DETERMINING STRUCTURAL VARIATIONS BETWEEN THE NORTHERN AND SOUTHERN PROVINCES OF THE MALAWI RIFT BY USING AUTOMATIC LINEAMENT EXTRACTION METHODS

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February, 2015

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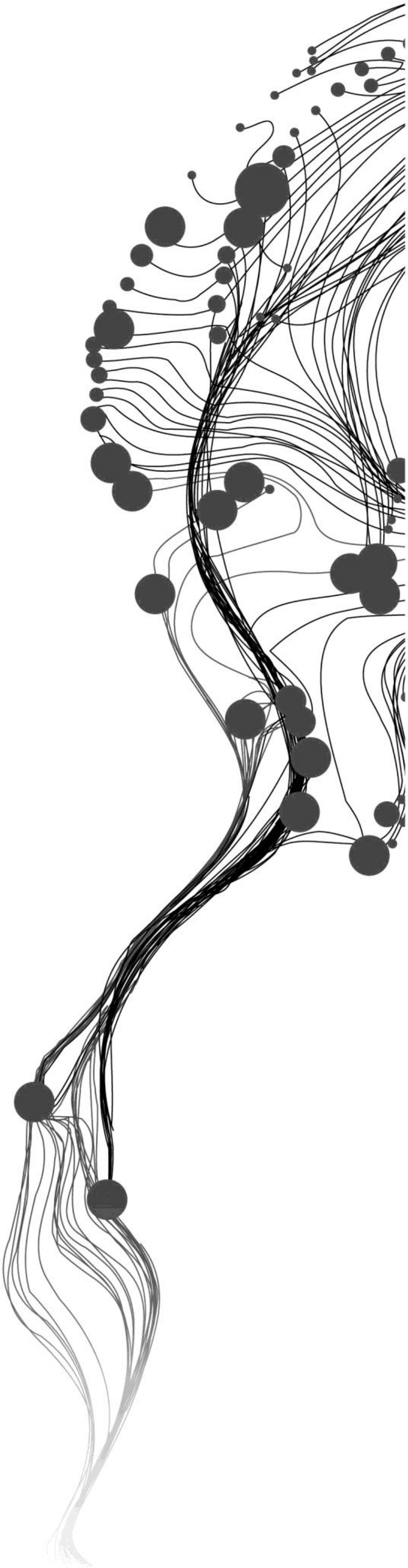

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Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Earth Resource Exploration

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ABSTRACT

The geology and tectonic setting of the Malawi Rift is characterised by Basement Complex rocks which were subjected to orogenic movements, faulting and rifting. The orogenic movements were characterised by mobile belts that caused brittle and plastic deformation of the Basement Complex rocks across the country. The Geology and tectonic setting of the country was divided into two divisions by Cannon et al., (1969) which are Northern and Southern Provinces. These divisions were based on lithological, structural and metamorphic differences between the two provinces. During this division of the provinces, it was observed that some geological structures that were present in the Northern Province of the country were not present in the Southern Province. However, these divisions were described by other researchers as not clearly defined.

Previous researches done in the area mainly focused on understanding the development of the Rift itself. Little has been done to define and understand the structural variations between the two provinces. Defining and understanding geological structures within the Malawi Rift is a key factor in understanding the structural variations and tectonic history between the two provinces. By using information from automatically extracted lineaments on satellite images integrated with geological data of the Malawi Rift, the understanding of structural variations between the two provinces has been established by the author.

Lineaments within the study area were automatically extracted by the author from hill shaded SRTM DEM using LINE Module algorithm in PCI Geomatica. Establishment of structural variations from the automatically extracted lineaments revealed that the structural variations between the Northern and Southern Province of the Malawi Rift are well pronounced at a local scale rather than at a regional scale as results at a regional scale showed structural similarities between the two provinces. At a local scale, structural differences were observed mainly on lineament orientation pattern for selected lithological units i.e. the Karroo and semi pelitic rocks. Lineament density for semi pelitic rocks also showed structural differences and minor differences were also observed on the type of lineament extension pattern between structural divisions within each province.

Results from the analysis of the observed lineament extension pattern led to the development of a proposed generalised structural component model of the Malawi Rift which shows the Malawi Rift having three major structural components that are dominated by orthogonal lineaments patterns on the far northern and southern end of the Rift and oblique lineament patterns within the central part of the Rift.

Keywords: Malawi Rift; Basement Complex; Mobile Belts; Geological Structures; Lineament Extraction; Satellite Images

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My wife Violet, my twin brother Hussen and my sisters Aluwa & Loreen for being there with me in prayers ("Broken Arrow") throughout the entire period of this MSc. My late son Yamikani and my late Mom & Dad, though gone your inspirations still lives on. Above all I give GOD the glory for making this MSc a success.

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DEFINTION OF TERMS

Fault : Approximately plane surface of fracture in a rock body, caused by brittle failure, and along which observable relative displacement has occurred between adjacent blocks (Dictionary of Geology and Earth Sciences - Oxford Reference, 2015).

Lineament : Mappable simple or composite linear feature of a surface whose parts are aligned in a rectilinear or slightly curve linear relationship (O'Leary et al., 1976).

Monocline : A geological formation in which all strata are inclined in the same direction (Thesaurus - The Free Dictionary, 2003 - 2015)

Half Graben : A geological structure bounded by a fault along one side of its boundaries (Half-graben - Google Search, 2014)

Tension crack : A discrete, commonly lens-shaped, rock fracture which forms and propagates perpendicularly to the direction of maximum extension (Dictionary of Geology and Earth Sciences - Oxford Reference, 2015).

Positive Lineament : Also referred to as topographic highs they represent scarps, ridges and troughs (Anwar & Akhir., 2010)

Negative Lineament : Also referred to as topographic lows they represent joints, faults and shear Zones (Anwar & Akhir., 2010).

Shear Zone : A region, narrow compared to its length, within which rocks have undergone intense deformation (Dictionary of Geology and Earth Sciences - Oxford Reference, 2015).

Mobile Belt : A synonym for orogenic belt, most often used for those earlier (i.e. early Precambrian) belts where tectonic activities happened (Dictionary of Geology and Earth Sciences - Oxford Reference, 2015).

Craton : Area of the Earth's crust, invariably part of a continent, which is no longer affected by orogenic activity (Dictionary of Geology and Earth Sciences - Oxford Reference, 2015).

1. INTRODUCTION

1.1. Background

The Malawi Rift is underlain by crystalline Basement Complex rocks of Precambrian to Palaeozoic age, mostly consisting of gneisses and granites. In some localities in the North and South of the country, the Basement Complex rocks are overlain by sedimentary and sub-volcanic rocks (Carter & Bennet, 1973). Most of the Basement Complex rocks comprise gneisses and granulites that have undergone medium to high grade metamorphism. The Basement Complex rocks of the Malawi Rift have undergone a prolonged structural and metamorphic history that was dominated by orogenic movements, faulting, rifting and formation of the Malawi Rift Valley (Carter & Bennet, 1973). Three mobile belts, the Mozambiquian, Irumide and Ubendian (Ring, 1993) have affected the Basement Complex rocks in almost the entire country. These orogenic movements, rifting and faulting caused brittle to plastic deformation of the Basement Complex rocks and manifestation of geological structures.

The Malawi Rift is composed of four main types of rift structures which are: Boundary faults, step faults with riftward tilted blocks, half grabens and horsts and monoclinal structures (Chapola & Kaphwiyo, 1992). These rift structures range in size from a few meters to several kilometres long. Some of these structures can clearly be noticed mainly on the Basement Complex rocks, though in some areas they are overlain by thick sedimentary cover i.e. alluvial (Figure 1.1). Most of the geological structures associated with the Malawi Rift were mapped during field geological mapping surveys that were done in the 1950s to 1970s (Carter & Bennet, 1973). These field geological mapping surveys mainly used topographic base maps and aerial photos in systematic geological mapping of the country (Carter & Bennet, 1973). Cannon et al., (1969), divided the geology and tectonic setting of the country into two divisions which are the Northern and Southern Province. During this division, Cannon et al., (1969) argued that some geological structures that were present in Northern Province were not found in the Southern province. This division was based on the lithological, structural and metamorphic differences between the two provinces. Kemp & Thatcher, (1970) observed that the differences between these two provinces were not clearly defined.

The structural division between the Northern and Southern Province of the Malawi Rift can be understood through the analysis of lineaments within the area. Lineaments give information on the topographic expressions of geological structures on the earth's surface. This information is a reflection of the earth's crust underneath. Information from automatically extracted lineaments integrated with geological data of an area provides vital clues in establishing and identifying differences in geological structures and their associated tectonic events within an area. Automatically extracted lineaments have an advantage in that even those lineaments that are located in difficult accessible areas can be mapped. The only disadvantage of automatically extracted lineaments is that in some cases non-geological features are extracted. This research therefore is aimed at determining geological structural variations between the Northern and Southern Province of the Malawi Rift by using automatically extracted lineament from satellite images integrated with geological data of the Malawi Rift.

Lineaments can be defined as mappable, simple or composite linear features of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship (O'Leary et al., 1976). Automatic extraction of lineaments (geological structures) from satellite data has been used to provide information on the tectonic history, spatial distribution, density and degree of fracturing of different geological structures (Sulaksana & Hamdani, 2014; Henderson et al., 1996). In the geological sense the term lineament refer to those structures that have been formed due to a variety of geomorphological and geological processes (Pinto et al., 2013). According to Pinto et al., (2013) these structures could be rivers or dry river beds, geologic faults, joints, shear zones, valleys, mountain crests and fractures. Anwar et al., (2010) described two types of extracted lineaments from satellite images which are negative and positive lineaments. Negative lineaments which are also referred as topographic lows are those lineaments which mostly represent joints, faults and shear zones, while positive lineaments also referred to as topographic highs are those which mostly represent scarps, ridges and troughs.

This research used automatically extracted lineaments from satellite data integrated with geological data of the Malawi Rift to understand and determine the structural variation between the Northern and Southern Provinces. By integrating information from automatically extracted lineaments and geological data, the researcher was able to determine geological structural variations between the two provinces. Structural variations between the two provinces will be determined in terms of: (i) dominant trending pattern of the lineaments, (ii) Direction of extension pattern to which the lineaments relate (iii) length and frequency of the lineaments, (iv) degree of lithological fracturing and (v) density and frequency of the lineaments.

1.2. Problem Statement

Most of the geological structures associated with the Malawi Rift were mapped from field geological mapping surveys that were done in the 1950s – 1970s (Carter & Bennet, 1973). These field geological mapping surveys mainly used topographic base maps and aerial photos in systematic geological mapping of the country (Carter & Bennet, 1973).

Carter & Bennet (1973) described the geology and tectonic setting of Malawi by dividing it into two divisions, the Northern and Southern Provinces. These divisions were initially proposed by Cannon et al., (1969) using lithological, structural and metamorphic criteria (Carter & Bennet, 1973; Thatcher, 1974). Carter & Bennet, (1973) noted that the differences between the two provinces were not clearly defined as studies done by Kemp & Thatcher, (1970) in the same area showed that the two provinces seem to have similar structural and metamorphic history (Carter & Bennet, 1973). The Champhira dome was identified to mark the provincial divisions; it extends in a NE – SW direction (Figure 1.1). It was suggested by Cannon et al., (1969) that some geological structures to the north of the Champhira dome (Northern Province) are not present in the southern part of the dome (Southern Province). Carter & Bennet (1973), defined the Champhira dome as a tectonic wedge that is bounded by a complex fault system involving both lateral and vertical movements.

Previous researches work done in the study area mainly (Malawi Rift) focused on understanding the development of the Rift itself. This gives background information to the understanding of the structures within the rift. However, little has been done to define and understand the structural variations between the two provinces. Previous studies by Piper (1989) on lineament analysis within the Malawi Rift aimed at providing a detailed quantitative assessment of the onshore fracture pattern but did not necessarily define the structural variations between the two provinces.

This research therefore employs the use of automatic lineament extraction methods integrated with geological data of the area to define the structural variations between the Northern and Southern Provinces. By using the criteria described above in section 1.1 the researcher was able to determine geological structural variations that have been manifested during the orogenic and rifting periods in the Northern and Southern Province of the Malawi Rift.

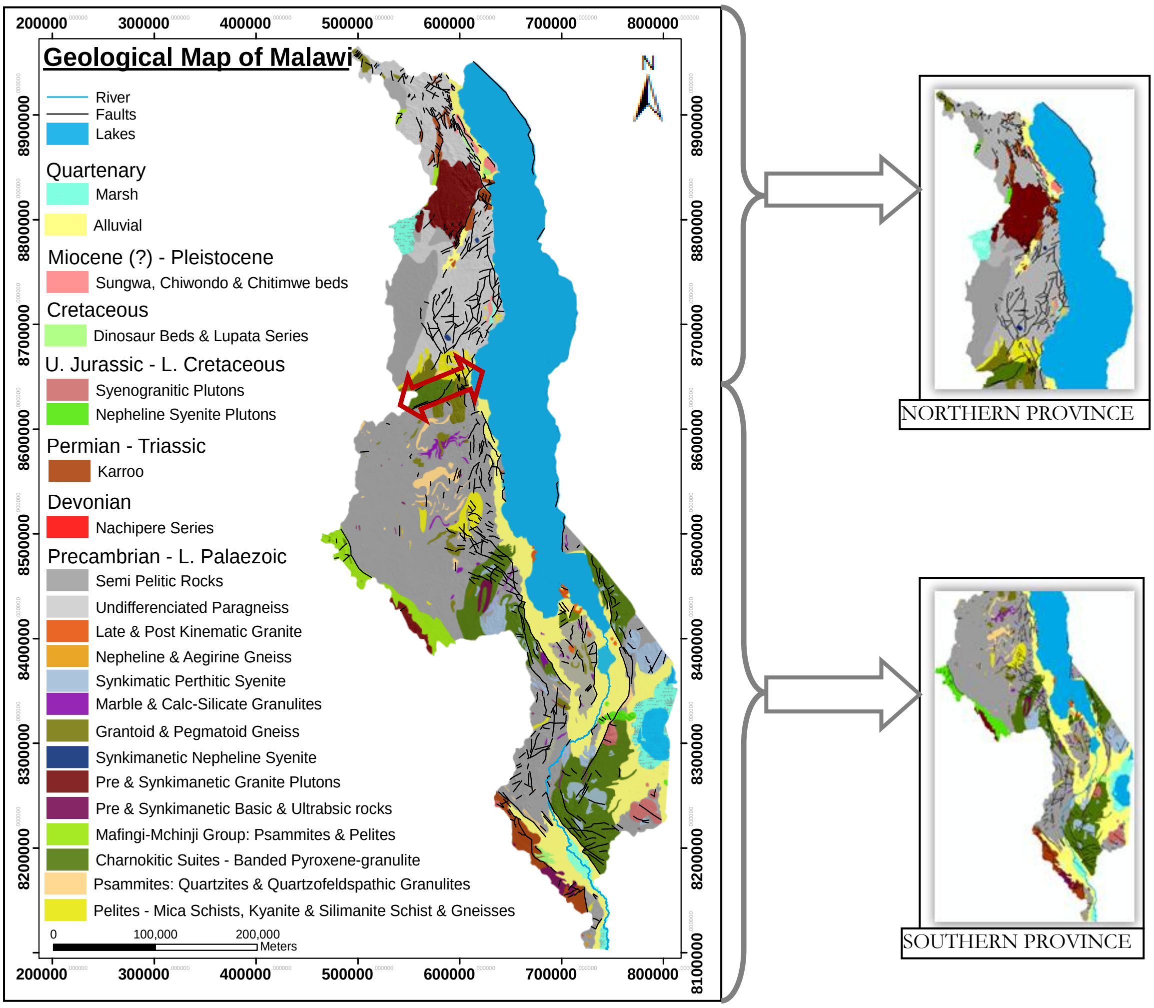

Figure 1-1: Geological Map of Malawi after Carter & Bennet, (1973). Note the location of the Champhira dome (indicated by the red arrow) which marks the provincial divisions between the Northern and Southern Province. Insert, individual maps for the Northern and Southern Provinces.

1.3. Main Objective

The main objective of this research is to determine and interpret the structural variations between the Northern Province and Southern Province of the Malawi Rift by using automatic lineament extraction methods.

1.3.1. Specific Objectives

1. To identify major lineament trending pattern, length, density, frequency and dominant direction of tectonic events in each province.
2. To characterise geological structures, i.e. types of lineament extension patterns associated with the two provinces.
3. To characterize lithological units in relation to their degree of fracturing
4. To produce lineament maps from the extracted lineaments for the two provinces and compare their spatial and structural patterns.

1.3.2. Research Questions

1. What are the variations between trending pattern, length, density and dominant direction of tectonic events between the two provinces?
2. How does the dominant direction of lineaments relate to the orientation of tectonic events?
3. How does degree of fracturing relate within different lithological units / geological age groups?
4. What are the spatial and structural variations from the extracted lineament maps between the two provinces?

1.4. Literature Review

1.4.1. Automatic Lineament Extraction

Hung et al., (2005) identified two types of lineament extraction methods: (i) Manual extraction and (ii) Automatic extraction. In manual extraction, the user applies image processing techniques and then digitizes the lineaments manually from the image, this is very tiresome and the user may overlook some lineaments. However, manual extraction has an advantage in that the user is able to detect the non-geological lineaments such as roads, fences and field boundaries (Kocal, 2002). On the other hand, in automatic lineament extraction the whole process is automated (computer based). Automatic extraction of lineaments has shown to be efficient in the sense that it runs quickly and at the same time it is able to detect more lineaments in a well detailed spatial distribution even in areas where accessibility is poor. However non-geological lineaments may sometimes be extracted, hence filtering of the extracted lineaments is necessary.

Different algorithms and software have been applied by different researchers in the delineation and extraction of lineaments from satellite images. These algorithms include Line Module in PCI Geomatica (Sarp, 2005; Kiran & Ahmed, 2014; Thannoun, 2013; Hung et al., 2005), TecLine (Rahnama & Gloaguen, 2014) edge detection filters (Sobel, Prewit, Canny and Laplacian) and Hough Transform in ILWIS and MATLAB (Anwar et al., 2010; Corgne et al., 2010; 2008; Arenas, 2006). Each algorithm and software has its own applicability and parameter settings which are defined in relation to the research's objectives and structural complexity of the research area. This research uses the LINE Module algorithm to automatically extract lineaments within the Northern and Southern Province of the Malawi Rift so as to establish if there exist any structural variations between the two.

1.4.2. Lineament Extraction in Geological applications

Automatic lineament extraction by using LINE Module has played a major role in different geological applications. Different authors have used different satellite images to extract lineaments using the LINE Module algorithm in PCI Geomatica (Mostafa & Bishta, 2005; Sarp, 2005; Abdullah et al., 2013; Bishta, 2009; Qari, 2010; Anwar et al., 2010; Anwar et al., 2013, Hung et al., 2005; Kiran & Ahmed, 2014; Thannoun, 2013; Kocal, 2002; Awdal, 2012)

> **Mostafa & Bishta, (2005)** extracted lineaments for the eastern part of Egypt using LINE Module algorithm in PCI Geomatica on LANDSAT images with an aim of classifying and designating lithological units. The results showed that the algorithm was able to delineate lineaments which were correlated with aeroradiometry total count contour maps to interpret the fracturing pattern for different lithological units and also to delineate lithological units which had a high potential for uranium mineralization.
>
> **Hung et al., (2005)** extracted lineaments in a tropical catchment area in Vietnam from LANDSAT and ASTER images. The objective of this study was to compare accuracy of

lineaments extracted from LANDSAT and ASTER images. In this work Hung et al (2005) used LINE Module algorithm in PCI Geomatica to extract the lineaments. Results from this work showed that the algorithm was able to extract lineaments whose dominant direction was almost similar to the general orientation of faults in the area in both images but with a high accuracy on ASTER images as compared to LANDSAT images due to the high resolution of the ASTER images.

Abdullah et.al., (2013) applied the LINE Module algorithm in PCI Geomatica to extract lineaments from LANDSAT images for the south western part of Taiz area in Yemen. The purpose of this study was to test the automated lineament extraction method and investigate the ability of this method in extracting accurate lineaments as compared to published field based fault map. Results of this work showed that using this technique lineaments belonging to major faults zones within the area were properly extracted.

Qari, (2010) used the LINE Module algorithm to extract lineaments from satellite imagery. His main objective was to define the advantage of using satellite imagery of different resolution in structural mapping. The results of his work showed that the LINE Module algorithm was able to extract lineaments from the different resolution satellite images with more lineaments being extracted from the high resolution images and less from the low resolution images.

Anwar et al., (2010) extracted lineaments from Digital Elevation Model (DEM) using LINE Module in PCI Geomatica. The aim of this work was to clarify the ability of multidirectional shaded relief images in extracting both negative and positive lineaments. The DEM was hill shaded from different directions and later combined to give a single image. The results showed that the algorithm was able to extract positive and negative lineaments from almost all directions on the combined hill shaded images.

Awdal et al., (2012) extracted lineaments for North-eastern Iraq from Digital Elevation Models using the LINE Module algorithm. This study aimed at using DEM with GIS to classify lineaments into positive and negative effects on a drainage pattern with emphasis on ground water exploration. This study used multidirectional hill shading of the DEM, later the hill shaded images were combined to give a single image from where lineaments were extracted. Results from this study showed that the algorithm was able to extract both negative and positive lineaments within the study area.

Kiran & Ahmed, (2014) extracted lineaments from LANDSAT and ASTER GDEM images for southern Chitradurga schist using LINE Module in PCI Geomatica. Their work mainly aimed at examining the automatic extraction of lineaments with band merged LANDSAT TM and ASTER GDEM shaded relief in a schist region. Results from this work showed that the algorithm was able to extract lineaments, although the extracted lineaments showed variations in terms of length and frequency of occurrence which was attributed to the differences in spatial resolution of the source data.

Thannoun, (2013) used LINE Module in PCI Geomatica to extract lineaments from LANDSAT images in Northern Iraq. The aim of this study was to use the extracted lineaments in understanding the tectonic relationship between lineaments and structural elements of the study area. Results from this work showed that the algorithm was able to extract all possible linear features that might be representing fracture zones within the area.

Sarp, (2005) used the LINE Module algorithm in PCI Geomatica to extract lineaments on LANDSAT images for the North-Western side of Ankara. The main purpose of this study was to apply remote sensing techniques for lineament analysis on north western Ankara. The algorithm was able to extract more lineaments though less connected as compared to manually extracted ones.

Kocal, (2002) extracted lineaments using LINE Module in PCI Geomatica from a high resolution 1 meter Ikonos image for an Andesite mine in Ankara, Turkey. The objective of this study was to identify rock discontinuities within the study area. Results from this work showed that the algorithm was able to extract the lineaments (rock discontinuities) within the study area more effectively than manual extraction.

This study employs the use of remote sensing techniques, satellite images and LINE Module algorithm in PCI Geomatica to extract and analyze lineaments from the Northern and Southern Province of the Malawi rift (Figure 1.1) with an aim of understanding and determining their structural variations (much on how the LINE Module algorithm works has been explained in Chapter 3). The LINE Module is one of the most widely used algorithms for lineament extraction (Hung et al., 2005; Sukumar et al., 2014).

All the above reviewed literature used different image pre-processing techniques prior to lineament extraction. It is observed that those who used Digital Elevation Models (DEM) (Anwar et al., 2010; Awdal, 2012) had to run a multidirectional hill shading process; this was aimed at reducing the effect of biased lineaments extraction which is a common problem of one direction illuminated hill shaded images. Information on the general orientation of published field based faults within the study area assisted in defining the azimuth angle for hill shading.

2. STUDY AREA AND DATA SET

2.1. Study area geology and tectonic setting

This research was conducted on Malawi (Figure 1.1 & 2.1). The area of study is situated on the western branch of the East African Rift System (EARS), it is located within 9^0 South and 17^0 South parallels of latitudes and 33^0 East and 36^0 East longitudes (Figure 2.1). Geologically, it is underlain by crystalline Basement Complex rocks of Precambrian to Palaeozoic age mostly gneisses and granites in most parts.

The Basement Complex rocks have been overlain by Karroo System sedimentary rocks which range in age from Permian to upper Triassic or lower Jurassic. The Karroo System sedimentary rocks are dominant in the northern part of the country (Northern Province), though some are found in the southern part of the country (Southern Province) to the south western side of Mwanza fault and north western side of Nsanje (Carter & Bennet, 1973) (Figure 1.1).

Overlying the Karroo rocks are the Chilwa Alkaline Province rocks that comprise syeno-granitic and nepheline syenite plutons, volcanic vents and carbonatites of upper Jurassic to cretaceous age. Sedimentary rocks of cretaceous, pleistocene and quaternary follow in succession over the Chilwa Alkaline rocks (Figure 1.1). These sedimentary rocks crop out in the northern part of Malawi, central Malawi and south western side of Blantyre in southern Malawi (Carter & Bennet, 1973).

Tertiary and Quaternary deposits are the last in the succession, these comprise alluvium and colluvium sediments and they are mostly found aligned in a narrow belt just parallel to Lake Malawi and along the Lilongwe-Kasungu plains in the central region of Malawi and the Phalombe plain to the southern end of Lake Chilwa. In these areas, most of the Basement Complex structures are obscured by thick layers of residual cover, therefore lineaments extracted in these areas may represent traces of foliation in the underlying rocks (Piper, 1989).

2.2. Tectonic Setting and Events

As explained in the previous section the Malawi Rift is mostly underlain by Precambrian to Lower Palaeozoic Basement Complex rocks (Ray, 1975); and is located within the western branch of the EARS (Figure 2.1). All the three mobile belts, Ubendian, Irumide and Mozambiquian affected the Basement Complex rocks across the country. Carter & Bennet (1973), identified that the three mobile belts occurred in two different tectono-metamorphic events. The first event involved the Ubendian Mobile belt (Figure 2.2) from south western Tanzania, this event caused plastic deformation of the Basement Complex rocks and the second event involved both the Irumide and the Mozambiquian cycles (Figure 2.3 & 2.4); these two events were associated with brittle deformation of the Basement Complex rocks. It is noted that signatures of the above explained mobile belts are visible in the Northern Province with the Ubendian and Mozambiquian dominating. In the Southern province of the Rift, signatures of the Mozambiquian and Irumide mobile belt dominate (Carter & Bennet, 1973).

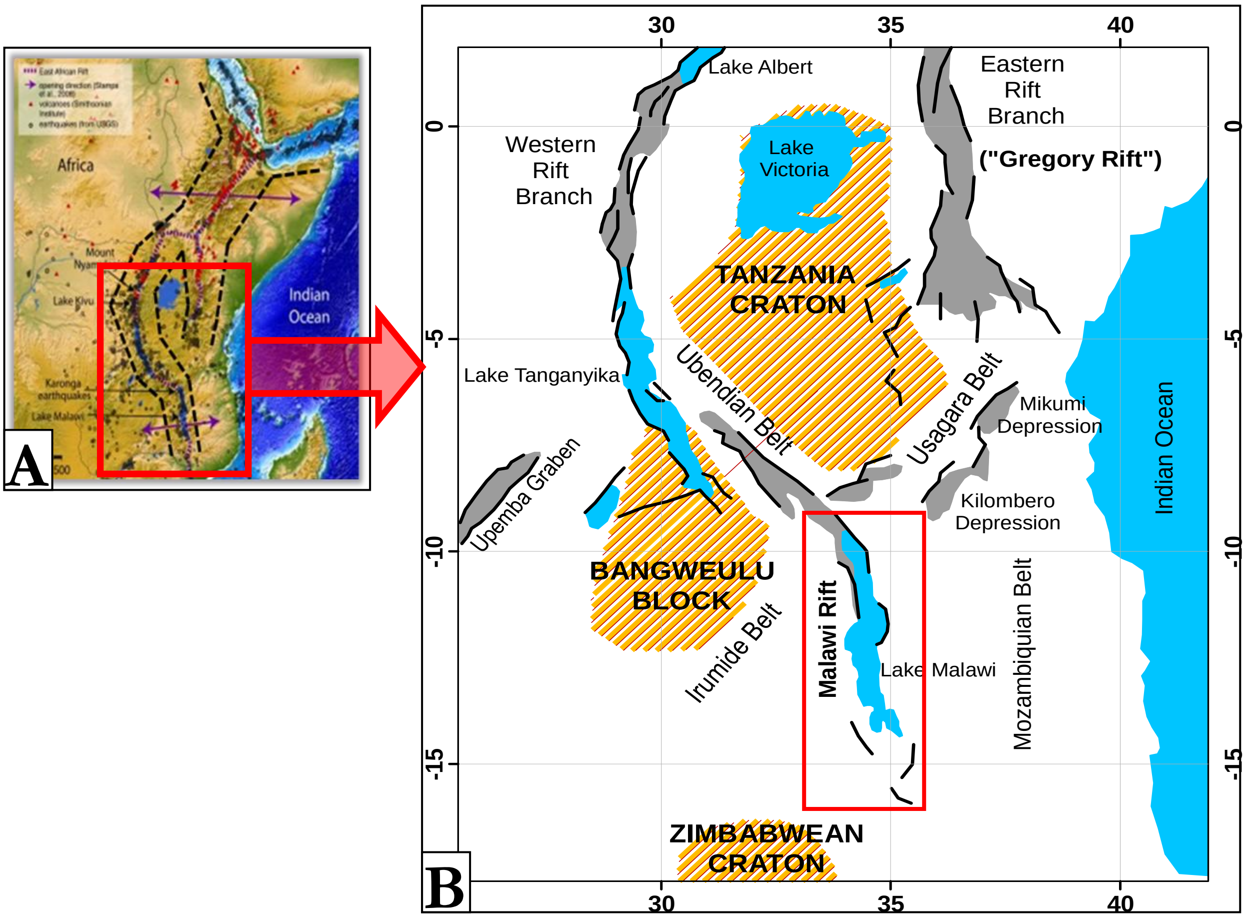

Figure 2-1: **(B)** Schematic diagram of the East African Rift System showing approximate location of the Malawi Rift indicated by the red rectangle. Note the location of the Malawi Rift within the western branch of the East African Rift System and its surrounding mobile belts (Modified from Macheyeki et al., 2015). Insert **A** is a satellite map of the East African Rift System (Shillington, 2010), showing location of map **B**.

Carter & Bennet, (1973) and Chapola, (1997) described the tectonic structures of Malawi to be divided into two age groups namely; Pre-Cenozoic age structures and Cenozoic age structures. The Pre-Cenozoic age structure mainly comprise those structures which were formed during the Karroo rifting of Permian to Triassic (~280 to 195 Ma) and Post Karroo rifting of Jurassic to Cretaceous period (~195 to 65 Ma), these include faults, shear zones and dyke swarms. The Chimaliro fault zone which is to the southern side of the Champhira dome is an example of a Pre-Cenozoic structure. In southern Malawi NE-SW trending dyke swarms are examples of the Pre-Cenozoic structures. The second group of structures comprise those structures which were formed during the Cenozoic age, these structures are associated with the initiation of the EARS, which in Malawi started about 10 million years ago. Much on the Pre-Cenozoic and Cenozoic structures has been explained in detail in section 2.6. The general orientation of the rift related structures in both Northern and Southern Province of the Malawi Rift is mostly dominated by a NW-SE and N-S trending pattern with a minor NE-SW trending pattern. This according to Delvaux, (1991) is a clear indication that the present orientation of the rift related structures is a reflection of the orogenic related structures orientation pattern most probably the Ubendian, Mozambiquian and Irumide mobile belts respectively. From this it can be deduced that the present orientation pattern of the rift related structures exist along the same orientation of the orogenic mobile belts (related structures). Understanding the morphological, tectonics models and the type of faulting through profiles (Figure 2.5 & 2.6) of the Malawi rift assisted in understanding the type of morphological processes that happened within the rift and the type of lineaments expected to be extracted in the study area. As described above, the Malawi Rift has been affected by orogenic movements and rifting & faulting. For description purposes in this research they are being referred to as orogenic episode and rifting episode meaning the orogenic movements and rifting & faulting respectively.

2.3. The Orogenic Episode

This episode has been associated with the formation of Pre-Cenozoic structures (Figure 2.7A). These structures include faults, shear zones, monoclines and dyke swarms which were identified mostly in the Southern Province (Chapola, 1997). Three mobile belts have been characteristic of the orogenic period and these include; Ubendian, Irumide and Mozambiquian much on these mobile belts have been explained in the next sections.

2.3.1. Ubendian Mobile Belt

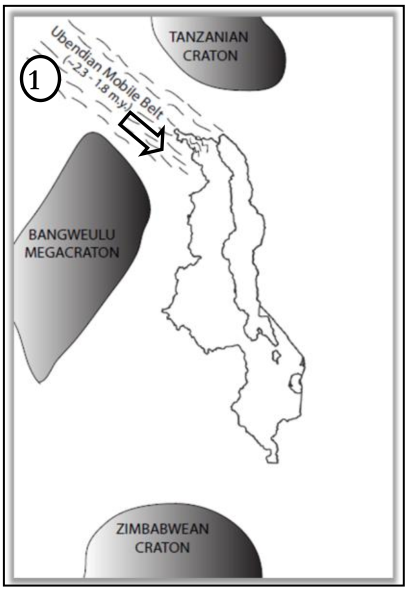

Figure 2-2: Schematic diagram of the Ubendian Mobile Belt dated ~2300 – 1800 m.y. It is depicted as the first and oldest mobile belt within the Malawi Rift. Black circle with number indicate sequential order of the belt and black arrow indicate direction of the belt. (Source: Carter & Bennet, 1973; Roberts et al., 2012).

The Ubendian Mobile belt is dated ~2300 - 1800 million years (Ring, 1993). It originates from the south-western part of Tanzania (Ray, 1975) and it extends into Malawi in a south-easterly trending pattern this makes it to be characterized in Malawi by a NW – SE trending pattern (Figure 2.2). It is well pronounced in the Northern Province. Most of the geological structures that were as a result of this mobile belts show a NW –SE trending pattern. It is described to have caused the Mugheshe shear zones in the Chitipa – Karonga area. The shearing which was associated with the Ubendian mobile belt may have deformed pre-existing geological structures in this area (Ring et al., 2002).

2.3.2. Irumide Mobile Belt

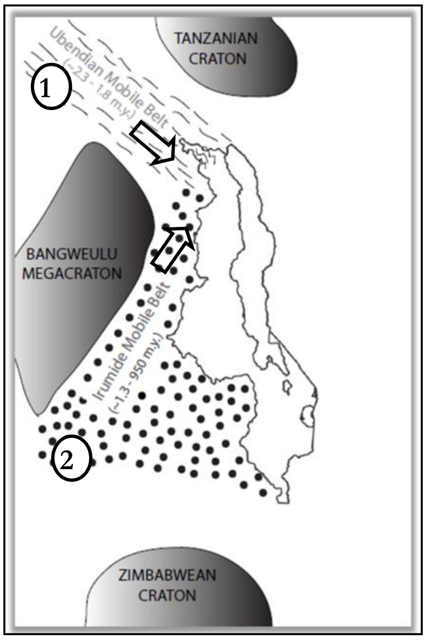

Figure 2-3: Schematic diagram of the Irumide Mobile Belt dated ~1350 – 950 m.y. It is the second mobile belt that followed the Ubendian. Black circles with numbers indicate sequential order of the belts and black arrows indicate direction of the belts. (Source: Carter & Bennet, 1973; Roberts et al., 2012).

The Irumide Mobile belt extends into Malawi from Zambia, it is dated ~1350 – 950 million years and it is made up of reworked Ubendian Basement (Ring, 1993). It is well pronounced in the Northern and Southern province of the Malawi Rift (Figure 2.3) and is characterized by NE – SW trending pattern (Carter & Bennet, 1973). Geological structures that were formed during the period of this mobile belt have similar orientation and trending pattern to the belt i.e. NE – SW. Roberts et al., (2012) showed the Irumide mobile belt as extending to the south-eastern part of the Bangweulu megacraton and to the far end of southern Malawi where it is called southern Irumide mobile belt.

2.3.3. Mozambiquian Mobile Belt

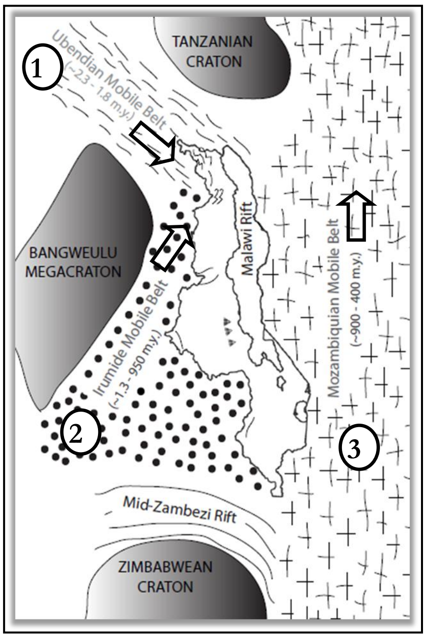

Figure 2-4: Schematic diagram of Mozambiquian Mobile Belt dated ~900 – 400 m.y. Black circles with numbers indicate sequential order of the belts and black arrows indicate direction of the belts. (Source: Carter & Bennet, 1973; Chapola, 1997; Roberts et al., 2012).

The Mozambiquian mobile belt is categorized to be the last mobile belt that affected the Malawi Rift, it is dated ~900 – 400 million years (Thatcher, 1974). It is observed to have affected both provinces. This mobile belt caused deformation of the Basement Complex rocks which resulted into folding and movement along shear zones which are oriented parallel to the structures of the Ubendian belt (Ray, 1975) in the Northern Province. It approximately run in a N - S trending pattern (Ring, 1993) (Figure 2.4). The Mozambiquian mobile belt is observed as covering a wider area from the southern end to the far north of the EARS; hence regarded as the biggest mobile belt of the three with regards to area coverage.

2.4. The Rifting Episode

2.4.1. Initiation of the Malawi Rift

At the end of the orogenic period, initiation of rift faulting that resulted into the formation of the Malawi Rift began; this episode was associated with the formation of Cenozoic structures (Figure 2.7B). Ray, (1975) stated that the actual rift faulting started in the Upper Jurassic. Initiation of the rift faulting in the Upper Jurassic may have reactivated older faults of the orogenic episode, this might have added to the complexity of geological structures within the Northern and Southern Provinces. Rifting caused normal faulting i.e. border faults that are characteristic of the Lake Malawi basin (Biggs, Nissen, Craig, Jackson, & Robinson, 2010; Piper, 1989) (Figure 2.7B). Other structures associated with rifting include half grabens and horsts (Chapola & Kaphwiyo, 1992). Crossley, (1984) observed that the Malawi Rift is in its young stage hence denudation processes have not yet obscured rift boundary structures from being recognized (example to this is the Bilira-Mtakataka and Zomba faults). The observation by Crossley, (1984) gives confidence to the author in extracting lineaments from areas that are overlain by alluvial deposits within the Northern and Southern Provinces.

2.5. Structures of the Northern and Southern Provinces

2.5.1. Known Faults / structures within the Northern Province

Some lithological units that are present in the Northern Province study area are not present in the Southern Province e.g. the Synkimanetic Nepheline Syenites (Figure 1.1). The greater part of this province is mostly underlain by Precambrian to Lower Palaeozoic rocks mainly undifferentiated paragneisses, semi-pelitic, late and post kinematic granitic rocks which form the Basement Complex. In some parts, Permian to Triassic Karroo system rock outcrops are seen which are mostly found in basin like structures, forming the Karroo basins of Northern Malawi. The eastern side of the area is covered with quaternary (alluvial) and Miocene – Pleistocene (Sungwa, Chiwondo and Chitimwe beds) deposits.

Field based fault map of the area, shows the Livingstonia fault on the eastern side of Lake Malawi as the longest fault zone in the area. Almost all the Karroo basins in this province are structurally controlled or fault controlled. Visual analysis of the geological map of Malawi, shows that most of the faults are occurring in the undifferentiated gneisses, late and post kinematic granites and the Karroo rocks, less faulting is observed in the pre & synkimanetic granitic plutons, semi-pelitic rocks and the alluvial (Figure 1.1).

2.5.2. Known Faults / structures within the Southern Province

The Southern Province is mostly characterized by Charnokitic rocks (banded pyroxene granulites) and Semi-pelitic rocks forming the lager part of Basement Complex in the area. Similar to the Northern Province, some lithological units present in the South are not available in the Northern Province i.e. the Syenogranitic Plutons and Nepheline Syenite Plutons (Figure 1.1) which belong to the Upper Jurassic and Lower Cretaceous period. The central and eastern part of the area is overlain by quaternary (alluvial) deposits, these are accumulated in what is referred to as the Shire Trough (Crossley, 1984). Karroo rocks of Permian to Triassic age outcrop on the south-western part of the area parallel to the Mwanza and Thyolo faults.

Geological structures related to the orogenic and rifting episodes are clearly visible in the area, the Bilira-Mtakataka, Zomba, Thyolo and Mwanza faults. The Zomba fault forms the contact between the alluvial and the Basement Complex on the eastern side of Shire River while the Bilira-Mtakataka fault forms the contact between the alluvial and Basement Complex rocks on the western side of Shire River (Figure 1.1). The central and southern parts of the Southern Province are characterised by alluvium which are deposited within the Shire Trough. Crossley, (1984) observed that the flow of the Shire River within this trough is structurally controlled by following fault angle depression.

2.5.3. Comparison of structures of the Northern and Southern Province

Profiles drawn on selected areas on the SRTM DEM within the Karonga – Livingstonia and Kirk-Range – Zomba faults (Figure 2.5B) show that the Livingstonia and Zomba faults on the eastern side of the rift in Northern and Southern Province respectively has very steep slope gradient as compared to the Karonga and Kirk-Range faults on the western side of the rift which may suggest that the Livingstonia and Zomba faults may have formed from a single major fault block. This observation concurred well with studies of Crossley, (1984) and Ebinger et al., (1987) done in the same area. According to the rifting model proposed by Ebinger et al., (1987) and Crossley, (1984) shown in figure 2.5A & 2.6, it can be concluded that, structurally major tectonic movements which involved a single major boundary fault occurred on the eastern side of the rift than in the western side where the tectonic movements involved a series of several fault blocks in a stepwise form towards the rift (Figure 2.5B & 2.6A & 2.6B). The steepness of the escarpments (slope) for the Livingstonia and Zomba faults, Karonga and Kirk-Range faults as observed from profiles in figure 2.5B suggests that the Livingstonia and Zomba faults were formed as a result of a single major fault block than the Karonga and Kirk-Range faults to the western side of the rift which shows evidence of several fault blocks.

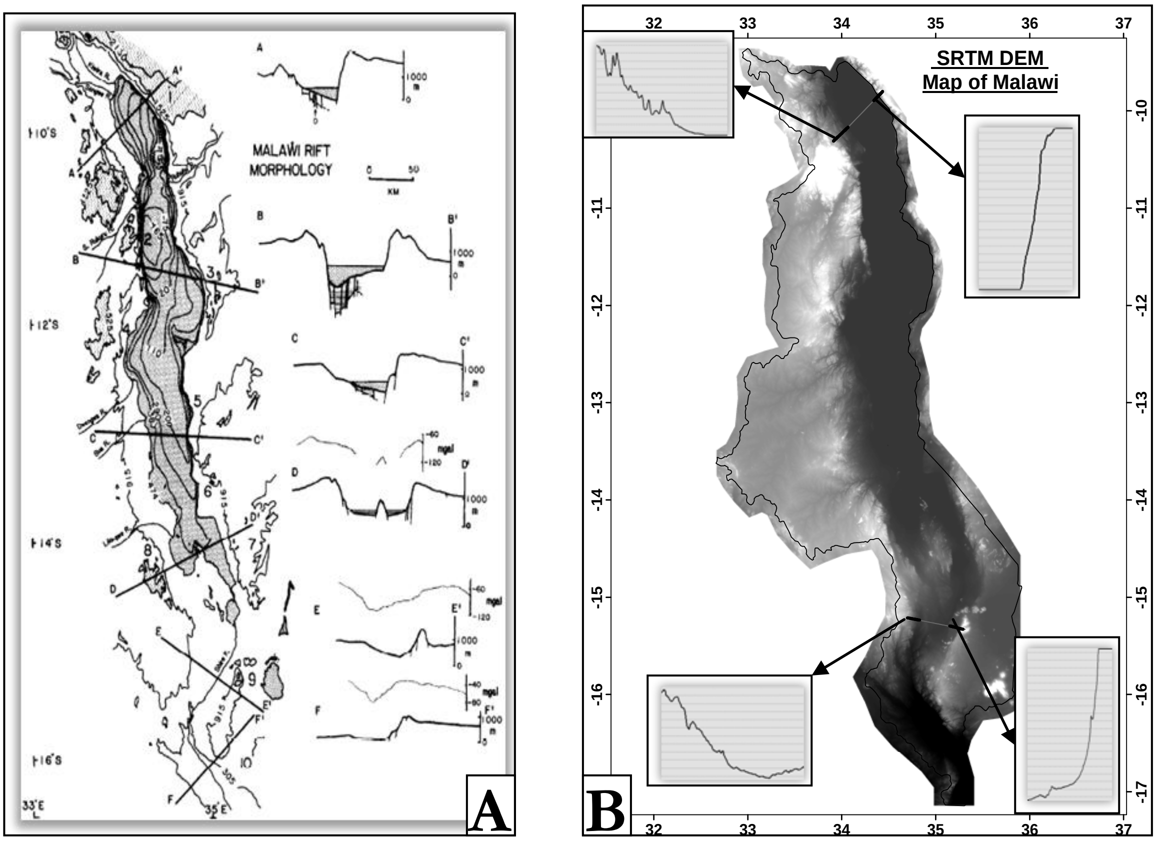

Figure 2-5: **(A)** Tectonic Model of The Malawi Rift (Ebinger, 1987) showing profiled areas and their cross sections. **(B)** SRTM DEM showing profiled areas. Note the similar pattern in the topographic expression of the structures from the profiles drawn on the western and eastern side of the rift on SRTM DEM and those of the model.

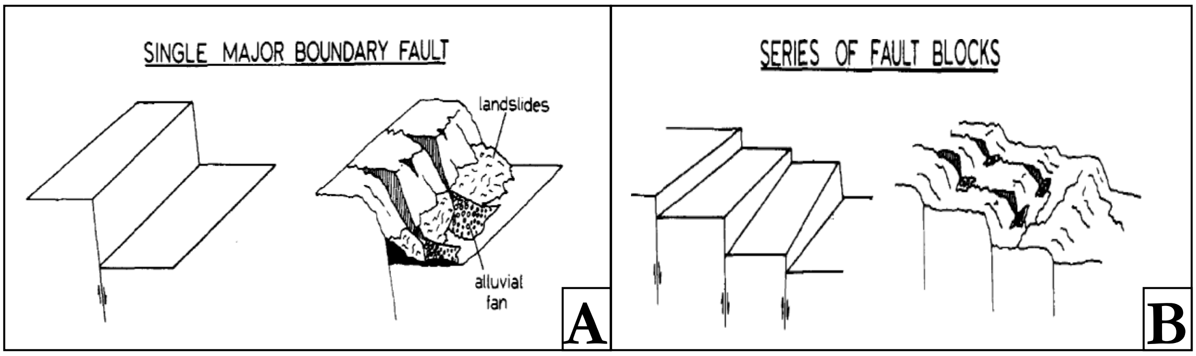

Figure 2-6: Common-Rift Margin Structures model and their geomorphic expressions (Crossley, 1984). **(A)** corresponds to geomorphic structures found on eastern side of the Malawi Rift and **(B)** corresponds to geomorphic structures found on western side of the Malawi Rift

2.6. Structural history of the Malawi Rift

As explained above the Malawi Rift has been affected by two tectonic events that led to the present position and orientation of geological structures within the rift. From this background structures within the Malawi Rift can be divided into two which are Pre-Cenozoic and Cenozoic structures (Carter & Bennet, 1973; Chapola, 1997). Pre-Cenozoic structures covers structures that were associated with the orogenic period and Cenozoic structures covers structures associated with the rifting episode. The Pre-Cenozoic period caused what might be referred to as a foundation for the Cenozoic structures i.e. structures associated with the rifting episode followed within the same structural trends of the Precambrian – Palaeozoic mobile belts (Pre-Cenozoic period). Structures of the Cenozoic period were characterised by border faults that formed the backbone of the Lake Malawi basin (Figures 2.7B). The above characterisation on the tectonic history of the Malawi Rift led to the production of schematic maps showing the structural history of the Malawi Rift; information for the production of these maps was derived from Carter & Bennet (1973), Chapola (1997), Ebinger et al., (1987) and Roberts et al., (2012).

2.6.1. Pre-Cenozoic age structures

The first group of structures within the Malawi Rift belong to the Pre-Cenozoic age (in this thesis these are characterised as belonging to the orogenic episode). Structures in this group developed during the Karroo rifting of Permian to Triassic (~280 – 195 Ma) and post Karroo rifting of Jurassic – Cretaceous (~195 – 65 Ma). Some known structures belonging to this period include the Chimaliro fault which has a NE-SW trending pattern, dyke swarms in the Southern Province with a NE-SW trending pattern (Chapola, 1997) and the Mugheshe shear zone in the Northern Province which has a NW-SE trending pattern (Figure 2.7A).

2.6.2. Cenozoic age structures

The second group of structures comprise those structures belonging to the Cenozoic age (in this thesis these are characterised as belonging to the rifting episode). These structures are mainly those related to the formation of the Malawi Rift and they are being identified as border faults (Half grabens) and they form a backbone of the Malawi Rift (Figure 2.7B). Most of these border faults are characterised by a N-S trending pattern except in some areas in the far northern part of the Northern Province (Livingstonia border fault) where the trending pattern is NW-SE and the southern part of the Southern Province where the trending pattern is NE-SW and NW-SE for the Zomba and Thyolo border faults respectively.

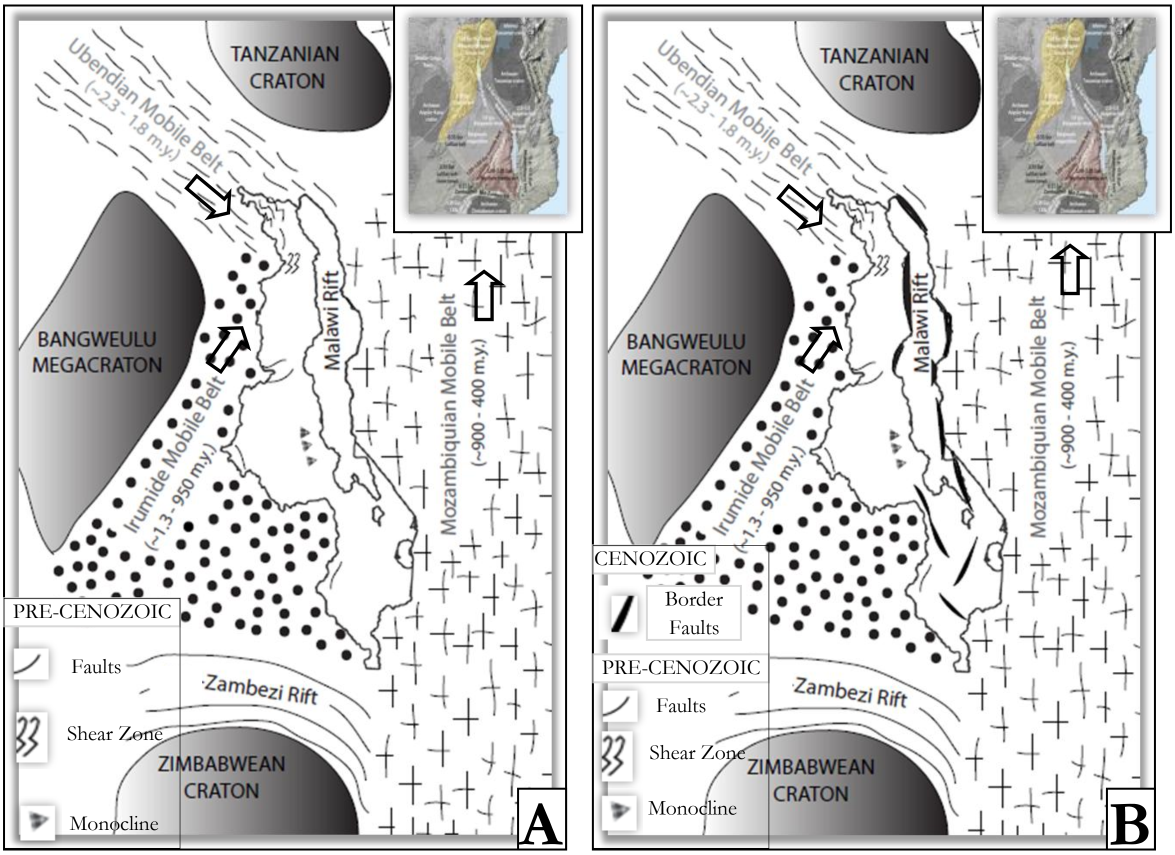

Figure 2-7: Generalised maps for the structural history of the Malawi Rift. **(A)** Pre-Cenozoic age structures which are associated with the orogenic episode and **(B)** Cenozoic age structures which are associated with rifting episode note the border faults forming backbone of the Malawi Rift (Source: Carter & Bennet, 1973; Ebinger et al., 1987; Roberts et al., 2012; Chapola, 1997). Insert is a tectonic/structural map of eastern-central Africa showing tectonic elements (Courtesy: Roberts et al., 2012), see Appendix 2 for a large image.

It can be generalised here that structures within the Malawi Rift belong to either Pre-Cenozoic or Cenozoic period and that the Cenozoic related structures are emplaced within Pre-Cenozoic structural trends as also noted by Thatcher (1968), that rift valleys turn to occur within Precambrian Mobile belts. Understanding the known structures within the two provinces, their structural history and their formation mechanism was very vital as it gave clue on the type and frequency of lineaments expected to be extracted within the two provinces. From the above profiles on SRTM DEM it is indicative that most of the lineaments in the study area are expected on the western side of the Malawi Rift as it have been observed from both the model by Crossley, (1984) and the profiles that the greater part of the western side of the Malawi Rift has resulted from a series of fault blocks which forms a stepwise pattern towards the Lake Malawi basin.

2.7. Research data set

Two data sets have been used in this project these comprise satellite and geological data. For better analysis and interpretation of results in some cases, the two data sets were integrated. The geological data set was mainly used on the initial stage and late stage of the research which mostly involved selection of optimal parameters for the extraction of lineaments from the whole research area and interpretation of results respectively.

2.7.1. Satellite Dataset

The satellite dataset consist of Digital Elevation Models i.e. Shuttle Radar Topographic Mission (SRTM DEM). The SRTM DEM was collected by the Japan Oil and Gas Metal National Cooperation (JOGMEC) during a joint mineral exploration project with the Malawi Geological Survey Department (MGSD) from 2010 to 2012. The SRTM DEM was collected in scenes, in total there are almost 24 scenes covering the whole country; each scene covers 110 km x 110 km. Out of these scenes only 10 covers the Northern Province and 14 covers the Southern Province. The coordinate system for the SRTM DEM is Geographic Coordinate System (GCS) 1984. In the course of the research this coordinates system was projected to Universal Transverse Mercator (UTM) WGS 1984 Zone 36S.

The other satellite data set was initially ASTER. However, ASTER was later replaced with LANDSAT ETM$^+$ 7 images because the ASTER images had a lot of clouds in some parts hence masking these clouds ended up removing information which might have been useful in the expression of geomorphic features and extraction of lineaments (Figure in Appendix 1A). The LANDSAT ETM$^+$ 7 images were downloaded from the USGS website Earth Explorer. Image selection was based on acquisition date and cloud cover; in this regard images which were acquired during the dry season were downloaded because of their less clouds and vegetation cover. LANDSAT images were no longer used in this research as preliminary analysis and interpretation of results showed that lineaments extracted from these images were short and less connected as compared to the SRTM DEM (Figure in Appendix 1B). From this background it was concluded that the research work should proceed with the SRTM DEM in extracting the lineaments from the Northern and Southern Province of the Malawi Rift. However from the preliminary analysis it was observed that LANDSAT images can best be used in the study area on a local scale rather than large scale to extract lineaments.

2.7.2. Geological Dataset

The geological data is divided into two sets. The first set comprise vector format shapefiles of lines which are faults, joints, lithological units, streams / rivers, main roads, international boundaries and points which are districts, towns, and villages. This first data set covers the Northern Province of the Malawi Rift. All these shapefiles are in UTM (WGS 1984 Zone 36S). These were digitized from geological map of Malawi during an Active Fault Mapping project that happened in the Northern Province in 2010 (Macheyeki et al., 2015). This project was conducted by the Eastern and Southern Africa Regional Seismological Working Group (EASARSWG) with an aim of mapping active faults within the area. The second geological data set was a scanned geological map of Malawi which was georeferenced and layers such as faults, joints, lithological units, streams / rivers, districts, main roads for the Southern Province were digitized from. In general similar shapefiles as those of the Northern Province were digitized in the Southern Province.

2.8. Research software

In this research six software were used in both pre-processing, data analysis and interpretation since there is no single software that can be used in all steps. These software include: ArcGIS 10.2, Rockworks 16, ENVI 5.1, SPSS version 22, Adobe Illustrator and PCI Geomatica 2014.

ENVI was mainly used in the pre-processing stages of the images which included multidirectional hill shading of the SRTM DEM. PCI Geomatica was used for the actual extraction of lineaments from the combined hill shaded image. Rockworks, SPSS and ArcGIS were used for the final geospatial analysis and interpretation of the extracted lineaments; this included plotting of rose diagrams, calculation of lineament length and calculation of lineament density. Adobe illustrator was used in drawing some schematic diagrams for the structures associated with orogenic and rifting episodes. Much on the actual usage of some of these software has been explained in chapter three of this thesis.

3. METHODOLOGY

3.1. Introduction

The main aim of this thesis was to determine structural variations between the Northern and Southern Province of the Malawi Rift using automatically extracted lineaments from satellite images. The term lineament has been explained in Chapter 1 of this thesis. With regard to this research it is being used to mean extracted lineaments from the Northern and Southern Province of the Malawi Rift which might represent geological structures, i.e. faults, joints, shear zones, monoclonal structures, tension cracks, ring complexes, dykes and mountain ridges hence the term lineament is being used in view of these structures except where it is mentioned in reference to already know faults (field based faults from the Geological Map of Malawi) within the research area, then, it means a "fault".

Satellite images show expressions of different geological structures on the earth's surface. Expression of these structures is a reflection of different tectonic activities happening within the earth's interior. In this thesis satellite data comprising Shuttle Radar Topographic Mission Digital Elevation Model (SRTM DEM 90 meter resolution) which can be freely downloaded from the United States Geological Survey website (USGS - EarthExplorer, 2014) was used for the extraction of lineaments. This satellite data was integrated with geological data for the Malawi Rift in the analysis and interpretation of results.

To achieve the main objective of this thesis different processes and methods were followed which involve image pre-processing, adjustment and selection of optimal parameters, lineament extraction and verification, visual and geospatial analysis and geological interpretation which led into defining and establishing structural variations between the Northern and Southern Province of the Malawi Rift. A methodological flow chart for all the processes has been presented in figure 3.1.

In order to achieve a better selection of optimal parameters for lineament extraction a training area was chosen whose structures and lithological units are known from literature review (Figure 3.3A). Selection of these areas was based on the condition that, structures of all the tectonic events (orogenic and rifting) are present in the area. Parameter adjustment and selection was done in relation to knowledge of fault length and fault segmentation within the study area. A geological map of the selected training area was adopted from Biggs et al., (2010) where reference published field based faults were identified (Figure 3.3A). These faults were used in the adjustment of LINE Module parameters. The SRTM DEM was subsetted within this area and parameter adjustment and selection of optimal parameters was done on this training area (Figure 3.3B) before being applied to the whole research area. The process of lineament extraction was done by using LINE Module algorithm in PCI Geomatica (much on this algorithm will be explained in section 3.3). The extracted lineaments were visually and geospatially verified to validate the effectiveness of the selected optimal parameters and the LINE Module algorithm. The verification of the extracted lineaments was done using the selected published field based faults for the Malawi Rift (Figure 3.3A).

After selection of the optimal parameters, they were applied to the whole research area to extract lineaments. In both provinces the same standard set of selected parameters was used (table 3.2). The extracted lineaments were verified both visually and geospatially before being analyzed and interpreted. The last part towards achieving the objective of this research was to do visual and geospatial analysis and interpretation of the results from both provinces. This has been briefly explained in this chapter but much will be explained in detail in chapter 4 of this thesis where interpretation of results has been done. Interpretation of results was done in two parts, i.e. at a regional scale and local scales for better establishment and understanding of structural variations between the Northern and Southern Province of the Malawi Rift.

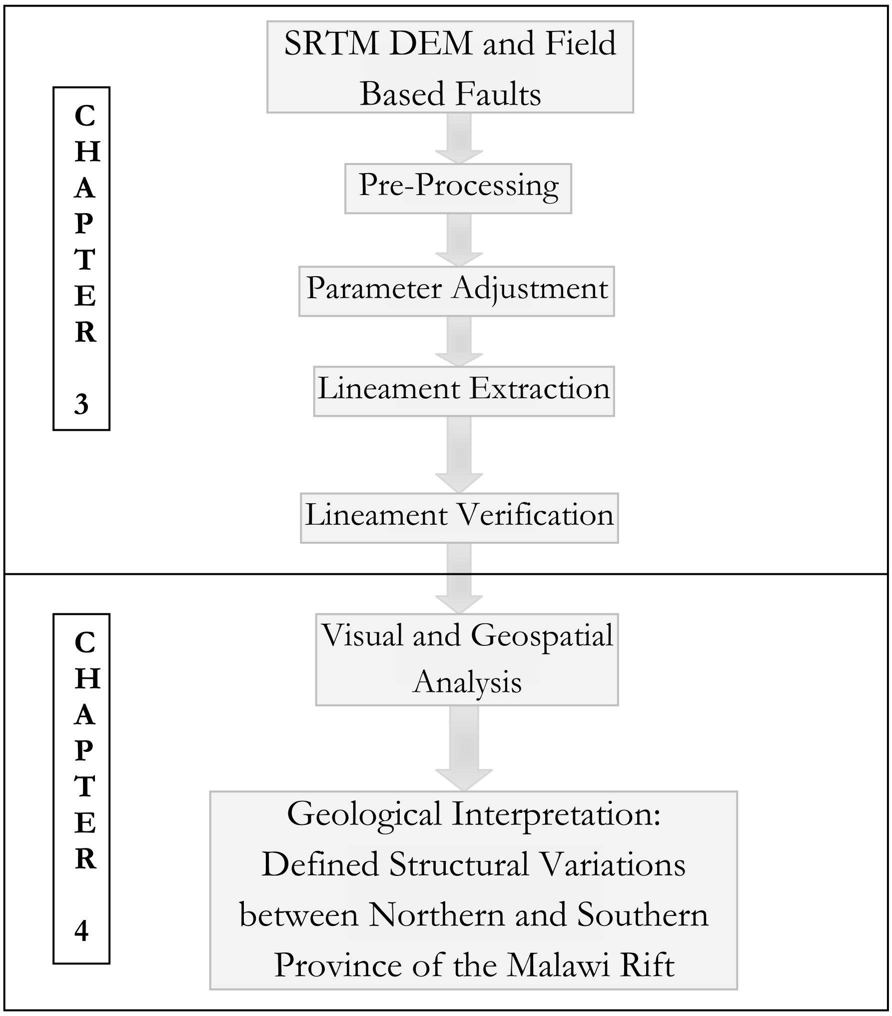

Figure 3-1: Flow chart for the processes carried out in chapter 3 and chapter 4 of this thesis

3.2. Automatic Lineament Extraction Algorithms

Different algorithms have been developed by different researchers and used in automatic lineament extraction. One of them is the LINE Module algorithm in PCI Geomatica. Of recent a MATLAB based software has been developed which is specifically for lineament extraction (Rahnama & Gloaguen, 2014). Apart from using the LINE Module algorithm, the author also tried TecLine algorithm to extract the lineaments. TecLine algorithm normally uses satellite images and digital elevation models as input images for lineament extraction (Rahnama & Gloaguen, 2014). According to Rahnama & Gloaguen, (2014) for the actual process of lineament extraction TecLine mainly uses two main steps which are edge detection and edge linking. In principle the edge detection process generates set of pixels lying on edges from the input image on the other hand the edge linking process describe edges on the image as linear segments of specified shape.

It was observed from results of the TecLine algorithm that it had some limitations as compared to LINE Module algorithm. The first observed limitation for TecLine algorithm is that it did not take very big image sizes as input images for lineament extraction. In this thesis different image sizes for the SRTM

DEM were tried in the first stage of producing an edge map from where the lineaments are extracted. The tried images were in GeoTIFF format and ranged in size from 11 MB, 2 MB, 500 KB and 125 KB (see appendix 3) out of these images only the 125 KB image produced an edge map (intermediate results for this have been presented in appendix 4).

The second observed limitation of TecLine was that it has a lot of parameters (in total there are 11 parameters in TecLine as compared to only 6 in LINE Module algorithm) that needs to be adjusted for the accurate extraction of the lineaments (table 3.1); this makes it difficult to come up with a reliable optimal set of parameters for lineament extraction. However, the two algorithms (TecLine and LINE Module) have similar usage in that they are all capable of extracting accurate lineaments when optimal parameters have been defined.

Table 3-1: Parameters for TecLine algorithm which needs to be adjusted for accurate extraction of lineaments

ALGORITHM FUNCTION	PARAMETER TO BE ADJUSTED	WHAT THE PARAMETERS DO
Extract Line Segments Based on Hough Transform	1. Fill Gap 2. Minimum Length	These parameters define the kernel size of the window in which the line segments will be extracted.
Intermediate Line Segment Mapping	1. Distance 2. Angle 3. Azimuth 4. Minimum Length	These parameters are used to define the extent for grouping the extracted lines segments.
Polynomial Curvilinear Mapping (connecting Segments to linear feature)	1. Radius of circle sector 2. Opening angle 3. Maximum difference in azimuth 4. Minimum length 5. Minimum group size	These parameters are used in fitting polynomial curves between grouped line segments

Though the LINE Module and TecLine has similar usage, they do have differences in their edge detectors. The LINE Module has only one edge detector Canny which is used in the process of lineament extraction, on the other hand TecLine has both first and second derivative edge detectors which include Sobel, Prewitt, Canny and LoG (Laplacian of Gaussian) respectively.

In the interest of time, the author did not proceed using TecLine in this thesis as it needed a lot of time in adjusting the parameters so as to come up with optimal parameters. At the same time the limitation on image size made it impossible to extract lineaments from the whole research area, i.e. Northern and Southern Provinces hence the research continued with LINE Module algorithm in PCI Geomatica.

3.3. Lineament Extraction using LINE Module Algorithm

As explained above, lineaments were extracted from the Northern and Southern Province of the Malawi Rift using the LINE Module algorithm in PCI Geomatica 2014. This algorithm has been used by many authors in a wide number of similar researches as indicated in section 1.4.2 of this thesis. The LINE algorithm extracts linear features from an image; the extracted linear features are then recorded as polylines in vector segments. For the extraction of the linear features LINE Module uses three stages which are: edge detection, thresholding and curve extraction (Sarp, 2005). These three stages are associated with six parameters which have been explained in section 3.3.2. The LINE Module algorithm uses an inbuilt Canny edge detector to detect edges from the input image.

3.3.1. How does Canny Edge Detector work

To extract the lineament the LINE Module algorithm only uses Canny edge detector to detect edges from the input image. Canny is a first derivative edge detector that detects edges on an image. No specific reason has been given as to why the LINE Module algorithm uses Canny but after a review of literature; the author assumes that it might be because of the ability of Canny in having a high probability of detecting edges, having good localisation of edges on an image and having one response to a single edge (Canny, 1986). Based on the above described characteristics Canny edge detector smoothes the image to suppress noise then it finds gradients on the image and highlight those regions with a high gradient (Green, 2002). According to Green, (2002) after highlighting the areas with high spatial derivatives, Canny edge detector searches these areas and if it finds pixels that are not reaching a maximum value it suppresses them. The remaining non-suppressed pixels are then tracked in a process called hysteresis.

Hysteresis is a process that uses two threshold to define edge pixels on an input image, during this process pixels in the input image are searched and any pixels that are lower than the first threshold are turned to black on the other hand any pixels above the upper threshold are turned white (Nixon & Aguado, 2002). In this regard the black pixels are assigned a zero and grouped as non-edge pixels while the white pixels are assigned as edges. It is these pixels that are later picked as lines segments by the LINE algorithm.

3.3.2. Canny Algorithm in LINE Module

The LINE Module algorithm has a Canny edge detection that is used to produce an edge strength image. The first step in the production of this edge strength image involves the filtering of the image with a Gaussian function (Kiran et al., 2014; Sarp, 2005), this Gaussian function is defined by the parameter Filter Radius (RADI). RADI defines the radius of edge detection in pixels; it defines the size of the Gaussian filter which is used as a kernel during edge detection. After the edge strength image is produced it is then thresholded to produce a binary image, the value for this threshold is defined by the parameter Edge Gradient Threshold (GTHR). GTHR defines the minimum change in brightness to edges and spectral differences at edges its values vary from 0 to 255. The last step involves the extraction of curves from the binary image. According to Kiran et al., (2014) the step of extracting curves from the binary image has substeps which are; the application of a thinning algorithm to the binary image to produce pixel-wide skeleton curves followed by a sequence of pixels for each curve that are extracted from the image, this process is defined by the parameter Curve Length Threshold (LTHR). LTHR specifies the minimum length of curve in pixel distance, it maps linear curve features as valid lineaments. The other parameters for LINE Module algorithm define different attributes that are also necessary for the extraction of accurate and appropriate lineaments. These parameters are: Line Fitting Threshold (FTHR), this defines a buffer zone within which a line segment can be fitted to a curved lineament, it also defines the minimum length of a curve (in pixels) to be extracted as lineament. The Angular Distance Threshold (ATHR) parameter, defines an angle (in degrees) between which lineaments can be connected as one segment. The last parameter Linking Distance Threshold (DTHR) defines the distance (in pixels) between two vectors for them to be connected (Sarp, 2005; Help-PCI Geomatica, 2014).

3.4. Image Pre-processing

Literature review guided in the pre-processing steps for the images prior to lineament extraction. Most of the geological structures in the study area are related to the two tectonic events that affected the area i.e. orogenic and rifting episodes and they are mostly oriented in relation to the direction of these tectonic events. In his study Rosendahl (1987), described that most of the rift related structures (faults) in the study area are composed of fault segments (rift blocks) which are approximately 55 Kilometres long. In some areas these segments are connected forming fault zones which are ~ 100 Kilometres long (Biggs, et al., 2010; Jackson & Blenkinsop, 1997) for example the Livingstonia fault in figure 3.3A and the Bilira-Mtakataka fault in the Southern Province.

To overcome the effects of hill shaded images, which is production of biased results in that the structures that are lying perpendicular to the direction of illumination are enhanced more than those in the parallel direction; multidirectional illumination was applied (Anwar et al., 2010; Awdal, 2012). Hill shading was done in four different illumination directions 0°, 45°, 90°, and 135° (Figure 3.2). The black arrows in figure 3.2 indicate direction of Sun Azimuth Angle which was based on literature information on the general orientation of geological structures within the study area. To enhance these structures, hill shaded images of different solar azimuth were produced which are; 0^0, 45^0, 90^0 and 135^0 in all these a sun elevation angle of 45° was used. The whole process of hill shading was done in ENVI 5.1 then the hill shaded images were saved as GeoTIFF format and exported to ArcGIS for further processing. In an effort to minimize the biased effects of lineaments extracted from hill shaded images, the resulting images from the above different azimuth directions were combined in ArcGIS using the overlay technique to give a single image that was used as inputs in PCI Geomatica for lineaments extraction. The overlay technique in ArcGIS uses a weighted sum of the raster images to produce a single image that is representative of all illumination directions from the input images.

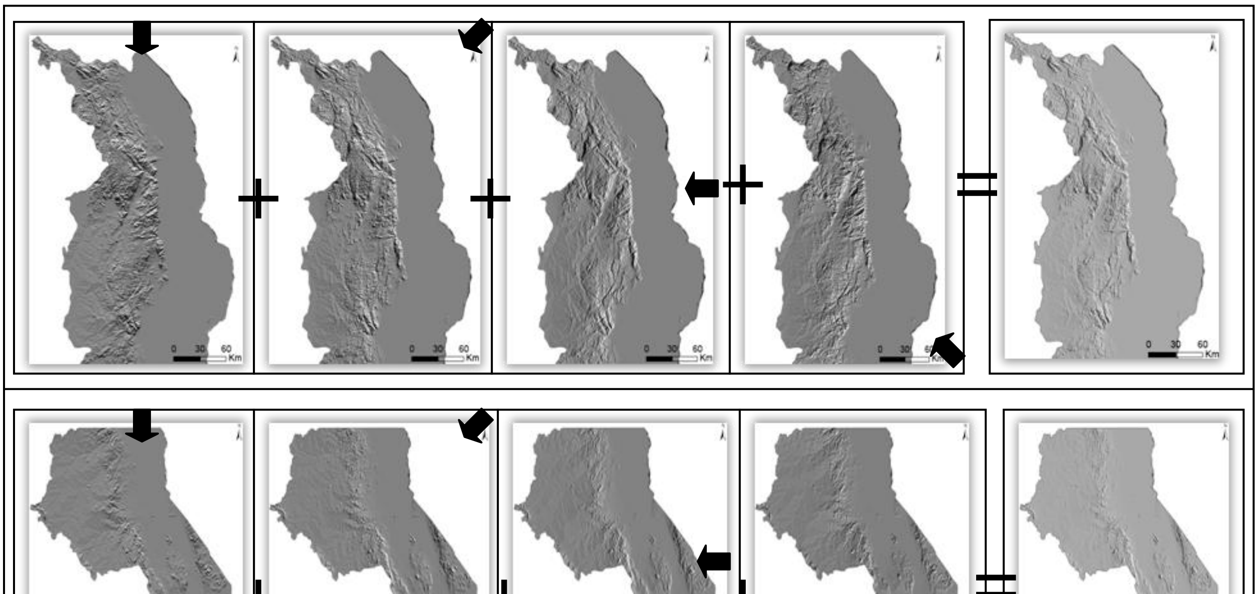

Figure 3-2: Hill shaded SRTM DEM images for the Northern and Southern Province. Multidirectional hill shading was used and the black arrows indicate different directions of illumination. The plus sign means that the images were combined to produce one image which is at the end of the equals sign.

3.5. Parameter Adjustment

For better selection of parameter settings of the LINE Module algorithm, default and adjusted parameters were applied on the selected training area (Figure 3.3B). The parameters were adjusted in relation to reference published field based faults which were selected within the training area. In this regard some published field based faults of the area as shown in figure 3.3A (Biggs et al., 2010) were used as reference faults. The actual process of adjusting the parameters was done by keeping other parameters constant and adjusting others in relation to the above described structure characteristics of the study area. Different parameter settings were tried. Parameter settings that were able to delineate / extract the reference faults in a long and well connected segment pattern were chosen as optimal parameters and were used in the actual lineament extraction process for the whole study area (table 3.2).

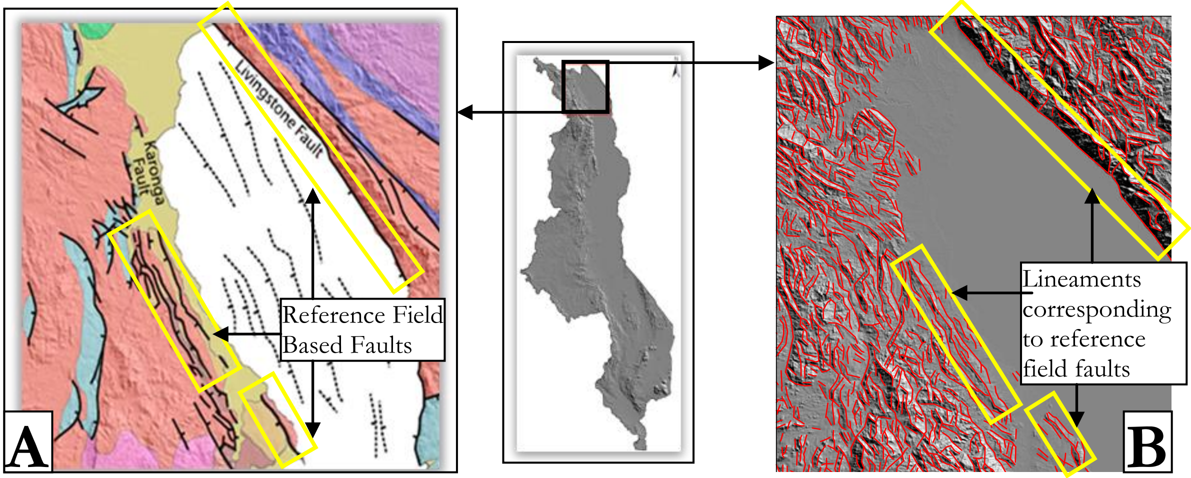

Figure 3-3: **(A)** Geological Map of Malawi (Source: Biggs et al., 2010) showing reference field based faults and **(B)** Extracted lineaments from hill shaded SRTM DEM showing areas with lineaments corresponding to the field based faults. Insert is a map of Malawi showing location of the images.

3.6. Lineament Verification

3.6.1. Verification of extracted lineaments

Extracted Lineaments were overlain on the hill shaded SRTM DEM in ArcGIS and visually inspected to verify them i.e. visual verification was done with regards to inspecting whether the algorithm and optimal parameters have been able to extract both negative and positive lineaments within the research area, at the same time connectedness of the extracted linear segments was also observed (Figure 3.4). It was observed that apart from extracting lineaments that matched with the reference field based faults; positive and negative lineaments were also extracted (Figure 3.4 zoom window) positive lineaments are those lineaments which characterise high areas i.e. mountain ridges while negative lineaments are those lineaments characterising low lying areas i.e. valleys (refer to page ix for the definition of these terms). The extracted lineaments were saved as keyhole markup language (kml) file and draped on Google earth where the topographic expression of positive and negative lineaments was observed visually (zoom window figure 3.4). Visual observation also showed that most of the lineaments extracted within lithological units were short as compared to those extracted within lithological contact boundaries and along border fault zones. The extracted lineaments were also overlain on a second derivative filtered (Laplacian) SRTM image. This was done so as to observe if there was a similar pattern between the extracted lineaments from the combined hill shaded image and the second derivative filtered image. Visual observation of the overlay showed a well matching pattern (Figure 3.5.) between the extracted lineaments and the Laplacian filtered image. The above described visual verification of extracted lineaments gave confidence on the accuracy of the image pre-processing steps, selected optimal parameters and the effectiveness of the LINE Module algorithm in extracting lineaments.

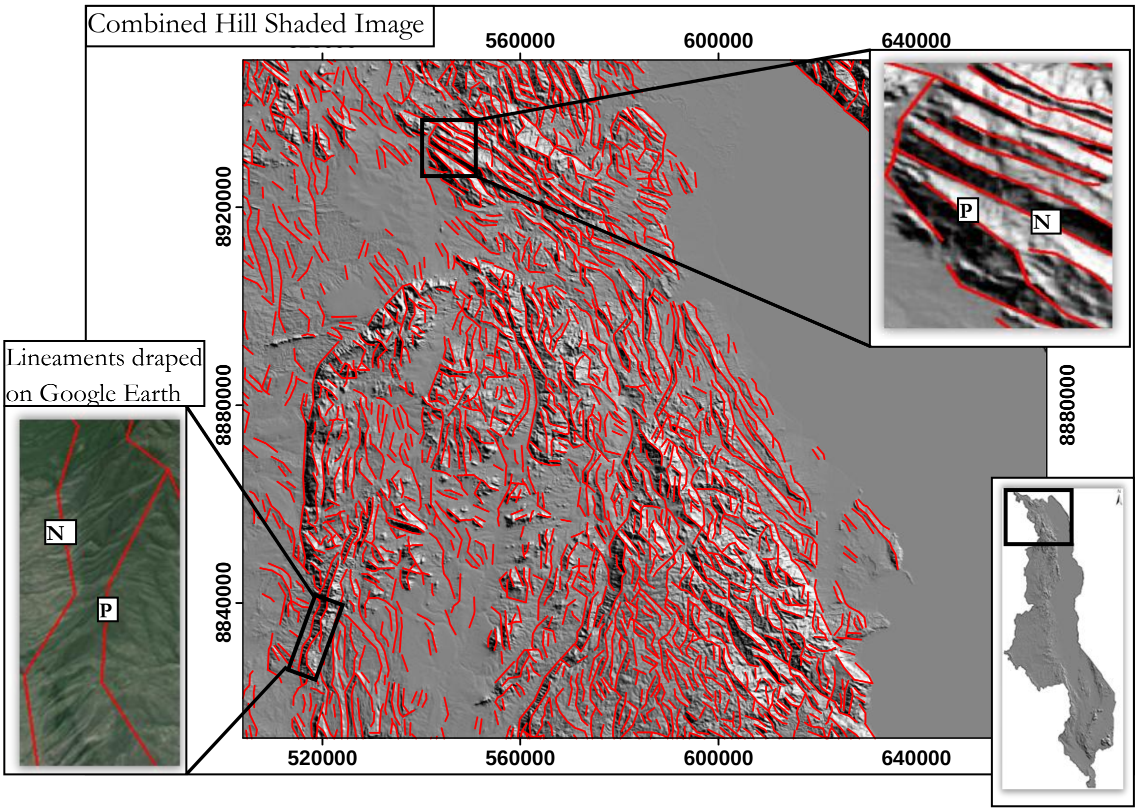

Figure 3-4: Extracted Lineaments overlain on hill shaded SRTM. Zoom windows showing positive lineaments symbolised by **P** & negative lineaments symbolised by **N**, overlain and draped on hill shaded SRTM DEM and Google earth respectively. Insert is a map of Malawi showing location of the image.

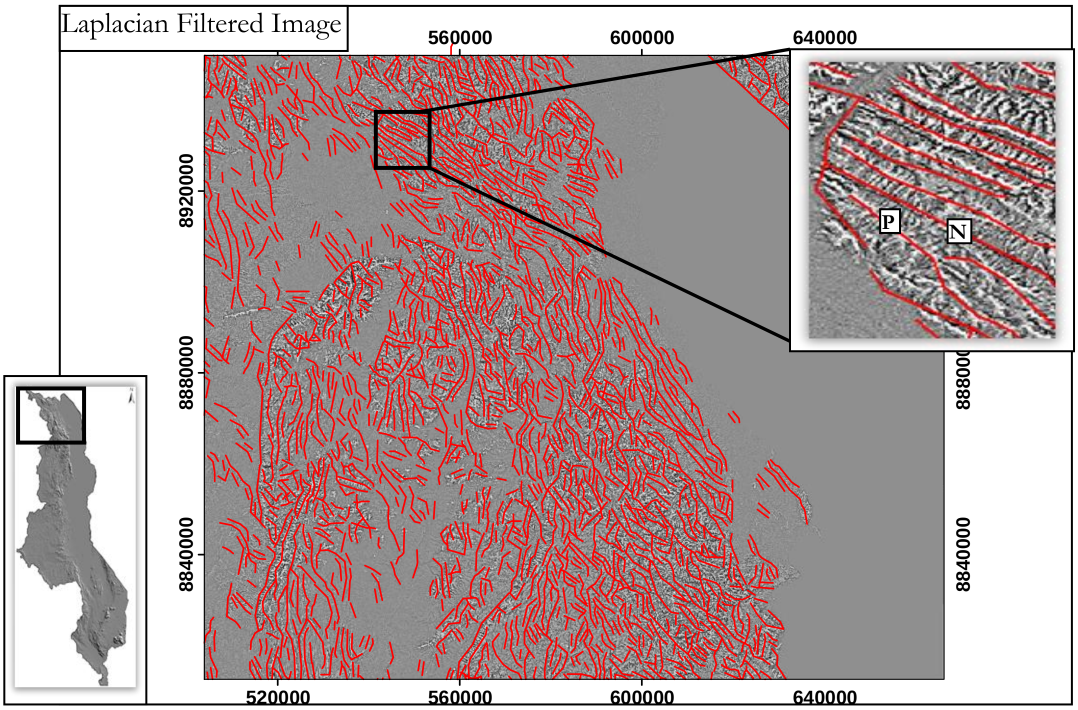

Figure 3-5: Extracted Lineaments overlain on second derivative (Laplacian) filtered SRTM DEM. Zoom window showing positive lineaments symbolised by **P** & negative lineaments symbolised by **N**. Insert is a map of Malawi showing location of the image.

3.6.2. Geospatial verification

Extracted lineaments were also verified geospatially. Rose diagrams for both field based faults and extracted lineaments were plotted. It was observed that both field based faults and extracted lineaments had a similar general orientation pattern of NW-SE which is associated with geological structures related to the Ubendian mobile belt. However it was interesting to note that the extracted lineaments had a well pronounced orientation pattern in the N-S direction which reflects geological structures related to the Mozambiquian mobile belt; this pattern was missing on the field based faults (Figure 3.6). It is assumed here that the missing of a N-S orientation pattern on the field based faults may imply that faults in this orientation pattern might have been missed during the 1950 – 1970 mapping exercise due to inaccessibility of some areas.

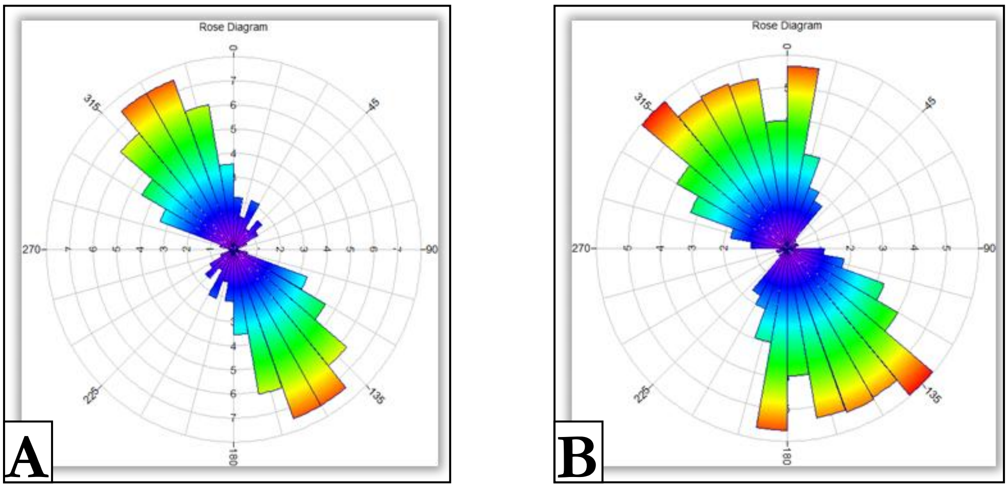

Figure 3-6: Rose diagrams **(A)** for field based faults and **(B)** for SRTM extracted lineaments. Note the similarity in the NW-SE orientation pattern between the field based faults and extracted lineaments. The extracted lineaments have a pronounced N-S orientation which is missing in the field based faults.

The process of verifying the extracted lineaments was done in order to justify the effectiveness of the selected optimal parameters, image processing techniques and the LINE Module algorithm in lineament extraction before applying them to extract lineaments from both provinces (Northern and Southern Provinces of the Malawi Rift). Results from the visual and geospatial verification of extracted lineaments showed that the selected optimal parameters and the LINE Module algorithm are effective in lineament extraction within the study area.

3.7. Lineament Extraction from the Northern and Southern Province of the Malawi Rift.

As explained in the previous sections, lineaments were extracted from the combined hill shaded images for both Northern and Southern Provinces using the LINE Module algorithm in PCI Geomatica. In both provinces the same standard set of adjusted parameters (table 3.2) was used. The extracted lineaments were converted into shapefile and DXF format for further process in ArcGIS and Rockworks respectively.

Table 3-2: Used optimal parameters for lineament extraction using the LINE Module Algorithm

Parameter	Value	Parameter	Value	Parameter	Value
RADI	14	**LTHR**	20	**ATHR**	35
GTHR	50	**FTHR**	3	**DTHR**	15

To verify the connectedness of the extracted lineaments they were overlain on hill shaded SRTM DEM and visually inspected in ArcGIS. A layer of the field based faults was overlain on the extracted lineaments. It was observed that the extracted lineaments matched well with the field based faults though in some areas it was observed that the extracted lineaments were segmented than being a complete one fault line as the overlain field based faults. In these areas the segmented lineaments were manually edited (connected) to form one fault line as seen in the field based faults. In total five lineament zones were connected i.e. three in the Northern Province and two in the Southern Province.

3.8. Lineament Analysis Approaches

Two approaches were used in the analysis of the lineaments; visual and geospatial analysis. Visual analysis involved the production of lineament maps for the two provinces to observe their spatial distribution and structure pattern (the extracted lineaments were overlain on the hill shaded SRTM DEM as shown in figure 4.1). Geospatial analysis was done using four lineaments indices which are; lineament orientation pattern, degree of fracturing, lineament length and lineament density. Each of these lineament indices provided information which was vital in achieving the specific objectives and answering research questions of this thesis. The process of interpreting results from the lineaments was done at two scales i.e. regional scale and local scale which represent the whole province at once i.e. North or South and specific structural divisions within the provinces respectively. For the interpretation of lineaments at local scale using structural division per province, the structural divisions of the Malawi Rift by Chapola & Kaphwiyo, (1992) were adopted in the analysis and interpretation of results.

3.8.1. Orientation Pattern Analysis

Orientation pattern of lineaments was done by plotting rose diagrams. The extracted lineaments were saved as AutoCAD vectors in a data interchange file (DXF) format and exported to Rockworks 16 where rose diagrams were plotted using the linears algorithm under the utilities function. Before the actual process of plotting rose diagrams, lineament properties were defined, i.e. projection system of the extracted lineaments later length and bearing of each lineament was calculated by using the lineation properties techniques which is part of the Linears options under utilities function. Plotting of lineament rose diagram was done by using start and end points of the lineaments; the rose diagram option under utilities function was used to plot roses. In this regard; the petal radii of the rose diagram were defined by using frequency percentage of total population. With this option the length of the petals of the rose diagram represent the percentage of total measurements (lineaments) that fall within that direction.

3.8.2. Degree of Fracturing Analysis

Degree of fracturing was done to characterize lithological units / age groups within the two provinces in relation to their fracturing pattern. To calculate this, density of lineaments within each lithological unit / age group was used. The process of calculating density of lineaments per lithological unit was done in ArcGIS where the extracted lineaments for each and every lithological unit were selected and clipped. The density of lineaments (frequency) within each and every lithological unit was calculated in the attribute table. Later the lithological units were plotted in relation to the density of lineaments within the unit to observe their fracturing pattern. Histograms for the fracturing pattern per lithological units and geological age groups were calculated in excel.

The Northern and Southern Province of the Malawi rift has different lithological units, hence apart from calculating the degree of fracturing per lithological unit (Figure 4.5A) it was necessary to calculate the degree of fracturing per geological age group. Lithological units were assigned to their age groups, their density of lineaments summed up and had their degree of fracturing calculated as a representation of the age group (Figure 4.5B). However it was still observed that the two provinces have different lithological age groups, hence the researcher also calculated degree of fracturing for only those age groups that were present in both provinces i.e. similar age groups (Figure 4.5 C).

3.8.3. Length and Frequency Analysis

Length of the lineaments was calculated to observe length variations for the extracted lineaments. Variation in lineament length provided information on the type of rock from which the lineaments are extracted. Length of the lineaments was calculated in ArcGIS using the calculate geometry option in the attribute table, and later the column for length was exported to excel where the length of lineaments for each province was calculated in SPSS using the option histograms under the function graphs-legacy dialogs. Calculation for lineament length and frequency was done on a regional scale i.e. the whole Northern and Southern Province.

3.8.4. Density Analysis

Lineament density analysis calculates the frequency of lineaments per unit area (Hung et al., 2005). This results in a map showing concentrations of lineaments within unit areas. In this thesis lineament density was calculated using the line density option under spatial analyst tool in ArcGIS. A search radius of 10 km was used in plotting the density maps. The line density option in ArcGIS calculates the number of lineaments per unit area; and areas that recorded a high number of lineaments were plotted as high density areas followed by medium and low density zones, these zones were later contoured using the same spatial analyst tool in ArcGIS to enhance the boundaries between them. Knowing that SRTM contains regions of no data specifically over water bodies (CGIAR-CSI, 2014), the area around Lake Malawi, Lake Malombe and Lake Chirwa (Figure 1.1) were masked out in calculating the lineament density.

3.8.5. Lineament Direction of Extension Forces

Analysis of possible direction of lineament extensional pattern that resulted into the present orientation of the lineaments within the two provinces was done by visual and geospatial analysis. In geospatial analysis, rose diagrams were plotted in relation to the different structural divisions of the Malawi Rift proposed by Chapola & Kaphwiyo (1992), the plotted rose diagrams per structural division were used in defining the direction of lineament extension force (Figure 4:11). The rose diagrams were plotted in Rockworks using the same procedure as explained in section 3.8.1. Interpretation of direction of lineament extension pattern was done using these rose diagrams and sandbox models for the East African Rift System done by Acocella & Faccenna (1999), McClay & White (1995) and Bonini et al., (1997), and scaled physical models by McClay & Dooley (2002). Results from this analysis led to the development of a proposed structural component model for the Malawi Rift (See chapter 5)

4. RESULTS AND INTERPRETATION

Interpretation of results was done in relation to the four criteria set in section 1.1 of this thesis, these criteria are: (i) dominant trending pattern of the lineaments, (ii) direction of extension pattern to which the lineaments relate (iii) length and frequency of the lineaments, (iv) degree of lithological fracturing and (v) density and frequency of the lineaments.

For a better interpretation of results; the understanding and establishment of structural variations between the two provinces was done at regional and local scales. Regional scale in this paper shall mean the Northern and Southern Provinces as a whole while local scale shall mean specific selected lithological units, geological age groups and analysis that is done per structural divisions as adopted from Chapola & Kaphwiyo (1992).

4.1. Establishment of structural variations at a regional scale

For a better understanding, determination and establishment of structural variations between the two provinces it was necessary to divide the analysis and interpretation in two scales. From this background the researcher did the analysis and interpretation of results at a regional scale and local scale. This section presents results and interpretation which were observed at a regional scale only.

4.1.1. Lineament pattern and spatial distribution

Visual interpretation of the lineaments was done to observe spatial distribution variations and pattern of the lineaments in relation to the topographic expression of structures on the hill shaded images. The extracted lineaments from both provinces showed to be much concentrated on the central part of the rift (western side of Lake Malawi) forming a narrow ridge that runs through the centre from Karonga in the Northern Province to Mwanza in the Southern Province (Figure 4.1). In the Northern Province the central western part of Chitipa which is characterised by Semi pelitic rocks (Figure 1.1) hardly recorded any lineaments, this is also observed on the western side of the same province (and same lithological unit Semi pelitic rocks) just south of the Nyika Granitic Pluton (to the south western side of Mzimba district) where the lineaments are sparsely distributed. The Southern Province has shown sparse distribution of lineaments on the north western side, i.e. part of Dowa, Kasungu and Mchinji districts. The part of Dowa and Kasungu which has shown sparse distribution of the lineaments is characterised by the same rocks i.e. Semi pelitic rocks.

It was interesting to observe from the extracted lineaments that lineaments have also been extracted within the border faults locations which form the backbone of the Malawi Rift and most of these lineaments within these areas are longer than 10 kilometres (Figure 4.2). Some of these areas where the lineaments have followed border fault locations have been shown in the zoom window in figure 4.1 & 4.2. However there are some areas in which longer lineaments (10 kilometres and above) have been extracted but not following border fault zones (Figure 4.2). These areas are assumed by the author to be forming parts of major faults within the study area e.g. the area around the Karonga and Mwanza faults indicated with black circle in the zoom window of figure 4.2.

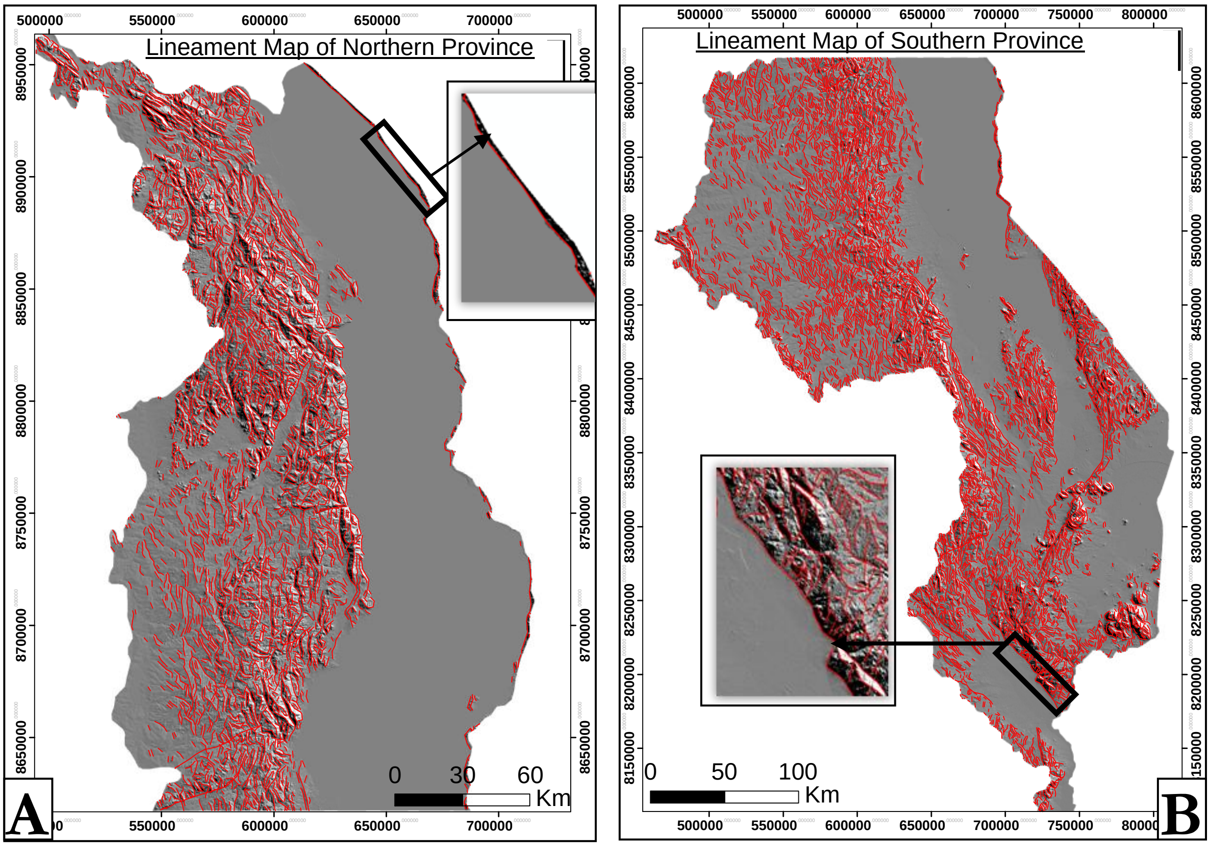

Figure 4-1: Lineament Maps for **(A)** Northern Province and **(B)** Southern Province of the Malawi Rift. The extracted lineaments have been overlain on hill shaded SRTM. Zoom windows shows areas where the longest lineaments (as one connected segment) were extracted in both provinces.

Visual analysis of extracted lineaments from the Northern Provinces showed that most of the longest lineaments were extracted on the eastern side of the Malawi Rift mainly on the edges of the Lake Malawi basin and on the south eastern side of the Nyika granitic pluton (Figure 4.1A). In the Southern Province most of the longest lineaments were extracted along the southern end of Lake Malawi and on the edges of the Shire trough (Figure 4.1B).

This observation is similar to the tectonic model of the Malawi Rift which was proposed by Ebinger et al., (1987) and Crossley, (1984) which showed that most of the faults on the western side of the Malawi Rift are as a result of a series of fault blocks (Figure 2.5A & 2.6). This has clearly been observed on the extracted lineaments as in both provinces more lineaments have been extracted on the western side of the Lake Malawi basin and Shire basin where according to the model of Crossley, (1984) formation of the structures involved a series of fault blocks while in the eastern side of the rift the greater part of the faulting mechanism involved a single major fault block.

In the Southern Province, longer lineaments have also been extracted along the Chikwawa – Nsanje basin in which the Shire River flows. The longest lineament extracted in the Southern Province is approximately 55 kilometres long while in the Northern Province the longest extracted lineament recorded approximately 45 kilometres (Figure 4.4, 4.2 & 4.5). Lineaments extracted on the north western part of the Southern Province were observed to be short and according to Piper (1989), they may represent sections of structurally controlled drainage systems, thereby giving a reflection of the fracturing of the underlying

Basement Complex rocks. In the Shire valley trough, the lineaments seem to be concentrated on the southern part of Blantyre and the along the Kirk-Range in the Ntcheu – Neno areas.

Although the two provinces have shown similarities in the spatial distribution of the lineaments; some differences have been depicted. It has been observed that some parts of the Southern Province are characterised by lineaments patterns that are completely missing in the Northern Province. These characteristics include circular (rounded) pattern of the lineaments which are mostly observed within the Syenogranitic and Nepheline Syenite Plutons within the Southern Province. These lineament characteristics seem to be defining circular patterns which are a reflection of the surrounding lithological units.

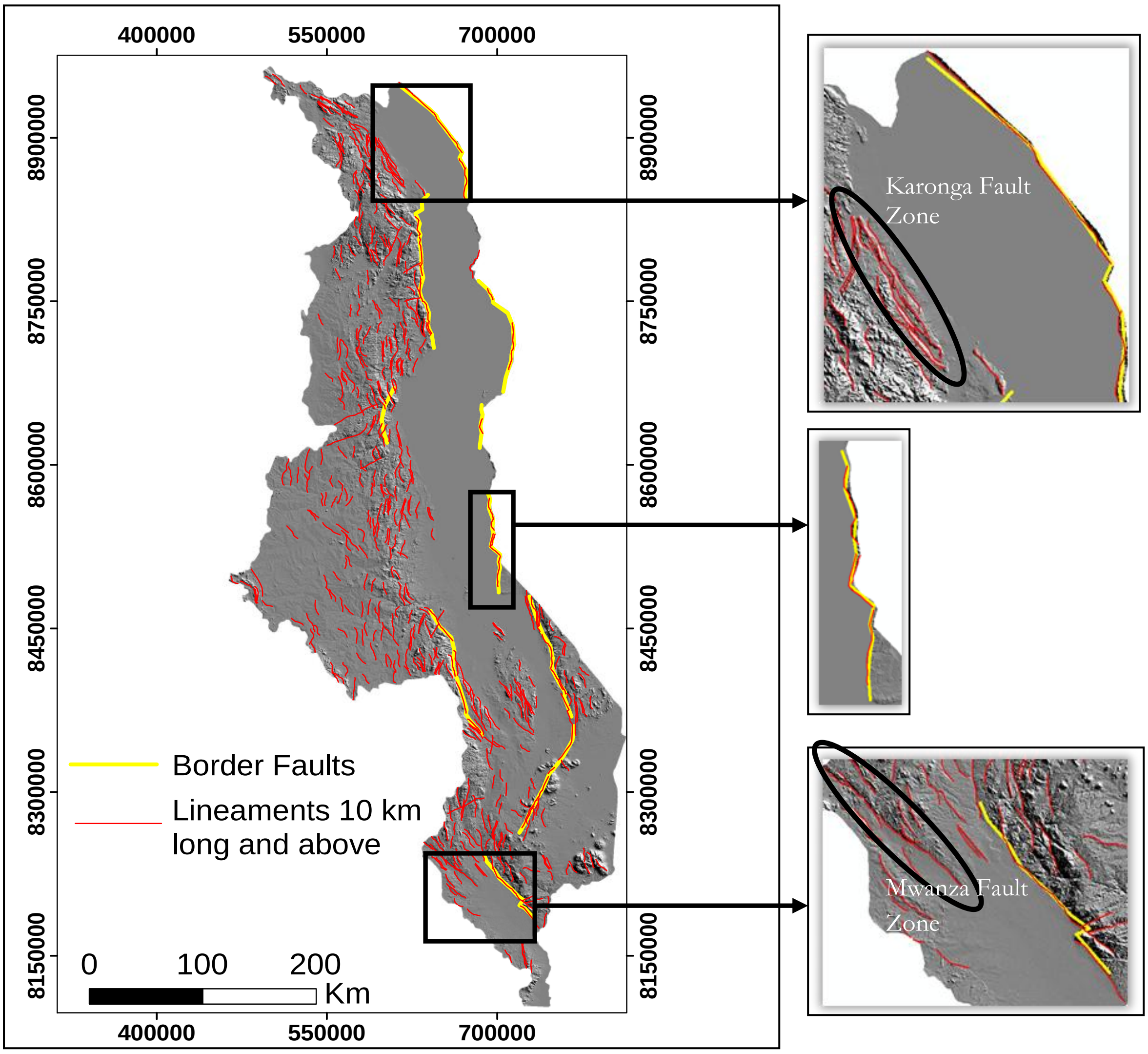

Figure 4-2: Map of the Malawi Rift showing border faults (yellow lines) as mapped by Ebinger et al., (1987). Red lines are lineaments of 10 kilometres long and above. Note that lineaments have been extracted in almost all the areas where the border faults are located. In both provinces the longest lineaments have been extracted along border fault zones (zoom windows). Area in a black circle is the location of the Karonga and Mwanza Faults in the Northern and Southern Province respectively where lineaments above 10 kilometres long have been extracted (refer to the last paragraph of section 4.1.1 for explanation).

4.1.2. Lineament Orientation Pattern

Rose diagrams are mostly used in the interpretation of orientation pattern of lineaments as they gave information on the general trending pattern of lineaments within specific areas. In most cases lineament orientation is a reflection of direction of geological structures within an area and local tectonics of an area. In this thesis lineament orientation pattern was calculated to establish differences in the general orientation of structures within the Northern and Southern Province of the Malawi Rift (Figure 4.3).

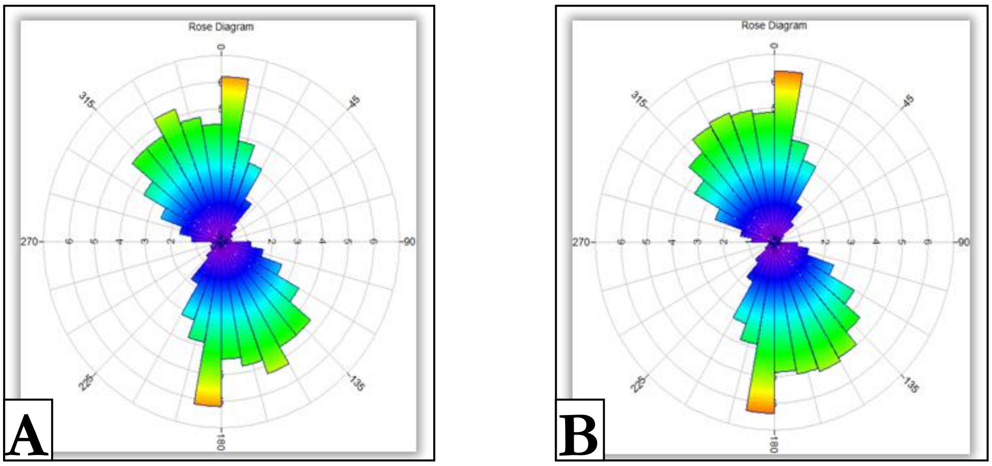

Figure 4-3: Rose diagrams for extracted lineaments from **(A)** Northern Province and **(B)** Southern Province. Note the similarity in the general trending pattern of lineaments on the NW-SE and N-S directions.

Analysis of lineament rose diagrams from the two provinces showed a similar general orientation pattern of NW-SE which is pronounced at 300 to 345 degrees NW. This pattern is similar to that of geological structures which were formed during the Ubendian orogeny (Carter & Bennet, 1973). Another pattern observed from the rose diagrams is a N-S orientation pattern, this pattern seems to follow the direction of the Mozambiquian orogeny. These two orientation patterns also give a reflection of the structures that were formed during the Cenozoic / Rifting episode i.e. the border faults. In both rose diagrams there are little pronounced signatures which might be related to the Irumide orogeny these are noticed between 15 and 30 degrees NNE. Despite the above described similarities in the orientation pattern of lineaments between the two provinces, a closer observation shows minor differences at 330 degrees NW where there is a better pronounced orientation pattern of the lineaments in the Northern Province than the Southern Province. This means that signatures of the Ubendian orogeny which resulted into formation of geological structures of this pattern are better pronounced in the Northern Province than in the Southern Province.

From the interpretation of the rose diagrams it is observed that the greater part of the Malawi Rift in both provinces has been mostly influenced by the Ubendian and Mozambiquian orogeny and that the present orientation of the Malawi Rift has been emplaced in orientation patterns that were initiated during the orogenic period. This observation concurred well with what Delvaux, 1991 observed that the present orientation of the rift related structures is a reflection of the orogenic related structures' orientation pattern. It is interesting to note that the general orientation pattern of the extracted lineaments (NW–SE) is similar to the orientation observed on field based faults (Figure 3.6A) and lineaments which were extracted on LANDSAT images for the same area by Piper, (1989).

4.1.3. Lineament Length and Frequency

The length and frequency of lineaments give information on the different types of rock units from which the lineaments are being extracted. Visual analysis of the extracted lineaments showed that most of the lineaments which are less than 5 km are localised within the topographic highs which mostly defines mountainous areas and are characterised by "hard rock" formations though some are still found within the low lying areas. On the other hand lineaments greater than 10 km are most found within topographic lows which mostly defines lithological contacts and valleys within the area. Observation of lineament length histograms has shown that the longest lineaments extracted by the LINE Module algorithm were recorded in the Southern Province (Figure 4.4).

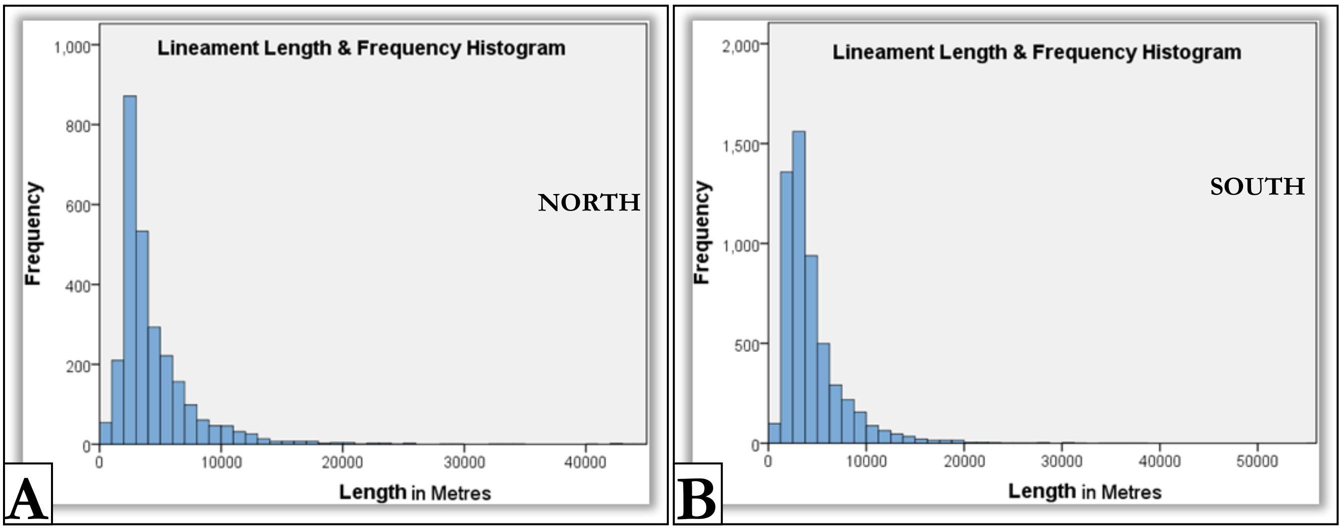

Figure 4-4: Lineament length and frequency histograms for the two Provinces **(A)** Northern Province and **(B)** Southern Province. Note the similar pattern in the highest frequency of lineaments within the length of 500 to 10000 metres. The longest lineament extracted in the Northern Province was 45 kilometres and in the Southern Province was 55 kilometres.

Lineament length histograms showed almost similar pattern in frequency and longest extracted lineament from both provinces (Figure 4.4). The longest extracted lineaments are approximately 55 kilometres and 45 kilometres for the Southern and Northern Province respectively. Observation of the highest frequency of extracted lineaments showed that most of the lineaments within both provinces are within 500 metres to 10 kilometres length and above 10 kilometres length their frequency decreases with increasing length. Visual interpretation showed that most of the lineaments less than 5 kilometres occur within "hard rock formations" although some are localised within lithological contacts and soft rock formations, this signifies the type of rock formations in which they are occurring (this reflects that the hard rock formation in which these lineament are extracted are brittle hence they easily fracture, resulting into short segmented lineaments). It is also observed on density maps for the two provinces (Figure 4.6A & 4.6B) that the great part of the medium to high lineament density zones is characterised by lineaments that are less than 5 kilometres, these lineaments may represent tension cracks which may have formed by horizontal movements of the main rift faults within these areas (Bloomfield & Garson, 1965). Visual analysis also showed that in both provinces most of the lineaments longer than 10 kilometres occur within lithological contacts or along topographic lows; this suggests that these lineaments may be forming the greater part of the main rift faults and major faults within the area.

4.1.4. Degree of fracturing pattern within lithological units and geological age groups

The degree of fracturing within lithological units and geological age groups was calculated to observe the fracturing pattern within lithological units and geological age groups, which provided information on charactering different type of lithological units / age groups from where the lineaments have been extracted. Different lithological units and age groups recorded different degrees of fracturing, but overall it was observed that a high degree of fracturing was recorded mostly within the hard rocks which are characterised by the Basement Complex rocks as compared to the other types of rocks within the area (Figure 4.5).

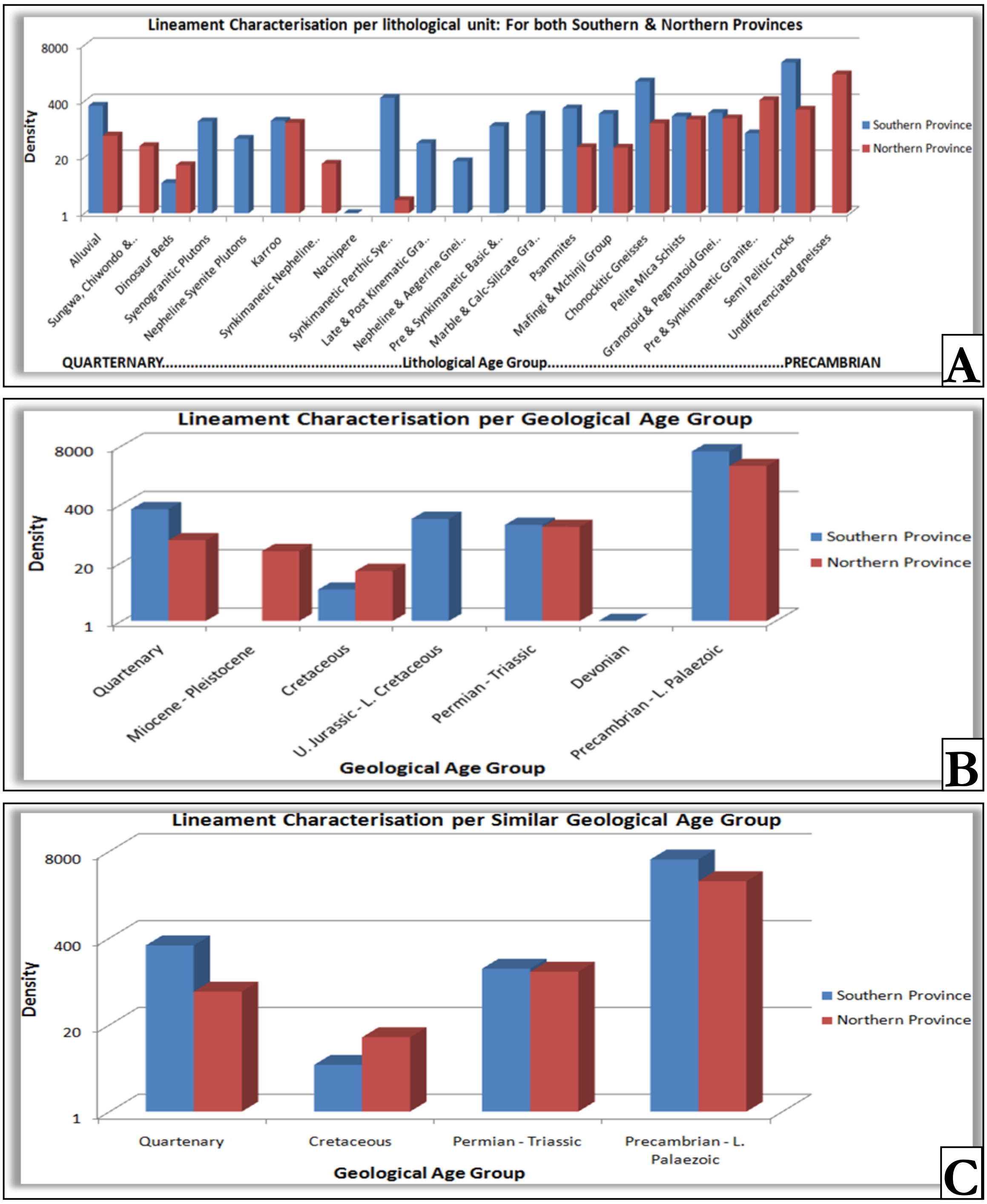

Figure 4-5: Lineament characterisation densities **(A)** per lithological unit, **(B)** per all age groups and **(C)** per similar age groups. Overall in all histograms the Basement Complex rocks have recorded a high degree of fracturing.

From the figures 4.5 A & B it is apparent that the two provinces have different lithological units and geological age groups. It was observed during analysis and interpretation of results that some of the lithological units and geological age groups present in the Southern Province are not present in the Northern Province (Figure 1.1). It is from this background that the analysis of lineament characterisation per geological age group was done in reference to those age groups that are present in both provinces (Figure 4.5 C). Analysis of lineament characterisation per similar geological age groups showed a high degree of fracturing within the "hard rock formations" which forms part of the Basement Complex rocks within the study area i.e. mostly igneous and metamorphic rock as compared to the "soft rocks" the sedimentary rocks. The high degree of fracturing within the Precambrian – Lower Palaeozoic rocks is a clear indication that these rocks have experienced longer periods of tectonic activities that were associated with folding, faulting and fracturing causing a lot of lineation within them.

High degree of fracturing has also been noted within the Permian – Triassic rocks (The Karroo System rocks) from both provinces, this signifies the history behind the formation of these rocks, a review of literature has shown that the Karroo rocks are deposited in basin structures that were formed as a result of rifting and extension forces related to the formation of the Malawi Rift. During this formation there was a high rate of faulting and fracturing which resulted in the high degree of fracturing within the Karroo basins.

In the Southern Province the quaternary period which is characterised by alluvial shows a high degree of fracturing as compared to the Northern Province, this degree of fracturing is a reflection of fractures in the underlying Basement Complex rocks most probably the semi pelitic and Charnockitic gneisses (Piper, 1989) which dominate the Basement Complex in the Southern Province. In the Northern Province most of the quaternary rocks are characterised by the Miocene – Pleistocene and Cretaceous rocks (Sungwa beds and Dinosaur beds) and in some areas weathered gneisses which are less fractured thereby giving a low degree of fracturing within the alluvial.

4.1.5. Characterisation of density for extracted lineaments per geological age group

This was calculated to give information on the variations in the density of extracted lineaments within lithological age groups. Variations in the percentage of extracted lineaments within the age groups provided useful information in understanding the mechanical behaviour of lithological units within the age groups.

Table 4-1: Densities for extracted lineaments per Geological Age Groups. Areas with a dash line indicate that rocks (lithological units) of that age group are not present in that Province.

LITHOLOGICAL AGE GROUP	NORTHERN PROVINCE		SOUTHERN PROVINCE	
	Total Lineaments	Percentage (%)	Total Lineaments	Percentage (%)
Quaternary	63	2.04	310	4.54
Miocene – Pleistocene	36	1.17	________	________
Cretaceous	13	0.42	5	0.07
U. Jurassic – L. Cretaceous	________	________	188	2.81
Permian – Triassic	125	4.05	139	2.08
Devonian	________	________	1	0.01
Precambrian – L. Palaeozoic	2849	92.32	6036	90.37
Total Extracted Lineaments	3086	100	6679	100

In relation to table 4.1, it has been observed that over 90 % of the lineaments in both provinces are found within the Precambrian – Lower Palaeozoic rocks which form the Basement Complex rocks. The majority of the fractures have been recorded mainly within the undifferentiated gneisses, charnokitic gneisses and semi pelitic rocks in the Northern and Southern Provinces respectively (Figure 4.5A). These results concurred well with observations from the degree of fracturing. On a regional scale, this may be an indication that in both provinces much of the fracturing and faulting occurred during the orogenic episode and it also signifies the brittle behaviour of these rocks at the time of their formation that resulted into a lot of fracturing in response to the tectonic forces. Low lineament percentage has been observed in the Cretaceous rocks which comprise the dinosaur beds and lupata series in the Northern and Southern Province respectively (the lupata series are well pronounced in Mozambiquian). Ray (1975) explained that the dinosaur beds in the Northern Province consists of friable sandstone, sand marls and clay, on the other hand the lupata series in the Southern Province are characterised by a sequence of pebble conglomerates, coarse sandstone, sandy shales, marls and volcanic rocks (Habgood, 1963). The characteristics and mineralogical composition of these rocks means that the low percentage of lineaments in these rocks may be due to ductile behaviour during the time of their formation causing them to absorb shear stress making these rocks less fractured.

In total a large number of lineaments have been extracted in the Southern Province, this does not necessarily mean that the Southern Province experienced prolonged tectonic activities than the Northern Province rather it is attributed to a large area coverage by Precambrian – Lower Palaeozoic and Upper Jurassic – Lower Cretaceous rocks within the Southern Province (Figure 1.1) which have recorded a high number of lineaments as compared to the Northern Province thereby giving the Southern Province a high percentage.

In conclusion it has been observed from the above interpretation that the Basement Complex rocks in both provinces responded to the tectonic activities in a brittle behaviour as they recorded a high lineament density. Most of the lineaments within the Basement Complex rocks were within the ranges of less than 5 kilometres as observed during visual analysis; this may indicate tension cracks which were formed during tectonic activities within these rocks.

4.1.6. Lineament Density

Lineament density maps give information on the total number of lineaments per unit area. The calculation of total number of lineaments per unit area helps in defining regions with high lineament density and low lineament density. Information obtained from this is very helpful in determining properties of different lithological units and tectonic activities which were associated with specific geological areas. Some research work has used lineament density analysis in mapping potential areas for ground water exploration (Kim et al., 2004; Corgne et al., 2010), others have used lineament density in mineral exploration (Mostafa & Bishta, 2005). In this thesis lineament density analysis was done to identify variations in the properties of lithological units within the two provinces and their associated tectonic activities, so as to establish structural variations between the Northern and Southern Province of the Malawi Rift. Density maps were produced in ArcGIS using the spatial analyst tool and three different density zones which reflect high, medium and low were identified (Figure 4.6). Much on the methods has been explained in section 3.8.4

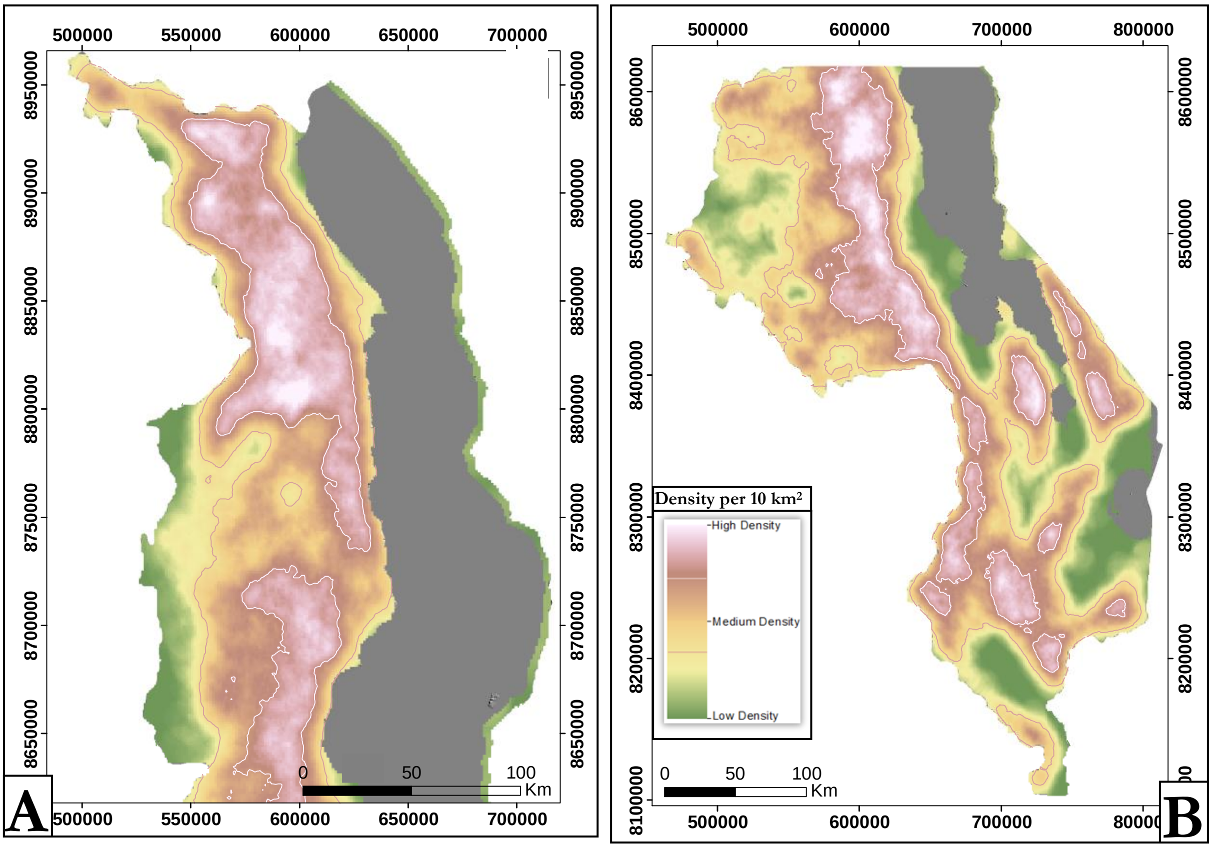

Figure 4-6: Lineament Density Maps **(A)** Northern Province and **(B)** Southern Province. Note the narrow ridge of high lineament density zone within the centre of the Malawi Rift which runs from north to south in both provinces. In most parts this ridge is characterised by areas with hard rock formations.

Interpretation of density maps for the two provinces has been made in reference to the whole provinces with specific reference being made on specific lithological units i.e. the Semi pelitic rocks. Of interest with the Semi pelitic rocks is that they showed different lineaments densities zones of low to medium; and low, medium to high in the Northern and Southern Province respectively (Figure 4.8). Literature review showed that the differences in density zones within the Semi pelitic rock may be attributed to variations in the mineralogical composition of these rocks (this will be explained in detail in section 4.2.2).

Another point of interest to note on the density maps for both provinces is the narrow ridge to the western side of Lake Malawi which forms a continuous ridge of medium to high lineament density zone in both Provinces; it runs parallel to Lake Malawi in a N-S direction. This ridge defines a major zone of stepwise riftward faults (Chapola & Kaphwiyo, 1992) that forms the western edge of Lake Malawi basin (the western horst of the Malawi Rift). Visual analysis of extracted lineaments showed that, most of the lineaments within this narrow ridge take almost the same orientation pattern which is well pronounced in the N-S direction except for an area on the far north end and far south end of the Northern and Southern province respectively where the orientation pattern is more pronounced in the NW-SE direction. This pattern (N-S) is also clearly identified on the rose diagrams for the two provinces (Figure 4.3). From this analysis, it is suggested that geological structures within this narrow ridge of high lineament density might have been reworked during the Mozambiquian mobile belt giving them their present orientation which is similar to the orientation pattern of the Mozambiquian orogeny (N-S).

Observation and comparison of both Northern and Southern Province lineament density maps have revealed that the highest percentage of the Basement Complex rock has a high lineament density in both provinces. This implies that the Basement Complex rocks are highly fractured and faulted than the rest of the rocks within both provinces, this gives similar interpretation to the analysis of degree of fracturing in section 4.1.4.

4.2. Establishment of structural variations at a local scale

To fully understand the structural variations between the Northern and Southern Province of the Malawi Rift a closer look at a local scale was necessary. In this regard specific lithological units, i.e. Karroo System and Semi pelitic rocks were chosen; other interpretations at a local scale involved lineament direction of extension pattern associated with structural divisions within each province. Karroo System rocks were specifically chosen because they showed a closer similarity in their degree of fracturing in figure 4.5 in section 4.1.4, on the other hand the Semi pelitic rocks were chosen because of their variations in lineament density which they recorded in figure 4.6 section 4.1.6.

4.2.1. Interpretation of structural differences within the Permian – Triassic age group (Karroo System rocks)

Analysis and interpretation of the Karroo System rocks at a regional scale showed similarities in their degree of fracturing and percentage of extracted lineaments. These observations prompted further analysis and interpretation of the same at a local scale to observe the orientation pattern of the lineaments extracted within these rocks. Rose diagrams were plotted for these rocks, results from these rose diagrams showed clear differences in the orientation pattern between the Northern and Southern Province Karroo rocks (Figure 4.7)

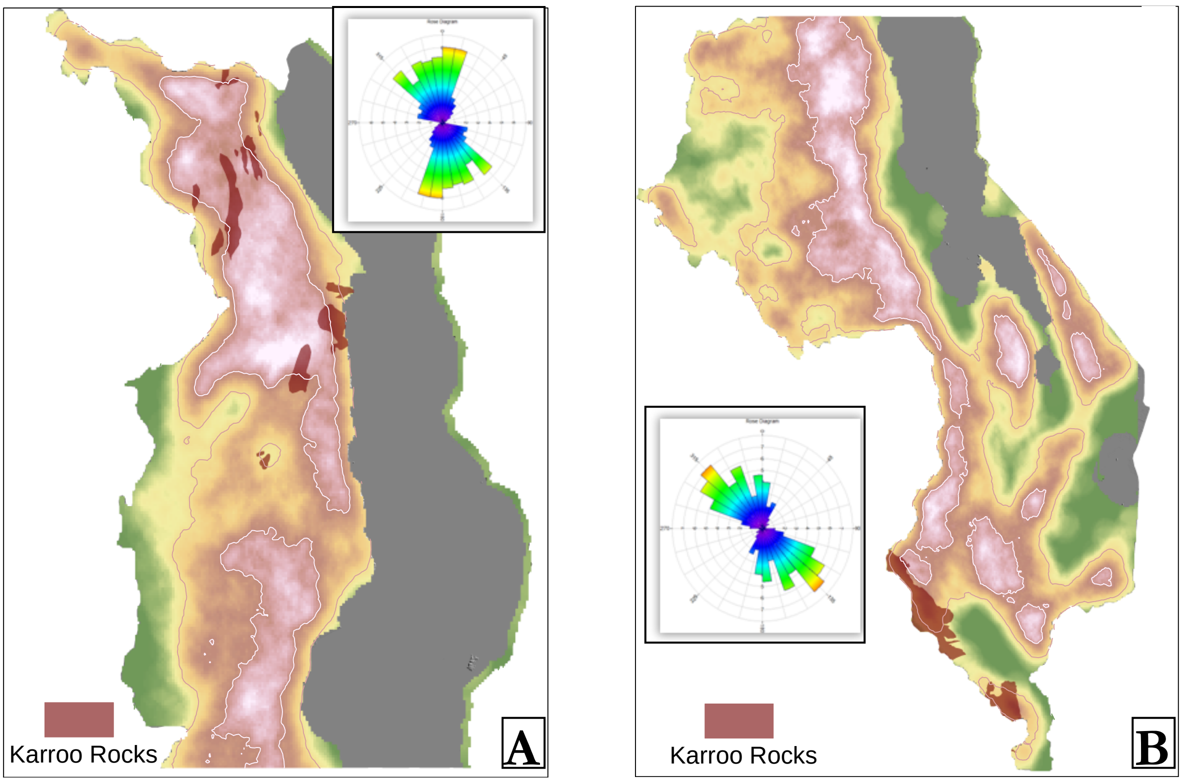

Figure 4-7: Lineament density maps showing Karroo System lithological units and insert is their Rose diagrams **(A)** Northern Province and **(B)** Southern Province. Note the clear differences in the lineament orientation pattern for these rocks between the two provinces.

From figure 4.7, it is observed from the rose diagram petals that the Northern Province Permian – Triassic age group (which comprise Karroo system rocks) has a higher percentage of lineaments extracted in the N-S direction than those in the Southern Province. It is also observed from the rose diagrams that the two provinces have different lineament orientation patterns. The Karroo rocks in the Northern Province have well pronounced NW-SE and N-S orientation patterns, while the Southern Province has shown a pronounced orientation pattern in the NW-SE direction only. The orientation pattern of the Karroo lineaments in the Northern Province is extending towards the north from 315 degrees while in the Southern Provinces it is extending towards the west from 315 degrees. These observed differences reflect differences in the controlling mechanism behind their formation. This concurs well with Bennett, (1986) who observed that the Karroo System structures in the Northern Province were more influenced by structural controls during the formation of the Lake Malawi basin which mostly take N-S orientation pattern a reflection of the Mozambiquian mobile belt. While those in the Southern Province were much influenced by similar structural controls but showing a reflection of the Southern Irumide mobile belt.

Interpretation of lineament density maps shows that the Karroo rocks in the Northern Province have recorded medium to higher lineament density values than the Southern Province where low to medium lineament density have been recorded. This is clear evidence that the Northern Province Karroo System rocks were associated with intense fracturing and faulting during the formation of the basins in which they are deposited. In the Southern Province, the Karroo System rocks have revealed high area coverage of medium lineament density which also signifies that a large part of the Southern Province Karroo rocks may have been subjected to moderate degree of fracturing and faulting.

4.2.2. Interpretation of structural differences within the Semi pelitic rocks

The semi pelitic rocks form a greater part of the Basement Complex rocks in both provinces. Analysis and interpretation of lineament density and orientation pattern for these rocks within the two provinces showed differences (Figure 4.8).

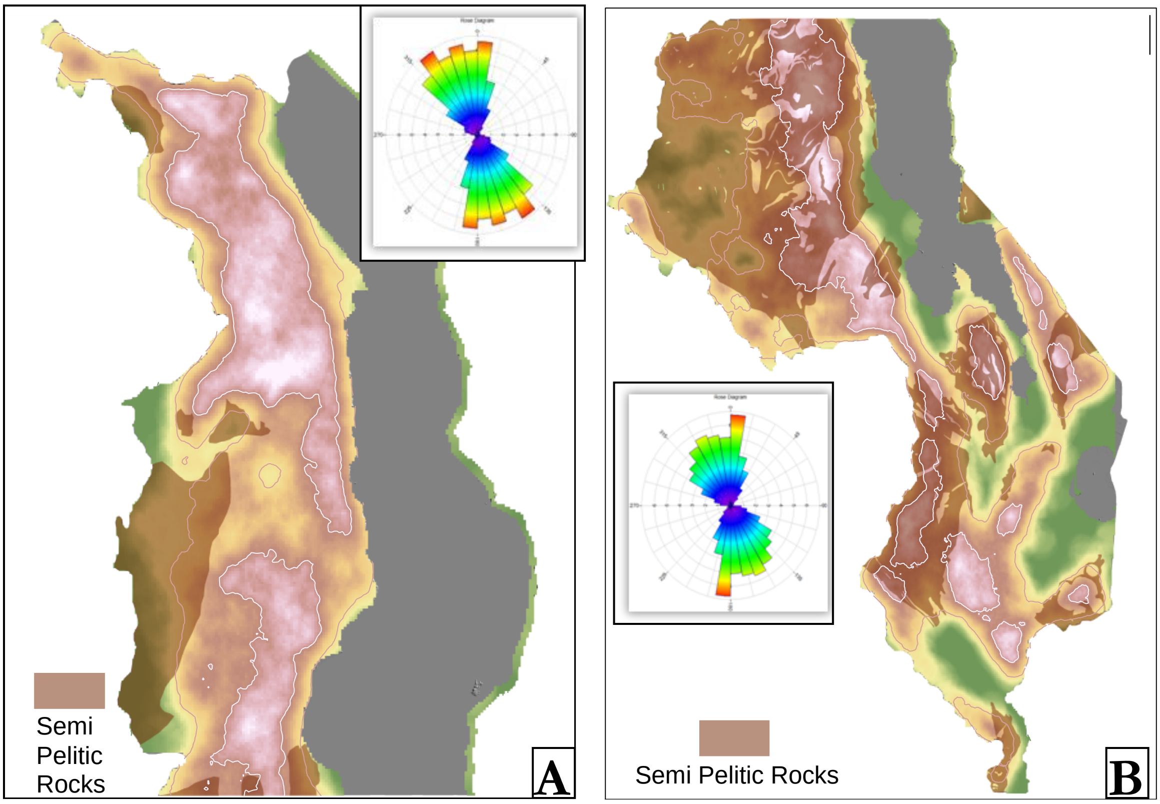

Figure 4-8: Lineament density maps showing areas of semi pelitic rocks and insert are Rose diagrams for semi pelitic rocks **(A)** Northern Province **(B)** Southern Province. Note the clear differences in the lineament orientation pattern for these rocks between the two provinces from the rose diagrams.

Interpretation of rose diagrams for semi pelitic rocks within the two provinces shows that the orientation of lineaments within the semi pelitic rocks in the Northern Province has mostly been affected by the Ubendian mobile belt. It is observed in figure 4.8 above that the Northern Province has well pronounced orientations in the NW-SE and N-S orientations. However lineaments for semi pelitic rocks in the Southern Province have been dominated by a N-S orientation pattern, a pattern that matches signatures of the Mozambiquian mobile belt.

This entails that the greater part of the semi pelitic rocks in the Northern Province was highly subjected to the Ubendian and the Mozambiquian mobile belts. In the Southern Province it is evident that the Mozambiquian mobile belt (N-S) dominated as it has shown a high percentage of extracted lineaments on the rose diagrams in the same direction, followed by less pronounced signatures of the Ubendian mobile belt. However it is interesting to note that signatures of the Irumide mobile belt are less prominent in both provinces. This observation concurs well with what Carter & Bennet, (1973) observed that the Irumide mobile belt which extends from North-Eastern Zambia is locally manifested in Malawi.

It is also interesting to note that the semi pelitic lithological units which have showed a medium to high lineament density zone in most parts within the Southern Province except for the north western side where they have recorded a low lineament density, are characterised by a low to medium lineament density zone in the Northern Province most precisely on the central western side of Chitipa and south western side of the Nyika Granitic Pluton. This observation might be attributed to the differences in the mineralogical composition of the semi pelitic rocks within the two provinces. Review of literature indicates that the Semi pelitic rocks mainly comprise biotite and hornblende gneisses commonly garnetiferous and locally graphite (Carter & Bennet, 1973).

Review of geological bulletins for the north-western part of the Southern Province where the semi pelitic rocks have recorded low lineament density shows the presence of graphite within these rocks in this area (Walter, 1972; Carter & Bennet, 1973). It is suggested here that the semi pelitic rocks with low lineament density zone in the north-western part of the Southern Province might be the result of the presence of graphite contents, i.e. on a local scale giving them a less number of lineaments per unit area since graphite acts as a lubricant that reduces shearing (Oohashi et al., 2011). The presence of graphite in these rocks acts as a lubricant that reduces the shear strength hence giving them a ductile behaviour which makes them to be less fractured. On the contrary a review of the geological bulletins for the Northern Province in areas where there is low lineament density within the semi pelitic rocks showed no presence of graphite. It is therefore suggested by the author that though there is no mention of graphite in the geological bulletins, there is a need to revisit these rocks as results from the analysis of the lineament density maps suggest a low lineament density zone which might indicate the presence of graphite.

4.2.3. Establishing differences in lineament direction of extension pattern

Analysis and interpretation of possible direction of extensional pattern that resulted into the present orientation of the lineaments was done by visual and geospatial interpretation. For geospatial interpretation, lineament rose diagrams, Sandbox model and scaled physical models for the East African Rift System by Acocella et al., (1999), Bonini et al., (1997), McClay et al., (2002) and McClay & White, (1995) were used. In their models Acocella et al., (1999), Bonini et al., (1997) McClay et al., (2002) and McClay & White, (1995) showed that the direction of extension pattern for most of the structures related to the East African System is orthogonal or oblique to the orientation direction of the structures. Direction of lineaments extension pattern was also interpreted in relation to the kinematic models developed by Delvaux & Barth, (2010), in his models Delvaux & Barth, (2010) interpreted the direction of extension forces for Africa specifically the East African Rift System using focal mechanism data.

In this thesis, to better understand and interpret structural differences between the Northern and Southern Province of the Malawi Rift, interpretation of lineament direction of extension pattern was done by using lineament rose diagrams which were interpreted in relation to the fault extension pattern models (sand box models) by Acocella et al., (1999), Bonini et al., (1997), McClay et al., (2002) and McClay & White, (1995). The conceptual models (sand box models) by McClay et al., (2002), McClay & White, (1995), Acocella et al., (1999) and Bonini et al., (1997) were specifically used here because of the fact that apart from being tested in the lab they were also proven in the field.

For the purpose of establishing structural differences between the two provinces in relation to direction of fault extension pattern, the structural divisions for the Malawi Rift used by Chapola & Kaphwiyo (1992) were adopted here. These structural divisions are: Livingstonia, Mbamba-Usisya and Bandawe which covers the Northern Province and Makanjira and Shire which covers the Southern Province. For meaningful interpretation of variations in the type of fault extension pattern some adjustments were made to the boundary between the Bandawe and Makanjira divisions. In this regard the Makanjira division was extended further north up the edge of the Champhira dome so that the provincial divisions between the two provinces is still maintained. The Shire division was also further divided into two, i.e. Upper and Lower Shire (Figure 4.9B).

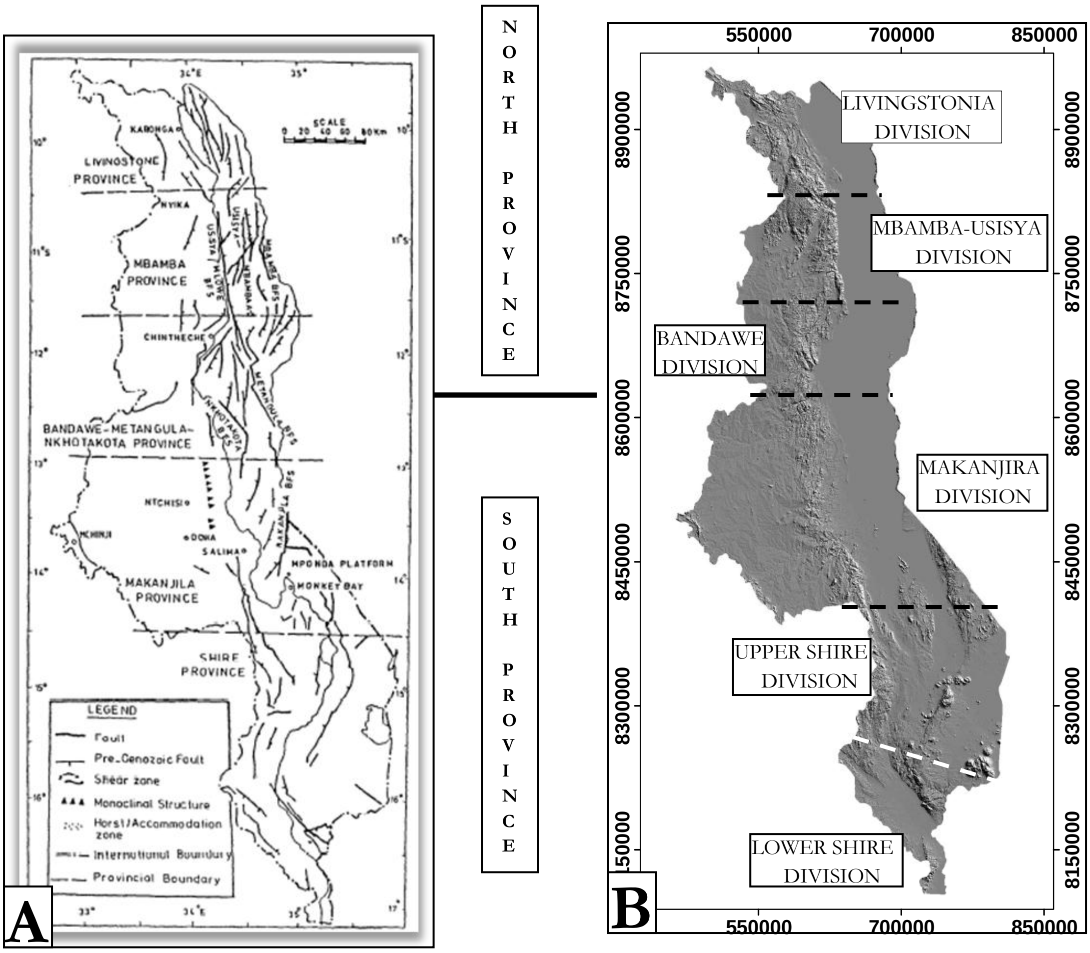

Figure 4-9: **(A)** Structural map of the Malawi Rift showing structural division (Courtesy of: Chapola & Kaphwiyo, 1992) and **(B)** SRTM map of Malawi showing structural divisions modified from Chapola & Kaphwiyo, (1992). Dashed white lines in the Southern Province indicate the division between the Upper and Lower Shire as explained in the text.

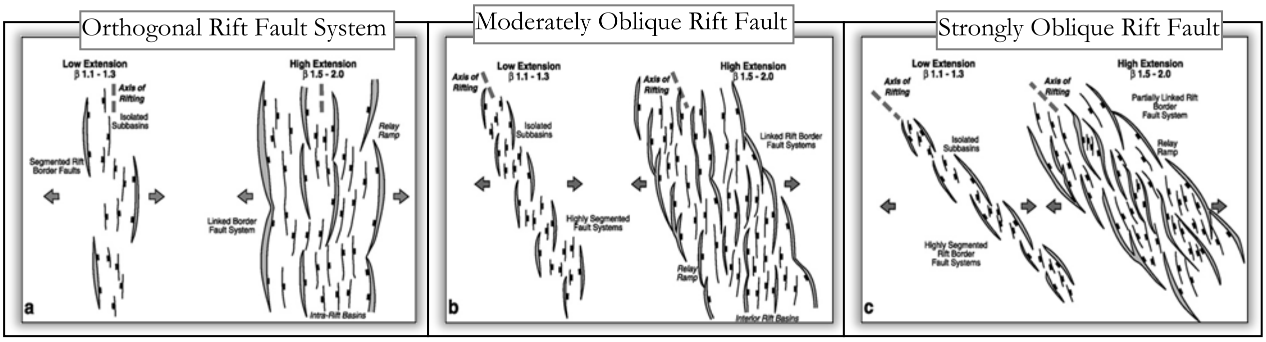

Figure 4-10: Conceptual extension fault patterns for orthogonal and oblique rift systems (Courtesy of: McClay et al., 2002). Note the tree types orthogonal, moderate and strong oblique rift fault patterns.

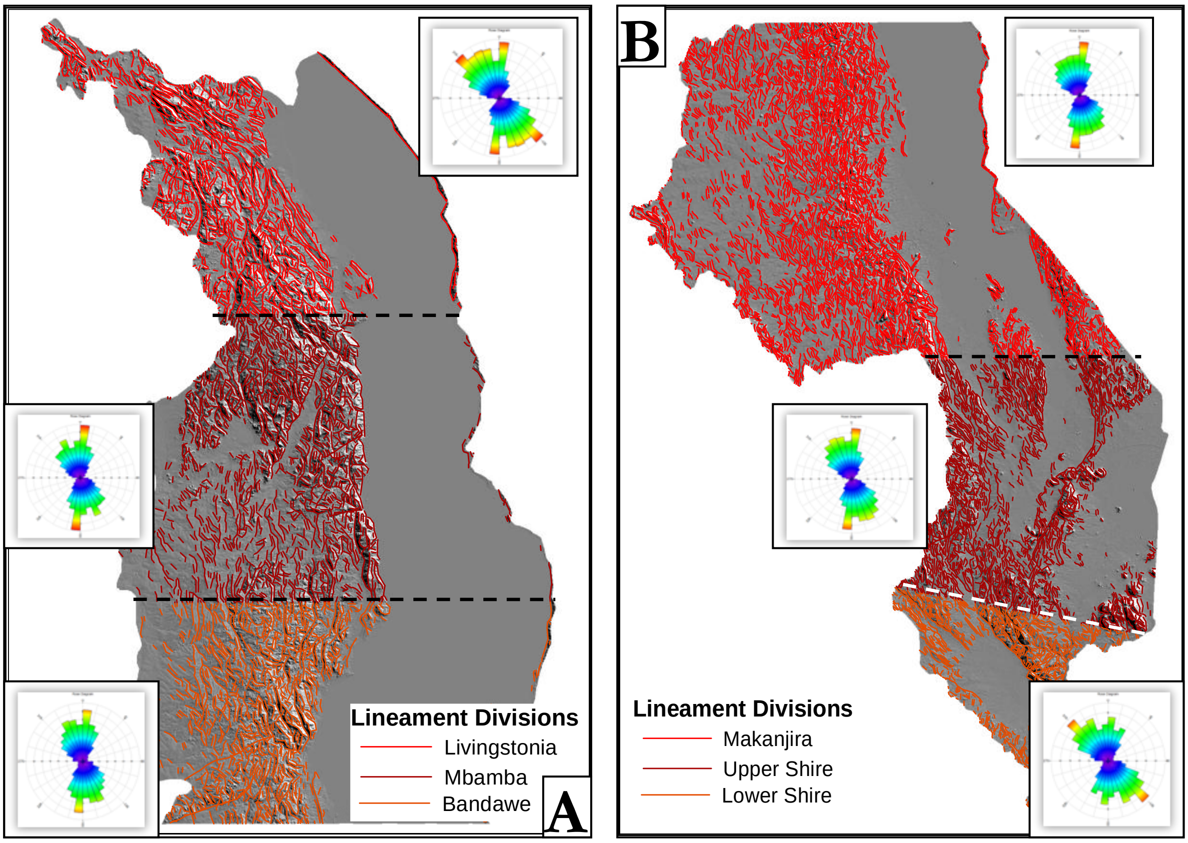

Figure 4-11: Identification of lineament extension pattern. Insert are rose diagrams which are plotted for each structural division **(A)** Northern Province and **(B)** Southern Province. Dashed lines indicate boundary within structural divisions as outlined in figure 4.9B

From the interpretation of rose diagrams in figure 4.11 it is observed that the Northern Province has three different lineament extension direction patterns which are NW–SE and an almost N-S for the Livingstonia, Mbamba-Usisya and Bandawe structural divisions and a less pronounced NE–SW for the Mbamba-Usisya and Bandawe structural divisions respectively. Structural divisions in the Northern Province have recorded almost a similar pattern. These extension patterns corresponded well with the general orientation of structures caused during the orogenic episode more precisely the Ubendian, Mozambiquian and Irumide orogenies. The observed lineament orientation patterns on the rose diagrams have been used to interpret the possible type of extension lineament pattern and their possible direction of extension within the two provinces. It is therefore clear that the possible direction of extension forces for lineaments in reference to the conceptual model for the extension fault pattern (Figure 4.10) within the Livingstonia, Mbamba-Usisya and Bandawe divisions is in the East-West direction with the Livingstonia division having a strike-slip pattern. With regards to the type of lineament extension pattern, the three divisions in the Northern Province show different lineament extension patterns which are: well pronounced strongly oblique and orthogonal for the Livingstonia division; and well pronounced orthogonal for the Mbamba-Usisya and Bandawe divisions. The Mbamba-Usisya and Bandawe divisions seem to have a moderately oblique lineament pattern around 330 to 345 degrees NNW.

Chapola & Kaphwiyo (1992) used two structural divisions in the Southern Province. In this thesis the Southern Province has been divided into three divisions, the Shire division has been further divided into two, i.e. Upper Shire and Lower Shire where Upper Shire covers the area around Zomba and Kirk-Range fault zones and Lower Shire cover the area around Thyolo and Mwanza fault zones. This further division was arrived at after visual analysis of extracted lineaments for the Chikwawa – Nsanje basin which showed that most of the lineaments within the area have a NW-SE orientation pattern. From the analysis and interpretation of rose diagrams in relation to conceptual models by McClay et al., (2002) and McClay & White, (1995) it was observed that the Lower Shire division has a well pronounced lineament extension pattern that is similar to the Livingstonia division, i.e. a well pronounced strongly oblique pattern with a less pronounced orthogonal pattern (Figure 4.11). The Makanjira and Upper Shire divisions showed similar well pronounced orthogonal patterns, with less pronounced moderately oblique pattern. However the moderately oblique pattern for the Upper Shire division has a high percentage of lineaments extracted around 330 to 345 degrees NNW direction than the Makanjira division. This suggests that part of the lineaments within the Upper Shire division may have been affected by the same forces that controlled the formation of the Lower Shire division lineaments.

Analysis of extension fault patterns between the two provinces has shown similarities in the strongly oblique pattern between the Livingstonia and Lower Shire divisions, however the two divisions have showed differences in the percentage of lineaments that are associated with the orthogonal extension pattern in that the Livingstonia division has a high percentage of lineaments that were extracted in the N-S direction than the Lower Shire division. This is also clearly visible on the lineament map (Figure 4.1) using visual analysis.

Other similarities have been observed in the Mbamba-Usisya, Bandawe and Makanjira, Upper Shire divisions for the Northern and Southern Provinces respectively. In both of these a well pronounced lineament extension pattern of orthogonal has been observed with a less a pronounced moderately oblique pattern. In the Northern Province the Mbamba-Usisya and Bandawe divisions showed differences in percentage with regards to the moderately oblique lineament extension pattern in the NE-SW direction, the Bandawe division has showed a high percentage of lineaments extracted in this direction than the Mbamba-Usisya division. This difference may be attributed to the fact that a lot of lineaments within the Bandawe division resulted from tectonic activities that resulted in the formation of the Chimaliro-Champhira fault zone, and some of the lineaments in NE-SW direction within the Bandawe division might represent tension cracks. In the Southern Province Makanjira and Upper Shire divisions have shown differences in the percentage of extracted lineaments in the NW-SE direction (moderately oblique pattern). The Upper Shire has recorded a high percentage of lineaments in the moderately oblique NW-SE direction, this might be as result of the tectonic activities that resulted into the formation of the Bilira-Mtakataka and Kirk-Range fault zones.

The above analysis and interpretation on lineament extension pattern have mostly shown similarities between the two provinces. The Mbamba-Usisya, Bandawe, Makanjira and Upper Shire structural divisions though showing a well pronounced orthogonal lineament patterns they still show a moderately oblique pattern that can clearly be observed in the NW-SE direction. This implies that the Malawi Rift is generally characterised by an oblique lineament extension pattern followed by an orthogonal lineament extension pattern. This also means that the overall orientation of geological structures and lineaments within the Malawi Rift is in the NW-SE and N-S directions. The above observed structural similarities between the Northern and Southern Province with regard to lineament extension pattern implies that the two provinces may have experienced similar tectonic events that caused the present orientation of lineaments and geological structures within these areas. However the availability of differences in the type of lineaments extension pattern and percentage of extracted lineaments at local scale within individual structural divisions cannot be overlooked. The pattern of lineament orientation observed within the structural divisions led to development of a proposed structural component model for the Malawi Rift. This model has been explained in detail in chapter 5 of this thesis.

5. PROPOSED STRUCTURAL COMPONENT MODEL OF THE MALAWI RIFT

5.1. Development of the Model

Analysis and interpretation of the lineament extension pattern and directions of extension forces within the Northern and Southern Province of the Malawi Rift showed a pronounced pattern that is being depicted by the lineament rose diagrams (Figure 4.11). This observation and the pronounced pattern of the lineaments within the structural divisions encouraged the author to develop a proposed structural component model for the Malawi Rift. The general pattern for the lineament extension showed a similar trend within the Mbamba-Usisya, Bandawe, Makanjira and Upper Shire structural divisions; the patterns seem to change their trends in the Livingstonia and Lower Shire divisions where a more prominent NW-SE trend is observed. These trending patterns were interpreted by the author in relation to the conceptual models by McClay & White, (1995) and McClay et al., (2002) as indicated in section 4.2.3 of chapter 4 to produce the proposed structural component model for the Malawi Rift.

5.2. The Model

From the proposed structural model (Figure 5.1), it is observed that the Malawi Rift can be generalised by three main structural components (component 1 which covers the Livingstonia division, component 2 which covers the Mbamba-Usisya, Bandawe, Makanjira and Upper Shire divisions and component 3 which covers the Lower Shire division). These proposed structural components are characterised by orthogonal and oblique extensional lineament patterns with a general extension force from the east – west direction for the Mbamba-Usisya, Bandawe, Makanjira and Upper Shire structural divisions and east – west direction with a strike-slip pattern for the Livingstonia and Lower Shire structural divisions (Figure 5.1). It is clearly visible that lineaments in the central part of the model which comprise Mbamba-Usisya, Bandawe, Makanjira and Upper Shire depicts a well pronounced orthogonal pattern which in this case reflects signatures of the Mozambiquian mobile belt and structures which were associated with the formation of the Lake Malawi basin (border faults/half grabens). Though this is the case a moderately oblique pattern for the lineaments is observed in all these structural divisions.

From the model it is also observed that the far northern part of the Northern Province and far southern part of the Southern Province where there are the Livingstonia and Lower Shire divisions respectively has shown a more pronounced pattern in the NW-SE direction which is characterised by a strongly oblique pattern. The trending pattern of the Livingstonia structural division might have been strongly influenced by the Ubendian belt and the Livingstonia border fault/half graben. The Livingstonia division has also shown an orthogonal pattern which might be a reflection of lineaments within the Karroo basins in the area. On the other hand the Lower Shire structural division might have been influenced by the southern Irumide belt (Roberts et al., 2012) and the Thyolo border fault/half graben. It is noted that the pronouncement of the orientation patterns for the extracted lineaments within the structural divisions varies as a result of differences in the percentage of extracted lineaments within that direction.

From this proposed structural component model it can be concluded that the central part of the Malawi Rift which comprise Mbamba-Usisya, Bandawe, Makanjira, Upper Shire structural divisions was much affected with similar tectonic activities that resulted into the present orientation of geological structures. The orientation of lineaments in the central part of the model gives a dominant reflection of the Mozambiquian mobile belt, this means that structures that were formed during the Cenozoic period were emplaced in the same orientation pattern of the Mozambiquian belt. Similar patterns are also depicted in the Livingstonia and Lower Shire structural divisions which are a reflection of the Ubendian and Southern Irumide mobile belts respectively. Despite showing signs of experiencing similar tectonic activities; the general orientation of the resulting geological structures is different as evident from the model that some structures (lineaments) are oriented in an orthogonal pattern while others show an oblique pattern. Generally the proposed structural component model of the Malawi Rift has shown orientation patterns that are similar to both Pre-Cenozoic and Cenozoic structures.

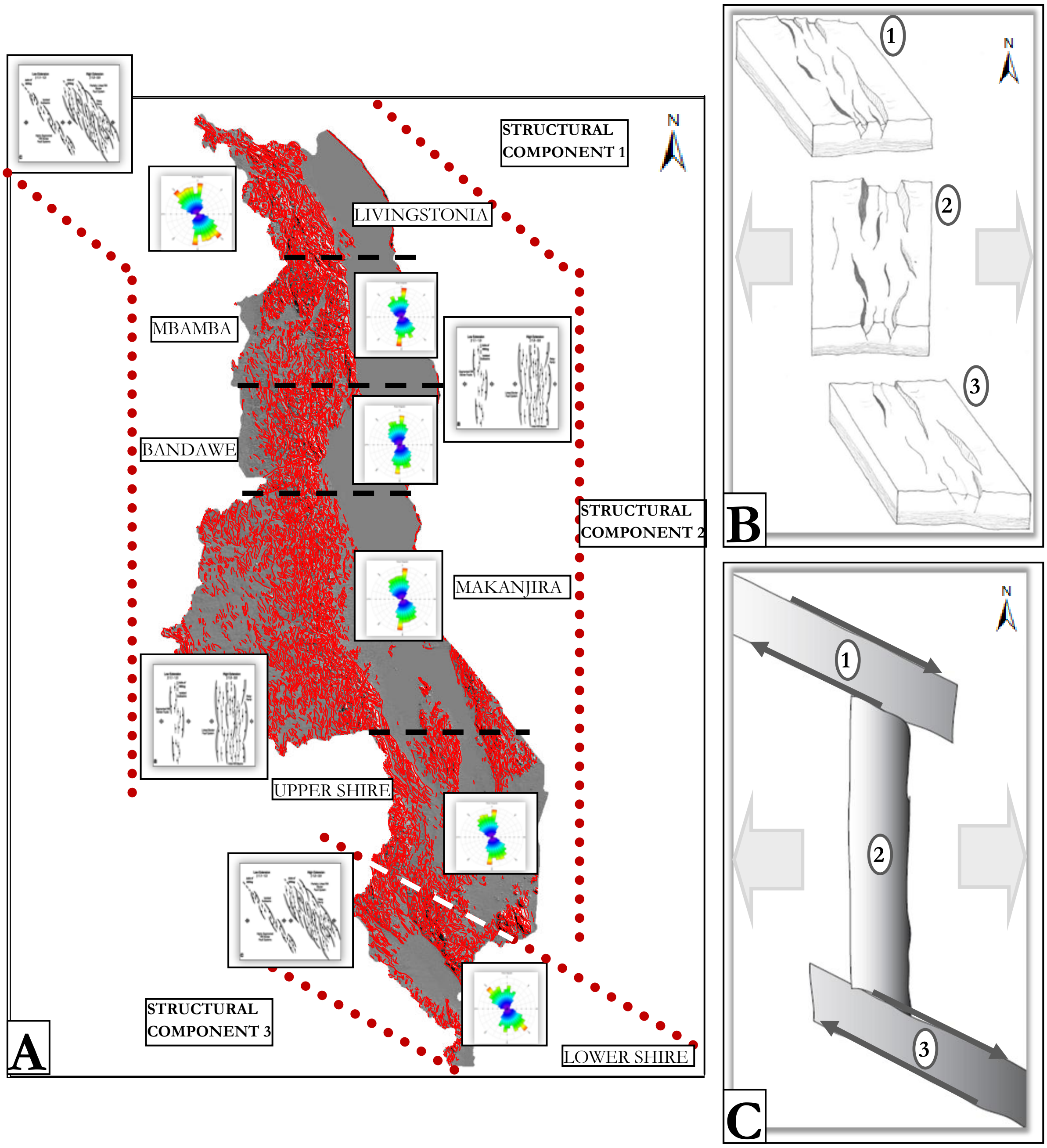

Figure 5-1: **(A)** Proposed generalised structural component model showing the possible major structural components of the Malawi Rift indicated by the red dotted lines; insert are rose diagrams and conceptual extension fault patterns (McClay et al., 2002) for each component. **(B)** Schematic representation of figure **A** presented in three-dimensional form. **(C)** A sketch of the same proposed structural component model figure **A**. Numbers in circles represents structural components 1, 2 & 3, note the pattern for structures (lineaments) in each structural component which corresponds to oblique for component 1 & 3 and orthogonal for component 2. Big gray arrows show direction of extension and black arrows indicated strike – slip faulting pattern.

It is interesting to note that the proposed structural component model for the Malawi Rift has shown similar patterns to both Pre-Cenozoic and Cenozoic structures in reference to figure 2.7. The orientation pattern of the Pre-Cenozoic and Cenozoic structures i.e. faults, shear zones and border fault which forms a backbone of the Malawi Rift have been well depicted by the rose diagrams in the proposed structural component model. For the entire Northern Province and Southern Province prominent orientation pattern of the Cenozoic structures i.e. border faults/half grabens has been depicted. In most of the structural divisions from both provinces orientation patterns of the Pre-Cenozoic structures is visible from the rose diagrams. This suggests that most of the Cenozoic structures followed the mobile belts (which represent zones of crustal weakness) hence they were emplaced within the Pre-Cenozoic structural trends.

The above proposed structural component model has shown that the Malawi Rift is generally characterised by three structural components which are a reflection of both the Pre-Cenozoic and Cenozoic related structures. The structural divisions on the central part of the model, i.e. Mbamba-Usisya, Bandawe, Makanjira and Upper Shire have shown a similar orthogonal pattern in the orientation of the lineaments. On the other hand the two divisions on the northern end and southern end of the Northern and Southern Provinces have shown a better pronounced strongly oblique pattern in the orientation of the lineaments. Reference to these observations from the proposed structural component model, it is deduced here by the author that the general orientation of structures within the Malawi Rift is dominated by NW-SE and N-S orientation directions with less pronounced NE-SW direction.

6. DISCUSSION

Three aspects of this study are discussed in this chapter in relation to the research objectives and research questions of this thesis. These aspects are: (i) structural similarities between the Northern and Southern Province of the Malawi Rift which were mostly observed at a regional scale, (ii) structural differences between the two provinces which were mostly observed at a local scale and (iii) the proposed structural component model of the Malawi Rift.

6.1. Observed structural Similarities

Analysis and interpretation of data at a regional scale has shown similarities in most of the structures within the two provinces. Analysis and interpretation of results both visually and geospatially done on regional scale have showed that the two provinces may have undergone similar tectonic history.

Visual and geospatial analysis of the extracted lineaments from the Southern and Northern Provinces of the Malawi Rift on a regional scale have shown similarities in the general orientation pattern of lineaments, degree of fracturing within lithological units and geological age groups, lineament density, lineament length and frequency, and the total percentage of extracted lineaments within geological age groups. These observations imply that on a regional scale the two provinces underwent similar structural tectonic history.

Plots of rose diagram to establish the general orientation pattern of the lineaments from both provinces showed a similar orientation pattern which is well pronounced in the NW–SE and N-S direction. This orientation signifies the dominance of the Ubendian and Mozambiquian orogeny in both provinces; however the Ubendian seems to be well dominated in the Northern Province as the rose diagram plots showed a higher percentage of lineaments being extracted at 330 to 345 degrees NW in the Northern Province than the Southern Province (Figure 4.3).

Results from the degree of fracturing in relation to lithological unit / age group for both provinces has shown that in both provinces the Precambrian – Lower Palaeozoic rocks which forms the greatest part of the Basement Complex within the rift have a similar degree of fracturing, followed by the Karroo System rocks (Figure 4.5). Results from degree of fracturing were similar to observation of density of extracted lineaments per age group as they also show the Precambrian – Lower Palaeozoic rocks having a high lineament density (above 90 % as shown in table 4.1). Characterisation of density of lineaments per age group has shown the Southern Province having a higher density of extracted lineaments than the Northern Province. This does not necessarily mean that the Southern Province has experienced a longer period of faulting and fracturing than the Northern Province rather it is attributed to the larger surface area covered by this province which translates into more lineaments being extracted within this province than the other.

Interpretation of results from lineament spatial and structural pattern from lineament maps of the two provinces showed similar spatial and structural patterns between the two provinces. In both provinces the longest lineaments have been extracted along the border faults and within lithological contacts. High spatial distribution of lineaments seems to follow a narrow ridge which extends from Chitipa in the Northern Province to Chikwawa in the Southern Province on the centre of the Malawi Rift (western side of Lake Malawi and the Shire trough). This ridge may represent a horst on the western side of the Malawi Rift which formed during the rifting episode. Extension of this narrow ridge in both provinces may signify that the two provinces experienced similar regional tectonic activities. With regards to structural pattern it was observed that there are some circular lineament patterns in the Southern Province (defining the syenogranitic plutons and nepheline syenite plutons lithological units) which are not found in the Northern Province. This signifies that geological process that resulted into the formation of these circular lineament patterns may not have affected the Northern Province hence, their absence.

Analysis of lineament density for the Southern and Northern Provinces of the Malawi Rift has shown that there are no large variations in the lineament density between the two provinces. In both provinces it has been observed that a greater part of the Precambrian – Lower Palaeozoic rocks (Basement Complex rocks) has shown a medium to high density with low density characterising most parts of the Quaternary rocks. This implies that most of the Basement Complex rocks in both provinces experienced similar fracturing and faulting mechanism.

Analysis and interpretation of lineament length and frequency has also shown similarities in the highest frequency of extracted lineaments. It is observed from the length histograms (Figure 4.4) that most of the lineaments within the two provinces are within the length of 500 metres to 10,000 metres. It was also observed that most of the lineaments longer than 10 kilometres in both provinces are localised within lithological contacts or along topographic lows. This suggest that these lineaments may be forming the greater part of the main rift faults within the two provinces. On the other hand shorter lineaments less than 5 kilometres may represent tension cracks which may have formed by horizontal movements of the main rift faults within these areas.

The above observations might indicate that the two provinces underwent similar structural deformation history during the orogenic and rifting episodes. It is also clear that the greater part of the Basement Complex rocks (Precambrian – Lower Palaeozoic rocks) within the two provinces have experienced similar prolonged tectonic activities that have resulted into the present orientation of structures.

6.2. Observed Structural Differences

Despite the above similarities on regional scale interpretation, closer analysis during this research at local scale showed structural differences within the two provinces. These structural differences have been identified in terms of lineament density for selected lithological units and the general orientation pattern of lineaments for selected lithological units / age groups. Minor differences have been observed in the dominant type of extension lineament pattern between the Livingstonia and Lower Shire divisions in the Northern and Southern Province respectively (Figure 4.11).

Interpretation of the lineament extension pattern for the two provinces has shown similarities for the greatest part of the two provinces (Figure 4.11). However there are some differences being identified on the dominant type of extension patterns between the Livingstonia and Lower Shire divisions. It has been observed in this research that the two divisions though having similar strongly oblique pattern, they do have differences in the pronouncement of the orthogonal pattern. The Livingstonia division in the Northern Province seems to have a better pronounced orthogonal pattern than the Lower Shire division in the Southern Province. The well pronounced orthogonal pattern in the Northern Province is a reflection of lineaments associated with the Karroo basins which are more pronounced in the N-S direction. In the Northern Province differences were also observed in the percentage of extracted lineaments along the direction of NE-SW lineament extension pattern between the Mbamba-Usisya and Bandawe divisions in that the Bandawe division has a higher percentage of lineaments in the NE-SW direction than the Mbamba-Usisya division. These differences may signify that many of the lineaments which might be representing tension cracks may have formed within the Bandawe division during the formation of the Champhira – Chimaliro fault zones.

Geospatial analysis of lineaments from selected lithological age groups has shown that the Karroo System rocks which form the Permian-Triassic geological age group for the two provinces have different orientation pattern. Interpretation of rose diagrams for the Karroo System rocks has shown differences in the orientation directions between the Northern and Southern Province Karroo rocks (Figure 4.7A & 4.7B). This difference in lineament orientation direction means that these rocks may have undergone different driving mechanism during the time of their formation / fracturing. Literature review has revealed that most of the fracturing within the Karroo basins in the Northern Province was influenced by extensional forces that resulted in the formation of the Lake Malawi basin, while those in the Southern Province were influenced by extension forces that resulted in the formation of the Mwanza – Thyolo faults.

Analysis of rose diagrams for the Semi pelitic rocks showed different pronounced orientation patterns for the two provinces. In both cases it was observed that the orientation pattern for the Northern Province was more pronounced in the direction of the Ubendian and Mozambiquian related structures which implies that the greater part of these rocks in this province were highly subjected to the Ubendian and Mozambiquian orogeny (Figure 4.8A). The Southern Province has shown well pronounced orientation pattern that follows the direction of the Mozambiquian orogeny (figure 4.8B). However it is noted here that in both provinces less pronounced signatures of the Irumide orogeny are found which imply that the influence of the Irumide in both provinces was minimal or that the signatures of the Irumide orogeny may have been reworked during the onset of the last orogenic cycle of the Mozambiquian orogeny.

Of interest in the analysis of lineament density distribution between the two provinces are the variations within the Semi pelitic rocks. It was observed that in the Northern Province these rocks recorded a low to medium lineament density which was different from the Southern Province where the highest part of this lithological unit recorded a medium to high lineament density with a small part recording low lineament density. Review of literature showed that mineralogically the semi pelitic rocks mainly comprise biotite and hornblende gneiss commonly garnetiferous and locally graphite. A detailed look at geological bulleting per district showed that the low lineament density area for these rocks in the Southern Province has graphite as one of the mineral constitutes. From this background it was concluded by the author that the low to medium lineament density of lineaments in the Semi pelitic rocks in this part of the Southern Province may be attributed to the presences of graphite in these rocks since graphite acts as a lubricant that reduces shearing making these rocks behave in a ductile manner. However a review of geological bulletins per district for the Northern Province did not indicate the presence of graphite in these rocks. Though this was the case, the author suggests that there might be some graphite present in these rocks in the Northern Province. Therefore there is a need for ground truthing and geochemical survey to be done in these areas so as to establish and verify the low to medium lineament density observation.

6.3. Structural Component Model

The proposed structural component model for the Malawi Rift has clearly shown three possible structural components of the rift which are of different orientation directions (well pronounced in NW-SE & N-S and less pronounced in the NE-SW) but generally being characterised by orthogonal and oblique lineament patterns. Both structural patterns related to the Pre-Cenozoic and Cenozoic ages have been depicted in the model but the pattern for Cenozoic structures i.e. border faults/half grabens seem to be very prominent almost throughout the whole rift. This suggests that most of the Cenozoic structures followed the mobile belts (which represent zones of crustal weakness) hence they were emplaced within the Pre-Cenozoic structural trends.

It is observed from this discussion that the identification of structural variations between the Northern Province and Southern Province of the Malawi Rift is dependent on the scale at which one is looking at them. It has been shown from the discussion above that at a regional scale the Northern and Southern Provinces show similar structural patterns. On the other hand a closer look at a local scale has produced structural differences between the two provinces. Results from the proposed structural component model have shown that the orientation of the structures within the Malawi Rift is generally dominated by NW-SE and N-S directions.

7. CONCLUSION AND RECOMMENDATION

7.1. Conclusion

The use of satellite images, remote sensing techniques and automatic lineaments extraction methods have proved to be useful in establishing and defining structural similarities and differences between the Northern and Southern Province of the Malawi Rift. Establishment of the structural differences have shown that on a regional scale the two provinces seem to have undergone similar tectonic activities that resulted into the present orientation and emplacement of geological structures within the two provinces. Though most of the similarities have been observed on a regional scale some differences can still be observed mainly in the percentage of lineaments being extracted within different orientation patterns.

However, structural differences have been well identified on a local scale rather than on a regional scale. Most of the analysis and interpretation done on local scale has proved that the two provinces have structural differences with regards to lineament density within the semi pelitic rocks, orientation pattern of lineaments within the Karroo System rocks and the orientation pattern of lineaments within the semi pelitic rocks. Minor differences have been observed on the analysis and interpretation of the lineament extension pattern of the structural divisions.

Of importance to mention in this thesis is that apart from determining structural variations between the Northern and Southern Province of the Malawi Rift; a generalised model for the possible major structural components of the Malawi Rift has been proposed (Figure 5.1)

7.1.1. Observed structural Similarities

Analysis and interpretation of data at a regional scale has shown similarities in most of the structures within the two provinces. This may imply that the two provinces may have undergone similar tectonic history. The observed similarities are summarised as:

- In both provinces the general orientation pattern of the lineaments showed well pronounced similar trends which are NW-SE and N-S which corresponds to the Ubendian and Mozambiquian mobile belt respectively with a less pronounced NE-SW trend which corresponds to the Irumide mobile belt. A high degree of fracturing has been observed within the greater part of the Basement Complex in both provinces.
- Medium to high lineament density has been observed within the hard rock formations (Basement Complex rocks) as compared to the soft rock formations.
- Lineament length and frequency showed that most of the lineaments in both provinces are within the range of 500 meters to 10 km with only a few lineaments being observed above 10 km.

7.1.2. Observed Structural Differences

Despite the above similarities on regional scale interpretation, closer analysis at local scale showed structural differences within the two provinces. These structural differences have been identified in terms of types of the general orientation pattern of lineaments for selected lithological units / age groups and lineament density for selected lithological units. Minor differences have been observed in the dominant type of extension lineament patterns between the Livingstonia and Lower Shire divisions in the Northern and Southern Province respectively. The observed structural differences at local scale are summarised as:

- The lineament extension patterns has mostly showed similarities, however differences in the dominant type of lineament extension patterns between the Livingstonia and Lower Shire divisions have been observed. These differences are mainly observed in the pronouncement of the orthogonal pattern between the Livingstonia and Lower Shire divisions.
- The lineament orientation patterns for the Karroo System rocks between the two provinces have shown difference. Karroo rocks in the Northern Province have a dominant N-S and NW-SE direction while the ones in the Southern Province have a dominant NW-SE direction. These differences are attributed to their differences in the driving mechanism during their formation.
- The lineaments within semi pelitic rocks between the two provinces showed differences in their orientation and density. The Northern Province recorded low to medium density with a pronounced NW-SE orientation while the Southern Province recorded a medium to high density with a pronounced N-S orientation pattern. Differences in density were attributed to differences in the mineralogical composition of these rocks such as graphite.

Analysis and interpretation of results in this research have shown structural similarities between the two provinces on a regional scale with structural differences mostly being observed on a local scale. It is therefore concluded in this thesis that the proposed structural differences by Cannon et al., (1969) between the Northern and Southern Province of the Malawi Rift should be considered at local scale not at regional scale. At a local scale structural differences are well noticed on associated lineament orientation patterns and lineament density for selected lithological units, i.e. semi pelitic and Karroo system rocks. Minor differences are noticed on the type of lineaments extension patterns. Structural differences have also been noticed on the structural pattern of lineament extracted within the two provinces. In the Southern Province circular lineaments have been extracted which are a reflection of lithological units within the province, these circular lineaments have not been depicted in the Northern Province which means that geological process that resulted into the formation of these circular lineament patterns may have not affected the Northern Province hence their absence.

7.2. Recommendation

From the proposed structural component model in chapter 5, the author recommends doing a follow up research to the proposed structural component model. This follow up research should consider coming up with sandbox models of the Malawi Rift so as to test and validate this proposed structural component model.

Another recommendation is to do further research in the areas where low lineament density was recorded within the semi pelitic rocks so as to verify whether the low lineament density within these areas is due to the presence of graphite. If the low lineament density in these areas is due to the presence of graphite, then the author proposes development of an index that can be used in exploration for graphite potential areas using lineament density analysis within the Malawi Rift.

A field check / ground truthing for the extracted lineaments is also recommended as some lineaments have shown to be forming parts of major fault zones within the Malawi Rift, mostly those lineaments longer than 10 kilometres (and above). Field verification of these lineaments is very important as it will assist in updating the structural map of the Malawi Rift. At the same time it will assist in identifying active faults that are associated with the seismically active Malawi Rift.

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1. APPENDIX

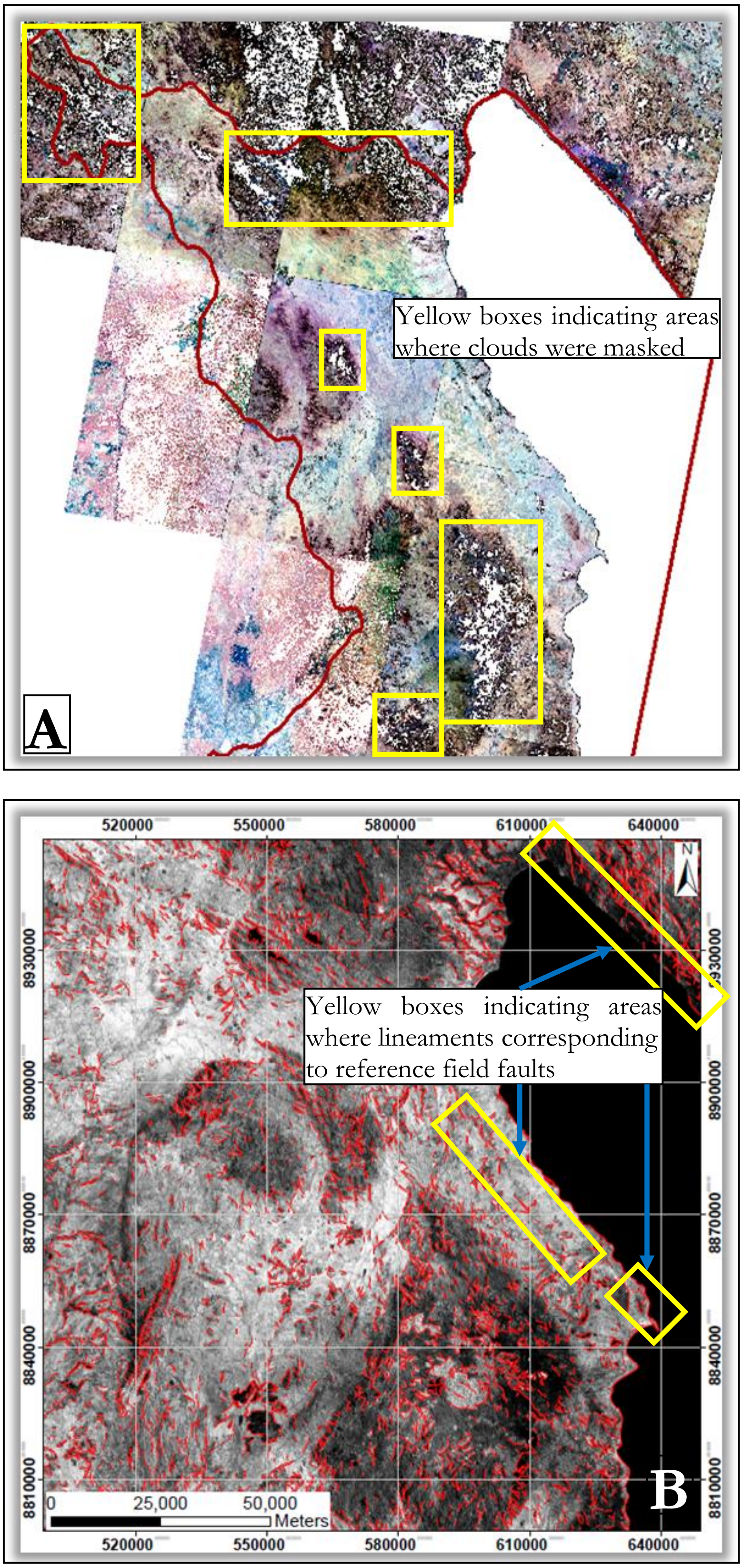

Figure 1-1 (A) ASTER image, the yellow boxes indicate areas where clouds were masked. The process of masking clouds caused some topographic expressions to be lost. (B) LANDSAT image showing extracted lineaments, the yellow boxes indicate areas corresponding to the reference field based faults as in figure 3.3 A. In this case the corresponding lineaments failed to be extracted.

2. APPENDIX

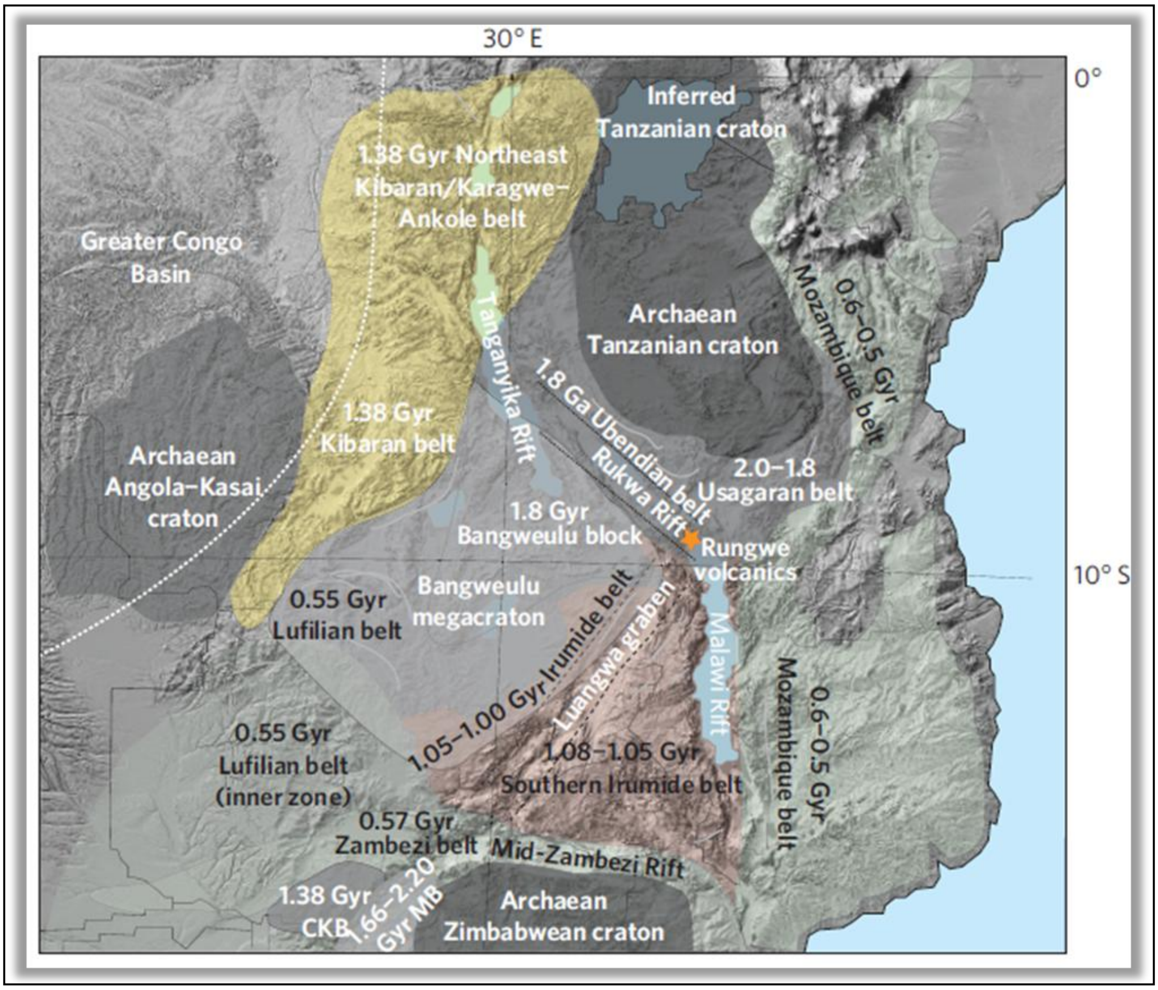

Figure 2-1: Generalised tectonic/structural map of eastern-central Africa showing tectonic elements and their ages (Source: Roberts et al., 2012). Note the location of the Malawi Rift, the surrounding Archean Cratons and the mobile belts. Some elements of the schematic diagram 2.7 have been taken from this map.

3. APPENDIX

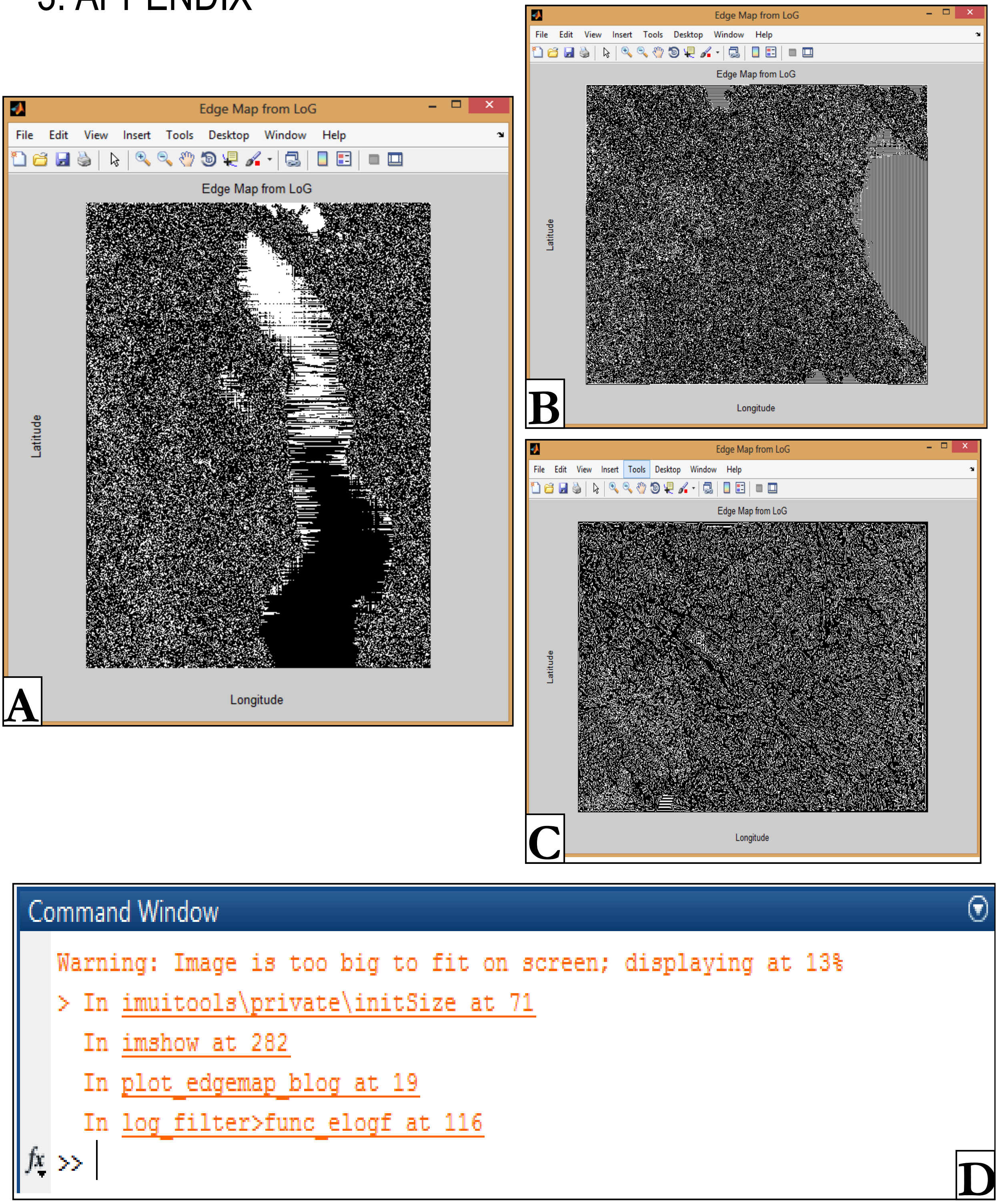

Figure 3-1: Results of edge detection from TecLine Algorithm using the Laplacian of Gaussian (LoG) edge detector. **(A)** Image of the Northern Province study area with a size of 11 MB. **(B)** Image of part of the Northern Province study area with a size of 2 MB and **(C)** Image of part of the same study with a size of 500 KB. Note that in all the above images the algorithm failed to detect edges because the image was too big as shown in the command window **(D)**. The input image was SRTM DEM GeoTIFF format.

4. APPENDIX

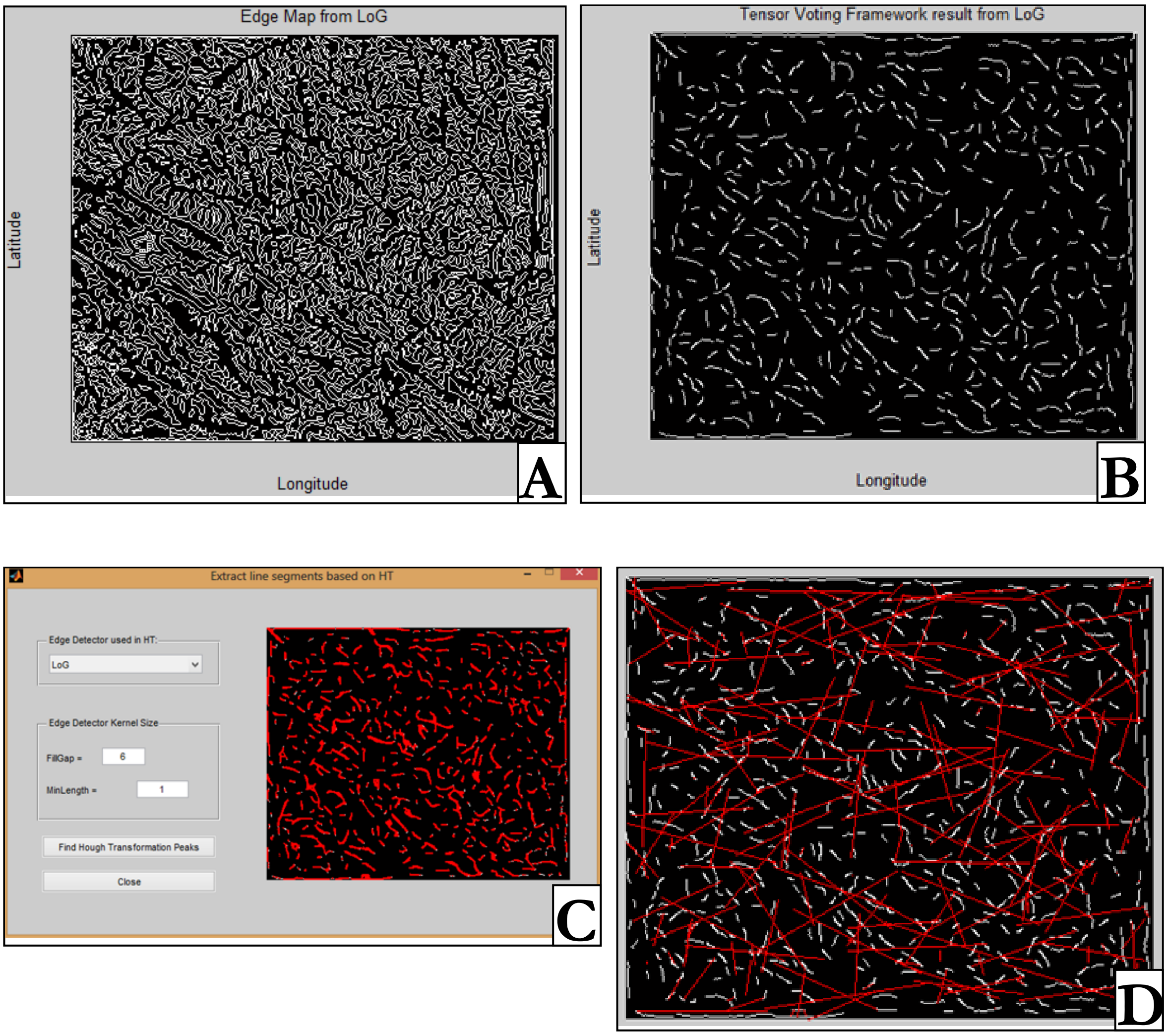

Figure 4-1: Intermediate results of edge detection using the Laplacian of Gaussian (LoG) edge detector and linear extraction from TecLine Algorithm. **(A)** On a small size image of 124 KB part of the Northern study area the algorithm was able to detect edges. **(B)** Intermediate results of tensor voting. **(C)** Lines extracted from the image based on Hough Transform and **(D)** Lineaments extracted from image C. Note that the lineaments in D does not follow the detected lines as in C, this is attributed to the suboptimal parameter adjustment.