and the new gravity data. With similar grid cell size the 1998-1999 gravity present good quality data than that obtained from the 1972-1973 gravity survey. Their results show the features which correspond to the major structure in NE-SW trend over study area. Artifacts disappear in the 1998-1999 gravity data spectrum while they are shown when making 2-D power spectrum analysis in the 1972-1973 gravity data. The pattern presented in figure 3.4 (a) and (b) are probably affected by the grid processing in FFT. Two dominant linear features are strongly recognized in 2-D power spectrum of magnetic data, after comparison to the 1998-1999 gravity survey with similar grid cells size.

2. Most of geophysical data processing are working mainly in filtering methods. The quality of the processed results depends on the quality of the input grids. The filtering for image enhancement, such as first vertical derivatives, can be failed to produce an interpretable map from such improper gridded data, because noise and false information with short wavelengths are often magnified, which obscure the useful signal enhancement.
3. In radially averaged spectrum, the slope of the graph in the low frequency part of the curve represents the regional component of the field while the slope of the high frequency part represents the residual component produced by more shallow source. However, it is suggested that the aliasing is occurred when sampling grid is equal or less than half of the sampling interval. In this studying the aliasing as can be seen in figure 3.7 is located between wavenumber 0.13-0.15 cycles per km or high frequency (short wavelength).

4. The gravity lineament pattern obtained from figure 3.7 (b) can be correlated to the observed patterns, namely Damara and Magondi Belt in figure 1.2 (a). Also, information from shaded relief image and vertical derivative map reveal the NE-SW lineaments are interrupted by younger formation lying in the northwest portion of the map.
4. Apparent physical property map

4.1. Introduction

One of the main purposes of geophysical mapping is the identification of units that can be related to known geology. On a regional scale, aeromagnetic and gravity maps are some of the most useful tools presently available. Interpretation now makes extensive use of enhanced maps like susceptibility maps for magnetic data and density maps for gravity data. The objective of susceptibility and density mapping is to transform the potential field data into a physical property map i.e. the continuous laplacian anomaly field into the discontinuous geology (Zhou, 1992).

New techniques of visualization have led to styles of presentation that make the data more attractive. Colour images are very often made to reveal areas of high and low relative anomalies for assisting the human perception. An innovative idea was introduced by Everaert (1990) and adopted to the present study to convert magnetic and gravity data to apparent magnetic susceptibility and apparent density and present them together on one map.

The combined grid colour composite of derived density and magnetic susceptibility data can display information with physical meaning and interpretability. Geological contacts, the gravity field, and the magnetic field provide distinct sets of observations that can be used to constrain the structure and provide less ambiguous information for interpretation.

4.2. Rock property data

The primary controls on the density, magnetic susceptibility and remnant magnetisation of a rock volume are the original lithology, the structural evolution, and the metamorphic and metasomatic mineral assemblages. As a first order approximation, lithology controls density and magnetic properties by the mineralogy and sharp variations in rock properties which typically coincide with lithological contacts such as unconformities and intrusive contacts.

Generally, only part of a stratigraphic interval will have a high magnetic susceptibility so that a geophysical rock property map need not correlate directly with the equivalent geological map. The structural evolution of an area will change the position and orientation of these contacts and may introduce new ones, e.g. faults. The role of metamorphism and metasomatism is to alter the mineralogy either locally, within shear zones or as contact aureoles, or regionally, such as the gradual densification associated with burial. Individual lithologies may posses a remnant component of magnetisation that may also be affected by deformation and metasomatism. The combination of these factors leads to geophysical rock properties that are characterised by both discrete and continuous spatial variations.
In an important and pioneering study of the properties of rocks by Henkel (Reeves, 1998; Henkel, 1994), almost 30,000 specimens were collected and measured for density, magnetic susceptibility and NRM. Diagram such as Figure 4.1 shows a frequency plot of magnetic susceptibility against density for Precambrian rocks. It is seen that while density varies continuously between 2.55 and 3.10 g/cm$^3$, the distribution of magnetic susceptibility is distinctly bimodal. The cluster with the lower susceptibility is essentially paramagnetic peaking at $k=2 \times 10^{-4}$ SI, whereas the higher cluster peaks at about $k=10^{-2}$ SI is ferrimagnetic. The bimodal distribution appears to be somewhat independent of major rock lithology and so gives rise to a typically banded and complex pattern of magnetic anomalies over Fennoscandian shield (Reeves, 1998).

The whole subject of rock magnetism is an extremely complicated one that defies simple description, the fact that crystalline rocks fall almost equally into two categories. Those can be considered magnetic and those that are effectively non-magnetic means that contrast between geological units of different lithology are very often contacts between rock units of different magnetic susceptibility.
It follows that the use of magnetic anomalies as a geological mapping tool is much more effective than might be expected. Much of the information contained in a magnetic anomaly map is therefore of a qualitative nature and the importance of the systematic extraction of qualitative information should not be underestimated (Reeves, 1998). It should be noted from that graph that a better knowledge of the rock properties which give rise to gravity and magnetic anomalies may be expected to materially assist the semi-quantitative interpretation of gravity and magnetic anomalies in extensive terranes.

4.3. Data presentation

4.3.1. Colour composite scheme

An attempt to present the derived density and magnetic susceptibility together in the one map which would combined both information at the same time and produce a map with physical meaning which should therefore be directly interpreted. In order to display those properties together in the map, a different colour table is attached to each of two data sets.

To the apparent density values a colour table was assigned by varying colour from yellow for the low density, through white for normal density, and to cyan for high density rocks. In the same way, a colour table was attached to the apparent magnetic susceptibility map which varies from white to magenta representing non magnetic to high magnetic rocks. The combination of these colour gives new colour categories (Figure 4.2)

This method give the possibility of a kind of physical property mapping which might correspond to a mapping which is closer to a geological map. The map may help us to achieve a better perception of geology and can help to delineate geological boundaries which have not seen earlier.

For physical property mapping, some hypotheses and simplifications are made. The earth model is assumed to consist of right rectangular prisms of finite (gravity) and infinite (magnetics) depth extent. For ease of data processing, the potential field is interpolated onto a regular rectangular array, so that each point in the array corresponds to one prism.

4.3.2. Apparent magnetic susceptibility map

The AMMP grid data were processed to get a new grid data set with a similar grid cell size and retained magnetic sources at the same depth as gravity data. Low pass filter is the first filter to be applied to the original grid to suppress the high wavenumber information caused by dike swarms which can obscure the lower wavenumber information due to source bodies of more geological interest. The filter is also used to emphasize deeper features which, in this care, would be located at the same depth as in gravity. Figure 4.3 (a) is the low pass filtered map applied to AMMP grid data (wavenumber cut off 0.00002 cycle/m or 50 km). Noticed in Figure 4.3 (b) its radially averaged spectrum was well behaved and close to the radially averaged spectrum of gravity which means the magnetic was influenced due to deep sources at similar depth as in gravity.

A susceptibility filter used, in this case, is a compound filter that performs a reduction to the pole, downward continuation to the source depth, correction for the geometric effect of a vertical square ended prism, and division by the total magnetic field to yield susceptibility with unit in emu.
Figure 4.2 Colour scheme for generating apparent physical property map (a) described colour for apparent magnetic susceptibility (b) described colour for apparent density (c) colour composite of apparent physical property map.
Figure 4.3 (a) The filtered map after applying low pass filter to AMMP grid data with low pass wave number cut-off = 0.00002 cycles/m (b) Its radially average spectrum was changed and coincided with the radially averaged spectrum of gravity. This means that the two spectrum are results of the same response due to bodies at similar depth.
Magnetisation and susceptibility terms and units can be confusing. Magnetisation is the magnetic moment per unit volume. Magnetic volume susceptibility ($k$) is the magnetic moment acquired per unit applied field per unit volume; it is the ratio of a magnetization to a field as such is dimensionless. In the cgs system susceptibilities can be labeled emu to identify the quantities. In S.I. unit susceptibilities are $4\pi$ times the cgs values (Clark and Emerson, 1991)

The process simplifies the shape of anomalies and peaks occur directly over the sources as if the anomalies were measured at the pole and if all anomalies were caused by inductively magnetized bodies. This will restore anomalies to the positions which lie directly over the source bodies. The parameters defined in the susceptibility filter are; depth to the top surface of the prisms of 1000 m, magnetic inclination of –60 degree, magnetic declination of 13 degree west of north azimuth, and a total magnetic field strength of 30000 nT

In this calculation, the subsurface is assumed to be made up of a large number of square-topped vertical prisms, one per cell of the original data grid, extending to infinite depth. The magnetic susceptibility of each of these prisms is calculated such that the combined magnetic effect of all prisms is the originally total magnetic intensity.

The map derived from this processing can be related to rock type distributions in the map area primarily reflecting their magnetite content and indirectly their metamorphic history. Susceptibility is a procedure that produces an apparent susceptibility grid from a magnetic grid. The final result (figure 4.4 a) is an apparent magnetic susceptibility map that have quantitative meaning only if the following criteria are met (Yunsheng, et al., 1985; Urquhart and Strangway, 1985).

1. The magnetic field can be described as due to an assemblage of bodies of rectangular cross section, one grid cell in dimension.
2. The bodies are vertical sided
3. The bodies are infinitely deep (bottomless)
4. The bodies are only magnetized in the direction of the Earth’s magnetic field

In general, three different types of processes can alter or influence macroscopically the natural abundance of iron minerals in the rocks (Everaerts, 1990);

- Igneous activity, such as diabase and gabbro which are comparatively rich in ferromagnesian (mafic) minerals. This also includes volcanism which bring to the surface lavas which sometimes have abundant magnetite.
- Metamorphism and alteration processes can either build up or destroy the ferromagnetic minerals in the rocks
- Sedimentary process specifically the chemical precipitation and iron formations which are often rich in magnetite

It would seem clear from what has been seen above that mapping rock unit from their magnetic susceptibilities is going to present problems of interpretation by not only natural variation in iron oxide within each unit at the time of its emplacement but also the alteration processes.
Figure 4.4 Calculated apparent physical property maps (a) apparent susceptibility map with contour interval 0.0004 emu, half of the map consists of negative value. Depth to the top surface of the prisms of 1000 m is calculated, which is situated on the plane at ground surface. (b) data distribution of the calculated values. To the right of the histogram is located by a group of value greater than 0.0012 emu. Which is marked by 1
4.3.3. Apparent density map

To complete the lithologic mapping of Archean basement the apparent density of bedrock were prepared from Bouguer gravity map. For gravity data, a similar procedure without the need for pole reduction is carried out to produce an apparent density map. The process involves two operations; downward continuation and apparent density calculation. Theory demands that the depth of both the top and the bottom of the prisms is supplied by the user in this case. For agreement of the results of most such studies in Precambrian areas with observed surface rock densities, the base of the prisms need to be set at a depth of 6-7 km (Gupta and Grant, 1985; Everaert, 1990; Reeves, 1998). Apparent density mapping is useful to delineate geological units with a similar density.

Figure 4.5 (b) shows the apparent density contours for the study area. The contour interval used in this drawing is 0.05 g/cc. The lowest values are approximately 2.40 g/cc. The highest value, as expected, occur along the greenstone body (Matsitama) on the eastern and also present an area along the arc on the northwest and these reach almost 2.9 g/cc. Elsewhere, the apparent density values lie between these two limits. New features also appeared after applying apparent density calculation to Bouguer anomaly map as shown in Block 1 on figure 4.5 (a)

4.4. Limitations

From the calculation point of view some errors may occur on the map. The magnetic field can be described as due to an assemblage of bodies of rectangular cross-section, one grid cell in dimension; the bodies are vertically sided, the bodies are infinitely deep (bottomless), the bodies are only magnetized in the direction of the Earth’s magnetic field. The validity of the results is then naturally subject to how well the actual observed field conforms to those assumptions. Deviation of the source body from the vertical prism model, presence of remnant magnetisation, variable depth to the ensemble top leads to apparent susceptibility values. Presence of remanent magnetism effects will lead to misplaced anomalies and erroneous values.

The susceptibility, as well as the density contrast, is calculated at uniform horizontal plane, in this case situated on the ground surface. It means that the topography of bedrock is not taken into account in this calculation. Then the calculated rocks properties can be related to experimental result only when the plane of calculation made corresponds to the surface of the bedrock.

Another limitation is that the values calculated from the two potential fields are likely very coarse grained maps because the sampling interval is very large. It means that all magnetic susceptibility and density contrast are averaged over large area, which is only correct when the area over which one average has homogeneous rock properties.
Figure 4.5 Calculated apparent density map (a) apparent density map with contour interval 0.05 g/cm$^3$, notice that most of observed patterns are similar to that observed in Bouguer anomaly map (figure 2.2). (b) data distribution of the calculated values. The map is calculated from a plane situated on the ground surface.
4.5. Comparison with Geology

The main problem in geology information of the study area is rarely exposed and some rock types are still unknown and undifferentiated (Key and Ayres, 2000; Geology of Botswana, 2000). Then with the technique in the study it is hope to help understanding and gain more geology information in the study area. In order to test the two variable rock property mapping that was carried out as a pseudo geological mapping, the boundaries of the geology were overlaid on the final apparent rock property map (figure 4.7 and figure 4.8).

The main conclusion obtained on combined physical property map were of structural trending and lithological boundaries. Concerning the structural point of view, It can be seen from Figure 4.6 that the trend in NE-SW observed in the rock property map agrees with the geological strike direction as seen in the geological map (figure 4.7)
**Figure 4.7** Outline of rock unit over the study area classified by group (modified after Geology of Botswana, 2000) in (a) general rock type with group outline (b) rock unit classified by group, see table 4.1 for index.
Figure 4.8 Final apparent physical property map with an overlain of geological outline from figure 4.7b to find out the relationship between geology and the interpreted map units.

To south of Maun where the area is composed of red colour. This zone corresponds to Kgwebe formation (Sks). Rock group RB can be seen on the map as an alteration of continuous yellow pattern. This colour zone has a wide extent to the north, which giving the possibility of a wider occurrence of RB than that shown on the geological map.

Northwestern section on the map is characterized by blue colour indicating low density and high magnetic susceptibility. This rock is located in part of the Kwando complex (WC) which lead to deduce that the body could be granite, granite gneiss (figure 4.9a).

To east of Kwando complex, there is a broad structure of rocks situated such as equivalent Sinclair Group and an intrusive rock of dolerite (D) but they cannot be differentiated from both gravity and the final apparent physical property map. This zone shows, generally, high density and high magnetic but appear to have isolated zone of low density and high magnetic susceptibility. A gravity high and an associated magnetic high probably reflect underlying metamorphosed rhyolitic rocks (Sg) of Sinclair Group. Rock formation located along the northern part is though to be part of granite complex that extend to northeast Botswana from Zambia. Interesting features located in the middle part of this
region is characterized by zone of irregular shape which show the deformed outlined. This part should be highly deformed formation of metamorphosed rock formation. Unexposed metamorphic rocks (Xg) can be extended to the north where there are no outcrops (figure 4.9 b). This is because the extension to the north fits within the general strike of the rocks by cyan colour. The complicated composition of this formation account for the alternation between various colour on the display.

The only exposures to the right this zone are found in the Sua Pan area where an undeformed granite and older migmatites form two rocky islands in the salt pans lead to be a rock type of this feature (Key and Ayres, 2000; Majaule, et al., 2001). Basement rocks penetrated by a borehole drilled near Gweta consist of high grade, garnet and sillimanite bearing granitic gneisses showing lithological affinities to rocks exposed in the Dete Inlier in Zimbabwe which making it reasonable to infer that the Gweta rocks are part of the Magondi Belt (Majaule, et al., 2001).

On the eastern part of the map, the Maitengwe and Tati-Vumba greenstone are easily picked up (figure 4.9 b). It was also suggested on the apparent physical property map that Matsitama has its extension westward into Botswana. All of these greenstones are bordered by blue colour indicating a low density and a low magnetic susceptibility.

Table 4.1 General rock types classified by group (modified after Key and Ayres, 2000)

<table>
<thead>
<tr>
<th>Legend</th>
<th>Rock types</th>
<th>Era</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>Undifferentiated migmatite</td>
<td>Archaean</td>
</tr>
<tr>
<td>Xg</td>
<td>Unexposed metamorphic rock</td>
<td>Precambrian</td>
</tr>
<tr>
<td>G</td>
<td>Granite</td>
<td>Archean</td>
</tr>
<tr>
<td>Sg</td>
<td>Metamorphosed rhyolitic volcanics and sedimentary rocks</td>
<td>Mesoproterozoic</td>
</tr>
<tr>
<td>DZc</td>
<td>Metamorphosed calcareous sandstone and siltstone</td>
<td>Neoproterozoic</td>
</tr>
<tr>
<td>Kvd</td>
<td>Undifferentiated intrusive and/or extrusive Karoo dolerite</td>
<td>Jurassic</td>
</tr>
<tr>
<td>WC</td>
<td>Granite gneiss, amphibolite-gneiss, migmatite</td>
<td>&lt;=550 Ma</td>
</tr>
<tr>
<td>RB</td>
<td>Amphibolite, magnetite-schist and granite gneiss</td>
<td>Neoprotrozoic</td>
</tr>
<tr>
<td>Sks</td>
<td>Metamorphosed rhyolitic and basaltic volcanics</td>
<td>Mesoproterozoic</td>
</tr>
<tr>
<td>TS</td>
<td>Ferruginous and micaceous quartzite, shale,ironstone</td>
<td>Paleoprotrozoic</td>
</tr>
<tr>
<td>AX</td>
<td>Aassorted metasedimentary including ironstone</td>
<td>Paleoprotrozoic</td>
</tr>
<tr>
<td>QM</td>
<td>Granite gneiss, deformed granitoid</td>
<td>Paleoprotrozoic</td>
</tr>
<tr>
<td>CH</td>
<td>Igneous and meta igneous rock</td>
<td>Neoprotrozoic</td>
</tr>
<tr>
<td>KKG</td>
<td>Paragneiss?, granite gneiss, and dolomite marble</td>
<td>Neoprotrozoic</td>
</tr>
<tr>
<td>DZm</td>
<td>Weakly metamorphosed arkosic sandstone</td>
<td>Neoprotrozoic</td>
</tr>
<tr>
<td>DZn</td>
<td>Weakly metamorphosed, purple arkosic sandstone</td>
<td>Neoprotrozoic</td>
</tr>
<tr>
<td>D</td>
<td>An intrusive rock of dolerite sheet and stock</td>
<td>Various ages</td>
</tr>
</tbody>
</table>
Figure 4.9  (a) Yellow colour consists mainly of rock unit RB which is bordered by rock unit QM to the west and rock unit WC to the right respectively. To the south is immediately white colour showing lens-like structure which is corresponding to Chihabadum complex and Koanaka complex respectively. These formations consist of igneous rock and paragneiss. (b) Rock unit Xg is expected to reflect the cyan colour zone located on center of the map while three orange colour zones on the right correspond to the well known greenstone rocks; Maitengwe, Matsitama, and Tati (refered to figure 1.2 c). However, the Vumba area corresponds to only the white colour zone which means non magnetic and normal density.
4.6. The Final interpretation Map

The final interpretation map has been done, using mainly of geological map for the known controlled parts. Gravity lineament interpretations from figure 3.8 has been used to define the faulting system. The final map (figure 4.10 and figure 4.11) is subjected to be a geological map represented the regional geology over the study area. Most of the observed features on the final interpretation map are similar to that have been seen in the previous interpretation.

The southeastern part on the map comprises of lithologies dominated by strongly deformed meta-magmatic rocks that are exposed south and west of Francistown. Accordingly to Key and Ayres (2000) this zone is also interpreted as a Plate Boundary Zone between Zimbabwe craton and Limpopo mobile belt.

4.7. Summary and Disscusions

The regional gravity and magnetic data analysed in this study provide considerable insight into complex structural relations. New property map provides vital information about lateral variation in density and magnetisation of crust on regional scale and can be summarized as the following;

1. Gravity with 7.5 km grid provides a broad information about the area, this information is related to long wavelength anomalies, which means that the gravity is more related to deep sources and in this case more information about the structural geology in the area of concerned. Magnetic data give much more detailed information since the sampling interval is smaller. It means that magnetic field give more information about the detail geology. However, magnetic give information on the deep sources as well as the shallow sources.

2. Low pass filter is first applied to the AMMP grid data in order to extract the regional information due to similar depth as in gravity and suppress the effect of shallow information, in this case, the dyke swarm. The grid result in figure 4.3 (a) shows broad anomaly amplitude and more smooth features. Its radially average spectrum was changed and coincided with the radially averaged spectrum of gravity. This means that the two spectrum are results of the same response due to bodies at similar depth.

3. Both apparent physical property maps of gravity and magnetic provide useful information for outline the rock boundary having same property.

4. The combination of calculated density and magnetic susceptibility grid gives the possibility of a kind of physical property mapping to investigate beneath the cover. The overlying of the geological map on the outcropping part of the area shows how well geology can be defined by this method and help in the extrapolation of geological boundaries in to areas devoid of outcrop.
Figure 4.10 Final interpretation map showing regional geology over the study area. The gravity lineament interpretation obtained from figure 3.8 (b) are superimposed on the map. The kimberlite field (Key and Ayres, 2000) located around Orapa can be correlated to the weaked zone tracing southward from eastern limit of Magondi mobile Belt.
Figure 4.11 Regional geology over the study area (Thomas, et. al., 1993) overlain by the final apparent physical property map. The outline and pattern appeared on of the final apparent physical property map are in good agreement with the major structural trends in geology. More detailed features reveal the correlation among Okwa Inliner, Magondi mobile Belt, and Limpopo mobile Belt implying the triple junction. The yellow features located on the northwest portion of the map is the youngest features obtained in the study area.
5. Discussion

- A well known Paleoproterozoic orogen is located middle and west of the study area. They are represented by the Magondi mobile belt and Damara belt respectively. Northeast Botswana comprises three major greenstone belts; Matsitama, Tati-Vumba, and Maitengwe. They are associated with migmatites and gneiss as well as generations of granitic intrusives. These rocks form part of an Archaean basement complex that incorporates the Zimbabwe craton and possibly a northwest trending extension of the Limpopo Belt which can be observed in figure 4.10 and figure 4.11 along the south-eastern part of the map.

- The really more extensive Masitama greenstone belt is seen to be progressively to the west which can not be seen in the geological map. It is clear that more detailed gravity surveys in this studying are valuable defining features such as that expected to be extended more accurately. There is also a prominent lineament which is suggested to be an eastern limit of Magondi mobile belt that extend from Zimbabwe. The pattern can be observed in both gravity and magnetic. That fault has a length of about 100 km pass through Nata and stop somewhere around the Makagdikadi pan.

- It can be argued that the lineaments reflect a basic property of the crust within each domain. The difference in that trend indicates differences in the tectonic history of the lithospheric rocks. Thus they show an orientation dictated by an inherent fracture pattern in each particular domain of the crust and the recognition of these domains could help to elucidate the tectonic history of the different Archaean terrane.

- Toward the western part of the study area, the later Precambrian rocks of this area are represented by three groups; the Kgwebe formation volcanics, Ghanzi group weakly metamorphosed sediments and Damara sequence sediments. The complex structure zone occurred along the Okavango delta as obtained from the lineament interpretation (figure 3.8) and final apparent physical property map separate this zone into sub area. The Damara rocks continue both westwards to be widely exposed in Namibia where they form the Windhoek Highlands. The dominant zone on this section is characterized by continuous pattern of width greater than 30 km which has a wider extent in northern part than in southern part. It is denoting by main rock unit of amphibolite. The group can be traced along its northeasterly strike across northwest Botswana. This pattern is lying between the complex structure zone on the west and central area of Botswana.
6. Conclusion and Recommendation

6.1. Conclusion

The broad application of gravity and magnetic data have led to new insights and reconfirmed previous interpretations of regional structure in Northern Botswana. Based on the present study, the main purpose of which is to provide new knowledge that helps in the understanding regional geology in northern Botswana, the following conclusions can be reached:

1. Gravity survey in 1998-1999 was compared with the 1972-1973 gravity survey. New survey shows more details with improvement in shorter wavelength and also shape of anomaly.

2. Analysis of grid data before further processing is quite useful to check the quality of data, noise and also unwanted signal.

3. The apparent physical property map, e.g., magnetic susceptibility and density are very useful to delineate geological boundary. Final apparent physical property map created from grid colour composite provide a vital information about the geology in the study area, especially the younger pattern lying across the country in NW portion of the map. The geology of the study area was mapped using these data set to classified the possible rock basement.

6.2. Recommendation

There are several techniques should be applied to the data for shaping up the qualitative interpretations. The following strategy is recommended:

- According to the results obtained in the studying in geology pattern the Euler deconvolution techniques (Reeves, 1998; Reid, et.al., 1990; Roy, et.al., 2000) should be applied to the data to gain more understanding relationship about depth to basement in the area.

- It is useful to perform forward modeling along selected profiles to find the relationship between different rock formation and compare the result with that get from Euler depth.
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