GEOLOGICAL INTERPRETATION OF LANDSAT IMAGERY -
SOUTHERN EAST AFRICAN RIFT SYSTEM (MOZAMBIQUE)

by

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ABSTRACT

This work describes the methods and results obtained from the study of an area in north-west Central Mozambique by using Landsat imagery. The area, about 190,000 km² is covered by six 1/500,000 scale images. The dominant structural feature of the area is the southern extension of the East African Rift which cuts across the area, from north to south for about 400 km.

Landsat Computer Compatible Tapes were treated for quantitative restoration and enhancement which enabled the production of over 200 slides for interpretation. Some of the slides are reproduced as photographic prints (plates). In the qualitative analysis stage geological and structural maps were drawn and analysed; further structural analysis involved the digitising of fracture trace (Tectonic Fabric) maps and computer processing using a modified FRACAN programme.

Besides the Landsat imagery, aerial photographs, aeromagnetic and vegetation data were also interpreted and compiled. All this set of information has made it possible to produce Tectonic fabric, Structural and Tone Reflectance maps.

A detailed study of the extreme northern part of the area (Angonia), representing a “case history” of the Study and has shown that Landsat data can be useful in both detailed and regional investigation.

The rift structures of the area have been defined and illustrated, the tectonics, structure and geology of large areas have been discussed. Although tone reflectance has not provided useful information for this type of environment, by careful interpretation and correlation with existing information, tone reflectance data can yield useful regional information in vegetation covered terrains.

A number of magmatic bodies have been mapped from Landsat including large numbers of small ring structures some of which coincide with magnetic or radiometric zones. Also small volcanic (agglomerate) vents which do not usually exceed a few 100 m in diameter have been mapped easily on digitised scenes.

Lineaments have been analysed in some detail and show new indicators of the structural complexity of the region. It has been noted that the ENE, or trends close to the E-W orientation, represent a very important structural trend of regional significance and probably a trend of metallogenic importance. These ENE (E-W) trends, called “topographic lineaments”, persist along the whole length of the study area (14°-19°S); their occurrence over such a range of latitude makes it more likely that the illumination bias is of little importance for their appearance in the region.
ACKNOWLEDGEMENTS

Many thanks to Dr J. MacMahon Moore for his supervision and encouragement, reading of the manuscript and many kindly criticisms. Equally many thanks to the IC Remote Sensing Centre which has made possible the image processing part of the investigation.

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CHAPTER ONE
ACQUISITION OF DATA IN REMOTE SENSING

INTRODUCTION

This thesis is a two part document in which the geological applications of remote sensing techniques are reviewed in relation to a specific case history. It contains a discussion of the application of selected Landsat 1 and 2 imagery to geological mapping in part of northern Mozambique (Figure 1.0).

"Remote Sensing" as expressed by Johnstone and Janza (1977) is generally restricted to the detection and analysis of radiant energy (emitted or reflected) in some part of the electromagnetic spectrum. In this context, sensing of phenomena, such as gamma radiation, gravity, magnetism and other force fields are excluded as is the detection of odors and chemicals. There are other authors, on the other hand, who consider that geophysical methods by their essence would also be considered as remote sensing techniques. For this study, Landsat information is the basic remote sensing data, while geophysical data, equally considered here as remote sensed data, is included for the purpose of correlation.

According to A. Eardley (1942), remote sensing has its beginnings in the middle of the last century with the invention of the photograph which was then applied to topographic mapping. He points out that one of the first applications of aerial photographs was during the Hamilton Rice Expedition to the Amazon in 1924 and 1925, where no ground control was available. Aerial photography perhaps the first practical form of remotely sensed data has considerably assisted geological exploration.

The invention of multilayer colour film and infra-red sensitive emulsions, nonimaging radar, and thermal sensors, and later sounding rockets for high altitude photographs were just the first steps to the modern era of remote sensing. It was during the 1950's that remote sensing began to assume its modern character. Imaging radars and thermal infrared scanners were built. The first orbiting satellites were sent into space for periodic observation of the earth's atmosphere, starting with TIROS-1 in 1960, ESA-1 and the first geostationary orbiting ATS-1 in 1966. However the most important development to geologists was the introduction of systematic imaging of most of the Earth's surface by the three Landsat satellites (1, 2 and 3) launched in 1972, 1975 and 1978 respectively.

Many authors have pointed out that the object of remote sensing in mineral exploration is to acquire information from a distance about the geology and the minerals contained in the area. It seems evident that the three Landsat satellies have proved to be quite successful for geological purpose, let it be structural or mineral investigation.
FIGURE 1.0. Map Showing the Location of the Study Area
A brief summary of some recent satellite missions oriented towards Land resources is shown below.

<table>
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1.1 ENERGY SOURCE FOR REMOTE SENSING

Electromagnetic Radiation in Remote Sensing

Remote sensing information about the geological nature of a given area is acquired usually from a distance, by measuring the electromagnetic energy emitted, scattered, polarised, or reflected by elements of the scene. This energy propagates through space and is detected only on its interaction with matter.
The sun can be described as our greatest "passive" source of radiation; the moon; the earth and its atmosphere are also passive broad spectrum sources of considerably less intensity. Geological remote sensing techniques are referred to, also, as active or passive, active being those in which man supplies the source of the radiation (e.g., radar) and passive those which use a naturally occurring source (e.g., Landsat).

The interaction between electromagnetic energy and matter may be analysed in terms of waves; in their turn, the waves can be described in terms of their velocity, frequency and wavelength. The relationship between these properties is given by:

\[ C = \lambda \nu \]

where \( C \) is the velocity, \( \lambda \) is the wavelength and \( \nu \) is the frequency.

The ordering of this radiation according to wavelength, frequency, or energy defines the electromagnetic spectrum. Electromagnetic spectrum is therefore the continuum of energy ranging from kilometer to nanometer (nm) wavelengths, travelling at \( 3 \times 10^8 \) sec \(^{-1} \) (Figure 1.1 and 1.2). All matter radiates a range of electromagnetic energy with the peak intensity shifting towards progressively shorter wavelength with increasing temperature (Figure 1.3).

Energy source in the visible and infrared parts of the electromagnetic spectrum may be classified generally as either discontinuous or continuous. Discontinuous sources emit either a single or a series of individual spectral lines or bands as a consequence of transitions between the discrete energy levels of the course materials; for example high voltage sparks or laser emissions. However, for general illuminating purposes, discontinuous sources are of limited usefulness especially in remote sensing applications.

The essential elements of a remote sensing system are the generation, interaction with the object (e.g., earth surface), transmission collection and wavelength separation, and the detection and recording of the electromagnetic radiation. The radiation or energy detected, \( E_{\text{total}} \), at any particular wavelength, may be written as:

\[ E_{\text{total}} = E_{\text{source}} \cdot E_{A} + E_{E} \cdot E_{RS} \]

Where \( E_{\text{source}} \) is the energy from the source; \( E_{A} \) is the energy emitted; and \( E_{RS} \) that energy reflected or scattered.

As with the source, different types of detectors are effective in different wavelength ranges. The function of most detectors is to convert the electromagnetic radiation reaching them into the form of an electrical voltage, which can then, usually after suitable amplification, be used to drive some recording device that presents the intensity data as a function of wavelength in a form suitable for interpretation.
FIGURE 1.1. Electromagnetic spectrum showing a picture of the wavelength ranges in various units, the type of radiation, and the atomic and molecular effects that produce spectral features in each range. From Hunt (1980, Fig. 2.2).
FIGURE 1.2
Electromagnetic spectrum showing bands employed in remote sensing
From Sabins (1978, Fig. 1.2)
FIGURE 1.3
Spectral distribution curves of energy radiated from objects at different temperatures. From Sabins (1978, Fig. 1.1)
Remote Sensing Bands

The spectral range between the ultraviolet and microwave, which corresponds to the energy transitions between electronic, vibrational, and rotational levels, can be considered to be the range where electromagnetic energy truly interact with matter, and consequently they are the regions where most information about the nature of a material can be obtained from a study of the electromagnetic energy which has interacted with it. As a result, this is the range that is of prime interest for remote sensing purposes. Remote sensing bands described here are grouped into three regions:

- Visible photographic region.
- Infrared spectral region
- Microwave region

Visible Photographic Region

The human eye is capable of detecting wavelengths between approximately 0.4 to 0.7 μm. Photographic emulsions are sensitive to the wavelength region from 0.3 to 0.9 μm, which is known as the photographic region. This region is determined by the property called albedo. Within this region albedo designates the total radiant reflectance of a surface, and is the ratio of the reflected energy to the incident energy. Dark surfaces have a low albedo and light surface have a high albedo. Another photographic property is reflectivity which is expressed in images either by photographic tone or colour. Photographic tone is a measure of the relative amount of light reflected by an object in a given wavelength region and displayed as shades of gray on a black and white photograph.

A material’s geometry relative to the sun determines the amount of incident radiation. On an image, similar objects might show different brightness differences due to topography; differences in moisture content can affect the tones in which similar rocks are represented; and due to improper processing the relative separability of two materials or objects may also be reduced. This caused great problems in the interpretation of data in the case of this study especially in rock discrimination in areas covered by heavy vegetation or soil.

Photographs can be either black-and-white, multi-spectral or coloured. Colour is probably the single most useful recognition element in interpreting imagery because although the human eye can simultaneously discriminate 20 to 30 grey levels, it has the ability to distinguish a larger number of colours, up to 100 times it’s panchromatic ability.

Colour can be described by attributes, hue, saturation and brightness. Any colour can be generated by the superposition of three primary colours (usually red, green and blue)
in an additive system or by the subtraction of three primaries (cyan, magenta, and yellow) from white in a subtractive system. Colour pictures are produced from digital multi-images by selecting three components for modulation of the primary colours. The brightness values in these three component images are called tristimulus values (Moik, 1980). The hues and intensities in a true colour picture are a function of the film characteristics, photographic processing and the type of illumination used in viewing.

Films used in aerial photography can be orthochromatic, panchromatic and infrared. Orthochromatic film is sensitive to green and blue, panchromatic responds also to red, and infrared responds to the near infrared region in addition to the visible spectrum. Colour positive film yields photographs with colours approaching those seen by the eye, this closely approximates the interpreter's perception of the natural scene and is therefore the easiest to interpret, especially in determination of sedimentary sequences. Colour negative film yield colours complementary to those on colour positive film, and may be used directly to make colour positive prints.

Infrared Spectral Region

Infrared Spectral Region is generally defined as that portion of the electromagnetic spectrum ranging in wavelengths from 0.7 to 300 µm. It is classified as follows:

- Reflected Infrared Spectral region - is a region between 0.7 to 3μm, it is primarily reflected solar radiation and thus contains no information about the thermal properties of the materials. This wave range can be detected with sensitive IR film and is called photographic IR region.

- Thermal Infrared Spectral region - has ranges from 3 to 5μm and 8 to 14 μm which are also known as the principal atmospheric windows. Most IR scanners record the radiant temperature of an object, and typical IR detectors are sensitive to temperature differences on the order of 0.1°C.

Infrared radiation at wavelengths longer than 14 μm is not employed in remote sensing because it is absorbed by the earth's atmosphere.

Microwave Bands

The microwave electromagnetic spectral band spans the 0.3 to 300 cm wave length range. Microwave sensing shows two distinct areas of sensor utilisation, active and passive. The active systems have been employed to generate radar images for a variety of geoscience studies. In contrast passive systems have not yet proved to be practical for most geological studies at these wavelengths.
Radar Systems are active imaging systems that can operate independently of weather and time of the day. In addition the terrain can be illuminated in the optimum direction to enhance features of interest. Conventional radar utilise the frequency range from 230 to 40,000 MHz although neither end of this range is truly definitive of the frequency limitation for radar operation.

Of the various radar systems in use the Side-Looking Airborne Radar (SLAR) has been widely applied, at least for geological purposes. It was originally developed to acquire reconnaissance military images without the necessity of overflying unfriendly regions (Eardley, 1942). SLAR is a system generally used to obtain fine angular resolution and can provide imagery on one or both sides of the aircraft flight path. It differs from other radar scanning systems in that a large antenna (up to 7m) is fixed to the aircraft and its radiation pattern is directed perpendicular to the ground track. The antenna is limited by the difficulty of stabilising a very large structure in flight.

Based on the antenna configurations the system (SLAR) has been separated into two primary methods of operation:

- Real Aperture or bruto force (Figure 1.4a) and
- Synthetic Aperture (Figure 1.4b)

Real-Aperture Radar Systems are simple in design and do not require sophisticated data recording and processing. However, coverage in the range direction is relatively limited and only shorter wavelengths can be employed if a high resolution is required.

Synthetic Aperture Radars use signal storage and processing techniques to simulate the performance of an antenna that is electronically much longer than the actual physical antenna employed, and therefore, can provide a very narrow beam of constant width that results in improved azimuth resolution.

Radar Scatterometer, a nonimaging airborne radar system for quantitatively measuring the radar backscattering of terrain, this data is very useful for example, characterising surface roughness properties of material and in identifying types of sea ice.

Space Radar imagery, Synthetic aperture imaging radar was flown by NASA in Sea-Sat-A which provided a few but excellent radar imagery of some areas with a 25 m. resolution and swath of approximately 100 km.

1.2 REMOTE SENSORS

The different types of sensors utilise electromagnetic radiation collected from the land, water and atmosphere, from the X-ray to microwave region. Imaging sensors can be classified according to: detection process (e.g., photographic or television), wavelength region, or to operational mode, (that is either active or passive).
Figure 14 Sketch diagrams side-looking radar systems. (A) Real-aperture system (B) Synthetic aperture system.
The active sensors are largely mode-made, and can be thermal or radio-electromagnetic radiation generators like lasers and radars. Active radiations generated by laser and radar sources have extremely high power densities that can be generated over very narrow spectral bands. Passive radiation usually generates power densities that are considerably lower and have much broader spectral bands.

The most utilised sensors are probably photography and television systems.

Photographic System

Photography (including cameras, lenses, filters and films) is widely used. It has extremely high spatial and spectral resolution. Unfortunately photography does not offer quantitative analysis because the film, which is the collector of information has several short-comings. Three types of cameras have been developed, these are: frame, slit and panoramic cameras.

In space sensing, photography is limited because of difficulty of either digitising the film-recorded data or returning the processed hard-copy to earth.

Television Systems

Television systems are widely used in space imagery and observation because of small size and weight, lack of moving parts, and the ease with which images can be transmitted to earth. The TV system operates within the visible spectrum, and also has very good low-light level capability and resolution which ranges from 10nm with the wisp ocean sensor to 100nm for Landsat. The image quality, spatial and spectral, depends on the type used in the system. Three types of tubes are common in spacework; image dissectors, vidicons and return beam vidicon (RBV). The tubes differ significantly from each other.

Other imaging tubes, like the image orthicons and plumbicons, are available but not generally used for spacecraft.

In most of the TV systems used in space, the signals from the tubes are digitised and telemetered to earth along with synchronisation information. These data are then used to produce imagery or are stored on magnetic tape for later processing.

Television has proved highly valuable, especially in weather satellites, for producing real and near-real time imaging of the earth’s surface.

Other Sensors

Infrared Scanners are a group of instruments that produce strip maps of emissions from the earth from the IR portion of the electromagnetic spectrum. The system observes IR radiation during the day in the short wave length region of 0.7 \( \mu \text{m} \) to 4 \( \mu \text{m} \); it is principally...
measuring scattered radiation from the sun; when it operates in the long-wavelength region (longer than 4 \( \mu \text{m} \)), it measures emitted radiation.

**Infrared radiometers** nonscanning instruments are used in remote sensing to measure the radiant flux of IR radiation from an object or area. By comparing the energy thus collected with the energy from a blackbody source at a known temperature, the absolute temperature of the body can be obtained quite accurately. These instruments are, therefore, very useful for measuring temperature of extended bodies.

Radiometers generally work in the 8 to 14 \( \mu \text{m} \) atmospheric window. However, they can also operate in the short-wavelength optical region to measure scattered radiation.

As the system is IR, it has day and night capabilities, however, it cannot penetrate dense cloud cover and is therefore limited in use to cloud-free weather.

**Infrared Imagers** form a frame-type image of the IR radiation emitted or scattered from the area under observation. They differ from IR scanners in that they scan in two directions (i.e. line and field scan), thus forming an image without the requirement of platform motion. IR imagers are ideal for real-time qualitative detection of thermal anomalies.

**Spectrometers** measure and record the amount of radiation emitted from an object as a function of wavelength. The reflection spectrum is a function of the material and of the illuminating source. Thus, if the spectrum of the object can be observed and measured, it can be compared with spectra of known materials and identification can be made. This is the basic principle used in the application of spectroscopy to remote sensing.

**Multispectral Scanners (MSS)** are designed to measure the radiant flux from a large number of spectral bands scattered from the surface of the earth. They usually operate from 0.4 \( \mu \text{m} \) to 2 \( \mu \text{m} \). The spectral resolution is not high, usually between 10 and 50 nm approximately as those of TV multispectral systems. Spatial resolution is comparable to that of IR scanners and resolutions of about 3 mrad are typical. The operational mode of one such system is explained under Landsat 1 and 2.

**Microwave Radiometers** are passive systems which collect and measure the flux of microwave radiation incident upon the antenna. The amount of radiation obtained is limited by the system bandwidth and the size of the area at which the antenna looks, or the beam width. The equivalent temperature record is not equal to the temperature of the area observed.

As with radar, the spatial resolution of the microwave radiometer depends on the wavelength of the radiation and the size of the antenna. However, the system is very useful for, it gives much information concerning soil moisture, ice, water interfaces, vegetation and other parameters, relevant to earth resources measurements.
Advanced Sensors

Advanced types of sensors have been developed over the years. Among them are the Laser Scanner for use in the active Airborne Scanning System, and the Thematic Mapper (TM), with improved resolution of 40m, carried on Landsat-4. Of the nonimaging sensors in this group, the Laser profiler, Fraunhofer-line discriminator, is capable of detecting weak solar-induced fluorescence, and the Scatterometer is capable of measuring the microwave reflectance of an object or terrain elements as a function of angle.

Although passive systems have many difficulties in interpretation that can be eliminated in active systems, passive systems have an advantage due to their size and power requirements since they do not use transmitting equipment. Passive systems also produce a good deal of information not available from active systems, since some of them measure self-emissions from the targets rather than scattered radiation.

SPOT SATELLITE

SPOT (System Prebetoire d'Obervation de Terre) is a satellite developed by the French Centre National d'etudes Spatiales, was previously planned for launch in 1984. It is an advanced satellite and great expectations are put on the Spot satellite because of its technological innovation. For the sensing of the earth the satellite will be using two identical instruments: viz two HRV's (High Resolution Visible). These instruments are shown in Figure 1.5a.

Both instruments carry out imaging in the visible and near infrared spectra with a field of view 60 km wide and a sampling interval in the ground 20m or 10m according to whether the instrument is operating the multispectral mode (3 spectral bands) or panchromatic mode. A mirror placed in the opening of each instrument and capable of being oriented perpendicular to the satellite track, allows the direction of line of sight of each instrument to be changed within an angle of ±26° by steps of 0.6°. This makes it possible to obtain stereoscopic pairs of the same area of the earth and to have access to zones situated quite far from the satellite track (400km in either direction), as shown on Figure 1.5b.

The spectral bands in which spot will operate will range from 0.50 to 0.90 μm, divided into 0.50 - 0.59, 0.61 - 0.69, and 0.79 - 0.90 μm respectively. Radiometric resolution (multispectral), of 0.5% for a solar zenith angle ≤ 60° is designed.

With the satellite placed in a sun synchronous orbit at 822km altitude the first mission so defined will allow, according to its utilisation mode:
FIGURE 1.5
SPOT's High Resolution Visible instrument arrangement (a), and Principles of Stereoscopy imaging (b).
- a systematic coverage of the globe in 26 days.
- an accessibility to any point on the earth's surface with an average time of 2.5 days.
- the obtaining on an experimental basis of stereoscopic pairs of the same zone at very close time interval (for a period of a year, at the latitudes of Europe, there are 84 opportunities to obtain a stereo pair of a given zone within a one-day interval).

**Stereosat**

Stereosat is envisioned as a free flying satellite in sun-synchronous orbit utilising a three-camera electronic pushbroom scanning system. Two cameras are positioned 26° off nadir fore and aft and the third camera is pointed at the nadir. This configuration yields two different base/height ratios of 1.0 and 0.49. Horizontal and vertical resolution at 1.0 base/height is approximately 15m. The data will be compatible with Landsat to such an extent that multispectral stereopairs can be made using data from both systems.

**Spaceborne Imaging Radar**

Spaceborne Imaging Radar was flown experimentally on the SEASAT-1 satellite, is likely to be flown again by the mid-eighties. The Japanese and Soviets have also announced an intention to launch their own unmanned earth resources satellites. By 1990, it seems certain that there will be sensors in orbit that view the earth with a resolution of 10m or better, in many spectral bands including the cloud-piercing radar wavelengths (Sheffield 1981).

### 1.3 OPERATION MODE OF LANDSAT 1–4

The Landsat satellites are launched into near polar orbits at an altitudes of approximately 900 km. They are stabilised for velocity vector and altitude-pitch, yaw, and roll by a system of flywheels and rate gyros.

The orbit of Landsat satellites is sun-synchronous between 82°N and 82°S. This orbital configuration insures repeatable sun illumination conditions, and also guarantees midmorning imagery at intermediate sun angles, normally between 9.30 and 10.00 A.M. Repeatable illumination conditions are necessary for mosaicking of adjacent tracks of imagery and for comparison of yearly changes in landscape cover. The polar areas above 81° are the only regions not covered by Landsat orbits. The sidelap in Landsat coverage is from over 60% in Alaska to only 14% at the equator (Figures 1.6, 1.7 and Table 1.1).

**Landsat Payload**

In both Landsat 1 and 2, payload consists of two sensor systems, the MSS and RBV, a payload system known as Data Collection System (DCS), relay antenna, and two Wide Band Video
FIGURE 1.6
Typical daytime Landsat orbit paths for a single day. Each day the paths shift westward 160 km at the equator so that every 18 days the paths are repeated. Images are acquired between 5:30 and 10:00 AM local sun time, except at high latitudes. Note location and ranges of receiving stations in the United States.
From Sabins (1978, Fig. 4.6)

FIGURE 1.7
Landsat orbits over the United States on successive days. Note the 62-km sidetap of successive image swaths at 40°N latitude.
From Sabins (1978 Fig. 4.7)
Table 1.1. Relationships between latitude. From M-Kaye and Peters (1982, Fig. 30)

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</table>
Tape Recorders (WBVTR's). Because of problems with the tape recorders on Landsats's 1 and 2, little RBV data is available or has been used for mineral exploration. The DCS is primarily a real-time data relay system which can relay 8 separate ground measurements. This system has been used to monitor volcanoes, hydrologic phenomena, and production platforms at sea.

**Multispectral Scanner System (MSS)**

The MSS system records radiation reflected from the earth's surface features in four spectral channels or bands using a total of 24 detectors (Figure 1.8).

An oscillating mirror sweeps the six-element detector array in a direction normal to the orbital plane, the multispectral scanner scans six lines of data at a time. Each scan line is about 185.2 km long on the ground. The earth is scanned from west to east in approximately 33 milliseconds (the mirror oscillates at 13.64 Hertz). Because spacecraft move south as six lines of data are scanned at one time the scan lines are not perpendicular to the line of flight.

During the west to east scan the voltage produced by each detector is sampled every 9.95 microseconds. For one detector, approximately 3,300 samples are taken along a 185.2 km swath. By division the instantaneous field of view of 79m by 79m must move a distance close to 56m on the ground between each scan sample. This means that the analog signal generated by each detector is sampled at 56m intervals which results in rectangular picture elements (called pixels) which are 56m by 79m covering approximately 0.45 hectares (1.1 acres) on the ground. For handling conveniences the strips of pixels are aggregated into "scenes" (Figures 1.9a, 1.9b).

Recording of the data onboard satellites Landsat 1 and 2 is done by wide band video recorders each having a 30 minute recording capacity at 15 megabits of digital data per second by four recording heads.

**Return Beam Vidicon (RBV)**

The RBV system utilised on Landsat 1 and 2 is a three boresighted television camera system which records brightness in the three wavelength bands simultaneously (camera 1, blue-green; camera 2, green-yellow; and camera 3, red-IR wavelengths). The three camera imaged a 185 by 185 km square every 25 seconds when the sensor was operable. The image is formed on a photosensitive camera tube instead of film, that is scanned by a fine stage multiplier. RBV failed early in orbit in Landsat 1 and was only as a backup unit to MSS in Landsat 2.

**Characteristics of Landsat-3**

Landsat 3 carried the same MSS as Landsat 1 and 2, except that an additional channel (band 8) utilised to record temperature variations of the earth's surface. The thermal
FIGURE 1.8 MSS Scanning arrangement. 
From Lowe (1980, Fig. 3.36).
Reference system of scan lines and pixels for Landsat MSS image. Note location of digital image files on computer compatible tapes.
From Sabins (1978, Fig. 7.4)

FIGURE 1.9 (a)

Plot of terrain reflectance along a Landsat scan line. The 79-m ground resolution cell of each MSS detector produces a reflectance curve that is sampled at intervals of 57 m to generate the digital number for each pixel.
From Sabins (1978, Fig. 7.3)
channel detects thermal radiation which is emitted from the Earth's surface at 10.2 to 12.5 μm. Most of this come from the sun, and is absorbed and re-emitted by the Earth's surface. However, local “geothermal” anomalies, which are related to transfer of heat from Earth's interior to the surface, maybe detectable on band 8 if they are of a large enough size and high enough temperature.

The two thermal infrared detectors used for band 8 cover the same area on the ground as the six detectors used for each wavelength band in band 4, 5, 6 and 7, with an instantaneous field of view of the ground of 238m by 238m.

The RBV system on Landsat-3 has a resolution improved from 80 m to 35 m and uses one broad wavelength band from 0.505 μm to 0.750 μm, in a black and white mode. The resulting image covers 99 x 99 km. However, MSS scanners have been more successful than the RBV; the MSS scanner also gives better geometric accuracy and radiometric quality than the RBV (Lowe, 1980).

Landsat 2 and 3 were placed in standby mode on 31/3/83, effectively putting an end to their data acquisition activities. Both vehicles were scheduled for permanent retirement on September 30, 1983.

Landsat 4

Landsat 4 (or D), which was launched on July 16, 1982, is said to be the only satellite of the Landsat series that is collecting data. It carries on board a seven channel multispectral scanner called the Thematic Mapper (TM). Most of the spectral bands on the TM were selected for agricultural application. However, Channel 6 (solar infrared) is said to have been proposed by geologists for research in rock spectral reflectance. The Channels are divided from 1 to 7 (see Table 1.2), and the TM parameters are illustrated on Table 1.3.

The TM has a ground field of view (IFOV) of 30m for Channel 1 to 6, and IFOV of 120m for Channel 7, when flown at a recommended lower altitude of 705 km. The TM measures landscape brightness in 256 levels instead of the 64 levels used by the MSS or Landsat 1, 2 and 3. The data output of TM is of 150 Mbps compared with the 15Mbps for Landsat MSS. Landsat-4 Mission operation is shown in Figure 1.10.

As of May 31, 1983, 12,400 Landsat-4 MSS scenes and 200 TM scenes have been placed in the Landsat data archive. However Landsat-4 is experiencing problem as 2 of its 4 power cables failed.

NASA has issued comparative statistics which show that the previous satellites have produced a huge amount of data in their lifetime. Landsat 2 acquired a total of 615,720 MSS scenes and 2,916 RBV scenes, whereas Landsat 3's acquisition during its period of service totalled 324,655 MSS scenes and 266,990 RBV scenes.
LANDSAT-D SATELLITE ALTITUDE = 705 km

Figure 1.10 LANDSAT-D Mission
From NASA Application Notice (1981, Fig. 2).
Table 1.2 Comparison of Landsat-D TM and MSS Sensor Characteristics. From NASA, Applications Note (1981).

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<th>Micrometers</th>
<th>Radiometric Sensitivity (NEAP)</th>
<th>Spectral band</th>
<th>Micrometers</th>
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Table 1.3 Significant TM Parameters. From NASA, Applications Note (1981).
Characteristics of Remotely Sensed Data

The changes, sometimes called "signatures", in the electromagnetic radiation from source to sensor can be subtle or pronounced depending upon the interaction that take place with the media or materials involved. These changes provide data for the analyst or photointerpreter about the properties of these media or materials.

All images can be described in terms of certain fundamental properties regardless of the wavelength at which the image is recorded. These properties can be summarised as:

- scale, which can be small, intermediate and large (<1:50,000, 1:50,000, and > 1:50,000 respectively);
- brightness, the magnitude of the response produced in the eye by light, can be calibrated with a grey scale: there are 255 shades from black to white in the grey scale. Computers can store 256 (0 to 255) grey levels in bytes of 8 bits.
- contrast, which is the ratio between brightest and darkest parts of the image can be improved by using photographic and digital methods.
- spatial resolution, is a very important property of the image because it is inherent in the imaging system and is a property of an image we most use to judge its quality. Spatial resolution is defined as the ability to separate objects or geometric terrain features.

For example: in the visible band (0.4 to 0.7 μm) with the angular resolution at a wavelength of 0.5 μm and a lens about the size of the human eye (0.5 cm = 10,000 wavelengths), the angular resolution is 0.1 mrad. Thus this lens at 100m can distinguish a point source only 1cm apart. Such resolution is phenomenal (Johnston and Janza, 1977). In comparison, at a radar wavelength of 10cm and for the same angular resolution, an antenna 1000m in diameter would be required. The conclusion is that the shorter the wavelength, the greater the spatial resolution possible for a given size of lens aperture, or antenna.

1.4 PROCESSING OF LANDSAT INFORMATION

MSS images are formed by an optical system that projects the radiation onto a photosensor in the image plane. The photosensor converts the radiation into a latent image on photographic film or into an electrical signal that is amplified for analog transmission and amplified, sampled and quantised for digital transmission.

Landsat MSS data are transmitted to the earth in a serial stream at 15 megabytes per second using a 5-band frequency of 2265.5 MHz. The data are acquired continuously along the orbit path and are transmitted to a ground receiving station for recording on
magnetic tape. The tapes are processed to produce images that cover a 185 by 185 km area on the ground (see Figure 1.11).

The original data archiving was in analog form. The process of converting what is basically a digital 'bit stream' from the satellite directly into analog form, with the dynamic range limitations inherent in photographic emulsions, provides a built in degradation of the data. This analog format has been useful for a one-time look at the entire world, but there exist now digital interactive tools with which it is possible to look at basic CCTs which retain all 64 signal levels in each of the four channels (in the case of Landsat 1, 2 and 3) without any loss of information.

As it has been observed from above, a digital image is in fact a numerical representation of sampled field. The digital image is generated by sampling and measuring the local field strength at a number of points that are usually arranged in a rectilinear pattern. The field strength measured at each of those points is encoded as an integer. Thus the digital image is actually an array of numbers, which can be stored on magnetic tapes or disk. In this form the digital image cannot be inspected visually, but can be manipulated readily by a digital computer.

Usually there are eight bits ($2^8$) or 256 grey levels or DN (Density number) in the dynamic range of a picture, ranging in value from 0 (black) to 255 (white). As each band's image consists of an array of numbers corresponding to the reflectance in that band of raster of spots on the ground, the array contains 2340 lines with each line divided into 3240 elements. Each element is termed a pixel and each assigned a number from 0 to 127 (from 0 to 63 in band 7). There are 7.6 million pixels in each of the four channels per image. To understand the enormous amount of data involved, a single black-and-white 35 mm photographic slide can contain more than $2 \times 10^8$ bits of information and require a 12 in reel of magnetic tape for digital storage. For Landsat D Thematic Mapper (TM) multi-image the total number of bits is $2 \times 10^9$.

Digitisation

After images have been formed and recorded, they must be digitised for processing by a digital computer. Image formation and recording can be described in terms of two-dimensional continuous function $f(x,y)$ and $g(x,y)$ respectively (J. Moik 1980). Digitisation consists of sampling the grey level in an image at an $M$ by $N$ matrix of points, and of quantifying the continuous gray levels at the sampled points into $K$ usually uniform intervals. The finer the sampling ($M, N$ large) and the quantisation ($K$ large), the better the approximation to the original image.
Figure 1.11 - Data processing path for MSS data. From M-Kaye and Peters (1982, Fig. 43).
The aim of sampling and quantisation is to represent a continuous image by an array of numbers called samples, such that a continuous image can be reconstructed from the samples. A digital multi-image with \( P \) components is represented by \( PMN \) samples. The raster-scan operation of image digitisers and scanners imposes a sequential row structure on the sampled image data. Therefore, the fundamental unit of the data structure is one row of the image matrix. For multi-images the rows of different components maybe stored as records in separate files, resulting in a band-sequential (BSQ) storage formation. Alternatively, corresponding rows from the \( P \) components may be concatenated and stored in one file. This storage format is referred to as band-interleaved by line (BIL). Finally, the values from all components for a given raster point may be combined to a \( P \)-dimensional vector, and the vectors for one row are concatenated, resulting in one record of the digital image file. This storage format is known as band-interleaved by pixel (BIP). This is the tape format used in the study.

**Sampling**

Images are usually sampled at fixed increments \( x=j\Delta x, y=k\Delta y \) (\( j=1,...,m, k=1,...,n \)), where \( x \) and \( y \) are the sampling intervals in the \( x \) and \( y \) directions, respectively. The matrix of samples \( j(j\Delta x, k\Delta y) \) is the samples or digital image. In a perfect sampling system the uniform sampling grid is represented by an array of Dirac delta functions. However, in practical systems, the sampling function is not a Dirac delta function, but an array of impulses of finite width (Moik, 1980).

**Quantisation**

The amplitudes in the sampled image \( g_j(j\Delta x, k\Delta y) \) must be divided into discrete values for digital processing. This conversion between analog samples and discrete numbers is called quantisation (Moik, 1980). In other words, quantisation is a process by which a gray value or a range of grey values in an image assigned a new value from a given finite set of gray level.

The number of quantisation levels must be sufficiently large to represent fine detail, to avoid false contours in reconstruction, and to match the sensitivity of the human eye. Selective contrast enhancement in digital processing justifies quantisation even well beyond the eye's sensitivity (Moik, 1980).

To obtain a faithful representation of digital images, at least 6 bits are required and 8 bits are used in general. MSS 4, 5, and 6 digital images from Landsat 1 and 2 are logarithmically quantised to 6-bit words onboard the satellite to meet transmission constraints and 7-bit words on the ground.
Digital Imagery from other sources of data

Digital images can be acquired from other sources of data even though not recorded directly in a digital form. If the original data is recorded on photographic film, the conversion into digital format is obtained by scanning the transparency with a light beam of constant intensity. Different amounts of light are absorbed by the transparency during scanning, and the light that is transmitted is measured by a photomultiplier tube. The signal is stored as a string of integers on magnetic tape. By using logarithmic or linear amplifiers, it is possible to record either \(D\), the photographic density, or \(t\), the transmittance.

Digital images can also be acquired from nonimaging sources. Data, for example obtained through sampling of a scene (geochemistry) may be represented as a digital image. The original data thus need not have described reflected light. For example, the U.S. Geological Survey and the Defence Mapping Agency have sampled the topography from 1:250,000 contour maps to create digital images. In addition the USGS has prepared a limited number of 1:24,500 (7 1/2 minute quadrangles) digital elevation maps directly from stereo air photographs, skipping the intermediate contour maps. Such attitude images are available on magnetic tape for most of the continental US from the National Cartographic Information Center at the USGS in Reston, Virginia. The importance of these attitude images to the image analyst is that they allow computer manipulation of other image data registered to the attitude images to compensate for shading, solar heating or other function of topography.
CHAPTER TWO
COMPUTER IMAGE PROCESSING AND ENHANCEMENT APPLIED TO THE
STUDY AREA

2.1 TYPE OF COMPUTER DATA AND DISPLAY FACILITIES

The image enhancement stage started with the acquiring of digital computer compatible tapes (CCTs) for the region. Six CCTs were used, one was original EROS data tape whereas the rest were copies, all of them obtained from Hunting.

Before any information contained in a CCT can be transformed into useful information or into photographic illustration, quantitative restoration, that is: ratification, removal of random noises and geomatric correction are necessary. The Imperial College IS System 500 was very helpful in solving some of these problems, but its greatest contribution for this study has been in the field of image enhancement.

Enhancement procedures applied in the study are restricted to a few of the many options offered by the System. Restriction in time and the complexity of some of the operations, be it theoretical or in practice, led to a decision to work only with those operations most often applied and easily understood to the author.

The theoretical problems connected with image processing are in many cases complex. However because of their importance in the correct application of the software and the correct choice of operations, one is obliged to have a minimum knowledge, otherwise it will be like working blindly; as Moik (1980), has pointed out, a prior knowledge about the characteristics of the object to be observed and of the imaging system is necessary, otherwise there would be no basis for judging whether a picture is a good representation of an object. For this reason, the first part of the chapter is devoted to the theoretical aspects of image enhancement while the practical aspects are discussed in the second part.

CCT Formats Employed

The original EROS magnetic tape used in this work was in the old <<LANDSAT>> Format, whereas the other five were in a different format <<ENTER>> (see Table 2.1), external to the System 500. With these programs the default values create a 512 by 512 pixel image that has been subsampled in such a way as to yield an overview of the entire image. Stripping problems were acute in some of the copied tapes and some areas of interest were missing from them. It will be noted from Figure 2.1 that there is no overlap between Landsat 180/71 and 180/72. A strip of terrain between Mandie and Changara, about 20 km wide, has no data and therefore no interpretation or enhancement was done.
Original EROS tape had bands 4, 5, 6 and 7, the other five contained only bands 4, 5 and 6. That is why most of the processing has been confined to these bands and as a consequence, it was not possible to utilise enhancement techniques which require four bands like FFT1D, HADAMARD, SLANT TRANSFORM, etc.

The \texttt{\textasciitilde\textasciitilde} format was organization such a way that each scene has been put to tape in two halves so that the System 500 could read them in. File one on each tape is the first 1700 samples and File two is the last 1700 samples. The data organization was in SAMPLES, BANDS, LINES and was South Africa data read into HUNTING HIPAS system and written to suit the I²S System 500.

As pointed out above, some type of prior knowledge must be applied to an unenhanced image in order to extract information from it. Processing an enhanced image may be different depending on whether the source of the image is known or not. Knowledge about the physical process of forming an image is also very important. This includes object characteristics and properties of sensor, recording, transmission, digitisation, and display system. The understanding of all this information can help to reduce the number of variables involved in image processing thus save time and expensive computer hours.

The process of “manipulating” multispectral data in order to enhance the various patterns contained in them is known as Digital Image Processing. It is performed in order either to prepare an image for display and interpretation or extraction of information from the image. This is a critical stage in remote sensing, especially for geologists, because in the long run our interpretation is not based on numbers but on patterns like drainage, linear features, tone, etc. observed on the image.

Computer compatible tapes are the format which provides the most faithful rendering of each scene as sensed electronically and recorded digitally. The CCTs contain the image data in digital form, without the significant loss of radiometric detail associated with the photographic processing of these data. As pointed out by Lillesand/Kiefer (1979), in many applications, computer processing of digital Landsat data permits the fullest use of the image data.

The advantage of computer compatible tapes can be summarised in the following way:

- **Dynamic range**: up to 128 grey levels can be present on CCTs, whereas only 15 to 30 are discernible on film products (particularly important for soils).
- **Precision**: the quantitative nature of the medium permits a user to determine a gray-level value exactly.
- **Repeatability**: a copy of a CCT contains exactly the same data as the original, whereas a fourth generation photo product is substantially degraded with respect to the original.
7.00 LANDSAT(?) ULONGUE:

INT AREA (006) = 1 1 3072 2048 6 4 ?1
INT BANDS (004) = 1 2 3 4 ?
INT FORMAT = 2 ?
INT AREA (006) = 1 ? 1
INT BANDS (004) = 1 2 3 4 ?2
INT FORMAT = 3 ?
INT AREA (006) = 1 1 ?
INT BANDS (004) = 2 ?2
INT FORMAT = ??

Image ULONGUE
Number of lines = 512
Number of samples = 512
Number of bands = 1

Mount LANDSAT PEEL 4 1
INT FOR WHEN READY:

* OR: FRAME ID: 10047-07152
INT IDENTIFICATION: 73487202
NR3 DATA MODE/CORRECTION CODE: 3
* POSTURE DATE: 083EF"2
* FACT COORDINATE
LATITUDE: S14-26
LONGITUDE: E034-23
* FACT COORDINATE
LATITUDE: S14-24
LONGITUDE: E034-24
* FILE LAYER: 4K
* LATLON MUTH: 053
* ATTITUDE PATH: 100
* ATTITUDE LAT: 100
* PATH WIDTH: 810
* START OF FILE # 1
* START OF FILE # 2
* START OF FILE # 3
* START OF FILE # 4

File start time 0:17:02.5

318.00 ENTER(?) FOUR:

INT FILES = 1 ?
INT TOTSAMPS = 512 ? 3072
INT TOTTINES = 512 ? 2048
INT STARTSAMP = 1 ?
INT STARTLINE = 1 ? 1024
INT NSAMPS = 512 ? 1024
INT NLINES = 512 ? 1024
INT DELSAMP = 1 ?
INT DELLINE = 1 ?
INT NBANDS = 1 ?
INT DATATYPES = 1 ?

Table 2.1 Frequently applied CCTs Format for the J2S System 500.
- **Resolution**: many investigators report that smaller ground details are observable from CCT data than from film products. In this study, some large topographic features not observed on hard copy products were detected and mapped.

Display Facilities for Image Analysis

A large number of regular and special types of equipment is available for remote sensing data analysis. These can be categorised as:

- optical
- optical - mechanical/electronic
- computer facilities

The simplest of these are the optical display facilities whereas the computer aided facilities are probably the most complex.

**Computer-aided display facilities** - here one can include the small interactive minicomputers or large “mainframe” or “batch” computers for processing/analysing Landsat digital tapes. Interactive image processing systems allow the user to view the effects of the image processing in real time on video display units and to interactively optimise the analysis sequence until the desired end product is obtained.

In the most complex and costly process the digital data analysis requires not only participation of the discipline specialist, but also the computer programmer and/or image analysis specialist. Multispectral digital image processing facilities can be from extremely expensive to lower cost systems, all depending on the computer type and capacity and associated peripheral input and output devices. These systems typically include hard copy and/or video terminals for controlling programs, image display units for direct user viewing of the imagery, analog controls to directly interact with the displayed image, and tape/film recording units to produce the final products.

2.2 DIGITAL IMAGE PROCESSING TECHNIQUES

Digital image techniques can be divided into two basically different groups (Moik, 1980): quantitative restoration; and the extraction of information from the images (here called Image interpretation).

(1) **Quantitative restoration**

In this group includes, quantitative restoration of images to correct for degradations and noises registration, for overlaying and mosaicking and subjective enhancement of images features for human interpretation. The required operators are mapping from images into images.
Quantitative restoration operation can be classified into the following groups:

- Image restoration
- Image enhancement
- Multi image enhancement

(2) Image Interpretation

The second group is concerned with the extraction of information from the images. This area of image analysis includes objective detection segmentation of images into characteristically different regions, determination of structural relationships among the regions. Operators of this group are mapping from image into description of images. These operators convert images into maps, numerical and graphical representations, or linguistic structures.

The extraction of information from the imagery is usually done after most of the quantitative restoration of the imagery has been accomplished and is very much dependent on the restoration techniques employed and the quality of the digital operations. During the course of the study both these stages were devoted sufficient time. The first group of operations were accomplished with the IC i²S System 500 image processing facility while the operations of the second group involved interpretation of twelve hard copy black and white and colour composite imagery (1:500,000), as well as 290 slides of varying scales and processing history. Digitising and statistical analysis of the interpreted fracture maps are also included in the second group.

It was not possible in the course of this short investigation to indulge deeply into the many techniques being applied today, however much information can be obtained from authors like Moik (1980), Sabins (1978), Gillespie (1980), Lillesand/Kiefer (1979), Martin-Kaye/Peters (1982), Pratt (1978), and many others.

2.3 IMAGE RESTORATION

Image restoration operations act to "restore" distorted image data to a more faithful representation of the original scene. This involved correction of a variety of radiometric and geometric distortions that may be present in the original image data.

Radiometric Correction - radiometric distortion arise from blurring effects of the imaging system, nonlinear amplitude response, vignetteing and shading, transmission noise, atmospheric interference (scattering, attenuation and haze), variable surface illumination (differences in terrain slope and orientation) and changes of terrain radiance with viewing angle.

Geometric Correction - varying amounts of geometric distortion are caused by sensor-related phenomena such as aberration in the optical system, nonlinearities and noise in the scan deflection system, sensor-platform related distortion caused by changes in the attitude
and altitude of the sensor; and object-related distortion caused by Earth rotation, Earth curvature and terrain relief. Amounts of distortion vary in relation to multiple factors, (see Figure 2.2).

The process by which the geometric transformation are applied to the original data is called resampling. It entails the following operation (Lillesand and Kiefer, 1979):

- a geometrically uniform “output” matrix is defined in terms of ground coordinates;
- the computer proceeds through each cell in the output matrix. The coordinates of each output cell are transformed to determine the corresponding coordinates in the image data set;
- the appropriate pixel value is transferred from image data set to the output matrix.

After each cell in the output matrix has been processed in this manner, the result is a geometrically correct ground-coordinate based matrix containing digital image data.

Another geometric correction procedure is known as squaring. Squaring geometrically corrects the data to equalise the scale factor in the along-track direction with the scale factor in the across-track direction. Some of these questions have been dealt with in Chapter 1.

2.4 IMAGE ENHANCEMENT

The goal of image enhancement is to aid the human analyst in the extraction and interpretation of pictorial information. Enhancement is achieved by the articulation of features or patterns of interest within an image and by a display that is adapted to the properties of the human visual system.

The information of significance to a human observer is definable in terms of the observable parameters contrast, texture, shape and colour.

Image enhancements involve adjustments to the brightness values of individual pixels. The range and the frequency of occurrence of brightness values are commonly displayed as histograms. But because one Landsat scene contains 7,581,600 pixels (each pixel having 4 values) histogram displays are usually normalised so that the maximum count of pixel of one brightness value is displayed as 10 per cent of the ordinate axis. The abscissa usually has values of 0-127 for bands 4-6 and 0-63 for band 7. Most computer processing is done in an 8 bit mode so histogram abscissas in this case have values of from 0 to 255. Therefore enhancement techniques are intended to improve the interpretability of an image by increasing the apparent contrast between the features in the scene.

Most enhancement techniques may be characterised as either point or local operations. Point operations modify the brightness values of each pixel in an image data set
A. NON-SYSTEMATIC DISTORTIONS.

B. SYSTEMATIC DISTORTIONS.

FIGURE 2.2
Geometric distortions of Landsat images. From Sabins (1978, Fig. 7.11)
independently. Local operations modify the value of each pixel in the context of the brightness value surrounding it.

A choice of bands or band combination was made for this particular study, usually bands 4, 5 and 6 (for reasons explained earlier). Band 7 was available for scene 180/70. Several enhancement techniques were applied in the study. But only the following enhancement results will be illustrated in detail in the second part of this chapter:

- Contrast enhancement (TLM)
- Colour enhancement (colour composite, matrix, FFT1D)
- Edge Enhancement (convolution)
- Multispectral image enhancement (ratios, classification, principal component analysis, cluster).

It should be mentioned also that contrast enhancement, edge enhancement, and pseudocolour enhancements are performed on monochrome images or on individual components of multi-band images.

**Contrast Enhancement**

Contrast is a local difference in luminance and may be defined as the ratio of the average gray value of an object to the average grey level of its background. The sensitivity of the human visual system depends logarithmically on light intensities that enter the eye. Thus the greater the brightness, the greater must the contrast between objects be to detect any differences. This relationship is known as the Weber-Fechner Law. The apparent brightness of objects depends strongly on the local background intensity. This phenomenon is called simultaneous contrast.

The ability of the visual system to detect sharp edges that define contours of objects is known as acuity. The eye possesses a lower sensitivity for slowly and rapidly varying patterns, but the resolution of midrange spatial frequencies is excellent. Thus visual system behaves like a band-pass filter in its ability to detect fine spatial detail.

Technically the MSS data was designed to accommodate a wide range of scene illumination conditions, from poorly lit Arctic regions to high reflectance desert regions. Because of this, the pixel values in the majority of Landsat scenes occupy a relatively small portion of the possible range of image values. If the pixel values are displayed in their original form, only a small range of gray values will be used, resulting in a low contrast display on which similar features might be indistinguishable.
Contrast stretch enhancement techniques can be basically linear or non-linear. In the non-linear contrast enhancement techniques an algorithm distributes the data values in such a manner that increments of scene brightness are equally distributed over the range 0-255. The principle of contrast stretching is illustrated on Figure 2.3.

The frequency of occurrence of a gray level in an image is called the histogram of an image. The slope of an image histogram provides information about the contrast characteristics of an image. For example a narrow histogram indicates a low contrast image, and a multimodal histogram (Figure 2.3a) indicates the existence of regions with different brightness.

Nonlinear gray scale transformations may be used to correct for display nonlinearities, (e.g. Figure 2.4b). On Figure 2.4a, the linear contrast transformation is illustrated. For images with bimodal histograms, each of the histograms zones may be enhanced to full brightness range by the transformation shown on Figure 2.4c.

However, one drawback of the linear stretch is that it assigns as many display levels to the rarely occurring image values as to the frequently occurring values. For example, in Figure 2.3, half of the dynamic range of the output device (0 to 127) would be reserved for the small number of pixels having image values in the 60 to 108 range. The bulk of the image data (values 109 to 158) are confined to half the output display levels (128 to 255). Although better than the direct display in (b), the linear stretch would still not provide the most expressive display of the data.

Some of the distributions that can be in the non-linear contrast enhancement are (Martin-Kaye/Peters, 1982)

- Piecewise Linear
- Ramp cumulative - distribution
- Probability distribution
- Sinusoidal
- Gaussian
- Power logarithmic

Probability stretch: In this technique the brightness values having the highest frequency of occurrence are stretched apart and those with the lowest are compressed. Martin-Kaye and Peters describe this type of contrast enhancement as extremely useful in geological applications especially when used by a skilled operator, but it needs to be carried out on interactive analysis system such as the Hunting HIPAS facility (Martin-Kaye and Peters, 1982).
FIGURE 2.3 Principle of contrast stretch enhancement. From Lillesand/Kiefer (1979, Fig. 10.18)
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**Estimated Mean**: 2.47962 x 10^1

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**Minimum Value**: 0.00000 x 10^0

**Global Mode**: 0.00000 x 10^0

**Maximum Value**: 6.97799 x 10^1

Figure 2.3a Raw data histogram of Landsat scene of Angonia (180/70).
For special analyses, specific features may be analysed in greater radiometric detail by assigning the display range exclusively to a particular range of image values. For example, if water features were represented by a narrow range of values of a scene, characteristics in the water features could be enhanced by stretching this small range to the full display range.

The I²S System 500 has several applications programs designed to perform a series of different types of contrast stretch. These are divided into two basic groups:

**Standard programs**, requiring no interactive prompting by the operator, and these are
- logarithmic - applies a logarithmically shaped stretch to the input data;
- Exponential - applies an exponentially shaped stretch to the input data;
- Hist' Normalisation - produces a normalised (Gaussian) distribution of pixel intensities in the output image. Parameters may also be specified to control the standard deviation and mean of the normal curve desired;
- Local enhance - which perform a space variant contrast stretch on the input display image.

**Histogram modification** is another important type of contrast enhancement in which a grey scale transformation is used to give the picture a specific distribution of grey values (Rosenfeld A. and Kak C. 1976). Two frequently used distributions approximate a normally distributed (Gaussian) or a flat (contrast) histogram. Histogram modification is important in cases, for example, when we have to compare two pictures of the same scene taken at different seasons. In this case it is advised to apply histogram modification before their comparison. If the pictures were taken under different lighting conditions, the differences can be compensated for by transforming both pictures to a standard histogram.

**Histogram flattening** (also called histogram equalisation) produces pictures with higher contrast, because the points in the densely populated regions of the grey scale are forced to occupy a larger number of gray levels, resulting in these regions of the grey scale being stretched. Points in sparse regions of the grey scale occupy fewer levels.

**Histogram Match** performs an operation to transform one image such that the resulting histogram of this image matches the histogram of a second image.

**Interactive Programs** require stretches to be carried out interactively utilising the Trackball unit.

(a) **TLM** (Trackball linear mapping) utilises the trackball unit which interactively manipulates a cursor. When the cursor is moved it changes the contrast and brightness of the input image linearly.

(b) **PIE** (Piecewise Linear Intensity Mapping) maybe executed manually or interactively. A user may specify a stretch by selecting pairs of points (breakpoints) from the input histograms.
FIGURE 2.4 Gray-Scale transformations for enhancement (b) Piece-wise Linear gray-scale transformation (b) Saturation of low and high values to black and white. (After Moik, 1980)
FIGURE 2.4a Linear contrast enhancement. From M-Kaye and Peters (1982, Fig. 62).

FIGURE 2.4b Nonlinear contrast enhancement. From M-Kaye and Peters (1982, Fig. 63).
Figure 2.4c. Nonlinear contrast enhancement. Enhancement of different intensity ranges to full brightness. From Moik (1980), Fig. 4.4.
During the course of the investigation all these operations were tried. Histogram Equalise is a fast way to contrast enhance a colour composite image but the histogram are in many cases not satisfactory. Frequently used was the interactive version of the system, TLM and PIE because of flexibility and speed.

Local enhancement which was sometimes applied on the TLM enhanced scenes was quite useful as this helps to enhance the spectral contrast between dark and bright grey levels. This seemed to be quite useful in differentiating edges of features, sometimes “pseudo relief” impression was obtained when watching on the TV monitor. In fact local enhance is achieved by suppressing slow brightness variations, which tend to obscure the interesting details in an image. Slow brightness variations are composed of low spatial frequencies, whereas fine details is represented by higher spatial frequencies. Therefore a filter that suppresses low spatial frequency components enhances local contrast.

A very small amount of local enhanced slides were produced because when the enhanced bands are transformed into colour composites they tend to be too bright resulting in loss of detail. However as single band images they can be quite useful.

Edge Enhancement

This is a local operation needed to modify the values for each pixel by considering the pixel values that surround it. It is generally employed either to emphasize or de-emphasize abrupt changes in pixel brightness values. In this way local operations alter the textural appearance of the image (Lillesand/Kiefer, 1979).

Operations that de-emphasise abrupt changes are useful when random, spike-like noise is present in the image data. Figure 2.5a illustrates a line printer gray scale output of a portion of a NOAA satellite image. This rendering of the raw data shows the “pepper and salt” or “snowy” appearance caused by significant noise in the data. Because the noise values change much more abruptly than the image values, they are said to have high “spatial frequency”. Operations that de-emphasize, or “block”, the high spatial frequency values are low pass filters. The simplest form of low pass filter replaces each pixel value with the average value computed within 3 x 3 pixel neighbourhood. Figure 2.5b illustrates the effect of this operation (Lillesand/Kiefer, 1979). The processed scene has slightly reduced spatial resolution, but is far more useful for interpretation. Because the spiky noise values are “smoothed out”, low pass filtering is also referred to as a smoothing operation. The smoothing operations are generally used to reduce radiometric anomalies in image data, and as such they are applied to noisy image data prior to numerical as well as visual analyses.
FIGURE 2.5 Noise reduction through low pass filtration. (a) Raw image data with noise induced "pepper and salt" appearance. (b) Data smoothed by averaging values in each pixel's 3 x 3 pixel neighborhood. From Lillesand/Kiefer (1979, Fig. 10.24).
FIGURE 2.6 Concept of spacial frequency enhancement. From M-Kaye and Peters (1982, Fig. 63A).
In interpreting Landsat data, random noise is not normally a problem. Often it is useful to exaggerate, rather than de-emphasise abruptly occurring image values (Lillesand/Kiefer, 1979). In noise-free data, these high spatial frequency values usually indicate small, sub-resolution sized features. By emphasising such features, an increase in apparent spatial resolution is provided. This operation is referred to as high pass filtering or edge enhancement. It is frequently applied by:

1. computing the local average surrounding each pixel;
2. noting the deviation of the pixel from its surrounding average; and
3. doubling that deviation;

Thus, a pixel that is brighter than its surroundings will be made brighter yet, and a relatively dark pixel made darker. This operation is mathematically implemented by doubling the value of given pixel and subtracting its local average value. The edge enhancement operation is performed independently in each band.

When a picture is blurred and noisy, differentiation or high-pass filtering cannot be used indiscriminately (Moik, 1980) for edge enhancement. Noise generally involves high rates of change of grey levels and hence high spatial frequencies. Sharpening enhances the noise. Therefore, the noise should be reduced or removed before edge enhancement.

Because of the low-pass characteristics of imaging systems, higher spatial frequencies are weakened more than lower frequencies. Thus, sharpening or edge enhancement can be achieved by high-pass filtering, emphasising higher spatial frequencies without quantitative knowledge of the point spread function (PSF) Rosenfeld, A. and Kak, C., (1976).

Filtering may be performed in the spatial domain or by multiplication of Fourier transform in the frequency domain. Frequency-domain filtering permits the enhancement of features in a specific direction. This enhancement is possible because the two-dimensional Fourier transform contains information about the direction of features. High spatial frequencies in a certain direction in the frequency spectrum indicate sharp features orthogonal to that direction in the original image.

Whenever the filter weight matrix exceeds a size of about 13 x 13 elements, filtering in the frequency domain, including the necessary Fourier transforms, is faster than direct convolution. However, frequency-domain filtering requires that the dimension of the input image be a power of 2 (Moik, 1980).

The Laplacian operations can be computed by the convolution operation with the 3 by 3 filter matrices. This type of filter was mostly used throughout this investigation, e.g.

\[
[H] = \begin{bmatrix}
0 & -1 & 0 \\
-1 & 5 & -1 \\
0 & -1 & 0
\end{bmatrix}
\]

Plate 5/30

(whereby H=1)
A high frequency filter produces a sharper image but its use may introduce artifacts into the data by producing shadows adjacent to features which have abrupt changes in brightness values. Such techniques work best for geological applications in areas of uniform vegetation and soil cover (Martin-Kay, Peters, 1982).

In the System 500, edge enhancement operation is carried out using the CONVOLVE function.

This function performs a 2-dimensional high pass filtering. The integer elements used in the matrix are essentially weights. If they are all equal then all edge orientations are sampled equally. Enhancement of selected edge orientations is achieved by assigning different values to different elements.

Differencing is a simple method for edge enhancement which was used on the I2S. Shifting an image by one row and one column and subtracting it from the original produces a picture that represents the first difference in row and column direction (Plate 5/34).

2.5 COLOUR ENHANCEMENT

An observer perceives colour as a result of the properties of the human visual system and of the display device used, i.e. the type of display medium in connection with the type of display excitation, e.g. film and primary-colour illuminants. When display devices having slightly different sets of primary colours are employed, a transformation may be necessary to obtain colour consistency (e.g. if an image is displayed temporarily on a television monitor and then recorded on film).

Digital multi-images may be displayed as colour pictures by selecting three components for assignment to the primary colours. By varying the values of these components, all colours realisable within the constraints of the display medium may be generated. A colour space, being linear in the colour parameters brightness, hue, and saturation, therefore in general does not lead to a visually perceived linear colour range if linear relationships between parameters and primary components are used. However the components of a multi-image or the primary colours may be transformed to the colour parameters brightness, hue, and saturation. An approximately equal colour distribution may then be obtained by subsequent independent nonlinear transformation of each colour parameter. This approach is justified because colour perception cannot be as simply defined in an image as for isolated uniform areas (upon which colour order system are based) but must be defined for spatial changes (variegation). Colour perception space is shown on Figure 2.7.

False Colour

The normal Landsat colour product is a false colour image printed so that the visible green band (4) is blue, the red visible band (5) is green and the invisible near infrared band (7) is red. However, simulated natural colour images can be produced using a computer
In this Figure, representing Munsell System, consisting of Cylindrical Space, hue is represented by the polar angle; saturation, by the radius; and brightness by the distance on the Cylinder axis.

(After Moik, 1980)
generated blue band. This blue band is displayed as visible blue, band 4 as visible green, and Band 5 as visible red to simulate natural colour as it would appear to an observer if the atmospheric effects were removed. A schematic diagram of the process is shown on Figures 2.8 and 2.9 (also see slide 139/299).

The goal of false colour is to present certain spectral information from the object scene rather than to have colour fidelity. By assuming spatial registration, any three components of a spatial image may be selected and combined by using appropriate primary colours. Variation in the spectral response of patterns then appear as colour differences in the composite image. These colours may show no similarity with the actual colours of the pattern. Ratios, differences, and other transformations of the spectral bands may also be displayed as false colour composites.

Production of good false-colour images requires careful contrast enhancement of each component to obtain a good balance and range of colours in the composite. Generally, good results are obtained by applying contrast transformation to the three component images in such a way that their histograms look similar in shape and that each individual component has appropriate contrast when displayed as a black-and-white image. These transformations ensure good colour and brightness variations.

Furthermore it is recommended (Moik, 1980) that filtering of the component images may be performed before false-colour composition. Some filtering techniques, such as edge-enhancements to correct for the low-pass characteristics of the imaging system or band-pass filtering to enhance visual perception, can be performed separately on the component images without loss of colour information.

**Pseudo-colour**

In observing black and white images, the eye responds only to brightness differences, i.e. black and white images restrict the operation of the visual system to the vertical axis of the colour perception space. The ability of the visual system to distinguish many hues and many saturations at each brightness level is not used. By simultaneous brightness and chromatic variation, many more levels of detail can be distinguished. Small gray-scale differences in the black and white image that cannot be distinguished by the human eye are mapped into different colours. Consequently, more information can be extracted in a shorter time through the substitution of colour for black and white.

**Level Slicing**

One pseudocolour technique is known as level slicing, where each grey level or a range of gray levels is mapped into a different colour. To avoid the introduction of artificial
FIGURE 2.8 Simulation of natural colour. From M-Kaye and Peters (1982, Fig. 67).
FALSE COLOR
"NATURAL" COLOR
BLUE GREEN RED

FIGURE 2.9 Simulation of natural colour - extrapolation of the blue band. From M-Kaye and Peters (1982, Fig. 68).
contours, a continuous transformation of the gray scale into the colour space may be performed. One transformation that results in a maximum number of discernible levels is to project the gray values onto a scale of hues. The projection can be scaled and shifted to include only a particular part of the entire hue scale.

Therefore by digitally delineating equal density levels it is possible to discriminate or highlight specific materials, texture, temperature etc. Density analysis can be accomplished through photographic, photometric video or digital processing.

2.6 Multi-image Processing

In relation to monochrome images multi-images convey more information and are therefore better for most types of interpretation work. Multi-images are obtained by imaging a scene in more than one spectral band or by monitoring a scene over a period of time. Multi-image enhancement techniques involve independent contrast enhancement of the component images or linear and non-linear combinations of the component images, including ratioing, differencing, and principal component analysis. The enhanced components may be displayed as false-colour composites.

Ratioing

Ratioing is a mathematical combination of reflectance values for two different Landsat spectral bands. Ratioed images enhance scene quality to provide surface-feature information not discernible on conventional images, and they have proven particularly valuable in geologic applications, and in location, recognition, and interpretation of vegetation. Unfortunately they have not proven to be very successful in the study area, especially if they are two spectral band ratios.

Multispectral images may be enhanced by ratioing individual spectral components and then displaying the various ratios as colour composites. Ratioing two spectral component images suppresses brightness variations due to topographic relief and enhances subtle spectral (colour) variations. The mathematical expression of a ratio image (Moik, 1980) can be explained in the following way:

If $g$ is a multi-image with $N$ components, $g_i$, $i=1, \ldots, P$, then a ratio image $g_R^k$, $K=1, \ldots, P (P-1)$, is given by:

$$g_R^k = a \frac{g_i}{g_j} + b$$

The contrast in the ratio picture is greater for features with ratios larger than unity than for those with ratios less than unity. By computing the logarithm of the ratios, equal changes in the denominator and numerator pictures result in equal changes in the logarithmic ratio image. Thus, the logarithmic ratio image shows greater average contrast between features.
Ratioing also enhances random noise or coherent noise that is not correlated in
component images. Atmospheric effects may also be enhanced by ratioing. It is therefore
important to remove striping before ratioing. This phenomena was noted during the enhance­
ment, some of the destriped images still showed strong striping during ratio processing.

The selection of the most useful ratios and their combination into colour composite is
a problem. The number of possible ratios from a multi-image with P components is n=P (P-1).
The number of possible combinations of three of these ratios into a colour composite is
m=n!/3!(n-3)!. The primary colours may be assigned to each triplet in six different ways.
Thus, ratioing is only efficient with a prior knowledge of useful triplet and colour combina­
tions. Although this can be achieved quite fast in the computer, the determination of the
many combinations of components and bands can be time consuming and sometimes
difficult to differentiate the ratios easily in the TV monitor.

Another method of single scene spectral band ratioing is illustrated in Figure 2.10.
A ratio of two Landsat bands is obtained by dividing the BV (brightness value) in one
band by the BV in another band for each picture element. The ratioed values are then
multiplied by a factor from a "look up" table so that all the values will lie between 0
and 255. The rationale of ratioing is shown in Figure 2.11. Even though two slopes receive
a different flux of electromagnetic radiation from the sun and even though the same
materials have different BV's on the opposed slopes, the ratios of the brightness values will
be the same on either slope if the data has been adjusted for atmospheric effects. Ratioing
tends to reduce the effects of topography and allow the analyst to concentrate on changes
in brightness values between materials.

On the I^S System ratio images are obtained by the computation of the ratio of four
refresh channels on a pixel by pixel basis and displaying the results as a colour image. The
ratio is computed as follows:

First channel/second channel = red
Second channel/third channel = green
Third channel/fourth channel = blue

The output can be scaled using user specified clip levels or through the default parameters.

2.7 Image Classification

Classification is the placing of objects into more or less homogeneous groups, in a
manner so that the relation between groups is revealed (Davis, 1973). In other words,
image classification is a segmentation method whereby particular areas, points or regions,
of an image are assigned to one of a pre-specified set of classes or categories. In unsuperv­
ised classification the class limits are defined by natural breaks in the data.
FIGURE 2.10 Spectral band ratioing. From M-Kaye and Peters (1982, Fig. 64).
FIGURE 2.11 Rationale for spectral band ratioing. From M-Kaye and Peters (1982, Fig 65).
From the previous descriptions it is clear that no more than three spectral bands may be combined in a colour composite image. When we intend to combine or deal with more than three spectral bands it is very difficult to fully evaluate the spectral information presented by the image data. There are computer packages (e.g. IS System 500) where the four band data can be viewed as one composite image. For example, Fast Fourier Transform (FFT1D) has proved a good spectral recognition instrument (Plate 1/5, p. 199 in detecting vegetational variations in the type of environment like the study area.

As has been pointed out earlier, one approach for reducing the number of spectral dimensions used in a classifier is to transform the original data statistically. Essentially the original two-dimensional pixel values are converted to values as measured on an alternative set of coordinate axes. That is, the (band 3, band 4) values for each pixel are converted into corresponding (axis I, axis II) values. It can be noted that the relative orientation of the observations is maintained, just the coordinate system is changed (Figure 2.12).

Some of the statistical techniques used to determine the transformation axes are: principal component analysis, factor analysis and canonical analysis.

As implemented computationally, the transformation functions are determined during the training process. The category spectral response data are converted into transformed coordinate values. Some classifiers use separate transformations for each category type to be interpreted. During the classification stage, unknown pixel values are transformed and then compared to the transformed training data. Any of the classification strategies can then be employed to determine the appropriate class for the unknown pixel.

Unsupervised classification - if an algorithm is used to delineate “natural” groups of multi-spectral data in a multispectral space formed of the 4 bands without any information as to what the groups represent, then the image is said to have been analysed using an unsupervised approach. This method was much used in the study as no previous spectral and vegetation information is known of the area.

Supervised classification - On the other hand, if an analyst selects known cover types and programmes the computer to delineate area with similar spectral characteristics the image is said to have been analysed using a supervised approach.

A common supervised approach uses the “parallelepiped” classification algorithm. An analyst trains an electronic cursor over a particular cover type on an image on a TV screen. The computer determines the minimum and maximum B.V.s within the cursor area for that cover type in the four Landsat bands. The computer then searches the entire scene, pixel by pixel to determine which picture elements have B.V.s that fall within the maxima and minima of the “training” area. The computer can be asked to identify such pixels by colour or letter code.
FIGURE 2.12 Rotated coordinate axes used in a processing transformation. From Lillesand/Kiefer (1979, Fig. 8.14)
It has been recognised, however, that with an increase in vegetational cover the method becomes difficult to apply and problems are further compounded by the effects of atmospheric scattering and absorption, as has been found during the study.

The supervised classification can be summarised with three stages:

- **Training stage** - when an analyst compiles an "interpretation key" developing numerically the spectral attributes for each feature of interest.
- **Classification stage** - when each pixel in the image data set is compared to each category in the numerical interpretation key
- **Output stage** - commonly in the form of a map, or tables of the areas of various cover types in the scene.

Classification is based upon training areas comprising one or more pixels, considered representative of a class of terrain. Training area size must be a function of homogeneity in terrain spectral properties. The limiting training area size is a single pixel - representing approximately 8000 square metres.

**Cluster analysis** - The grouping of sets of observations into their natural classes is also achieved by cluster methods. In cluster analysis the computer accepts from the analyst the number of clusters to be located in the data. The computer then arbitrarily locates that number of cluster centers in the measurement space, and interactively repositions them until they are optimally located. The optimum locations are those in which the clusters have maximum spectral separability. This is an unsupervised classification.

**Hybrid classification**

When the analyst combines spectral classes so that they will correspond to desired information categories, the "unsupervised" analysis is, in effect, being supervised. Such approaches are termed, hybrid classification techniques, in that they involve elements of both supervised and unsupervised data analysis. One such technique is controlled clustering. In this procedure, the analyst first selects a series of training areas containing multiple cover types and clusters them independently. The spectral classes from the various areas are then analysed to determine their identity and subjected to a pooled statistical analysis to determine their spectral separability and normality.

Hybrid classifiers are said to be particularly valuable in analysis where there is complex variability in the spectral response pattern for individual cover type present. This appears to be a suitable tool for the study area but the process has proven complex and the limited number of refresh channels in the system can not handle large amounts of data.
2.8 **PRINCIPAL COMPONENT ANALYSIS**

Principal components are nothing more than the eigenvectors of a variance-covariance matrix (Davis, 1973). Random sample of pixels can be plotted on a scatter diagram according to their bands. By expressing the pixel values as measured on a rotated set of coordinate axes, we can provide a more efficient description of the data. These axes are characteristic of a principal component analysis. When applied to four channel Landsat MSS data, four axes (or "components") would be used; the first component would express a maximum portion of the variance in the data. Subsequent axes would account for successively smaller portions of the remaining variance. Principal component enhancements are generated by displaying contrast stretched images of the transformed pixel values.

The Karhunen-Loeve (K-L) transform to principal components provides a new set of component images that are uncorrelated and are ranked so that each component has variance less than the previous component. Thus, the K-L transform can be used to reduce the number of spectral components to a few principal components that account for all but negligible part of the variance in the original multispectral images.

The principal component image \( g^C \) is obtained from the original \( P \) component of a multi-image \( g \) by the transformation (Moik, 1980):

\[
g^C = T(g - m)
\]

where \( g \) is a vector whose elements are the components at a given location \((j,k)\) in the original multi-image, \( m \) is the mean vector of \( g \); i.e. \( m = E(g) \). The components of vector \( g^C \) are the principal components at the location \((j,k)\), \( T \) is the \( P \) by \( P \) unitary matrix whose rows are the normalised eigenvectors \( t_p \), \( p=1, \ldots, P \) of the spectral covariance matrix \( C \) of \( g \) arranged in a descending or according to the magnitude of their corresponding eigenvalues:

\[
T = (t_1, t_2, \ldots, t_P)
\]

Principal component enhancements techniques are supposed to be particularly appropriate in areas where little prior information concerning the region is available. Because of this, great attention was given to them, however the results have not been very encouraging for geological purposes but still the obtained slides have been useful to the study.

On the _2S 500_ system many options are available for classification, CPU-Classify, Cluster and Vegetation. The CPU classify performs supervised classification on imagery having up to 4-bands and all the necessary statistical data to carry out a classification is generated for each class. While the Principal Component analyses is carried out using the program KL. This performs a Karhunen - Loeve transformation, as described earlier, of the input image which must have at least 3 bands. The resultant display can be up to 3
components on the colour monitor. An image statistics file must be supplied using CPU statistics.

2.9 IMAGE ENHANCEMENT OF THE STUDY AREA

Six Landsat Computer Compatible Tapes (CCTs) covering an area of approximately 194,000 km² were the main source of data for this investigation.

These six tapes were chosen because they do cover completely the south branch of the East African Rift including large areas adjacent to the Rift System. The extent of the Landsat cover is approximately 500 km north to south, and about 300 km in the E-W direction. The Landsat configuration and positioning is shown on Figure 2.1.

Temporal variation data was not available, all the six tapes were taken during the dry season July-Sept with the exception of Scene 180/72.

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The first operation applied to these tapes was the quantitative operations mentioned earlier in this chapter. The original data has been corrected for some geometric and radiometric degradation so that only destriping and deskewing were the two operators left to be carried out. However the deskew operation was abandoned because the resulting deskew subscenes were exaggerated (elongated) in the north-south direction making them impossible to fit into the existing base maps. This might suggest that the tapes were applied deskew operation already. Image Enhancement operations followed later devoting to them a large amount of time, because it was necessary to have good imagery for interpretation purposes.

The six tapes were subdivided into predetermined areas of interest. In the first stage 40 test slides were produced and analysed. In the second stage another 210 slides were produced and 80 slides were acquired from Hunting's HIPAS Image Processing Facility. The digital enhancements used and the relevant page on which each plate can be found is shown in Table 2.2.

The main purpose of the enhancement techniques was to try and cover a varied type of environments and rocks, especially on those for which there is some existing information. In this manner the interpretation could be more reliable and correlation more easily made.
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<th>No. of samples</th>
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The single-seasonal nature of the scenes and the lack of detailed geological information was a reason for the author to find it extremely difficult to discuss with certainty the many geologic features observed on the imagery. The whole of the image enhancement exercise was prompted by the desire to try to:

- recognise and trace known fault structures as well as unknown ones;
- recognise and trace known ring structures as well as unknown ones;
- define the structural pattern of the region by detecting different linear features;
- investigate if there is any difference in structural style between the Karroo basin and the surrounding basement terrains.
- trace out the continuous rift faults across the area; and
- try to discriminate the rock-types wherever possible;

The success of these objectives lay in the correct selection of enhancement techniques which would allow the enhanced data to be interpreted correctly and be compared with other sources of data, like the aero-magnetic data which the author managed to obtain in the course of the study.

2.10 TRACKBALL LINEAR MAPPING (TLM)

In the Application programme arrangements of the l²S system 500, TLM is categorised as a radiometric transformation program together with Piecewise Linear Intensity Mapping, Exponential, and Adjust.

The purpose of these processes is to produce a picture that uses the full dynamic range of a TV display device. As it has been pointed earlier the contrast characteristics of an image is influenced by factors like camera exposure settings, atmospheric effects, solar lighting effects, etc. These factors often cause a recorded image not to span the dynamic range which is digitised. Therefore grey-scale transformation is necessary in order to restore into its full dynamic range, in other words the image has to be contrast stretched after the geometrical transformation.

The TLM function allows the user to manipulate interactively a positive or negative linear intensity transformation of the input image by changing the cursor position. By moving the cursor, the user controls the transform's slope and intercept. It is a technique which allows the shifting and spreading (or compressing) the histograms of the image.

The use of a TLM technique is quite straightforward and as it is an interaction operation an operator is more free in determining the final product. Operation like "Adjust" are faster but only 1 to 3 bands can be stretched simultaneously by giving the operator's values for mean and standard deviation. As it is an automatic operation usually the histograms are not as good as those offered by TLM as illustrated by computer printout of this operation.

10.00 $B>ADJ\text{UST}\ (\text{MEAN}=128\ \text{STDEV}=60);\ \\
\text{WARNING - DATA TRUNCATED, OUTPUT NOT EXACT.}
Piecewise Linear operation and Exponential were employed during the contrast enhancement but of all the methods described TLM was most employed, especially because of its flexibility. Some of the TLM products thus obtained will be described below.

One of the scenes selected for pictorial illustration of the Contrast Enhancement technique is an area of the southern tip of Lake Niassa. The area is covered by the Landsat scene 180/70 in which the Lake is a dominant feature capable of influencing the shape of the spectral histogram of the scene. The following types of graphics were produced from the scene:

- Plate 6/56 raw data histograms,
- Figure 2.3a - raw data line printer print out histograms.
- Plate 6/36 - “Adjust” contrast stretched histogram of raw data. (Not included).
- Plate 6/46A - Computer generated intensity profile line along NE-SW direction across the middle of the scene.
- Plate 6/46B - spectral frequency distribution plots of the four bands along the intensity profile line.

Plate 6/56: On this slide is shown a typical histogram characteristic of the CCTs raw data used in the study. This particular slide is chosen for illustration because of its bimodal histogram characteristic. As we can observe, two data types (water and land mass) are demonstrated on the same histogram.

The four bands displayed on Plate 6/56 are the raw data input from the tapes before being contrast stretched. The histograms are displayed in order from band one to four (top to bottom), these correspond to bands four, five, six and seven as usually known.

As shown on Figure 2.3a, all the raw data occupy the grey-level range between 0 and 61, this is a mere quarter of the full dynamic range which can be obtained through contrast enhancement.

Band 4 has all the data concentrated between 0 and 61, the peak being at 31. Band 5 has all the data between 0 and 55 with the peak at 26. Band 6 has all the data concentrated between 0 and 48 with peaks at around 27, whereas band 7 has its data concentrated between 0 and 8 with a peak at 4.

From theoretical investigations and practical observations we know that water is transparent to band 4 spectral region. Although most of the sunlight that enters a clear water body is absorbed within about two meters of the surface, the best light penetration is achieved between the wavelengths of 0.48 and 0.60 μm. Red wavelengths penetrate only a few meters. Therefore in areas of clear, deep water, greater water penetration is achieved with band 4. Band 5 generally has a better atmospheric penetration of red wavelengths and as such is preferred for showing silty water flow into clear water. Both band 4
and 5 are generally best for detecting cultural features such as urban areas, roads, gravel pits, quarries, but because of its better atmospheric penetration band 5 is much better for linear feature detection. Bands 6 and 7 (reflected infrared) are best for delineating water bodies. Since energy of near-infrared wavelengths penetrates only a short distance into water, where it is absorbed with very little reflection, surface water features have a very dark tone in band 6 and 7.

Also chlorophyll strongly absorbs energy in the wavelength bands centered at about 0.45 and 0.65 μm. Plant leaves, in these wavelengths, have a high absorption of blue and red energy and very high reflection of green energy. As we go from the visible to the reflected infrared portion of the spectrum at about 0.7 μm the reflectance of healthy vegetation dramatically increases. In the range from 0.7 to 1.3 μm, a plant leaf reflects about 50% of the energy incident upon it. Most of the remaining energy is transmitted, since absorption in this spectral region is minimal, that is why bands 6 and 7 emphasise vegetation in remote sensing.

From the above observations we can understand the reason for the behaviour of this particular histogram along the computer generated intensity profile across the water mass and land mass (Plate 6/46).

As Figure 2.3a and Plate 6/47 show, there is no serious separation of water and land as is manifested in band 6, and 7. From the Plate 6/47 breakpoints can be clearly observed on these two bands indicating water and land. By stretching these histograms separately good information can be achieved about the water and the land as described earlier under special analyses.

2.11 COLOUR ENHANCEMENT

Several colour enhancement techniques were applied during the study as the System 500 offers a variety of options. As the study area has a good vegetation cover, which in turn is the source of information, on Landsat MSS data, attention was given to this group of enhancement. Of the methods available on the System 500, colour composite, matrix, and FFT1D were most used.

Plate 1/1 is a colour composite of bands 4, 5 and 6. Colour composites are a very useful tool in lithology discrimination and sometimes can help in fracture detection.

This image is chosen because of the clear contacts between at least three types of rocks. The red tone represents the Furancugo granite batholith. On top of the granite at the left hand corner, along a linear fracture, we can observe about four patches of very intensive red hue. These might be an example of evergreen forest relics that can be found sometimes in some areas of Angonia. They usually indicate a microclimate, especially in deep valleys which, in this case, might have a relationship to the lineament along which they tend
to be aligned. Whitish patches usually indicate agricultural activity or settlements. A tonal lineament is vivid along the NW-SE direction across the top of the scene. Most of the rivers tend to be disturbed by this lineament, (see also Figure 5.8), and it strikes SE towards the Rift Valley south of Metango Belame. This might be a shear zone or a lithological contact. A fire burning along the lineament can be seen by the white smoke. Rocks to the right of lineaments are rocks of the granulite facies and banded gneisses, and those to the left are rocks of the amphibolite facies paragneisses; there is no real tonal difference between them. The tonal lineament is an interesting feature for it has not been pointed out on the geological map previously, it looks more like a lithologic contact than a shear zone.

By applying MATRIX (Plate 1/5b) other types of information can be obtained. MATRIX TRANSFORM is a function which performs a linear transformation on the bands of the input image to produce red, green and blue outputs.

The user may specify the colour weights and bias in the operation, or select either the SATURATE or ROTATE parameters for algorithmic computation of the colour weights. The matrix COLOURWEIGHT has three rows corresponding to the red, green and blue outputs. This matrix will be printed on the user’s terminal after each transformation (see Table 2.4) with each value given in terms of a percentage (i.e. 0 to 100 instead of 0 to 1). The user may, optionally, specify the CURSOR parameter in conjunction with either the ROTATE or SATURATE parameters for trackball control of colour weight generation. The red, green, and blue outputs signals are automatically scaled and clipped with the user specifiable clip value.

As it is an interactive operation one is free to test the various values before choosing the best image. Throughout this operation the CURSOR parameter was in conjunction with the SATURATE parameter with values varying from 0.9 to 0.1. Usually the smaller the saturation value the less colour components we get and approximate false colour composites.

Plate 1/5, however, shows that the colour separability is better. Also the grouping of colours is more uniform. Some information is however lost in this plate, especially lineament information. The NW-SE tonal lineament is obscured, the fire smoke has disappeared and the drainage is poorly expressed. MATRIX is a flexible operator and can easily be manipulated to suit an operator’s taste. Therefore using it can add extra information especially as three bands can be manipulated together at one time.

Fourier Transform (FFTID) - with this function we are able to perform a discrete fast Fourier transformation on the spectral dimension of a four band display image. The transform occurs across the spectral dimension (i.e. across the bands), not in the spatial dimension.
Table 2.3 Colour Enhancement applying MATRIX operator.

245.00 $TH\ \text{MATRIX(SAT=.2)}$;

Transform matrix =
\[
\begin{pmatrix}
100 & -20 & -20 \\
-20 & 100 & -20 \\
-20 & -20 & 100
\end{pmatrix}
\]

Elapsed time 0:00:05.4

246.00 $TH\ \text{MATRIX(SAT=.1)}$;

Transform matrix =
\[
\begin{pmatrix}
100 & 10 & 10 \\
10 & 100 & 10 \\
10 & 10 & 100
\end{pmatrix}
\]

Elapsed time 0:00:05.4

247.00 $TH\ \text{MATRIX(SAT=.3)}$;

Transform matrix =
\[
\begin{pmatrix}
100 & 30 & 30 \\
30 & 100 & 30 \\
30 & 30 & 100
\end{pmatrix}
\]

Elapsed time 0:00:05.4

248.00 $TH\ \text{MATRIX(SAT=.4)}$;

Transform matrix =
\[
\begin{pmatrix}
100 & 80 & 80 \\
80 & 100 & 80 \\
80 & 80 & 100
\end{pmatrix}
\]

Elapsed time 0:00:05.4

249.00 $TH\ \text{MATRIX(SAT=.5)}$;

Transform matrix =
\[
\begin{pmatrix}
100 & 40 & 40 \\
40 & 100 & 40 \\
40 & 40 & 100
\end{pmatrix}
\]

Elapsed time 0:00:05.4

250.00 $TH\ \text{MATRIX(SAT=.6)}$;

Transform matrix =
\[
\begin{pmatrix}
100 & 60 & 60 \\
60 & 100 & 60 \\
60 & 60 & 100
\end{pmatrix}
\]

Elapsed time 0:00:05.4

251.00 $TH\ \text{MATRIX(SAT=.7)}$;

Transform matrix =
\[
\begin{pmatrix}
100 & 70 & 70 \\
70 & 100 & 70 \\
70 & 70 & 100
\end{pmatrix}
\]

Elapsed time 0:00:05.4

252.00 $TH\ \text{MATRIX(SAT=.8)}$;

Transform matrix =
\[
\begin{pmatrix}
100 & 80 & 80 \\
80 & 100 & 80 \\
80 & 80 & 100
\end{pmatrix}
\]

Elapsed time 0:00:05.4

253.00 $TH\ \text{MATRIX(SAT=.9)}$;

Transform matrix =
\[
\begin{pmatrix}
100 & 90 & 90 \\
90 & 100 & 90 \\
90 & 90 & 100
\end{pmatrix}
\]

Elapsed time 0:00:05.4

254.00 $TH\ \text{MATRIX(SAT=1)}$;

Transform matrix =
\[
\begin{pmatrix}
100 & 100 & 100 \\
100 & 100 & 100 \\
100 & 100 & 100
\end{pmatrix}
\]

Elapsed time 0:00:05.4

The trackball button options are:
- Button A) Horizontal annotation
- Button B) Vertical annotation
- Button C or D) Quit.

Enter annotation message: 29/115 BANDS '456 MATRIX(SAT=.3)
The results of the transform will be displayed in red, green and blue with the red output containing the real part of the first frequency, the green output containing the DC component, and the blue output containing the imaginary part of the first frequency. The highest frequency is not displayed.

Plate 1/5a is a four-band display of the FFT1D transform. Tonal differences are enhanced here by a variety of contrasting colours. Granitic rocks are easily distinguished (blue); also the tonal lineament is easily seen as in the colour composite.

### 2.12 EDGE ENHANCEMENT

Edge enhancement in the System 500 is achieved by the function CONVOLVE. This function performs a two-dimensional spatial convolution on a display image utilising a 256 element kernel specified by the user. The user must specify the number of columns, rows and weights in the kernel. Weights contains the convolution kernel, specified with rows varying most often. The number of centres must equal the number of rows times the number of columns.

Edge sharpening without regard to edge direction, can be obtained by convolution of an image with a Laplacian mask. Several types of masks have been pointed out by different authors, for example, W. Pratt (1978). However, these masks do not always suit every type of environment or scene. It is advised to test and try as many masks as possible for the best results.

Syntax for a high pass filter convolution operation (3 by 3 mask) is shown below:

```
59.00 $A>CONV (NR=3 NC=3 WE=-19 -1 -1 -1 -1 -1 -1 *SCALE);
```

Elapsed time 0:00:05.6

60.00 >ANN;

The trackball button options are:

- Button A) Horizontal annotation
- B) Vertical annotation
- C or D) Quit

Enter annotation message: 5/31 BAND 5 TLM CONVOLVED (not included), and the resulting plate (Ulongue Structure) is obviously a high pass filtered image. The study has shown that high pass filters are better for this type of environment, as other convolved plates (not included) have also shown (e.g. Plate 129/201, 18/72, 27/107 and 28/110, etc).

High pass masks have the characteristic that the sum of their elements (weights) is usually a unity (H=1) while in low pass masks the sum of their weights is usually less than unity.

Plate 5/30 is also a band five scene of the same Ulongue structure. Here the WEIGHTS values were changed to produce a different 3 by 3 mask which is shown below:
The track ball button options are:
- Button A) Horizontal annotation
- Button B) Vertical annotation
- C or D) Quit

Enter annotation message: 5/30 BAND'S TLM CONVOLVED

The resulting image shows only broad features, very clear and noiseless. This is usually characteristic of low-pass filtered image.

A variety of edge enhancement techniques are in existence, many of which are theoretically complicated to understand. For the purpose of this study the above illustrations were used to acquire data which have been very useful for fracture and tectonic fabric interpretation. Sometimes mask windows were increased or a directional filtering was applied when ever the previous masks did not produce satisfactory products. Plate 5/32 is an example of a directional filtering by changing the mask windows. In this case, for example 3 by 6 window was used and the resulting picture is a high pass filtered image with more fine detail enhanced.

By shifting pixels the computer performs pixel by pixel addition of any number of the display channels. The user has the option, by using the operation ‘ADD’, of specifying a weighting factor for each channel. This enables the user to perform subtraction and addition of channels in any combination. By changing the values of the starting line and row of the image we are able to perform horizontal, vertical or diagonal shifting.
The trackball button options are:
A) Horizontal annotation
B) Vertical annotation
C) or D) Quit
Enter annotation message: 5/34 BAND 5 TLM APPLIED PIXEL SHIFT

The algorithm for this operation is shown above and the resulting image Plate 5/34 looks like a low pass filtered image.

2.13 Multispectral Image Enhancement

Ratios: many investigators (e.g. Pratt, 1978) have emphasised the importance of ratio images. Although simple, ratioing is a highly effective method of multispectral image enhancement. One problem with the ratioing method as pointed out by Pratt, is accentuation of the gray scale quantisation error associated with each plane. Probably another problem with this method is the number of combinations it is necessary to perform on a four band image before an operator can choose the right picture for interpretation.

The ratio function, in the System 500, computes the ratio of four refresh channels on a pixel by pixel basis and displays the result as a colour image. The ratio is computed as follows:

1st Channel/2nd Channel = red signal
2nd Channel /3rd Channel = green signal
3rd Channel /4th Channel = blue signal

The output can be scaled using user specified clip levels or through the default parameters.

Two band ratios have not produced satisfactory results. Better results were achieved by producing colour composites of the ratios. This was achieved by ratioing four or three bands and then merging them into a colour composite (e.g. Plate 19/82), in which four main tones are well discriminated.

Probably the best results, in this group of enhancements, were achieved by applying statistics of the ratio images. For it is possible to compute statistics of the ratio images, then with this information we can generate a Karhunen-Loeve (KL) transform and thus be able to display up to three components on a colour monitor.
With the KL transform we can display three ratioed bands where red is given to band 7, green to band 5 and blue to band 4 or combine both components and bands.

Plate 19/82: is a colour composite of ratio 4/5, 5/6 and 4/6 of the area where the Rift crosses the Zambezi River valley. Four principal tones can be distinguished on the image: white, dark red, light-red and blue. The alluvial sediments are distinguished by their light-red colours, water is depicted as white to white-green. The dark-reddish tones seem to correspond to sandstone-conglomerates as shown on the geological map. As no detailed geological map exists for the area, it is difficult to speculate on the identity of the blue tones found only south of the river. On the geological map the whole of this area, south of the river, is mapped as sandstones - conglomerates with rare calcareous rocks. These are the Lupata Graben sediments.

The geological and structural interpretation of Plate 19/82 (p 207 ... ) is shown on Figure 6.4. The volcanic vents (not observed on this particular plate), are mostly located outside this formation or at its edges. Besides, the formation seems to be occupying higher ground (may be an antiform), as drainage, landsat fractures and aeromagnet maps tend to show.

Plate 25/101: is an image of three merged ratios (4/5, 5/6, and 4/6) from which statistics has been extracted and then KL applied. This type of combination produced nice pictures suitable for the purposes of the study.

From little geological information available, we know that the structure in the left centre of the scene (Mt. Morrumbala) is a granitic granodiorite intrusion at the edge of the rift, in whose central part are located syeno-nepheline rocks and carbonatites. The plate offers some spectral information capable of giving a crude but reasonable surface geological interpretation.

From the plate it looks as though the syeno-nepheline rocks which occupy the central part of the structure are reddish colour coded. Their extension is about 12 km from south to north and seem to be wider at the north. If so, then they are much more widely spread than shown on the geological map. The granites and the diorites are coded dark blue surrounding the syeno-nepheline rocks. The green colours might be gneisses which occupy the eastern part of the picture. No speculation can be made yet of the other colours seen on the picture, but they might have some geological significance.

A swarm of dykes can be seen at the bottom of the picture, they are located in rocks with blue tones (may be granites, granodiorites or diorites). These dykes take an E-W sharp turn at the contact with the green coloured rocks. Roads and drainage are easily seen
and the many E-W fracture traces can be seen with clarity. Besides the E-W lineaments several N-E trending lineaments are visible. Also the rift faults can be seen. (Plate 25/100)

**Classification**  It has been shown in Section 2.5 that classification is a segmentation method whereby particular areas, points or regions, of an image are assigned to one of a pre-specified set of classes or categories. Classification can be supervised or unsupervised (e.g. CPU CLASSIFY and CLUSTER respectively).

In System 500 CLASSIFY is a hardware implementation of a minimum distance classifier. The image to be classified must be display-resident and theoretically can have up to ten bands. But the Model 70 has only six refresh memory channels therefore the Classifier is limited to four channel inputs because the function requires two bands to hold its interim and output results. This limitation of space also does not allow us to perform the two-dimensional discrete Fourier transform, because for this a minimum of five channels of refresh memory is required.

The classification function can accept input statistics for each class in three different ways:

- by producing a statistics file like that generated by the PREPARE, CLUSTER, or previous CLASSIFY function.
- by going through a simplified training process from which statistics is extracted.
- by manually typing in a set of mean and standard deviation vectors for each class.

**CLUSTER** performs an unsupervised classification. The initial number of classes is specified by the user but other parameters can be specified that will cause classes to be merged or be split. The image for input must be display one band image; although it will accept two bands the data will be treated separately. The output is in the form of an image which can be displayed in pseudo colour and two class statistics (see Table 2.4). Clustered images have proved not to be interesting for this area of study.

**Supervised Classification** can be achieved by using the CPU'CLASSIFY function on a 1-4 Channel image using the traditional maximum log-likehood decision criteria. The CPU'CLASSIFY function is used in conjunction with TRAIN (feature extraction process function) and PREPARE (which generates the necessary statistical data required to perform a maximum log-likehood classification) functions in order to accomplish a maximum log-likelihood classification.

This Classification process was attempted. Usually the PREPARE function takes a long time to generate the necessary statistics unlike the CPU'CLASSIFY, CLUSTER or TRAIN. For this reason, it was not much used. Some classification images were obtained
Starting seed table

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ITERATION= 2 NCLASS=7 NBORN=0 NDIED=1 NET MIGRATION=8.5
ITERATION= 3 NCLASS=8 NBORN=1 NDIED=0 NET MIGRATION=4.3
ITERATION= 4 NCLASS=9 NBORN=1 NDIED=0 NET MIGRATION=3.4
ITERATION= 5 NCLASS=9 NBORN=1 NDIED=1 NET MIGRATION=17.2

Results of iteration 5

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Table 2.4. Manipulation with CLUSTER operator.
during the work but they were unsatisfactory. Some classified (unsupervised 16-classes) slides were obtained by the author using HUNTING'S HIPAS facility. The statistics extraction for classification procedures on System 500 for the Furancungo (180/70) area is given on Table 2.5.

Other enhancement techniques like COLOR, EXPONENTIAL, LEVEL'SLICE, HADAMARD, LOCAL'ENHANCE, SLANT'TRANSFORM, STASH, and others were also tried during work with the System 500. As their products have been of less value for this thesis, they are not discussed.

TABLE 2.5 STATISTICAL EXTRACTION PROCEDURES FOR CLASSIFICATION

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<td>170.517</td>
<td>197.721</td>
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<tr>
<td>3</td>
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<td>125.342</td>
</tr>
<tr>
<td>4</td>
<td>93.345</td>
<td>99.042</td>
</tr>
</tbody>
</table>

Mean vector:

| 27.615 | 29.276 | 23.773 | 24.796 |

Min vector:

| .000   | .000   | .000   | .000   |

Max vector:

| 61.000 | 64.000 | 57.000 | 49.000 |

Std dev:


Eigen values:

| .940   | .049   | .008   | .001   |

Eigen vectors:

| 1   | -.551 | -.619 | -.431 | -.354 |
| 2   | .162  | .546  | -.407 | -.712 |
| 3   | .087  | -.254 | .750  | -.604 |
| 4   | .813  | -.502 | -.291 | -.032 |

Elapsed time 0:15:15.3
CHAPTER 3
LINEAMENTS THEIR SIGNIFICANCE AND INTERPRETATION

A linear trace on the earth's surface can be the expression of two dimensional geological structures. Therefore, to identify a lineament is, in many cases, to determine the existence and possible significance of a geological structure.

It is because of their importance that this chapter is dedicated to the subject of lineaments. Besides the definitions a short review of the mechanism and formation of lineaments as well as statistical methods for their analysis is described.

3.1 DEFINITION AND HISTORICAL BACKGROUND OF LINEAMENT INVESTIGATION

There is no universal definition of lineaments and many definitions are in use today. Probably the oldest definition was given by Hobbs (1912). Other investigators like Sander (1938), Lattman (1958), Billings (1972), Gay (1972), and others, have each contributed in the expansion of the lineament definition.

In this study the term "Lineament" is applied in its general context, to define all linears observed on airborne or satellite imagery used in the study irrespective of their genetic relationship, age, ground truth or scale. The reader will come across terms like "topographic/morphologic" lineament, tonal lineament, fracture trace, drainage lineament, and rift faults, all to mean lineaments without any genetic considerations. Gay (1972) defines a lineament as a linear feature annotated on a two dimensional document by an observer who believes it to represent a natural feature of the landscape (this includes geophysical documents, after Gay (1972).

BACKGROUND The study of lineaments started a long time ago. What attracted the first investigators was the phenomena of the "systematic" arrangement of fractures and faults and their common tendency to intersect at nearly right angles. This phenomena was well documented by 1835 in Britain to allow Wm. Hopkins to develop an advanced mechanical theory to account for the phenomena. In 1841 he published a map of the Wealden Dome which shows directly the orthogonal relations of the major linear features of the region as predicted by his story. This map appears to be a first attempt to show lineaments directly and in relation to other structures.

A first improved and "modern" lineament map was produced by Doubree in 1879. Using straight, intersecting lines on topographic base maps he showed the distribution of fault and joint systems over larger areas of France. His work was very much helped by the experimental work on the mechanics of folding and fracturing in layered media, extensive
fold observations of joints and the availability of greatly improved topographic maps at the
time. In 1880 Kjerulf followed with a similar interpretation for Norway based largely on
the geologic map of Norway just completed.

Between 1840 and 1880 very considerable advances were made in the techniques of
observing and analysing systematic fracturing. In 1839, Phillips developed the convention of
the rose diagram and used it to determine the disposition of fracture systems and trends
in Yorkshire. Others, such as De la Beche, Harkness, Sedgwick and Murchison continued to
compile voluminous observations on both the local and regional aspects of joint systems
and, towards the end of this period, it became conventional to plot joint direction on the
quadrangle geologic maps being produced by the Irish Survey under the direction of people
such as Foote, King and Kinahan. In spite of the greatly increased knowledge of the nature
of fracture systems and their physiographic expressions, there were, however, no further
attempts to produce "lineament" maps in the manner of Hopkins.

The American geologist Wm. Herbert Hobbs can be considered as the first
man who contributed greatly to the principles of observation and interpretation of line­
aments and lineament patterns which are in general use today, in a series of classic geologic
studies reported on over the first decade of the present century. Through his own detailed
observations he was able to confirm and greatly extend the work of Doubree and Kjerulf.
In a series of fundamental studies he developed the concept of "lineament" and "fracture
field" and outlined the principles of observation and interpretation of lineaments widely
used today.

The advance of imagery and photography has added a new dimension in our ability
to recognise and map the great lineaments of the earth’s surface on a broader manner as
well as on a local scale. Lineaments as such are playing an important part in geological
investigation.

The problems of interpreting photo-lineaments are complex. A lineament as viewed
on an image, may be a grey-level edge or a thin line on a contrasting background. An edge
or line may change polarity along the length of a lineament, or a line may change into an
edge. Some lineaments are still more complex. For example a valley illuminated normal to
its length will display a dark shadowed wall immediately adjacent to a strongly illuminated
wall. A lineament might be discontinuous due to erosion or deposition of materials and
might in fact, correspond to nothing more than an alignment of unconnected lakes.

The sun azimuth and scan line biases and the omission of lineaments parallel to strike
result in highly peaked orientation rose diagrams. The lineaments which lie near the sun
azimuth and scan lines trend are characterised as shorter and more poorly expressed and
thus not interpreted. The study has shown that by digital enhancement, even poorly
expressed lineaments can be successfully mapped irrespective of the bias of sun azimuth and scan line.

A rigorous analysis of lineament and joint orientation is not possible in many studies because of the subjective and qualitative methods of estimating the effects of bias. That is why there is no rigorous structural description of remotely sensed images because of the complexity of the images and the presence of noise.

3.2 INTERPRETATION METHODS OF LINEAMENTS

Many investigators have, over the years, been trying to find the best method of interpreting and analysing lineaments. Among these are: Blanchet (1975), Permyakov (1949), Pretorius et al (1974), Nemec and Kvet (1976), etc.

**Blanchet's Method**

Blanchet's technique (1957) is based on the assumption that the crust of the earth is abundantly and systematically fractured in four principal directions, that is N-S, E-W, NW-SE and NE-SW. If the crust was completely homogeneous the fracturing would have approached complete homogeneity. Therefore any irregularity and departure from symmetry is a direct result of various regional or supraregional heterogenous conditions within the crust. Any local departure from the systematic and regular fracture pattern can provide valuable information in fracture trace analysis.

He interpreted air photos for fracture traces which were measured for azimuths and length, and azimuth and length frequency diagrams were drawn. A directional analysis of fracture sets were carried out on the basis of azimuth comparison between the dominant directions of fracture sets and the hypothetical direction norms of the crustal fracture system which is assumed to exist in his area of investigation.

A contour map based on the number of fracture traces per sample unit area was drawn and called a fracture incidence map. Afterwards the directional and contour analysis, a map showing the maximum disturbance zones was drawn. These zones in effect represented areas which cover possibly positive structures. Blanchet also suggested that areas of low fracture density surrounded by areas of high density might indicate buried domes or anticlines.

**Permyakov's Method**

Permyakov suggested a method of structural analysis based on the analysis of fracture sets in bedrock, using empirical formulae. His aim was to discover the relationship of "megajoints" (he used the term "megajoint" to include all types of fractures whatever their size) to possible covered fold structures and then to determine the fold trend, style and dimensions of the structure.
Permyakov suggested a ‘parallelogram rule’ to determine the strike of a fold structure. This rule states that: the diagonal of a parallelogram constructed on the principal rays of a megajoint rose diagram, runs along the axis of the structure. The strike direction is usually the long diagonal.

The dimensions of the structure, such as the length and width as well as the length of both steep and gentle limbs, can be determined by simple trigonometric calculations using the length of principal rays and the angles between them. In general, the longest rays of a rose diagram are selected as diagonals of a parallelogram. If there are several rays of roughly equal length, a series of variations can be tried and the appropriate rays selected.

The minimum number of megajoints (fracture traces) required to have a valid result is 50. It is recommended that the fractures should be distributed over at least four sample areas well within the structure and preferably at right angles to the strike.

**Némec and Květ Method**

Nemec and Kvet, basing on the much older work of Doubree (1879), who is said to be the first to recognise the identical or nearly identical distances between joints and rupture zone, have tried to solve the problem of fracture trace analysis by using the so called “Planetary Equidistant Rupture System” (PER) method.

The PER system as a method is based mainly on the existence of pair sets (directions of joint zones perpendicular to each other) also forming rectangular pattern at the Earth’s surface. Six main directions are pointed out by the authors as characteristic for each grid of fractures: 54°, 90°, 306° and 324°, 0°, 36°, the last three directions being at right angles to the first three (Figure 3.1, 3.2).

According to Nemec and Kvet, a universal regularity of structural pattern can be expressed by a simple formula:

\[ Y_x = 2^x D \]

where: \( x \) = a given order of structures
\( Y \) = equidistances of a given order
\( D \) = the original constant (equal to the diameter of the Earth)

Using the above formula the authors have predicted equidistances for 40 orders; the first with 6377.000 km, the 20th order with 12.163m whereas the 40th order has a mere 0.12mm. The principle of equidistance for the same order and of halving the unit distance for deriving immediately lower orders serves as the methodological basis for predicting structural patterns.
Figure 3.1 Directions in the geometrical network of the joint zones.
1. primary lines, 2. secondary orthogonal lines. The angle of 90° connects points. From Kvet (1976, Fig. 1).

Figure 3.2 Outline of the Planetary Equidistant Rupture Systems
A = Alpine System, B = Hercynian System, C = Astypelic System, D = Nameless System. From Kvet (1976, Fig. 2).
Further, it is stressed that the PER system can be used in solving various problems of a global as well as a regional or local character (including some technical problems connected with mining activity). The number of observations of joints and ruptured zones can be reduced substantially if some parameters can be used a priori. With a priori knowledge of controlling directions for fracture grids and their respective equidistances, a new exploration strategy can be introduced and developed which can enhance the ability to predict in advance the occurrence and disturbance of economically favourable fracture systems (Nemec, Kvet, 1976).

Mohr (1974) reports that for the East African Rift System some groups of lineaments tend to be spaced at about 30-50km, this would correspond Nemec's 8th order equidistance (49.820 km).

Pretorius' method

Pretorius, et. al. (1974), approach to lineament analyses is an interesting one. A number of investigations have been carried out recently applying Pretorius's thinking, e.g. Critchley (1981), Hunting (1983), etc. Pretorius used a method for mineral exploration based on the analysis of the angular atypicality, that is, the degree of departure in the dominant (typical) orientations of the fractures in the field.

During the investigation a great number of fracture traces were interpreted on air photos and mapped. The sum of the lengths of fractures in angular (i.e. azimuth) intervals of one degree was calculated and plotted against the azimuth range of 0° to 180°. The result was sinus curve showing two peaks and three lows.

From the graph (Figure 3.3), it can be seen that a high proportion of fractures have orientations near those two peaks. These could be regarded as having "typical" orientations. In the same sense, those with orientations near the frequency low could be regarded as being "atypical". The proportion of fracture lengths with atypical orientations in a grid square (5 km x 5 km) was calculated. This gave an index of atypicality ranging from 0 to 1. These values were contoured using a standard computer program.

The contours of angular atypicality were used to deliniate target areas in the following ways, areas with high atypicality were noted. Approximately 20% of the total area had indices of 0.5 or more and 40% of the 180 features were within this part of the area.

The pattern of angular atypicality anomalies was carefully studied in relation to:

(a) known mineral occurrences within the area, and
(b) photogeological anomalies.
An association such as the occurrence of a series of contour peaks around a “quiet” area, within which several known features were clustered, and the occurrence of isolated peaks within areas of very low background were given special significance. In this way, target areas were delineated with clusterings of local occurrences of high atypicality peaks. Further detailed exploration could be confined to a small highly anomalous area.

Pretorius and his colleagues concluded that an angular atypicality analysis of fracture traces provided an effective screening technique by which unbiased identification of anomalous areas can be achieved.

3.3 MECHANISM OF FORMATION OF LINEAMENTS

Lineaments observed on the imagery of study area are either joints, faults, bedding (in Karroo sediments), dykes, or drainage. Man-made linear features like roads, railways and
even high voltage power lines on Scene 180/72 (not included) can be seen. However, the most important and dominant linear features on the imagery are faults, joints and drainage.

Most of these linear features should reflect the bedrock structure of the area. The mechanism of their formation and their genetic relationship is beyond the scope of this work. However a brief description of some of the possible causes for linear features is necessary so that a correlation can be made with the known lineaments of the study area.

In explaining the origin of fractures or lineaments many authors point out that crustal fracture systems are "store" systems of stress release at depth which are propogated upward into continental and oceanic lithosphere alike. As a consequence of ocean floor spreading and subduction, such systems are ultimately stored permanently only within continental lithosphere.

Brittle failure occurs in two ways; by extension and by compression.

**Extension**: during extension the fracture which forms is a plane perpendicular to the extension axis (minimum stress) and thus in a principle plane with zero shear stress. Minimum stress is the tensile stress and the fracture formed is the extension fracture (Figure 3.4a). Therefore extensional fractures are fractures parallel to maximum stress ($\sigma^1$), or that the direction of maximum stress lies in the plane of extensional fractures.

![Figure 3.4](image)

**FIGURE 3.4**

(a) extension fracture: $\sigma_2 = $ tensile stress.
(b) conjugate shear fractures: $\sigma_3 = $ maximum compressive stress; $\sigma_4 = $ minimum compressive stress. From Wilson (1974, Fig. 4)
Compression: during compression, when is the maximum compressive stress, often two conjugate shear fracture form at an acute angle to each other (Figure 3.4b) with movements in opposite senses. In shear fracture, the displacements after fracture are parallel to the fracture plane. Therefore all geologic faults may be described as shear fractures. C.A. Coulomb (1776) was the first to develop the theory of shear fracture. Conjugate shear fractures may occur singly or in some combination. Figure 3.5 shows the two types of shear mechanisms.

Faults: Some structures are faults and are shown as “trend lines” which show the “fabric” or “grain” of the crystalline basement.

The word fault refers both to the fault plane and to the displacements that have gone on along it. Where rocks have undergone observable displacement along a macroscopic shear or fracture plane in the earth they are said to have been faulted. Under certain conditions of rupturing, the fault plane may be a plane of cleavage fracture, that is, a tension crack as is suggested for some large fault troughs and perhaps for ring structures associated with igneous activity. The majority of fault planes are, however, either shear fractures or slip planes.
There are three main fault processes involved in the deformation of rocks and these are dependent upon the nature of the stress application:

- In the homogeneous isotropic materials, under compression, the compressive stress can be expressed in terms of a set of three mutually perpendicular axes: $\sigma_1^1, \sigma_2, \sigma_3$

- When rigid materials are stressed beyond their strength (breaking point) rupture results. The rupture takes the form of two sets of shear planes. These two shear directions are bisected by the maximum stress axis ($\sigma_1$) in such a way that this axis forms an angle of approximately 30° with each of the shears. The medium stress axis ($\sigma_2$) is parallel to the line of intersection of the two shear planes. The air/earth interface is a surface of zero shear and is thus normal to one of the three stress directions. Consequently, the maximum stress axis is usually horizontal or vertical.

The three main fault processes are thrust faulting, normal faulting and wrench or strike-slip faulting. Transcurrent wrench and strike-slip are synonymous except that transcurrent requires the presence of folding which is not a necessary attribute for the other terms. The three main fault processes are shown on Figures 3.6 and 3.7. It seems that two fault processes are dominant in the study area, normal and strike-slip faulting. There is no evidence of major thrust faulting in the area, however, rifting might be the cause of most of the fault traces seen on Landsat imagery as most of them tend to coincide with the principle rift trend. Some transcurrent faulting might be present in the Angonia structural region (see Chapter 5), where some evidence of folding has been confirmed and large scale fault traces seen on Landsat imagery.

Joints: Large numbers of joint traces can be observed in rocks, and although apparently the simplest, being merely cracks, they include a variety of types of diverse origin and dimension.

The lack of visible displacement in a direction parallel to the plane of a joint distinguishes a joint from a fault, but planes that appear to be incipient faults with no visible displacement are also classified as joints in many cases.

The majority of joints are of tectonic origin and represent either tension cracks or incipient shear-fractures, but jointing is often prominent in little-disturbed rocks including flat laying sediments as well as in folded and faulted beds. Accordingly, it has been suggested that such jointing may represent fatigue cracks formed by small alternating stresses.
FIGURE 3.6  INITIAL STRESS DISTRIBUTION CAUSING FAULTING, ACCORDING TO ANDERSON From Badgley (1959, Fig. V11-19).

\[ \sigma_1 \text{ maximum, } \sigma_2 \text{ mean, } \sigma_3 \text{ minimum (compressive) stress.} \]

In B, ab = dextral (clockwise) and cd = sinistral (anticlockwise) displacement.

FIGURE 3.7  Theoretical Wrench Fault, Thrust Fault, and Fold Directions for a Homogeneous Media Under Simple North-South Compression From Badgley (1959, Table 16).

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<tr>
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<tr>
<td>LL N30E</td>
<td>E-W</td>
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<tr>
<td>RL N15 E</td>
<td>N45 E</td>
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<tr>
<td>RL N75 W</td>
<td>N45 E</td>
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<tr>
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<td>N45 W</td>
</tr>
<tr>
<td>RL N30 W</td>
<td>N-S</td>
</tr>
<tr>
<td>RL N30 W</td>
<td>N-S</td>
</tr>
<tr>
<td>RL N60 E</td>
<td>E-W</td>
</tr>
<tr>
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<td>LL N60 W</td>
<td>E-W</td>
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</table>

Note: A homogeneous isotropic material subjected to simple compression will shear at angles of 30° to the direction of maximum stress application even though the planes of maximum shearing stress are parallel to the intermediate stress axes and lie at 45° to the maximum compressive stress. The 13° angle between the 45° maximum shear planes and the 30° shear planes which actually form is believed to be due to internal friction.

A compressive stress applied to a uniform isotropic material commonly can be resolved into three stress directions (maximum, intermediate, and minimum stress axes). The air-earth interface is a surface of zero stress and is frequently normal to one of the principal stress directions. Consequently one of the three principal stress directions is often vertical.

If movement is in progress on a main fault or master shear, stresses in the "adjacent blocks" will have such orientations so as to cause failure on new pairs of mutually complementary planes (second order shears). The new major stress direction is reoriented through 13° from the previous main stress direction. This 13° angle has been observed commonly in the field and is simply an empirical average. This angle has not been explained satisfactorily from a mathematical point of view as yet.

The shear and anticlinal directions in the above table indicate that the third-order directions start to duplicate the first-order directions. Thus it is impossible to distinguish between first- and second-order orientations. Consequently an infinity of shear directions does not exist. The system is resolved into eight major shear directions and four major anticlinal and thrust directions for any tectonic province. In practice the first- and second-order features are distinguishable without difficulty whereas the third order features commonly are difficult to find.
First order joints originate as a direct result of strain and second order joints result from readjustment of stress following the first order jointing or taking a different pattern.

Tension joints are fractures formed at right angles to the direction of extension of rocks. The formation of tension joints involves an increase in volume of the affected rock mass, unless this increases the density by compaction to compensate for the joint openings. The increase in volume accompanying all joint formation indicates that many joints may form with decreasing rather than increasing stress, being then due to relief of strain including relief from geostatic loading consequent upon erosion.

Shear joints are smoother and straighter than tension joints, they are tighter when unweathered and those related to a regional fault pattern may persist along the strike for long distances, of the order of kilometers or tens of kilometers. Shear joints tend to be more intensely developed (i.e. having closer spacing) in certain belt or zones, with less intensely jointed rock between these. It is along such joint zones that weathering and erosion is concentrated and streams tend to take their courses. Shear joints are probably dominant traces seen on Landsat imagery of the study area, most of them linked with the basement structures (NNE), rifting and sometimes rocks types.

Regional mapping of joints will generally reveal geometrical relationsip to faults, folds, warps, intrusion and other tectonic elements that will suggest genetic connections with the stress distribution and strain pattern. But Hills (1963) warns that is rare that an entirely satisfactory synthesis can be made. Classification of joints by displacement is shown in Figure 3.8.

FIGURE 3.8 Classification of joints by displacement. (a) Extension joint. (b) Shear joint. (c) Shear joint with finite normal displacement, alternatively classed as an "oblique extension joint".
Orthogonal Fracturing

Among the most discussed and most frequently observed fracture pattern on aerial photographs or satellite imagery, with a regional coverage, is the phenomena of orthogonal fracturing which has been reported by many authors. Polygonal fracturing or regmatic shear patterns are nothing more than terms describing orthogonal fracturing. Many investigators describe orthogonal fracturing or orthogonal symmetry as a characteristic of lineaments aligned along specific directions, roughly oriented NE and NW and said to be due to the earth’s spin.

Many investigators have been attracted by this phenomena for many years back. Saunders was among the first investigators to explain that major lineaments diverging in trend from great circles are in reality a fracture pattern due to failure of the crust resulting from torsion about the earth’s axis of rotation. And Hobbs (1911), explains that in precambrian shield and basement rock areas on most continents persistent, quasi-orthogonal fracture and joint patterns have been recognised. Later Sounders designated this as a "Regmatic Shear pattern". Four major trends are recognised in this pattern: NW, NE, N and S. The diagonal sets seem to be more dominant. Landsat linear features of the study area have shown little of N and S trends and the WNW, NE trend is not as frequent as NNW, NNE, ENE and NW trends.

Many theories about the origin and actuating mechanism of the orthogonal fracturing pattern (linears and lineaments) have been introduced since the early decade of the nineteenth century. These theories range from those related to extra-terrestrial (or planetary induced) stresses such as polar displacements, change in the rotational speed of the earth and earth tides, to those related to internal stress within the earth (intraterrestrial) such as those resulting from deep-seated tangential compression convective currents, and post glaciation isostatic recovery.

The mechanisms responsible for the origin of the orthogonal lineament system are as yet unknown, but some investigators suggest that the systems are inherited from underlying jointed rock, possibly through earth tide induced fatigue or as "bridging" (Gay, 1973) mechanics. Wise (1974) has suggested that orthogonality in fracturing may result from the fact that failure by rupture in one direction relieves the minimum stress in that direction, shifting the minimum stress 90° to form a second fracture set at right angles to the first. If lineaments are related to fracturing, such an explanation also may be valid for their patterns.

Plate tectonic models also produce orthogonal fractures pattern for example at the junctions of transform faults with extensional rift and compressional subduction zones.

In the non-orthogonal system, fracture orientations are more apt to be consistent with predictions based on maximum shear stress theories. While the orthogonal fracture pattern appears to be one of strong orthogonality.
3.4 STATISTICAL AND DIGITAL PROCESSING OF LINEAMENTS

Interpretation methods for lineaments differ greatly, according to the specificity of the problem. Problems like scale of interpretation, the environment, type of rocks, statistical method employed, quality of the imagery, etc. must be taken into consideration.

In this investigation Landsat lineaments have served as the principal source of information. The statistical method attempted can add extra information which when combined with other data can help to solve geological problems. The objectives of adding statistical analysis to the study can be summarised as:

- to identify major lineament trends;
- to assess the lineament distributions pattern and their significance;
- to identify and trace rift faults;
- to assess the Landsat and aeromagnetic lineaments and their importance;
- to assess the relationship between lineaments and mineral occurrences;

A word of caution on computer techniques or geostatistics in geology is given by J. Robinson (1982). He points out that "computer geology should not be looked upon as a black box producing mystical or mythical solutions to exploration problems. Exploration geologists can best utilise computer aids when they understand the data used by the computer and the processes that convert those data to the final display."

Geology is sometimes called descriptive science, however, it is a logical science, and most geological observations can be coded or quantified in systematic ways so that geologic processes can be described or modelled.

Robinson further points out that "Statistical procedures are very important in exploration, for much of statistical science deals with the estimation of some fact or parameter from an incomplete set of samples. Exploration geologists never know the complete picture of the subsurface; they deal entirely with sampled data, often very poorly sampled, and they must make the best in interpretation or statistical inference from these data". This is in fact true for all Landsat data.

Applied statistics can aid the exploration geologist estimate, however, one must be selective in utilising statistical tests, for they are not universal and many may work only under specified conditions. The statistical utilisation in the study has in mind the above mentioned limitations and no detailed statistical work or analysis is involved.
Digitising Fracture Maps

Careful preparation of the fracture map to be statistically analysed is a very important stage in digital image processing of lineaments. Factors like the scale at which a map is to be digitised is also important. During the study it has been noted that we do not get the best reproduction of a computer fracture map if it is digitised at a small scale (e.g. 1/500,000).

Besides, it has been noted that many inaccuracies are introduced by mapping from an image nonstructural lineaments as structural lineaments, this is a problem in all satellite based imagery interpretation. This problem can be overcome by mapping a great number of lineaments, and handling them statistically assuming that only a limited percentage of interpretations are in error. This technique is very widely used by photo interpreters for the purpose of defining structural trends and locating faults in regions of poor bedrock exposure. The introduction of the computer has facilitated greatly this approach as now we are able to process thousands of lengths, azimuths, intersections of linears, etc. in a few seconds. Besides, the computer can transform this data easily into graphical displays which can help the interpreter to do trend surface analysis, strain analysis and other analyses.

This study is not intended to investigate computer implemented mathematical and statistical techniques, the computer program has been employed in order to illustrate how the sorting out of the large amount of fracture traces and production of graphic displays for visual analysis is done rapidly.

Over 1800 Landsat fracture traces and 400 aerial photo fracture traces were digitised. Landsat fracture traces were for parts of Tete and Angonia, whereas the aerial photo fracture traces covered the area between Ulongue and Metango Belame of Angonia Structure. The Landsat and aerial photo fractures were digitised each separately at 1/100,000 scale. Whereas for Tete digitising was done at 1/150,000 scale. In Angonia the faults shown on geological map and having the same azimuth as Landsat fractures were also digitised.

Digitising a fracture trace map involves converting the fracture traces from graphic or line form into digital form. There are two main digitising methods, line information and point information, the latter method was applied in this study.

An example of point information digitising method is shown in Figure 3.9. Digitising the maps was done by placing them on a digitising table which was connected to a computer terminal. An American Scientific Accessories Corporation (SAC) Graph/Pen digitiser was used.
The map axis was digitised first, then the map boundary corners were digitised. Digitising was done as shown on Figure 3.9, starting with the SW corner (point 1), followed by points 2, 3 and 4 respectively. When this was accomplished the fracture traces (lineamens) within the map were digitised. As fracture traces are of different shapes and lengths, the number of digital points on each fracture trace varied. A straight trace was identified by two digital points (e.g. A-B), all curvilinear traces were identified by three or more digital points (e.g. A - B - C - D - etc). For the computer to identify the end of each individual trace a point has to be digitised outside the axis line, in this case point 5 (or any point with a negative Y-axis value). While digitising the point values are simultaneously displayed on the TV monitor as a pair of coordinates (+X, +Y), irrespective of where the starting point position. Any negative Y value (e.g. +x, -y) means an end of a fracture trace, and this arrangement was used by the computer program to identify individual fractures.
Computer Program for Image Analysis

Using the computer program FRACAN used by Critchley (1981) and refined for the study, statistical processing of the fracture traces was accomplished. However, before the digital point values could be used by the computer, it was necessary to transform the points values into new computer format, this was accomplished by writing a short program which was called FRACAO (See Appendix 1).

The program FRACAN is designed to extract statistical information including the number and relative number, length and relative length, and average length of fractures in the 0-180° area for every cell of the map sheet grid and the whole map sheet. Atypicality and entropy analysis is the other set of data which the program offers. Also several graphics, rose diagrams, rossets and fracture trace maps are produced. It was also possible to display fracture traces subdivided into different orientations.

In geology often we are interested in the manner in which points are distributed on a two dimensional surface or a surface or map, this data can be represented as a two-dimensional spatial frequency distributions or as contour maps. Both are in fact closely linked and both involve the counting of statistics on some form of grid system. The most common method of generating computer contoured maps is first to interpolate a grid of uniformly spaced values and then contour this grid. Also for the construction of a display of rosettes a grid has to be determined prior to analysis.

The grid construction is important and a well thoughout and justified decision has to be taken before a grid is chosen. Fractures are not always absolutely rectilinear and may migrate across an area. For example, if we intend to redraw all fractures between 15° - 25° east it can happen that in parts of an area migration has taken place due to changes in regional stress; some traces may have moved out of the filter range 15° - 25° and likewise perhaps another group of traces may have moved in. Herein lies one of the more complex problems encountered in automatic analysis and points to the fact that it may often be more practical to split large regional areas into smaller area units (cells).

The grid size can be obtained automatically, in programmes designed to drive a plotter or similar graphic device, the cell size generally is under the control of the operator, as is the case in this study. Reducing the size of the interval between grid lines produces an aesthetic improvement in the map, because line segments become smoother; however, this also increases points that must be estimated, increasing thus the running time and cost of the program.
The choice of the grid in the study was done by taking into consideration the manner in which the fracture traces are distributed and also the limitations imposed by the program. Two types of grids were employed: 15 x 15 km for the Tete area and 10 x 10 km for the Ulongue area. Smaller grids would produce huge amount of cells and rosettes beyond the capability of the program. Also smaller cells would have reduced considerably the amount of fractures analysed in each cell, resulting in a display of varying rosette orientations which in turn obscured the regional trends which were of more importance to this work.

3.5 COMPUTER PRODUCED GRAPHIC DISPLAYS AND STATISTICS

A summarised list of the most applied computer generated plots (from Gallagher and MacGuire, 1976), are listed below:

data plots, rose diagrams, histograms, orientation bar diagrams, scatter diagrams, trend orientation plots, and contour maps. Scatter diagrams are made by the number and length fractures vs orientation, usually they are not widely used.

**Data plots** - data plots show the actual map positions of the lineament, and the spatial relationship of each individual linear feature to all other lineaments in the specified data set. These computer displays, here called “Tectonic Fabric maps” allow rapid verification by direct overlay at the digitisation scale into the original lineament maps that all desired features have been properly digitised and entered into the computer, and therefore, are ready for statistical analysis.

Data plots were produced for both Ulongue and Tete, these were of two types: the first type displayed all fracture traces irrespective of their orientations and the second type showed determined directions.

**Rose diagrams**: rose diagrams display the frequency distribution for the direction of lineaments with the frequency expressed in both absolute and relative values; that is amplitude and percentage. Rose diagrams are good instruments in representing the directional distribution of fracture traces. In order to make data of the distribution more interpretable the frequency values are normally transformed into percentages and then used in the plotting of a rose diagram. For this work frequency, length and average length rose diagrams were produced.

**Histograms**: Three types of histograms are potentially useful (Gallagher and McGuire, 1976). These are:

- frequency distributions for total length per cell versus length cells - showing the total length of all lines within the specified cell limits;
- Number of linears per unit length versus length cells - showing how many lines there are with lengths within the specified cell limits.
- Orientation bar diagram - showing the frequency distribution for the orientation of lineaments.

Cartesian plots are preferred by some authors over rose diagrams and histograms because, as Gay (1973) points out, rose diagrams do not provide an investigator with quantitative appreciation of the primary strike directions present, and this refers to histogram plots too. These plots, according to Gay, do not lend themselves to averaging, which he considers necessary to eliminate the erratic variations that occur many times from one narrow acute segment to the next. However he recognises the fact that rose diagrams have an advantage over cartesian plots in indicating strike direction. Therefore to overcome this disadvantage of the cartesian plot he has employed a plan diagram showing the characteristic strike directions at the bottom of each of his cartesian plots (e.g. Figure 3.10).

**FIGURE 3.10.** Cartesian plot and Plan diagram showing Characteristic Strike directions. Gay (1973, Fig. 3).

Trend Orientation plots (rosettes)

To create the trend orientations plots, the computer program is designed to divide the entire data set (or any selected portion) into square domains with dimensions specified by the interpreter. The length and slope of the linear segments are calculated for each cell, and the sum of the total length of segments which fall within each orientation cell whose width is also chosen by the interpreter are calculated. The orientation cells which contain the highest total length of linear segments are determined, and the cell which has the
greatest total length of linears is specified. The length for this cell is converted to a unit vector whose magnitude is half of the dimension of the selected cell size. The magnitude of the other vectors to be plotted are calculated in proportion to the unit vector. All vectors are then plotted such that the starting point for each is at the midpoint of the corresponding area domain, and the slope of each is the midpoint of the limits of the corresponding orientation cell.

The most useful aspect of trend orientation plots is that the changes in preferred orientations across a sheet are usually apparent. No other computer-generated plot, diagram, or map displays this aspect of the lineament data set so vividly.

Relative Entropy and Atypicality Statistics

Based on the Pretorius' principle, the FRACAN computer fracture analysis program was designed to prepare these statistics which could be input for contouring. In such a way contoured maps for fracture length density, relative entropy, atypicality index could be obtained (see Critchley, 1981).

Relative Entropy: relative entropy is a measure of the randomness of the orientation of the fractures and is expressed as a percentage figure. A value near 100 per cent indicates that the fracture orientations are randomly distributed; a low value indicates that the fractures fall into one or a few of the class intervals. The figures do not give any specific information on direction, only upon the variety of it.

Atypicality: atypicality is a figure for a statistical cell expressing the proportion of occurrence of fractures of non typical orientations, atypical orientation being established on regional data. An example of its use as an aid to mineral exploration is given by Pretorius and Partridge (1974). The atypicality computer program searches through the fracture data of a whole sheet to find the angular intervals with the smallest number of fractures (from the length data). This search is continued until 40% of the total number of fractures have been accounted for. The angular intervals involved in this 40% of data are taken as the atypical orientation. If most sectors contain similar numbers of fractures, the search may halt prior to 40% mark. The atypicality is then expressed for each cell, a value of one showing that all the fractures are atypical in direction, whereas zero indicates that all are in the typical direction.

Examples of tables containing the relative entropy and atypicality statistics are shown in the appendix. Rose diagram and rosettes were also obtained, but no contour maps were prepared as time did not allow. From the above discussion it is clear that statistical methods are important in Lineament analysis, and taking into consideration the huge amount of data that satellite imagery offers.
FIG 3.11a AERIAL PHOTO TECTONIC FABRIC MAP.
FRACTURE TYPE=ALL
ROSE DIAGRAM OF WHOLE SHEET

FIG 3.11b AERIAL PHOTO TECTONIC FABRIC MAP.
FRACTURE TYPE=ALL  FRACTURE FREQUENCY
FIG 3.11c AERIAL PHOTO TECTONIC FABRIC MAP.
FRACTURE TYPE = ALL
FRACTURE FREQUENCY
FIGURE 3.11d

ANGONIA LANDSAT TECTONIC FABRIC MAP.
FRACTURE TYPE=ALL
ROSE DIAGRAM OF WHOLE SHEET

FIGURE 3.11e
ANGONIA LANDSAT TECTONIC FABRIC MAP.
FRACTURE TYPE=ALL
FRACTURE FREQUENCY
ANGONIA LANDSAT TECTONIC FABRIC MAP.
FRACTURE TYPE = ALL
FRACTURE FREQUENCY
FIG 3.11g AERIAL PHOTO TECTONIC FABRIC MAP.
FRACTURE TYPE = 4
ROSE DIAGRAM OF WHOLE SHEET

FIG 3.1 lh AERIAL PHOTO TECTONIC FABRIC MAP.
FRACUTRE TYPE = 4
FRACTURE FREQUENCY
FIG 3.11i AERIAL PHOTO TECTONIC FABRIC MAP.
FRACTURE TYPE=4
FRACTURE FREQUENCY
Figure J.11

Fracture Type = 4

Angonia Landsat Tectonic Fabric Map.

Fracture Type = 4
ROSE DIAGRAM OF WHOLE SHEET

FIGURE 3.11k

ANGONIA LANDSAT TECTONIC FABRIC MAP.
FRACTURE TYPE = 4  FRACTURE FREQUENCY
FIGURE 3.11

ANGONIA LANDSAT TECTONIC FABRIC MAP.
FRACUTRE TYPE = 4
FRACUTRE FREQUENCY
CHAPTER FOUR
REVIEW OF THE GEOLOGY OF THE SOUTHERN SECTION OF THE EAST AFRICAN RIFT SYSTEM

4.1 INTRODUCTION

Five ancient structural provinces are recognised in South and Central Africa constituting the Cratonic nuclei (Figure 4.1). These Cratonic nuclei are separated by mobile belts in which subsequent tectonothermal events have caused polyphase deformation and high grade metamorphism. The craton areas are composed of granitoid gneisses and greenstone belts constituting a shield overlain in places by Precambrian and Phanerozoic supracrustal rock sequences. The intervening linear mobile belts mark the sites of repeated intense deformation and metamorphism. The origins of these linear zones are still imperfectly known but there is an increasing volume of evidence to suggest that they are ensialic in origin.

The East African Rift System is located in one of these mobile zones and it extends from the Limpopo Belt to the Arabian Gulf. The Ethiopian and North Kenyan section of the rift is called the northern rift, further south it branches into the Western and Eastern rift systems. As shown in Figure 4.2 the two branches merge in southern Tanzania before extending towards the Limpopo Belt through the study area. This part of the rift is here called 'Southern Rift'. To the south of Lake Niassa the Southern rift is represented by the Shire graben, and south of river Zambezi, by Urema graben.

In this chapter the geology and structure of the East African rift system is summarised, including that of the study area despite the little information about this region.

RIFTING, MAJOR FAULTING AND RIFT STRUCTURES

There is still no clear understanding of the mechanism of rifting and it has been a point of debate in recent years. As pointed out by Neumann and Ramberg (1977), even the term "Rifting" has been a subject of debate because the problem of the definition of the term is entangled with some of the most important but still unanswered questions concerning the process of rifting.

In relation to the East African rift, Pallister (1971) points out that there is a tendency to assign all major faulting in East Africa to rift tectonics; or on the other hand restrict the term "rift structure" to the Late Cainozoic faulting which has given rise to striking topographic troughs.
Fig. 4.1. Simplified map of southern and central Africa showing the distribution of cratons and mobile belts. The Limpopo mobile belt is ~2.6 Ga and older, the Ubendian (2) is ~1.85 Ga; the Kharan, Irumide, Khiba—Matsap, and Namaqua—Natal belts (3) are ~1.1 Ga and the Damara, Gariep, Malmesbury and Zambezi belts are ~0.6 Ga. Solid black areas within the Damara belt are inliers of older basement. A = Kafue anticline; B = Hook granite, C = Grootfontein inlier, D = Kamanjab inlier. The unlabelled area near the southern flank of the Damara belt is the extensive inlier south of Windhoek. From Hunter and Pretorius (1981, Fig. 7.1).
Figure 4.2. The taphrogenic lineament of eastern Africa in relation to the line of Bushveld igneous complex of southern Africa. From McConnell(1980, Fig. 1).
Dixey (1956) defined the term "rift" as applying to a system as a whole" indicating a structure due to parallel faulting, usually of the normal type.

On East African rifts a lot of pioneering work has been carried out by investigators like Gregory (1936), Bucher (1933), Cloos (1939), Baker (1957), Dixey (1956), and many others. But many of the modern concepts about rift systems are due to the upsurge of the new global tectonics and geophysical investigations.

The question about the formation mechanisms of rifts is not the scope of this investigation; this subject has been covered by many investigators like McConnell (1951), Bishop (1966, Baker (1974), Dixey (1941), Vail (1967), Cloos (1939), Freund (1965a), Bailey (1961), Meinesz (1950), Logatchev (1978), Wilson Ramberg (1967), and others. Two principal theories exist about the formation of rifts, by means of doming and by extension.

Cloos (1939) argued that rifts are formed by crustal doming, and this idea is still current. Bhattacharji and Koide (1978) argue that the "initial development of ridge-basin and ridge rift valley structures is directly related to extension resulting from excess magma or intrusive pressure. Later subsidence in the central basin or graben due to lowering of magma pressure immediately above the intrusion accentuates ridge-rift valley or graben structures. This is contrary to the collapse hypothesis of rift valley formation by reduction of magma pressure as invoked by some authors".

Rifting and Magmatism

The nature of the relationship between magmatism and tectonics in rifting is still unclear. Some authors, like Logatchev (1978) think that there is a simple relationship between structure formation and vulcanicity. In a series of regions, the volcanic fields and rift structures (troughs, faults) are associated with each other only paragenetically, i.e. magmatism and tectonic movements in the upper crust proceed more or less independently of one another though they have the same abyssal source.

It has been recognised that the patterns of magmatism in the continental rift systems differ. They may vary between those with strong volcanicity and close interrelation between magmatic activity and extensional tectonics, and others with weak magmatic activity where the volcanism seems to be essentially independent of the faulting (Logatchev, 1978; Milanorsky, 1978). Rift zones commonly bear evidence of several separate periods of rifting and volcanism. Rift magmatic products are generally mildly to strongly alkaline, but tholeiitic and calcalkaline rock types may also occur (e.g. Milanorsky, 1978). It is known also that there is a decrease in alkalinity with time e.g. the Kenya rift (Baker et al, 1978), and increasing alkalinity with distance from the rift axis, e.g. East African System (Barberi, and Varet, 1978).
In relation to volcanism the East African Rift System can be divided between the northern rift with very strong volcanism (Kenya and Ethiopia) and the southern rift which manifests somewhat weak volcanism. Logatchev has pointed out that in the rift zones with strong volcanicity magmatic activity crustal movements are closely interrelated and interdependent. This is the case in Kenya and Ethiopia where still existing hot springs, steam jets, fumaroles and microseismicity is still evident, is an evidence of the strong volcanism of the northern rift. In rifts with weak volcanism, magma formation and volcanicity are essentially independent of the development of rift faults and valleys proper; Baikal and the Rhine rifts are considered examples of this. We can assume that the rift in the southern part of East Africa is probably a zone intermediate between the two types, that is, a zone of weak volcanicity but occupying an intermediate position in terms of the relationship between magmatism and tectonic structures. Figure 4.3 is Logatchev's illustration of the two stage history of continental rift zones. From this illustration Figure (a) corresponds to the lake Edward type, whereas Figure (b) corresponds to the lake Albert type.

Figure 4.3 Schematic illustration of the two-stage history of rift zones with strong volcanism (a), and weak volcanism (b). 1-sialic crustal rocks; 2-volcanics, mainly basalts; 3-zones of attenuation and permeability for the upper mantle melts; 4-sediments of various origins 5-faults. From Logatchev (1978, Fig. 1).
Many authors have also suggested that there exists a correlation between rift characteristics and tectonic regime. Rift systems closely connected in time and space with orogeny tend to be isolated and to exhibit complex horst and graben provinces, poorly defined triple junctions, and calc-alkaline volcanism; on the other hand, rifts believed to represent embryonic accreting plate boundaries have an obvious main axis, well defined triple junctions, and alkaline to tholeiitic magmatism (e.g. Milanorsky, 1978). However, it is not known if these differences are related to the causal mechanism of rifting, or if they result from differences in the structure of the lithosphere.

The configuration which a rift will have depends on many factors including magmatism and time. It is assumed that all successful rift systems will develop into oceans, and this have led to some authors like Burke (1978) to call all preserved rifts as “failed rifts”, because they have not succeeded in developing into oceans.

Although Tuzo Wilson’s suggestion that the earth’s history should be regarded as recording a series of complex, interwoven, cycles of ocean opening and closing, sometimes known as “Wilson Cycles” (Dewey and Burke, 1974), “failed rifts” in the Archean have not yet been recognised (Burke, 1978). The oldest preserved “failed rift” structure, according to Burke, is the Great Dyke of Zimbabwe (2.5 Ga) which represents the axial dyke of a rift valley system and terminates in fold belts, with sature zones marking the place where oceans have closed in the Zambesi and Limpopo Valleys. Axial mafic dyke systems have been located in both active and ancient rifts and activation of the basalt-ecologite transition in these systems may be an effective way of promoting the repeated subsidences that characterise many rift complexes, such as those of the North Sea. Ancient rifts striking into fold belts are known as aulacogens.

4.2 MAJOR FAULTING AND RIFT STRUCTURES OF EAST AFRICA

The southern part of the rift system of East Africa may be regarded as a chain of grabens, faulted basins and monoclinical flexures of neogene age comprising narrow zones of tectonic depressions extending from the northern borders of Uganda and Kenya to the coast of Mozambique near Beira, and probably further south towards the Limpopo Belt.

In some parts of this region the Neogene movements which give rise to the rift valleys have been regarded as rejuvenations of structures established during Pre-Cambrian, Late Palaeozoic and Cretaceous periods of tectonism (Dixey, 1956; McConnell, 1951).

In regional terms, the zones of rift fractures separate the Somalia-east Kenya, north Mozambique and Lake Victoria stable blocks from the rest of Africa, and the Lake Victoria block separates the southern part of the eastern rift from the northern part of the western rift (Baker, 1971). These two parts of the rift system are joined in eastern Tanzania, where
there are connecting fractures causing asymmetrical faulted troughs. In this region the meridional trend of the rift zone is recognisable, but the trend of the component faults of the system is influenced by the fact that it crosses a series of fractures of north-east orientation.

According to Dixey (1956), the rift valleys traverse regions which have been uplifted epeirogenically to form part of the “basin and swell” structure in Africa. Two branches of rift valley are recognised in East Africa (north of the study area): western and eastern rifts.

The eastern rift traverses the Ethiopia and Kenyan domes, and the western rift traverses a region of uplifted and locally warped plateau.

There is good evidence, according to Baker (1971), that the continental uplifts and the subsidence of the eastern parts of the Somalia-east Kenya block, which gave rise to the extensive Tertiary marine sediments of Somalia and east Kenya, were synchronous and related movements. It appears reasonable to associate the updoming of the interior, seaward tilting of the blocks of eastern Africa and downwarping of the continental margin as fundamental processes of tectonic activity in this part of the continent. The rift valleys were formed at a late stage of this process along the axes of internal uplift by fracturing and collapse of elongated strips of the crust (Baker, 1971).

Throughout East Africa from the continental margin to the western rift, major fracturing along a diversity of directions, sometimes accompanied by tilting or warping, has given rise to differential uplift and depression of blocks of varying dimensions and shapes. Movement has been active intermittent since pre-Karoo times.

Horsts, according to Pallister (1971), are represented by the coastal islands of Zanzibar, Pemba, Mafia, and on a major scale by Madagascar. Probably here could be included numerous islands along the Mozambique coast, like Vamizi, Ibo, Matemo etc. Likewise on the mainland the massifs of the Ulunguru, Usambara, Pare mountains in Tanzania and Bur Akaba in Somalia form prominent topographic features, while less prominent topographically are structurally similar. Further inland many elevated blocks such as the Ruwenzori massif of Uganda, Livingstone range and Mbeya mountain of Tanzania owe their altitude to combined faulting and tilting. Conversely, structurally negative areas are recognised in the Zanzibar and Pemba channels, the depressions containing Karroo sediments and overlying beds in western Madagascar, south-east Tanzania and Malawi.

Within this broad region of block faulting certain zones exhibit a concentration of sub-parallel faults which have by their magnitude and concentration given rise to major rectilinear features. Such zones as developed in Late Cainozoic times display prominent
topographic characteristics: the rift valley west of Nairobi in Kenya, the rift valley of the Shire river and Lake Niassa, the Albert rift of Western Uganda and the Rukwatrough of Tanzania.

Therefore, as points out Pallister (1971), there is a certain broad distinction to be drawn between block-faulting and the special concentration of parallel faults which is termed rift faulting. Both types of systems are associated with upwarping - a fact well recognised by Bailey Willis and well documented by Dixey in his various studies of east Africa erosion surfaces.

Dixey (1956) has stressed the very early antecedents of rift structures and has related the Cainozoic faulting to old tectonic lines, some Pre-Cambrian in origin. The genetic relationship during such a long period of time is not established. It is certain however that the crystalline basement of east Africa has many lines of structural weakness some of which reacted to stresses in later geological epochs. Elsewhere new lines of fracture appeared. At various periods in Post-Karroo, Post-Jurassic, Late Cretaceous, Pre-Miocene and Pleistocene, stresses were relieved by movement on old lines and by new fractures.

According to Pallister (1971), five principal concentration of tectonic fracture are discernible:

- East African coast of Mozambique channel;
- the NNE line of the Somalia coast and the "fall-line" of Tanzania;
- the eastern or Gregory rift system;
- western rift system and;
- the Gulf of Aden zone.

The main periods of faulting of the eastern rift valley and the northern part of western rift valley were more or less contemporaneous, but the amount of movement that took place during each phase varied considerably from place to place. The earliest fault movements recognizable in Kenya were of approximately earliest Miocene times, initiating the Turkana depression. Subsequent more extensive faulting took place on the west side of the rift valley at the end of the Miocene period, but the largest displacement started in Mid-Pliocene times and extended to the Mid-Pleistocene period.

In the northern part of the western rift, movements began in Early Miocene times, with major movements taking place in Late Pliocene in mid-Pleistocene times. In the remainder of the western rift system the ages of movements are not well established owing to the scarcity of dated formations affected by faulting or deposited in fault basins.

Karroo and Late Mesozoic movements in the western rift have been presented by Dixey (1956), but the most recent movements which gave rise to the well-preserved fault
escarpments are generally regarded as of Quaternary age. These can be found in Kenya, northern Tanzania and Malawi. It is thought that the Late Cainozoic faults giving rise to Lake Niassa is concealed by the lake. The exact dating of these late movements in this southern region is not clear, but the many scarps in the shire and Urema grabens, well documented on Landsat imagery, indicate the Late Tertiary rejuvenation. Miocene sediments in the north part of the Shire graben and in the Urema graben suggest that Mid-Tertiary movements also occurred.

Precise calculation of the extent of total displacement in the East African rift is hindered by unknown thickness of sediments or volcanics in the rift floor.

Displacement varies greatly from place to place. According to Baker (1971), in the Kenya rift the central part has certainly been displaced by not less than 2000 m while in the less uplifted parts of the regions displacements of 500 to 1000 m are common. At the western margin of the Ruwenzori block the total displacement was at least 4500 m.

In general, there is a notable correlation between the amount of uplift of the marginal plateaux and the amount of displacement on the rift faults, an observation which has led many investigators to the conclusion that the rift valleys were formed primarily as a result of the uplift of the surrounding regions while the graben themselves remained static or were actually depressed by the action of gravitational forces.

The eastern rift especially is characterised by the extent and variety of volcanic rocks associated with it. Studies in Kenya illustrate the close relationship between faulting and volcanism in time and space.

In the western rift volcanic rocks are more reduced, and consist of very localised fields of Pleistocene-Holocene age closely associated with rift faults in Lake Kivu–Lake Edward area, and the Rungwe Volcanics of south Tanzania. In Malawi late Jurassic carbonatite and other related alkaline igneous centres occur in the rift valley floor or nearby and show alignment parallel to rift structures.

A group of Miocene carbonatite centres occurs in the floor of the Kavirondo graben of Western Kenya and extends northward in eastern Uganda. Other carbonatite centres occur scattered along the Western rift, in southern Kenya and in north Tanzania. These centres are of a variety of ages ranging from Mesozoic to late Tertiary. Many of the more recent neophelinitic volcanoes of the rift zone undoubtedly have unexposed carbonatite cores, and one natrocarbonitite volcano, Ol Doinyo Lengai is still active in northern Tanzania. The association of alkaline igneous activity and carbonatite emplacement with the rift valleys is one of the notable features of the region (King and Sutherland, 1960).
The magmas of East Africa differ decisively from the potash-poor theoliites of the oceanic ridges. They are said to be among the most strongly alkaline rocks of the earth, many with sodium plus potassium making up more than 10 per cent of the rock, according to some studies. Some are potash rich, others are highly sodic, and many carbonatite pipes exist, some of which are still active. Most of these rocks are rather basic but some of the younger lavas are salic and, according to Baker (1971), perhaps owe their peculiar chemistry to contamination by fenitised crustal rocks.

4.3 THE GEOLOGY OF UREMA AND SHIRE RIFT SYSTEM

In this study, “Mozambique Rift” refers to the portion of the rift extending through Mozambican territory from the Malawi border. The Mozambique Rift covers an area of the Urema and parts of the Shire Grabens. This portion is still poorly known; however studies by Theile and Wilson (1915); McConnel (1951), Mouta (1957), and others have helped later investigators like Beater (1960), Dias (1956), Flores (1973), and Afonso (1976) to increase knowledge of the geology and structure of this southern part of the rift. Unfortunately, no systematic study of the Urema graben has been undertaken over the years and our knowledge about the geology and structure of this section of the rift still remains poor.

Petroleum companies have lately contributed greatly to the understanding of the post-Karroo geology of the region in their search for oil. A few papers have been published on these investigations (e.g. Flores, 1973), which give a brief description of the stratigraphy, geology and structure of the sedimentary basin through which the rift cuts. This and similar work was followed up by Afonso (1976) who has tried to compile a regional tectonic map of Mozambique at 1/2,000,000 scale.

The location of the East African rift in this part of Mozambique can be said to be structural; the Urema graben is fault controlled, and the basement rocks are cropping out only on the west side.

Landsat Geological Rift Features

As it can be observed in Map 1 and other detailed interpretation Landsat maps, a large number of geological features can be identified, in some cases more than what a geological map of the same scale can offer. Most of the geological features have appeared on Landsat imagery as ring structures, irregular bodies, and linear and tonal alignments. Most of them indicate magmatic activity mostly related to the rift system. Besides these magmatic bodies a large number of linear features have been identified, usually as joints, bedding and faults. These linear features are illustrated in many tectonic fabric maps contained in this thesis.
FIGURE 4.4. Geologic Cross Section of the Urema Graben at Gorongosa pluton. From Flores (1973, Fig. 3).
It is not possible to tell from Landsat the genetic relationships of the geological and linear features seen in the imagery. However existing information about the area can help in identifying some of the features genetically by correlation, with known ones. This is the approach which has been adopted here and this type of information might be useful to future work of the area.

**Post-Karroo Volcanics**

The basic rocks forming the outer ring of Mt. Gorogonsa pluton, including a large number of alkaline dykes, agglomerate vents and some masses of basalt are known to be part of the post-Karroo activity. These type of igneous products are more abundant in the Urema Graben, especially at the intersection of the Zambezi river basin and the Shire-Urema graben. Here a number of volcanic vents can be seen even from Landsat imagery (Plate 15/15), aligned on the Western flank of the graben, intruding Mesozoic sand and gravel valley fill sediments.

On the western side of the rift valley, north of Mutarara, a considerable number of similar vents can be seen on Landsat; also on the rift floor just north of river Zambezi. South of river Zambezi on both sides of the Urema Graben several ring features have been mapped, these might indicate the flanks of both the Urema and the Lupata Grabens.

**Upper Jurassic-Lower Cretaceous Volcanics**

Related to the Karroo, probably upper Jurassic-Late Cretaceous period, we find a number of intrusives concentrated especially along the eastern flank of the Shire graben. These features are so large that they are dominant features on the Landsat imagery and in the literature they are known collectively as “Chilwa alkaline Province”. These are (see also maps 1 and 2) Mt Tumbine, Mt. Mlanje, Mt. Chiperane, Mt. Derre, Nachidwa Hills and the Serra Morrumbala syeno-granites. On the western flank we find the Salambindwe granosyenite and Mt. Muambe Carbonatite north of the Zambezi. Further south, along the western flank of the Urema graben we find the alkaline volcanic vents south of Mutarara and the Gorogonsa grano-diorite intrusion. At the Zambezi graben intersection with the Lupata graben we find the Lupata alkaline complex. The cone Negose carbonitite further west of the rift is also considered to be of the same age.
A number of other, smaller, ring structures, probably of Upper Jurassic-Lower Cretaceous age have been mapped on the Landsat imagery. These are located SW of Tsangano, SW of Mt. Salambidwe, north and SE of Muambe Carbonatite, SW of Chiromo, north and NE and of Mt Morrumbala and several bodies north and SE of Mt. Mlanje. All these ring structures tend to be structurally controlled, appearing in groups and close to the major intrusive bodies discussed earlier. Most of them are situated on or close to aeromagnetic bodies or along magnetic and Landsat lineaments.

**Structures**

Of the Lower Jurassic rift fractures in this part of the Rift System are included a system of faults which have controlled the Karroo sediments in this area. The most important of these are the faults controlling the Zambezi river basin. Afonso (1976) reports a NW-SE fracture pattern between the parallels 16° and 17° and an EW pattern from Tete westwards. The Landsat interpretation of the area shows four main directions of fracturing, these are:

- NNW and NNE; these seem to be the dominant directions north of Zambezi river as shown by major fractures.

- The NW-SE direction is less dominant compared to the first ones and on Landsat is manifested principally by short fracture lineaments, foliation and bedding along the river itself. The numerous dykes to the west and north however, take the NNW direction.

- The ENE trend is also important especially as expressed by the behaviour of the drainage and bedding north east of Tete. This trend has been shown as airborne magnetic lineaments and also as Landsat topographic lineaments.

The Zambezi river basin has a NW-SE axis between Mutarara and Lupata. At Lupata the basin is cut by the Shire-Urema north-south trending rift faults.
From Landsat interpretation (see Maps 1, 2 and 4) we can describe the tectonic fabric pattern of the area in the following way:

- NNW and NNE trends; these trends might represent the fundamental basement structures and probable rift subordinate trends. Schistosity and foliation usually take this direction, for example in the Angonia region. However rift faults north of Zambezi river take the NNW trend as far as Lake Niassa.

- The NE trend is mostly evident east of the rift (Nampula Province) as confirmed also by airborne magnetic survey. Around Macossa and north east of Tete this trend can be observed. This trend is considered to represent the Mozambique Belt structure.

- The ENE trend is mostly represented by topographic lineaments on Landsat and also as magnetic lineaments east and west of Tete. NW trends are also frequent and N-S tends very rare.

**Cretaceous Structures** - Carbonatites and syenogranitic plutons, mentioned earlier are considered to correspond to the cretaceous rift structures. These features are: Cone Negose, Salambidwe, Muambe, Lupata, Gorogonsa, and Murrumbala. Another important feature here is the “Lupata Graben” (called “Zambezi Graben” by Flores, 1973). The structure of this particular area will be discussed in Chapter 6.

**Pliocene Structures** - These are the present rift structures with roughly NNW-SSE trends north of the Zambezi river and NNE-SSW trends south of the river. The rift faults are usually detectable on Landsat imagery especially where these form scarps as in the case of the Mwanza, Cholo, Inhaminga, and Zomba Faults.

The rift can be traced by its long and sub-parallel lineaments, from Lake Niassa, dislocated in some places by transcurrent lineaments mostly trending NE, NW and ENE. As the rift crosses river Zambezi the graben changes direction from SSE to N-S before continuing with a SSW direction along the Urema graben (Map 2). As the Urema graben continues south, its eastern flank can easily be detected by the tonal alignment and by a series of short SSW trending fracture traces. On the geological map, this part of the rift is flanked to the east by a scarp known as the “Cheringoma planalto”. The scarp continues from Inhaminga southwards beyond the cover of the imagery interpretation. To the west the rift faults can be interpreted with difficulty as they are obscured by the recent alluvial sediments. However as the rift is in contact with Precambrian rocks some tonal and structural differences can be observed. A number of short fracture traces in “en e’chelon” arrays can be traced. These traces have a general NNE trend although at Inhamacala one branch of the traces takes a NNW trend, probably marking the western flank of the “Lupata graben” north east of Mt. Gorogonsa.
CHAPTER FIVE
GEOLOGICAL AND TECTONIC INTERPRETATION OF THE ANGONIA - DEDZA AREA

5.1 INTRODUCTION

Landsat scene 180/70 and several aerial photographs are the basic source of information on which this chapter is based. The Landsat scene covers Angonia (Fig. 5.1) and Malawi, mainly south of Lake Niassa. The area of main interest in this section is a strip of terrain about 35 km wide by 120 km long lying between the Dedza perthitic syenite complex and the town of Metengo Belame. This area is to be called the Angonia structure. This structure is investigated in detail as a "case history", to demonstrate how an area with little geological information can be investigated in detail based on remote sensing data.

Very little geological information is available for the region due to the fact that no systematic geological work has been done in the past. This was a motivation for trying to use Landsat imagery, hoping that regional geological information can be obtained quickly and with reasonable detail. By the time this study had begun, geological mapping of parts of the region had started; this included airborne geophysical survey by Hunting. These data and some ground geological information collected have helped the Landsat interpretation. However, as these surveys have not been published the author had to rely heavily on Landsat and on aerial photographs.

In this chapter, the application of the imagery in investigating the area is described. This includes interpretation of aerial photographs and Landsat imagery, aeromagnetic data analysis and studies involving soil and vegetation. Then a vegetation distribution map and several structural maps are illustrated and discussed. Although little geological and no structural information is available, an attempt is made to discuss the geology, structure and tectonics of the area. Computer statistical information is also added to the study but not discussed.

5.2 TOPOGRAPHY

Topographically the Angonia region can be described as an area of high plateau with heights of between 1,000 and 1,600 m, as shown on Figure 5.2. The principal morphologic features of the area are the Maravia - Angonia mountains which continue into Zambia and Malawi.

In relation to topography and vegetation the area can be described as having three principal types of environment:

- Angonia Plateau which supports mostly poor quality grasslands, shrub grasslands and Miombo bushland.
- Dissected Miombo woodlands, in Lower plateau, which also supports semi-evergreen and deciduous miombo woodland, and wooded tall grassland.
Figure 5.2 Schematic Profile across the Shire Graben and Angonia region.
Areas of semi-evergreen miombo woodland and short sub-montane grassland.

The type of vegetation developed is due both to the soil and to the topography, this in turn has controlled the distribution of human population. Areas with intensive human activity or farming can be recognised on colour composites by the whitish or white-bluish colours.

Landsat interpretation alone without thorough field investigation cannot solve the complex tectonic and structural problems of the area. An attempt is however made to use the little information available on the Mozambican side and correlate this with the Malawi geological information which is in many aspects much better.

The Angonia Structure runs almost sub-parallel to the general trend of the rift system, as shown on Map 4. When observing the Landsat scene 180/70 (Plate 180/165) one is attracted by a large number of topographic features; for example: Lake Niassa (or Lake Malawi), Mt. Dedza, "Ulongue Synform", Ncheu syenites, etc. A large granitic batholith (Furancungo batholith) occupies most of the bottom left corner of the scenes.

5.3 BRIEF SUMMARY OF THE GEOLOGY OF ANGONIA - DEDZA AREA

Angonia lies within the Mozambique Belt of East Africa and is underlain by gneisses and schists of the Basement Complex and associated igneous and metasomatic rock types. The general strike of the rocks is NNW-SSE and has probably evolved in several tectonic cycles. (UN 1983, Hunting 1983d).

Based on existing geological information we can assume that the Angonia region has a geological history very similar to the area to the east rather than the area to the west. If so, Angonia is structurally influenced by the rift system and its geology is similar to that of southern Malawi. For this reason, basic geological data are compiled by correlating with the Malawi information available during the investigation.

The basement complex of this region as well as that of Malawi is dominated by two principle facies:

The granulite and amphibolite metamorphic facies.

Granulite Facies rocks. High grade granulites and gneisses, as described by K. Bloomfield (1968), comprise charnockitic granulites and charnockites (sensu stricto), characterized by diagnostic hypersthene and khondalites with the assemblage silimanite-garnet-K-feldspar quartz; they usually make up highland areas.
Amphibolite Facies Paragneisses

Amphibolite facies paragneisses have been described by Bloomfield (1968) as having wide extension in Malawi and show more open-folding than the granulites. They make up the widespread semipelitic biotite-gneiss, cafemic gneiss, psammites, pelites and locally abundant marbles as well as graphitic types and some ferruginous gneisses; aegirine and nepheline gneisses also occur. They are distinguished by complex folding and locally, by intense migmatitic effects but in general, they possess the N-S trend, in the Malawi part of the Mozambique Belt, whereas in the region of Angonia their trend is generally NNW-SSE. The contact zone of granulite facies and amphibolite facies rocks according to Bloomfield (1968), are usually gradational and “relics of charnockitic granulites are common within areas of dominantly hornblendeic gneisses”.

Pre-Karroo Plutonic Activity

The late pre-Karroo events are thought to be associated with different intrusions of kinematic perthitic syenites and several infracrustal ring complexes as well as some ultrabasic rocks.

In Malawi this activity is said to be associated with the calc-alkaline rocks which are abundant in the Lake Malawi granite province. They are structurally high level calc-alkaline granites, most of which are aligned along Lake Niassa parallel to the general trend of the para-gneisses. According to K. Bloomfield (1968), they may follow a proto-rift zone and mark a final intrusive phase in the complex tecto-thermal history of the Mozambique Belt in this region. Some of these questions were touched in Chapter Four.

From the results of recent projects in the area (Hunting, Geozovod, and UNDP), including first mineralogical investigations of the rocks, and from personal contacts made during the study it is possible to formulate a generalised subdivision of the rocks of the area. This information, though incomplete, with that of aerial photographs and Landsat imagery, has helped in the compilation of the geological map on Figure 5.3 and the geological classification is given below.

PARAGNEISSES

Granulites

Granulites are the most widespread and frequent rocks. The rocks are well stratified, massive and compact. They are resistant to weathering and show a marked positive relief. This rock unit, called Para-Series in photo-geological interpretation, is very widespread in Angonia. On the stratigraphic column they are supposed to be the oldest basement complex rocks, of Precambrian to lower Palaeozoic age. Radiometric age for Malawi and north Mozambique indicate a Kibaran age (about 1,000 my) for all these rocks. These main granulite types are:
LEGEND

- Perthite Syenites and granite
- Basic and Ultrabasic rocks
- Granitoid and pegmatoid gneisses
- Marbles
- Psammites: and quartzofeldspathic granulites
- Pelites: mica-schists and gneisses
- Semi-pelitic rocks: biotite and hornblende gneisses
- Charnockitic Suite: banded granulites and gneisses, hypersthene granite
- Landsat Lineaments
- Landsat "topographic" Lineaments
Charnockitic granulites
- Clino-pyroxene granulites
- Leucocratic granulites

Rhombic pyroxenes hypersthene are usually in smaller quantities in relation to monoclinic pyroxenes (diopside). In the mineralogical composition pyroxene and plagioclase can be said to be the principal minerals. Besides these two main minerals, amphibole, biotite, chlorite, scapolite, microcline, antiperthite, perthite, graphite, sphere and apatite are present in varying quantities.

Clino-Pyroxene Granulite

The main mineral in this group of granulites is monoclinic pyroxene. Mafic minerals are widespread; felsitic minerals include microcline, quartz, perthite, antiperthite, microcline-perthite, and orthoclase. The Plagioclase is acid andesine usually corroded by quartz and replaced by perthite or microcline. This type of granulite nearly always adjoins migmatites.

Leucocratic Granulite

These are massive leucocratic rocks, with little mafic mineral, mostly amphibole and biotite. These rocks are formed from highly metasomatically altered leucocratic clino-pyroxene granulites. They are usually developed in the migmatisation zone, and are frequently intersected by pegmatite veins. Graphite is a permanent constituent of these rocks usually cutting through grains of plagioclase and pyroxene, or passing between grains or impressed between biotite cleavage planes or building isolated accumulations. Sphene and apatite are permanent accessory minerals. Myrmekitic, poikilitic and porphyroblastic textures prevail.

Gneiss

Gneiss is another very widely distributed rock group in the area (UN 1983). This is interstratified with granulites, pyroxenites, quartzites, migmatites, and amphibolites. The gneisses are heterogeneous in texture, structure and mineral characteristics. Gneisses with well developed foliation are associated with augen gneisses. The latter are recognised in a zone between migmatites and biotite gneisses into which they are gradually converted. In relation to mineral composition, several types of gneisses can be distinguished:
- charnockite gneisses with ortho-pyroxene;
- amphibole plagio-gneisses passing into amphibolite;
- sillimanite gneisses with disthene;
- mica gneisses;
- biotite amphibole gneisses.
The gneisses in contact with migmatites are highly altered metasomatically changing into gneiss-granite or granite-gneisses. Mineral composition of the gneisses is: quartz, perthite, microcline, plagioclase, pyroxene, garnet amphibole, sillimanite and kyanite, and biotite. The main minerals are usually accompanied by hematite, limonite, sphene, apatite, graphite, calcite, chlorite, sericite and scapolite.

Amphibolites

Amphibolites are usually interbedded with the granulites and gneisses. They are not as abundant as granulites and gneisses but can be found scattered in small masses all over the area. The dominant textures are nemetoblastic and granoblastic.

The main minerals in these rocks are hornblende, pyroxene and plagioclase. Epidote, biotite, quartz, garnet, apatite, sphene, and limonite are also present. Metasomatic changes are not noted. From recent mineralogical analysis, the amount of amphibole varies from 50% in leucocratic to 80% in melanocratic amphibolites.

Orthogneisses

In south Malawi two generations of orthogneisses have been described, namely pre-kinematic orthogneisses and late-kinematic orthogneisses. Pre-kinematic orthogneiss* include metadolerites and meta-anorthosites. The late-kinematic orthogneisses consist of perthitic syenites and gneisses, and several infracrustal ring-complexes of associated syenites and ultrabasic rocks.

Meta-Anorthosites

These are whitish massive rocks with infrequent intercalations of amphibole-biotite gneisses. The meta-anorthosite is mainly made up of plagioclase, pyroxene, amphibole and biotite in places with garnet which is usually rare. Among the accessory minerals found are chlorite, calcite, opal, quartz, hematite, and apatite, while sphene and zircon are accessory minerals. Graphite is a very rare constituent, usually concentrated with altered amphibole. One specific feature of the Angonia anorthosite is that metapyroxenites occurs on the edge of the anorthosite masses.

Metapyroxenite

Metapyroxenite rocks are often found in migmatite bodies or migmatite zones. They are very compact, massive rocks which often contain only diopside, and therefore are referred to by some Malawi geologists as diopsidites. Diopside and plagioclase are the main minerals of these rocks. In addition to these two main minerals, the rock contains sphene, apatite, graphite, biotite, and amphibole.
Marbles

The paragneisses enclose bands of marble and calc-silicate rocks. The commonest mineral in the marbles is crystalline calcite. Scapolite is often present in these rocks replacing plagioclase. Besides monoclinic pyroxenes, rhombic pyroxene is normally present. These rocks are recognised in migmatites. Zones of migmatisation are usually well exposed and can be easily traced on aerial photographs.

5.4 GEOMORPHIC CHARACTERISTICS OF ANGONIA

Landform or geomorphic characteristics of a terrain is an important tool in understanding the subsurface geology of an area. It combines both the description of surface expression with the inference of structure or attitude.

No landform studies have been carried for Angonia yet. Recent work by the UNDP/FAO Land use investigation has offered some useful information about the soil characteristics, topography and vegetation of the area. A map with these data has been compiled by the author (Figure 5.4) As the pattern of vegetation is one of the most fundamental sources of information in any Landsat image interpretation and analysis, this section is dedicated to the subject.

As pointed out earlier Angonia is mainly a high plateau with heights ranging between 1000 and 1600 m above sea level, known as the Angonia Plateau. It is an ancient erosion surface of gently to almost flat undulating relief, forming the watershed between the Zambezi and Chire River catchments. The slopes are usually mild with the exception of mountainous areas (e.g. Mount Domue) and in the deep valleys.

The UNDP/FAO valley types can be simplified into two groups:

- Wide, humid valleys - these have gentle concave or straight transverse slopes. They have broadly concave valleys (dambos), associated with old age surfaces. They are associated with deep to very deep, poorly and very poorly drained dark grey clays. In some of the valley floor centres permanent swaps are formed.

- Narrow, infilled, colluvial valleys, they are associated with rejuvenated surfaces. They have straight colluvial slopes, infilled by transported material from the surrounding upland. A stream channel may be absent, well defined or incised. These valleys are typical for surfaces of advanced rejuvenation.

Two types of colluvial valleys are developed in the area: Imperfectly drained colluvial valleys with different types of colluvial infill, covered with grassland and dispersed bushes or cultivated. The other type is the poorly and very poorly designed colluvial valleys with different types of colluvial infill sometimes covered with tall grassland or reed swamp.

Besides these two principal valley types alluvial valleys are also developed. They have narrow strips of alluvial deposits along incised or meandering streams, and also uncover rock outcrops in narrow river floodplain.
SOIL AND VEGETATION COVER

No information on spectral response pattern for individual vegetation cover type is available. It was possible in this study however to produce computer generated profiles (Figure 5.5) across the strike of vegetation and rock formations, and thus produce spectral response profiles of the four bands, as demonstrated on plates 6/46B and 6/47B. Some general comparison can be made between these spectral profiles with the vegetation cover regions of Figure 5.4.

Cover Type One

The region to the east (Figure 5.4) can be described as an area of gently undulating landscape of old age topography, with super-imposed rejuvenation. Wide compound dombos remain upstream and are replaced downstream by narrow colluvial alluvial valleys due to headward stream erosion.

Convex crests and midslopes are developed. The soils consist of deep red clays on top and shallow laterite beneath. They are covered with miombo shrubland, usually late deciduous. Shrubland and shrubgrassland is developed largely because soils are leached ferrallitic clays which are poor in fertility.

In the NE of the area, the terrain is an undulating to rolling landscape of late youth topography with few relics of the old age surface. Colluvial - alluvial valleys are narrow and swampy.

The soils are well drained red clays, strongly leached and of very low fertility, but resistant to erosion. They are covered by degraded woodland and shrubland.

To the west of the river Muazi the topography is a gently undulating landscape. The deep, weathered mantle of a former peneplain has been stripped by gradual denudation, but old-age topography has been maintained. Very deep somewhat imperfectly drained brown, heavy clays of moderate fertility are found. These areas are mostly covered by medium high, dense grassland of good quality.

On landsat colour composite imagery, vegetation cover type 1 is depicted by intensive greenish tone trending along the international border from south of Biri Biri to Calomue on the north. The area west of river Muazi has dark green tone with indications of fire burns, probably due to widespread grass cover.

Within area one several regions with characteristic vegetation are found. These regions are marked as 1a in Figure 5.4. They are regions with rolling landscape of late youth topography, with incised streams in colluvial-alluvial valleys. Relics of the old age surface occur only on interfluves. Land unit pattern is greatly determined by geological banding.

Moderately well to imperfectly drained reddish and greyish brown clays of variable agricult-
MAJOR VEGETATION DISTRIBUTION MAPS

FIGURE 5.4
Compiled from UNDP Landuse Map (1980)
Figure 5.5 Tone Reflectance Interpretation of Scene 180/70 and Computer Generated Profiles
ural suitability is developed. Vegetation is mainly of dense medium high to tall hyporrhenia cymbane with scattered trees. Shrub to bush grassland with open medium high hyperrhenia themeda andopogon grassland.

On landsat these units are recognised by their reddish tone and they stand up as crests parallel to the Angonia Basement trends. They have been mapped on Landsat as banded gneisses.

Cover Type Two

This cover type forms a laterite plateau of gently undulating old age topography which is partly incised and rejuvenated. Laterite occurs in summit areas, with imperfectly to poorly drained soils, which support only poor quality grassland. The soils are usually poorly drained gravelly sandy clays with laterite, covered with degraded shrub-grassland or shrubland.

On Landsat false colour composite this type of environment is manifested by whitish tones, especially south of Mt. Domue. The laterite soils occupy large areas (more than shown on the Land Unit Map), around Ulongue Velha to the east of Mt.Domue and also in the NE of the area. However a good correlation can be found between Landsat and the Land unit map for this particular area.

Cover Type Three

In this region the soils are developed in areas of mountaneous relief. Due to orographic rainfall, the northern area supports evergreen forest patches in ravines. These evergreen forest remnants have specific intensive red tones on Landsat false colour composites.

To the north west of Mt. Domue the soils are poorly drained, yellow grey and brown gravelly sandy clay loams, with concretions of laterite, covered with coppiced miombo woodland and medium high grassland.

To the north east and east of Domue moderately well to imperfectly drained reddish greyish brown clays covered by poor grassland and shrub-grassland are developed.

To the west of Domue moderately well drained yellowish-red clays of low fertility are developed with coppice bushland on summits and grassland on the lower slopes.

To the south of Domue is an area of intensive cultivation. Very deep, well and moderately well drained dark reddish brown clays and shallow laterite occur, in mid slope and lower slope positions the area is highly cultivated with fallows of high-tall hyporrhenia grassland; scattered tall trees of ficus and erythrina and low trees of combretum-syzigium brachystegia. On degraded sites open, short grassland is developed.

On Landsat the southern part of Domue has whitish tones. Light yellow tones occur to the north while green tones are mostly seen on the western side. On the summit of
Mount Domue itself (cover type 3a) the tones are deep reddish indicating healthier semi-evergreen forests.

The Ulongue Synform is dominated by the M’passadzi river Valley which can be said to be the axis of the Synform.

In the area between Mt. Domue and Ulongue Velha we find surfaces in various stages of rejuvenation. The Landscape represents remnants of a former erosion surface, with ferrallitic soils of low fertility. Around Mr. Domue, as pointed out earlier, parent rock is perthitic syenite which support more favourable soils. Towards Ulongue Velha the parent rock grades into felsic and charnockitic granulite. Felsic rock types usually support miombo bushland.

South of Ulongue Velha the area is gently undulating of late youth topography. Relics of old age topography occur on the tops of interfluvies and as hanging dambos. The main rivers are deeply incised resulting in gully erosion on valley sides and along stream banks.

Further south, south of Ulongue town, the M’passadzi river runs parallel to the Synform, enclosed by hard rock ridges. The relief is almost flat to undulating with simple dambos and interfluvies and imperfectly to poorly drained soils. The geomorphic process has been a gradual overall denudation (etchplain formation). The area is little cultivated and supports good quality posture, seen as dark green on the Landsat false colour composite.

The topsoil is usually dark grey-black clay which lies over grey clay of moderate-strong coarse angular composition. Vegetation in this area is mostly tardily deciduous coppice bushland with open, medium high grass cover. To the south dense, medium high themeda-hyparrhenia grassland with scattered trees like acacia rehnani and piliastigma is developed.

In the extreme south of the Ulongue Synform, the relief is almost flat with the same geomorphic evaluation as the area to the north. The lower slopes of structural ridges (Ulongue Synform limbs) have dark reddish brown clay topsoil over dark red clay subsoil. The area is mostly cultivated. There is open medium high themeda-hyparrhenia grassland with scattered bushes of brachystegia spp., acacia, ficus etc.

Cover Type Four

The area with this cover type extends NW-SW from the border, west of Domue to river Mecamo on the Malawi border to the south east. It is a wide belt of densely cultivated, fertile soil consisting of an ancient erosion surface in the north and of rejuvenated surface in the south.
In the north the landscape is almost flat to gently undulating with broadly convex interfluves. The soil is of leached dark red brown to dark red clays and sandy clay topsoil over dark red brown clay. The vegetation is composed mainly of fallows of tall grassland with scattered trees like, perinari, acacia, ficus and pericopsis. In places bush grassland, with a sparse short grass cover is found.

In the south we find an undulating landscape of early mature topography with many rock outcrops and mountain ranges. The angular drainage system is deeply incised in the surrounding upland and occupies narrow colluvial valleys. Along the main streams and at the head of valleys severe gully erosion occurs. The top soil is mainly dark red brown-black sandy clay loam-clay sitting over dark and brown clay subsoil. It is densely cultivated and with tall hyperrhenia grassland. Scattered trees like acacia, pericopsis, erythrina, kigelia africana, are frequent and evergreen forest relics are scattered throughout the area.

To the north, on Landsat imagery, this belt is seen as having alternating patches of green and white, probably indicating grassland, laterite and cultivation. NE trending ridges are easily seen, especially in the south and are usually banded.

Although there are many inconsistencies in detail, there is a general correspondence in the distribution of cover type described above and the profile intensities of Band 4,5,6 and 7 of the Landsat imagery shown in Plate 6/47. The peak in the centre of the profiles corresponds with cover type 3. The low values towards B correspond to cover type one although these values are still higher in relation to the rift valley vegetation values. The intermediate values towards A' correspond to cover type four.

5.5 LANDSAT AND PHOTOGEOLOGICAL STUDY OF ANGONIA

Landsat imagery and aerial photographs were the two basic source of data at the beginning of the Study. The existing 1:1 000 000 and 1:2 000 000 scale geological maps did not contribute greatly to this work due to their small scale and also due to the fact that no field proof is included for the Angonia region. Towards the end of the investigation some data from the unfinished 1:250 000 geological map of the area was obtained and correlated.

Two stages of work were involved for the study of Angonia:
- Survey of all available geological data, acquiring of aerial photographs and Landsat imagery, and verbal contacts with some geologists who have some knowledge of the area. This information was interpreted and analysed, followed by a field reconnaissance visit.
In the second stage digital processing of Landsat data, further interpretation of images and digitisation of fracture maps was carried out. Some extra geological information plus aeromagnetic data and Landuse maps of the area were compiled.

**Landsat Imagery**

Landsat imagery interpretation was the first logical step in the systematic investigation. At the beginning of the work only hard copy photographic material was available so that CCT's were only used during the latter stages of the study. The computer work and techniques involved have been explained in Chapter 2. Here only the interpretation work of the photographic and digital computer data are discussed.

The inverted "V" shaped structure seen in the center of Landsat scene 180/70 especially attracted the interest of the author. This structure is to be called the ULONGUE SYNFORM in the study. Although it is a large structure it has not been mapped or mentioned before; that is why there was a feeling that it is necessary to have this large geological feature take its place on the geological map of Mozambique.

In a wider context the Synform is situated within a large structure of regional dimension which has here been called the Angonia Structure. This structure is structurally bounded by Rift faults on both ends, that is by the rift faults north of Dedza perthitic massive and by the Ncheu rift faults in the south. The structure measures about 120 km by 35 km, trending NW from Ncheu area and then turning into a N-S, or rather NNE-SSW direction from Domue.

All the interpretation of the 1/200,000 and 1/500,000 hard copies was done under artificial light using a hand held lense. No proper magnifying instruments or variable lighting conditions existed throughout this work, so that the advantages of different angles of illumination were missed.

However the ordinary table lamp, illumination was changed sometimes from normal vertical to overhead illumination from behind. To compensate for the lighting insufficiency, the images were constantly rotated in order to enhance some features. The practice of rotating the images under a magnifying glass is helpfull in creating an impression of "Pseudo relief" useful for obscured curvilinear features, especially ring structures. The author had used this technique before (1978) in making a "morpho-structural" map of Mozambique (unpublished). It should be pointed out that better results are achieved if the rotation is done under a fixed magnifying glass and of good magnifying capabilities.

**Characteristics of the Ulongue Aerial Photographs**

For photogeological interpretation a small area was chosen within the Angonia Structure. It measures about 1000 km², covering entirely the Ulonggue Synform.
The area is covered by two generations of black and white aerial photographs. The first generation of photographs were taken during the late 1950s but do not cover all the area. The photographs are at 1:50,000 scale, and flight lines are oriented north-south. As the flight lines did not cover the north-eastern part of the study area and because of their bad quality, these photographs were not used in this study.

The second generation of aerial photographs was obtained in the 1960s. Flight lines are NE-SW covering the whole of the Ulongue Synform. The area of detail has been covered by flight lines 39-48. The photographs are of standard 23 x 23 cm format and of very high quality. The focal length of the lenses used were 15.16 cm. The flight lines are almost perpendicular to the general strike of the Basement complex.

Photogeologic interpretation was done by using a Wild Heerbrug stereoscope. The photointerpretation was not divided into various thematic or topical interpretations; all structure land forms and fracture traces were annotated on the same transparency. The drainage was traced on a separate transparency and later reduced to fit the Landsat imagery. The thematic or topical interpretation was not necessary at this stage of work because all the photogeological interpretation work was merely support data to the Landsat interpretation.

After the interpretation has been accomplished the photogeological data were transferred to the 1:50,000 base map visually. These maps were later reduced to 1/100,000 scale and later to 1/200,000 and 1/500,000 scales.

5.6 PHOTOGEOLOGICAL AND LANDSAT INTERPRETATION OF THE ULONGUE SYNFORM.

Aerial photo interpretation covered an area shown on map 4. From the interpretation of aerial photographs and Landsat imagery, and from field observation it can be concluded that vegetation cover, lithology and morphology are closely linked in this region.

As seen on the two types of imagery drainage is well developed and structurally controlled. The hills and ridges are usually not covered by deep surface soils, and foliation on them can be easily traced. Vegetation can be differentiated according to tone and topography, as discussed in the previous section.

Photogeological Interpretation.

A photogeological map for the synform was compiled during the study updated during the field reconnaissance checking and is presented as Map 5.

Two major metamorphic rock groups were identified from aerial photographs, the "paragneiss series", and the "Ortho-gneiss series". Residual soils, laterite, colluvium and alluvium were also identified. The main interpretation key for recognising these rock groups were tonality, foliation and morphology.
**Paragneiss Series.**

Probably morphology is the most important feature of identifying this metamorphic rock group on the Ulongue aerial photographs. The rock group usually represents an almost uninterrupted chain of hills and ridges, manifesting thus topographic highs.

From Metango Belame the series extends northwards in two distinct zones both of which have an almost uninterrupted NW-SE state.

- the first zone extends north westwards along the western limit of the area with a very clear foliation pattern;
- the second zone extends north-westwards along the eastern limit of the area. Here the foliation is not very distinct as the first zone, probably due to deep soil cover.

The measurements of dip and strike of foliation reveal that the general strike is uniform for both zones, and that both have dips of over 50° east, that of the southern zone being much steeper.

On aerial photographs, this series is characterised by “banded” features, namely, alternations between dark and white band’s easily traced all along. These bands are known to be rich in felspar and garnets, they are banded and make up highland areas in the region, therefore they should represent banded gneisses which are well developed to the north.

**Orthogneiss Series.**

Indistinct foliation and a wide range of tonality from light grey to grey and heterogeneous pattern of the outcrops are the main characteristics which identify this rock group from the previous one. The rocks lack a consistent strike direction and when they desintegrate they from sharp edges. This rock group is called here as orthogneiss series. They are mostly located in the Synform (See Map 4).

**Laterites**

Laterites are abundant at the north end and on the southern limb of the synform. They have a darker tone on the aerial photographs. In the field they actually look dark-reddish. Laterites are more resistant to erosion than residual soils and their thickness varies between two and three meters. As these two types of soils cover large areas of the Angonia plateau, they tend to reduce the amount of outcrops thus limiting the photographic interpretability.

**Colluvium**

Colluvium consists of poorly sorted angular heterogeneous mixtures of rock fragments derived from adjacent bedrock. Their distribution is usually parallel to the ortho and paragneiss series. On aerial photographs these deposits show lighter tones with gentle to steeply sloping sides. Their thickness is variable, reaching 3 m in places.
Alluvium is widespread in the area but is mostly limited to the larger drainage systems like river Maue. On the aerial photographs it is distinguished by its darker tone. It is usually made of gravel and sand. The elements are polygenetic and well rounded, these can be observed along many river valleys.

On the photogeological interpretation map the geological boundaries in some places have been extrapolated beneath the soil cover. Otherwise an attempt has been made to make a reasonable interpretation bearing in mind the level of previous geological information and the number of outcrops observable.

On the reconnaissance field trip other rock-types were recognised. Several traverses across the synform were made and some samples collected. This has resulted in an upgraded photogeological map (Map 5) on which three cross sections are drawn. This map is called a geological map since it has been upgraded with the reconnaissance investigation and some rocks have laboratory identifications.

Landsat Interpretation

Unlike aerial photographs, Landsat imagery gives a synoptic view of a larger region, revealing areas beyond the aerial photographic interpretation. It has therefore been possible to understand better the Ulongue Synform in relation to the regional geological and structural framework.

Although Landsat imagery does not offer the best rock discrimination possibilities large units can still be discriminated despite the vegetation cover (e.g. Figure 5.6) Structural interpretation using Landsat has however been the greatest contribution to this investigation. Again as in aerial photographs tonality, foliation and morphology were the key for Landsat structural and geological interpretation.

The Ulongue Synform has been better defined on Landsat imagery. The Dedza perthitic syenite complex has been extended across the border to englobe Mt. Domue which should be of the same lithology. Also it has been possible to relate the Ulongue synform to other structures across the border and thus to construct a structural map (Map 4). Block diagram (Figure 5.9) and a simplified geological map (Figure 5.3) were compiled.

5.7 STRUCTURAL INTERPRETATION

In Angonia as well as in neighbouring Malawi it is known that the whole of the metamorphic complex is folded into isoclinal folds in NNW-SSE direction, with steeply to moderately inclined axis. In Malawi much of this complex is reported to display a N-S trend.
FIGURE 5.6
MAJOR LANDSAT GEOLOGICAL UNITS

Scale
1/2 000 000

Para Series
Ortho Series
Syenite outcrop
Foliation
Lineaments
This metamorphic complex which can be referred to as “gneiss - Migmatite” or “granulite - migmatite” complex has rocks which are well banded, and according to Bloomfield (1968) and Hobgood (1968) the gneissic banding is generally thought to represent sedimentary layering. In Angonia the “beds” range in thickness from 30 cm up to 3 m in places.

Both Bloomfield and Hobgood have pointed out that two structural styles exist each associated with a particular metamorphic grade in the gneisses. In granulite facies areas, consisting principally of banded charnockitic rocks, uniform linear trends are usual and the folding is isoclinal about steeply inclined axis. In the amphibolite facies rocks folding is generally more complex producing antiforms and synforms ranging in acuteness, e.g. from close to gentle.

No general sequence of fold episodes have yet been elucidated. It often happens that in one area NW-trending isoclinal folds are refolded by more open structures trending NE. Sometimes the reverse happens where a NW trend is superimposed on an earlier NE direction. Boudinage in pegmatite and ptygmatic folds are very characteristic in migmatised rocks more particularly in amphibolite facies gneiss. Rodding and mullioning are common in meta-psammites and thin hornblendic layers in feldspathized biotite-gneiss commonly show intricate close recumbent folding.

Another characteristic of southern Malawi is the existence of prominent transverse zones, oblique to the general Mozambique trends. For example Bloomfield (1965) mentions the ENE lines of weakness, in southern Malawi, which are masked by the alignment of ring complexes of plutonic alkaline intrusions near Zomba.

The Angonia Structure

Bloomfield (1968) mentions “a zone of lenticular bodies and narrow bands of perthitic syenites trend NW for about 50 miles..... At its northern end this zone impinges upon the Dedze perthitic Complex and becomes involved in superimposed foldings”. It is “this zone”, on Mozambican territory to which the name Angonia Structure has been applied for this study. Although this anti or synclinorial belt (Figure 5.6) has been mapped on both sides of the Malawi border, it has not previously been extended across the border through Mozambique (Angonia). In this way the Ncheu, Angonia and Dedze (Figure 5.1) areas can be linked structurally, and tectonically into a unique structure across Mozambique using Landsat imagery.

According to Evans (1965), Walshaw (1965), Garson and Walshaw (1968), and Thatcher (1968), the perthitic syenites are late - kinematic and formed after
the main synkinematic phase of migmatisation and associated granitisation. They make up a distinctive lower Palaeozoic calc-alkaline province in southern Malawi (Bloomfield, 1965D; Evans, 1965; Thatcher, 1968), They form lenses and concordant bands in amphibolite facies gneisses whereas in granulite terrains they form perthitic complexes (e.g. Dedze).

In defining “perthite”, Termier (1956) considers perthite to be a “stress mineral” and an association between perthitisation and tectonism is evident. The major “perthitic complexes” lie within structured interference zones and concordant perthitisation with some dilation occurs along F1 trends. This is thought to have been followed by mobilisation and intrusion during F2 cross folding, concentrated in these interference zones. Bands of perthite syenite have been folded into broad anti-forms and synforms, but apart from some thickening and local mobilisation in the hinge zones, there does not seem to be any connection between these folds and the process of perthisation.

Ncheu Complex - the Ncheu perthitic syenites represent a zone of lenticular bodies which trend NW towards the Mozambique border and parallel to the dominant trend of the enclosing paragneisses of the amphibolite facies.

They are elongated concordant masses ranging in composition from biotite - perthite gneiss to perthite syenite or locally granite and usually show gradational contacts with the hornblende - biotite gneiss country rocks (Walshaw, 1965; Dawson and Kirkpatrick, 1968). Locally the narrower syenite bands have been tightly folded into sharp antiforms and synforms some of which have nuclei of ultrabasic rock (Bloomfield, 1968).

As seen from Landsat imagery the Ncheu perthitic complex has been intercepted at its northern tip by a NNE trending rift fault which displaced the complex in a left lateral sense.

Dedza Complex - is a perthitic syenite grading into perthite gneisses with local monzonitic and granitic phases. Its outcrop in Malawi Covers some 600 km², and through interpretation of several sets of data an outcrop of about 200 km² can be extrapolated on Mozambican territory. The complex in Malawi makes up such mountains as Dedza, Changoni and Mpunzi which are formed of weakly foliated rocks with an igneous aspect, including some separate oval shaped outcrops. In Mozambique the main outcrops are the Domue mountains, whose outcrop seen on Landsat covers just over 60 km².

Malawi geologists consider the Dedza Complex to form the core of an antiform. It is characterised by a fold pattern consisting of converging and diverging “V” shaped trend lines and by arcuate and uniform folds, the traces of which swing around from NW to NE. The isolated syenitic bodies occupy the cores of closed-eye folds and all these features are very characteristic of superimposed folding (Ramsay, 1962).
Hence, Dedza appears to lie within the mutual interference zone of two fold systems, the first phase (F1) trending NW and the second phase (F2) trending NE. The former is the regional trend and is characterised by tight isoclinal folding. The second is said to consist of broad antiformes and synforms.

Thatcher’s (1968) structural map of Dedza does in fact show the primary folds (F1) and secondary folds (F2); the F2 folds being almost perpendicular to F1 folds, as shown on map 3. From this map it is fair to conclude that the F2 folds appear only in or close to the contact between the Dedza complex and the surrounding charnockite gneiss.

From the above it can be concluded that the F2 fold pattern is more likely to be local than regional. The regional isoclinal folding was followed by local folding, associated with the intrusive bodies like that of Dedza. This was followed by faulting associated with the faulting of the rift valley. In fact the rift faults north of Dedza do have a NW trend very similar to the F1 fold trend, and Mt. Domue does show signs of superimposed folding as is shown by the diversity of foliation pattern on some digitised imagery.

The whole of the Angonia Structure can be identified by local names, as either synforms or antiforms. In the north, on the Salima sheet, the structure is locally known as the Tuma or Ulongue Synform. On the Dedza sheet the continuation of the above synform is locally known as the Nkhoma Synform. We should therefore expect the continuation of the Nkhoma Synform towards the south on Mozambican territory. This continuation, according to the results of this work is the Ulongue Synform.

To the east of Dedza Complex a number of Antiforms and Synforms have been reported by authors like Thatcher (1968). These are the Chinamba and Mlanda Synforms; the Linthipe, Chitana Hill, Mulunduni and Nadzipulu Antiforms. These structures have been extended southwards into Mozambique in the course of the Landsat interpretation and discussed later in this Chapter.

Ulongue Synform

The Ulongue Synform is named after the district centre of Angonia which lies on its southern limb. The core of the synform is composed of granulites and anorthosites. The limbs are composed of banded gneiss and dip to the east at angles of more than 55°. The axial plane trace runs parallel to the river M'passadzi which is fault controlled. The edges of banded gneiss converge to the north of Ulongue indicating that the synform plunges to the south in this region. Complex folding displayed by granulite bands in this region, and cross folding of the band observed on Mt. Domue may be possible to explain for variations in the plunge of the synform. The limbs of the synform are displaced by numerous NE and NNE trending faults.
\[\text{Fig. 5.7 is an interpretation map of the Angonia Structure. In this figure two synforms and two antiforms are shown; they extend northwards into Malawi where they join other structures mentioned earlier. These structures are described below.}

- **Ulongue Synform (1),** has been described above.
- **Muazi Antiform (2),** this name is used to describe the structure east of the Ulongue Synform. It extends northwards towards Domue and the Dedze complex. The Linthipe and Chitana Hill Antiforms are just east of Dedza. The interpretations shown on Map 5 implies that these two antiforms converge southwards to form the Muazi Antiform.
- **Maue Synform (3),** this synform can be extended across the border to make the continuation of the Mlande Syncline of Malawi.
- **Lizulo Antiform (4) is located east of the Maue Synform. Its presence is inferred by N-S trending lineaments and bands of syenite bodies which occur in the cores of antiforms elsewhere.**

**Faulting**

The faulting depicted on geological maps and observed on the Landsat imagery is described below.

In the Ulongue area the major trends of faulting are NNW and NNE; also the ENE trend is important. In this area the NNW-SSE trend is better expressed on Landsat than on aerial photographs as shown on Figure 5.10. This trend should represent mostly jointing parallel to the Basement strike. Major Rift faults in this area also have the NNW trend. Another important trend is the NE and NNE trends which can be observed on both aerial photographs and Landsat imagery. Aero-magnetic lineaments take NE to ENE trend.

Besides the major rift faults shown on map 4, four important lineaments traverse the Angonia structure and the major rift faults. These are from north to south: Metongo Modzi, Ulongue Velha, Metango, and Mecamo Linements.

A fifth lineament trends parallel to the strike of the Angonia Structure. This lineament, called here Rio Chimodzi Lineament, can be seen on plate 1/5 which can also be called "Tonal Lineament". Drainage has been displaced along the lineament (Figure 5.8). It also marks the contact between the charnockitic granulites and the amphibolite facies. Along this lineament the vegetation is tall to giant grass with acacia as typical trees; that is why the tonal alignment is strongly expressed.

**5.8 DRAINAGE**

The drainage in the area is well developed and structurally controlled. Two main directions of drainage orientation are noted. The main rivers have a NNE trend for example
STRUCTURAL INTERPRETATION OF ANGONIA STRUCTURE BASED ON LANDSAT AND AERIAL PHOTOGRAPHS.

Figure 5.7

LEGEND

1. ULONGUE Synform
2. MUAZI Antiform
3. MAUE Synform
4. LIZULO Antiform

Axis of overturned Synform
Axis of Synform
Axis of antiform
Major Lineaments

0 5 10 Km.
the rivers Maue, Lifidzi, Metaia, a second group of rivers, usually less large, have a NNW trend, for example the rivers Mp'assadzi, Chimodzi and Muazi.

The second group of drainage system might represent the fundamental basement structures as is concordant with the strike of rock formation and the basement joint trend. No E-W or ENE trending drainage is noted in the area.

5.9 AEROMAGNETIC DATA ANALYSIS

An Aeromagnetic survey was carried out by Hunting in the area in the 1982/83 season, and the first information of the survey has been made available. A good correlation can be made between this data and other data used in the study, especially Landsat imagery.

The Angonia Structure is occupied by the strongly NW grained Angonia Group, which forms two main magnetic zones. The western part is dominantly non-magnetic, with sparse magnetic bands giving anomalies of 50-200 nT, while the eastern part is more magnetic, with anomalies which are of similar amplitude but more closely spaced. The more magnetic area if extended across the border into Malawi, would correspond to a 'perthite complex' (probably perthitic gneiss), while the less magnetic zone would be equivalent to basement gneisses, charnockites and granulites. The charnockite suite rocks are not radiometrically distinctive, but the 'perthite complex' is perhaps distinguishable by slightly higher amplitude and a change in character to a more cluttered appearance with a variable directional trend (R171), see Figure 5.10 for aeromagnetic lineaments.

Of the ENE and NE trends, the ENE trend is more dominant. It is possible to correlate both these aeromagnetic lineaments with Landsat Lineaments of the same trend. The ENE trend of lineaments is an important one and it might reflect deep seated lineaments reactivated later with the rifting tectonics so that at their intersections, or near their intersections with the rift faults a large number of magnetic bodies are located.

The main economic material in Angonia in the past has been graphite. There are also some iron deposits, recently Cr, asbestos, Pt and Ni have been reported.
LANDSAT TONAL LINEAMENT AND OTHER STRUCTURES OF THE Mt. DOMUE AREA:

- Tonal Lineament
- foliation or bedding
- ring structure
- drainage

FIGURE 5.8
SCHEMATIC
Block Diagram of the Dedza-Angonia Region

LEGEND

- Sedimentary deposits
- Semi-pelitic rocks
- Charnockitic suite
- Landsat Syenites outcrop

FIGURE 5.9.
CHAPTER SIX
REGIONAL GEOLOGICAL AND STRUCTURAL ANALYSIS OF THE STUDY AREA

6.1 INTRODUCTION

Structural geologists observe and map the present condition of the rock exposed. The deformation or strain is the change in attitude (rotation), position (translation), shape (distortion), or volume (dilation) that the rock has sustained from its initial condition. Without an initial “fabric” in a known condition to serve as a reference, strain cannot be determined. Conditions of the primary structural or fabric elements must be known if the kinematic and dynamic stages of analysis are to be attempted. This constraint has made it impossible for this study to go beyond the simple qualitative lineament (fracture trace) analysis.

Fracture traces can be systematically analysed on the basis of their quantitative and qualitative characteristics.

- Quantitative analysis usually involve the azimuth, length and frequency of fracture traces, and in some cases their geographical position. In other words, it is based on the characteristics that are related to the geometry and pattern of fracture traces.

- Qualitative analysis on the other hand is based on the geometrical and pattern characteristics of fractures and their relationship to other geological features.

These two approaches are based on many observations which have convinced many investigators that lineaments do not occur accidentally. For example in relation to size and length, there is a proportional relationship between the size of fracture traces in general and the depth which they may reach. Regional fractures or crustal fractures are deep seated and therefore basement controlled, whereas small or medium sized fracture traces are comparatively restricted to inconsiderable depths and are probably controlled by local structures. In relation to tectonics, it is logical to expect more fractures in areas which have been subjected to severe tectonic forces than in those which have been under minimum tectonic pressure.

Besides recording the manifest surface geology, in fracture trace analysis we are also concerned with the more complex deduction of subsurface, buried geological features. Because of this other subsurface exploration geological techniques, such as seismic or aeromagnetic exploration, should be consulted. This will allow us to correlate the different informations and make our conclusions more reliable.

Reconnaissance exploration is in part the delineation of inhomogenities within an otherwise homogenous pattern. This applies equally to fracture trace analysis and consequently one of the first functions of this analysis must be to locate and assess the extent of
any homogeneity. Only then it is assumed it is possible to recognise true anomalies. Coupled with the problems of scale in fracture trace analysis some writers point out that, for a given field, with respect to a given structural element, homogeneity of fabric increases inversely with scale. Therefore to obtain a greater degree of structural homogeneity within a given field, the field must be examined on a smaller scale. However, interpreting information on structural geometry must be preceded by a very complete study of the deformed body on all scales.

Different scales have been used in this study because from CCTs one is capable of generating imagery at varying scales. It has been found that each scale adds a different set of information which would in many cases be absent if working only on one scale. Therefore data from different scales have been either reduced or enlarged in order to produce the final maps.

Quantitative treatment of the Landsat data for this study has been discussed in Chapter three, (also see Appendix 1). In the rest of this chapter qualitative analysis of the regional fracture trace pattern (or tectonic fabric) is discussed. Also some typical interesting areas are discussed. Geophysical data is incorporated and compared to Landsat data.

6.2 REGIONAL ASPECTS OF THE GEOLOGY AND STRUCTURE OF THE AREA

Six Landsat images cover the whole of the study area. As it can be seen on Figure 2.1, Scene 180/70 was discussed in Chapter five and therefore is not discussed further here. The geology and especially the structure of these areas is still a matter of discussion. On Mozambican territory a lot of further geological work will be required in the future before any concrete conclusions are reached.

Landsat interpretation of the geology based on the tonal characteristics of the imagery has not been very successful, basically due to dense vegetation cover, and also due to the large area involved in the interpretation. Some exceptions can be made however. These are digitised subscenes to which different colour enhancement techniques have been applied. Their interpretation has been helped by the availability of some good geological information. Some of these subscenes (e.g. Morrumbala) have been discussed in Chapter two, the other interesting subscenes will be discussed later in this chapter.

Based on the description by Afonso (1976), the tectonic trends of the Mozambique Belt in Mozambique (Figure 6.1) can be summarised in the following way:

- Nampula Province has an ENE-WSW tectonic trend and is considered to represent earliest structures and the N-S and NE trends are more recent.
- Niassa Province is thought to have the N-S trend as its principal tectonic trend. In Malawi such trends have been recognised. However due to the diversity of magmatic activity in the Province a diversity of local structural trends are also
FIGURE 6.1. Schematic Tectonic Map of Mozambique from Afonso (1976, Fig. 1)
Afonso (1976) reports that in areas underlain by granitic intrusions the WNW-ESE structures are dominant and that in areas of folded migmatitic gneisses and other remobilised gneisses of sedimentary origin the fold axis take the N-S and NE-SW trends. The NNE-SSW directions are observed near the Zambeze river.

Medio Zambeze Province which is in contact with the Rhodesian Craton, is characterised by structures with E-W directions to the north of the craton and by N-S trends to the east of the craton.

Landsat scene 179/71 and 179/72 cover both the Nampula and Niassa Provinces. Scene 179/73 covers only a small portion of the Medio Zambeze Province. Scene 180/70 and 180/71 lie entirely in the Niassa Province, whereas scene 180/72 covers the Medio Zambeze Province and a small portion of the Rhodesian Craton. It is important to mention also that the Niassa Tectonic Province cover most, if not all of Southern Malawi:

The geology of each scene, numbered from area one to six, is described in the following pages.

Area One (Landsat Scene No.197/71)

Topographic features like Lake Chirwa, river Shire, and several syenite plutons (Mlanje, Zomba, etc) are the dominant morphologic features on this scene.

As part of the Niassa Province, gneissic granites, migmatitic gneisses, granites, semi pelitic rocks, nepheline syenites and Quaternary sediments make up the sequence of the rocks seen on the scene.

The emplacement of granites and quartz syenites might have contributed to the metamorphism of the basement complex. After a long period of erosion, syenites, carbonatites, different basic dykes, all of the Chirwa series of Late Jurassic age, were intruded. It is thought that the hot spring alignments of the area belong to this period, representing late carbonatitic activity or associated with rift valley faulting.

Besides the Lake Chirwa and river Shire valley, a large number of linear features are also easily observable on the imagery. The most important of these are the scarp rift faults like the Zomba fault, Cholo fault, and long dykes trending N-S from the southern tip of Cholo fault.

The intrusive bodies seen on the imagery, Mlanje, Derre Chiperone, Zanga, Tumbine, Blantyre and Zomba can be distinguished easily by their topography and tone. Some of these bodies are described as synkinematic perthitic syenites, granitic or monozonitic in part (e.g. Blantyre, Lirangwe, Derre, Chiperone and the Zomba intrusives). Much younger intrusives are mostly syeno-granitic (e.g. Mlanje and Tumbine). The first group is of Late
TONE REFLECTANCE MAP OF THE MLANGE AREA

LEGEND

Sedimentary rocks

Areas of thick vegetation

fracture traces

basement rocks

ring structures

FIGURE 6.2
Palaeozoic age while the second group of intrusions are of Jurassic to Late Cretaceous age, representing the Chirwa Alkaline Complex.

Several other identical features, not indicated on the geological maps, have been mapped using Landsat (Figure 6.2 and plate 139/299). A criterion used to identify their age relationship, in this area was tone and morphology. It has been noted that on colour composites older intrusives, e.g. Blantyre pluton, have little topographic expression due to erosion and have mainly brownish tone. Whereas younger, syeno-granitic plutons (e.g. Mlanje, Zomba) have very pronounced topography and are very rich in vegetation which gives them strong blue tones because of the colour gun choice during image compositing. This criterion is easy to use in the Malawi low lying terrains where grassland and bush are dominant thus giving sharp tonal contrast. On the east of the imagery, which is a high plateau compared to the Malawi terrains, reddish tones are dominant. This makes it difficult to judge correctly whether Derre, Tumbine, Chiperone, etc. are of the same age or type. The usefulness of Landsat has not been in the genetic discrimination of these bodies, but rather in the possibility of mapping more bodies so far unmapped on geological maps.

Area two (Scene 179/72)

The area is just south of area one. Most of the scene falls in the Niassa Province whereas the SE part falls in the Nampula Province.

Different rocks of the Basement complex make up the east of the area and there is a noted increase in dyke swams, basaltic lava flows and alkaline intrusives especially at the junction of river Zambezi and the Urema graben. Post Karroo sediments dominate the area as these occupy over two thirds of the scene. The largest single magmatic intrusive is the Mt. Morrumbala syeno-granite.

Sedimentary rocks in the basin are of Karroo to Quaternary age. Karroo feldspathic sandstone, tertiary volcanics including alkaline basalts and Quaternary terraces of sand and gravel of different origins make up the sequence of the sedimentary formations. Basaltic intrusions, of the Jurassic-Cretaceous period, tuffs, ignimbrites and sandstones are frequent; and the Morrumbala syeno-granite is attributed to this age. The many limburgite vents, porphyrites and breccias found especially south of Mutarara town are of Miocene-Pliocene age.

Two main tones are dominant on the imagery. e.g. red tones are found over all basement rocks including Mt. Morrumbala, whereas on the sedimentary terrains a dark green tone is dominant. Basalts are very distinct on the imagery due to their tone and surface pattern.
Figure 6.3 is the Chemba area. Basalts are recognised by their "banding" and "U" shapes (Plate 18/70) probably indicating the direction of their flows. Shire rift graben sediments can easily be differentiated from the other sediments by tone and pattern. South of Mutarara several agglomerate volcanic vents mainly "augites" and similar rocks of Miocene period have been mapped. Some of them coincide with hills, for example Mt. Nhatomore and Mt. Nhacangane as shown on Figure 6.4. Although these volcanic features are small, only a few tens of metres across, they can be seen easily on Landsat digitised scenes of 1/150,000 scale.

**Area Three (Scene 179/73)**

Area three is mostly covered by sedimentary rocks. To the west we find Precambrian charnockites, gneisses and migmatites, into which is intruded the Gorongosa granodiorite and basic complex. The Urema graben which extends across the scene from north to south separates the sedimentary rocks to the east from the Precambrian outcrop of the Medio Zambeze province on the west.

Karroo is represented by feldspathic sandstones and basaltic lavas which are mostly found along the rift faults bordering the Precambrian rocks. The Gorongosa Complex is made up of gabbroid rocks, dolerites and micropegmatitic granites. Rhyolites, dacites, alkaline lavas, quartz-breccia dykes, and sandstones make up the Cretaceous and post Cretaceous rocks. Quaternary arenaceous eluvium is usually formed by bright sandy soil covered by dense forest, seen to the east of the imagery on the Inhaminga plateau.

All these rocks have their specific tone manifestation. Gorongosa pluton is a ring structure covered by heavy vegetation which gives it intensive orange hues. Numerous dykes, especially dolerites, can be seen to the north and south of the massif. Precambrian rocks have a blue tone north of Gorongosa whereas in the south vegetation has given them orange pink hues. They also show specific foliation trends south and north and the contact with the sediments is sharp.

Sediments in the Urema graben can be identified by their diversity in tone. These colours are probably due to the different sediments being eroded into the graben and the vegetation growing on them in contrast to the forest rich terrains to the east. Identical graben sediments can be seen trending NW at Inhauranga, they probably follow the Lupata Graben.

The Quaternary sediments to the east can be identified by their intensive red tone showing dense forest, especially on arenaceous eluvium.
TECHNICAL FAIRIC AND TONE REFLECTANCE MAP OF THE AREA
NORTH OF CHEMBA

LEGEND

- Alluvium
- Elluvium
- Basalt
- Basement outcrop

- Topographic lineaments
- Fracture traces
- Dyke
- Ring Structure

Figure 6.3
A number of ring structures have been observed on the imagery. Besides the volcanic vents south of Mutarara, other ring features on both sides of the grabens have been identified; these include those south-east of the Gorongosa massif.

**Area Four (Scene 180/70)**

Landsat scene 180/70 was discussed in chapter five; therefore the geology will not be repeated here.

**Area Five**

Area five represents Landsat scene 180/71 covered by the rocks of the Niassa Province and Karroo sediments.

The geology of the northern part of the scene is little known, but in the Karroo basin in the south a good amount of geological work has been done in the search for coal.

In the north the area is mostly covered by gneisses, schists and the granite batholith mentioned in chapter five. Other rock types, granodiorites and diorites are also frequent. To the south sedimentary, basic and ultrabasic rocks: norites, gabros, Anorthosites and Serpentines of middle to upper Precambrian age, known as “Tete gabro-Anorthosite Complex”, occur.

Several ring structures can be seen on the imagery. These include Mt. Salambidwe, syeno-granite (Plate 6.41), Mt. Muambe carbonatite, and two syeno-granite hills of Txizita and Messumbe.

The rock groups can be discriminated with confidence based on colour. The Tete gabro anorthosite complex can be identified by the light greenish tones in the center of the imagery (Plate 139/196) whereas the granite batholith complex in the north manifests reddish tones. The syeno-granite rocks can be identified by their intensive reddish tones and high topography.

The Karroo sediments are difficult to map depending only on tone because when in different surroundings these rocks show different colours. However, combining structural style, for example bedding traces, and tone it is possible to map these rocks. Texture and colour of the Lupata rhyolites differentiates them from the surrounding basalts which have a greyish tones and show some lamination similar to bedding.

Besides the three carbonatite ring structures shown on the geological maps other bodies can be mapped from the imagery. These as well as the three carbonatites tend to be aligned in the NNE direction and are close to the larger bodies. The largest ring structure in the scene is Mt. Salambidwe which is enplaced between two large ENE and NW trending lineaments, as shown on Map 2.
STRUCTURE AND TONE REFLECTANCE MAP
OF Mt. SALAMEIDWE

Figure 6.5

LEGEND

- Tete Ultra basic and Basic Complex
- Karroo Sediments
- Basement rocks

Fracture trace
Foliation or bedding
Dyke
Ring Structure
Area Six

The Medio Zambeze Province occupies the whole of scene 180/72. The few scattered sedimentary basins can be distinguished by the tone of their sediments.

Basement rocks of Medio Zambeze Province are highly remobilised and folded, as can be seen on the Landsat colour composites. Therefore pattern can be a useful tool for discriminating rocks of the Basement Complex (bad quality of the CCT did not allow good photograph print). Four distinct foliation styles can be observed in the area, when looking from east to west.

The first zone is found at the contact with the Lupata graben. Foliation traces have different directions; these rocks are leucocratic microperthitic gneisses of the Barue Formation extensively foliated. To the west of this we have a zone of less foliation traces representing a zone of migmatites, paragneisses, amphibolites and schists of the Barue Formation. Further west we have a third zone of intense N-S foliation traces, these are the schist-gneisses of the Fronteira Formation. A fourth zone is found at the extreme left of the imagery. It is a zone with foliation traces having directions between NE and NNE and marks the contact with the rocks of the Rhodesian Craton.

In terms of tonality all these zones have specific tonal differences. The first zone is intensive red, the second has dark-reddish tones, the third resembles the first zone, and the fourth zone manifests blue tones, somewhat similar to the sedimentary basins. Most of the intrusive bodies (mostly gneissic domes) are concentrated in the second zone.

On this scene a number of N-S trending dykes can be seen cutting across the basement complex. Roads, and even paths for high voltage power lines can be seen. Basalts lining the contact between the Lupata graben and the basement complex have no tonal or structural manifestation on the colour composite and as such are difficult to discriminate.

6.3 REGIONAL STRUCTURAL ANALYSIS OF THE AREA

The best way of analysing the structural pattern of the study area is by representing as many illustrations as possible because the area, especially the south, lacks structural and tectonic information necessary. Therefore it would be a grave error to come to structural conclusions based only on Landsat interpretation and the few geological data available.

Stress analysis is also not possible for reasons expressed earlier. Many and intricate tectonic events of the Mozambique Belt makes this difficult, for example, even the exact radiometric dating of these rocks has proven impossible. Also the Rift can not be discussed independently of the surrounding basement geology and structures.
Investigation of the rift in Malawi was pioneered by Dixey (1942) who recognised that rifting was initiated in Pre-Tertiary times and was possibly developed along ancient lines of weakness.

There is no doubt that there exists an apparent relationship between lines of certain Basement Complex intrusions and rift faults. According to Garson (1965), Later Karroo dyke swarms and carbonatites and alkaline intrusives of Upper Jurassic to Lower Cretaceous age are closely associated with rift faults and an associated depressed zone in the Southern Region of Malawi.

Dixey's investigations ranging from 1921 until 1939 have provided very important clues about the Malawi rift section. His work has led to the recognition of five main erosion surfaces comprising the high Gondwana surface, the early Cretaceous valley-floor planation, the post Gondwana surface, the Mid-Tertiary (Miocene) African surface and Late Tertiary to Quarternary post African surfaces. He also showed that large parts of the Lake Niassa trough are merely resurrected Cretaceous surfaces, and that Lake Niassa during its lowering in stage to the present level was gradually elongated southwards to flood the head of the Shire Valley graben. For the past fifteen years the waters of Lake Niassa have continuously flooded the eastern coast and many settlements along the shores have been moved to higher ground. No explanation is yet available, probably the present movements of the Rift might be the main reason.

Area Four

Mapping in the area SE of Dedze Complex has revealed down-warped features of the extensive Miocene African surface west of the escarpment. To the south of the area Walshaw (1965) has described distinct "Scarp and Shelf" topography due to parallel rift faults. Over much of the Nchea area the rifting direction parallels the strike of the Basement Complex gneisses. Walshaw has determined that some of the fault blocks are tilted to the NW. The Chirobwe fault (Map 2), has a relative throw of about 760 m at Chirobwe and about 150 m north of Goa because of this tilting. While the parallel Ncheu Fault at Goa has a relative throw of 150 m and 30 m at Rivi Rivi river. Along the Bilila Fault two ages of
movement have occurred with the latest movement having produced a steep scarp from 5 m to 15 m.

South of the Ncheu-Balaka area we have an area called Kirk-Lisungwe Area. Bloomfield and Garson (1965) describe the rift pattern as being similar to that to the north. This contrasts with the large rift escarpment to the east, but according to the authors, the culmulative downthrow is about the same in each case, that is, at least 900 to 1200 m.

The main NNW pattern of rifting is displaced by major “tear faults” which are infilled by solvsbergite dykes. The authors give an example of wrench faults through Nenco and Chigaru which have a displacement of between 450 m to 900 m. To the south springs occur along similar fractures. Bloomfield and Garson (1965) think that low steep terrace scarps may be due to recent faulting.

**Area One**

This area was mapped by Bloomfield who has shown the close association of the Chilwa Alkaline Province intrusions and hot springs with rift faulting. The best observed scarp fault on the Landsat imagery is the Zomba Fault. Bloomfield has estimated that the throw of the Zomba Fault is at least 1100 m and the head of parallel fractures is about 45°. These parallel fracture are well evidenced to the east of the Zomba fault as shown on the Landsat interpretation (Map 1). An alignment of syenite intrusions follows the fault north and south of Zomba. Parallel fractures at 45° relative to the fault observed only to the east should indicate uplifted contact between Precambrian outcrops on the east and recent sediments to the west of the Fault, the Fault should represent a deep line of weakness.

To the east of the imagery we have the Lake Chilwa area which was mapped by Garson in 1960. He has shown that the Chilwa Alkaline Province rocks were mainly distributed along a NE-SW line of weakness paralleling the Karroo dolerite dyke-swarm. Faulting of rift type occurred during the emplacement of the Tundulu carbonatite complex. According to Garson (1960) the Lake cretaceous surfaces occur on some hills, and part of the Mid-Tertiary surface at about 750 m forming the Palombe Plain is downwarped along a NE-SW trend through Lake Chiuta and Lake Chilwa. This depression is partly infilled by coarse gravels succeeded by sands, silts and clays. With increasing downwarp in Quaternary times Lake Chilwa has receded leaving fossil beaches at about 110 m, 35 m, 25 m, 17 m, 12 m and 3 m above present level.

Describing the Middle Shire Area, south of Blantyre Highlands, Morel (1958) shows the main western rift fault (Zomba Fault) tailing out to the south and in a similar fashion the large Cholo Fault (Plate 17/66) petering out to the north. Morel (1958) suggested that the Central area is broken up into many small fault-blocks each with a small displacement but together a considerable vertical movement. The rift direction is believed to have been controlled largely by the regional orientation of the foliation of the metamorphic rocks.
Mapping the same area Hobgood (1968) considers the rift valley below the Cholo escarpment to have been unstable from Archean times. There is a pronounced parallelism between the present fault directions, the trend of the Cholo syenite and the general direction of foliation of Basement gneisses.

Large movements along the Cholo scarp during the Stormberg igneous episode tapped deep-seated basaltic magma and led to the emplacement of the doleritic dyke-swarm into tension fractures in the Shire Highlands, and of doleritic sills and plateau lavas in the downfaulted Karroo basin. The throw of the Cholo Fault is supposed to be less than 6000 m contrary to Dixey's earlier calculations (Hobgood, 1968).

Area Five

W. Cooper and K. Bloomfield (1961) mapped the southern part of Area Four, in the Mwanza Area.

The main feature is the Mwanza Fault which has a vertical throw of at least 300 m to 600 m. There is a considerable mylonitisation and infilling by chalcedonic quartz and flinty crush rock. In some places this material is up to 1500 m thick.

Cooper and Bloomfield (1961) also report that the sediments below the scarp indicated that the scarp was in existence in Karroo times. Evidence of movement of different ages is shown by the relationship to the fault-line of Stormberg dolerite dykes and cretaceous solvsbergite dykes. The Korroo sequence is repeated by faulting.

Parallel to the Mwanza and Mtumba Faults there is an alignment of Basement Complex and according to Hobgood (1968), the deepest part of the rift valley (Shire) in this area is bounded by the Mwanza and Panga Faults.

The Mwanza Fault extends northwards into Mozambique marking the contact between the Karroo basin to the south and Furancungo granite batholith to the north. As it enters Mozambique the Fault is displaced by another fault trending NE called here as Mwanjidze-Mtembwe Fault. From the Landsat imagery the Mwanza Fault has been displaced left laterally, indicating that it is older. For identification the continuation of the Mwanza Fault is here called Salambidwe Fault, and the continuation of the transcurrent Mwanjidze-Mtembwe Fault is here called Condedzi Fault.

Area Two

Bloomfield (1958A) mapped the central area of the scene (179/72) known as the Nsanje area, His investigation has revealed that the cover of Karroo rocks is probably fairly extensive. According to Bloomfield (1958A) the throw of some of the faults (e.g. Namelambo) is possibly about 150 m. He further points out that some faults parallel to the eastern edge
of area (near the border with Mozambique) may indicate the presence of lower Shire rift valley and points to the need for further work in Mozambique to determine if there is an eastern boundary fault there. It is under such border restrictions that Landsat can play an important role as shown on Map 1. There is no doubt that the linear or fracture traces observed on the imagery south of the Cholo Fault are in fact a manifestation of the sediment covered Cholo rift fault continuation into Mozambique.

E-W and ESE-WNW faults have been mentioned in this area. These are infilled by siliceous fault rock similar to very large areas of fault rock at the northern end of the Namalambo Fault (Bloomfield, 1958A). E-W or ESE-WNW faults are quite frequent on the western side of the rift according to the Landsat interpretation.

Unlike the Shire greben to the north, the southern part of the rift has been more active resulting in large syeno-granitic intrusions, basalt lava flows, especially along the graben margins. Magmatic products in this part are ranging from alkaline to basic magmas marking the later stages of activity as manifested by the Gorogonsa massive and other bodies.

To the West of the Urema graben we have the Karroo sediments deposited in a belt running parallel and adjacent to the Zambezi River. Further south these sediments are scattered in a discontinuous belt adjacent to the eastern edge of the graben. In the Zambezi River area the Karroo occupies well defined fault bounded troughs which bring the sediments into contact with Basement rock both to the south and north of the river.

Although structural information for this part of the rift is still little a brief discussion of the area is going to be attempted based on Landsat interpretation and previous work by other investigators. And for discussion the region is divided into two zones, first zone is north of the Zambezi river and the second zone is south of the river.

Area North of River Zambezi

The first zone is the area between the Mwanza Fault and the Zambezi River. Although there is no evidence that rift faults, which have been described earlier in Malawi, do cross into Mozambique in this area, Map 1 shows that regional ENE and NW lineaments do disturb the rift faults and continue into Mozambique. These lineaments might be older but reactivated by the rifting.

It had been pointed out by investigators like Afonso (1976) that the predominant tectonic directions of the area are NW-SE, NE-SW and N-S.

The NW-SE system of faulting is responsible for the creation of the tectonic basins into which the sediments of Karroo's coal "Productive Series" were deposited. The dolerite dykes of the area are linked with this system of faulting.

The NE-SW system has affected the Karroo formation especially the lower basalts which have been uplifted in relation to Upper basalts. The volcanic eruptions are supposed to be linked with this system.
The N-S systems (Afonso, 1976) have affected most of the rhyolite and basaltic lavas. The acid lavas which are stratigraphically lower are today found uplifted higher, in relation to alkalic lavas, by this fault trend.

Two types of folding have been observed:

- Pre-Karroo folding which is characterised by monoclinal folds of WNW-ESE direction.
- Post-Karroo folding, the most important of which is the asymmetric Synform of Zambezi River which has a NW-SE axis. The northern limb is more inclined than the southern (\(> 60^\circ\)).

All three tectonic trends have been observed on the Landsat, however the N-S trend here is more NNW-SSE than N-S, especially near the river. Therefore the NNW-SSE trend is dominant followed by the NW-SE trend. The near to E-W trends have been depicted mostly as "topographic" lineaments on Landsat and on the aeromagnetic interpretation and they are well expressed.

Strike of Basement Complex gneiss is parallel to the dominant fracture trend, to the north of Moatize a swarm of dykes, of curvilinear shape, cut across the Basement trends (Figure 6.9). In relation to drainage most of the rivers have been bent by the NW-SE trending lineaments. From what has been said earlier the NW-SE are older lineaments of Pre-Karroo times, much older than the NE-SW lineaments. The NNE and NNW lineaments are probably much younger that is why they are numerous on Landsat imagery but more likely they might just be reactivated Basement lineaments or jointing which are manifested on Landsat today.

Numerous large intrusive bodies are found in the area like Mt. Salambidwe, Muembe, Buzimwana, Necungas, and others. Their location seem to coincide with the intersections of large lineaments.

Area South of River Zambeze

The rift faults of the Urema graben can be traced with less confidence than those of the Shire Graben. Although recent (Quaternary) movements give rise to well-preserved fault escarpments, in the Urema Graben the Miocene sediments suggest Mid-Tertiary movements.

Three main directions of faulting are evident in this area: these are: NW-SE, NE-SW, E-W. The N-S trend do appear but with less frequency. The Urema Graben trends NNE and then NW before joining the Shire Graben. This trend, and the NW-SE trends are supposed to be responsible for dolerite dykes seen to the north and south of Gorogonasa pluton. To the north of the pluton, however, the dykes take an almost N-S trend. The N-S trend is probably responsible for the "step fault" pattern sinking towards the Urema Graben.
Afonso (1976) has pointed out that the system of faults of NNE-NNW have permitted the rising of the block between river Pungue (south of Gorongosa massive) and river Zambezi which has inclined 3° to 5° towards the sea on the east. The limit to west is formed by intensively eroded fault scarp, Flores (1973), calls this fault scarp the Inhaminga Fault.

Of the most important geological and structural features in this area are the Gorongosa pluton, Urema Graben, Lupata trough, Chissenga Graben, and the Inhaminga Fault.

Mt. Gorongosa Pluton - Plates 28/109, 28/113 are Landsat illustrations for the Gorongosa magmatic pluton. This ring structure is composed of post-Karroo basic and Ultrabasic rocks (gabbros, norites, serpentinites, and anorthosites) which have intruded as the western part of the ring structure. Granites, grano-diorites and diorites of younger age occupy the central and eastern part of the ring structure. Elluvial deposits surround the pluton especially on the eastern side of the ring.

The granites, grano-diorite and diorite are distinctive because of their characteristic tone reflectance. They show intensive red tones on the colour composites whereas on convolved images this rock group shows no “pattern”, that is, it is dark, because the chlorophyll from the vegetation cover absorbs energy in the wavebands 0.45 to 0.65μm. Ultrabasic and basic rocks as well as the elluvial accumulations support little vegetation and as such can be discriminated. The contact of Gorongosa pluton with the surrounding Basement gneisses (blue) is clear.

To the north of the pluton (Plate 29/114) a large number of dykes are manifested. Both the convolved and the colour composites clearly display all these features. The “topographic” lineaments which systematically displace the drainage and the dyke systems are also clearly seen. A large fluorite deposit of Marringe is in fact located at the intersection of two dyke systems seen at the top of Plate 29/114. From the Landsat interpretation the Gorongosa pluton is located at a structure (lineament) “interference zone” where NNE-SSW and ESE-WSW oriented lineaments intersect. The intersections of the Urema, Lupata and Chissenga grabens appear to reflect these structural interpretations.
**Urema Graben** - The Urema Graben is deliniated to the east by the Inhaminga Fault (Map 2), and to the west by parallel faults, dropped eastwards, detected by geology and confirmed by Gravity (Flores, 1973). The fault deliniating the western side of the Urema Graben continues to the SW for an unknown distance the recent aeromagnetic survey has confirmed the extension of this Graben, and it has been found that the outcropping Basement is more magnetic in the east where it is intruded by dykes, than it is in the west.

The Landsat, geological, and aeromagnetic lineaments do concide well in this area as it can be seen from maps 1, 2 and 3.

**Lupata Graben** was mentioned by Flores (1973) who called this structure “Zambezi Graben”. Not to be confused with the Zambezi river Graben, the name Lupata Graben is used here. At the north end of Lupata Gorge the Graben is interrupted by a large mass of alkaline lavas known as the “Lupata alkaline complex”.

Describing the lithology of the graben (Flores, 1973) points out that from the Lupata Gorge southwards there is a cretaceous series resting above the Karroo (Stormberg) basalts. The type of igneous effusives (Belo and Sena), found in this Graben are not known to exist beyond the margins of the Graben. This has led to the suggestion that these effusives were outpoured as the Graben was forming.

According to Flores (1973) the formation of the Lupata Graben (Late Jurassic-Cretaceous) was followed by volcanic outpourings along the graben margins over Jurassic continental sediments (Belo formation). Later, the Graben was filled by uplifted Lower Cretaceous continental sediments (Sena Formation), followed by volcanic outpourings along graben margins (Lupata Volcanic). Probable marine sedimentation exist in the SE area of Graben. Rifting of the Urema Graben (NE-SW trend) in the Upper Cretaceous to Late Tertiary took place later. SE tilting of the areas to the south of the Inhaminga Fault (between river Pungue and Zambezi river) followed.

Based on seismic and dip-hole drilling it has been possible to confirm the SE tilting of this block (also known as the Inhaminga “high” uplift). The Urema Graben can be said to have cut across the Lupata Graben based on the fact that, as pointed out by Flores (1973), the Urema Graben Western fault has affected the Belo and Sena igneous strip near
Paiva de Adrade (South of Gorogonsa pluton) and this can be considered good evidence that the Inhaminga system was developed in Post-Lower Sena times, that is it started to be active in times as old as the beginning of the Upper Cretaceous. The youngest sediments affected by the Inhaminga fault are the Mazambe sandstone of Lower Miocene Age. Therefore the Lupata Graben is older than the Urema Graben.

From aero magnetic data (Hunting, 1983) the Lupata Graben is traversed by a major magnetic feature which has also been observed on Landsat imagery near Chemba. The contact between basement and sediments was however not well defined due to a belt of basalts associated with rifting. However, geologically the basaltic belt should give us a general indication of the extension of the Graben.

Inhaminga Fault - from what has been said above, the Inhaminga Fault is a Rift Fault which marks the eastern age of the Urema Graben. It must have been accompanied by the uplift of the present day Inhaminga “plateau” or high. Probably due to intensive erosion of the Inhaminga “Plateau” erosional sediments do obscure the scarp so that it is difficult to trace it easily on the Landsat imagery.

6.4 REGIONAL OVERVIEW OF LANDSAT AND AEROMAGNETIC INTERPRETATION.

Airborne magnetic and radiometric surveys of the region was carried out by Hunting Geology and Geophysics under the contract by the Direccao Nacional de Geologia, during the 1982/83 season. The airborne survey was carried out at a mean height of 120 m above the surface at a 1 km line interval.

The interpretation done by the company was basically from contour maps of magnetic field strength and spectrometric total count. Regional interpretation was done on a 1/250,000 scale permitting the initial identification of major regional features, after which a detailed study was carried out.

By studying the amplitudes, wavelengths, shapes and directional trends of magnetic anomalies the interpretation of the magnetic maps was carried out. According to Hunting, zones of characteristic magnetic “signature” have been identified, mapped and numbered for reference. Magnetic discontinuities which are often but not necessarily linear and which may pass through a single zone or coincide with zone boundaries, were identified. Interpretation of the spectrometric total count maps was carried out in a similar way to magnetic interpretation, but with regard to the spectral characteristics of terrestrial radioactivity.

Almost as with Landsat MSS data, in radiometric mapping the radiation received emanates from the uppermost few centimeters of the ground; the method is essentially shallow sensing, because even a thin layer of alluvium will mask a signal from bedrock. In Landsat sensing any cover of vegetation reduces the information on the geology.
As part of the survey Landsat imagery and aerial photogeology were incorporated by Hunting. Landsat interpretation comprising of overlays at 1/150 000 scale prepared from false-colour composites, as well as Landsat scenes or black and white subscenes at 1/100 000 were referred to. As pointed out by Hunting, this greatly assisted the definition of large zones and regional features. Photogeological contribution was in the mapping of smaller zones and features, and to confirm the existence of features for which the geophysical evidence alone was doubtful.

The survey did not however cover some areas close to the rift, especially south of the Urema Graben, therefore it has not been possible to compile aeromagnetic data for the whole rift zone in Mozambican territory of the area.

Probably the best illustration of the aeromagnetic interpretation is presented on Map 3. This is a 1/1,000 000 scale map compiled by the author from the 1/250 000 original interpretation maps. These type of data as shown on the map are the aeromagnetic bodies, radiometric and magnetic “signatures”, and magnetic lineaments or faults.

The aeromagnetic lineaments tend to take different trends in different areas of the imagery. For example along the western edge of the Urema Graben the lineaments are generally N-S with very few NE trends. From Maringue they change to NW trend all the way up to river Zambezi. These lineaments should mark the western edge of the Lupata Graben. A few NE trending lineaments are seen crossing the Greben. On Landsat map 1 we can see that the majority of fracture traces coincide with the general trend of the aeromagnetic lineaments. However Landsat shows one more prominent trend ENE-WSW, and a large number of Volcanic eruptions and vents are found at the intersections of northerly trends with ENE-WSW trends (e.g. north of Canxixe, and south of Mutarara). The ENE-WSW lineaments should be referred to as “topographic”, probably they are deep seated; their existence is seen by the behaviour of the drainage and also that most of the dykes seem to curve or terminate at these topographic features (Figure 6.6). A number of NE-SW lineaments also occur in the area.

Although the nature of these ENE-WSW lineaments is not clear, it is possible that they are old zones of weakness of the Medio Zambezi Province which were later reactivated during the rifting through which volcanic magmatism has occurred. The foliation shown on Map 1, east of Canxixe represents elongated and curved aeromagnetic bodies which terminate against the aeromagnetic and Landsat lineament which runs towards Chembab town and across the Shire Graben. The foliated rocks are known as the Barue “gnaiisses leucocrates micropertiticos” with syntectonic granitoides.
TOPOGRAPHIC LINEAMENTS AND DYKE SWAM COMPLEX
NORTH OF GORONGOSA

Figure 6.6

Topographic Lineament
\/
Dyke
\/
Fracture trace
As we near the river Zambezi the aeromagnetic ENE-WSW trending lineament become more dominant. Across the Karroo basin till the contact with the Furancungo batholith, north of Mt. Salambidwe, this trend is the most important. A few NE and NW trends also do exist, and one fracture zone shows a N-S trend west of Tete town.

On Landsat the ENE and WSW trend is represented as topographic lineaments. The NNE and NE is much dominant in the Karroo basin north and south of the river Zambezi. Basement traces and bedding is also very clear north and SE of Tete town. Dykes can be seen west of Longitude 33° 30' trending N-S. Another swarm of curving dykes are seen at the contact of the Karroo-Tete Gabbro anorthosite Complex north of Tete. The contact between the basement Complex and Karroo NW of Mt. Salambidwe is marked by E-W trending traces which might be dykes or bedding, these traces do coincide with the isoline depths of “basement” (Figure 6.9).

From the Landsat and aeromagnetic interpretation it seems that Lupata Graben continues further into the “Tete Complex” from where numerous NNW trending lineaments are abundant, trending in groups of parallel zones.

From Map 2 we can speculate that the two big curves of the Zambezi river at 34° 00' and 35° 00' longitude mark the crossing points of the Lupata Graben as shown by the aeromagnetic survey also.

From Map 2 we can observe that the two big curves of the Zambezi river at 34° 00' and 35° 00' longitude should mark the crossing points of the Lupata Graben as confirmed by the aeromagnetic survey.

We can assume that the Tete Complex lies at the northern end of the Lupata Graben from where it branches into narrow zones bounded by faults between the town of Tete and Mt. Muembe. Into these two zones numerous structurally controlled magnetic bodies are located. And the Chissenga Graben, mentioned by Flores (1973), might be the southern extension of one or both of these zones (Figure 6.7).

To summarise we can point out that the qualitative analysis of the regional structural and geological interpretation of the study area using Landsat has been shown to be possible and reliable.

In the first place we aimed to trace the Rift Faults as they extend through the study area. Scarp Rift Faults like Zomba Fault, Cholo Fault and Mwawza Fault among others, can be traced without doubt. Others like Inhaminga Fault, Mwanjidze - Mtumba Fault and Condedzi Fault, are somewhat obscured, but their surface traces can be mapped using images which have undergone different enhancement techniques.

It has been noted on Landsat that at their bends or curves, the Rift Faults are usually accompanied by a large number of parallel fracture traces or jointings. This increase of fracture traces can be observed even on the Rift floor, for example SE of Dedze Complex, along Mwanza, Mtumba, Cholo and Mutarara Faults. These traces, which are more likely to be joints, usually follow the trend of the Rift faults they are associated with.
FIGURE 6.7

TETE TECTONIC FABRIC MAP WITH GEOPHYSICAL MAGNETIC BODIES
1/250,000

Upper Karroo Volcanic rocks
Karoo and Post Karroo Sediments
Tete Complex basic and Ultrabasic rocks
Basement rocks
Magnetic bodies
Isolines to basement
Foliation or bedding
Landsat Fracture traces
Landsat Topographic Lineaments

FIGURE 6.7
A number of "Wrench Lineaments" cut across the rift Faults and cause their displacement. These have been mapped from Angonia up to the river Zambezi. South of river Zambeze these lineaments have no clear expression but still their traces can be observed. These Lineaments are regional in nature extending for hundreds of kilometers across the rift. They usually have either the NE or ENE trend; sometimes they do have the NW trend, for example to Mecamo Fault.

Besides these Rift faults, a number of regional Lineaments have been mapped also, as shown on Map 2. The only unanswered question is the genetic relationship of all these lineaments and their classification. Much work is needed in the future especially in the field.

Also important are the large number of ring structures observed on Landsat. Their significance is unknown and their relationship yet unclear. However as they are mostly close to large Lineaments there is no doubt that they are associated with them.
CONCLUSIONS

From this study it can be appreciated that from a few Landsat Computer Compatible magnetic tapes much data has been extracted. Part of this data can be correlated with other information and used to update existing knowledge of the area. This is probably the main important contribution of this study. Lack of statistical analysis in the work might be viewed as a set back, but for reasons discussed earlier statistics would have contributed little to this phase of work.

Three main areas of enquiry have benefited from this study. In the first place the detection of surface fracture trace trends; secondly the application of tonal reflectance to geological mapping; and thirdly the correlation of Landsat Lineaments with known fault lines and magnetic lineaments. A brief discussion of these three aspects of the work is set out below.

Lineaments

There is no doubt that the complex behaviour of large numbers of fracture traces mapped from the surface on the Landsat imagery reflect the complex tectonic and stress history of the area. Existing knowledge about these structures is still immature and contradictory in many aspects, and the explanations about these structures and the tectonics will be a matter of debate for many years to come.

In chapters 3, 4, 5 and 6 structural problems of the area have been discussed and several conclusions attempted. However the reader should bear in mind that the environment involved in this work is not the best for Landsat application.

Humid and semitropical environments favour vegetation and consequently deep soil cover. Many observations in other parts of the world have concluded that in this type of environment the smaller lineaments are obliterated, so much so that structurally complex regions appear much simpler. Therefore the majority of lineaments interpreted on the study images are lineaments of regional importance. Local structural anomalies can however be detected in digitised images, especially if their scales are larger than 1/250 000.

Rift faults are easy to map especially if they are represented by fault scarps. Foliation bedding and jointing are easily recognised and can not be confused with other linear feature due to their appearance and length. Dykes mostly show positive relief and cut across different types of formations as straight linears and as dyke swarms.

With reference to the study area, four sets of lineaments pre-dominate: NNW, NNE, ENE and NW. Two more trends can be considered to be also frequent, NE and E-W.

The Urema Graben Rift faults have a NNE trend whereas in the Shire Greben the trend is mainly NNW. The Basement gneissic foliation strike is generally NNW. Both these trends should reflect deep seated old zones of weakness which have controlled the emplacement of
old Precambrian sediments and the rift faulting. Rift faults appear to be accompanied by parallel to sub-parallel fracture traces of varying magnitudes concentrated in the basement adjacent to the Rift faults. Similar fracture traces are found some distance from the main rift faults. This part of the rift appears as a graben which has been downthrown between parallel faults.

The ENE and E-W trends are observed on both the Landsat and on the airborne magnetic maps. On Landsat these lineaments appear as topographic features and cut across the main rift faults, displacing them in places. They are long but somewhat subdued on the Landsat imagery. The cause of these lineaments can not be said to be due to the illumination angle of the sun because during the imaging the area is usually illuminated from an angle not parallel to the scan lines of the Landsat imagery system. This type of lineaments has been reported in some other parts of the East Africa Rift (e.g. Bohr, 1974).

The occurrence of the ENE trending lineaments and their correspondence to airborne magnetic lineaments and to known faults indicate that they play a fundamental role in the structural evolution of the region, and probably in the formation of ore deposits.

The NE trend reflects in part the Mozambique Belt structures. It is evident on Landsat imagery but not very much expressed on the aerial photographs e.g. in Angonia. The parts of north west Tete the NW trend is more dominant than the NE trend which is in Angonia.

Gneissic foliation is mostly linked with the basement trend. It has been noted on Landsat that at the bends of the rift faults (or e.g. where ENE or WSW fractures have displaced the rift faults), jointing and foliation increases, even on the rift floor. This is because a center of compression is created at these places generating a radial stress field centered at the bend which has the appropriate orientation to generate the conjugate sets of fractures observed on the imagery. Also it is possible that some blocks are uplifted at these bends or junctions thus exposing the basement closer to the surface.

Based only on this structural information it is futile to attempt the construction of stress trajectories for such a large and complex region, it is possible that a fracture in the Precambrian rocks could result from one or more stress distributions ranging in age from Precambrian to present. Movements of these features could have resulted from different boundary conditions and could have been at different times. Folding, local rotations of beds during folding, refolding, radial dyke swarms, stratigraphic changes, major shear zones, etc. indicate the superimposition of a number of different stress fields through time and not a single simple stress field. The resulting pattern of lineaments cannot therefore be interpreted in terms of stress projections unless additional information which allows their classification as to type and age is available. Although it is difficult to speak of orthogonality in this region some sets of lineaments do in fact form orthogonal patterns, e.g. the NW and the NE trend.
Therefore it was not possible in the course of this investigation to draw stress trajectories using the (ground unconfirmed and simple two-dimensional) Landsat data to relate lineaments and stresses. Also we should not expect to observe on the ground all the Landsat linears because for example a lot of short and closely spaced linears on the ground are mapped as single linears on Landsat.

**Tonal Reflectance**

A successful use of Landsat data for vegetation and geological mapping depends largely on the optimal use of the image enhancement techniques. Chapter two was dedicated to this subject. Some of the diagrams discussed in chapter five and six are in fact products of the image enhancement techniques. One set back was lack of multi-seasonal imagery for the area, because seasonal variations in vegetation, soil and moisture content can alter the appearance of the earth's surface.

It has been found out that spectral information alone is not enough in lithologic mapping or identification of rock type. It is always necessary to extrapolate on the basis of both spectral and geomorphic information, and if possible structural (fracture trace) information. Usually interpretation of spectral reflecting data can be aided by analysis of spectra acquired in the laboratory or the field although there is a significant difference between these two spectras. There was no such information available for the areas described in Chapter five to aid the interpretation.

The study shows that in this type of environment spectral reflectivity alone gives little help to rock discrimination. However it has been possible to compile useful information maps which improve on the existing geological information.

It can therefore be concluded that spectral reflectance can be a useful instrument in rock discrimination but only when combined with the other criteria like geomorphology, drainage, laboratory or in situ spectra, image pattern, and if possible with available geological information.

**Metallogenic Analysis** - the study of linear features indicative of crustal structure is very important because they are the pathways for mineralising solutions and in some cases form fundamental boundaries between crustal blocks that may have experienced differing tectonic histories and may in consequence posses differing metallogenic character.

A few investigators contradict this concept amongst them J. Gilluly (1976), who is critical of those geologists who are over impressed by lineament as ore guide. World experience has shown beyond doubt that linear features are useful in defining target areas - local settings in which ore bodies maybe concentrated, and which merit more detailed study in the field.
Large areas of the study region have not been explored and no abundant mineral occurrences are reported. Therefore it has not been possible to correlate the mineral deposits with Landsat lineament. The few recorded occurrences shown on Map 2 does show that most of these scattered deposits are located within or between regional fracture zones.

On the basis of Figure 6.8 and the structural framework of the region, it is suggested that E-W or ENE eventually NNW trending lineaments are very important for the location of mineral deposits because a large number of magmatic bodies lie at the intersections of these with other lineaments. For example the largest workable fluorite mine, Marrinque is situated exactly at the intersection of two sets of dykes, one set trending N-S and the other trending close to E-W and no deposits have been reported on the numerous NW trending dykes alone. The Marrinque deposits are shown on Figure 6.9.

In economic terms the existing stage of investigation cannot allow us to evaluate fully the economic interest of the Rift region. Not much is expected from the rift floor itself, with the exception of possible oil and gas deposits. Several important gas fields in Temane, Pande and Buzi, are known south of Gorongosa pluton, in areas of possible extension of the rift faults. Deep and continuous sedimentary cover in areas extending from the Indian Ocean to the rift valley might prompt future exploration closer or in the rift valley itself.

Mineral occurrences have been reported in many places in Mozambique close to the rift valley. These include Zr, Fe, Be, Au, Semi-precious stone and Fluorite. However, genetic relationship of these deposits to the rift structures is unknown.
MAJOR LINEAMENT TRENDS AND FLUORITE DEPOSITS NORTH OF GORONGOSA COMPLEX
APPENDIX 1
COMPUTER STATISTICAL PROCEDURES

The use of statistical procedures (see Chapter 3) has become an increasingly useful tool for the analysis of geologic data. One of our main aims in structural analysis is to acquire a comprehensive picture of the subsurface tectonics of the area; this can be achieved best through the application of statistical methods.

The available methods for gathering many geologic data, particularly sub-surface data, require that analytical procedures which yield maximum information be devised. This requirement is often met by statistical analysis. The set of data obtained from this procedure could enable predictions to be made of unobserved values of the geologic variable of interest. As pointed out by Kodjopa (1974), the deviation of a predictive model is thus a major object in the statistical analysis of geologic data.

The incentive for seeking a predictive model in structural analysis is that many economic deposits can be related to the sub-surface structure. Hence the geologist often seeks to describe and predict the geometrical configuration of sub-surface stratigraphic horizons, which may be of economic interest, and from which only limited observations are available (Attoh 1974). For structural analysis, the data are commonly given in terms of two independent variables which specify the geographic location (U,V), obtainable by digitising and one dependent variable (D) which is a measure of the depth (below sea level) of a specific stratigraphic horizon (in case we deal with depth data). The U and V variables are enough to give us the information about the spatial distribution of fracture traces and surface trend analysis, whereas with the dependent variable D the information can then be expressed in terms of the functional relationship of the form:

\[ D_1 = f_1 (U_i, V_i) + E_1; \]

where \( E_1 \) is a random variable (which in this case is a measure of error in the measurement of \( D_1 \)). According to Attoh (1974), the existence of such a relationship forms the mathematical basis whereby statistical analysis can be applied to sub-surface structural analysis.

Although such mathematical modelling and predictions are attainable the information contained in the preceding equation must be interpreted so that it is geologically meaningful, and when the function \( f_1 \) is not simple, the interpretation may be difficult or ambiguous, especially as geological structures are difficult to predict with precision. However many computer programs are available today which can be used in the modelling or analysis of geological data.
In carrying out any statistical analysis the following steps are required:

(i) The raw data (in our case a Landsat image) must be filtered and enhanced allowing us to identify the spatial features in which we are interested;

(ii) The set of independent variables (UV) representing, for example, the end points of fracture traces is extracted from the modified raw data;

(iii) The required statistical analysis is carried out using the (UV) data;

(iv) The results of this analysis is finally presented in tabular or graphical (e.g. Rose diagram) form.

A computer package capable of automatically performing this entire sequence of operations was not available, necessitating the investigation of a number of possible methods. The hardware available consists of a PDP-11 mini-computer system with attached video display and line printer, and the separate ICCC Cyber 855 mainframe. The latter system includes a manual digitiser and various plotting devices. Both computer systems have facilities for writing to and reading from magnetic tapes. The software available on the PDP-11 system is called “System 500” and is designed to display and manipulate Landsat images producing a visual display. The ICCC mainframe has a complete graphical package facilitating the production of graphs and diagrams on terminal screens, microfilm or paper.

The first option investigated would have involved using System 500 on the PDP machine to produce one band contrast stretched images from the Landsat data. The resultant image shows the lineaments, which are to be statistically analysed, in sharp contrast. A program was then to be written for detecting and extracting the coordinates of the beginning and ending of each line, thus producing the (U,V) data. This data was then to be recorded on magnetic tape and transferred to the ICC mainframe. Statistical analysis and graphical presentation of results could then be carried out on the Cyber 855.

The weak link in the above sequence of operations is the transfer of magnetic tapes between the two machines. Differences in tape format, word-lengths and internal representation of data makes the reading of tapes produced on the PDP-11 computer by the Cyber a very difficult task. Conversion software is not available and the time and effort required to produce such software was thought to be beyond the scope of this project.

The first stage in the required process was however achieved. Using software on the Imperial College IPIPS computer the visual image produced by System 500 was transferred to a Line printer. The resultant image shown in Figure A1 is made up of black and white tones extracted from the digital representation of the pixel elements. In itself this “hard copy” of the image is of no real use in the statistical analysis, but it demonstrates how the
FIGURE A1. Line printer representation of contrast-stretched band 5 of scene 180/70.
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<td>18.0</td>
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TOTALS 5.0 100.0 9.4 100.0

NUMBER DENSITY = 0.050 (PER UNIT MAP AREA)
LENGTH DENSITY = 0.096 (PER UNIT MAP AREA)
RELATIVE ENTROPY = 44.9 PERCENT
ATYPICALITY INDEX = 0.7

CELL NUMBER 4

SEARCH SECTOR (DEGREES) NO. OF FRACTURES LENGTH OF FRACTURES AVERAGE LENGTH
array of pixels can be digitally represented. The edges and lineaments can be seen (although not very clearly) in the figure. If this digital representation can be used to drive the line printer it can also be used as the input data to a program which would scan the array of pixels and extract the coordinates of fracture and points.

The second option was the one adopted and requires the manual digitisation of the image. A photograph was taken of the Landsat image (although the line printer output might also have been used). Using the digitiser attached to the Cyber mainframe the \((U,V)\) data was extracted from this photograph, i.e. all lineament beginning and end-points were digitised.

A program called FRACAN (used by M. Critchley, 1981) was designed to read this \((U,V)\) data, carry out several types of statistical analysis and then produce both tabular and graphical output. FRACAN provides a number of statistics including number and relative number, length and relative length, and average length of fractures in each 0°-180° arc for every cell of the map sheet grid and for the entire map sheet. The program also allows atypicality and relative entropy analysis.

It proved to be a difficult task to use FRACAN. The only form of the program was a listing of it in Critchley 1981. No explanatory details or documentation was available. The program was typed into the Cyber 855 and eventually run. It was decided to convert the program from FORTRAN IV to FORTRAN 77. This necessitated a number of major changes in the program especially with respect to input/output and the handling of character strings. Other important changes were required in the calls to the graphics package due to major ICCC system and operating system changes in recent months. A program called SORT was written to prepare and re-format the \((UV)\) data, thus acting as an interface between the digitiser and FRACAN.

The results of statistical analysis using FRACAN are shown in Figure 3.11a - l.
APPENDIX 2
AEROMAGNETIC INTERPRETATION

It is recognised that aeromagnetic lineaments do represent earth fractures, or rather fractures can be recognised by the aeromagnetic lineaments they produce.

An individual feature which defines a lineament is referred to as an element. Thus, according to Gay (1972) an aeromagnetic lineament can be defined as a "disruption in the contour pattern". The disruptions are caused by the juxtaposition of blocks of rock of varying composition (varying "magnetic susceptibility") at various places along appropriate sides of the lineament. This line of reasoning leads to the conclusion that the most common geological cause of an aeromagnetic lineament must be a fault. However, in some cases, metamorphic "graining" and normal depositional, intrusive, and extrusive contacts can be the cause of lineaments.

Aeromagnetic lineaments are normally interpreted on magnetic contour maps using different criteria Gay (1972) has summarised these criteria in the following way:

Lineaments as Breaks in the Contour Pattern

It has been found that a limited number of basic features of aeromagnetic maps define most aeromagnetic lineaments.

- Termination of highs - perhaps the majority of aeromagnetic lineaments can be recognised by magnetic highs terminating against them.
- Termination of lows - boundaries of magnetic lows do also define lineaments.
- Steepening and flattening gradients - sometimes lineaments are bounded by simple steepening or flattening of the magnetic gradient. In reality, steepening and flattening gradients define highs and lows of shorter wavelength and lower amplitude than the anomaly responsible for the primary gradient, but for purposes of recognition, a changing gradient is considered a separate feature.
- Linear Contour patterns - one of the most diagnostic features of aeromagnetic lineaments are straight-line pattern of contours. These can, and usually do, accompany termination of highs and lows, and steepening and flattening gradients.

Occasional alignments of magnetic lows and/or highs can also define lineaments.

The regional aeromagnetic survey of the study area has revealed important magnetic and radiometric zones, as well as important magnetic lineaments, some of which coincide with the Landsat interpretation as discussed in Chapters five and six. A summary of important airborne results of geophysical investigation of the area is given below.
In the south, the Mt. Gorongosa pluton circular outline is clearly distinguishable magnetically, but the total counts are distorted by unavoidable geometric effects. A major dyke swarm north of Mt. Gorongosa is strongly magnetic. This is normal for dolerite dykes in this region.

The Lupata Graben which has been filled with Karroo and post-Karroo sediments shows that the sedimentary rocks are non-magnetic and mostly of rather uniform, moderate radioactivity except where modified by present-day drainage features. Different sedimentary facies can be distinguished radio metrically. The basalts along the margin of the Graben of a post-Karroo age are less radioactive than the Karroo basalts further north.

The Karroo basin north of the Zambezi river is geophysically non-magnetic and has uniformly rather low total counts. The highest total counts usually denote the rhyolite suite. The Tete basic and Ultrabasic Complex is magnetic and low in radioactivity.

Basalt and dolerites associated with rifting are highly magnetic.

The Furancungo granitic batholith west of Ulongue Synform is more radioactive than the surrounding rocks. Magnetic data have helped to suggest that the batholith is much larger than indicated by the radiometric criteria used for defining this zone.

The aeromagnetic and radiometric map shown on Figure B1 defines two magnetic zones: the western part is dominantly non-magnetic, while the eastern part is more magnetic. The Dedza perthitic complex is shown to be the more magnetic.

The main geophysical zones of Figure 6.10 are the following:

M205 - Weakly magnetic rock with magnetic bands trending NW-SE. Part of the strongly banded basement rocks.

M269 - Wavelength = 3-5; amplitude = 200 approx; length >5. A more magnetic zone of the basement rocks.

M271 - Wavelength = 1-5; amplitude <50. A weak magnetic part of the Basement rocks.

M272 - More strongly magnetic Basement rocks.

M273 - Weakly magnetic Basement rocks.

M274 - Moderately magnetic Basement rocks.
FIGURE B1. AEROMAGNETIC INTERPRETATION OF ANGONIA REGION

Scale: 1/250 000

Aeromagnetic lineaments

Magnetic bodies
Two important radiometric zones are expressed on Figure B1, these are: R271 "perthite complex", and R205 basement complex.

Some important aeromagnetic lineaments can be correlated with the Landsat Lineaments. This point is best illustrated on Figure 5.10 where aeromagnetic Lineaments have been superimposed on the Landsat Lineament. Only two of the nine aeromagnetic lineaments (L284 and L282) can be said not to correlate with any of the Landsat Lineaments, whereas seven can neatly be superimposed on Landsat. These lineaments reinforce the conclusion that the ENE (or near to EW direction) is an important lineament trend in this part of the East African Rift. Similar correlations could be made for the other areas of this investigation especially along the Rift zone.
Plate: 6/46A  Computer Generated Spectral Reflectance Profile across Scene 180/70 along Profile B - A

Plate: 6/46B  Spectral Histogram along Profile B - A of Plate 6/46A
Plate: 6/47A  Computer Generated Spectral Reflectance Profile across Scene 180/70 along Profile B - A

Plate: 6/47B  Spectral histogram along Profile B - A of Plate 6/46A
Plate: 5/30  Band 5 image of the Ulongue synform with applied TLM and convolution

Plate: 5/34  Convolved Band 5 image of the Ulongue synform applied by pixel shift
Plate: 5/32  High pass directional filtering of the Ulongue synform

Plate: 5/38  Ulongue synform reflectance characteristics when MATRIX Rotation processes are applied
Plate: 139/299 Colour composite image of Mlange area
Plate: 1/1 False colour composite of Furuncungo batholith

Plate 139/11 False colour composite (FCC) and classification (C) of the Furuncungo batholith
Plate: 1/5  Comparison of an (a) FFTID and (b) matric enhancement of the Furancungo batholith illustrating the tonal Rio Chimodze Lineament
Plate: 6/56  Raw data histogram of Scene 180/70
Illustration 9

Plate: 25/101 Principal component image of Morrumbala pluton

Plate: 25/100 False colour composite of Morrumbala pluton
Plate: 18/70 False colour composite of the Chemba area with 'U' shaped lava flows near the Zambezi River

Plate: 139/196 False colour composite of large scale ring structures of the Tete region
Plate: 17/66  False colour composite of the Cholo rift fault

Plate: 17/67  Band 5 and Band 6 images of the Cholo rift fault
Plate: 28/109  Gorongosa pluton - displayed as a false colour composite
            (Bands 4, 5 and 6)

Plate: 28/113  Gorongosa pluton - convolved Band 5
Plate: 29/114  Dyke swarm north of Gorongosa, with ESE trending topographic lineament

Plate: 26/135  False colour composite of the Inhaminga Area and Urema Graben
Plate: 6/41  Colour composite of Mt Salambidwe

Plate: 15/15  Mutarara agglomerate vents and the Lupata graben sediments, a colour composite using 3 ratios
Plate: 19/82  Colour composite of three ratios of the Lupata graben section

Plate: 180/165  False colour composite of Landsat scene 180/70
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