

# **Interpretation & Geodatabase of Dykes Using Aeromagnetic Data of Zimbabwe and Mozambique**

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# Interpretation & Geodatabase of Dykes Using Aeromagnetic Data of Zimbabwe and Mozambique

by

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This thesis submitted to the International Institute for Geo-information Science and Earth Observation in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation, APPLIED GEOPHYSICS.

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# Abstract

The capability of modern aeromagnetic anomaly mapping becomes apparent in providing information about the geology especially where rock outcrop are scarce or absent. Mafic dykes have significant expression on magnetic anomaly maps that covers now almost land area of the world. Storing the various trends of dyke in a relational geodatabase can help discover their implication for the tectonic events which still need to be answered by displaying on their age, strike direction, composition and by classifying them in swarms.

The dyke geodatabase made available on CD-rom so that the other makes use of it for their studies. Most of the dykes of the study area are digitised from the aeromagnetic grids using Oasis montaj and exported as shape file to the GIS program. To access the geodatabase the user needs to have ArcGIS 8.3 or later and Microsoft Access software and it was designed using standard Relational Database Management System (RDMS) technology.

With the interpretation of a new set of 9018 dykes from an aeromagnetic grid of Zimbabwe and new (2003) data from western Mozambique and by merging it with the previously interpreted dykes of southern and eastern Africa, the geodatabase now has over 24600 dykes with the most portable file format (shape file). The majority of the dykes in the database are grouped into 52 swarms. Displaying and analysing the dyke swarms in continental scale will be a great help to the users of the database to answer questions related to the uncertain tectonic movement of plates.

The recent arrival of the new western Mozambique aeromagnetic survey data was fascinating & crucial to this research since there was previously no geophysical information in this part of Africa. Of the large number of dykes known in South Africa, Zimbabwe and Botswana, many diverged from the Lower Limpopo valley in Mozambique, where there is no outcrop and until now, no aeromagnetic survey. Dykes have been identified and delineated from this survey including two new interesting trends of swarms. Prominently the NNE trending dykes are visible starting adjacent to the Lebombo monocline and extending up to the central part of Mozambique after loosing its anomalous character below the thick sediment cover.

By displaying the prominent Mesozoic swarms (Limpopo, Northern Botswana and Lebombo) and the newly identified Mozambique dyke swarm (SW1) in continental scale, the geometry, their emplacement and stress pattern suggest the triple junction nature of the swarms. The evolution of the triple junction is still complex and enigmatic and needs to be related more fully to what is known of the conjugate coast of Antarctica.

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# 1. Introduction

Airborne geophysical surveying is the process of measuring the variation of different physical or geochemical parameters of the earth such as distribution of magnetic minerals, density, electric conductivity and radioactive element concentration. The methods used to measure these kinds of parameters are magnetic, gravity, electromagnetic and gamma-ray spectrometry respectively.

The capability of modern airborne magnetic anomaly mapping, as one of several geophysical tools available to assist the geological mapping of largely concealed terrains, has been addressed repeatedly, underlining the high degree of sophistication achieved by technology in recent years (Reeves et al., 1997; Gunn, 1997; Reeves, 1998).

Aeromagnetic survey maps the variation of the geomagnetic field, which occurs due to the changes in the percentage of magnetite in the rock. It reflects the variations in the distribution and type of magnetic minerals below the earth surface. Magnetic minerals can be mapped from the surface to greater depth in the rock crust depending on their dimension, shape and the magnetic property of the rock. Sedimentary formations are usually non magnetic and consequently have little effect whereas igneous and metamorphic rocks exhibit greater variation and become useful in exploring bedrock geology concealed below cover formations.

Variation in magnetic susceptibility combined with other geophysical data and known geology provides important information about the regional geology especially where rock outcrops are scarce or absent and also helps to develop priorities for follow-up in the most prospective areas. Mafic dykes usually give rise to magnetic anomalies that are prominent on the aeromagnetic anomaly maps that now approach universal coverage for the land areas of the world (Reeves, 2000). In regional mapping, mafic dykes often give rise to well-defined topographic features and with respect to granitic and most sedimentary host rocks are darker coloured, covered by denser vegetation and more magnetic. Therefore they could have been easily traced from satellite imagery, aerial photographs and aeromagnetic maps (Chavez Gomez, 2000).

This research work aims at using aeromagnetic survey data from Zimbabwe and Mozambique to map and interpret mafic dykes and to create a geodatabase of dykes of the study area on universally applied and user-friendly software. The new aeromagnetic survey of western and central Mozambique that was conducted with the cooperation of Geological Survey of Finland (GSF) and The Ministry of Mineral Resources and Energy of Mozambique/National Directorate of Geology (DNG) has been included in this thesis. The new data was one of the missing parts in the AMMP coverage and was not previously interpreted in any previous works. This gives a broader perspective in the study and the construction of Gondwana and also helps to see how far the Zimbabwean and South African dyke swarms extend into western Mozambique.

## 1.1. Background

Mafic dykes constitute a common expression of crustal extension in both oceanic and continental environments, and represent a major avenue by which basaltic magma is transferred from mantle to upper crust. In oceanic areas they play a central role in the evolution of ridge crests and underlie the ocean floor at depth as sheeted dyke complexes. Within contemporary oceanic crust, dykes range in age from the Jurassic, which is the age of the oldest surviving sea-floor, to the present. Dykes are an integral part of the feeder system to most volcanic islands, whether they represent intraplate activity or are subduction related (Halls and Fahrig, 1987).

On continents mafic dykes have been intruded episodically throughout the last three billion years or so of earth history. In Precambrian shields, swarms of different trends criss-cross one another, often in profusion and many of the swarms extend for hundreds of kilometres. Most of the mafic dykes on the continents are either Proterozoic or late Phanerozoic in age (Mubu, 1995).

The occurrence, state of deformation and geochemical composition of dykes provide important information on the evolution of the continental crust into which the dykes were intruded. Cross-cutting relationships between dykes and host rocks, and between different generations of dykes, yield valuable relative time constraints, and dykes provide significant time marks between structural and metamorphic events. The compositions of the least altered and least metamorphosed dykes help to define the properties of their mantle source region, as well as the nature of the crust through which the magmas travelled.

Interpreted geophysical data in conjunction with ground-based geological observation can be placed into a global tectonic setting that helps understanding of major tectonic mechanisms. Rifts, evolving to continental break-up and the formation of new ocean basins are some of the most productive magmatic systems expressed at the surface of the earth. Understanding the processes operating in these settings is critical to our knowledge of how our planet works.

Reeves (2000) described that the multitudinous dykes of Jurassic age in southern Africa interpreted as product of successive stages in the interaction of the tectonic plates and intraplate fragments that underwent relative (modest) movement during the disruption of Gondwana. These stages commenced with east-west rifting of the eastern margin of the present Kaapvaal Craton, followed by southern drifting of East Gondwana against Africa. The separation of Antarctica-Australia from India-Madagascar subsequently led to clockwise migration of Antarctica around the southern margin of Africa, eventually with dextral strike-slip on the Agulhas Fault and the opening of the South Atlantic. All these events left a record of dyke emplacement in southern Africa (Reeves, 2000; Reeves and De Wit, 1998 & 2000).

## 1.2. Study area

Zimbabwe and Mozambique are found in the south-eastern part of Africa. Zimbabwe is a landlocked country located between the Zambezi River and the Limpopo River. The study area is bounded

approximately between  $10^{\circ}$  and  $26^{\circ}30'$  S and  $24^{\circ}$  and  $41^{\circ}$  E. It is bordered on the north by Zambia and Tanzania, on the east by the Indian Ocean, on the south by South Africa, on the southwest by Botswana and its extreme west corner touches Namibia. (See Fig 1.1)

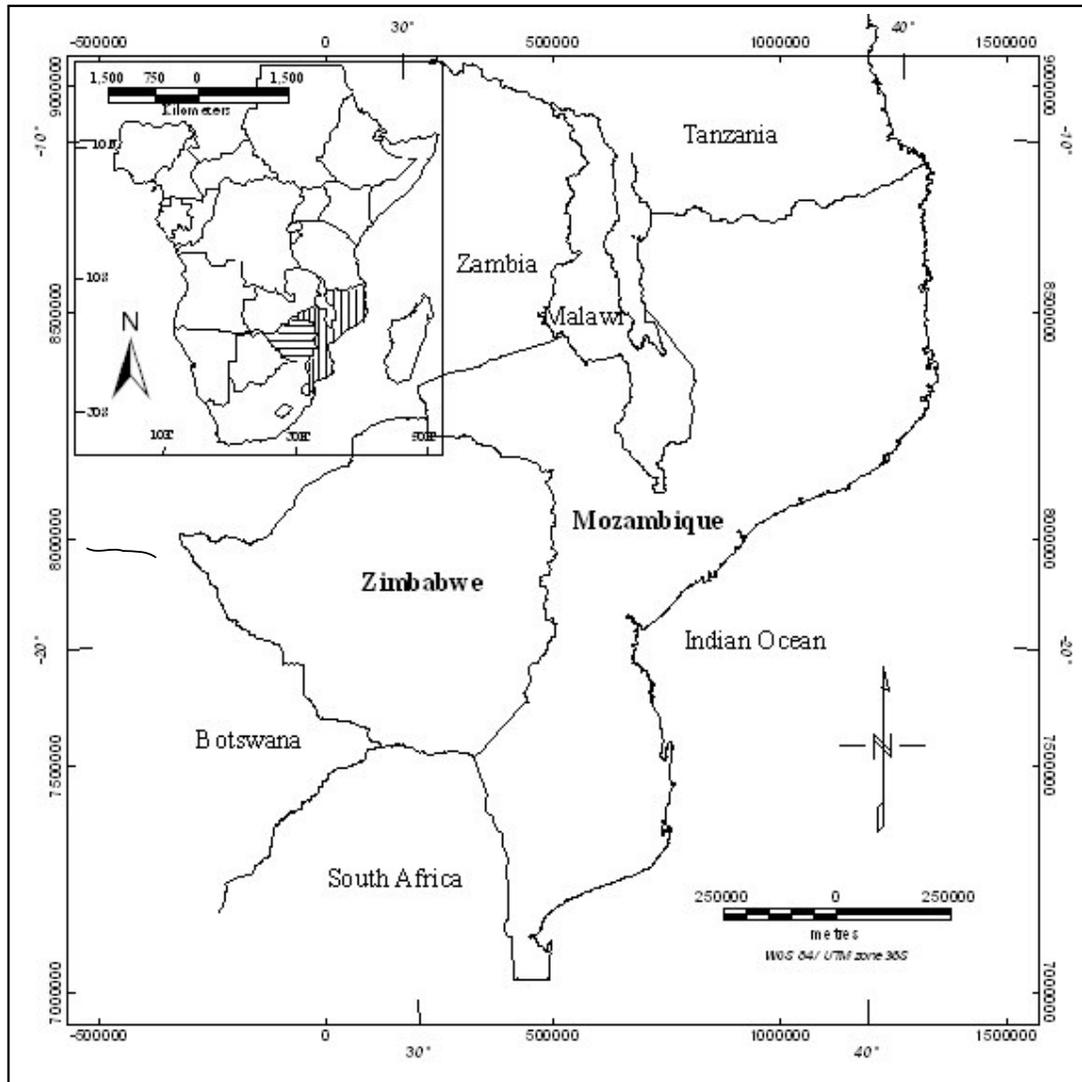


Figure 1.1 - Location map of the study area

### 1.3. Mafic Dykes in the study area

In southern African countries like Zimbabwe, Mozambique and Botswana various ages and types of dykes have been recognized through the years. Mafic dykes occur in a variety of geologic and tectonic settings including mid-ocean ridges, sedimentary basins and granitic shields. Different scientists studied, mapped and described the dykes of the area (e.g. Hunter and Reid, 1987 & Reeves, 1978) using various methods including aeromagnetic.

With the extension of aeromagnetic coverage in southern Africa in the 1970s and 1980s (Fig. 1.2) and the first attempt to assemble all these data in the African Magnetic Mapping Project (Barritt, 1993), it became possible to build a digital database of dykes from aeromagnetic data. Mubu (1995) made a database of over 14000 dykes for most of southern Africa using AMMP airborne magnetic data and incorporating several published interpretations. Chavez Gomez (2000) updated this database using the aeromagnetic data of eastern Africa.

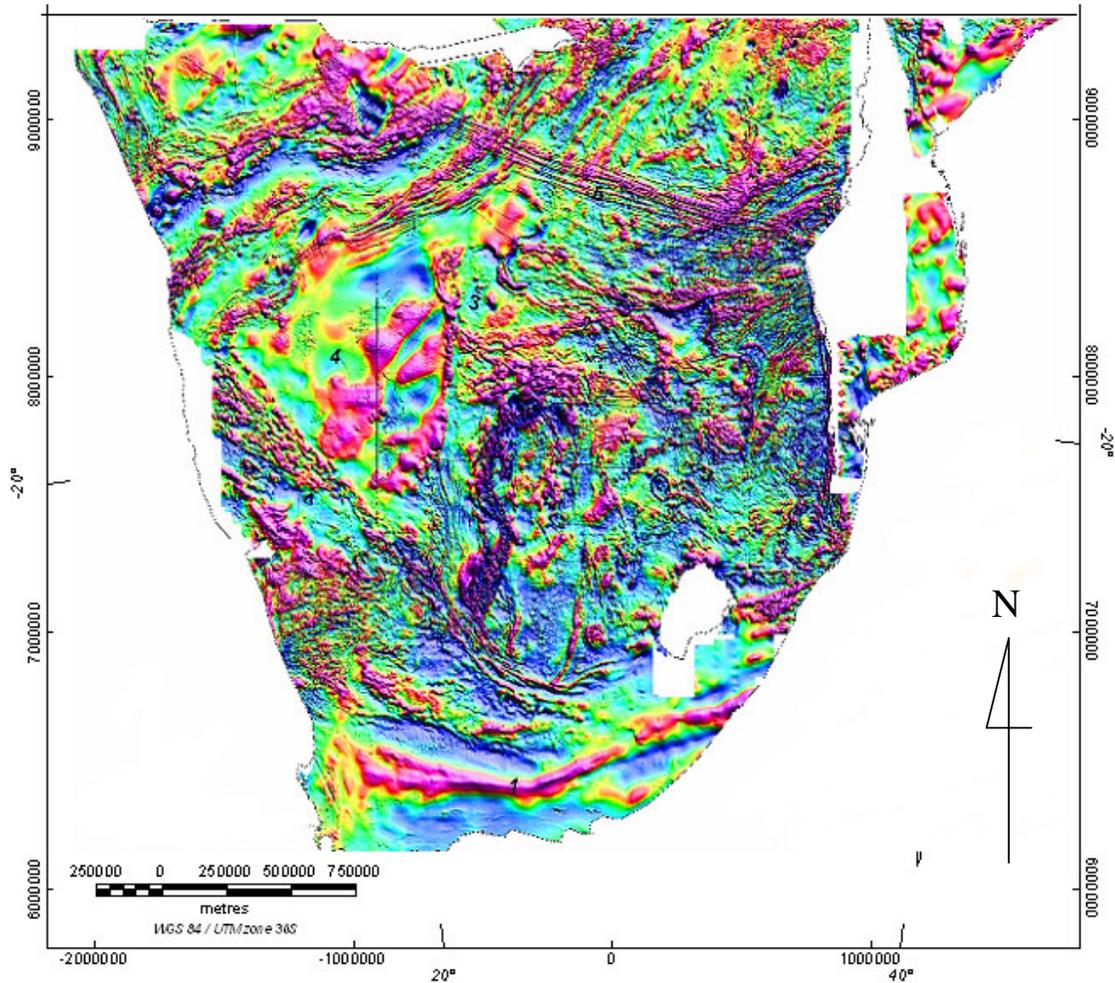
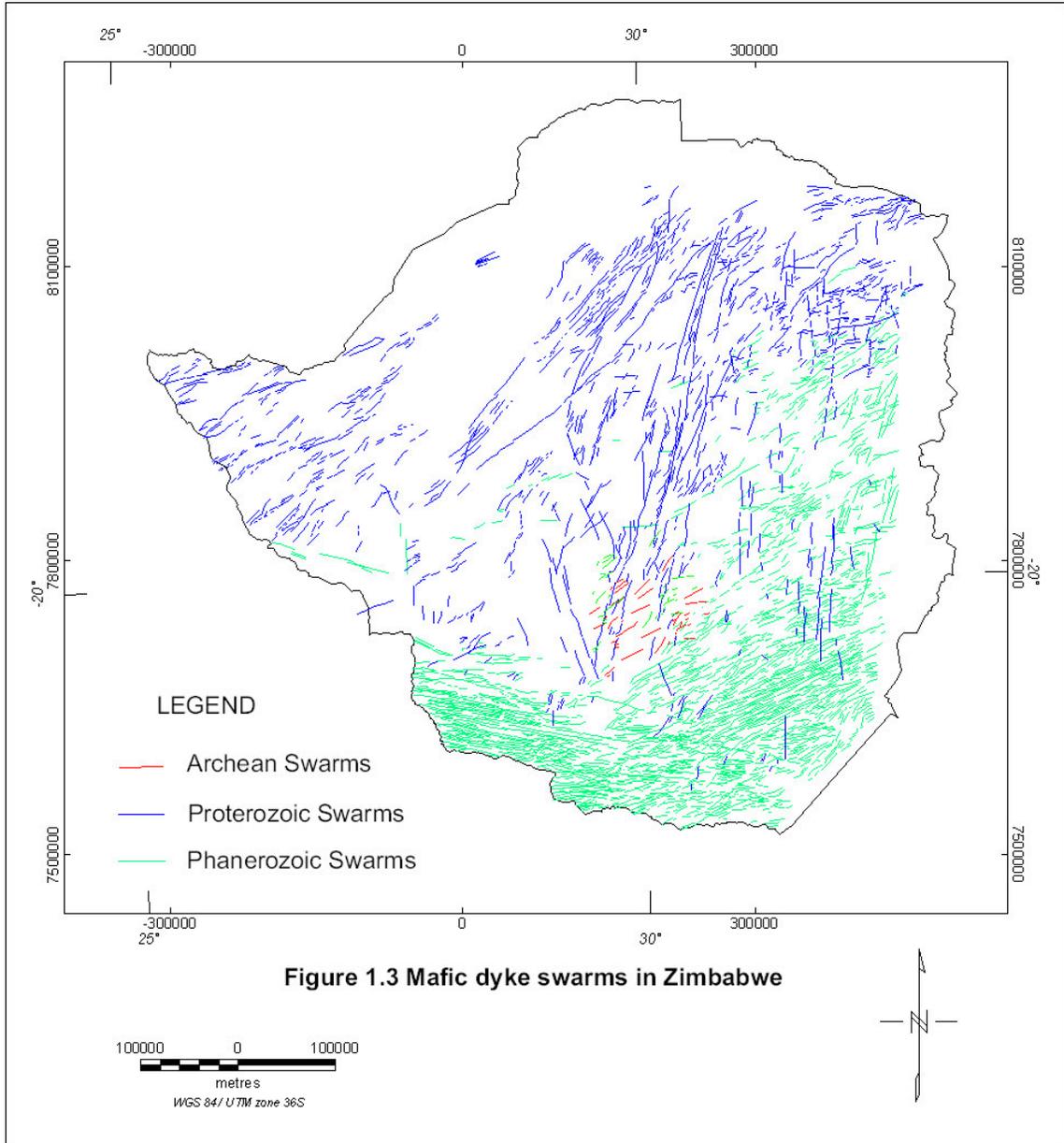


Figure 1.2- AMMP aeromagnetic survey coverage of southern Africa  
(Data Source : African Magnetic Mapping Project (AMMP))

Three Phanerozoic dykes swarms, eight Proterozoic occurrences involving dykes and/or sills, and the remnants of three late Archean dyke swarms are recognized in Zimbabwe (Wilson et al., 1987). The Archean swarms are confined to the south central part of the country and the most important Proterozoic intrusions are those of the Great Dyke and its satellites and the numerous dykes and sills of the widespread Mashonaland igneous events. The Phanerozoic dykes are represented by the Mesozoic late Karoo dolerites (200-170Ma); the major dyke emplacement is in the south and south east of the country where two long but wide and closely spaced swarms are developed (Fig. 1.3). These swarms were associated with events leading to the break-up of Gondwanaland.



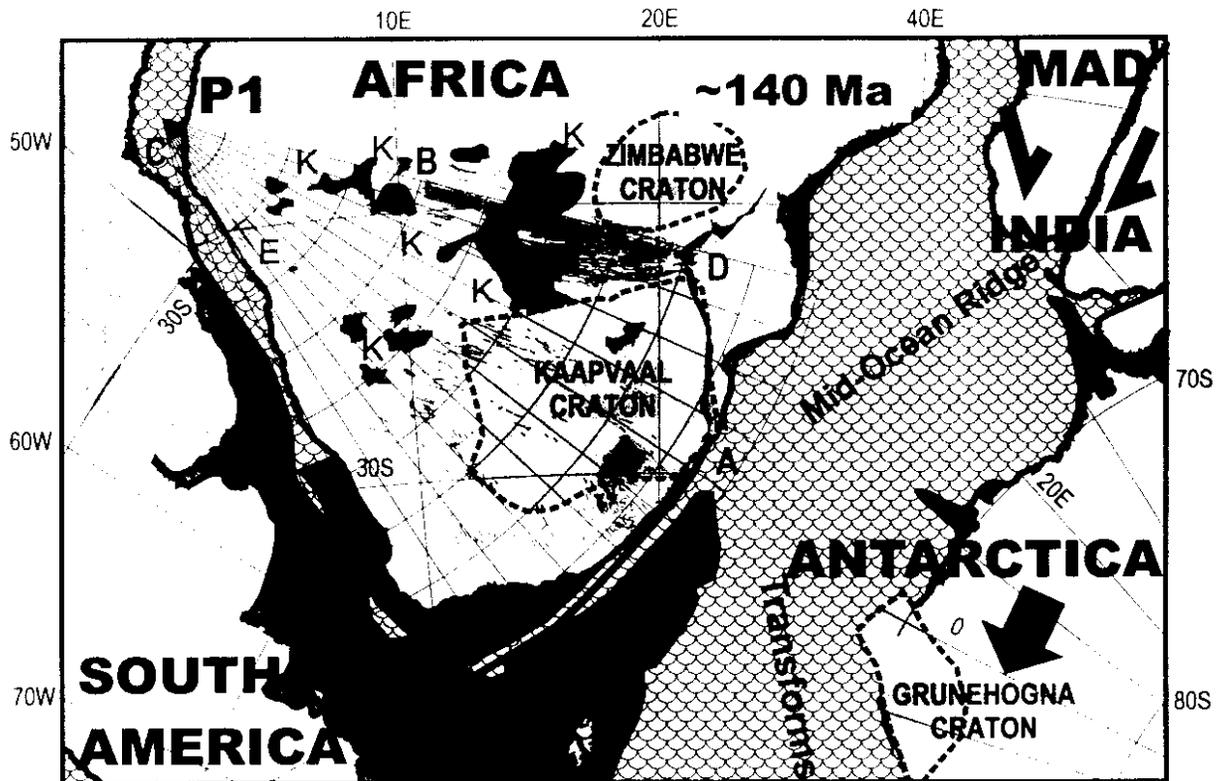


Figure 1.4 - The disruption of Gondwana (B-D: Northern Botswana dyke, A:Agulhas fault, K:Karoo basalt beneath Kalahari sand cover, E:Etendeka basalt in Namibia)  
 (Source -The geophysical mapping of Mesozoic dyke swarms in southern Africa and their origin in the disruption of Gondwana, Journal of African Earth Science, Vol. 30, No. 3, C. Reeves, 2000)

As explained by Reeves (2000), towards the start of the Cretaceous (~140Ma), East Gondwana started a clockwise rotation around southern Africa by dextral strike-slip on the Agulhas fault. The clockwise movement of East Gondwana, immediately prior to the initiation of the south Atlantic, tended to take southern Africa with it as a microplate pivoted at *P1* (Fig. 1.4). The northern Botswana dyke swarm is attributed to this phase of tectonic activity and can be observed by the magnetic data upto southern Zimbabwe. To complement this magnetic data, recent fieldwork including a complete transect of the Okavango Giant Dyke Swarm (OGDS) along the Shashe river (Northern Botswana) has provided rock samples, direct geological observation and geophysical profiling. Using Ar-Ar technique the rock samples, basalt and dolerite were dated leading to about 85% of the dykes to Middle Jurassic age ( $178.3 \pm 1.1$  to  $179.3 \pm 1.2$  Ma) the remaining are Proterozoic dykes (about 15%,  $758.2 \pm 6.6$  to  $1223.8 \pm 10$  Ma). (Dyment et al., 2003)

#### 1.4. Problem definition

The southeastern part of Africa is still a controversial region of Gondwana in the investigation of the evolution of the Mesozoic opening history of southern ocean between South America, Africa and Antarctica. Mafic dyke swarms record successive periods of magmatism and volcanism that in most

cases can be linked to continental-scale rifting and events. Dyke swarms are useful in the determination of regional crustal stress patterns through time and may relate to past plate configurations.

By extracting the dyke information from the aeromagnetic survey of Zimbabwe and new Mozambique data and incorporating the previous studies of Mubu (1995), Chavez Gomez (2000) & Bouw (in preparation, 2003), we can investigate the distribution of dykes, relation and the effects caused by the magmatism and volcanism to the shape of Gondwana by creating geodatabase in continental scale for easy access, upgrading and analysis of future use.

## **1.5. Objective of the research**

It is now understood by earth scientists that some of the emplacement of dykes of Zimbabwe and Mozambique are attributed to the tectonic movement of the plates. Eventhough there are numerous studies regarding the dykes of the study area, the availability of new and relatively high resolution aeromagnetic data and the development of latest and powerful software to manipulate, enhance and interpret invites researchers for further investigation.

### **1.5.1. General objective of the research**

The overall objective of the study is the interpretation of the aeromagnetic survey data and investigation of the use of this anomaly map to identify and delineate the mafic dykes of Zimbabwe and Mozambique. This objective also extends to generating and updating the existing database made by other researchers using universally popular and accessible software - ArcGIS.

### **1.5.2. Specific objectives of the research**

1. To identify and delineate mafic dykes from relatively high resolution aeromagnetic data using various enhancement filters and grid algorithms in conjunction with the satellite imagery so as to update and correlate the existing mafic dyke map created by Mubu (1995), Chavez Gomez (2000) and the study of Bouw (in preparation 2003).
  - The new western Mozambique grid (GSF & DNG, 2003) that was not surveyed at the time of AMMP compilation is now included and fill a most important 'hole' in the data coverage. This gives a new dimension to the research in particulate and earth scientist in general in the investigation of the tectonic activity and related rifting on this part of Gondwana.
2. To upgrade and generate a user-friendly digital database of dykes using universally applied software from the new work to be done (e.g. aeromagnetic data), in conjunction with the existing database created for mafic dykes of southeast Africa by Chavez Gomez, 2000.

3. Establish the relationship of dykes to major tectonic structure, intrusion, volcanic activity and implication of tectonic activity.

## **1.6. Research questions**

- General
  - Based on the work of Chavez Gomez and Bouw, can we do more to understand the distribution of dykes in Zimbabwe and Mozambique and their relation to tectonic activity using the aeromagnetic expression?
- Specific
  - Can we establish a relationship of dykes to major tectonic events from their distribution of the study area?
  - What are the criteria for creating a user-friendly GIS database system of the study area using the aeromagnetic survey data and previous works?

## **1.7. Outline of the thesis**

The thesis is divided in to five chapters. This first chapter has given an introduction to the overall view of the thesis and the study area. In the second chapter what has been done upto now in the study of mafic dykes worldwide will be reviewed, including the geology, tectonic setting and types of dykes of the study area. Chapter three discusses in detail the type of data used, the methodology, processing techniques applied on the magnetic and remote sensing data. Chapter Four shows how the database is constructed and how to use it. In Chapter Five the analysis and interpretation of the output result will be explained. It also includes the summary of the findings of this study and the major conclusions with recommendations will be given.

## 2. Literature review

### 2.1. Study area review

Many earth scientists have drawn attention to the southern part of Africa, which include countries like South Africa, Botswana, Lesotho, Swaziland, Mozambique and Zimbabwe. Interpretation of magnetic survey data in local and regional scale has provided a great deal of information in mineral exploration. Dykes of various ages and types have been recognized in cratonic, orogenic and sedimentary environments throughout Africa.

#### 2.1.1. Regional view

Reeves (1993) pointed out that aeromagnetic survey compilation has been done at the continental scale in several areas in cooperation with other partners. The compilation of magnetic data is useful to study the structures at global and continental scale. However, aeromagnetic surveys are usually conducted at the national scale and each has its own different specifications. Using a common reference datum provides the opportunity to display magnetic signature and the continuity of dykes in continental or regional scale without interruption at national boundaries. This is very useful, especially when the structure is covered by sediments e.g. the Kalahari of Botswana.

The African Magnetic Mapping Project (AMMP) (Barritt, 1993) was launched to compile aeromagnetic anomaly data into a digital dataset for the whole of the African continent. The aeromagnetic survey data incorporated in the project had digital grids, digital line data or contour map formats and each of these formats had their own diversities like the type of post processing and map scale. The final product of the AMMP project included:

- Survey atlas which contains the colour location maps and technical details of all magnetic survey for each country
- Survey dataset with all information regarding original survey specification, processing and reprocessing
- Digital dataset- the final 1 km grid covering the continent of 1:5,000,000 map sheet
- Map atlas- colour shaded relief map 21 maps at 1:2,000,000 scale

The output of unified dataset becomes a powerful tool for determining the structure, process and tectonic evolution of the continent, together with providing information valuable in the reconstruction of

the Gondwanaland supercontinent. In this regard, it is also useful for the study of the research area although it is not complete in some parts of the continent (Fig. 2.1).

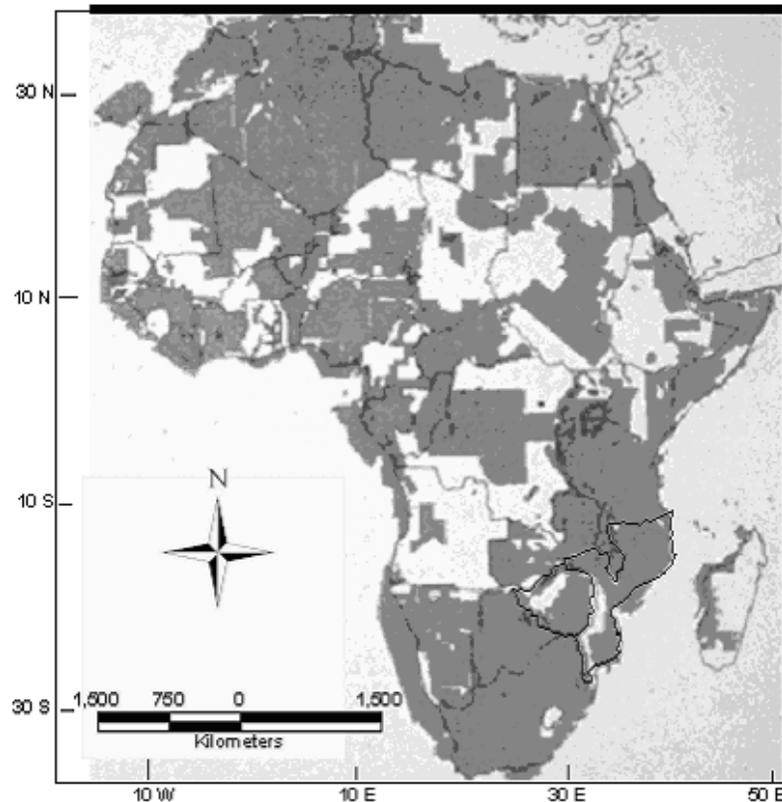


Figure 2.1 - The AMMP compilation of aeromagnetic data up to 1990

### 2.1.2. Local view

The economy of the Republic of Zimbabwe is largely sustained by agriculture and mining. The Mineral industry was diverse with more than 35 commodities produced from more than 1000 mines. The country is noted for its variety of economic minerals, which includes gold, chrome, lithium, asbestos and cesium, mines high quality emeralds and for many years was the world's largest producer of corundum (Bartholomew, 1990). Diamond was also produced previously on a small-scale but recent discoveries of diamondiferous kimberlites in an area bordering the Limpopo River invite more interest to the country.

Mozambique's geology is highly varied, containing a wealth of minerals including coal, natural gas, rare earth minerals, gold, titanium and non metallic minerals, with potential for oil and diamonds. Most of the country's mining output is derived from 3 major concerns, which includes gold, bauxite and graphite. Gold production in Mozambique is based mainly around the deposits of the Archean Muare-Manica greenstone belt, close to the Zimbabwe border. Prospecting for diamonds has been going on since the 1920's. In the 1970's diamondiferous bodies were found in the Zumbo region close to the Zambian border. (<http://www.mozambique.mz/economia/invoppt/mineral.htm>)

As can be seen in Fig. 2.1, part of the area around the border between Zimbabwe and Mozambique is not covered by the aeromagnetic survey compilation of AMMP. Recently acquired, a relatively high-resolution aeromagnetic survey of the western Mozambique (GSF & DNG, 2003) and Zimbabwe (Geological Survey of Zimbabwe) provide insight into the buried geology and complex dyke swarms.

Previous studies like Mubu (1995) using a low resolution 1 km grid AMMP dataset and Chavez Gomez (2000) using interpretation of aeromagnetic map with superimposed geological contacts shows a great deal of dykes in the study area. The high resolution aeromagnetic grid dataset of Zimbabwe and the new Mozambique aeromagnetic survey with the developing image enhancement software will help now to extract dyke swarms in detail in this study.

## **2.2. Geological setting**

Barritt (1993) explained that Africa represents 22 percent of the world's land area, made up of a vast stable crystalline basement of very old rocks, mainly of Precambrian age. It is the largest continuous block of Precambrian shield and hosts a large portion of Africa's mineral wealth, while the continental margins, areas of intra-plate faulting (which stopped short of disruption) and epeirogenic basins are the main loci of Mesozoic and Tertiary sedimentation that could host significant hydrocarbon accumulations.

The Precambrian basement of Africa can be divided into three large masses or cratons namely, the Kalahari, Congo, and West African cratons. They are separated from each other by a number of mobile belts active in late Precambrian and early Paleozoic times. The Kalahari mega-craton comprises the Archaean terrains of the Kaapvaal (3.7-3.0 Ga) and Zimbabwe (3.5-3.0 Ga), which are separated by the  $\approx 2.7$  Ga Limpopo Belt (Fig. 2.2).

### **2.2.1. Precambrian Geology of the Study Area**

The Zimbabwe craton is a heterogeneous assemblage of crystalline basement rocks of Archaean age comprising greenstones, mafic and ultramafic rocks, gneisses and migmatites and late intrusive granites (Carruthers et al., 1993) (Fig. 2.3). The entire Archean basement complex is intruded by the Great Dyke hosting the world's largest reserve of chrome and platinoids. Covering the edge of the Archean terrain are younger sedimentary rocks with huge coal reserves.

To the south the Zimbabwe craton is flanked by the Archean high grade terrane of the Limpopo belt which extends into South Africa and Botswana. To the east and north the craton is flanked by the Mozambique and Zambezi mobile belts. To the west the craton is overlain by rocks ranging from early Proterozoic to Phanerozoic. In NW Zimbabwe the oldest of these cover sequences are, from east to west, the Deweras, the Lomagundi and the Piriwiri Groups (Wilson et al., 1987).

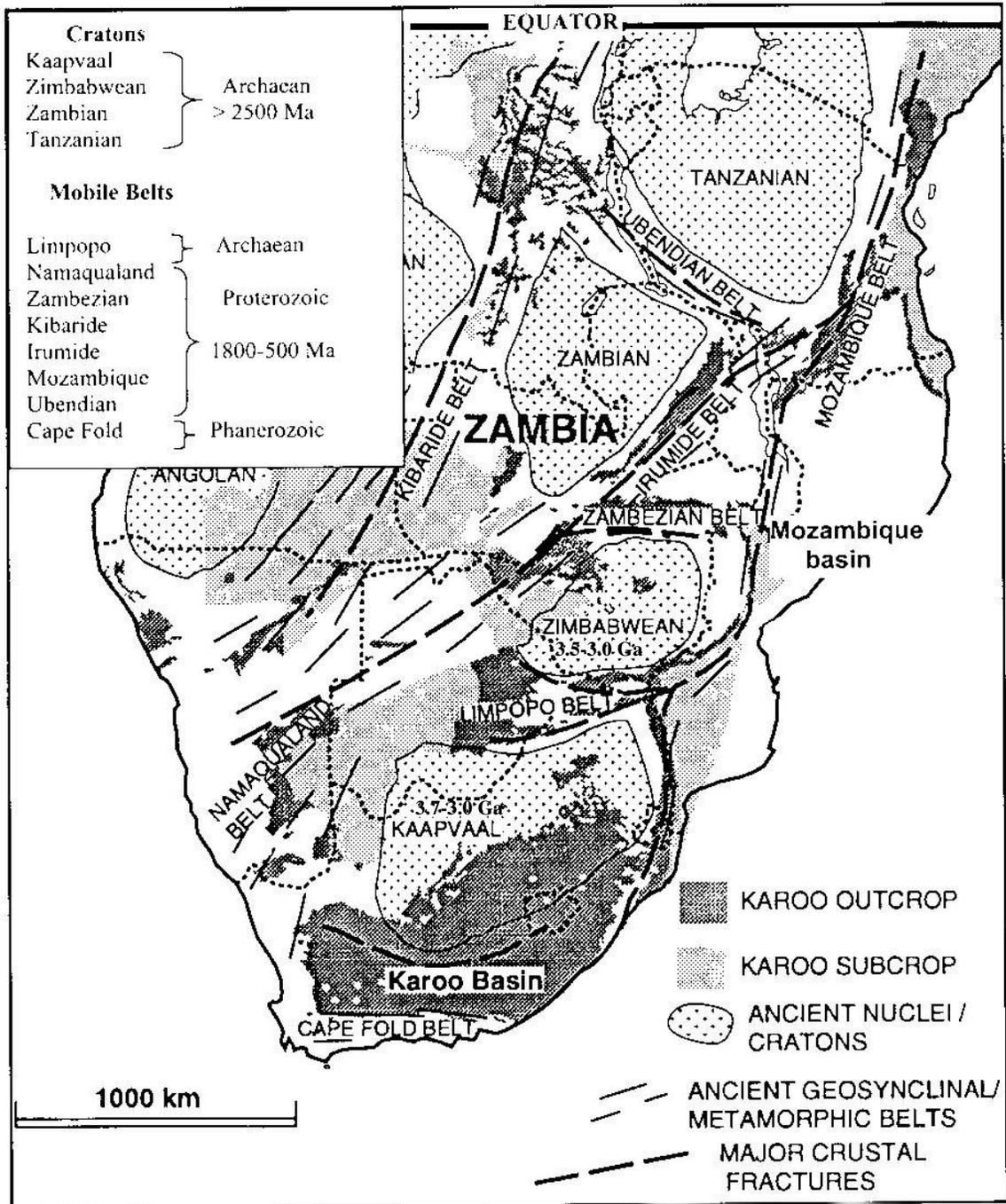


Figure 2.2 – The tectonic structure of Southern and Eastern Africa

(Source - Chavez Gomez, modified from Nyambe, 1999; de Wit et al., 1988; Reeves, 1978; Morrison, 1985; Oberhoize and Souza, 1976; Miller and Schalck, 1990, and Du Plessis et al., 1984)

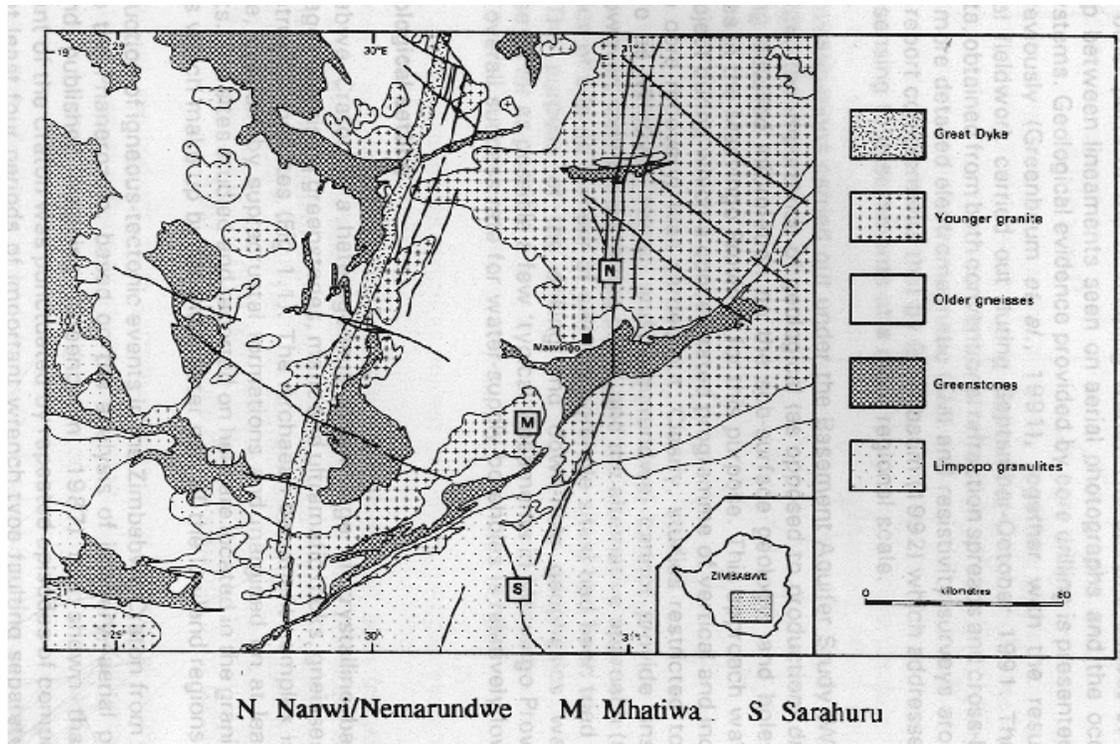


Figure 2.3 Regional geological map of the Zimbabwe craton.

(Source : Geological and geophysical characterization of lineaments in southern Zimbabwe, 1993, British Geological Survey)

The greenstone belts, representing the folded remains of more widespread volcano-sedimentary piles, are of three different ages. The oldest are those of the 3500-Ma Sebakwian Group; a second set the most widely developed, make up the lower part of the ~2700 Ma, consists of the upper part of Bulawayan Group and overlying, locally developed Shamvaian Group. The last one is a complex array of granites and gneisses, ranging in age from ~3500 to 2600 Ma.

Mozambique's geology is highly varied and consists mainly of Precambrian terrains (ranging from Archean to Upper Proterozoic rocks), covered predominantly in the south by Phanerozoic cover (ranging from Jurassic through to Tertiary rocks). Precambrian rocks underlie approximately half of Mozambique, mainly in the north and northwest of the country. The basement consists mainly of gneiss, schist, quartzite and limestone and partly contains mineral veins associated with alluvial gold deposit. Sedimentary and volcanic rocks of Karoo age (300-180 Ma) crop out in a narrow band along the western border. Karoo formation consists largely of conglomerate, sandstone schist and coal with some basalt (UN, 1989).

Jurassic sediments (180-135 Ma) include sandstone, conglomerate and limestone. These are minor but are found in the most northern part of the country. Cretaceous sediments (135-65 Ma) form mostly on the westerly limits of the lowland areas. These sediments consist of sandstones, some being calcareous, as well as clays and carbonate with occasional conglomerate which crop out around the central part of the country (UN, 1989).

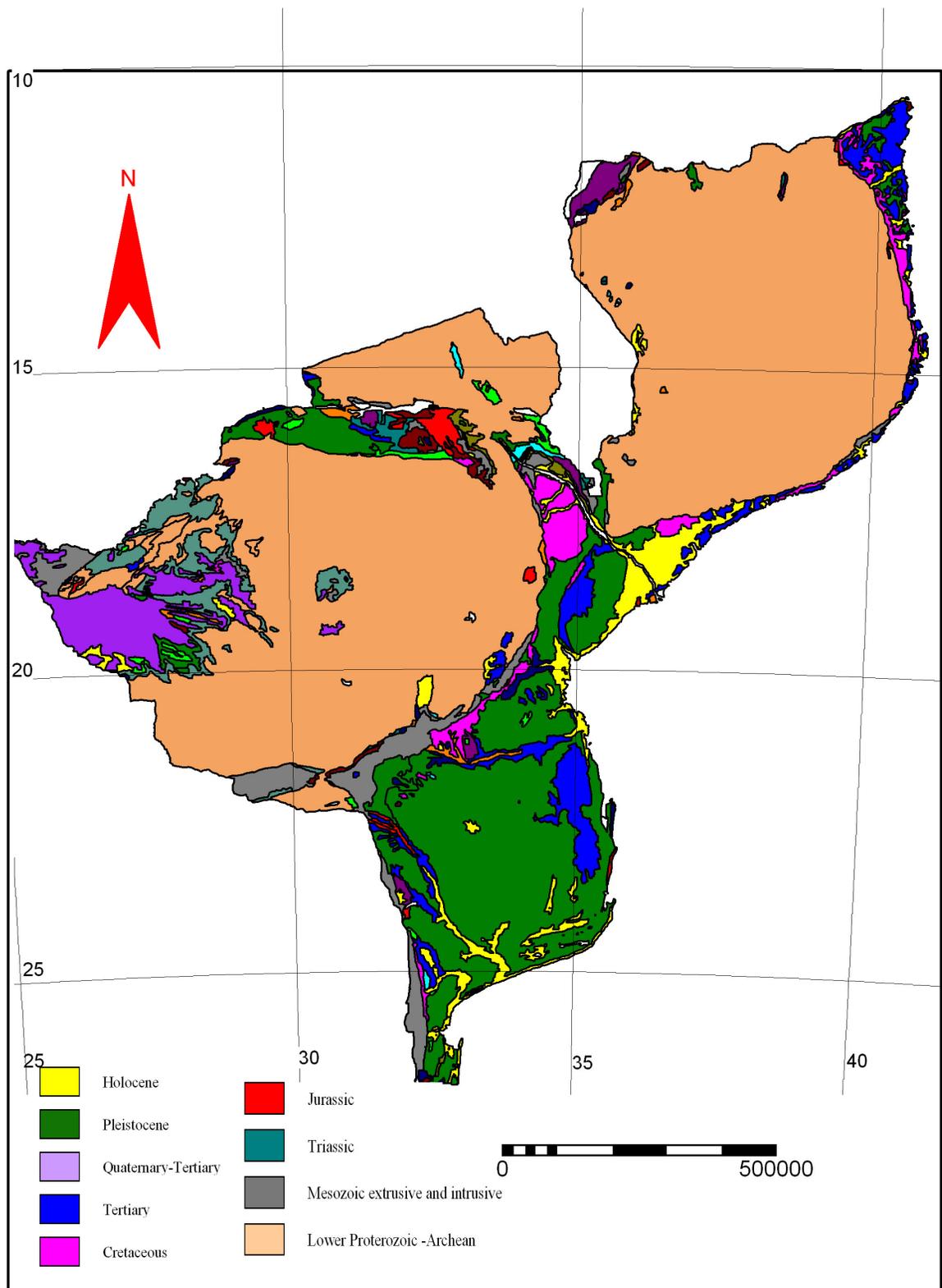


Figure 2.4 - Geological age Map of the study area  
(Source - US Geological Survey, 2000)

Tertiary sediments (65-2 Ma) mainly consist of marine carbonates and sandstones and are found in the coastal region of northern Mozambique and some southern part. Quaternary sediments consist mainly of unconsolidated sand, clay and limestone as coastal dunes, river alluvium and locustrine deposits in large part of southern Mozambique (UN, 1989) Fig. 2.4.

### 2.2.2. Phanerozoic geology

The period following the close of the Precambrian is known to have been tectonically stable. During this period of stability basins developed on continental sags and fault bounded troughs. In southern Africa these basins include the Karoo Basins (285-150 Ma), The Kalahari basin and Karoo troughs bordering the Proterozoic mobile belts in Zimbabwe, Mozambique and Namibia (Fig. 2.2 & Fig.2.5).

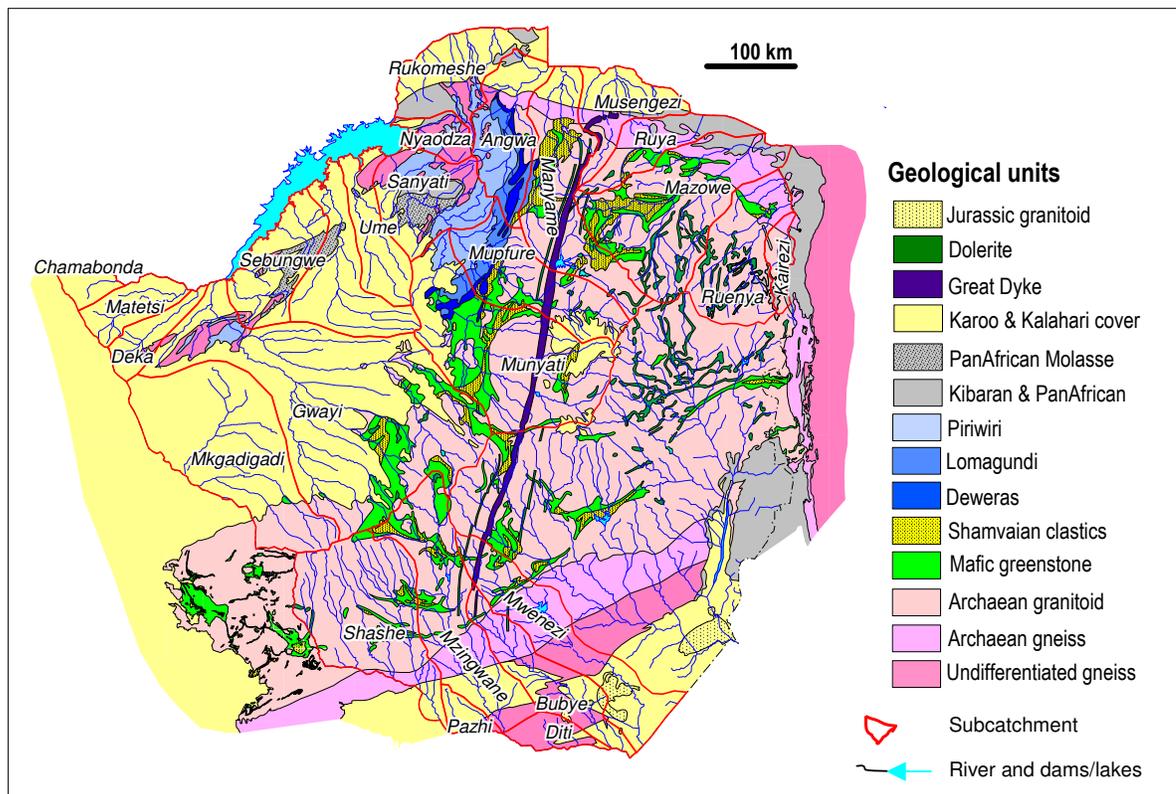


Figure 2.5 Distribution and extent of different geological units of Zimbabwe  
(Source Geological Survey of Zimbabwe - <http://www.mining.wits.ac.za>)

During the Carboniferous, land masses on the planet had coalesced into the supercontinent known to us as Pangaea but towards the end of the Triassic (225-200 Ma) it began to break up into two smaller land masses - Laurasia in the northern hemisphere and Gondwana in the south.

(<http://www.trump.net.au/~joroco/gondwanastory.htm>)

**Laurasia** was the Northern landmass formed 200 million years ago by the splitting of the single world continent Pangaea. It consisted of what was to become North America, Greenland, Europe, and

Asia, and is believed to have itself broken up about 65 million years ago with the separation of North America from Europe. (<http://www.hometown.aol.com/rsknol/Laurasia.html>)

**Gondwana** is the name for a continent that broke up in the Jurassic period (200 to 140 Ma). Gondwana included the modern southern hemisphere continents of Antarctica, Australia, Africa, South America, India and Madagascar. (<http://kartoweb.itc.nl/gondwana/page6.html>)

The accumulation of sediments in some basins triggered the reactivation of boundary faults in turn leading to minor tectonic activity of which the fingerprints have been masked by Phanerozoic cover that accumulated. The imprints of this period are seen as the major structural features and faults that controlled sedimentation during the Phanerozoic, particularly the Karoo rocks and the emplacement of dyke swarms and the basaltic lavas.

The dispersion of Gondwana and the creation of the Indian Ocean were preceded by a number of major igneous events. At 182 Ma, extensive basalt outpourings in southern Africa (so-called Karoo basalts) are evident. They have their equivalent over large areas of Antarctica. This event occurred when the first separation of Gondwana was just getting started.

### 3. Methodology

The steps taken for completing this research can be generalized into four groups (Fig 3.1).

1. Reviewing various literature
2. Reviewing and processing of existing database
3. Processing and interpretation of aeromagnetic data and satellite image
4. Construction of database

Previous geological and geophysical studies have identified and mapped dykes in general (e.g. Vail, 1970; Reeves, 1978; Bristow, 1982) and the study area in particular e.g. (Wilson et al., 1987; Mubu, 1995; Chavez Gomez, 2000) using the data available at the time and fieldwork outputs. The work started by gathering this information and reviewing various literature regarding mafic dyke swarms and their occurrences worldwide and the variety of settings around the study area. The review included exploring the regional geology of the area, the geological relationship of dyke swarms, their relative ages and many other relevant information.

The GIS database created for the dykes of eastern and southern Africa (Mubu, 1995 & Chavez Gomez, 2000) using low-resolution aeromagnetic data, geological and geophysical interpretation and various publications by linking spatial (e.g. geographic location and strike direction) and non-spatial (e.g. age and rock type) data include information about the dykes of the study area:

- A. Mubu (1995) produced a database of dykes for the Southern Africa that also have some of the dykes of the study area from the interpretation of the 1 km grid AMMP magnetic data and by digitizing from the geological map interpretation.
- B. Chavez Gomez (2000) produced a database of mafic dykes for Eastern and Southern Africa that also included dyke information for Zimbabwe imported from Mubu and additional interpretation from the International Geomagnetic Reference Field (IGRF) corrected aeromagnetic map with superimposed geological contacts (Geological Survey of Zimbabwe, 1996).

These databases also include some non-spatial information about the dykes such as rock type, geological age and magnetic polarity. The geological and geophysical interpreted maps and the literature searches provided the useful non-spatial information. Most of the dykes are categorized in different swarms according to their geometrical characteristics, the strike direction and references from published literature.

Bouw, 2003 (in preparation) made a detailed study of the geology of Zimbabwe and Structural interpretation of the Archean craton of Zimbabwe using aeromagnetic and other images. His output and recommendations were reviewed and used.

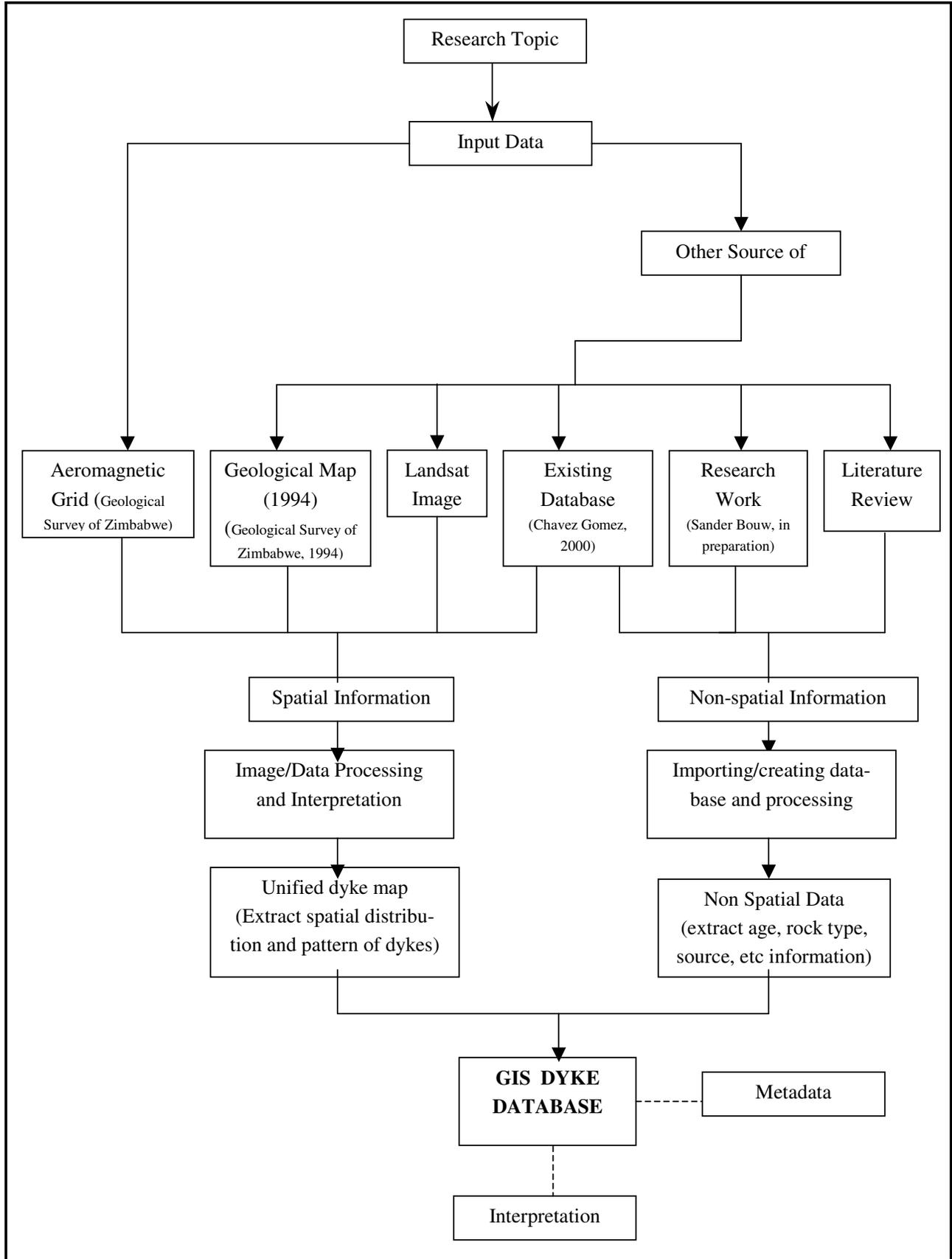


Figure 3.1 - Conceptual framework diagram

### 3.1. Available datasets

Although the main dataset of this thesis is the aeromagnetic grid, other sources of data were also used to complete the objective of this research. Dykes were digitized from various sources and imported using different software from existing database (e.g. Chavez Gomez, 2000).

The main sources of the data can be classified into two groups.

1. Aeromagnetic survey grid data
2. Former studies and thesis, geological and geophysical interpretation maps and previously created databases.

#### 3.1.1. Aeromagnetic survey grid

As mentioned before, the main source of data for this research is the aeromagnetic data. The relatively high-resolution grids can be grouped into two according to the survey area.

##### 3.1.1.1. Zimbabwe aeromagnetic grid

The grid was compiled from three surveys (Phases I, II, III) as shown in Fig. 3.2 with the specifications outlined in Table 3.1. A nominal 60 meters sample interval along line was maintained and the data were gridded on ¼ degree sections using akima spline technique with 250 meters grid cell size in Clarke 1880/Arc 1950 coordinate system. These data were regridded to the World Geodetic System of 1984 (WGS84) with Universal Transverse Mercator projection on Zone 36 south.

Date of Acquisition	1983 - 1992
Line Spacing	1 km
Observation height above ground	305 m
Instrument	Alkali Vapour and Proton precession
Total flight-line length	350,000 km

Table 3.1 – Specification of the Zimbabwe Survey

A wide variety of enhancement filters and algorithms have been used on the aeromagnetic grid data (Fig 3.3) and produced various magnetic anomaly maps. From these maps, mafic dyke swarms systematically identified and delineated.

##### 3.1.1.2. Mozambique aeromagnetic grid

As it can be seen in Fig. 2.1, one of the missing pieces in the compilation of the AMMP data is the western Mozambique area. In this thesis, recently surveyed high-resolution aeromagnetic survey shown in Fig 3.2 as grid-1 and previous survey data of AMMP grid-2 are used to interpret the dykes of these area. The interpretation was later included in the dyke database.

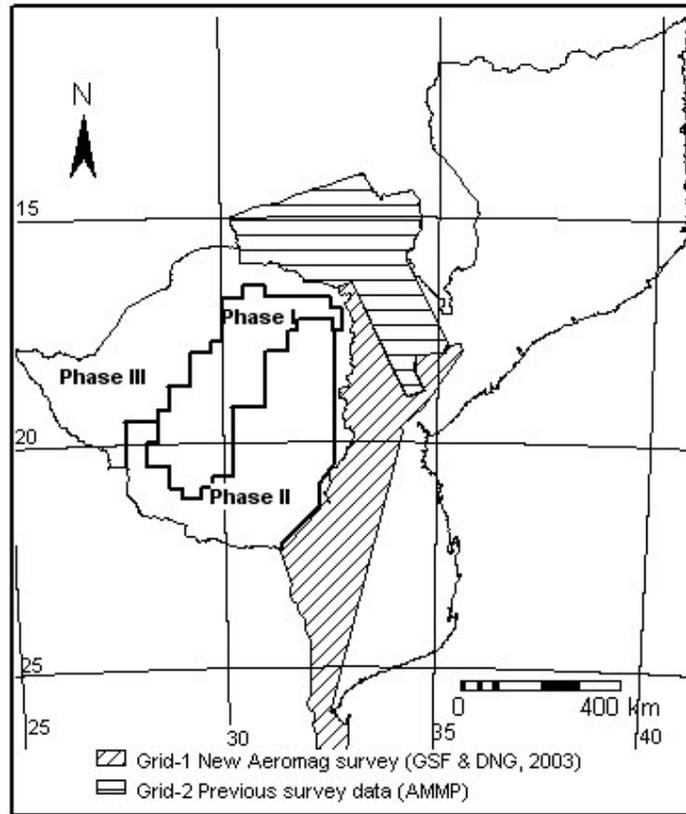
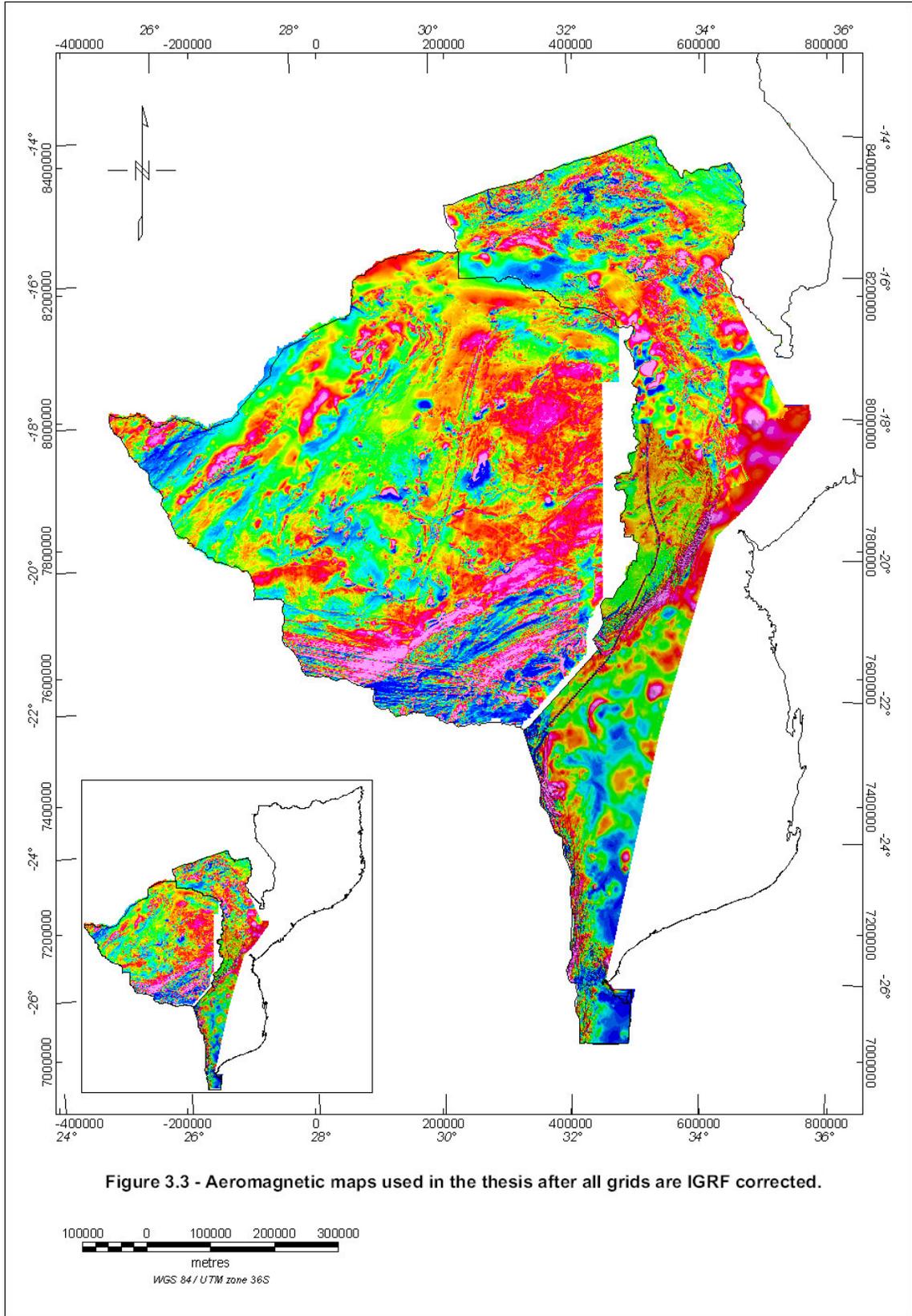


Figure 3.2 - Overview of aeromagnetic survey of Zimbabwe and Mozambique

Survey Date	214/05/03 – 24/06/03
Line Spacing	1000 m
Control Line Spacing	10000 m
Observation height above ground	100 m
Instrument	3 x Scintrex CS2 Cesium Vapour

Table 3.2 – Specification of the new Mozambique Survey

The Survey was conducted using the specification shown in Table 3.2 with recorded interval of 0.1 sec., approximately 7m and gridded with 250m grid cell size in World Geodetic System of 1984 (WGS84). The survey data was received for the southwestern part (grid-1) without The International Geomagnetic Reference Field (IGRF) removal and northwestern part (grid-2) with IGRF corrected. Since the xyz file has not been available, to remove the IGRF the grid was exported into the Oasis montaj database. The IGRF correction was made using Geosoft Geophysical Levelling system by calculating the IGRF channel for the specified survey date. The overall aeromagnetic survey data used in this thesis can be seen in Fig. 3.3.



### 3.1.2. Geological map

Published dyke interpretation from geological and geophysical maps is also included in the database. The author digitised the Recognized dykes, which are plotted in the digital Geological Map of Zimbabwe (Geological Survey of Zimbabwe, seventh edition 1994, scale 1:1,000,000) and extracted non-spatial information incorporated with it (e.g. rock type, age). This output later integrated with previous interpretation. World Geodetic System of 1984 (WGS84) with a Universal Transverse Mercator projection in Zone 36 of the Southern Hemisphere has been used.

### 3.1.3. Satellite image

The satellite image of Enhanced Thematic Mapper Plus (ETM+) was used in an attempt to determine the sequence of emplacement of dyke swarms in the Limpopo valley and Northern Botswana. A mosaic of three scenes of the ETM+ was created using ERDAS IMAGINE 8.6 for the Path 168 row 75, Path 169 row 75 and Path 170 row 75 (see Fig 3.4). It is georeferenced and projected also to WGS84, Universal Transverse Mercator Zone 36S. This will make it easier to determine the emplacement by overlaying the previously interpreted and digitized dykes and other maps on the image.

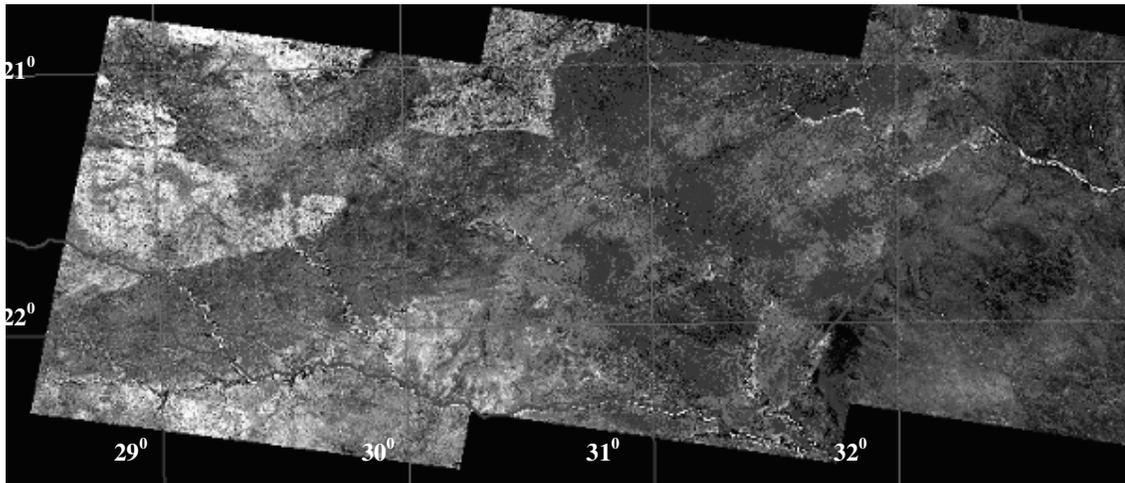
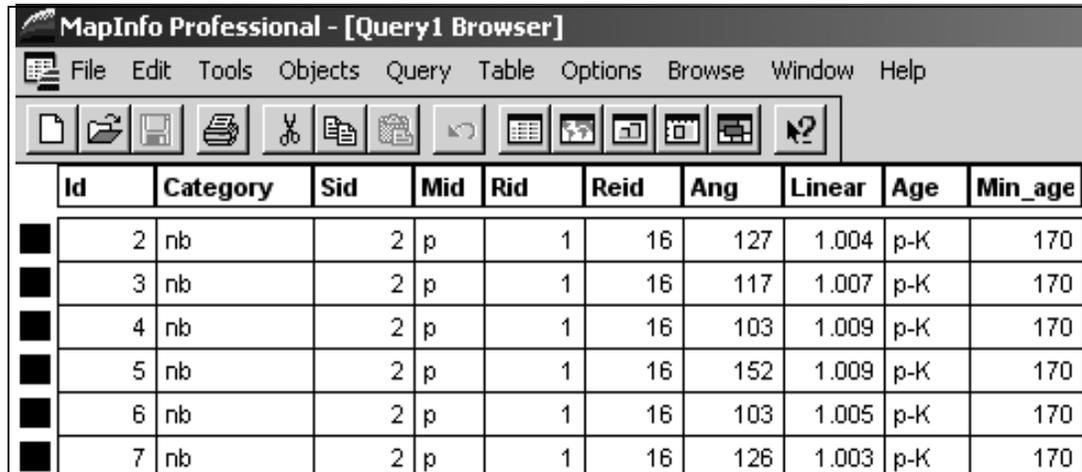


Figure 3.4 Landsat 7 three scenes mosaic of band 7,3 and 1

### 3.1.4. Existing database

Two databases made by Mubu (1995) and Chavez Gomez (2000) exists for the study area. In this thesis Chavez's database was used since it also comprises the Mubu database. The database was based on Mapinfo software. Because of the growing popularity and relation with major GIS software, in this thesis the ArcGIS 8.3 is preferred.

The first task was to review the database and the maps and extract the necessary information for the objective. It has also to be exported to the appropriate software and projected to the same coordinate system of the magnetic and remote sensing images. An example of the database can be seen in the table 3.3 below.



	Id	Category	Sid	Mid	Rid	Reid	Ang	Linear	Age	Min_age
■	2	nb	2	p	1	16	127	1.004	p-K	170
■	3	nb	2	p	1	16	117	1.007	p-K	170
■	4	nb	2	p	1	16	103	1.009	p-K	170
■	5	nb	2	p	1	16	152	1.009	p-K	170
■	6	nb	2	p	1	16	103	1.005	p-K	170
■	7	nb	2	p	1	16	126	1.003	p-K	170

Table 3.3 – Chavez Gomez main database content

### 3.2. Data processing

The aeromagnetic data used in this study is three grids provided by Geological Survey of Zimbabwe and The Ministry of Mineral Resources and Energy of Mozambique. The Zimbabwe grid (Geological Survey of Zimbabwe) was compiled from three aeromagnetic surveys between 1983 & 1992 with a total of 350,000 line kilometres. The data were gridded using an akima spline technique with a 250 meters grid cell size in Clark 1880/Arc 1950 coordinate system.

The Mozambique airborne survey (aeromagnetic and radiometric) data acquisition and processing were conducted in 2003 by Fugro Airborne Survey at request of The Ministry of Mineral Resources and Energy of Mozambique /National Directorate of Geology (DNG) with the cooperation of the Geological Survey of Finland. A high-resolution cesium vapour magnetometer with magnetic data recording interval of 0.1 second, approximately 7 meters was used for the aeromag survey. The sensor nominal terrain clearance was 100 meters with traverse line spacing of 1000 meters and control line spacing of 10,000 meters. The plotting specifications were UTM projection, WGS 1984 spheroid, central meridian 33 degree east, datum WGS84 and grid mesh size of 250 meters.

#### 3.2.1. Georeferencing & creating Mosaic

To start data processing, all the images (aeromagnetic grids, satellite images and geological maps) should have the same coordinate system and georeference to overlay, correlate and extract information from them. Since the World Geodetic System 1984 (WGS84) covers all the study area and some of the images are already in WGS84 datum, this system was preferred and used. The Zimbabwe data were gridded using an akima spline technique with 250 grid cell size in Clark 1880/Arc 1950 coordi-

nate system. These data were regridded to the World Geodetic System of 1984 (WGS84) with Universal Mercator Projection in zone 36 of the Southern Hemisphere (UTM zone 36S). The Mozambique data was already gridded using the same coordinate system.

The Digital geological map of Zimbabwe and the satellite images are also georeferenced with the World Geodetic System 1984 spheroid in Universal Transverse Mercator Zone 36 Southern Hemisphere projection. To see the regional view of the area three scenes of satellite images of southern Zimbabwe were stitched using Erdas Imaging version 6 software.

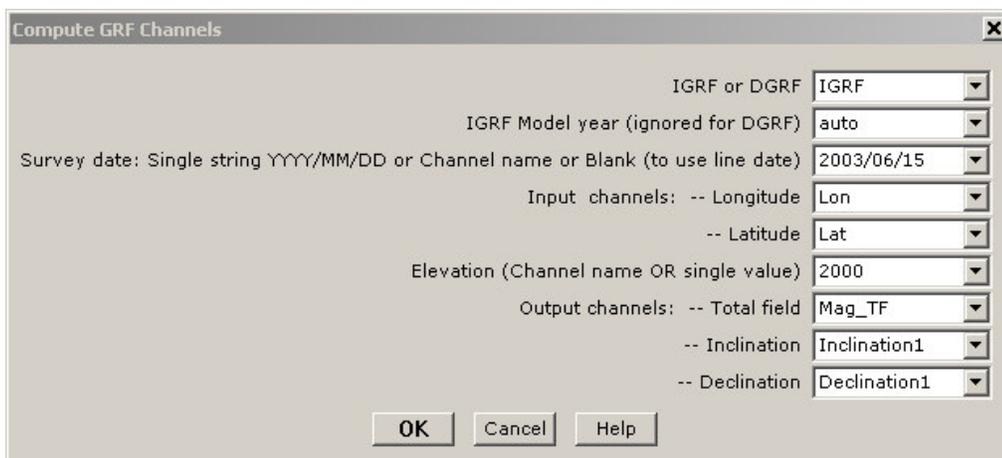
### **3.2.2. Removal of earth normal magnetic field ( IGRF Corrections)**

Although the procedure employed for removal of the Earth's normal magnetic field is not stated, for the Zimbabwe and the north western Mozambique (grid-2) aeromagnetic grids the IGRF are already subtracted. The other Mozambique survey grid (grid-1) was the only grid for which the normal magnetic field had not been removed.

The International Geomagnetic Reference Field (IGRF) is a mathematical model of the normal magnetic field background of the Earth. This model is a function of date location and elevation, and the model is updated every five years based on magnetic observations from base stations located throughout the world. A magnetic survey can be corrected for the IGRF by subtracting the IGRF model value at each point in the survey.

Using Geosoft's Geophysical Levelling system, the IGRF channel has been calculated and later subtracted from the magnetic channel. The following method is employed for the removal of earth magnetic field –

- Since we do not have the xyz file for the aeromagnetic survey data, a database is created from the grid file.
- Using Oasis montaj projection & coordinate feature, the latitude and longitude of the xyz file is calculated.
- Using the IGRF GX Module the program calculates the IGRF model at the longitude, latitude points specified in the lat and lon channels. The field is calculated for June 15, 2003 at an elevation of 100 meters. The IGRF strength (nT) is placed in the Total Field channel (Mag\_TF1) and Inclination /Declination results are placed in a specified channels (Table 3.4).
- The IGRF model used to calculate the field strength is –



- The Earth’s normal magnetic field is removed from the magnetic channel by subtracting the calculated IGRF model.
- Finally the xyz file regridded using the IGRF corrected column.

L4:0	X	Y	Lon	Lat	Z	z	Mag TF1	IGRF Cor1
0.0	415914.83	7030117.34	32.09.13.14	-26.50.52.87	28817.40	28724.3	93.09	
1.0	416164.83	7030117.34	32.09.22.20	-26.50.52.92	28916.18	28724.7	191.46	
2.0	416414.83	7030117.34	32.09.31.26	-26.50.52.98	29019.92	28725.1	294.79	
3.0	416664.83	7030117.34	32.09.40.31	-26.50.53.03	28935.98	28725.6	210.43	
4.0	416914.83	7030117.34	32.09.49.37	-26.50.53.09	28888.17	28726.0	162.21	
5.0	417164.83	7030117.34	32.09.58.43	-26.50.53.14	28861.59	28726.4	135.22	
6.0	417414.83	7030117.34	32.10.07.49	-26.50.53.19	28886.10	28726.8	159.32	
7.0	417664.83	7030117.34	32.10.16.55	-26.50.53.25	28860.27	28727.2	133.07	
8.0	417914.83	7030117.34	32.10.25.61	-26.50.53.30	28841.28	28727.6	113.66	
9.0	418164.83	7030117.34	32.10.34.66	-26.50.53.35	28819.89	28728.0	91.88	
10.0	418414.83	7030117.34	32.10.43.72	-26.50.53.40	28808.72	28728.4	80.28	
11.0	418664.83	7030117.34	32.10.52.78	-26.50.53.46	28803.72	28728.9	74.87	
12.0	418914.83	7030117.34	32.11.01.84	-26.50.53.51	28776.95	28729.3	47.68	
13.0	419164.83	7030117.34	32.11.10.90	-26.50.53.56	28811.55	28729.7	81.88	
14.0	419414.83	7030117.34	32.11.19.95	-26.50.53.61	28795.86	28730.1	65.77	
15.0	419664.83	7030117.34	32.11.29.01	-26.50.53.66	28767.64	28730.5	37.13	
16.0	419914.83	7030117.34	32.11.38.07	-26.50.53.72	28760.45	28730.9	29.53	
17.0	420164.83	7030117.34	32.11.47.13	-26.50.53.77	28852.71	28731.3	121.38	

Table 3.4 – Overview of the IGRF correction process

**X,Y** - Extracted points from the aeromagnetic grid that cover the survey area with WGS84 Universal Mercator Projection in zone 36 of the Southern Hemisphere (UTM zone 36S).

**Lon/Lat** - The corresponding longitude and latitude values of the survey area calculated from the X,Y using Oasis montaj in deg.min.sec.

**Z** - The final levelled and corrected magnetic channel (nT).

**Mag\_TF1** - Contains the calculated IGRF strength for the corresponding specified lat/lon (nT).

**IGRF\_Cor1** - Contains the IGRF corrected field.

### 3.2.3. Image enhancement

Image enhancement deals with the procedure of making a raw image better interpretable for a particular application using various enhancement techniques to improve the visual impact of the original data for the human eye. The magnetic field at the Earth's surface contains anomalies from sources of various size and depth. To interpret these fields, it is desirable to separate anomalies caused by certain features from anomalies caused by others. How to separate the anomalies depends on what type of feature is of interest to us. Anomalies could be separated by their wavelengths and certain features become visible that would be otherwise hidden. According to the interpreter's interest, the type of filter can then be selected. Linear magnetic anomaly caused by mafic dykes can also be enhanced using various filtering methods either in space or wavenumber domain.

Wavenumber filtering refers to the isolating or enhancing of data in the wavenumber or (spatial) frequency domain. To perform wavenumber filtering it is necessary to convert anomalies in the magnetic field, represented on an X,Y coordinate system, to a two dimensional set of amplitudes over a range of frequencies or wavenumbers. This is done with the Fourier transform. The Fourier transform can be used to transform a data set in the space domain to the frequency or wavenumber domain. Once in the wavenumber domain, the proper filter can be applied. The filtered data in the wavenumber domain can then be transformed back into space domain in the same manner using the inverse of the Fourier transform (Fogarty, 1985).

The Fourier transformation was done using MAGMAP 2D FFT system exists in Geosoft®. Mathematically, the Fourier transformation of a space domain function  $F(x,y)$  is defined to be :

$$\bar{f}(\mu, \nu) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) * e^{-i(\mu x + \nu y)} dx dy$$

The reciprocal relation is

$$F(x, y) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \bar{F}(\mu, \nu) * e^{i(\mu x + \nu y)} d\mu d\nu$$

where  $\mu$  and  $\nu$  are wavenumbers in the x and y directions respectively, measured in radians per meter if x and y are in units of meters. These are related to spatial frequencies  $f_x$  and  $f_y$  which are in cycles per meter (www.geosoft.com).

In the interoperation of dykes from the grid data, different anomaly maps have been produced from various enhancement filters. Some of them are mentioned below.

#### 3.2.3.1. Shaded relief grey-scale map

Shaded relief maps are very useful in determining the geological strike, structural boundaries, faults and near surface features that cannot be clearly seen in colour maps. Human eyes can easily be deceived into seeing the magnetic variation as though they were physical topography. A simple positive

anomaly which appears white (or black) in grey scale can be made to appear to the eye as a hill by calculating the first horizontal derivative in the direction of the supposed illumination (Reeves, 1994). In order to calculate the first horizontal derivative of the magnetic field, a computer algorithm in the space domain was used by illuminating light source in a specific direction at a given azimuth and angle from infinite distance. The resulting grid can be displayed in grey scale shading to emphasize the 3D effect.

Due to the complex geology of the study area, various shaded relief images were produced using different azimuth angles for the three grid data.

**Zimbabwe grid data** – To separately emphasize specially the most prominent and giant swarms of Northern Botswana ( $N110^{\circ}$ ) and Limpopo ( $N70^{\circ}$ ) dyke swarms,  $N45E$  and  $N320W$  azimuth respectively have been used. Using  $45^{\circ}$  &  $300^{\circ}$  inclination and declination angles respectively, both swarms are enhanced as shown in Map-1 and part of the delineated dykes in Slide-1.

**Mozambique grid-1** – In this grid the SSW-NNE dykes on Lebombo monoclines on the southwestern Mozambique extends further to the north central part of the country with the same strike after missing in the thick sediment of the Mozambique thinned zone. To emphasize these dykes,  $50^{\circ}$  &  $320^{\circ}$  inclination and declination angles have been used respectively as shown in Map 2 and the delineated dykes in Slide-2. By zooming in on the southern part of Lebombo and the surrounding area, Map-3 & Slide-3 the NNE strike dykes can be observed.

**Mozambique grid-2** - Due to the complexity of the magnetic anomaly patterns, different inclination & declination angles are used and best shading map is  $N45E$ .

### 3.2.3.2. Colour shaded images

One of the most important aspects in the design of presentable maps is the selection of the most appropriate colours. Colour images show anomaly magnitudes and long-wavelength features particularly well. However, small and low-magnitude anomalies may not be evident in colour images. The positions of colour changes are not only dependent on the positions, magnitudes, and widths of anomalies but also on how the data are assigned colours in image processing. Different colour lookup tables effect different colour distributions in an image. A greyscale image is more useful for showing fine details and locating anomaly boundaries even so they do not give much indication of the magnitudes of anomalies.

The tri-Stimuli model of colour perception is generally accepted. This states that there is three degree of freedom in the description of a colour (Bakker et al., 2001). Among various three dimensional space used to describe and define colours are:

1. Red, Green & Blue (RGB) space based additive principle of colours.
2. Hue, Saturation & Value (HSV) most related to our, intuitive, perception of colour.
3. Yellow, Magenta & Cyan (YMC) space based on the subtractive principle of colours for printing images.

### 3.2.3.3. Vertical derivative

The first vertical derivative computation in an aeromagnetic survey is equivalent to observing the vertical gradient with a magnetic gradiometer and has the same advantages, namely enhancing shallow sources, suppressing deeper ones and giving better resolution of closely spaced sources. Low-pass filter also used with this filter to remove the high wavelength noise.

### 3.2.3.4. Colour shaded image of the vertical derivative using HSV

Although it is convenient to display colour using additive combination of red, green and blue primary colours on screen in a Cartesian coordinate system, a more intuitive model in terms of colour variation perceived by human eye is the hue, saturation and value (HSV) model, using cylindrical coordinate system. In HSV model, hue refers to combination of red, green and blue primary additives, value is the intensity (energy) of the colour, and saturation is the relative lack of white in colour (Fig 3.5). The human eye perceives these variations in value and saturation.

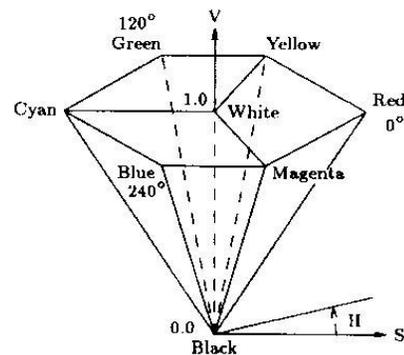


Figure 3.5 The HSV colour model

Areas in strong direct sunlight are under-saturated with excess white light reflected, whereas areas that do not get direct sunlight (in shadow) are low in value, with less intense reflected light, and hence appear to be darker. However the fundamental of the scene remains the same (Milligan & Gunn, 1997).

In Oasis montaj software, we have the possibility to assign the shading effect either Normal (RGB) - shading using RGB model or Wet-look (HSV) shading using Hue, Saturation, Value. For the "Normal (RGB)" shading effect, the specified colour table and contour interval are used to display the original grid data and the grey.tbl table is used to display the shaded-relief grid. If the "Wet-look (HSV)" effect is selected, the hsvc.tbl (Hue, Saturation, Value with colour) and hsvg.tbl (Hue, Saturation, Value with grey scale) are used to display the colour and shaded-relief grids respectively. The vertical derivative of the aeromagnetic grids shaded with HSV model were useful to delineate closely spaced dykes. This is shown using Map-4 and slide-2 and the zoomed area on Map-5 and Slide-3.

### 3.2.3.5. Reduced to pole

The shape of any magnetic anomaly depends on the inclination and declination of the main magnetic field of the earth. The same magnetic body will produce a different anomaly depending on where it happens to be. The reduction to pole filter reconstruct the magnetic field of a data set as if it were at the pole. This means that the data can be viewed in map form with a vertical magnetic field and a dec-

lination of zero. In this way the interpretation of the data is made easier and vertical bodies will produce induced magnetic anomalies that are centred on the body and symmetrical. The pole filter employs the phase as well as the amplitude spectrum.

### **3.2.3.6. Downward/upward continuation**

The purpose of the downward continuation filter is to calculate the magnetic field with the measurement plane closer to source. In this way the anomaly will have less spatial overlap and thus be more easily distinguished from one another. This process increases the amplitude of the anomaly. It also increases the noise. Short wavelength signals are from shallow sources and therefore must be removed to prevent a high amplitude and short wavelength noise data. This has been done by applying low-pass filter like Butterworth filter.

Conversely, upward continuation transforms the data into that which would have measured at a higher altitude than that at which it was actually measured. It is useful for smoothing data, among other things. Since it has fewer side effects, there is no need for noise reduction filter.

### **3.3. Software and hardware**

During this research, the author used different software in accordance with the task to be done. These includes: image processing software to enhance images and delineate features; gridding and mapping programs to grid and map aeromagnetic data and word processing, spreadsheet and database software (MS OFFICE). Some of the software used are mentioned below.

- ❖ Oasis montaj gridding, processing and mapping system (Geosoft Inc., 2002)
- ❖ ArcGIS 8.2 software (ESRI Inc., 2002)
- ❖ Integrated land and water Information System (ILWIS, 2002)
- ❖ MS Office 2000 (Access, Excel & Word)

In addition to the various software different hardware also were used

- ❖ One personal computer with Pentium IV processor
- ❖ Super VGA display screen
- ❖ Different printers, plotter and scanner

## 4. Database construction

The methodology and the steps followed in the preparation of the database are shown in Fig 3.1. The construction of database of mafic dykes of the study area are based mainly on the interpretation of available relatively high resolution aeromagnetic grids and the information extracted from existing database created by previous researchers. Mubu (1995) compiled a great deal of information on mafic dykes of southern Africa using his own geophysical interpretation and the works of others. Later, Chavez Gomez (2000) further upgraded this work using the interpretation of eastern Africa, by incorporating the eastern Africa dyke information.

After the interpretation of the aeromagnetic data and in order to transform, compile, construct & display the database, several software items were used to produce the final touch. Some of the programs used for the construction of the database starting (e.g., importing & designing to producing the final output) include:

1. Microsoft ® Visio ® 2000 SR1 (Visio Corporation, 2000)
2. MapInfo Professional version 4.5 (MapInfo Corporation, 1997)
3. Microsoft ® Access 2000 (Microsoft Corporation, 2000)
4. Microsoft ® Excel 2000 (Microsoft Corporation, 2000)
5. ESRI ® ArcGIS 8.3 (ESRI Inc, 2002)

In this research the database is constructed to be processed and displayed in ArcGis GIS program. The reasons for selecting this software includes:

1. A good capability of displaying both raster and vector images.
2. Manage and display easily by linking tabular (attribute) and geographic data.
3. Easy querying, displaying and query updating features
4. Management of unlimited vector and/or raster layers
5. The ArcGIS file type ( **.Shp**) can be easily used almost in any GIS software without intermediate program.
6. Nice final output maps and attribute data.
7. Their user-friendly behaviour and the above reasons gave them a growing popularity among users and now used by various organization.

### 4.1. Database design

The design of the database tables structures are done by modifying the previous Mubu (1995) and Chavez Gomez (2000) Model. Microsoft Visio Software is used to design the geodatabase structure as shown in figure 4.1 below.

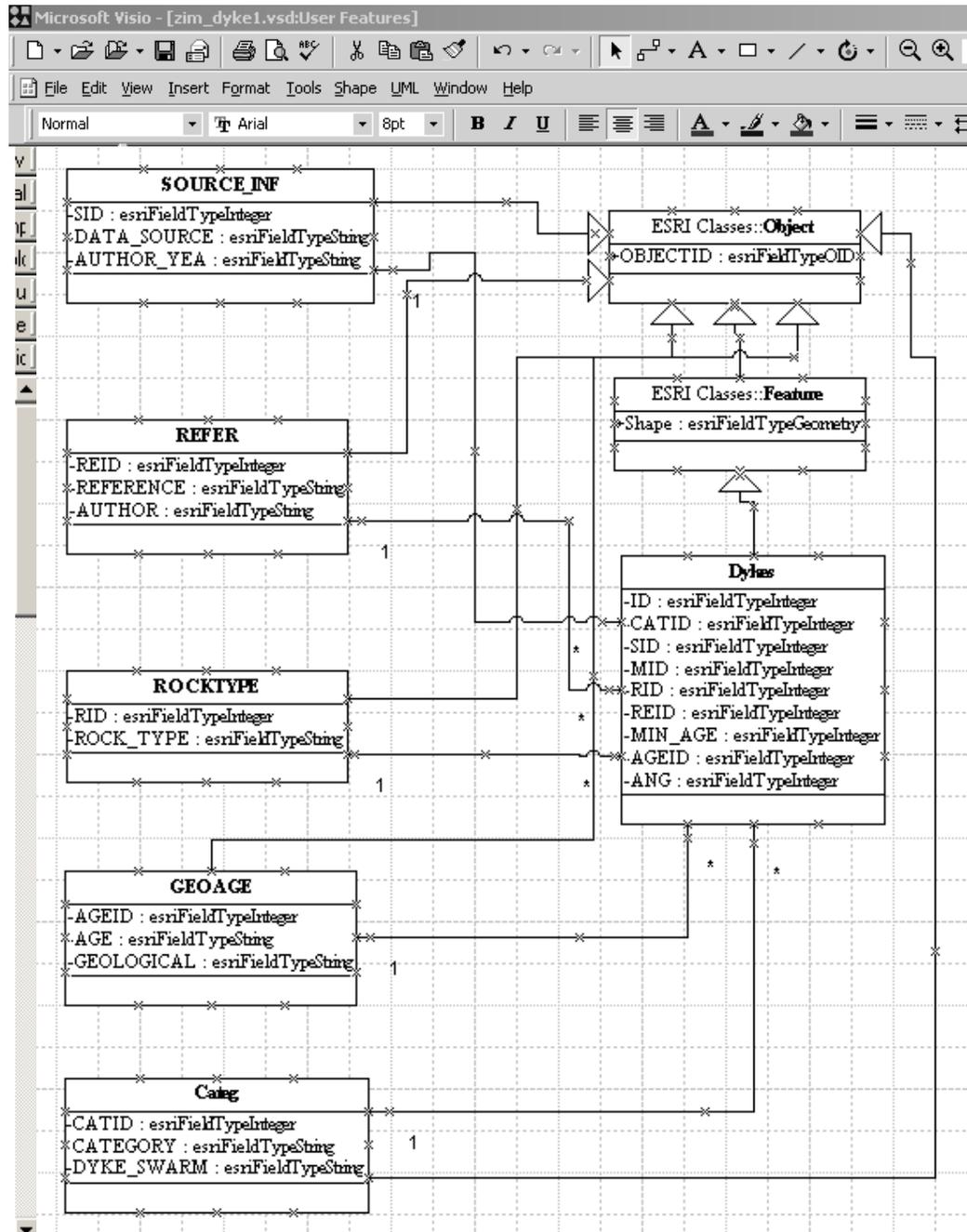


Figure 4.1 – Geodatabase design using Microsoft Visio software

The Unified Modelling Language (UML) program is used to construct the structure of the database tables and their relationship and exported to repository. The model is later exported to the ArcGIS program using ArcCatalog application.

## 4.2. Geodatabase tables structure

### 4.2.1. Main table structure

There are six tables in this geodatabase including the main table, which contains six indexed fields. These tables are related to one another through the index fields of the main table and the geographic information. The field contents and the description of each table are discussed below.

The contents of the main database table fields are:

OBJEC	ID	CATE	LON	LAT	ANG	SID	RID	REID	AGE	MIN_AGE	AGEID	CATID*	COUNTRY	Shape
4822	4987	?	27.98309	-21.4659	153	20	1	15	?	0	14	1		3494.169
4823	4988	pt	29.94869	-17.75946	39	20	1	15	eP	2150	4	37	1	33415.46
4824	4196	lp	30.78204	-20.29182	46	9	1	16	p-K	170	13	16	1	10128.38
4825	4197	sb	30.07296	-20.41554	147	9	1	9	eP	1900	4	40	1	11149.44
4826	4198	sb	29.9221	-20.484	153	9	1	9	eP	1900	4	40	1	18823.36
4827	4199	zg	29.93231	-20.60163	24	9	6	7	eP	2460	4	47	1	8930.492
4828	4200	lp	29.88861	-20.72625	50	9	1	16	p-K	170	13	16	1	14661.58
4829	4201	lp	30.03412	-20.5982	48	9	1	16	p-K	170	13	16	1	14639.03
4830	4202	sb	30.06422	-20.49866	131	9	1	9	eP	1900	4	40	1	9750.443
4831	4203	sb	29.63764	-19.45152	161	9	1	9	eP	1900	4	40	1	26489.16
4832	4204	sb	29.77017	-19.68725	156	9	1	9	eP	1900	4	40	1	53565.85
4833	4205	nb	29.36996	-21.11318	114	9	1	16	p-K	170	13	29	1	6540.614
4834	4206	nb	29.53734	-21.10107	105	9	1	16	p-K	170	13	29	1	11979.16
4835	4207	nb	29.67337	-21.12945	111	9	1	16	p-K	170	13	29	1	12817.91
4836	4208	nb	29.19413	-21.18962	105	9	1	16	p-K	170	13	29	1	10073.97
4837	4209	nb	29.05831	-21.19588	106	9	1	16	p-K	170	13	29	1	11398.34
4838	4210	?	30.8611	-19.24918	61	9	1	16	p-K	0	14	1	1	47341.28
4839	4211	sb	31.24282	-19.15402	115	9	1	9	eP	1900	4	40	1	21528.54
4840	4212	?	31.42578	-19.13345	39	9	1	16	p-K	0	14	1	1	15078.20
4841	4213	pt	28.99886	-20.74203	38	9	1	10	eP	2150	4	37	1	31490.86
4842	4214	pt	29.12152	-20.77996	31	9	1	10	eP	2150	4	37	1	28502.41
4843	4215	nb	31.79694	-21.52024	98	9	1	16	p-K	170	13	29	1	11256.24
4844	4216	lp	30.9324	-22.00377	88	9	1	16	p-K	170	13	16	1	8690.718
4845	4217	lp	31.78771	-20.83751	48	9	1	16	p-K	170	13	16	1	9407.827

Table 4.1 – Fields of the main table of the dyke geodatabase

- Id** (Number) - a unique identifier of each delineated dyke in the database.
- Category** (String) - Classification of the dykes in accordance to their belonging to a particular swarm that are linked to a “ Categ “ table of the dyke swarms.
- Sid** (Number) - Refers to the source of data used in the compilation of the database and is linked to a “ Source “ table.
- Rid** (Number) - linked to the “ Rock type “ table and describes the type of rock of the dyke.
- Reid** (Number) - linked to the “ Referense “ table and contains the information used in the classification of dyke swarms, geological age and rock type.
- Age** (String) - refers to the estimated geological age of dyke emplacement (as reported in the literature) and is linked to “ Geoage” table.

- Min\_age** (Number) - contains the absolute age of dykes according to the conversion time-stratigraphic ages.
- Ang** (Number) - Contains the calculated strike direction of the dykes.
- Lat/Lon** (Number) - The geographic location of the delineated dykes

#### 4.2.2. Auxiliary tables structure

In addition to the main table of the geodatabase, there are 5 more tables that have relation through the index fields. These tables contain additional attribute information regarding each dyke in the geodatabase compiled from previous studies, geophysical interpretation and geological maps.

#### Source of information table

Previous studies classified dykes into different swarms mainly based on the combination of their age, strike direction and composition. Grouping dykes to specific swarm had encountered problems due to lack of geological, geochemical and geochronological data (Hunter and Reid, 1987). The names of the swarms used in this thesis are those assigned by previous studies and used by Chavez Gomez (2000). The appropriate swarms are extracted from the database for the study area.

#### SOURCE FILE (Source Table)

SID	DATA_SOURCE	AUTHOR_YEA
1	Aeromagnetic Mapping and Interpretation of mafic dyke swarms in Southern Africa	Mubu, M.S., 1995, unpublished MSc. Thesis, ITC, Delft, The Netherlands.
2	Synoptic Interpretation Map of the Reconnaissance Magnetic Survey of Botswana	Geological Survey of Botswana, 1978.
3	Magnetic Anomaly Map of Eastern Botswana	Reeves, C.V., 1986, ITC, Delft, The Netherlands.
4	Geological Map of Mozambique	Geological Survey of Mozambique, 1976.
5	Geological Map of Malawi (1:1 000 000)	Geological Survey of Malawi, 1966.
6	Geological Map of Namibia	Geological Survey of Namibia, 1990.
7	Geological Map of the Republic of South Africa, Bophuthatswana, Venda and Ciskei and the Kingdoms of Lesotho and Swaziland	Geological Survey of South Africa, 1984.
8	Magnetic Lineament Map of the Republic of South Africa, Bophuthatswana, Venda and Ciskei	Geological Survey of South Africa, 1985.
9	Geological Map of Zimbabwe	Geological Survey of Zimbabwe, 1985.
10	Interpretation of the Reconnaissance Aeromagnetic Survey of Namibia	Wackerle, R., 1999 (in preparation).
11	Carta de Interpretacion Geofisica, 1: 250 000 scale (Interpretation by Hunting Geology and Geophysics Ltd.)	Direccion Nacional de Geologia de Mozambique, 1982.
12	Interpretation of the Magnetic Anomaly Map of Mozambique	Sahu, B.K., 1999, ITC, Delft, The Netherlands.

SID	DATA_SOURCE	AUTHOR_YEA
13	Rhodesia Geological Map	Geological Survey of Rhodesia, 1977.
14	Ground geophysical studies near the Kilembe mine, Uganda and their relation to the interp. of regional aeromagn. data in Central Africa	Nyakaana, J., 1994, unpublished MSc. Thesis, ITC, Delft, The Netherlands.
15	Lineaments Interpreted from the Aeromagnetic Contour Map of Tanzania	Ministry of Minerals of Tanzania, 1993.
16	Interpretation of the Magnetic Anomaly Map of Zambia	Mesfin, W., 1999, ITC, Delft, The Netherlands.
17	Interpretation of the IGRF Corrected Aeromagnetic Map of Zimbabwe with superimposed geological contacts	Chavez, S.G., 2000, unpublished MSc Thesis, ITC, Delft, The Netherlands.
18	Interpretation of the Magnetic Anomaly Map of Tanzania, Uganda, Burundi and Rwanda (AMMP Magnetic Data)	Chavez, S.G., 2000, unpublished MSc Thesis, ITC, Delft, The Netherlands.
19	Interpretion of IGRF Corrected High Resolution Aeromagnetic Map of Zimbabwe	Mekonnen, T.K., 2004, unpublished MSc Thesis, ITC, Enschede, The Netherlands
20	Digital Geological Map of Zimbabwe	Mekonnen, T.K., 2004, unpublished MSc Thesis, ITC, Enschede, The Netherlands
21	Interpretion of AMMP Aeromagnetic Map of Northern Mozambique	Mekonnen, T.K., 2004, unpublished MSc Thesis, ITC, Enschede, The Netherlands
22	Interpretion of Recent Survey of High Resolution Aeromagnetic Map of Southern Mozambique	Mekonnen, T.K., 2004, unpublished MSc Thesis, ITC, Enschede, The Netherlands

**AGE FILE (GeoAge Table)**

AGEID	AGE	GEOLOGICAL
1	Ar	Archaean
2	Ar-eP	Archaean-Early Proterozoic
3	Cr	Cretaceous
4	eP	Early Proterozoic
5	J	Jurassic (undifferentiated)
6	lJ	Late Jurassic
7	l-mP	Late-Middle Proterozoic
8	lP	Late Proterozoic
9	lP-eC	Late Proterozoic-Early Cambrian
10	Me	Mesozoic (undifferentiated)
11	mP	Middle Proterozoic
12	P	Proterozoic (undifferentiated)
13	p-K	post-Karoo
14	?	Unclassified

**ROCK TYPE FILE (RockType Table)**

RID	ROCK_TYPE
1	Dolerite
2	Kimberlite
3	Lamprophyre
4	Andesite
5	Gabbro
6	Tholeiite
7	Diabase-dolerite
8	Unclassified

**REFERENCE FILE (References table)**

REID	REFERENCE	AUTHOR
1	East Griqualand Kimberlites	Nilxon, P.H., Boyd, F.R., and Boctor, N.Z., 1983, Transactions of the Geological Society of South Africa, v. 86, p. 221-236
2	Aeromagnetic mapping and interpretation of mafic dyke swarms in Southern Africa	Mubu, S.M., 1995, M.Sc. Thesis, Department of Earth Resources Surveys, International Institute for Aerospace Survey and Earth Sciences (ITC), Delft, The Netherlands, 63 p.
3	The Cape Peninsula dolerite dyke swarm	Reid, D.L., 1990, in Parker, A.J., Rickwood, P.C., and Tucker, D.H., Mafic dykes and emplacement mechanisms, Balkema, Rotterdam, The Netherlands, p. 325-334.
4	Geochemical characterization of granitoids in the Namaqualand Geotraverse	Reid, D.L., and Barton, E.S., 1983, Geological Society of South Africa, Special Publication, p. 67-82.
5	A magnetometric investigation of the Lichtenburg-Zeerust area	Day, R.W., 1981, South African Geological Survey, Bulletin 68, 22 p.
6	The Pilanesberg Alkaline Province, Southern Africa	Ferguson, J., 1973, Geological Society of South Africa Transactions, v. 76, p. 249-270.
7	Sr Isotope and Trace Element studies on the Great Dyke and Bushveld Mafic Phase and their relation to Early Proterozoic magma genesis in Southern Africa	Hamilton, J., 1977, Journal of Petrology, v. 18, p. 24-52.
8	Tectonic control of dykes and related irruptive rocks in Eastern Africa	Vail, J.R, 1970, in, Clifford, T.N., and Gass, I.G., eds., African Magmatism and Tectonics: Oliver and Boyd, Edinburgh, Scotland, p. 337-354.
9	Mafic dyke swarms in Zimbabwe	Wilson, J.F., Jones, D.L., and Kramers, J.D., 1987, in Mafic dyke swarms, Editors: Halls, H.C. and Fahrig, W. F., Geological Association of Canada Special Paper 34, p. 433-444.
10	The geology of the country around Battlefield	Robertson, I.D.M., 1976, Geological Survey of Rhodesia Bulletin, n. 76, 258 p.

REID	REFERENCE	AUTHOR
11	Post-Pan-African tectonic evolution of South Malawi in relation to the Karroo and Recent East African Rift Systems	Castaing, C., 1991, Tectonophysics, 191, p. 55-73, Elsevier Science Publisher, B.V., Amsterdam.
12	An interpretation of mafic dyke swarms and their relationship with major mafic magmatic events on the Kaapvaal Craton and Limpopo Belt	Uken, R., and Watkeys, M.K., 1997, Journal of Africa Earth Sciences, v. 100 (4), p. 341-348
13	Rb-Sr ages and chemical composition of some deformed Archaean mafic dykes, Central Zone, Limpopo Mobile Belt, Southern Africa	Barton, Jr., J.M., Fripp, R.E.P., and Horrocks, P.C., 1983, Geological Society of South Africa, Special Publication 8, p. 27-37.
14	Personal Communication	Westerhof, A.B., 2000, International Institute for Aerospace Survey and Earth Sciences (ITC), Delft, The Netherlands.
15	Database of dyke of dykes in Eastern and Southern Africa	Chavez Gomez, S., 2000, International Institute for Aerospace Survey and Earth Sciences (ITC), Delft, The Netherlands.
16	Mafic dyke swarms in Southern Africa	Hunter, D.R. and Reid, D.L., 1987, in Mafic dyke swarms, Editors: Halls, H.C. and Fahrig, W. F., Geological Association of Canada Special Paper 34, p. 445-456.
17	Mafic dyke swarms of Tanzania interpreted from aeromagnetic data	Halls, H.C., Burns, K.G., Bullock, S. J. and Batterham, P.M., 1987, in Mafic dyke swarms, Editors: Halls, H.F. and Fahrig, W.F., Geological Association of Canada Special Paper 34, p. 173-186.
18	Diabase (Dolerite) dyke swarms of the world, First Edition. Geological Survey of Canada Open File 3241	Ernst, R.E., Buchan, K.L., West, T.D., and Palmer, H.C., 1996.
19	A global study of large rift-related dyke swarms	Goldberg, A.S., 2000 (Monash University, MSc. Thesis)

### Dyke Swarm Table (Category)

CATID	CATEGORY	DYKE_SWARM
1	?	Unclassified dykes
2	bc	Buby-Crystal Spring
3	be	Betty dykes
4	cp	Cape Peninsula dykes
5	ct	Central Tanzania NS dykes
6	ek	NW dykes in the Eastern Kaapvaal Craton
7	ew	EW dykes in the Kaapvaal Craton
8	ey	Lake Eyasi dykes
9	ga	Post-Gamberg dykes
10	gn	Gannakouriep dykes
11	gr	Guruve dykes
12	ht	NW dykes in Northern Namibia

CATID	CATEGORY	DYKE_SWARM
13	ka	Karub dykes
14	km	Kamativi dykes
15	lb	Lebombo (incl. Rooi Rand dykes)
16	lp	Limpopo
17	lv	Lake Victoria dykes
18	lw	Luwumbu dykes
19	ma	Mashaba-Chibi dykes
20	md	Mwadui dykes
21	mg	Migori dykes
22	mk	NE-Mafikeng dykes
23	ml-Cr	Malawi dykes of Cretaceous age
24	ml-pK	Malawi dykes of post-Karoo age
25	mr	Machinje Range dykes
26	ms	Messina
27	mt	Mutare dykes
28	mz	Mazowe dykes
29	nb	Northern Botswana
30	nm	NE dykes in Northern Namibia
31	np	Nelspruit
32	nw	NW dykes in the Kaapvaal Craton
33	or	Orange River
34	pb	Palabora
35	pg	Pongola
36	pl	Pilanesberg
37	pt	Plumtree dykes
38	rs	Rushinga dykes
39	sa	Sabi dykes
40	sb	Sebanga dykes
41	sc	Cedaberg dykes
42	ssw	Middleplaas dykes
43	sw	NW dykes in Southern Botswana
44	tns	Eastern Tanzania NS dykes
45	um	Umkondo dykes
46	wk	NNE dykes in the Western Kaapvaal Craton
47	zg	Zimbabwe Great Dyke and Satellites
48	go	Gorongosa Dykes
49	mu	Mualama Dykes
50	mo	Morrumbala Dykes
51	sw1	Mozambique SSW-NNE trend dyke swarm
52	sw2	Mozambique SW-NE trend dyke swarm

**COUNTRY FILE (Country Table)**

CountryID	Country
1	Zimbabwe
2	Mozambique
3	Botswana
4	South Africa
5	Namibia
6	Angola
7	Zambia
8	Malawi
9	Tanzania
10	Kenya
11	Lesotho
12	Swaziland

**4.3. Working with ArcGIS geodatabase**

This Dyke CD-ROM is created to be used by ArcGIS 8.3 or later version and MS Access software. The ArcGIS geodatabase (geographic database) was designed using standard Relational Database Management System (RDBMS) technology and support the storage and management of geographic information in tables. A table is used to store feature class where each row in a table represents a feature. The RDBMS geodatabase model make queries and view data easily from by relating the main and auxiliary tables through the index fields.

Using this short User’s Guide of the Dyke CD-ROM, the user can easily display, query, make minor edition and print the CD’s content. For detailed and advanced edition processing, the author advise to consult ArcGIS and MS Access User Guides (User Reference) .

**4.3.1. Hardware and software requirements**

The minimum requirement to to properly use this geodatabase Dyke CD-ROM

- Computer (PC or laptop) with 128 Mb or more memory
- Window 95/98 or later
- ESRI ® ArcGIS 8.3 or later
- Microsoft Access 2000 or later
- CD-ROM drive
- Dyke Geodatabase CD-ROM

### 4.3.2. Preparing the geodatabase for use

As mentioned earlier, to use the CD-Rom one has to have ArcGIS and MS-Access software. It is advisable to make copy of “ Dyke “ folder from the Dyke CD-Rom to your hard disk in order to access the data faster, to perform changes and for the safe keeping of the original data.

ArcGIS desktop composed of ArcCatalog, ArcMap and ArcToolbox integrated applications.

ArcCatalog application helps to organize and manage all of the GIS data. It includes tools for browsing and finding geographic information, recording, viewing, and managing metadata quick viewing any dataset, and defines schema structure of the geographic data layer. When you first start ArcCatalog, it displays the contents of your hard disk in the **Catalogue Tree**. You can add or remove a folder from the catalogue tree as you like to make your data management easier. In our case we have to add the ” Dykes “ folder from Dyke Geodatabase CD-ROM to the folder connection to access their contents. When you look in a folder connection, you see the items it contains. Unlike Windows Explorer, the Catalogue doesn't list all files stored on disk. A folder might appear empty in the Catalogue even though it isn't on the disk. Only the items that you choose to see will be included in the folder's contents.

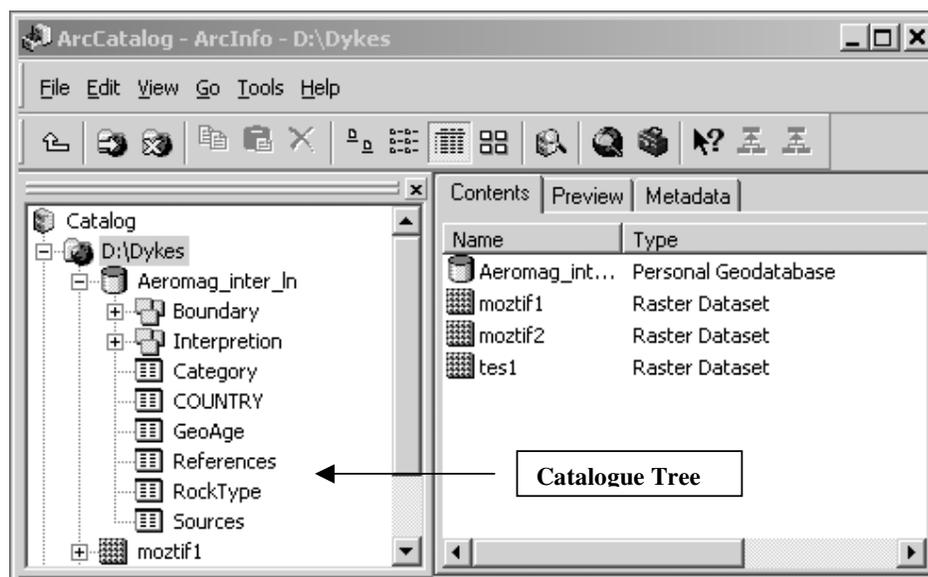


Figure 4.2 Desktop of ArcGIS

ArcMap is the central Application in ArcGIS desktop. It is the GIS application used for all map-based tasks including map analysis and editing. In this application, we work with maps and it's attributes. Maps have a page layout containing a geographic window called a data frame with a series of layers, scale bar, legend and other elements. ArcMap is used to display and query maps, create publication-quality hard copies, develop custom map applications, and perform many other map-based tasks. ArcMap provides an easy and natural transition from viewing a map to editing its geography.

**ArcToolbox** provides an environment for performing geoprocessing operations. Wizards and tools step you through many geoprocessing tasks including data conversion.

### 4.3.3. Using ArcCatalog

We can generalize the main functions of ArcCatalog as follow

- Browse or view attribute data
- Explore data
- View and create metadata
- Search for data
- Manage data source (import, export, etc.)

#### How to start ArcCatalog

You can access ArcCatalog from the Start button on the Windows taskbar.

1. Click the Start button on the Window Taskbar
2. Point to Programs.
3. Point to ArcGIS.
4. Click ArcCatalog.

These procedures open the catalogue that looks like Fig 4.2. The next step is to load the folders of our geodatabase from the CD-ROM to the Catalogue Tree.

1. Click the **Connect to Folder** button  from the toolbar
2. Select the drive name (CD-Rom drive)
3. Select a folder name “ Dykes”

The Connect to Folder dialog box appears

The folder “Dyke” will be displayed in the Catalogue Tree

**Note** - You can also remove the folders in the catalogue Tree you don’t want to see from the display

using **Disconnect from folder.**  This will not delete the folder only remove it from displaying in the catalogue tree.

You can access maps, layers, attribute tables, graphs and metadata to using **Contents**, **Preview** and **Metadata** tabs as shown in Fig 4.3, Fig 4.4. and 4.5 Notice that, ArcCatalog only displaying and managing the data.

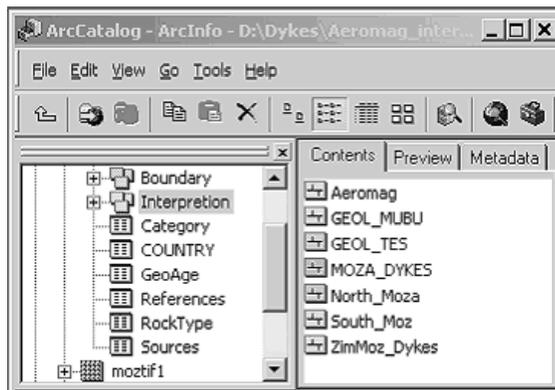


Figure 4.3 Displaying the contents of the geodatabase using the Content Tab



Figure 4.4 Displaying the raster map in Preview Tab

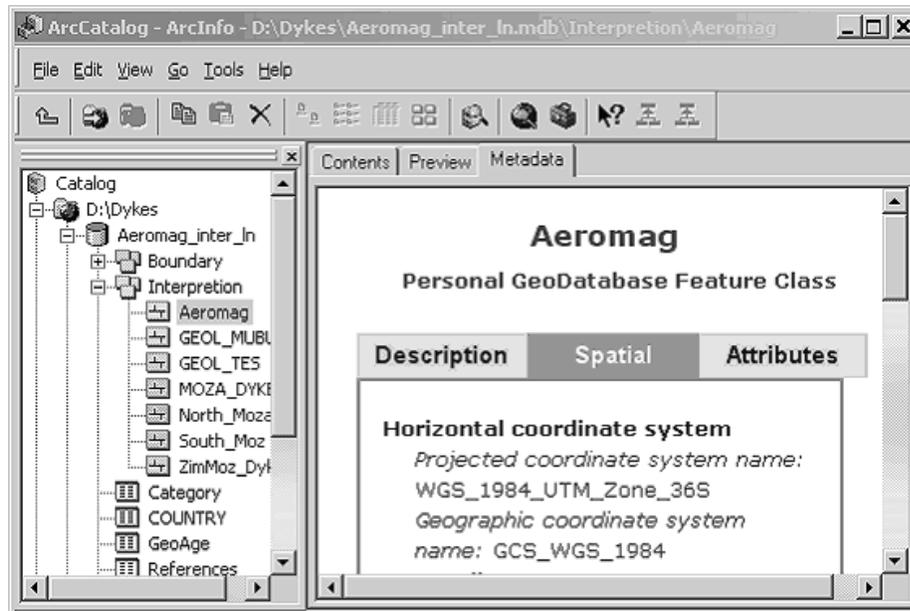


Figure 4.5 Displaying the projection information using the Metadata Tab

The Metadata shows descriptive information about a selected item in the catalogue tree. It consists of properties and documentation. Properties are information such as extents of the shape file and the projection system derived from the data source. Documentation is information supplied by the author about the selected feature. It is described in a standardized way to avoid errors and to clearly understand by other peoples. The metadata created with ArcCatalogue is stored as XML data either in a file along the item or within its geodatabase.

In the “Dyke Geodatabase” CD-Rom, we have the following layers

1. **Boundary Layer** which contains three feature classes
  - a. Boundary map of eastern and southern Africa
  - b. Boundary map of Mozambique & Zimbabwe
  - c. Boundary map of Angola, Botswana, Kenya, Lesotho, Malawi, Namibia, South Africa, Swaziland, Tanzania & Zambia

2. **Interpretation Layer**, which contains the interpretation of the Mozambique and Zimbabwe, dykes from aeromagnetic maps and previous interpretations of south & eastern Africa.
  
3. **Geology Layer** which contains  
**Previous\_int**
  - a. Generalized geological map of eastern & Southern Africa
  - b. Generalized geological map of Zimbabwe
  - c. Generalized geological map of Mozambique
  - d. Kalahari sands
  - e. Karoo sediments
  - f. Karoo basalt
  
4. **Raster image layer**  
**Aeromag.tif**
  - a. Zimbabwe aeromagnetic grid (.tif file)
  - b. Southern Mozambique grid, grid-1 (.tif file)
  - c. Western Mozambique grid, grid-2 (.tif file)

Notice that ArcCatalog application is used only to view maps and attribute tables not to edit them.

#### 4.3.4. Using ArcMap

ArcMap can be accessed mainly in two ways.

##### A. From Windows Task Bar

1. Click the start button
2. Point to program, go to ArcGIS and select ArcMAP

##### B. From ArcCatalog

- Click ArcMap button from the ArcCatalog Application toolbox 
  
3. In the “Start using ArcMap with” window click an existing map and clicl OK
4. In the “Open” dialog box click the “Look in” dropdown arrow and navigate to your hard drive and select the folder you copied from the Dykes CD-Rom.
5. Select the Map and click open.

A map stores the representation (maps, graphs, tables, etc) and the reference to the location of the data source displayed on it. When you open a map in ArcMap, it creates the link to the data and will display the lined data with representation, which was done in ArcMap.

ArcMap has three main parts (Fig. 4.6)

1. The **Map Window** – the big window which shows the data and the representation of the data. In here the shape files, attribute tables etc are displayed according to our choice.
2. The **Table Content** – is the smaller window on the left side that shows what data the map contains, organize the layers, shows the type of the layers and check box whether to display the layer or not.
3. **Toolbars and Menus** – which contains the commands and the toolbars that helps to perform various tasks.

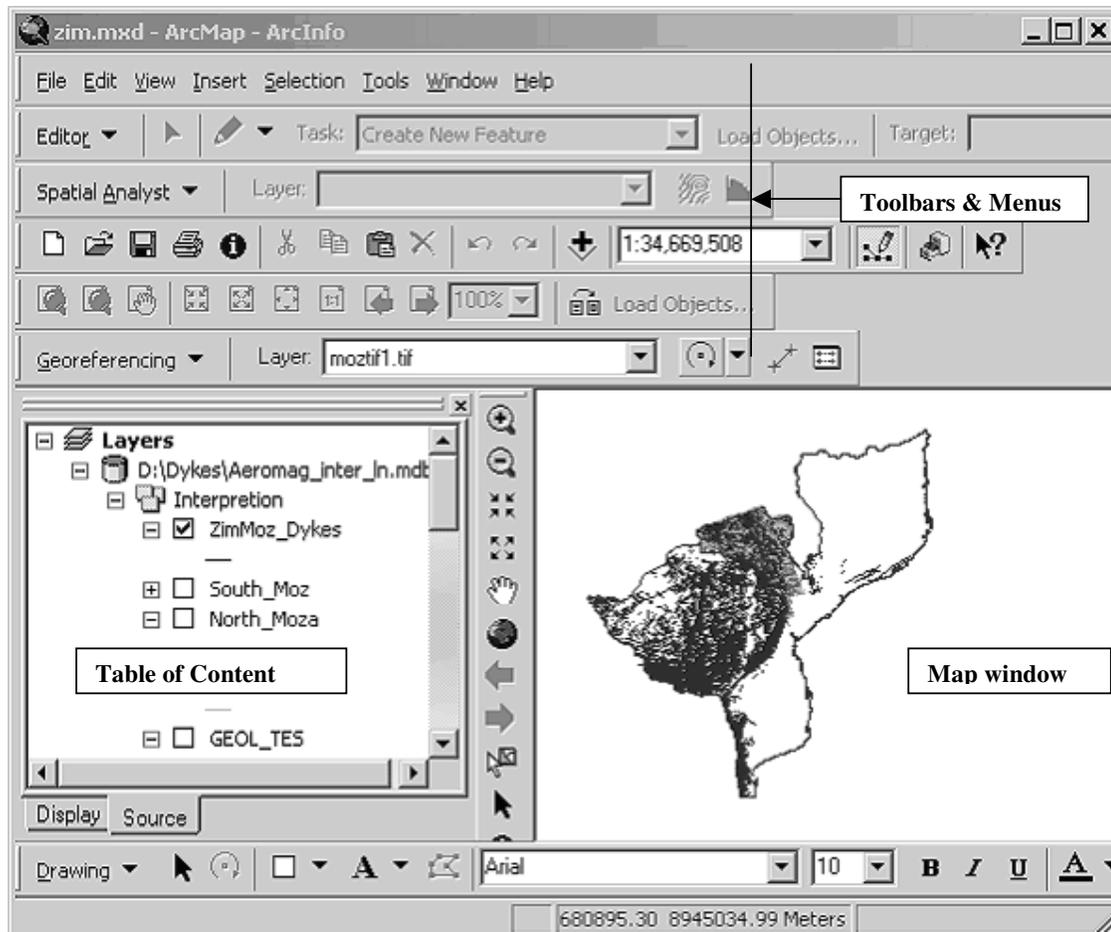


Figure 4.6 ArcMap application main desktop parts

### Note

- Moving around the maps like zoom in or out, pan, full extent and others are done similar to other GIS applications.

- There are different ways of viewing maps.
  - Data view is used for displaying, exploring and selecting data on your map
  - Layout view is used to show the map as it would be printed on a paper, which has been supplied in the page set up and items like title, legend, scale bar etc.
  
- You can explore the viewed map using like.
  - Identify Button  – to get information in the active layer about a selected item that is available in attribute table.
  - Select Feature Tool  - select features by clicking on item or by dragging a box around them for editing the map or attribute table.

#### 4.3.5. Changing Map Projection

All feature classes in a feature dataset must have the same spatial references. A feature dataset can be added to the feature class either by importing existing map or creating a new one. The spatial reference of the feature dataset is described by

- Coordinate system
- Spatial domain (X,Y or Lat/Lon coordinate range)

The coordinate system can be modified to another system or projection according to our needs. We have several options to set the coordinate system for any feature class.

##### Steps for changing the coordinate system

1. Open the map document
2. Make active the data frame you want to change
3. Go to “view” menu and choose “Data Frame Property” and select Coordinate System tab (Fig 4.7)
4. In coordinate system box select Modify, click select and follow the steps by selecting the coordinate system you want (Fig. 4.8).

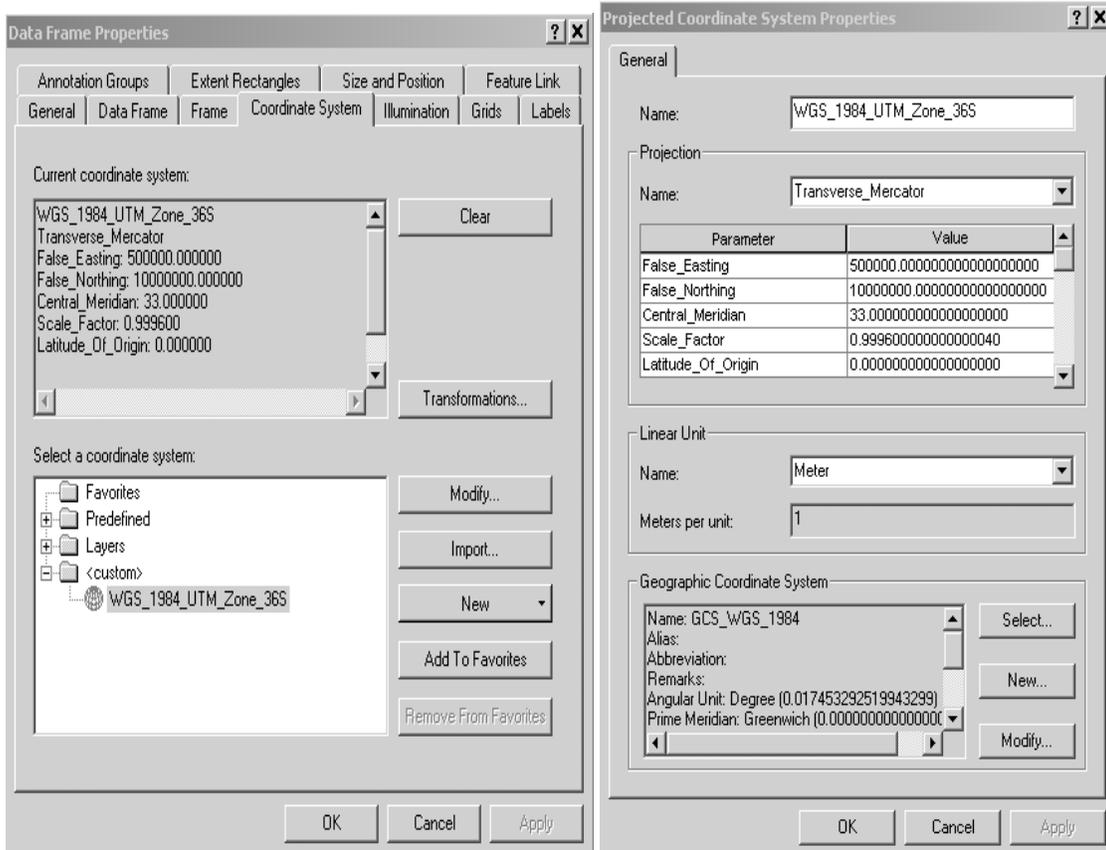


Figure 4.7 -Data Frame Property dialog box      Figure 4.8- Coordinate system Property dialog box

#### 4.3.6. Querying the geodatabase

All feature classes in a feature dataset must have the same spatial references. A feature dataset can be added to the feature class either by importing existing map or creating a new one. The spatial reference of the feature dataset is described by

Looking at a map may be isn't enough. You must also want querying it according to feature locations and attributes to solve problems. You can discover new information by displaying only some of the dykes in the geodatabase information by asking questions such as :

- Specific type of swarm
- Specific country dykes
- Specific trend dykes etc

#### Selecting features interactively

You can select features with your mouse by clicking them one at a time or by dragging a box around them. Before you select features with one of these methods, you can specify the layers you want to

select from. When you select feature records in a table or map, the feature highlights on the map or the table.

### **Selecting features by clicking them in the map**

1. Click the Selection menu and click Set Selectable Layers.
2. Click the layers you want to select from.
3. Click Selection, point to Interactive Selection Method, then click Create New Selection.
4. Click the Select Features tool.
5. Click the feature you want to select.

To select additional features, hold down the Shift key while clicking the features. To remove a feature from the selected set, click the Selection menu, point to Interactive Selection Method, and click Remove From Current Selection.

### **Selecting features by dragging a box around them**

1. Click the Selection menu and click Set Selectable Layers.
2. Click the layers you want to select from.
3. Click Selection, point to Interactive Selection Method, then click Create New Selection.
4. Click Selection and click Options.
5. Specify how you'd like to select features with the box and click OK.
6. Click the Select Features button.
7. Click and drag a box around the features you want to select.

### **How to select features by searching with an SQL expression**

1. Click the Selections menu and click Select By Attributes.
2. Click the Layer dropdown arrow and click the layer containing the features you want to select.
3. Click the Method dropdown arrow and click a selection method.
4. Double-click a field to add the field name to the expression box.
5. Click an operator to add it to the expression.
  - If you have a very large number of values, click the Complete List button to see them all. Double-click a value to add it to the expression.
  - To see if you're using proper syntax or if the criteria you've entered will select any features, click the Verify button.
  - The status bar at the bottom of the ArcMap window tells you how many features are selected.
6. Click OK (Fig 4.9).
  - The status bar at the bottom of the ArcMap window tells you how many features are selected.

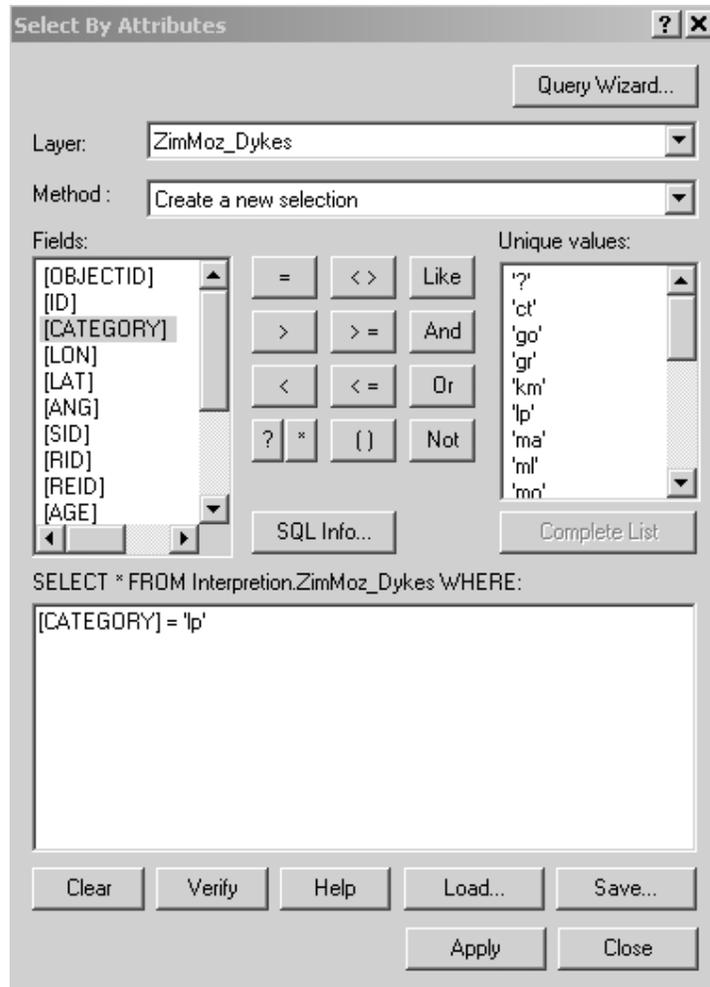


Figure 4.9 – Searching using SQL expression

## 5. Analysis & interpretation of dykes

While other aspects of continental rifting such as structure, stratigraphy and related volcanism are well studied, the geological implication of dyke implement was explored little before the first International Dyke Conference of Canada in 1987. Prior to this, dykes have been studied mainly for paleomagnetic research due to their characteristic magnetic properties. Most mafic dykes swarms are related to mantle plumes and typically associated with divergent plate margins (Fahrig, 1987). Hence they provide valuable information in the evolution of plume activities of all ages that help to understand Large Igneous Provinces (LIP) like the Karoo that happened about 40 Ma before the break-up of Gondwana.

### 5.1. Geophysical mapping of mafic dyke swarms

It is not surprising that the study of the multitudinous dykes of southern Africa has attracted many earth scientists. Some of the reasons of the involvement include that the emplacement and structure of those dyke swarms (specially Karoo age) may resolve still unanswered controversial questions like when Gondwana break-up started and what the shape looked like in late Jurassic and early Cretaceous times. The interpretation of these dykes from aeromagnetic data at continental scale helps to make a detailed observation of the swarms and their association with the dispersion of Gondwana.

In this section, we discussed the aeromagnetic interpretation of the dykes of Zimbabwe and Mozambique and their implication within the previous studies and dyke swarm databases of eastern and southern Africa (Mubu, 1995 & Chavez Gomez, 2000).

#### 5.1.1. Mafic dyke swarms in Zimbabwe

Most of the dyke swarms of Zimbabwe are identified and delineated by previous studies (e.g. Wilson et al., 1987; Hunter and Reid, 1987; and Chavez Gomez, 2000). The resolution and detail of the interpretation depends mainly on the type of the source data. The most detailed digitisation of dykes of Zimbabwe was been done by Chavez Gomez (2000) using a scanned image of the aeromagnetic map with superimposed geological contacts (Geological Survey of Zimbabwe, 1996). It was not possible for the researcher to process the image with geophysical image processing software (e.g. Oasis) as was done in this thesis to display different trends of dyke swarms with various enhancement methods and appropriate illumination angles according to the strike direction.

Dykes of different ages and trends have been delineated from the available relatively high resolution aeromagnetic grid (Geological Survey of Zimbabwe) and assigned to a particular swarm when possible in accordance to the previous studies (Wilson et al., 1987; Hunter and Reid, 1987; Reeves, 1978 & Chavez Gomez, 2000). Each dyke is given a unique ID and constitutes the dyke geodatabase of the country.

Zimbabwe has various trends of dyke swarms ranging in age from Archean to Mesozoic. The Precambrian geology has passed through several metamorphism and deformation phases and hence needs detailed studies. Most of the Archean dyke swarms are confined to the south central part of the country (Fig. 1.3) and possibly represent feeders to the greenstone belt of the Bulawayan Group ~2.7 Ga. The most important Proterozoic dykes include the layered intrusion of the Great Dyke (2460 Ma) and its satellites and the numerous dykes that are related to the Mashonaland Igneous events (2.0 -1.8 Ga).

Among others, there are two important and predominant giant dyke swarms interpreted from this grid. The N110°E North Botswana (Okavango) dyke swarm and N70°E Limpopo dyke swarm (Map-1 & Slide-1) which are closely related to the disruption of Gondwana. New  $^{40}\text{Ar}/^{39}\text{Ar}$  palgioclase dating put both dyke swarms and lava flows tightly clustered around 178-181Ma and indicates a short time span (183 Ma) for the bulk of the magmatic activity of Karoo igneous province of southern Africa (Le Gall et al., 2002). These two swarms represent the two arms of the supposed triple rift junction caused by a mantle plume which may have led to the breaking-up of Gondwana. Recent field geological observation (Watkeys, 2002) puts the emplacement of the Limpopo swarm before the North Botswana swarm.

### 5.1.2. Mafic dyke swarms in Mozambique

The Mozambique aeromagnetic grids composed of new (GSF & DNG, 2003) and previous survey Africa Magnetic Mapping Project (AMMP) are shown in Fig 3.2. The new survey has not been previously interpreted and it is exciting to see the interpretation since it covers one of the most important missing parts of the AMMP data. It gives a great benefit in the investigation of crustal structure of the southeastern part of Africa that helps to study the tectonic events, which lead to the break-up of Gondwana. Various aeromagnetic maps (such as Map-2 & 4) were produced by applying different enhancement filters. This lead to the classification of the grid into different magnetic relief zones that appear to have distinct geological units as shown in Map-6.

1. **Relief Zone I (RZ-I/ Map-6)** – Comprises of the high magnetic relief zone concentrated on the southern part of the grid, east of Lebombo monocline and on the northern part of the grid. Previous interpretations and databases (e.g. Chavez Gomez, 2000) have identified a NS trending Lebombo dyke swarm (including Rooi Rand swarm) from the South Africa data. In this thesis, a prominent NNE trending dyke swarm was identified and delineated (Map-2, Slide-2 & Map-3, Slide-3) beginning from the southwestern margin of the grid that is part of the Lebombo monocline. These dykes have a different strike than the mentioned Lebombo swarm and is not known from existing literatures and hence has been given a new name **SW1** by the author for identification. The same trend of dykes is again observed in the central part of the grid disappearing below the thick Karoo sediments of the Mozambique thinned zone (Map-2 & Slide-2). The dykes probably continuous below the thick sedimentary cover eventhough the magnetic signal is attenuated. In addition to this swarm, NS trending dykes similar to the Lebombo swarm and some NNW trending dykes (Map-5 & Slide-4) are also identified that could be part of the Lebombo swarm, east of the Lebombo mountains that form the geographic boundary.

According to the model proposed for the breakup of Gondwana (Jokat et al., 2003) on the basis of aeromagnetic survey conducted on the east Antarctica coast around Weddell, Lazarew and Riiser-Larsen Seas, Mozambique Basin, the first oceanic crust between Antarctica & Africa was formed around 155 Ma (Fig. 5.1 a & b). His scenario explains how the divergent mantle flow in the central part of Gondwana caused the separation of Africa and south America from Antarctica with a difference of spreading direction as much as  $60^{\circ}$  (South America  $335^{\circ}$  & Africa  $035^{\circ}$ ) (Jokat, et al., 2003). The SW1 trend direction almost coincide with the direction of the Jokat angle and can be seen in Fig. 5.2 by overlaying the Karoo dyke swarms and the Jokat angle on the Reeves Gondwana model (<http://kartoweb.itc.nl/gondwana/page6.html>, 2001).

The three swarms (Limpopo, North Botswana & Lebombo) are the three arms of the supposed triple junction which developed to normal faulting pattern on the western margin section of the Lebombo monocline that eventually led to the opening of an ocean. The newly discovered swarm (SW1) might be also part of these rifting events and its age might be estimated to this period.

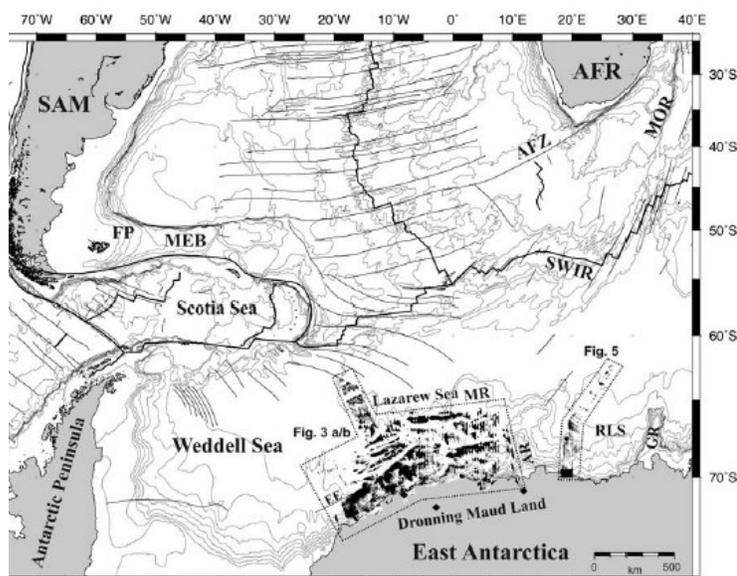


Figure 5.1 - (a) Recent continent configuration of the “Atlantic” Southern Hemisphere. The major tectonic units as well as the plate boundaries and fracture zones are marked. The survey areas in the Weddell, Lazarew, and Riiser-Larsen Seas are shown.

Abbreviations are AFR, Africa; AFZ, Agulhas Fracture Zone; AR, Astrid Ridge; EE, Explora Escarpment; FP, Falkland Plateau; GR, Gunnerus Ridge; MEB, Maurice Ewing Bank; MR, Maud Rise; MOR, Mozambique Ridge; RLS, Riiser-Larsen Sea; SAM, South America; SWIR, South West Indian Ridge (Source – Jokat et al., 2003).

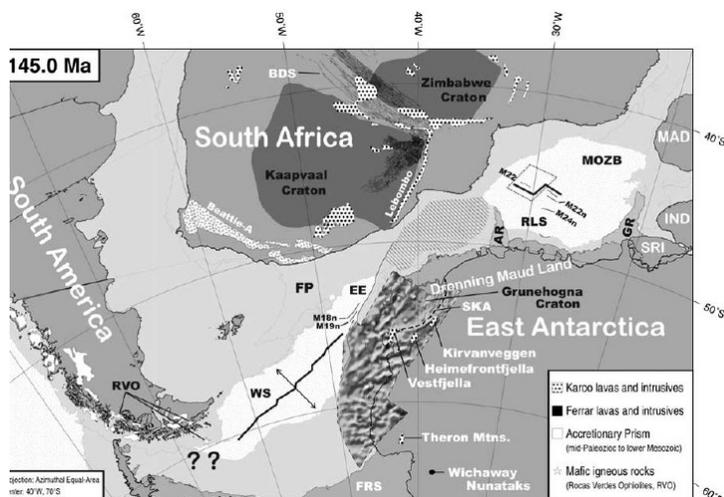


Figure 5.1 –(b) Model of 145 Ma plate tectonic. Seefloor spreading at WS & RLS. Abbreviations are AR, Astrid Ridge; BDS, Botswana Dyke Swarm; Beattie-A, Beattie Anomaly; EE, Explora Escarpment; FP, Falkland Plateau; FRS, Filchner Ronne Shelf; GR, Gunnerus Ridge; IND, India; MAD, Madagascar; MOZB, Mozambique Basin; RLS, Riiser-Larsen Sea; RVO, Rocas Verdes ophiolites; SKA, Sverdrupfjella-Kirvanveggen Anomaly; SRI, Sri Lanka; WS, Weddell Sea (Source – Jokat et al., 2003).

Earthworks/CPSL - 170.00 Ma - reev605

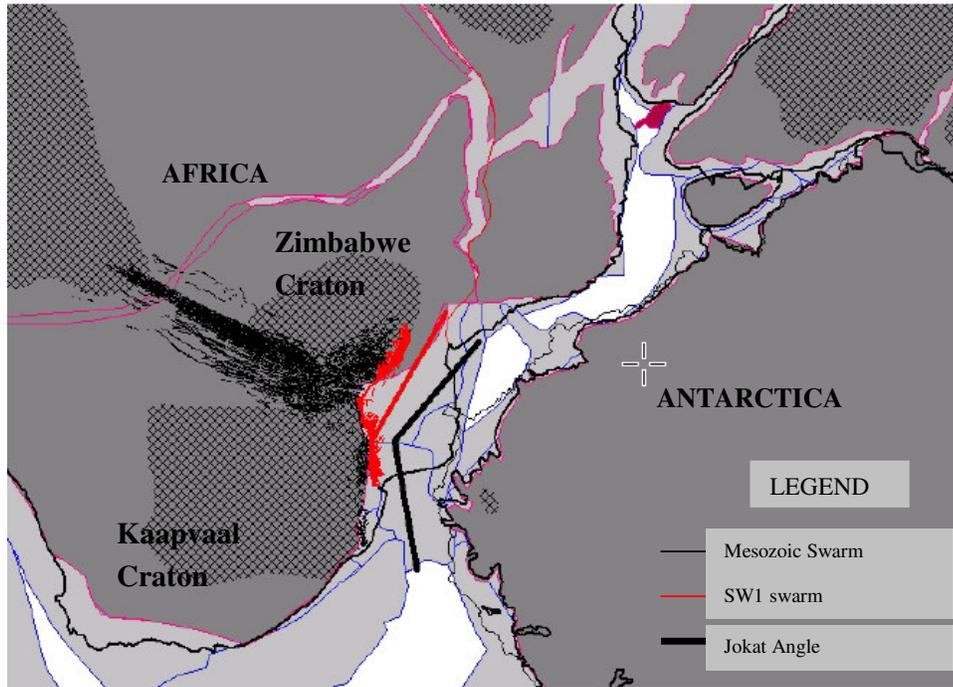


Figure 5.2 – Gondwana model at age 170 Ma with superimposed post-Karoo dykes (Source – Modified from Reeves model - <http://kartoweb.itc.nl/gondwana/page6.html>, 2001)

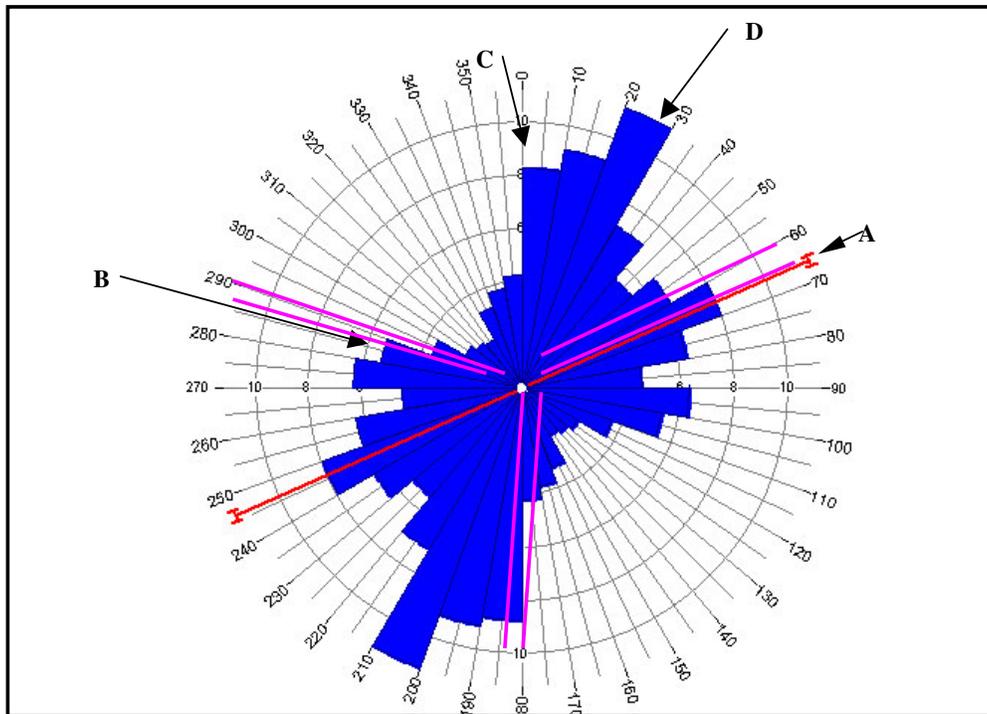


Figure 5.3 – Rose Diagram for all the interpreted dykes in this thesis and the Lebombo dyke swarm from the previous database. A) The Limpopo swarm which is the most prominent one for the study area B) The North Botswana swarm C) The Lebombo swarm D) SW1 dyke swarm &   
— Ideal triple junction &

In Zone I (Map-6) there is also another swarm that strikes NE (Map-2 & Slide-2) which starts from the Zimbabwe border in the northern part of the grid. This swarm looks continuous from the Zimbabwe Limpopo swarm even though this cannot be concluded definitely as the aeromagnetic data on the Zimbabwe side of the border are missing. For this reason the author assigned a new name **SW2** (Map-2 & Slide-2) for the swarm.

2. **Relief Zone II (RZ-II/Map-6)** – represent the intermediate magnetic relief zone around the north-eastern part of the grid near Zimbabwean border. This zone contains mainly NE trending dykes, but minor NNW and NW strike dykes are also evident.
3. **Relief Zone III (RZ-III/Map-6)** – representing low magnetic relief zone is confined mostly on the Mozambique plan/ Thinned Zone corresponding to thick sedimentary development.

The contrast between different magnetic relief zones might be due to different reasons. Since magnetic sources lie at depth between zero and several tens kilometres below the surface, the range of anomaly wavelength likely to be encountered varies over several orders of magnitude (Reeves, 1994).

The wavelength of anomalies over magnetic bodies increases with increasing depth of the source whereas the amplitude of the anomaly decreases. The occurrences of the multitudinous dykes and the depth of their burial could be one reason for the different relief zones. The thick post Karoo sedimentation of the Mozambique thinned zone causes the loss of amplitude to the dyke anomaly.

## 5.2. Large Igneous Provinces (LIP), mantle plumes and Gondwana

LIPs' are regarded either as the result of the impingement of a mantle plume on the base of the lithosphere, or as the initial products of adiabatic decomposition melting of anomalously hot mantle (Dalziel et al., 2000). When continents rift to form new ocean basins, the rifting is sometimes accompanied by massive igneous activity. Large Igneous Provinces are thought to be caused mainly by the arrival of a mantle plume in the Earth's outermost layer, the lithosphere. The plumes are proposed to be richer in lighter elements and hotter than the surrounding mantle. As they rise, magma (liquid rock) is generated by partial melting of the plume material. The magma is injected into the lithosphere and erupted onto the Earth's surface to form huge basalt lava flows. In the Palaeozoic and Proterozoic, LIPs are typically deeply eroded. They are represented by deep-level plumbing systems consisting of giant dyke swarms, sill provinces and layered intrusions.

The Karoo-Ferrar (Antarctica) large igneous province (Fig. 5.4) covers  $6 \times 10^6$  km<sup>2</sup> and is one of the largest continental flood basalt provinces in the world (Le Gall et al., 2002). The African section of this LIP, the Karoo igneous province, consists of flood basalts, sills and giant dyke swarms that together cover more than  $3 \times 10^6$  km<sup>2</sup> in southern Africa (Le Gall et al., 2002).

After a prolonged period of relative tectonic stability and sedimentation (320 – 182 Ma) in southern Africa (Karoo Supergroup), the following period saw the extensive magmatic events between 200 to 175 Ma (Karoo magmatic provinces). The low MgO continental flood basalt that covered most of southern Africa erupted at 183 Ma (Duncan et al., 1997; Marsh et al., 1997) synchronous with emplacement of an extensive network of subvolcanic dolerite dikes and sills (Encarnacion et al., 1996).

The rifting of the margins of southern Africa is related to two major events (Watkeys, 2002):

- Karoo volcanism ca. 183 Ma influenced by the production of melts in the mantle with main plume head centre 22°S, 31°E (<http://www.largeigneousprovinces.org/>) and the lithospheric architecture.
- The opening of the South Atlantic ca 135 Ma.

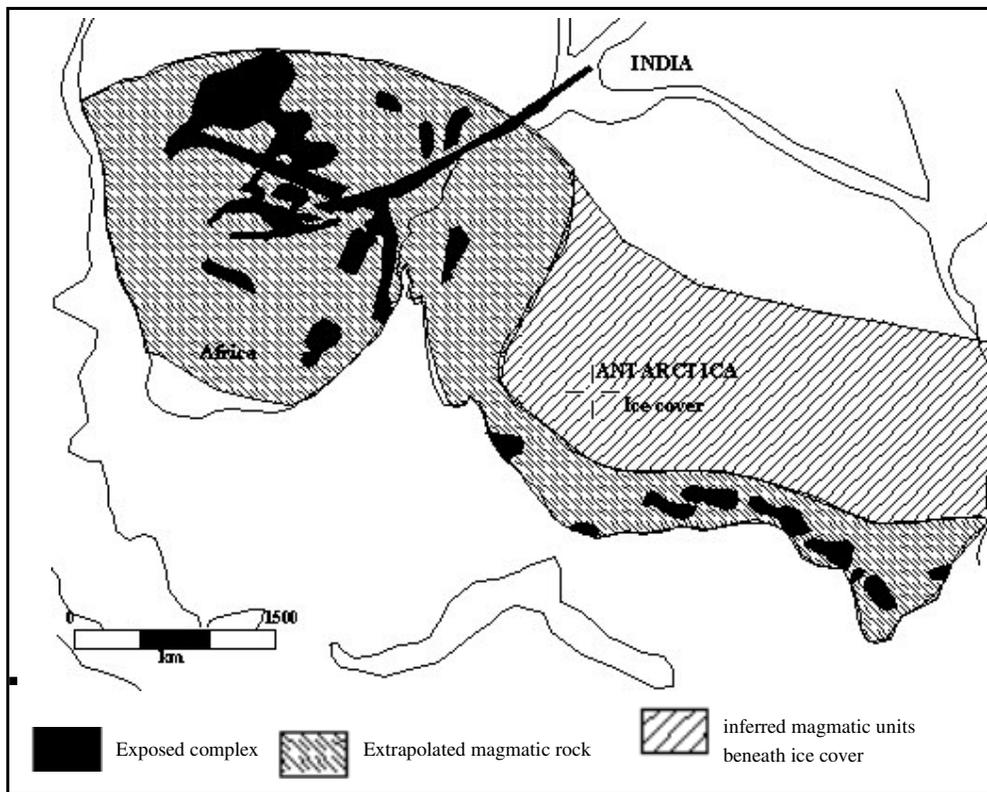


Figure - 5.4 Distribution of continental flood basalt and related intrusive rocks of the Karoo-Ferrar-Antarctica LIP in a pre-drift Gondwana reconstruction.

(Modified -  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology and structural data from the giant Okavango and related mafic dyke swarms, Karoo igneous province, northern Botswana, Le Gall et al., 2002)

Published literatures and geometry evident from the plotted dykes (e.g. Map-7) shows no direct influence caused by the initial Karoo igneous activity for the continental breakup, though it might have controlled the ultimate position of the major faulting system. It is the opinion of the present author that the stress pattern can be subdivided into four major phases (Map-7):

1. The first activity was the Limpopo dyke swarm through the central zone of the Limpopo Belt. These dominantly east-northeast trending dykes are strongly structurally controlled (Watkeys, 2002). (Map-1 & Slide-1). i.e. adopted the weakness direction of the country-rock.
2. The west-northwest trending Northern Botswana (Okavango) dyke swarm that is slightly younger than the Limpopo swarm and related to the initial Karoo volcanism. Recent Ar-Ar dating has also shown the swarm to be  $178.3 \pm 1.1$  to  $179 \pm 1.2$  Ma in age (Dyment et al., 2003). Other dykes that are the same age as the Northern Botswana swarm related to the volcanism are the Olifants River dykes emplaced into the Kaapvaal craton (Watkeys, 2002).
3. After the injection of the above two major dyke swarms, at later stage the triple junction pattern had emerged by the emplacement of north-south trend dykes on the Lebombo monocline. It is from this time that east-west extension took place, resulting in the development of the normal faulting pattern observed on the western section of the Lebombo. Plus relative movement of continental masses over distances more than just tens of kilometres associated with crustal stretching
4. In this study, another swarm (SW1) is identified using the new aeromagnetic data with the rifting how the swarm extend to the east of the Lebombo monocline and further to Mozambique plain. The change from NS Lebombo swarm to NNE SW1 swarm might be related to the NW-SE stress as shown in the Map-7. The Four-phases volcanism and dyke emplacement can be seen in Map 7. It also indicates that E-W extension (normal to the Lebombo direction) was later (maybe gradually) replaced by extension with a N-S component as Antarctica slowly changed direction with the evolution of Mozambique Ocean.

### 5.3. Conclusion

1. A GIS geodatabase has been designed and implemented using ArcGIS 8.3 by incorporating the newly-interpreted dykes with the previous database.
2. For ease of understanding and overlay, the raster image of the all the aeromagnetic grid used in this work, and other existing geological, polygon and boundary maps (e.g. Karoo sediments and basalts) are included in the geodatabase to see the relation with the dykes.
3. From the interpretation of the available grids, most of the identified dykes are assigned to a particular swarms according to the previous studies and the assignments of previous database. Since the used grids are relatively high resolution and include a new grid compared to the previous works, it resulted a detailed interpretation of dykes for the study area.
4. From the relatively high resolution aeromagnetic grid (250 m) of Zimbabwe a total of 4988 new dykes are identified and digitized and stored in the geodatabase.

5. From interpretation of the AMMP compilation and new survey data of southern Mozambique, a total of 4030 new dykes has been digitised and stored in the geodatabase.
6. From the new survey of Mozambique, a prominent NNE trending dyke swarm adjacent to the Lebombo monocline has been interpreted which is different and might be younger than the NS striking Lebombo dyke swarm. From what we saw of the interpretation of the aeromagnetic survey of Antarctica (Jokat et al., 2003), the trend highly matches with the direction of Jokat angle.
7. Various studies and interpretations have been made on the complex history of the evolution of the supposed triple junction of the Limpopo, Northern Botswana, Lebombo dyke swarms and the pre-drift rifts of Africa and Antarctica. The interpretation of this study also supports the triple junction pattern of these swarms from the geometry of the dyke emplacement (Map-7) and using the rose diagram (Fig. 5.3).

#### **5.4. Recommendations**

1. The geodatabase can be further upgraded for the whole of the continent of Africa with a new aeromagnetic data.
2. The missing gap in the southeast Africa in the compilation of aeromagnetic coverage of the continent (AMMP) is partly filled with the recent survey of the western Mozambique. Effort still needed to complete the picture which is still missing from the aeromagnetic coverage of the eastern Zimbabwe bordering Mozambique and to replace the low-quality old data (more than 50 yrs old) covering other sedimentary areas of Mozambique.
3. Much works is still needed to make complete the geodatabase by correlating the geophysical information with ground based geological observation and extracting the non-spatial information like rock type, age, etc.
4. Similar survey as has been done on the conjugate Antarctica coastline would also be very useful on the Mozambique coast to solve some of the still unanswered and controversial questions of Gondwana breakup and its shape specially in the Cretaceous time (Jokat et al., 2003). To solve this problem it is good to know the origin of large-scale geological features like the Mozambique Ridge and the Mozambique plain and the nature of the dyke complex and what caused the final breakup.

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## Appendix: List of maps & transparent overlays

Map-1	Aeromagnetic Map of Southern Zimbabwe (Shaded Relief Image)
Map-2	Aeromagnetic Map of Southwest Mozambique (Shaded Relief Image)
Map-3	Aeromagnetic Map around Lebombo (Shaded Relief Image)
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Map-6	Magnetic Relief Zones
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Slide-5	Aeromagnetic Interpretation of New Mozambique Grid

