THE CHARACTERISTICS OF PLUTONIC ROCKS IN VARIOUS CLIMATIC ZONES AS SHOWN ON MULTIBAND SATELLITE IMAGERY

A thesis submitted for the Degree of Doctor of Philosophy of the University of London and for the Diploma of Imperial College

by Adrian Hugh Lloyd-Lawrence, BSc, MIMM

Department of Geology
Royal School of Mines
Imperial College
London SW7

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ABSTRACT

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A study of LANDSAT-1 satellite imagery was carried out in order to evaluate the usefulness of multiband satellite imagery for photogeological investigations, and to obtain possible criteria for the interpretation of those features of plutonic rocks which can be observed on the imagery.

Climate was found to be the most important factor affecting the appearance of rocks on the imagery, and consequently six regions of plutonic rocks in different climatic zones were selected for case studies. The six climatic zones chosen were desert, semi-arid, wet-and-dry tropical, wet tropical, mediterranean and temperate.

The main factors responsible for the photo-characteristics of the imagery are ground factors which include rock composition, structural characteristics, geomorphology, soil cover and vegetation. The assessment made of the importance of these various factors attempts to promote a more general understanding of the types of features which might be encountered on imagery of different climatic zones.

The photo-characteristics of plutonic rocks are examined and the recognition elements of tone, texture, pattern and shape assessed. Linear patterns were readily observed on the imagery and these patterns proved to be the most significant in photogeological interpretation. The patterns observed included drainage, lineaments, circular features and morphotectonic units. Lineaments were classified for

satellite imagery into four major categories based on length - geotectonic(>150 kms.), major regional(80 - 150 kms.), regional(20 - 80 kms.) and local tectonic(<20 kms.), these ranges being a general guide. Several circular features observed on the imagery stressed the polydiapiric nature of some of the larger batholiths examined. The concept of morphotectonic units was developed by the writer as a result of the synoptic views of large areas afforded by the satellite imagery. The types and sizes of plutonic features which can be observed for various scales of satellite imagery are classified.

The usefulness of satellite imagery in the determination of the structural style and control of pluton emplacement are discussed, and the control of mineralization in relation to lineaments is reported for five of the case study regions.

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CHAPTER ONE

BACKGROUND AND OBJECTIVES

The launch of LANDSAT-1[1] on July 23rd 1972 opened a new era in the exploration of the earth from space.

During the last twenty years a great number of new "remote sensing" techniques have been introduced. (Remote sensing in the earth sciences according to Barringer(1969) covers the "detection and mapping techniques which can be flown from aircraft or spacecraft".) Many of these methods have been described in the literature and summaries have been given by Barringer(1969) and Newton(1972). Undoubtedly, however, the most spectacular innovation in the field of photogeology has been the appearance of satellite photography and imagery of the earth and other planets.

Large numbers of pictures of the earth were returned by the Apollo and Gemini space missions of the 1960's. However, although these pictures were greeted with enthusiasm by the scientific community, their limited coverage and the high percentage of shots taken obliquely deterred many would-be investigators from examining this new material in depth.

With the launching of LANDSAT-1 a systematic image coverage of the earth was obtained for the first time with a resolution suitable for relatively detailed photointerpretation of ground

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1 Formerly named Earth Resources Technology Satellite-1, ERTS-1. Referred to as LANDSAT-1 throughout this thesis.

features. LANDSAT-1 is equipped with a Return Beam Vidicon(RBV) camera and a multispectral line scanner(MSS). The RBV developed a technical fault soon after launch and produced only a small number of pictures. The MSS on the other hand has produced a very large number of high quality images. The scanner data relayed from the satellite is ultimately converted into four separate photographic images for each LANDSAT scene. Each image records the reflected radiation from earth in one of four discrete wavebands of the electromagnetic spectrum designated 4,5,6 and 7. Two wavebands cover the visible part of the spectrum(MSS bands 4 and 5) and two, part of the near infrared(IR) (MSS bands 6 and 7). It is these MSS images which have been used as the basis of this research project.

The main objectives of this research project were:-

1) To evaluate the usefulness of multiband satellite imagery for photogeological investigations.

2) To assess the importance of the various factors contributing to the photographic appearance of plutonic[1] rocks on the imagery.

3) To obtain possible criteria for the interpretation of those features of plutonic rocks which can be observed on the imagery.

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1 Plutonic is used in this thesis in the broad sense of Turner and Verhoogen(1960, page 66) to apply to all intrusive igneous rocks as well as to those rocks formed by palingenesis or fusion of existing rock at depth. Hypabyssal rocks e.g. sills and dykes are therefore included in this study.

At an early stage in the research it was realised that the most important factor affecting the appearance of rocks on the imagery was climate. The writer therefore decided to carry out the investigation on the imagery by fully examining six areas from LANDSAT scenes of different climatic zones. Case studies were made on each of the six areas and this information provided the basic data for the research project.

As a preliminary to the full account of the research programme which follows, Chapter 2 of this thesis summarizes some of the results of early photogeological studies of satellite imagery. The chapter continues with some details on the LANDSAT itself and information about its image products, and concludes with a brief description of the main sources of information on LANDSAT photogeological studies. Materials used and the research methods employed are described in Chapter 3. The six case studies are described in Chapter 4. Each case study of Chapter 4 is sub-divided into an introduction of background information mainly obtained from the literature, a section on the photointerpretation of the imagery and a summary of the usefulness of the imagery from a photogeological viewpoint.

Chapter 5 examines the ground factors affecting the appearance of rocks on the imagery. The writer feels that a general understanding of the types of features found in the different climatic zones may enable the photogeologist to interpret imagery of unknown areas with more confidence. For this reason studies were made not only of the geology and geomorphology, but also of the vegetation and soil cover, as it is often the

latter which are largely responsible for the actual photo-characteristics of the imagery.

The photo-characteristics of plutonic rocks of the case study regions are summarized in Chapter 6. Possible criteria for interpreting the features of the rocks are included in the text. Chapter 7 gives an evaluation of the usefulness of multiband satellite imagery for photogeological studies and its contribution to economic geology and tectonics is discussed.

CHAPTER TWO

THE LANDSAT PROGRAMME

2.1 Earth satellite photogeological investigations before LANDSAT

General The first pictures of the earth obtained from orbital altitudes were provided by cameras mounted in sounding rockets, such as the American V-2's and Aerobees, which were launched in the late 1940's. However the information required from such photographs was at that time mainly of a strategic nature, and the pictures taken were in any case limited to areas close to launch sites. It was not until three years after the space exploration era began(1957 Sputnik 1, the first artificial satellite put into orbit) that the first significant batch of systematically taken imagery of the earth was obtained. These pictures came in 1960 from the TIROS I meteorological satellite,(although the very first pictures of the earth taken from an orbiting satellite were obtained the previous year by Explorer 6).

TIROS The TIROS series of satellites which had an orbital altitude of 692 x 740 kms. were equipped with a wide-angled television camera(104° field) and either a medium-angled camera(76° field) or a narrow-angled camera(12.7° field). The resolution achieved even by the narrow-angled camera was poor, generally less than 500 metres for irregularly shaped ground objects, compared with the theoretical 78 metres ground resolution of LANDSAT imagery. Nevertheless TIROS and the

later weather satellites like Nimbus, ESSA and ITOS/NOAA have returned hundreds of thousands of pictures of the earth's surface and cloud cover, which have been of inestimable value to metecrologists.

Some studies of the geological value of TIROS pictures were made by Morrison et al.(1965) and by Merifield and Rammelkamp(1966). The features which could be identified unequivocally on TIROS pictures were few; they included large bodies of water, shoreline beaches, desert sand seas, evaporite basins and Cainozoic orogenic belts in arid and semi-arid regions. The Cainozoic orogenic belts could be classified into two types, the sinuous fold belt type and the block-faulted type giving rise to basin and range topography. In arid regions Merifield and Rammelkamp found that by mapping the high albedo alluvium[1] covered areas some gross structural patterns were disclosed.

However one of the most serious drawbacks of TIROS imagery was the near impossibility of recognising the three dimensional aspects of the observed ground features. Vegetation produced further problems in interpreting bedrock geology as they were unable to relate the various tones it produced on the imagery to specific geological units. The small size of many geological units meant that they were often below the resolution of the camera system.

Mercury

Following the launching of TIROS I the first orbiting Mercury satellite MA-4 was launched in September 1961. This vehicle and subsequent

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1 Alluvium in Merifield and Rammelkamp's paper appears to be synonymous with the term eluvium(residual soils) of British geologists.

Mercury satellites were equipped with photographic cameras and the recovered film showed many hundreds of colour scenes of the earth. Morrison and Chown(1964) studied some of these photographs covering a strip of north Africa stretching from the Moroccan coast to Lake Chad. The original 70 mm true colour transparencies had a resolution of roughly 10-15 lines/mm(see Section 2.2.3). Although overlap between adjacent colour prints was available the stereoscopic effect was generally poor because of the small-scale, graininess of the prints, changes in satellite height and the general obliquity of the pictures. Their calculated estimate for the smallest ground feature which could be identified stereoscopically was of the order of 300 metres high. Because of the obliquity of these photographs they found that the foreground scales varied from 1:2,800,000 to 1:5,000,000, whilst background scales were much smaller.

Morrison and Chown mapped many extensive linear features which were represented by such factors as solution hollows, long narrow salt flats, elongated volcanic formations, drainage lines and changes of rock type. Overall they considered that structure was the most readily interpreted aspect of geology. The most remarkable discovery of this survey was the recognition of a major series of NW-trending lineaments extending inland from the Moroccan coast for over 650 kms. These lineaments run parallel to the Ougarta folded mountain ranges formed in the early part of the Hercynian orogeny. They noted also the interesting fact that if this zone of lineaments were produced south-eastwards it would parallel a 1,000 km. long straight stretch of the Niger river.

Gemini

The first high quality satellite photographs of the earth to become available were obtained by the twelve Gemini space missions between April 1964 and November 1966. According to Lowman(1969) over 1,100 usable pictures were returned, most of these being true colour photographs. Due to the orbital flight path limitations on these missions, coverage was obtained only for those areas lying between latitudes 32°N and 32°S of the equator. Hemphill and Danilchick(1968) in a brief but lucid account described and discussed the regional significance of some geological features on a Gemini V photograph of the Salt Range and Potwar Plateau of West Pakistan. They noted a number of faults, fold structures and lineaments in that area of folded sediments. Delineation of faults was based largely on sharp linear truncation of outcrop pattern and colour; whilst other lineaments were expressed as alignments of short stream segments. Anticlinal and synclinal axes were identified by close observation of the outcrop detail in the area of the fold axis. In that area anticlines are normally narrow closed structures whereas synclines are commonly open folds several miles across. Colour rendition was poor on the photography due to the effects of atmospheric scattering of the shorter wavelengths in the visible part of the spectrum. They concluded that for orbital photography colour infrared film would prove superior to conventional colour film.

Apollo

Three Apollo orbital flights between April 1968 and March 1969 collected a number of useful pictures of selected areas, generally from lower altitudes than the Gemini flights. The last of these satellites, Apollo 9, contained the

four-camera array of the important SO-65 multi-spectral experiment.

One of the principal targets selected by the National Aeronautics and Space Administration (NASA) for synoptic terrain photography by the Gemini and Apollo missions was the Red Sea rift zone. This area has been a centre of interest in recent years in connection with studies of continental drift and plate tectonics. It was thought that this economically interesting area would be an ideal one in which to test out the plate tectonic theories using evidence provided by satellite photography. Abdel-Gawad(1970) carried out such an investigation and concluded that the satellite photographs provided evidence which agreed with a previous estimate that the Red Sea had undergone a dilation of 150 kms.

The satellite photographs of the Red Sea zone clearly show the distribution and directions of trend lines in the Precambrian terrain of the region. The pattern of trend lines on both sides of the Red Sea showed significant variations in direction, and when these variations are compared across the rift they suggest a northerly displacement of Arabia. Other factors supporting this view include a matching of serpentinite belts, faults and shear belts across the rift and a matching of the structural pattern of the Hadramawt area of southern Arabia with that of the northern part of the Somali Republic.

Hamilton(1971) carried out a structural investigation on some Gemini and Apollo photographs of the Baja peninsula, California. This is an area of great interest because the peninsula is now considered to belong to the tectonic

plate of the Pacific Ocean floor. The area lies to the west of the crest of the East Pacific Rise and is separated from the North American Plate by the San Andreas strike-slip fault zone. Hamilton regarded most of the Gemini and Apollo photography to be of medium to low quality for scientific investigations. However he considered that a series of overlapping vertical photographs, allowing stereoscopic viewing, taken by the unmanned Apollo 6 mission to be of much greater value than some of the other material. The photographs examined illustrated well the nature of the strike-slip faulting of the area and showed up several contacts between metamorphic, granitic and Tertiary volcanic rocks.

Apollo 9 was equipped with a four-camera multispectral camera array designed to test out the usefulness of multiband satellite imagery in the visible and near infrared parts of the spectrum. One camera was loaded with colour infrared(CIR) film and the other three with black and white films. The cameras with black and white films had film/filter combinations which allowed radiation from three discrete wavebands of the spectrum to be recorded - two in the visible part and one in the red/infrared region. After examining some of the imagery from the Apollo 9 SO-65 experiment Lyon(1970) concluded that the particular bands chosen were more useful for agricultural projects than for geological purposes. This was because there are significant differences in spectral response from healthy green vegetation in the visible and near infrared parts of the spectrum; whereas the apparent lack of variation in spectral response in that part of the spectrum from rocks and soils meant that one band was almost as useful as any other for

lithological interpretation. Nevertheless similar bands were ultimately used in the LANDSAT multispectral scanner and in the Skylab S-190 scanner. LANDSAT MSS bands 4,5 and 6 correspond fairly closely to the three wavebands of the Apollo 9 multispectral photography. The advantages and disadvantages of these particular wavebands are discussed further in Chapters 5 and 6.

2.2 The LANDSAT programme and technical data

2.2.1 The LANDSAT programme

The Earth Resources Technology Satellite programme was initiated by NASA for the purpose of integrating space and remote sensing technologies in an R and D system for the efficient management of the earth's resources(NASA, 1971). The operational part of the programme was to launch a series of experimental earth orbiting satellites equipped with remote sensing instruments and imaging devices. NASA believed that only by disseminating widely the imagery returned by the satellites would enough information be forthcoming to determine the usefulness of such surveys. Accordingly participation was invited from the worldwide scientific community for the first LANDSAT-1 project, and of the many proposals for specific investigations received over 300 were officially endorsed by NASA.

The successful launch and return of the first pictures from LANDSAT-1 soon excited interest from the scientific community at large. The attractions of this new imagery were reasonably good ground resolution and the fact that imagery rapidly became available with relatively cloud free cover of most parts of the globe. NASA were soon innundated with requests for imagery at a new data processing centre set up at Sioux Falls[1]. Thus within a few months LANDSAT-1 virtually assumed the role of an operational rather than an experimental satellite.

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1 The data processing centre is the EROS Data Center, Sioux Falls, South Dakota 57198.

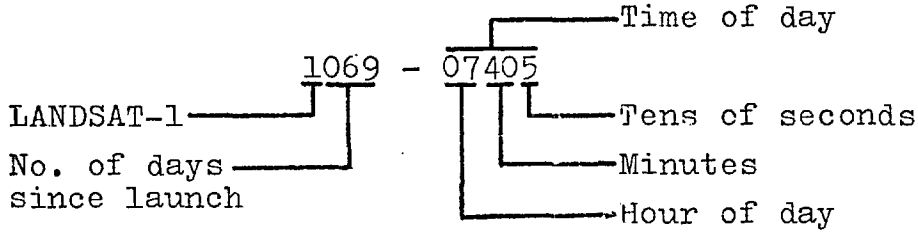
2.2.2 LANDSAT technical data

LANDSAT-1 was launched in a near polar, sun-synchronous orbit with a height of 901 x 920 kms. The satellite orbits the earth 14 times a day and covers the same spot at the same local time every 18 days. The LANDSAT contains a Return Beam Vidicon(RBV) camera and an optical-mechanical line scanner(MSS). The RBV failed soon after launch but the multi-spectral line scanner(MSS) is still operational. The MSS as described previously images the earth in four spectral bands simultaneously. The four wavebands are:-

MSS band 4 0.5 - 0.6 μm(green)
MSS band 5 0.6 - 0.7 μm(red)
MSS band 6 0.7 - 0.8 μm(red/infrared)
MSS band 7 0.8 - 0.1.1 μm(infrared)

Each MSS band has six detectors making 24 in all. The scanner scans a cross-track width of 185 kms., with the instantaneous field of view of each detector being a square area on the ground with a side of 79 metres. The output signals from the detectors are converted into digital data on board the satellite and either relayed directly(real time) to a ground receiving station or stored on magnetic tape for subsequent transmission to a receiving station, (transmission is generally made less than one hour later). There are two tape recorders on LANDSAT-1, one failed soon after launch and the other became malfunctional early in 1973. Since that time the amount of non-U.S. imagery has been very much reduced, although several new receiving stations have obtained imagery directly in real time.

At the data processing centre the digital information is recorded on to tape and this is fed into a system which ultimately produces the images of individual scenes. Although the scanner produces a continuous band of information it is split up into scenes for convenience so that each scene represents an area on the ground approximately 185 kms. square. There is an overlap(along-track overlap) of about 10% between scenes and a sidelap(cross-track overlap) between imagery of adjacent orbits of about 14% at the equator increasing to over 50% in the more northerly European latitudes. The imagery of each scene is marked with a unique image identification number or ID No. at the bottom right hand corner which gives the following information:-



The imagery is normally sent to users in the form of 70mm. black and white transparencies or 'chips', either positives or negatives. Negatives enable the user to produce his own paper prints of individual MSS bands at any desired scale. Alternatively EROS Data Center provide paper prints at scales of 1:1,000,000, 1:500,000 and 1:250,000. The majority of the imagery produced is referred to as system corrected(bulk) imagery. Precision processed imagery is available of a few selected scenes. False colour composite prints and negatives, made from combining three MSS bands, are also available of some scenes. Detailed work on land classification can be aided by use of the original computer compatible tapes, copies of which are available for selected scenes. The use of

the latter in geology is mainly confined to image enhancement techniques to aid specific exploration projects.

The EROS Data Center also provides a number of user services which include LANDSAT data catalogues, 16 mm "browse" microfilms of recently acquired imagery and computer print-outs of image ID Nos. of users' request areas.

2.2.3 The Quality and interpretability of LANDSAT imagery

There has in the past been a tendency to gauge the quality and usefulness of imagery by one major criterion alone which we call resolution. In general terms the resolution of an image can be defined as the minimum separation between two objects for which the images appear distinct and separate. Resolution in photogrammetry is defined in terms of lines per unit distance discernible by the human eye under standardized conditions i.e lines/mm. A line pair being one dark line and one adjacent light line. Such a definition depends on the ability of the human observer to discern these line pairs under the set conditions. Secondly it is not a very realistic definition as far as defining the resolution of specific objects on a satellite image or any other remotely sensed imagery. In fact resolution will vary all over the image for different objects depending on such parameters as contrast, reflectivity, shape, size and arrangement.

The definition of resolution used most frequently for satellite imagery is 'ground resolution'. This term though based again on

theoretical considerations does have some practical value as it gives an indication of the order of magnitude of the smallest objects which can usually be distinguished on the imagery. The estimated ground resolution of LANDSAT-1 imagery is approximately 78 metres. Two other terms besides resolution help to define the quality and usefulness of satellite imagery. These are detectability and recognizability. Rosenberg(1971) defined the two parameters as follows:-

> Detectability is the ability of a system to detect the presence or absence of a signal.
>
> Recognizability is the ability of a system to recognize or identify a signal.

System, here, means "the combination of a remote sensing system and a human observer or interpreter". Signal, here, means "an item of information in an image or other spatial pattern, or an item of spectral or temporal information". These two parameters are even less easily quantified than resolution and contain a highly subjective element. Like resolution, detectability can be computed for standardized targets: but when considering the images of actual low contrast linear features, the interrelated actions of variables such as granularity, spectral contrast and the observer seriously affect the differentiation of the individual lineaments.

The recognizability of a feature on an image is enhanced by a number of factors which include knowledge of its existence, location, shape, tone etc. Conventional photogeological studies are concerned with interpreting in geological

terms certain features on aerial photographs. It is obviously of value to know what objects produce individual patterns on aerial photographs but by no means essential for correct geological interpretation. For example, the trace of an open fold in a sedimentary sequence may be clearly depicted on an aerial photograph. Closer inspection or ground knowledge may reveal that the interpreted trend lines are due to a number of small shrubs following specific horizons along the outcrop of the folded rocks.

Satellite imagery, with its poorer resolution, will not always distinguish geological features with the clarity of aerial photographs. It is therefore important to find out for a particular region what ground features or groups of features are responsible for the observed image patterns. This knowledge will then enable the interpreter to decide what is their geological significance and to recognize those of importance wherever they appear on the imagery. It is this aspect of interpretation which has been stressed in this research project. By examining imagery of a number of different climatic regions the aim was to formulate possible criteria for recognizing the appearance of certain geological features within each type of region.

2.3 The main sources of information on LANDSAT photogeological studies

Numerous articles have been published in the last four years on photogeological investigations of LANDSAT imagery. At an early stage in the development of ideas on the usefulness of LANDSAT imagery several wild claims were made in the press about the great value of this new material in mineral exploration. However with the passing of time and the lessening of the initial euphoria related to the examination of the first images, geologists have been able to make a more objective assessment of the value of this new synoptic imagery of the earth's surface.

The findings of individual investigators have been presented at a number of symposia, particularly in the United States. The most important of these were probably the three NASA sponsored symposia held by the Goddard Space Flight Center in September, 1972(NASA, 1973a), March, 1973(NASA, 1973b) and December, 1973(NASA, 1974). The proceedings of these symposia have now become widely available, those of the second and third symposia being published as NASA Special Publications.

Some of the most distinguished contributions from LANDSAT investigators in the field of geology have come from a group working in South Africa. A very useful review article on the applications of LANDSAT in geology and mineral exploration was produced by Viljoen et al.(1975). This article is well illustrated with colour composite prints complete with transparent

photogeological overlays of some areas in southern Africa and Australia.

More recently a Professional Paper of the United States Geological Survey covering a number of LANDSAT investigations has been published(Williams and Carter, 1976). The book contains a description of several government sponsored projects in five disciplines including geology. A further source of less readily available information on LANDSAT photogeological investigations is contained in the reports sent in by the numerous NASA LANDSAT-1 Principal Investigators. These reports cover investigations from a number of different countries and photocopies are available from the National Technical Information Service(NTIS) in the United States at cost price to the user. Copies of some of these reports are held in the UK by the Technical Report Centre in Orpington, Kent.

Several papers on LANDSAT photogeological studies have appeared in the proceedings of the 8th and 9th International Symposia on Remote Sensing of Environment(Ann Arbor, 1973 and 1974).

In 1975 the new Manual of Remote Sensing was published by the American Society of Photogrammetry. This two volume work contains a number of useful ideas on the photogeological interpretation of LANDSAT imagery, as well as a wealth of background technical information on LANDSAT.

During the course of the writer's research a number of papers by other LANDSAT investigators were consulted. Where the work has been of

particular interest to the writer's study, reference has been made to it in the text of this thesis. The full titles of these papers will be found in the list of references at the end of the thesis.

CHAPTER THREE

OUTLINE OF THE RESEARCH PROGRAMME AND METHODS USED

3.1 General approach

Earth orbiting satellites equipped with imaging devices have provided photointerpreters with an entirely new type of imagery upon which to conduct their studies. To appreciate the value of this new data however it was necessary for photogeologists to re-examine a number of initial assumptions about the similarity between satellite imagery and aerial photographs and their practical uses.

The first assumption made about satellite imagery was that if it was to be of value it would be primarily for mapping many of the geological features normally interpreted during regional reconnaissance mapping projects using aerial photographs. At an early stage in the research the writer with such a view in mind decided to compare a mosaic of aerial photographs with a satellite image of the same region. The mosaic of aerial photographs was compiled from eight reduced print laydowns(PLD's) of aerial photographs. The area covered by these PLD's was the Zambian Copper Belt. The original PLD's were compiled from aerial photographs at approximately 1:30,000 scale. The final scale of the mosaic of reduced PLD's was 1:250,000.

The first examination of the corresponding LANDSAT scene selected for interpretation showed

up the tremendous difference in scale between unreduced aerial photographs and the satellite image. The area covered by the mosaic was less than one third of the whole LANDSAT scene, and to compile the mosaic over 200 photographs were used(this of course did not include stereoscopic mates). Both the mosaic and the LANDSAT scene were then examined to see how well they depicted a number of important geological features. The results of this simple experiment are set out in Table 3.1.

Table 3.1 Comparison of the interpretability of certain geological features on a mosaic of aerial photographs and a LANDSAT image of the Zambian Copper Belt

Feature to be identified	Mosaic	LANDSAT image
Drainage	Very distinct (well integrated system shown)	Only partially shown
Details of lithology of metasediments	One or two horizons identifiable	No sub-division possible
Boundaries of major granitic blocks	Fairly obvious but not sharp	Very distinct and sharp
Detailed structure	Not very distinct	Not shown
Main regional strike of Katangan metasediments	Distinct	Distinct
Major fractures	Not well shown	Very distinct

Although the Copper Belt exercise was only a superficial examination of the merits of satellite imagery versus aerial photographs, it did clarify a number of points in the writer's mind. Firstly that if a number of regions of a reasonable size were to be examined on satellite imagery it would not be feasible to

compare the satellite imagery with aerial photographs of these areas. Interpretation of the thousands of aerial photographs covering such areas, if available, would be far too time-consuming(and the cost of obtaining such photographs prohibitive). It was therefore decided that a comparison with the known geology of each area should be carried out using published maps of the areas. Secondly the experiment showed that the satellite imagery was superior to aerial photography in precisely defining the boundaries of major units on small scale maps in certain cases. Thirdly the satellite imagery was quite capable of defining major tectonic trends. Finally the satellite imagery was greatly superior to aerial photographs for depicting lineaments related to major fracturing of the rocks.

The second assumption made about remotely sensed imagery including satellite imagery was that for a given rock type almost any appearance was possible on the image. This view was based mainly on the detailed variations of ground conditions which appear on aerial photographs. Satellite imagery with its synoptic view and elimination of confusing detail gives however a much more uniform picture of the earth. It should therefore be possible to establish a much smaller number of criteria for interpreting individual geological units on satellite imagery than would be necessary to cover all the possible appearances of each rock type on aerial photographs.

It also became apparent that aerial photographs, useful in the assessment of the structural environment of individual or small groups of ore bodies, were not, as had previously been

assumed, necessarily the best photogeological tools to elucidate the structural control of mineralization of whole regions or provinces. It appeared to the writer that satellite imagery with its clear representation of some of the major tectonic features, together with advances in Plate Tectonic theories of mineralization, could have a significant part to play in future mineral exploration projects.

Framework of the research

The next phase of the research was to construct a framework in which to study the satellite imagery in order to assess its usefulness for photogeological investigations, and if possible to formulate interpretation criteria. A number of variables which might affect the appearance of rocks on the imagery were then considered. These included rock composition, rock structure, superficial cover, erodibility of the rocks, land use, vegetation cover and climatic environment. After closely examining these variables it was concluded that climate seemed to affect the appearance of rocks on the imagery more than any other single factor. Consequently it was decided that the imagery to be examined should be selected on the basis of geological interest and from different climatic zones.

Climate: the main variable

The variations in the surface conditions of the landscape conform to a broad zonation from the poles to the equator, related to surface temperature and water availability. Broadly there are four main climatic zones which are:-

1) The cold zone
2) The forested mid-latitude zone
3) The dry zone
4) The humid tropical zone

For the purposes of this study examples were excluded from the cold zone as these are areas subject to permafrost conditions and constitute an important field of study in themselves.

Several classifications have been used to describe the various climatic zones in detail e.g. those of Thornthwaite and Koppen. Fig. 3.1 shows a simple division into seven categories of the climates of Europe and Africa modified by the writer from a map by Trewartha(1962). Mountainous regions tend to have a vertical climatic zonation and although they have been distinguished on Fig. 3.1 they have not been considered separately in this study. The zones shown on Fig. 3.1 also coincide approximately with the biogeographic zones of the main plant communities. Table 3.2 shows the corresponding dominant natural vegetation type for each of the six climatic zones considered in this study.

Climate affects not only the erosional environment but also the distribution of the various plant communities, which so often largely determine the tonal characteristics of satellite imagery. The latter is not of course a fixed parameter but changes its appearance with the seasonal pattern of the weather(see Section 5.6). However it is important when purchasing imagery to obtain imagery which was taken at the best time of the year to get the maximum advantage from any possible geobotanical effects. It is also necessary to avoid seasons where there may be too high a percentage of cloud or snow or when dense haze conditions predominate.

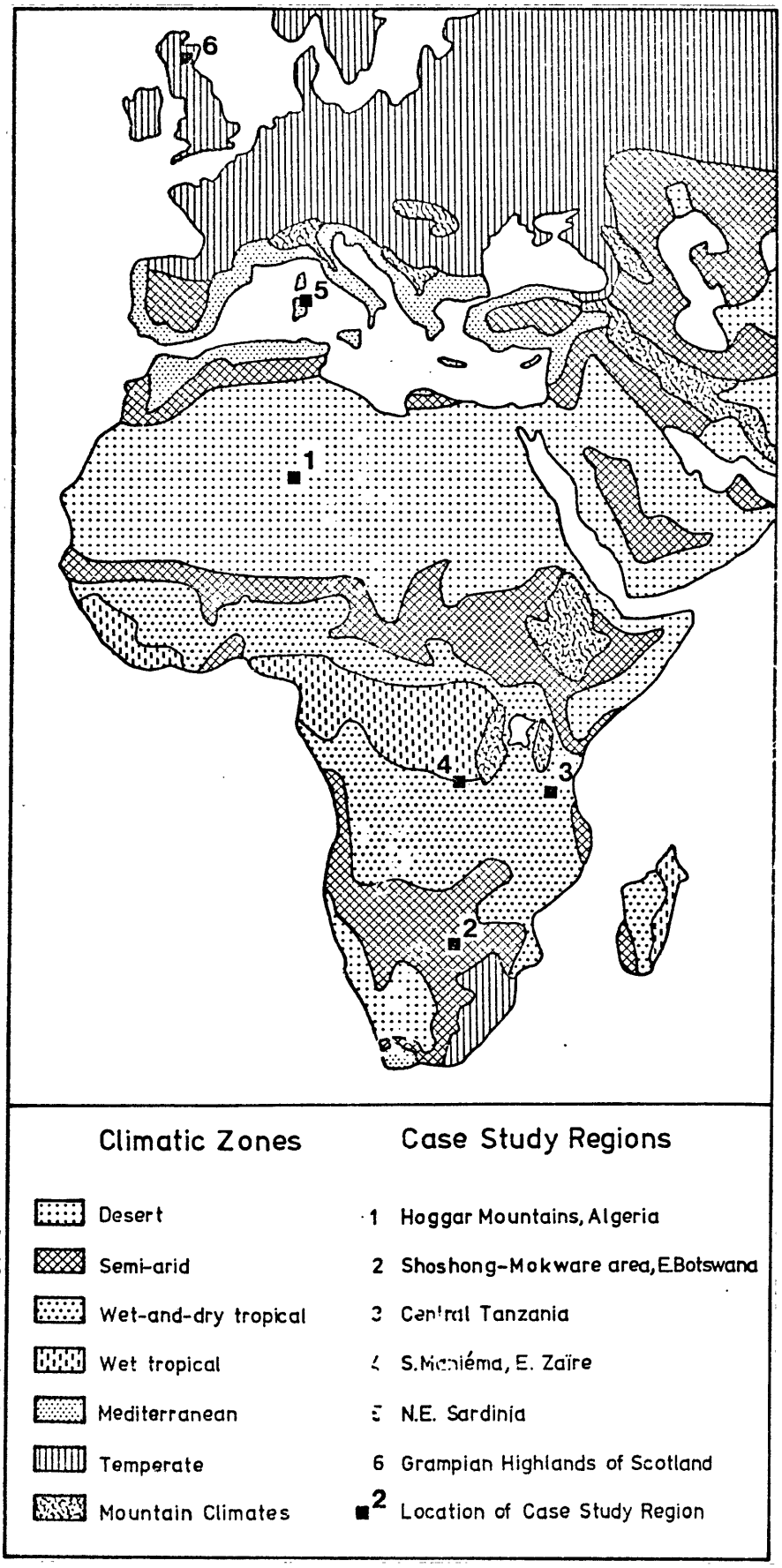


Fig.3.1 Diagram showing the main climatic zones of Europe and Africa (modified from Trewartha, 1962) and the locations of the writer's case study regions.

Table 3.2 Climatic zones and their corresponding main natural vegetation types

Climatic zone	Climate details	Vegetation type
1. Desert	No regular rainfall, but considerable range in temperature	Desert vegetation (drought resistant shrubs, grass and cactus)
2. Semi-arid	Winter warm and dry, summer hot with some rain	Steppe(short grass)
3. Wet-and-dry tropical	Winter hot and dry, summer hot and wet	Savannah(grass and thorn bush)
4. Wet tropical	Hot with heavy rainfall all the year round	Tropical rain forest
5. Mediterranean	Winter mild with moderate rain, summer warm and dry	Mediterranean scrub (citrus, olive, agave, etc.)
6. Temperate	Winter cool, summer warm, rain throughout the year	Broadleaf forest

Ecologists are also interested in seasonal changes in order to establish relationships between plant distributions and climatic factors. Seasonal variations can be shown graphically by the use of the climate diagram devised by Heinrich Walter. The World Atlas of Climate Diagrams(Walter and Leith, 1967) is a mammoth work containing over 8,000 of these climate diagrams from meteorological stations throughout the world. The climate diagram for the meteorological station within each of the writer's case study regions is included at the bottom of each geological sketch map in the thesis. These diagrams principally show the mean monthly rainfall and temperature curves.

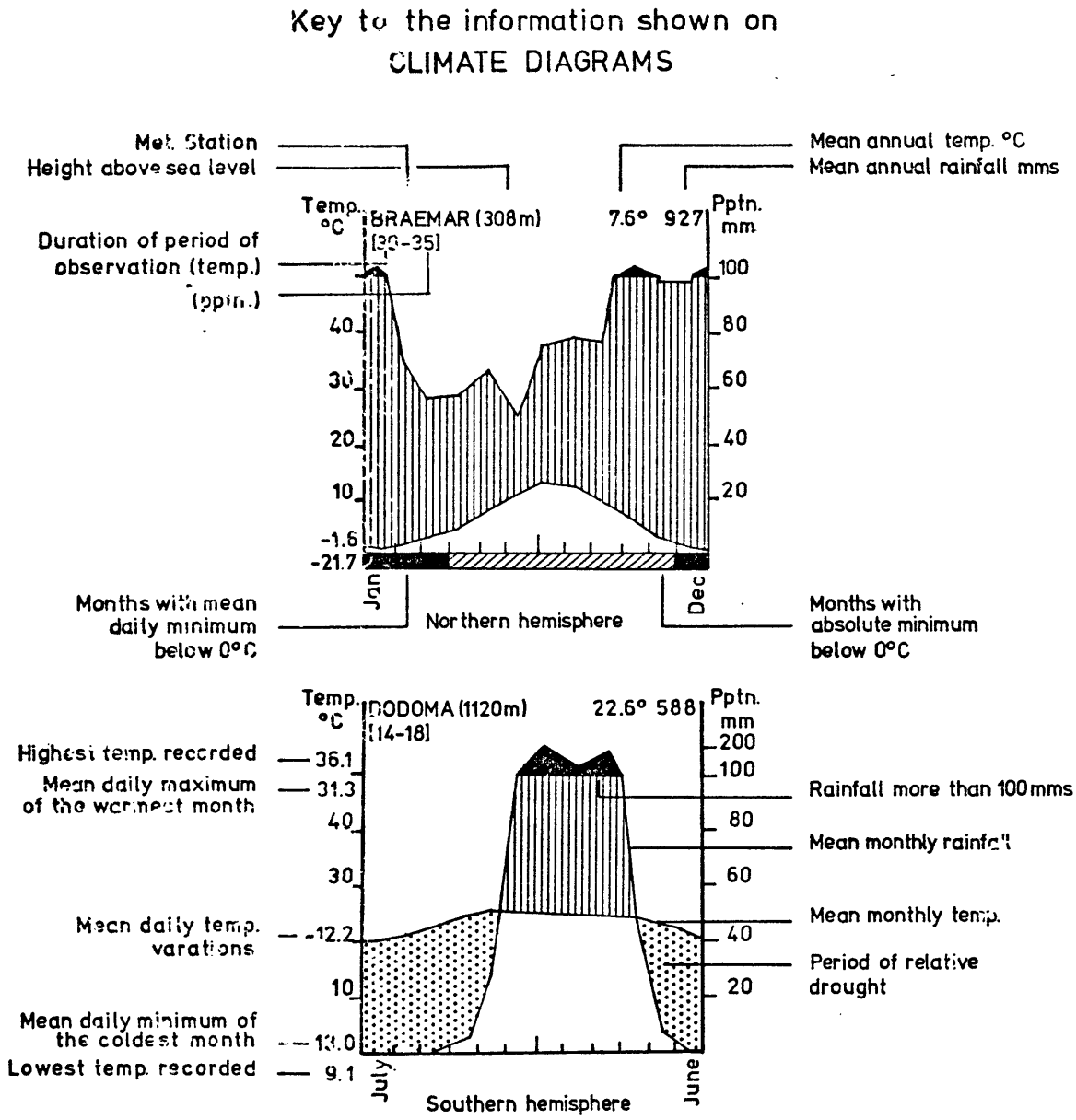


Fig.3.2 Key to the information shown on the climate diagrams of Walter and Leith (1967).

They also contain a considerable amount of other climatic data and a key to the interpretation of this data is shown as Fig. 3.2.

The choice of plutonic rocks

Rocks are commonly divided into four major rock groups - plutonic, volcanic, metamorphic and sedimentary. A really comprehensive study of the geological characteristics of LANDSAT imagery with examples from all four rock groups from each of the six climate zones shown on Fig. 3.1 would have required 24 case studies to be made. This would have been an almost impossible task to have accomplished in depth in the time allotted for the research project. The writer therefore decided to limit the investigation to examples of plutonic rocks, but to examine one example from each of the six climatic zones. Plutonic rocks were chosen because the writer has had some particular experience of mapping these rocks. Also they frequently appear as large enough entities to be picked up on the small scale of satellite imagery. One final consideration was that these rocks are sometimes associated with epigenetic mineralization and early LANDSAT investigations had showed that this might be of interest.

3.2 Data collection

The selection of the six case study areas took some careful thought as a number of factors had to be considered before the final choice was made. The writer decided to restrict the possible areas to those within the European and African continents. This was mainly because these are the regions where the writer during his training and working life has gained his background knowledge of rocks in the field. Naturally not all the areas finally selected were familiar terrain, but the writer had in most cases at least visited areas of similar geology and climatic conditions. In the case of the Grampian Highlands of Scotland a field trip was made.

A number of possible areas for study from each of the six climatic zones were selected on the basis of geological interest. The writer then spent some time examining catalogues of available LANDSAT imagery to see which areas had been covered. A self-imposed quality restriction was applied which excluded all scenes with more than 10% cloud cover and those which had any of the MSS bands as rated less than fair in quality. It must be remembered that this was still early in the LANDSAT programme and there was no such thing as the worldwide indexes to LANDSAT coverage, which were recently produced by the United States Geological Survey(Schoonmaker, 1976). The final images chosen were then ordered from the EROS Data Center, hopefully of the best quality(see Section 6.7.1).

The research programme proper was started with the examination of each of the six case study regions in detail(see Fig. 3.1 for location of the regions). The scheme of work was firstly to catalogue all the possible relevant information which could be obtained from the literature on each area. This was to provide a background body of knowledge with which to assess the importance of the various features depicted on the satellite imagery. As well as published papers and memoirs various thematic maps were consulted which included some of the following:-

1) Geological maps
2) Maps of superficial geology
3) Vegetation maps
4) Land use maps
5) Land classification maps
6) Topographical maps
7) Road maps
8) Aeromagnetic maps
9) Gravity maps

So that the information obtained could be standardized for each area a number of data sheets were drawn up. Seven data sheets were required. The first four covered the background data of each area. Data sheets 5 and 6 covered lithological and structural points of photogeological interest interpreted from the satellite imagery. Whilst data sheet 7 was for concluding observations and comments. The headings of each of the data sheets are set out in Table 3.3. Although there are a large number of these not all of the boxes were completed due to a lack of information. However in general most of the main categories of information were obtained and much of this has

Table 3.3 Headings under which information was classified on the data sheets

	Record no., Class, ID no., MSS band.
Satellite image interpretation data sheet no. 1	
Location	Coordinates of centre point of image longitude latitude Country Area of interest
Observation image basic details	Type Scale Date of pass Time of day Season of year Sun angle Sun azimuth Image quality general contrast amount of detail cloud cover
Climate	Climatic type General description Average annual rainfall Average rainfall for season of imagery (over a period of 1 month) Average annual temperature Average temperature for season of imagery(over a period of 1 month) References
Satellite image interpretation data sheet no. 2	
Topography and drainage	General Approx. height above sea level Geomorphological characteristics of investigated rock type Resistance of rock type to erosion Drainage pattern/s Drainage texture Factors controlling drainage patterns
Vegetation and land use	Natural vegetation Vegetation classification Land use Land classification Extent of communications networks Relevant publications

Table
3.3
(cont.)

Satellite image interpretation data sheet no. 3	
Solid geology	Rock type under investigation OR Nature of geological feature under investigation Lithological characteristics of investigated rock type Petrological description of investigated rock type Chemical description of investigated rock type Age of formation Distribution of investigated rock type Brief geological history of the area Published maps of the area Relevant publications
Satellite image interpretation data sheet no. 4	
Superficial deposits and soils	Description of superficial cover Thickness of superficial cover Provenance of superficial cover Description of soil cover Colour of soils Parent rock of soil cover Thickness of soil cover Soil drainage characteristics Soil moisture content for season of the imagery Major soils associations
Geological structure	Structural setting Lineation Fractures Faults Thrusts Folding Shear zones
Satellite image interpretation data sheet no. 5	
Photogeological interpretation: lithological	Interpretation equipment used Enhancement techniques used General appearance Tones Textures Shape of outcrops Size of outcrops Vegetation patterns Agricultural patterns Other patterns Ease of interpretation

Table
3.3
(cont.)

Satellite image interpretation data sheet no. 6	
Photogeological interpretation: structural	General Folding Lineaments Fractures Major faults Average length of fractures Dominant fracture directions Fracture densities Shear zones Manifestation of basement structure through overlying cover rocks
Satellite image interpretation data sheet no. 7	
Inter-relationships	Relationship of structure and/or lithology with known mineralization in the area Relationship of structure and/or lithology with aeromagnetic anomalies in the area Relationship of structure and/or lithology with gravity anomalies in the area Relationship of structure and/or lithology with geochemical anomalies in the area Relationship between geology, soil type and agriculture or land use
Conclusions	Accuracy of geological boundaries drawn on the imagery compared with published maps Geological features observed on the imagery not shown on published maps Important features shown on published maps not seen on the imagery Other conclusions

been recorded in the detailed descriptions of the areas given in Chapter 4 of the thesis.

3.3 Satellite image interpretation procedure

Following the arrival of the 70 mm negatives from the EROS Data Center of the four MSS bands for each LANDSAT scene, paper photographic prints were produced. The prints were mainly made on contrast 3 paper which is a little harder than normal grade paper. This helped to compensate for the rather high density of many of the negatives, without losing too many of the grey tones. Prints at 1:500,000 scale were mainly used for interpretation and normally the whole LANDSAT frame was printed giving an image approximately 37 cms square.

Interpretation was carried out on transparent acetate overlays using 'Rotring' pens. Clear transparent overlays were necessary as the prints were generally viewed monoscopically and a textured overlay would have obscured detail. Mistakes or discounted interpretation marks could easily be removed by rubbing the inked lines with a cotton bud dipped in water or methylated spirit. A hand lens was used for interpretation of obscure points of detail on the imagery.

Stereoscopic coverage was not generally available but there was sometimes an advantage to be gained from viewing together two different MSS bands of the same scene under a pocket stereoscope. Image enhancement was obtained in two ways by this method. Firstly the effect of binocular reinforcement was some advantage. Secondly due to some particular property of the imagery, possibly a small shift in the

position of the individual pixels of each MSS band, there was a very slight stereoscopic effect. This was mainly noticeable in the apparent deepening of drainage channels and was especially useful for the interpretation of lineaments. These were also enhanced by low sun angle imagery.

3.4 Presentation of the data

The ordered presentation of both background and photointerpretation data is made for each of the six case study regions in Chapter 4 of the thesis. The description of each case study region is divided into three sections, an introduction of background data, details of the photo-characteristics of the satellite imagery and a summary of the geological use-fullness of the imagery. The data is presented in the same order under the same or similar paragraph headings for each of the case study regions to aid comparison of the regions.

The account of each case study is accompanied by a geological sketch map, a LANDSAT image(s) of the region and a photogeological outline of the region derived from the satellite image. The sketch maps were compiled by the writer from published maps of various scales. Where a wider regional context is of value the sketch map covers a larger area than the actual case study region. In some cases the published maps had to be photographed and reduced and then redrawn omitting unnecessary detail. The satellite images shown are generally at smaller scales than the prints used for interpretation. The photogeological outlines accompanying the satellite images are intended as guides to illustrate certain points of the text and should not be considered as detailed interpretations. Specific locations and features on the images are indicated by arrows and numbers on both the image and photogeological outline and refer to points raised in the text.

3.5 Analysis of the data

Analysis of the data is divided into two parts, Chapters 5 and 6. Chapter 5 considers the ground factors which affected the appearance on the imagery of the various rocks of the case study regions. The theoretical aspects of some of these factors are examined and a number of hypotheses discussed. Chapter 6 examines the actual photo-characteristics of the imagery(i.e. tone, texture, pattern etc.) of the different climatic zones. Using the knowledge gained from the analysis of Chapter 5 the writer has attempted to broaden the scope of the investigation. This has been done by formulating a number of possible general criteria for the interpretation of plutonic rocks and related features on LANDSAT imagery of different climatic zones.

CHAPTER FOUR

EXAMINATION OF SIX REGIONS OF PLUTONIC ROCKS ON LANDSAT IMAGERY

4.1 Granite/granodioritic rocks of the eastern Hoggar mountains, Algeria - hot desert environment

4.1.1 Introduction

General

The region studied is one of complexly faulted and folded metamorphic rocks, which have been intruded both by syn- and post-tectonic igneous rocks. This mountainous area forms part of the eastern margin of the great Hoggar massif of the central Sahara. Fig. 4.1 shows the location of the region and its geological setting.

Climate

The climate of the Sahara is one of the hottest and driest in the world, as it is affected by the perpetual influence of the Azores high pressure atmospheric cell. At Djanet, which lies just to the north-east of the study region, the climate diagram on Fig. 4.1 shows that for June, July and August, the hottest months of the year, the average temperature is over 30°C. The temperature is probably slightly cooler on the mountains and decreases with altitude. Rainfall is scanty and sporadic, so that plant life is very restricted.

Topography

Steep mountains reaching heights of over 1,500 metres rise up from open pedimental areas of desert sand. Within parts of the mountainous area the drainage network is fairly well integrated though streams are ephemeral.

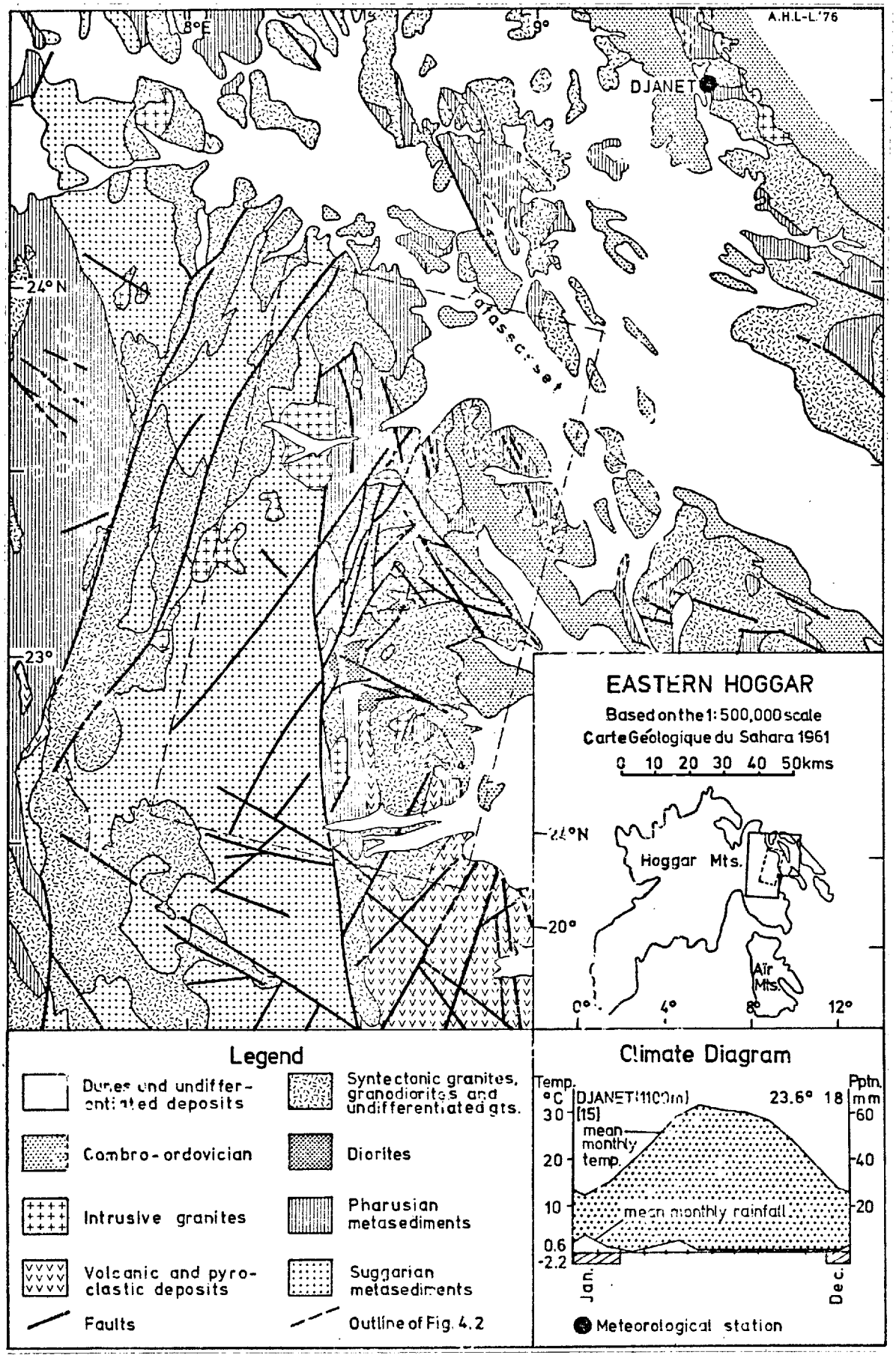


Fig.4.1 Geological sketch map of the eastern Hoggar mts. Algeria (Scale 1:1,700,000 approx)

All the streams in the region drain off the massif into the Tafassasset wadi. The wadi itself peters out 200 kms. to the south-east in the Kaouar erg.

Superficial deposits

Lithosols and blown sand deposits are the dominant superficial deposits in this barren region of sun-baked outcrop.

Vegetation

Vegetation is almost non-existent except for a few xero-halophytic species[1]. These plants usually take hold in cracks and crevices in the rock mass.

Communications

Occasional camel and jeep tracks are the only lines of communication, and most of these follow the major wadis.

The igneous rocks

The igneous rocks of the study region comprise syn-tectonic granites, intrusive granites, granodiorites and diorites as well as a small area of acid volcanics. There is also a "younger" set of intrusive alkaline or hyper-alkaline granites, similar in character to, but much older than the younger granites of Nigeria.

The bulk of the igneous rocks are considered to belong to a widespread suite of syn- and post-tectonic intrusions which range in age from 500 m.y. to 650 m.y.(Black and Girod, 1970). The "younger" alkaline granites have been correlated elsewhere in the Hoggar with the Taourits granites(Choubert and Faure, 1971). This puts their age at between 482 m.y and 532 m.y.(J. Boissonnas et al., 1964, quoted in

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1 The xero-halophytes are plants which like or can store large quantities of salt in their organs.

Choubert and Faure, 1971). Choubert and Faure think that these lower Cambrian granites represent the roots of volcanic centres which were emplaced at that time.

Geological background

Rocks belonging to two major units known as the Suggarian and the Pharusian occupy the greater part of the investigated region. These late-Archaean to early-Proterozoic rocks outcrop over extensive areas of the 250,000 sq. kms. of the Hoggar massif. They consist of thousands of feet of metamorphosed sediments which have been folded, faulted and intruded by the igneous rocks. The Suggarian rocks are mainly high grade gneisses whilst the Pharusian assemblages are of lower metamorphic grade.

Early workers in the Hoggar considered that the Suggarian and the Pharusian belonged to two distinct orogenic cycles, and were stratigraphically separated by an angular unconformity. More recently Black and Girod(1970) along with others have regarded the two units as belonging to closely succeeding orogenic cycles. In that case the Pharusian was regarded as a deposit laid down in unstable zones adjacent to rising Suggarian mountain chains which were undergoing rapid erosion. Caby(1969) goes even further to suggest that the two units represent only a single orogenic cycle. According to Schurmann (1974) Caby considers that the sharp changes in metamorphic grade and structural régime across the major N-S strike-slip faults of the region are due to: a) unequal setting of the isogeotherms during orogeny and b) to very unequal uplift related to graben tectonics of the lower Cambrian. In conclusion his thesis is that the Suggarian and Pharusian have only been subjected to one orogeny since 2,000 m.y. which was the

Pan-African orogeny(500 to 650 m.y.).

Structure

Structurally the region is one of complex block faulting. The most persistent aspect of the structural history of the Hoggar has been a tectonic constraint which has given a N-S trend to both major fold axes and faults. The study region is divided into two by the great N-S $8^{\circ}30'$ meridian fault which extends for over 300 kms. To the west of the fault are openly folded Suggarian gneisses, whilst to the east there is a complex of igneous and metamorphic rocks. The main structural features are shown on Fig. 4.1.

Schurmann(p.102, 1974) considers that the meridional faults were initiated during a phase of Pharusian rejuvenation at about 530 m.y., and they have suffered periodic displacements ever since. They were probably affected by the early Devonian movements which fractured the margins of the massif(Bogdanov, 1971). Schurmann believes that movements of Hercynian age(250 m.y.) were responsible for some of the extensive mylonitic zones of the region. Later during the Mesozoic and Cainozoic there was arched uplift of the Hoggar, being on the same N-S axis of uplift responsible for the elevation of the Air mountains and the Jos plateau. In those more southerly regions this tectonic event was accompanied by the intrusion of the Mesozoic alkaline granites(age 162 m.y.). Finally Tertiary and Quaternary movements affected the region and these were associated with minor volcanic activity.

4.1.2 Photointerpretation

Image quality

The western part of LANDSAT-1 frame 1071-09221 examined for this study was taken on October 2nd

1972 during a virtually rainless part of the year. The prints viewed were made from rather dense negatives - this was perhaps due to the high albedo of the sand deposits covering large parts of the scene. The high percentage of reflected radiation caused MSS bands 6 and 7 to suffer most from this phenomenon. Possibly some sort of gain control or filter should have been used on the scanner whilst imaging these desert areas. The denseness of the negatives made it difficult to obtain satisfactory enlargements with a normal aperture setting of f8 for the enlarger lens. More features were shown on the prints when the aperture was opened up to f5.6 or even f4.5. The consequent loss of detail from using a large aperture was found to be not too serious. When the smaller aperture was used the exposure time was so long that it was impossible to obtain a print with reasonable contrast.

Geomorphology

The most remarkable feature of the granitic/granodioritic rocks of this region is their subdued or almost flat topographic expression. Contrastingly the more basic igneous rocks and both low and high grade metasediments commonly form rugged hills. Similar weathering phenomena were observed by the writer whilst working on the Precambrian rocks of western Ethiopia. In that wet-and-dry tropical environment granodioritic rocks could be easily mapped from aerial photographs, as they appeared as flat areas of sheetwash deposits. These flat sandy areas were commonly surrounded by hills of more resistant greenschists. A "younger" intrusive granite in the north of the region, shown on Fig. 4.2 at point 1, forms the core of the Adrar Tiguluras massif. This granite has been almost completely eroded away leaving a circular crater.

The imagery strongly supports the contention made on p.55 that such intrusions represent the roots of volcanic centres.

Erodibility

The excessive weathering of the granitic rocks with respect to the other rocks of the region deserves further consideration. Cooke and Warren(1973) report that in arid climates granular disintegration of granitic rocks can take place as a result of chemical weathering of some of their constituent minerals. Others have suggested that preferential weathering of igneous rocks may take place because of the numerous fracture planes within them. The igneous/metamorphic complex of the eastern part of the region appears to be highly fractured throughout. At point 2 on Fig. 4.2 some remnants of Suggarian gneiss have formed a distinctive island pattern on the imagery. This is strongly indicative of criss-cross fracturing of the outcrop. In fact the remnant outcrops of the eastern complex are formed almost exclusively of Suggarian and Pharusian rocks and not from the granitic rocks. Thus in an area where both igneous and metamorphic rocks of similar competence have been intensely fractured, it does not seem logical to explain the lower relief of the former as the result of fracture weathering. It seems therefore that granular disintegration of the granite, is the most plausible explanation so far advocated for the general lack of granitic outcrop in these desert regions.

Drainage Features

The drainage of the eastern igneous/metamorphic complex is not well integrated, and due to the heterogeneous nature of the complex lacks any consistent preferred orientation. The Suggarian gneisses of the western block in contrast have a well developed parallel to sub-parallel drainage

system which can be seen on Fig. 4.2 in the region of point 3 . The Suggarian drainage is also partly controlled by the configuration of the major folds. Faulting and jointing are largely responsible for the orientation of the drainage channels in the igneous/metamorphic block. The drainageways in the sand-covered areas east of the mountains are best seen on MSS band 4 where the light toned wadis stand out clearly from the darker toned sand dune areas.

Vegetal Features

No obvious vegetation zones could be discerned on the imagery, but small patches and isolated bushes of xerophytic(drought resistant) plant species do exist. These may be thick enough on the highest ground to be contributing partly to the darker tones of the mountain peaks on MSS bands 4 and 5.

Tones

Areas of granitic rocks, where merely represented by residual soils, are generally light toned on all four MSS bands. Outcrops, on the other hand, of all rock types stand out clearly on every MSS band as much darker toned features. There do appear to be some slight tonal variations as for example between Suggarian gneisses(light to medium toned) and the dioritic rocks(medium to dark toned). Overall however there is little variation in tones between the individual MSS bands. These only slight tonal differences suggest a lack of significant vegetation cover. This is because a well vegetated area would have shown a sharp increase in the reflectance of radiation of wavelengths above 0.72 μm. In such an area MSS bands 6 and 7 would have been much lighter toned than bands 4 and 5, but this marked increase in reflectance was not observed on the IR bands of the LANDSAT imagery of this lifeless desert region.

The eastern half of the complete LANDSAT frame is almost totally white on all four MSS bands. This high albedo suggests that the tonal patterns observable in the sand dune areas of the western half of the frame could be due to a darker colouration of the sands, perhaps because of a higher iron oxide content. This possibility could be the result of seasonal water draining off the Hoggar mountains. The dividing line appears to be the Tafassasset wadi i.e. all the areas to the west are affected by the seasonal rains coming off the mountains whilst all areas to the east are in almost perpetual drought. The darker tones west of the Tafassasset may also be partly due to weathered products of Cambro-Ordovician rocks.

Rock boundaries

Boundaries of the various igneous rocks are not easily inferred from the LANDSAT imagery, because of the peneplanation of many of these units. These units on the 1:500,000 scale geological map were probably mapped from small pavement outcrops and the composition of residual soils. Such features either cannot be detected or have not been recognized on the satellite imagery. The dioritic rocks tend to form fault-bounded massifs, like 4 on Fig. 4.2, but their extent is small compared with the batholithic proportions of the granites.

Structural units

The main structural configuration of the region can be seen very clearly on the LANDSAT imagery. The major 8°30' meridional fault(5 on Fig. 4.2.) sharply divides the main outcrop block N-S. To the west is the hill country of the folded Suggarian gneisses, whilst to the east is the mountainous faulted complex of Pharusian, Suggarian and plutonic rocks. MSS band 5 shows a distinct tonal contrast between the two areas.

The darker tones of the eastern area are probably related to its greater elevation and the general steepness of the terrain.

Folding

Open folding of the Suggarian gneisses along major N-S axes like 6 on Fig. 4.2 can be clearly seen. Another set of large scale folds on NW-SE axes(e.g. 7 on Fig. 4.2) can also be distinguished. These NW-SE folds are nearly isoclinal and appear to represent a folded modification of the major N-S folds. The large scale folds are commonly picked out by beds of resistant quartzites as at 8 on Fig. 4.2 - an example of a phenomenon familiar to photogeologists working on conventional aerial photography.

Lineaments

A number of different types of lineament can be observed on this LANDSAT frame and those which appear to be geologically important are described as follows:-

1) Long straight wadis(dry water courses) often follow major faults like 9 on Fig. 4.2. These can be picked out by their generally lighter tone compared with the adjacent sandy areas.

2) Some of the major faults are remarkably well shown where there is a positive ridge of rock following the fault line as at 10 on Fig. 4.2. This may be due to indurated rock in a crush zone or to silicification of the fault zone by deposition of silica by permeating ground water.

3) Light toned wadis in darker toned outcrop areas may by their linearity suggest the existence of major faults such as 11 on Fig. 4.2

FIG. 4 . 2



Fig.4.2a MSS band 5 of part of LANDSAT-1 scene 1071-09221 covering the eastern Hoggar mountains (Scale 1:1,100,000 approx).

1-Adrar Tiguluras alkaline granite, 2-"island" outcrops of fractured Suggarian gneisses, 3-sub-parallel drainage system of Suggarian gneisses, 4-dioritic massif, 5-8°30' meridional fault, 6 and 7-major fold axes, 8-resistant quartzite bed, 9-major fracture along wadi, 10-Ad Azeteite fault, 11-major fault, 12-small outcrops denoting fault line.

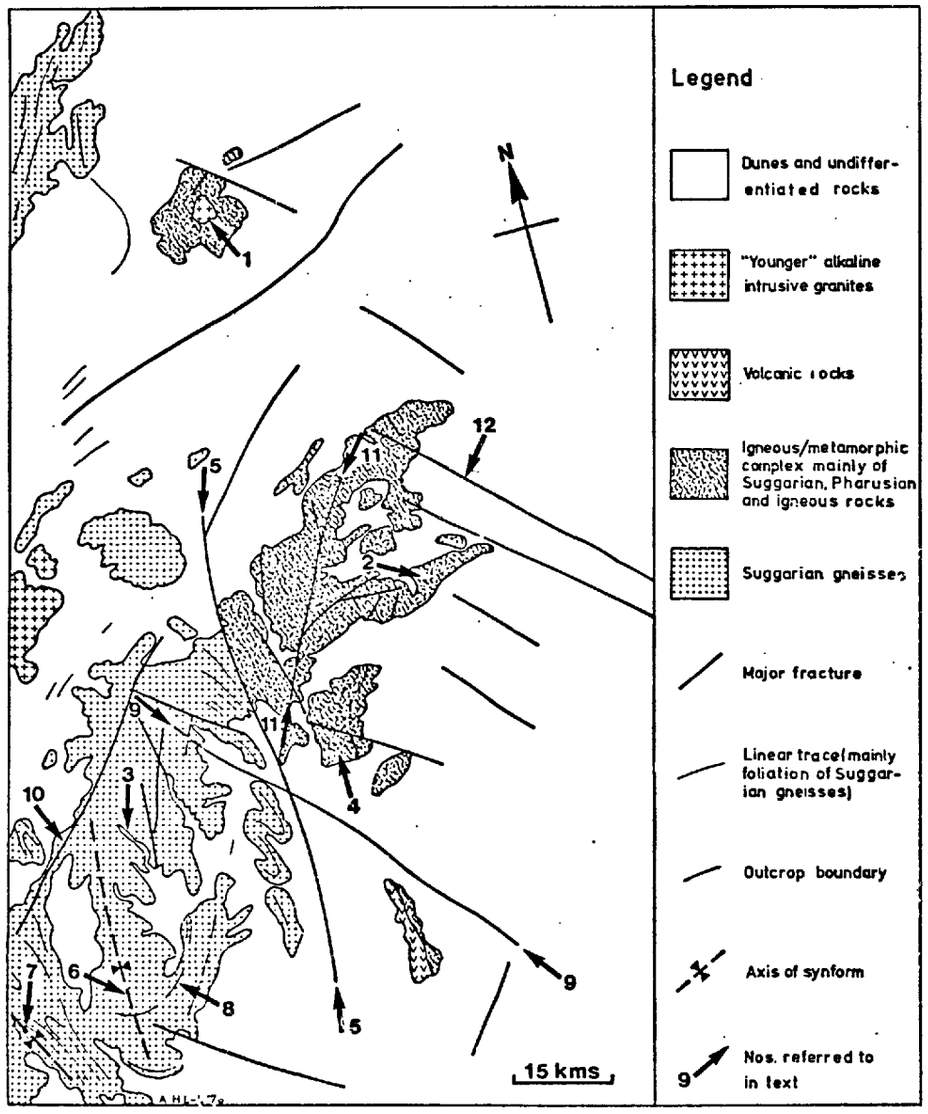


Fig.4.2b Photogeological outline of Fig.4.2a. Location of area is shown on Fig. 4.1.

4) Lines of small outcrops in sandy areas like 12 on Fig. 4.2 may denote the trace of major faults.

5) Individual marker beds form positive features which often follow a linear course.

Three sets of major faults can be picked out on this LANDSAT frame. The most important are the N-S meridional faults, including the $8^{\circ}30'$ meridional fault. A second set of almost equal importance is a NE-SW trending set which includes the prominent Ad Azeteite fault(10 on Fig. 4.2). The third set trend NW-SE and can be seen as a parallel group of linear features traversing the sandy area to the east of the mountains and include 12 on Fig. 4.2.

Shear zones

Mylonites are indicated on the Carte Géologique du Sahara(1961) along several of the major faults. However their extent cannot easily be judged from the satellite imagery. It may be that strong ridges like 10 on Fig. 4.2 represent mylonitised rocks.

4.1.3 Usefulness of the Imagery

General geology

The LANDSAT imagery provides a valuable view of this inaccessible region in terms of geomorphology and major geological structures. MSS band 4 was particularly good for the recognition of major faults in the sandy areas. MSS band 7 was the most useful for the detection of fractures within the main outcrop area. The following points summarise the main uses of this imagery in geological studies:-

1) The identification of all the main outcrops in the region.

2) The recognition of a lack of significant vegetational cover due to the similar tones on all four MSS bands.

3) The recognition of a highly fractured igneous/metamorphic complex in the eastern part of the region. This produced "island" outcrop patterns.

4) The delineation of the major folds within the areas of Suggarian gneisses.

5) Recognition of the fracture control of the drainage of the eastern igneous/metamorphic complex whilst the orientation of the major folds controls the drainage of the western gneisses.

6) The identification and delineation of many of the major faults of the region.

7) The ability to partly distinguish between areas of basic and acid rocks due to the darker tones of the former.

8) Observation of the circular "younger" granite of the Adrar Tiguluras massif.

9) The recognition of the almost universal lack of positive granitic outcrops tending to suggest that these have been chemically weathered.

Economic geology

Schurmann(1974) reports that prospecting for economic minerals in the Hoggar has been minimal. In 1952 he collected a sample of Pharusian granite from a site 25 km. south-west of Tamanrasset in the south-west Hoggar. Heavy mineral analysis of this sample yielded relatively

large quantities of topaz and traces of cassiterite and radioactive minerals. This encouraged further searches and in recent years a number of other discoveries have been made. These include diamond, platinum and wolfram as well as cassiterite. So far no discoveries have been reported from the study area. Large quantities of eluvial material are present in this area from the weathering of enormous volumes of granite. In the light of this and the discoveries made elsewhere in the Hoggar, the area appears to have some potential for the discovery of an economic placer deposit.

4.2 Basic intrusives of the Shoshong - Mokware area eastern Botswana - semi-arid environment

4.2.1 Introduction

General

This study covers the photointerpretation of two extensive basic sills in eastern Botswana. One outcrops in the Mokware hills whilst the other forms the tableland of the Shoshong hills 30 kms. to the south. The rocks are post-Transvaal system pre-Karroo system intrusives, and each sill has its own distinct petrological and structural character(Grubb, 1961). Their location and a sketch map of the geology are shown on Fig. 4.3.

Climate

The climate diagram on Fig. 4.3 shows that this region has reasonably wet, hot summer months and cool dry winters. During the winter there are pleasant daytime temperatures and cooler nights with rare frosts. Crockett(1965) describes the climate as "basically sub-tropical" and it can be distinguished from the similar wet-and-dry tropical climate by the overall lower temperatures.

Topography

The region is a gently sloping peneplain which drops about 350 metres from the edge of the Kalahari in the west to the Limpopo river just to the south-east of the area, a distance of some 140 kms. The two isolated hill ranges of Mokware and Shoshong rise up over a hundred metres above the plain, and stand out starkly in this open landscape. The Shoshong hills have a steep southern scarp face. According to Jennings(1963) two main erosion cycles can be recognised in this part of Botswana. The oldest(early Tertiary)

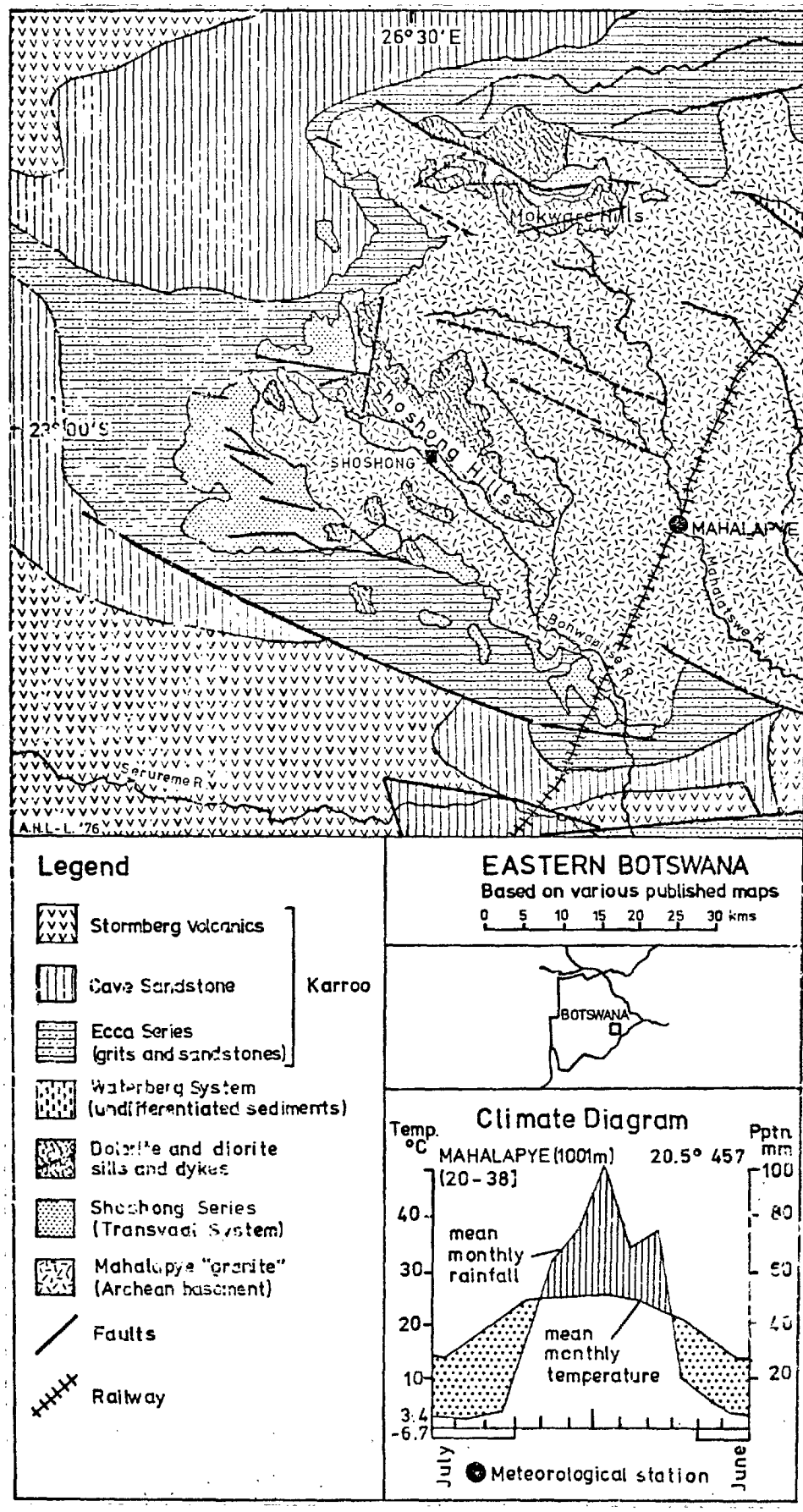


Fig.4.3 Geological sketch map of the Shoshong-Mokware region, eastern Botswana(Scale 1:850,000 approx). Based on the maps of Cullen(1961), Jennings(1963) and Boocock(1968).

surface, at over 1,400 metres above sea level, coincides with the summit plains of the Mokware and Shoshong hills. The younger(late Tertiary) surface is formed of the plain extending away from the foot of these hills.

Superficial deposits

Residual soils are developed extensively in this region and there are also some deposits of silcrete and calcrete. The soils developed on the hill tops of the two basic sills are shallow stony lithosols. Those of the Mokware hills are red-brown whilst the Shoshong dolerite decomposes to a black soil known as "mukutwane". Ferruginous tropical soils are developed over the intervening granitic areas. These soils are reddish-brown or grey-brown and are freely drained. They have been described by Bawden and Stobbs(1963) as acid sandy loams.

Vegetation

The hills of basic igneous rock are covered with communities of fairly dense tree savannah. The footslopes and the open plains are covered with open tree savannah, with local areas of woodland. Acacia dominates the tree types and various species of the same genus form abundant thicket in many places.

Communications

Numerous small tracks cross the area, and a railway and main road run parallel to each other up and down the eastern part of the region. The railway can be very clearly seen on the LANDSAT imagery.

The basic intrusives

The two "dolerite" sills belong to a suite of basic sills and dykes which have intruded both a series of Proterozoic sediments and the roof zone of the Mahalapye granite. The sediments known locally as the Shoshong series have been correlated with the Transvaal sequence of South

Africa. The latter has been dated between 1,950 m.y. and 2,300 m.y(Anhaeusser, 1973). The sills according to Grubb(1961) have many petrological affinities with rocks of the Bushveld igneous complex which has been given an age of 1,950(Nicolaysen, 1962).

The Shoshong sill is a composite intrusion being formed from two phases of magma injection (Grubb, 1961). The lower part of the intrusive contains a higher proportion of orthopyroxene phenocrysts than the upper part. The Mokware sill is also composite but is characteristically more acid in composition - the lower half is a grey dioritic rock and this is overlain by a thick upper zone of pink granophyric diorite (or red rock). Jennings(1963) and Grubb(1961) observed contact metamorphic effects adjacent to the Mokware and Shoshong sills respectively.

Geological background

Much of the study region is formed of a complex of granites and gneisses. These ancient rocks were intruded by an ENE-WSW trending series of microgranite dykes. Subsequently the Shoshong sediments which comprise quartzites, shales, dolomitic limestones and arkoses were laid down on an eroded peneplain of these rocks. Probably during the early Proterozoic these sediments and underlying granites were intruded by the NW-SE trending "dolerite" sills and dykes. Either before or after the mafic dykes sediments of the Waterberg system were laid down in the area. Rocks of the Karroo system represent the last major cycle of sedimentation before emergence of the area and the erosion cycles of the Tertiary period. The formation of sand, silcrete and calcrete deposits has continued up to the present time.

Structure

The sediments of the Shoshong Series in the Mokware area dip in a northerly direction at angles of up to 11°(Jennings, 1963). Both the Shoshong and Mokware sills also dip in a northerly direction. According to Grubb(1961) "this area is part of a huge low westerly-pitching anticline, with localised folds and an extensive system of faulting and tension joints". Cullen(1961) believed that most of these structures were related to a pre-Karoo period of major N-S compression. Fold axes within the granitic rocks are generally aligned parallel to the major E-W anticlinal fold axis. This compression has resulted in both wrench faulting and normal faulting of the region(Grubb, 1961).

4.2.2 Photointerpretation

Image quality

The NASA image quality rating for all four MSS bands of the LANDSAT imagery studied(ID No. 1069-07405) for this investigation was "good". However the negatives supplied by the EROS Data Center showed a number of defects. In almost each case the contrast and sharpness of the features depicted on the negative were only moderate. There were heavy scratch lines across the negatives at right angles to the scan direction. All the images were covered with small bubble-like grey marks, and on MSS band 4 there was a large patch of Newton's rings down the right hand side of the image.

A colour composite print of this scene was available and was studied along with black and white prints of the individual MSS bands. Correspondence with the EROS Data Center unfortunately revealed that the colour composite print was not considered to be up to their usual

quality standards. This was apparently due to a defect in the "master reproducible". In spite of this the colour composite showed some useful features.

Geomorphology

The difference in character between the Mokware and Shoshong hills is immediately apparent on the LANDSAT imagery. The southerly Shoshong "dolerite" forms a rugged, dark toned tabular mass as shown on Fig. 4.4a. The steep southern scarp face together with the broad summit plain and its ragged northern boundary with the residual soils of the main plains region make it easy to interpret this as a northerly dipping structure. Cullen (1961) suggested that the southern scarp represents a fault line scarp and a straight lineament on the imagery just to the south of the scarp confirms the existence of an important fracture line. The fractured appearance and rounded forms of isolated outcrop remnants at its south-eastern extremity express the igneous nature of this unit.

The more acid dioritic Mokware sill is lighter toned on all MSS bands than the Shoshong dolerite. The sill itself is topographically subdued, but it is interbedded with resistant quartzite beds which form the distinct ridges at 1 on Fig. 4.4.

Erodibility

The Shoshong dolerite can be seen on the imagery to form an upstanding block, apparently highly resistant to sub-aerial weathering. The Mokware sill is smoother textured, which suggests that it is less resistant to erosion and is covered by a surface blanket of weathered products. The sill appears only to have escaped complete destruction because of the protection given to it by the resistant, flanking quartzite beds. According to Grubb(1961) the difference in erodibility of the two sills is due to the

higher degree of oxidation of the ferro-magnesian minerals in the Mokware diorite. This coupled with better drainage conditions has given rise to a faster rate of disintegration. The ferromagnesian minerals of the Shoshong dolerite have mainly been preserved in a low state of oxidation due to the formation of an expanded montmorillonite mineral. Indeed chemical weathering of th Shoshong dolerite has been so little that the original columnar jointing can still be observed in the field(Grubb, 1961).

Drainage features

The main drainageways of the region are the Mahalatswe and Bonwapitse, which themselves are tributaries of the Limpopo river. Both these channels have strongly linear courses and emphasize the markedly parallel to sub-parallel nature of the drainage network of the region. This pattern is characteristic of rivers crossing a sloping area of sheetwash deposits. However the strongly NW-SE preferred orientation of these channels suggest additional structural control by NW-SE fractures or dykes. These courses cross the area underlain by the Mahalapye granite and in places the drainage texture is fine and has an almost pinnate (feathery) pattern. This is a useful criterion for identifying on the imagery areas covered by a thick layer of granitic soils. This blanket of easily eroded sheetwash deposits are the products of granite decomposition.

Soil/ vegetal features

Two main vegetation zones are visible on the LANDSAT images, and they more or less coincide with two major soil associations. The first is one of semi-arid shrub savannah developed over the Kalahari sands. Whilst to the east of the Shoshong hills ferruginous tropical soils support a tree savannah vegetation cover.

The boundary between these two areas is visible on all MSS bands and is especially well shown on the colour composite print, Fig. 4.4c, where it shows up due to differences in tone and texture. The Kalahari sands in the north-west of the frame can be seen to be lighter toned than the soils to the south-east covering the major part of the frame.

Land use patterns

The region is widely used for grazing cattle and also for cultivation. Cultivated areas are not easily distinguished on the imagery due to their irregular development, and limited extent.

Tones/ textures

Tonal and textural differences between the two major sills are most marked on MSS band 7. Fig. 4.4a clearly shows the compositional and structural differences between the Shoshong dolerite(dark toned) and the Mokware diorite (medium toned). The quartzites of the Shoshong series also show tonal variations on all the MSS bands, being medium toned in the Mokware area, 1 on Fig. 4.4 and very dark toned in the Shoshong hills, 2 on Fig. 4.4. The Karroo System sediments show up clearly on the imagery around 3 on Fig. 4.4. This is due to the even, medium-toned aspect of the soils derived from these rocks compared with the lighter more mottled tones of the granitic soils to the east. The even tone and smooth texture of the former may be due to a higher clay content in the residual soils compared with the freely drained granitic soils.

The colour composite print(Fig. 4.4c) shows the Mokware hills to have a pinkish tinge superimposed on a greenish background, whilst the Shoshong dolerite is a dark green. This

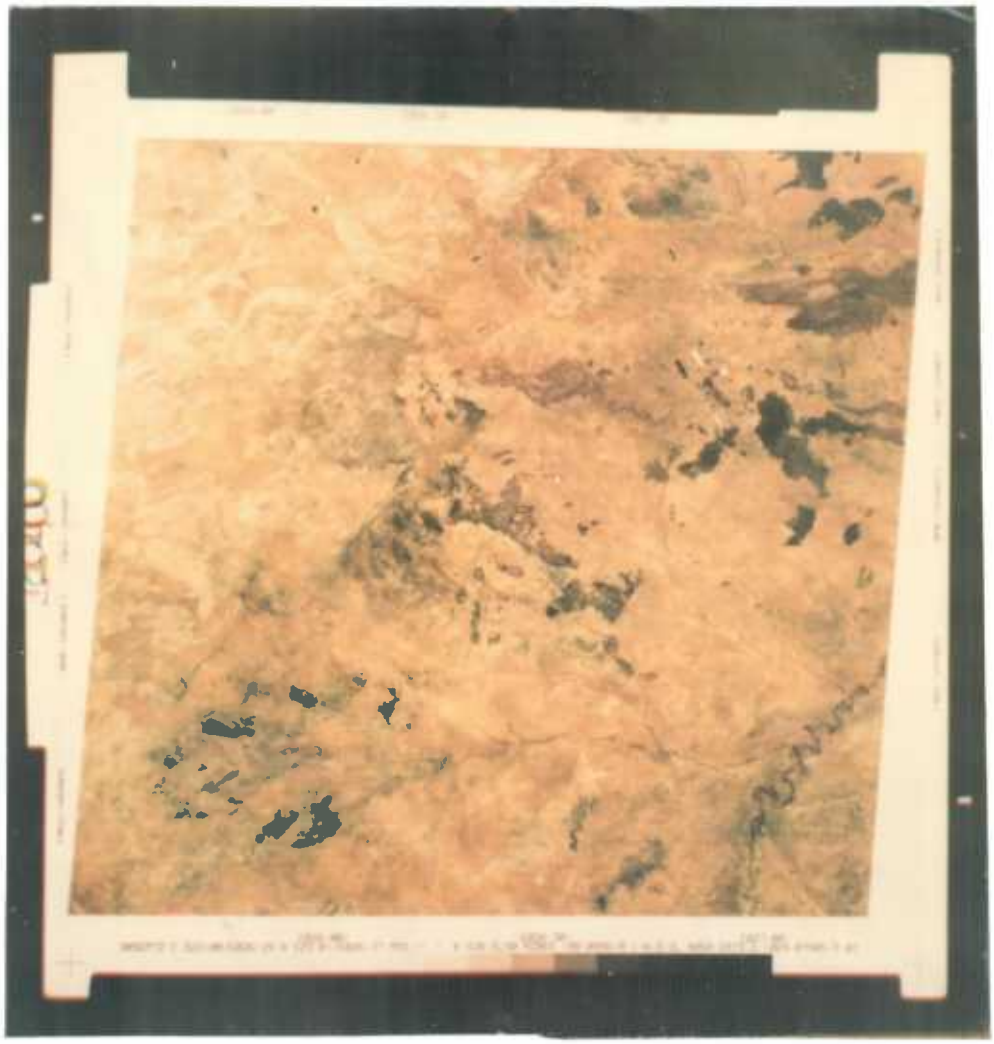


Fig.4.4c Colour composite image of LANDSAT-1 Scene 1069-07405 including the Shoshong-Mokware region with the Limpopo river in the bottom right of the scene (Scale 1:1,600,000 approx).

variation is the result of differences in soil colouration and vegetation cover over the two masses. The lighter coloured soils and denser vegetation of the Mokware hills are responsible for higher reflection in the IR, and for the consequent pink colouration of the print. The mottled granitic areas also have many pinkish tones indicating areas of shrubland. Elongated patches of burnt-off vegetation are a feature of the Kalahari sands area in the west of the region. Linear features orientated in a NE-SW direction are mainly the products of wind erosion and many of these represent "fossil" dunes preserved from an earlier more arid climatic environment (J.V. Hepworth, personal communication).

Rock boundaries

The lithological boundaries of the basic intrusives surrounded by residual granitic soils can in many cases be drawn in on an enlarged LANDSAT print with precision. These really consist of outcrop boundaries around the positive elements forming the Mokware and Shoshong hills. It is however more difficult to interpret the basic intrusives where they are enclosed by sediments of the Shoshong series, but the latter can sometimes be distinguished from the former by their lower relief and darker tones, as at 2 on Fig. 4.4. The boundaries of the Ecca Series(Karroo System) can also be inferred from the imagery due to its smooth texture and medium tone. The approximate area underlain by the Mahalapye granite can be shaded in due to its mottled tone, fine drainage texture and pinkish/ochre tones on the colour composite print. The light toned area occupied by the Kalahari land system[1] in the west is easily distinguished from other formations further east. That area is reputedly underlain by Karroo basalts, which may account for the sharp

1 Bawden and Stobbs(1963).

boundary with the area to the east underlain by the basement complex and Karroo sedimentary formations.

Structural units

The "huge low westerly pitching anticline" which Grubb(1961) has interpreted to lie between the Mokware and Shoshong hills, cannot be detected on the LANDSAT imagery. This may be because the structure is too subdued. The most important structural features which can be seen on the imagery are major fracture directions and the northerly dipping structures of the Shoshong and Mokware intrusions.

Lineaments

A number of prominent linear features can be distinguished on this LANDSAT frame, and many of these are geologically significant. Perhaps the most noticeable linear feature of the region is the strong NE-SW trend of the "fossil" dunes in the Kalahari sands area. Several lineaments have been detected in the basement area and these are described as follows:-

1) Lineaments picked out by straight sections of dry river courses. These appear as thin light toned lines on MSS band 7 like 4 on Fig. 4.4.

2) Lineaments which follow watercourses but which are also shown up by tonal differences on either side of the watercourse like 5 on Fig. 4.4.

3) Fractures(negative topographical features) within exposed igneous areas denoted by strong shadows on MSS band 7 as at 6 on Fig. 4.4.

4) Scarp features separating the Kalahari sands from the eastern area of basement rocks as at 7 on Fig. 4.4.

FIG. 4.4

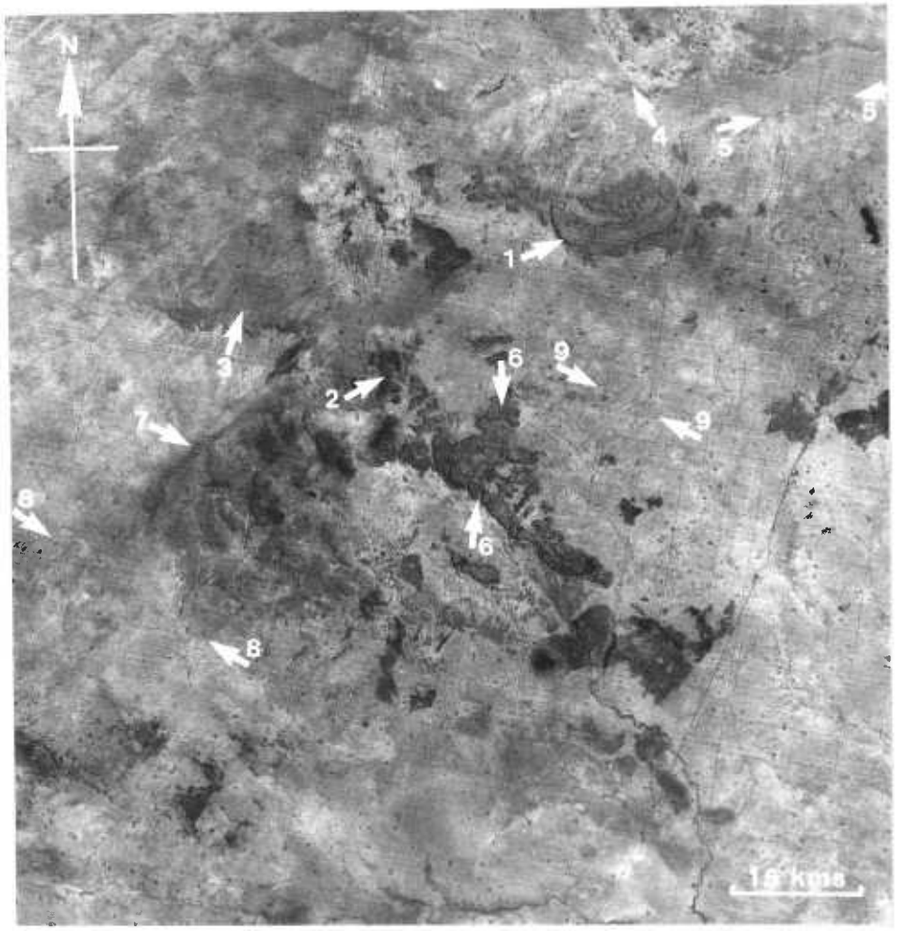


Fig.4.4a MSS band 7 of part of LANDSAT-1 scene 1069-07405 covering the Shoshong-Mokware region (Scale 1:850,000 approx).

1 and 2-quartzites of Shoshong series, 3-Karroo sediments, 4-dry river bed lineament, 5-boundary fracture, 6-macro-joint in Shoshong dolerite, 7-scarp feature, 8-major lineament, 9-dolerite dyke followed by river course.

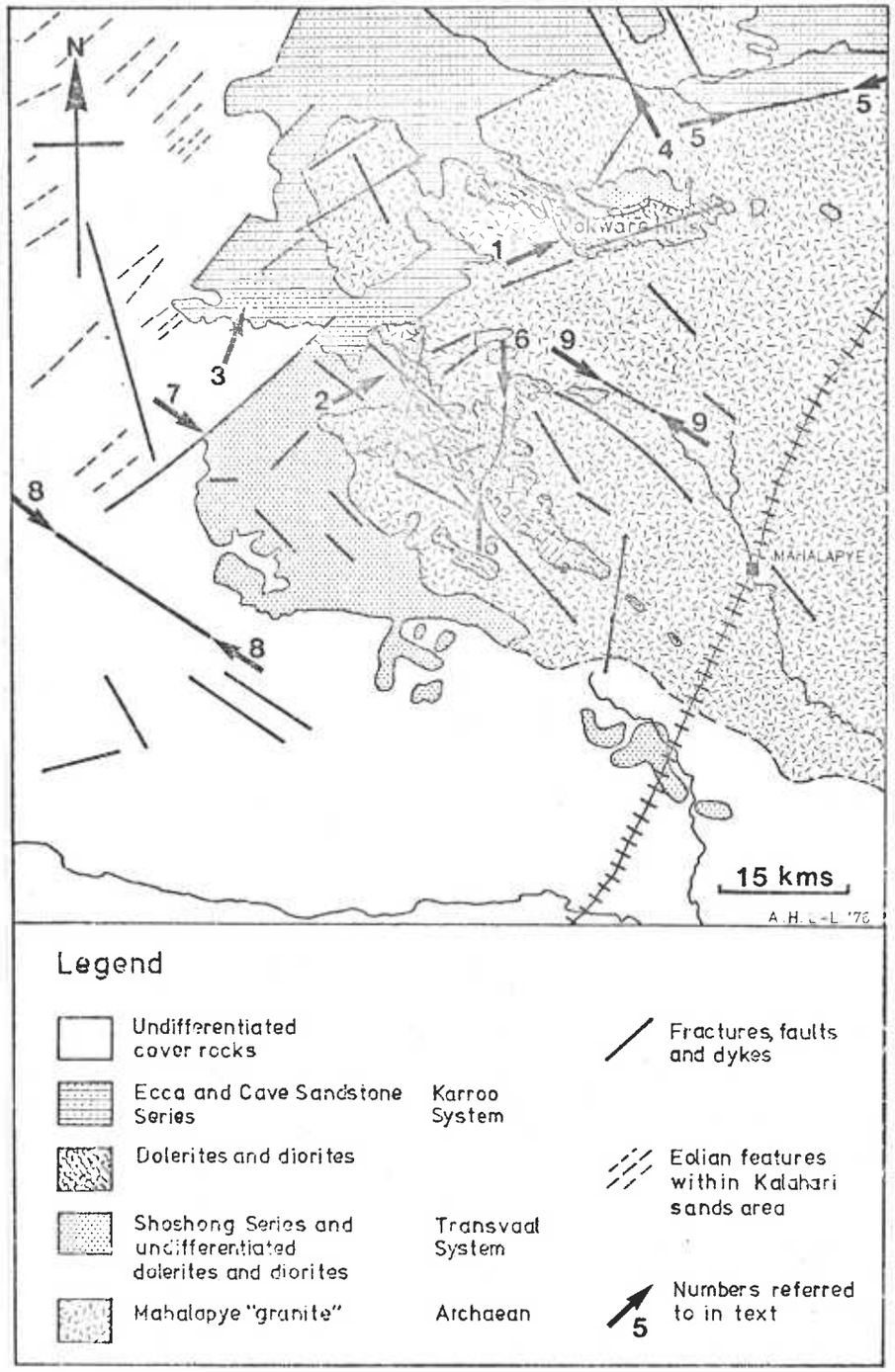


Fig.4.4b Photogeological outline of Fig.4.4a, area covered the same as Fig.4.3 (Scale 1:850,000 approx).

5) One major dolerite dyke can be partly seen at 9 on Fig. 4.4.

Lineaments in the western part of the region, underlain by Karroo rocks

6) NW-SE zone of major lineaments showing up due to an alternation of light and dark toned strips, 8 on Fig. 4.4. These lineaments show up especially well on MSS band 4. The trend of these lineaments coincides with the Shoshong dolerite's southern scarp face and the dolerite dykes of the area.

7) NE-SW lineaments within the Kalahari sands area("fossil" dunes).

4.2.3 Usefulness of the Imagery

General Geology

The most significant contribution to the knowledge of the geology of this area provided by this LANDSAT imagery is in the demonstration of the existence of a number of previously unmapped major fractures. Furthermore the imagery provides some reasonably reliable criteria for the mapping of lithological units. The following points summarise the main uses of the imagery in photogeological studies:-

1) The mapping of the main outcrops of the two major sills.

2) The observation of the marked dissimilarity in morphology and composition of the Mokware and Shoshong sills.

3) The recognition and mapping of several major fractures(compare Figs.4.3 and 4.4b).

4) The mapping and general distribution of the Karroo rocks of the region.

5) The approximate extent of the Mahalaype granite can be indicated by its mottled tones and fine dendritic drainage texture.

6) The boundary between the Kalahari land system and the basement complex and Karroo rocks of the eastern part of the region can be clearly seen on the LANDSAT imagery.

7) The colour composite print helped to outline some of the lithological units and was also useful for identifying areas of burnt-off grassland. The latter if not properly identified can confuse the photogeological interpretation.

Economic geology

Jennings(1963) has reported two occurrences of chrysotile asbestos veins in impure limestones in contact with dolerite sills and dykes. In view of these discoveries it might be worth carrying out further prospecting along all those features on the LANDSAT imagery with the characteristic NW-SE trend of the dolerite dykes. Especially promising could be the major zone of lineaments in the vicinity of 8 on Fig. 4.4a.

4.3 Synorogenic granite of the Tanzania Craton - wet-and-dry tropical environment

4.3.1 Introduction

General

An investigation was carried out over part of the eastern margin of the Tanzania Craton. The edge of this ancient granitoid nucleus forms part of the foreland zone of the Mozambique orogenic belt. The general geological configuration of the region is shown on the sketch map Fig. 4.5. Radiometric age determinations have put the age of this Archaean granite batholith at over 2.7 b.y.(Cahen and Snelling, 1966). The batholith is considered to be mainly an intrusive body. However within the granite there are abundant xenoliths and large enclaves of supracrustal greenschists(Dodoman Formation). Hepworth(1972) observed evidence of felspathization of Dodoman pelites at Paranga, just to the north of the study region. This suggested that perhaps large areas of the batholith were formed originally from these supracrustal rocks.

Climate

The characteristics of this climatic zone are a long dry season almost without rain, followed by a shorter rainy season. The rain is heavy at times during the latter season. Details of average rainfall and temperature can be seen on the climate diagram for Dodoma town shown on Fig. 4.5. The temperature during most of the year is hot(mean annual temperature 22.6°C) but not unpleasant due to the relative elevation of the region(1,120 metres).

Topography

The granite batholith forms varied scenery. A prominent NW-SE trending mountain chain, the Chenene Hills, marks the northern margin of

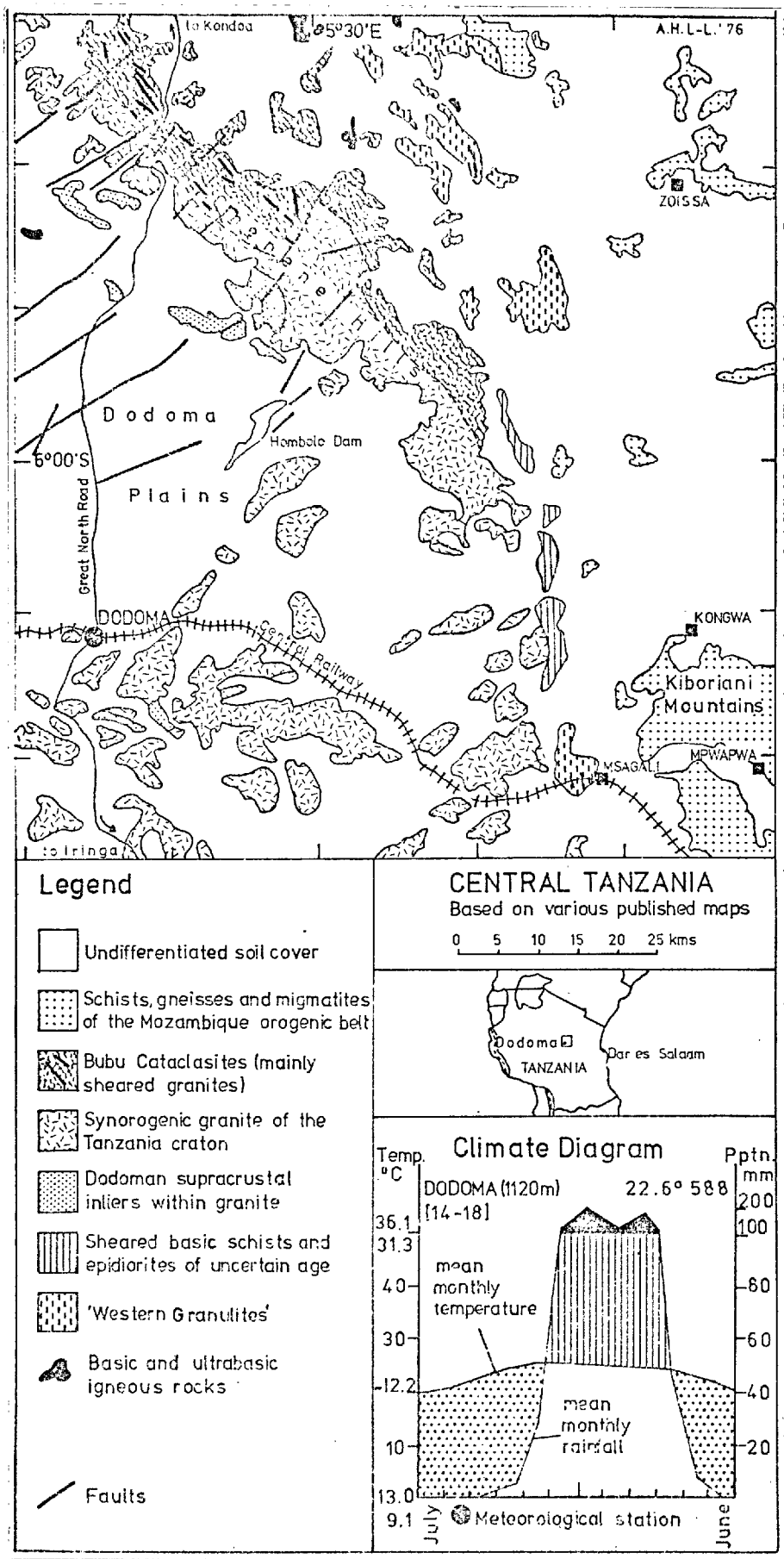


Fig.4.5 Geological sketch map of the Chenene Hills region, central Tanzania (Scale 1:1,200,000 approx).

the granite in this region. Southwards there is a zone of pediments and tors. This in turn flattens out into a region of open plains with isolated tors. Harpum(1963) regarded the granite scenery of Tanzania as the product of denudation an older erosion surface. The Chenene Hills he considered to be a horst block which is now undergoing active erosion. Contrastingly the tor scenery of the south represents a more advanced stage of the erosion cycle.

Superficial Deposits

Patches of calcareous and ferruginous duricrusts are developed sporadically in this region, but the area is mainly covered by residual soils. The dominant soil overlying the granite of the Dodoma region is a grey sandy type(Wade and Oates, 1938). This is underlain by an argillaceous subsoil. The soils were derived in situ from the weathering of the granite, and their thickness is very variable. Red-earths are also developed quite widely, especially in the vicinity of basic dykes and the Dodoman metasedimentary enclaves. Black mbuga soils represent the very fine clay fraction of weathered material washed down from the hills, which has settled in the lowest parts of the region. The mbuga areas of impervious black soils are generally the sites of seasonal swamps, and cover quite large parts of the plains area.

Vegetation

The vegetation covering the rocky outcrop of the Chenene Hills belongs to the "dry forest" category known in East Africa as miombo woodland. According to Julian et al.(1963) the plains area is covered with "thorny scrub thicket with several small areas of semi-open acacia-baobab bush". Around Dodoma this pattern has been modified by irregular cultivation. The mbuga areas are usually covered with grass and very occasional small shrubs.

Frequent burning-off of the whole region has probably played an important role in the destruction of weaker plant species and the survival of the tougher ones. However in general plant vigour and development are very much related to the total annual water available to the plants. There may be considerable local variations in this factor depending on the structure and porosity of the soils.

Communications

The region is traversed by numerous dirt roads, including the Great North Road. The latter can be seen on the LANDSAT imagery winding its way through a gap in the Chenene Hills. A group of hills known as the Dodoma Hills stretches E-W across the southern part of the region. These hills are formed of highly contaminated and sheared granite. The lower contours of their northern slopes have been advantageously used for the alignment of the Central Railway as described by Wade and Oates(1938).

The granite batholith

There is a range in composition from granite to granodiorite within the "main batholith" as it is sometimes called. A typical synorogenic granite from the Chenene Hills is a grey, foliated coarse-grained rock. It is composed of quartz, microcline, microcline-perthite, altered albite-oligoclase, biotite and accessory minerals(Julian et al., 1963). The north-eastern flank of the Chenene Hills includes some sheared rocks known as the Bubu Cataclasites.[1] Whilst the south-western flank is composed of unsheared, coarsely foliated synorogenic granite, which often contains large porphyroblasts of microcline-perthite(Fozzard and Kendrick, 1964).

The granite exposed in the tors to the south of the Chenene Hills and around Dodoma is

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1 The Bubu Cataclasites extend northwards along the margin of the batholith and within the study region have been described by Julian et al.(1963), Fozzard and Kendrick(1964) and Hepworth(1972).

either homogeneous magmatic granite, nebulite or granitoid gneiss(Hepworth,1972). It was the field relationships of mafic xenoliths and large enclaves of Dodoman metasediments found within the granite, which suggested to Wade and Oates(1938) that the batholith had behaved partly as a magmatic body. They regarded the Dodoman metasediments as screens and roof pendants caught up or surrounded by the magma.

Geological background

The oldest rocks of the region are some charnockitic granulites, first described by Temperley(1938) and more recently by Hepworth(1972) who referred to them as the "Western Granulites". They outcrop in an arc to the north-east of the Chenene Hills and these ancient rocks(>3.0 b.y.) have been intruded and partly mobilised by the Tanzania cratonic granite. The chelogenic cycle[1] during which the Archaean granite was emplaced involved the incorporation of earlier crustal material in the form of blocks of Nyanzian and Dodoman "greenschists". The relationship of the Dodoman metasediments to the Western Granulites is as yet not fully understood.

Deformation of the shield margin took place at a subsequent date, and was responsible for the formation of the Bubu Cataclasites. The final tectono-thermal episode affecting the region was the Mozambiquian orogenic cycle. This is now considered to have a polycyclic history and to be partly equivalent to Pan-African events in other parts of the continent. Deformation caused by this orogeny penetrated some way into the foreland rocks of the shield

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1 The term chelogenic cycle was introduced by Sutton(1963) to cover the shield forming process which ultimately leads to the production of rigid crustal plates.

as well as affecting the cover rocks to the east. The remainder of the Phanerozoic history of this region is little known as there are no major deposits belonging to this period. Dolerite dykes of Karroo age and older intruded the region during this period. Neogene rift faulting of the Alpine orogenesis was responsible for the formation of many of the major NE-SW faults of the region. Cyclic denudational systems were operative throughout this long period, with the formation of residual soils and duricrust deposits.

Structure

Four main structural trends have been recognised in the investigated region and these are outlined below:-

Within the granitoid shield

1) A NW-SE trend denoted by negative features within the Chenene Hills(Julian et al., 1963, Fozzard and Kendrick, 1964 and Hepworth, 1972). These represent zones of shearing within the batholith margin related to the Bubu cataclasis.

2) Curving WNW-ESE trending positive features referred to as Dodoman structures. These are related to zones of dislocation within the granite and they also include elongated inliers of greenstone rocks(Dodoman metasediments).

Within the Mozambique Orogenic Belt

3) WNW-ESE trending structures referred to by Hepworth(1972) as Kondoan. This trend is well displayed by the axial trend of the folded metasediments of the Kiboriani mountains in the south-east of the region.

Traversing both the shield and the Mozambique belt

4) NE-SW trending major faults related to the East African Rift System.

It is interesting to note that the most persistent lineament trend within the orogenic belt (WNW-ESE) is oblique to the main N-S trend of the fold belt. Hepworth(1972) maintains that the Dodoman structures have been rotated by regional strain into their present attitude(WNW-ESE). He suggests that this trend may have been imposed by a late Mozambiquian deformation.

4.3.2 Photointerpretation

Image quality

The NASA quality rating for the frames used for this study(ID No. 1155-07133) was good for MSS bands 5,6 and 7 but poor for band 4. As a consequence of this assessment band 4 was excluded from this investigation. The imagery was taken during the middle of the rainy season and the effects of variable soil moisture content can be detected on MSS bands 6 and 7. Vigorous plant growth throughout the region at that time has resulted in markedly differing tonal patterns on MSS bands 5 and 7. The negatives were all of moderate quality but MSS band 5 was generally lighter toned than the IR bands. This was probably responsible for the more contrasty prints obtained from this negative(Fig. 4.6a).

Geomorphology

The granites forming the Chenene Hills have been heavily incised by fault controlled drainageways. The rugged topography of these hills can best be studied under the stereoscope using prints of MSS bands 5 and 7. Although the two

images do not fulfil the requirements for true parallax of being taken from different observation points slight "stereo" vision of the hills can be achieved. This is due to a particular property of LANDSAT imagery(see Section 3.3). The Chenene Hills have the typical rounded margins and relatively coarse drainage texture of a granite massif. This contrasts strongly with the metamorphics of the Kiboriani mountains in the south-east of the region, which have a much finer drainage texture and sharper crests to the hills. A similar distinction between granites and metamorphics was observed by the writer on the LANDSAT imagery of northern Sardinia.

Drainage features

The drainage of the granitic batholith is strongly controlled by NE-SW fracturing. The Chenene Hills have a medium textured drainage system but that of the plains area is very coarse textured and poorly integrated with only a few straight elongated water courses.

Soil factors

The albedo of soils is important on the plains area of the region as the vegetation is thin and scattered. Soils derived from the weathering of Dodoman greenschists can be picked out very clearly on MSS band 7. This is due to their higher moisture content which shows up as darker tones on the IR bands, compared with the light tones of the freely drained sandy granitic soils of the surrounding areas. These red soils are not easily detected on MSS band 5 as they have almost the same reflectance as the granitic soils on that band. So that on MSS band 5 variations in tones over the granite are mainly related to the density of vegetation, with the denser areas appearing in darker tones. The impervious black mbuga soils show up especially clearly on MSS band 7. They are conspicuous

as areas of low reflectance(medium to dark tones).

Vegetal features

All the hilly outcrops of the region are covered with a fairly dense woodland formation. This generally shows as light to medium tones on MSS band 7. The same areas on MSS band 5 are normally very dark toned, and this provides a very useful way of locating inselbergs on the relatively poorly vegetated plains area, as at 1 on Fig. 4.6. Dense thicket covers parts of the north-east of the region and this can be seen on MSS band 5 as the very dark toned area at 2 on Fig. 4.6. The thicket is developed where water supply is adequate to support this type of vegetation. This thicket dies out north-eastwards towards the drier parts of the Masai plains.

Land use patterns

Agricultural patterns cannot easily be distinguished over the granitic batholith due to the mottled appearance of this region on the imagery. However the relatively light tone of the eastern part of the batholith on MSS band 5 is almost certainly due to extensive cultivation and the grazing of the area. The large regular rectangular patterns of paddocks belonging to the Kongwa cattle ranch can be seen at 3 on Fig. 4.6. In the NE of the region cultivation can be discerned on the fine red soils of the Masai plains, if MSS band 7 is examined.

Tones

The main batholith is generally medium to light toned on MSS band 7 and dark to light toned on MSS band 5. The greater variation in tone on MSS band 5 is due to differences in tone of sparsely vegetated(light toned) and densely vegetated(dark toned) areas. Also the considerable areas of red soils show up on MSS band 5 as very light toned areas. In general the plains area of the granite is distinctly light

toned on MSS band 5, and can be readily separated from the metamorphic area to the east.

Structural units

An examination of the LANDSAT imagery reveals a number of important structural features affecting the main batholith. These features are outlined and discussed below:-

1) Homogeneity of the main batholith: This is shown by the uniformity of tone and texture over the major part of the outcrop as shown on Fig. 4.6a.

2) The NW-SE Chenene Hills range: The imagery shows that this block is being heavily eroded. The steep northern scarp face and the more gentle slopes of the south-western pedimental zone suggest an uplifted fault block, tilted to the south-west. The steepness of the valley sides, rounded forms and fracture controlled drainage indicate the igneous nature of this block.

3) Zones of shearing and granulation: These are shown on the imagery by elongated lines of hills like 4 on Fig. 4.6. These sheared rocks are generally more resistant to erosion and tend to produce elongated lines of outcrop. ~~Several specific zones of granulated rock~~ have been mapped in the eastern part of the granite, and many of these follow curved lines(Temperley, 1938 and Wade and Oates, 1938) The manifestation of these zones of shearing can be clearly seen on the LANDSAT imagery as they have produced a very distinctive cuspate pattern in the drainage network of the area at 5 on Fig. 4.6. This pattern is particularly well seen on MSS ~~band 6 where the crescentic shapes of mbuga~~

areas emphasize the configuration of these shear zones.

4) Major NE-SW faulting of the batholith: These relatively recent faults(Neogene) have cut both the granite and country rock. They have also caused displacement of blocks of the Chenene Hills granite, as along fault 6 on Fig. 4.6.

Circular feature

A semi-circular feature about 13 kms. across can be picked out on the imagery just north of Msagali by the anomalous annular drainage course of the Kinyasungwe sand river(see Fig. 4.6). This feature lies directly on a major NNW-SSE zone of disjunction(described below under lineaments). The rocks within the ring structure are mainly migmatitic and granitoid gneisses of the Tanzania cratonic granite but there are also several tracts of basic meta-igneous rocks which extend northwards outside the ring along the NNW-SSE zone of disjunction.

Lineaments

The traces on the imagery of the major lineaments traversing the batholith are shown on Fig. 4.6b. Within the batholith at least four main lineament trends can be detected with some degree of certainty. Many of these lineaments appear on the LANDSAT imagery to represent shallow negative features on the surface of the plains region of the batholith. The lineaments are classified and described below:-

1) Major NE-SW fractures: These fractures belong almost certainly to the East African Rift System. They cross-cut most of the other lineaments and can be traced continuously on 1:500,000 scale LANDSAT imagery for distances of 20 kms. or more. One fault of

this set is the Makutapora fault, 7 on Fig. 4.6, which provides a structural trap for ground water. The main water supply for Dodoma town comes from this source. These faults are sometimes flanked on one side by an mbuga. Like the rift valley lakes of Eyasi and Manyara, this on a smaller scale may indicate the downthrow side of the fault.

2) ENE-WSW shear zones: These lineaments follow zones of shearing within the granite and can be seen in the eastern part of the batholith at 8 on Fig. 4.6.

3) WNW-ESE Dodoman structures: This is not a conspicuous lineament direction but the trend can be observed by the lines of Dodoman outcrops following this direction at 9 on Fig. 4.6.

4) NNW-SSE shield boundary zone of ?disjunction: This broad diffuse zone can be traced on the LANDSAT imagery for over 100 kms. and is particularly well shown on MSS band 5(see 10 on Fig. 4.6). Temperley(1938) showed that part at least of this zone of disjunction is represented by a zone of intense granulation. At one point, 11 on Fig. 4.6, it is followed by a large ancient metamorphosed basic dyke. At its northern end it intersects a zone of ultrabasic rocks known as the Haneti - Itiso complex. The latter is associated with a number of shear zones, and is exposed sporadically along a very broad NW-SE trending belt north-east of the Chenene Hills.

Hepworth(1972) reports that on aerial photographs the Bubu Cataclasites appear as "long,

FIG. 4 .6

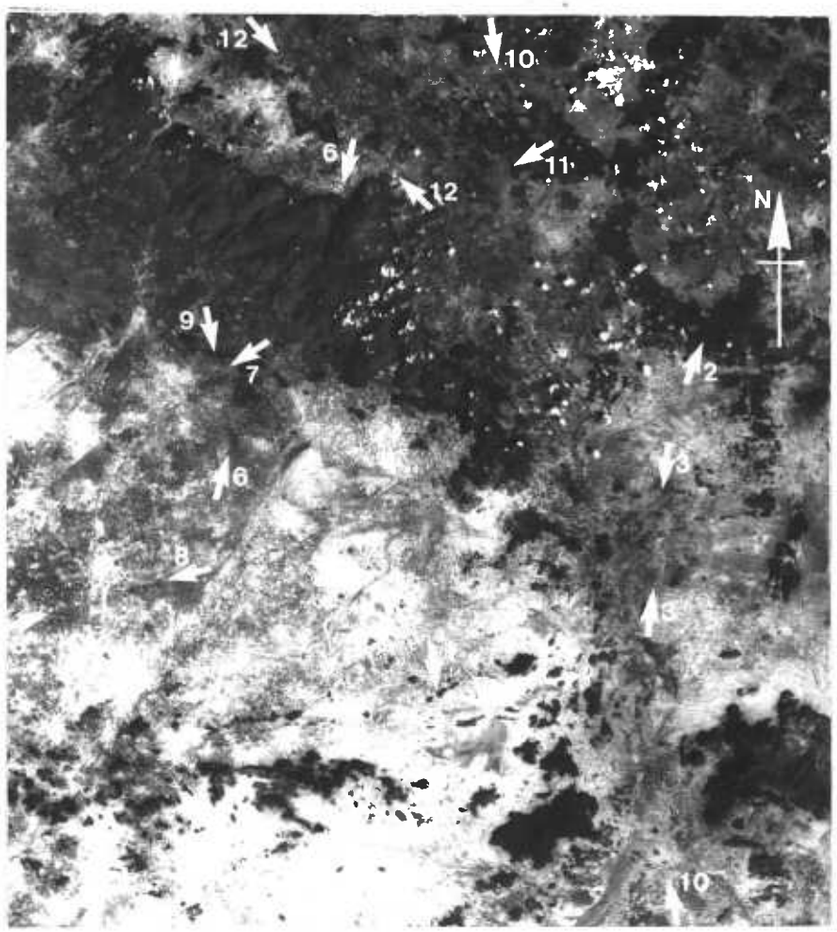


Fig.4.6a MSS band 5 of part of LANDSAT-1 scene 1155-07133 covering the Chenene Hills region (Scale 1:1,200,000 approx).

1-granite inselberg, 2-area of dense thicket, 3-boundary of Kongwa cattle ranch, 4-hills of sheared granite, 5-cuspate drainage related to a shear zone, 6-major fault, 7-the Makutapora fault, 8-shear zone, 9-Dodoman greenschist inlier, 10-major zone of disjunction, 11-ancient metamorphosed basic dyke, 12-lineaments within the Haneti-Ilisc ultrabasic zone.

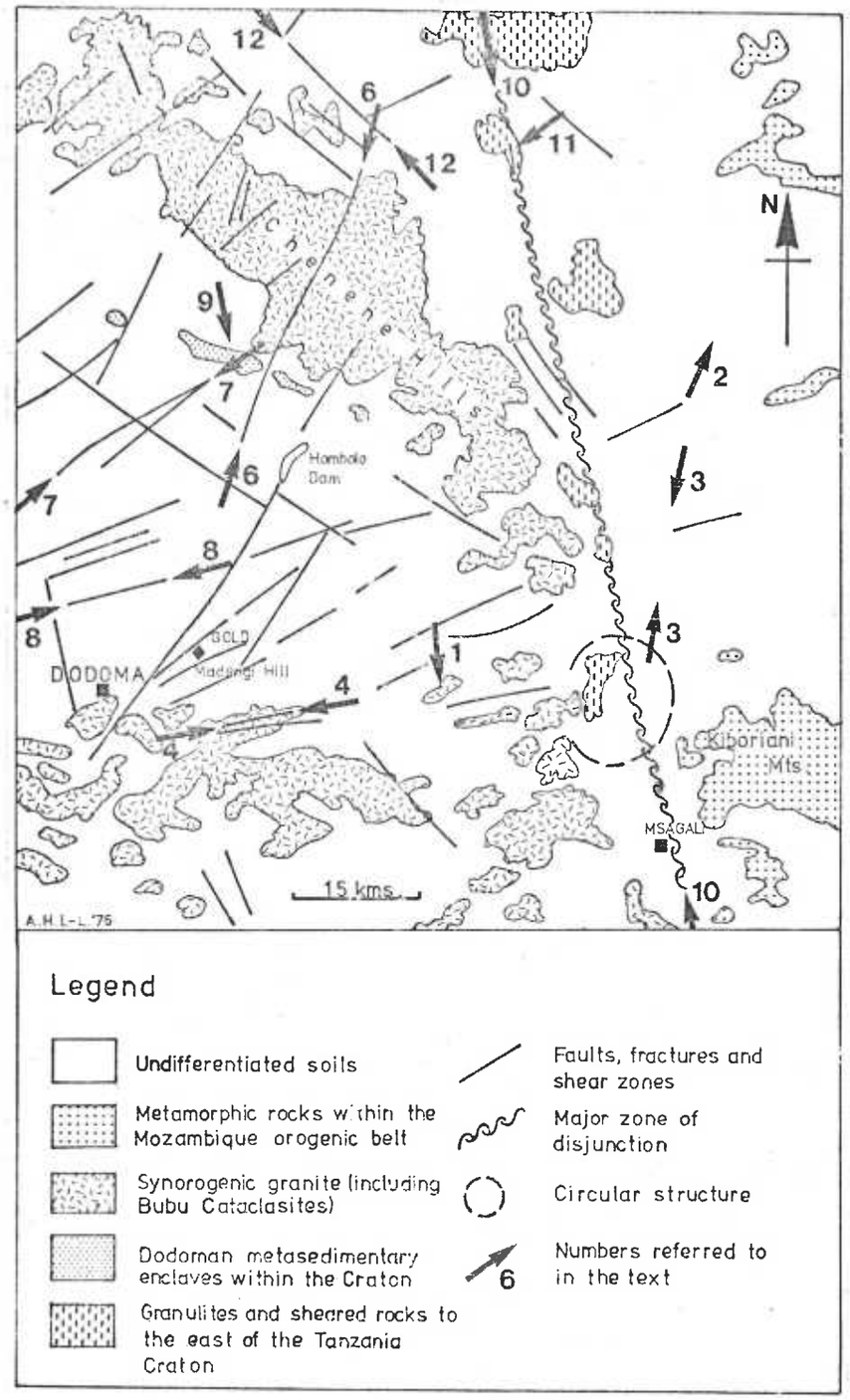


Fig.4.6b Photogeological outline of Fig.4.6a, area covered the same as Fig.4.5 (Scale 1:1,200,000 approx).

straight north-westerly trending features". These shear zones could not be distinguished on the LANDSAT imagery with any degree of certainty, in the elevated region of the Chenene Hills. However a number of lineaments with this trend could be observed further south in the plains area.

4.3.3 Usefulness of the imagery

General geology

This satellite scene indicates the complex nature of the boundary zone of the Tanzania cratonic granite. The marginal zone occupied by the belt of ancient "Western Granulites"(p.84) takes on a distinctive character not perhaps so readily observed in the field. Within the granite itself zones of dislocation can be picked out, although the negative features within the Chenene Hills related to the Bubu cataclasis, which show up well on aerial photographs, could not be easily distinguished. Some relics of supracrustal rocks could be seen on the imagery. The following points emphasize the usefulness of the imagery for photo-geological studies of the deformed margin of this cratonic granite:-

1) The observation of the characteristic granitic geomorphology of the Chenene Hills. The rounded margins of the hills, the coarser texture and fracture control of the drainage, distinguished this block from the finer textured metamorphics of the Kiboriani mountains in the south-east of the region.

2) The observation of variations in soil albedo considerably aided the identification of the superficial deposits of the region.

3) MSS band 5 was particularly useful for picking out isolated inselbergs in the

plains area due to the dark tones of the denser vegetation cover.

4) The imagery helped to confirm the structural interpretation of Harpum that the Chenene Hills is a horst block.

5) The variations in vegetation cover give very different tones on MSS bands 5 and 7, which enabled different points of geological information to be obtained from each of these bands.

6) Delineation of zones of shearing within the granite batholith.

7) Delineation of Dodoman(greenschist) roof pendant outcrops in the main batholith.

8) Identification of a NNW-SSE shield boundary zone in the eastern part of the region.

9) Delineation of major faults truncating the batholith.

Economic geology

At Madengi hill about ten kilometres ENE of Dodoma there is an outcrop of sheared and contaminated granite(see Fig. 4.6b). Within this outcrop there are some small E-W gold bearing quartz reefs. These have been considered to be genetically related to the granite(Wade and Oates, 1938). Thorough prospecting of the site failed to find any significant quantities of gold, although conditions for the eluvial concentration of a placer deposit are good in this region. The major structure of the locality is a NE-SW shear running along the western margin of the hill. Further gold prospecting of the

region might advantageously be carried out along other NE-SW lineaments not related to the Alpine faulting. It could be that the E-W quartz reefs represent complementary tensional features to the major NE-SW structures.

Pyrite and arsenopyrite have been reported from the WNW-ESE belt of Dodoman metasediments just south of the Chenene Hills(Julian et al. 1963). These are associated with some ferruginous quartzites and are probably related to contact effects between the granite and the metasediments.

Nickeliferous minerals have been found in association with the ultrabasic deposits of the Haneti - Itiso complex. The rocks of the Haneti - Itiso complex lie within an arc of catazonal rocks which bound the granite batholith. This zone almost certainly represents a deep suture within the earth's crust. NW-SE trending lineaments within the ultrabasic belt can be seen on the satellite imagery at 12 on Fig. 4.6. In view of the nickel potential of this district these lineaments may deserve further examination both on aerial photographs and on the ground.

4.4 The Burundian granites of southern Maniéma eastern Zaire - wet tropical environment

4.4.1 Introduction

General

The Burundian granites which are widely distributed in the northern half of the study region, part of the region of Southern Maniéma, are related to the Kibaran-Burundian-Karagwe-Ankolean fold belt. These rocks range in age from 1.3 b.y. to 0.8 b.y. Early members of the suite which were emplaced during the main phases of the Kibaran orogeny include syn-tectonic gneissic granites. Later late-tectonic and post-tectonic intrusions of tin-bearing muscovite granites and pegmatite dykes completed the cycle of magmatic activity. The latter are of some potential economic interest, lying as they do on the fringe of a much exploited tin field. The distribution of the Burundian granites and their adjacent rocks are shown on the sketch map Fig. 4.7.

Climate

A boundary between two climatic zones runs through the centre of the region from east to west. The northern part of the region is a perpetually wet area with an almost unbroken cover of tropical rain forest. South of the Lualaba river, which nearly bisects the region, there is a transition to a slightly drier climatic zone. The climate diagram for Kibangula on Fig. 4.7 shows that there is a short dry season from mid-May to early-July. The temperature remains very constant throughout the year at around 24°C. Even so this southern area still has an annual rainfall of almost 1,500 mms a year.

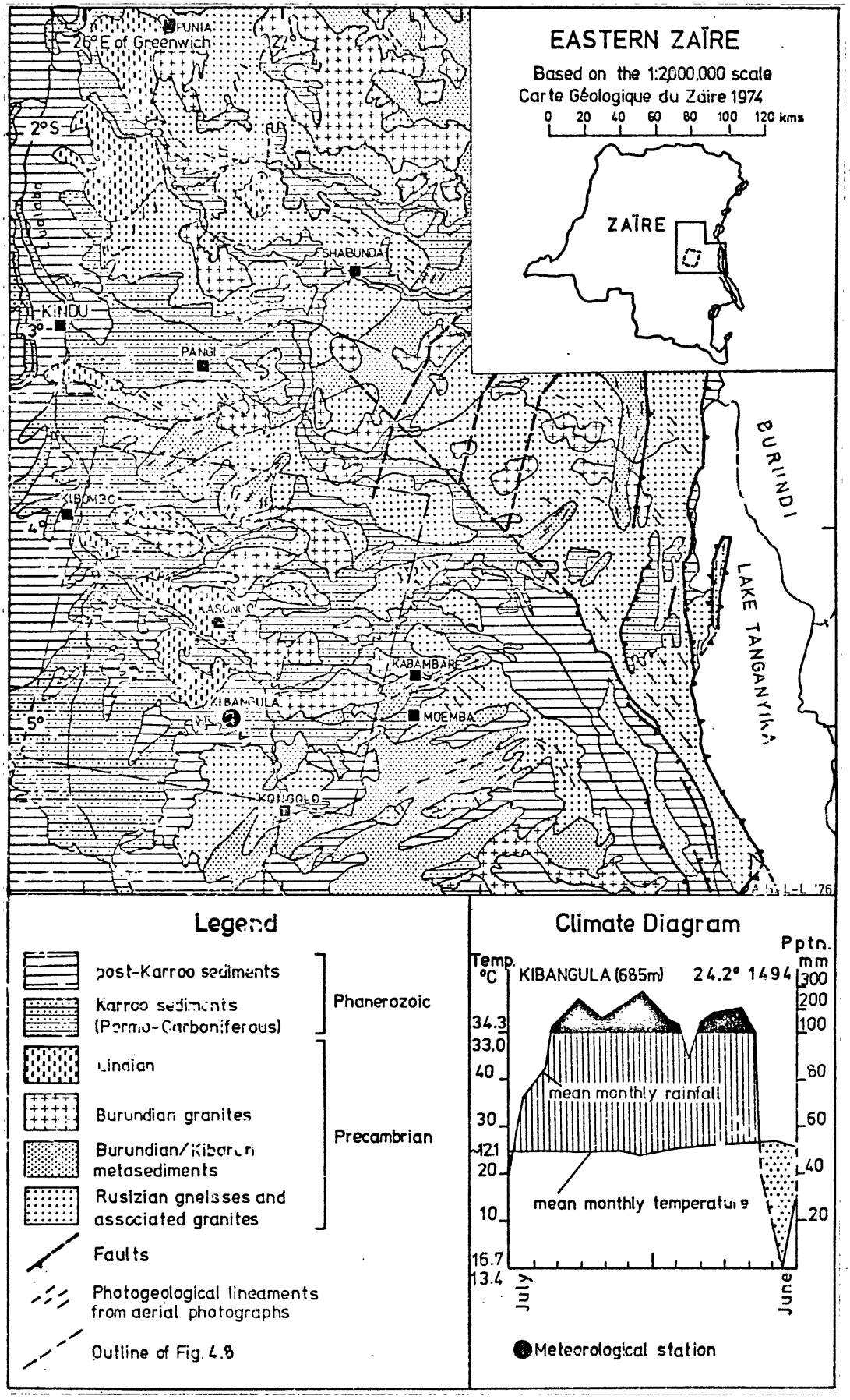


Fig.4.7 Geological sketch map of eastern Zaire (Scale 1:3,300,000 approx).

Topography and drainage

The region to the north and east of the Lualaba river, mainly underlain by crystalline rocks, is an ancient peneplain. South of the Lualaba much of the south-west of the region is underlain by Karroo sediments. The drainage patterns over these two regions are distinctly different, although all rivers drain into the northwards flowing Lualaba, the major tributary of the great Zaire river. The northern region has a curvilinear dendritic pattern reflecting the massive nature of the underlying basement. Whilst the south-western region has a NNE-trending parallel to sub-parallel drainage pattern, dictated by the northerly dip of the underlying Karroo sediments.

Superficial deposits and vegetation

Deep weathering of the rocks in this wet climate has resulted in a regolith which is almost everywhere over a metre thick. The soils developed under these conditions are therefore strictly zonal i.e. they are more related to climate and topography than to the composition of the underlying rocks. According to Sys(1960) there are two major soils associations in this region which he describes as:-

1) Hygro-kaolisols(ferralitic soils)
These are poorly drained soils which do not dry out during the course of the year. This group generally coincides with areas of dense equatorial rain forest.

2) Hygro-xerokaolisols(lateritic soils)
A leached zone is present in the profile of these soils which is related to the short dry season which causes them to temporarily dry

out during the year. They are generally found in the south of the region, and are mainly covered with broad-leaved tree savannah vegetation(Eyre, 1968).

Soils developed over the Karroo rocks of the south-west of the region have a tendency for iron oxides to be concentrated at the base of the soil profile. This leads to a build up of iron oxide (laterite) which is sometimes as much as ten metres thick.

Communications

There are several roads in the area serving the numerous small settlements. A railway runs in a NW-SE direction across the south-west of the region.

The Burundian granites

Cahen and Lepersonne(1967, p.212) indicate that the Burundian granites are calc-alkaline[1] and alkaline rocks. Although the granites do not have pronounced relief they often have medium to steep contacts with the younger rocks. Contact metamorphism is well developed to the north of the region at Punia(Varlamoff, 1950). The granite massif of Kiangala to the south-east of Kasongo(Fig. 4.8) was studied early on by Sluys(1944). He observed that in the middle of typical granite there were islands of aplite, 'granulite', tourmalinised granite and some patches of schorl rock. Later work by Varlamoff (1953 and 1957) has shown that the Maniéma granites are in fact zoned. Varlamoff concluded that the granitic massifs were composed of the following rock types from the centre outwards:-

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1 The calc-alkaline rocks are usually monzonites or akerites(equivalent to oversaturated syenites).

1) Pegmatite with giant microcline crystals, large plagioclase and quartz crystals with biotite.

2) Transition to a porphyritic zone in which rounded microcline crystals are set in a granitic matrix containing very fine grained biotite.

3) Medium and fine grained granite either with biotite alone or biotite and muscovite.

4) Medium and coarse grained muscovite granite.

Geological background

The oldest rocks of the region are granites and gneisses belonging to the Rusizian group. These rocks have been affected by the polycyclic Rusizian-Ubendian orogeny which lasted from 2.1 b.y. to 1.8 b.y. Then followed the deposition of geosynclinal sediments belonging to the Burundian group in the north of the region, and equivalent Kibaran rocks in the south-east. The Burundian granites were emplaced during the succeeding Kibaran orogeny(ca. 1.3 b.y.) when the Burundian sediments were converted to high grade gneisses and migmatites. Intrusion of post-tectonic pegmatite dykes continued up to about 820 m.y.(Cahen and Snelling, 1966). Soon after the main phases of the Kibaran orogeny sedimentation of the Lindian group began. This continued up to about 645 m.y. when the region was affected by a minor thermal event. This event may have been responsible for partial remobilisation of the Burundian granites. Much of the Lindian has since been removed by erosion in this region, but it does outcrop in two belts either side of the Lualaba river(Fig. 4.7). During the Permo-Carboniferous the area was blanketed with sediments of the Lukuga series

of the Karroo system. Sedimentation also took place during the succeeding Triassic period, and then followed a period of peneplanation and finally deposition of Plio-Pleistocene alluvial, colluvial and eluvial deposits.

Structure

A photogeological study carried out over the region using aerial photographs was reported by Lepersonne(1970). This showed that the Rusizian rocks have a dominantly NW-SE trend which is consistent over a very extensive region. The rocks in fact form a belt which is up to 450 kms. wide. The linear traces plotted (shown on Fig. 4.7) indicate the orientation of the bedding and not the fold axes.

The Burundian metasediments outcrop in three small belts in the north of the region and they have a NE-SW trend. The same trend is well displayed by Kibaran rocks of equivalent age crossing the south-east of the region.

4.4.2 Photointerpretation

Image quality

The LANDSAT imagery used for this investigation (ID No. 1054-07524) was taken during the middle of the rainy season. The imagery is relatively cloud free and good quality prints were obtained from MSS bands 5,6 and 7. However MSS band 4 was rather murky, which may have been due to the high humidity of the atmosphere at the time of imaging. MSS bands 6 and 7 proved to be the most useful for structural interpretation of the rainforested areas, as some details of relief could be seen. MSS band 5 is very dark toned in the forested areas, but shows some interesting details of drainage and structure over the savannah country of the southern half of the scene.

Geomorphology

Generally the Burundian granites are smoother and show less relief on the imagery than the adjacent Rusizian rocks. Small ridge and scarp features can be seen on MSS band 7 particularly in the areas of Rusizian rocks. A scarp in one case marks the boundary between granite and gneiss and is shown at 1 on Fig. 4.8b.

Drainage features

The drainage is only readily observed on the imagery in areas of tree savannah country. The rain forested northern region shows a broadly curvilinear drainage pattern, but details of minor tributaries are not easily discerned. The dominant trend of the drainage in this northern region is NE-SW, which may be a reflection of Burundian structural control. Drainage in the eastern and southern regions of the scene is well shown. A very characteristic fine-textured dendritic drainage pattern can be seen over the Burundian granites and Rusizian rocks of the eastern part of the scene. This distinctive pattern is well seen at 2 on Fig. 4.8a.

Vegetal and land use features

Rain forest vegetation shows up on MSS band 5 as very dark toned areas. This covers most of the northern part of the region. Clearings for cultivation within the rain forest are widespread. These are especially well developed on either side of the main roads of the region. They appear as sinuous light toned bands on MSS band 7, whilst on MSS band 5 they have a distinctive mottled texture as at 3 on Fig. 4.8a.

Tones

The rain forest cover produces very even toned areas on the imagery. Because the topography is generally subdued there is very little to

distinguish one rock type from another. Where the forest cover thins out the drainage pattern and soil albedo may give the vital clues needed to map in the lithological units. The hampering of photogeological interpretation by this rain forest cover is the reverse of the situation which occurs when interpreting large scale aerial photographs(say 1:10,000 scale). In that case variations can be observed in tree height, species and density which can be of great help in the interpretation of the underlying geology.

Textures

Texturally MSS band 7 has the most to offer as minor details of relief can be seen in the forested basement areas. Numerous rather obscure small ridges and scarps can be seen on the imagery of the northern region. These have a dominantly NW-SE trend and it is suggested that they are related to the Rusizian linear traces shown by the aerial photograph survey reported by Lepersonne(1970). The latter are shown on Fig. 4.7, and these can be compared with the NW-SE linear traces shown on the writer's interpretation(Fig. 4.8c).

Outside the rain forested areas the basement rocks show more definite characteristics. Three Burundian granite massifs in the south-east of the region show up well on MSS band 5. Their extent can be determined by the development of the characteristic fine textured dendritic drainage pattern, which was mentioned under the drainage section of this account.

Rock boundaries

It is not easy to draw boundaries around the Burundian granites for a number of reasons, the chief of which are:-

1) The boundaries are often masked by the rain forest vegetation blanket.

2) The boundaries are not always sharp, as there is an intricate relationship between Burundian granites and the Rusizian and Burundian metamorphic rocks.

3) Deep tropical weathering, peneplanation of the area and the widespread development of zonal soils have resulted in few distinctive topographic features in the region.

Structural units

Four main structural/lithological groups of rocks are present in this region(shown on the 1:2,000,000 scale Carte Géologique du Zaire, 1974).

1) Rusizian high grade metasediments and magmatic rocks(affected by the Rusizian-Ubendian diastrophism ca. 2.1 - 1.8 b.y.).

2) Burundian metasediments(includes the Kibaran rocks in the south of the region).

3) Burundian granites and associated intrusive rocks(ca. 1.3 - 0.9 b.y.).

4) Cover rocks which include late-Precambrian (Lindian), Permo-Carboniferous(Karroo), Permo-Triassic and Plio-Pleistocene deposits.

The Rusizian rocks underlie large parts of the region. Their distribution can be roughly ascertained by an interpretation of MSS band 7. This shows that these areas are covered by the short scarp and ridge features mentioned under textures in this account. These NW-SE short lineaments are unfortunately not confined to the Rusizian areas. This is because they also show through some of the cover rocks, especially

through the Lukuga series of the Karroo, which blanket most of the valleys of the region.

The Burundian metasediments with their dominantly NNE-SSW trend are not easily picked up in the north of the region. However the Kibaran rocks equivalent to them in the south-east of the region show a marked NE-SW trend. These rocks can be identified on MSS band 5 by a parallel set of lineaments with a very persistent strike at 4 on Fig. 4.8a. The Burundian granites themselves generally show rather nebulous structural trends on the satellite imagery. One major granitic block in the north of the region does have a pronounced structural grain. A closely spaced set of NW-SE trending lineaments can be seen cutting the granite at 5 on Fig. 4.8b. This may be an incorporation of an earlier Rusizian structure but more probably it is evidence of shearing and/or dyke emplacement.

Folding

There are no actual fold patterns visible on this LANDSAT scene. Only the persistent NW-SE trend of lineaments, referred to previously as Rusizian structures, suggests the axial trend of regionally folded gneisses.

Lineaments

The main lineaments observed in this region have already been referred to in the structural outline given above. There does not appear to be any significant sign of major faulting in the northern part of the region. South of the Lualaba river there are several long straight drainage channels which suggest fracture control like 6 and 7 on Fig. 4.8b. Indeed the straight NW-SE trend of the Lualaba itself in this region may be the result of exploitation of a major crustal fracture.

FIG.4.8

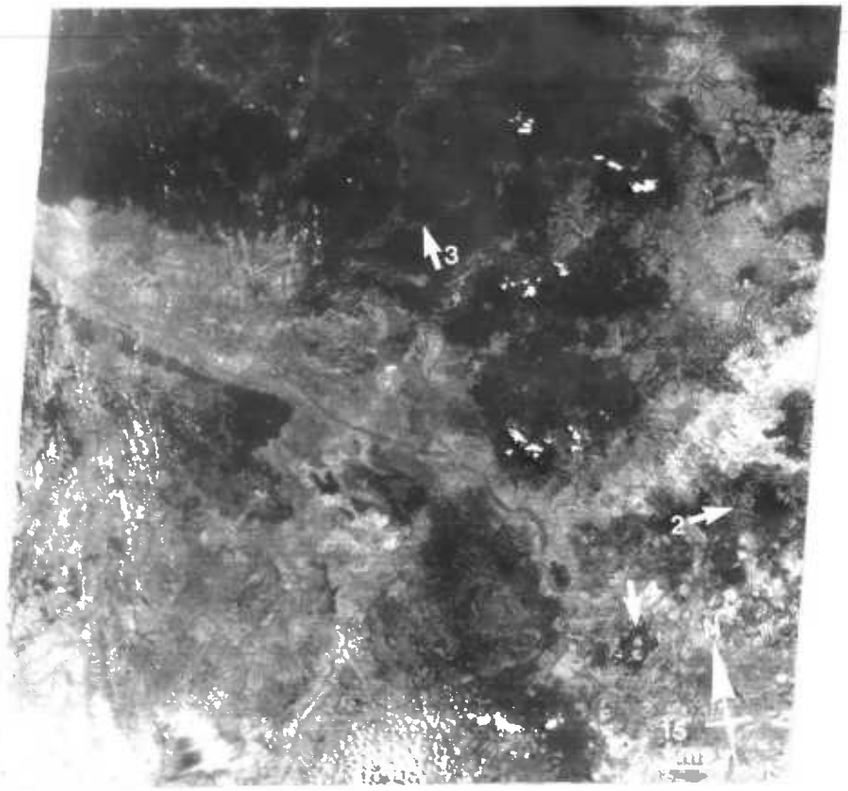
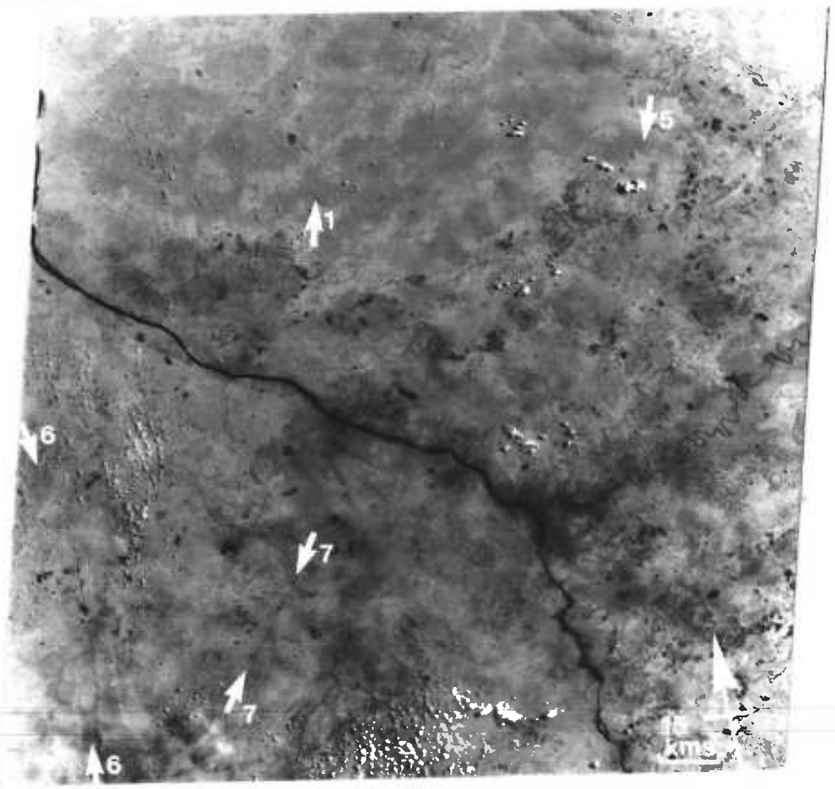
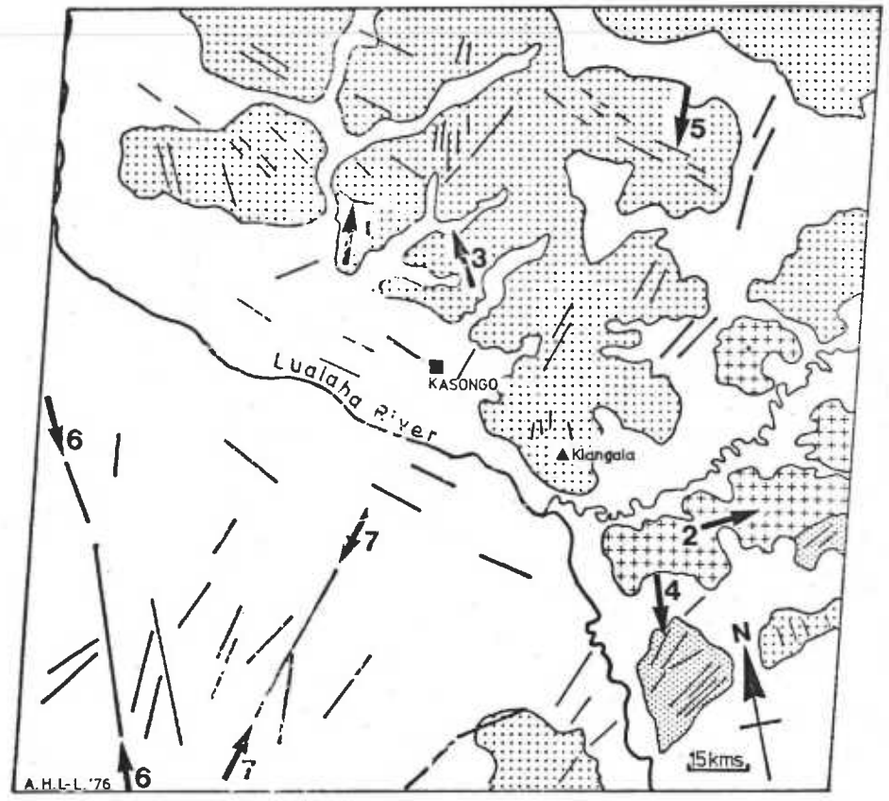


Fig.4.8a MSS band 5 of LANDSAT-1 scene 1054-07524 covering southern Maniéma, eastern Zaire (Scale 1:1,600,000 approx).

Fig. 4.8b MSS band 7 of LANDSAT-1 scene 1054-07524





Legend

- Sedimentary Cover
- Burundian granites
- Kibaran metasediments
- Undifferentiated granites and gneisses of the basement complex (Rusizian, Burundian and Kibaran rocks)
- Linear trace (mainly bedding)
- Fracture trace
- 4 Nos. referred to in text

Fig.4.8c Photogeological outline of LANDSAT-1 scene 1054-07524 (figs. 4.8a and b). (Scale 1:1,600,000 approx).

1-Scarp boundary between Burundian granite and gneiss, 2-dendritic drainage pattern over Burundian granite, 3-man-made clearings in forest, 4-strike of Kibaran metasediments, 5-?shear zone in Burundian granite, 6 and 7-major fractures in Karroo rocks.

4.4.3 Usefulness of the Imagery

General geology

Interpretation of deeply weathered rocks covered by thick equatorial forest cover is not easy on the LANDSAT imagery. Nevertheless MSS band 7 showed some details of the morphology of the country covered by forest. Where the forest cover was absent the very distinctive dendritic drainage pattern developed over the granites showed up clearly on MSS band 5. However compositional zoning of the Burundian granites reported by Varlamoff(1953 and 1957) was not seen on the imagery. The main features of geological interest showing on the LANDSAT imagery of this region are summarized as follows:-

1) Observation of minor ridge and scarp features which show the structural grain of the Rusizian rocks underlying the northern part of the region(MSS band 7).

2) Identification of the main area underlain by basement rocks due to the characteristic curvilinear drainage pattern developed over these rocks in the northern part of the region.

3) Delineation of the rocks belonging to the drainage basin of the Zaire river, by their coarse textured parallel to sub-parallel drainage pattern in the south-west of the region.

4) The Burundian granites in the east and south-east of the region are identified by their distinctive fine textured dendritic drainage pattern(MSS band 5). The boundaries of the granites in the northern rain-forested area were however impossibl to delineate on the imagery(p.104).

5) Identification of the Kibaran rocks in the south-east of the region by their strongly developed lineaments(MSS band 5).

6) Identification of some major fractures cutting the Karroo rocks of the south-west of the region.

7) Delineation of the equatorial forest areas on MSS band 5.

8) Delineation of cleared forest areas now used for agricultural cultivation(MSS bands 5 and 7).

Economic geology

According to Sluys(1944) the streams leaving the Kiangala granitic massif(Fig. 4.8c) carry fine particles of cassiterite downstream for up to three or four kilometres. He also reports on the presence of some stanniferous and tantaliferous dykes at Moemba just to the east of the LANDSAT scene(Fig. 4.7). One such dyke at Moemba occurs in an inlier of crystalline basement(Rusizian) and trends N 60° W. It is composed exclusively of crystals of tantalite of very high density. Additional data on the trend of the stanniferous pegmatite dykes would be of great assistance in directing future prospecting in the region. If they were found to have a dominant NW-SE trend as is suggested by the above account of Sluys, it would be worth carrying out a ground check on locality 5 on Fig. 4.8b. This locality described under the structural units section of this account is one of closely spaced NW-SE trending lineaments. These may well represent a shear zone or shatter belt which provided a locus for dyke emplacement.

4.5 The Hercynian granite/granodiorite complex of north-east Sardinia - mediterranean environment

4.5.1 Introduction

General

A suite of plutonic rocks ranging in composition from gabbro to granite outcrops in many parts of the island of Sardinia. These rocks are generally considered to belong to one main batholith of Hercynian age(average age 278 m.y., Del Moro et al., 1972). Indeed these rocks form what has been described as the "skeleton" of the island(Ricci, 1972). The part of the batholith studied occupies much of the north-eastern sector of Sardinia, and is referred to as the Ogliastra-Gallura region. It includes more than 70% of the total granitic outcrop of the island, and is contained within LANDSAT-1 scene 1020-09341. The location of the region and general geology of the island are shown on Fig. 4.9.

Climate

Sardinia is affected by the sub-humid climate of the mediterranean zone. The climate diagram on Fig. 4.9 shows that its main features are mild winters with rain, followed by very warm dry summers. July and August are the driest months of the year with only a few millimetres of rain. It is during this period of Saharan type weather that there is often a considerable build up of a dense dust known as calina. The latter is similar to the haze induced by the harmattan winds in west Africa.

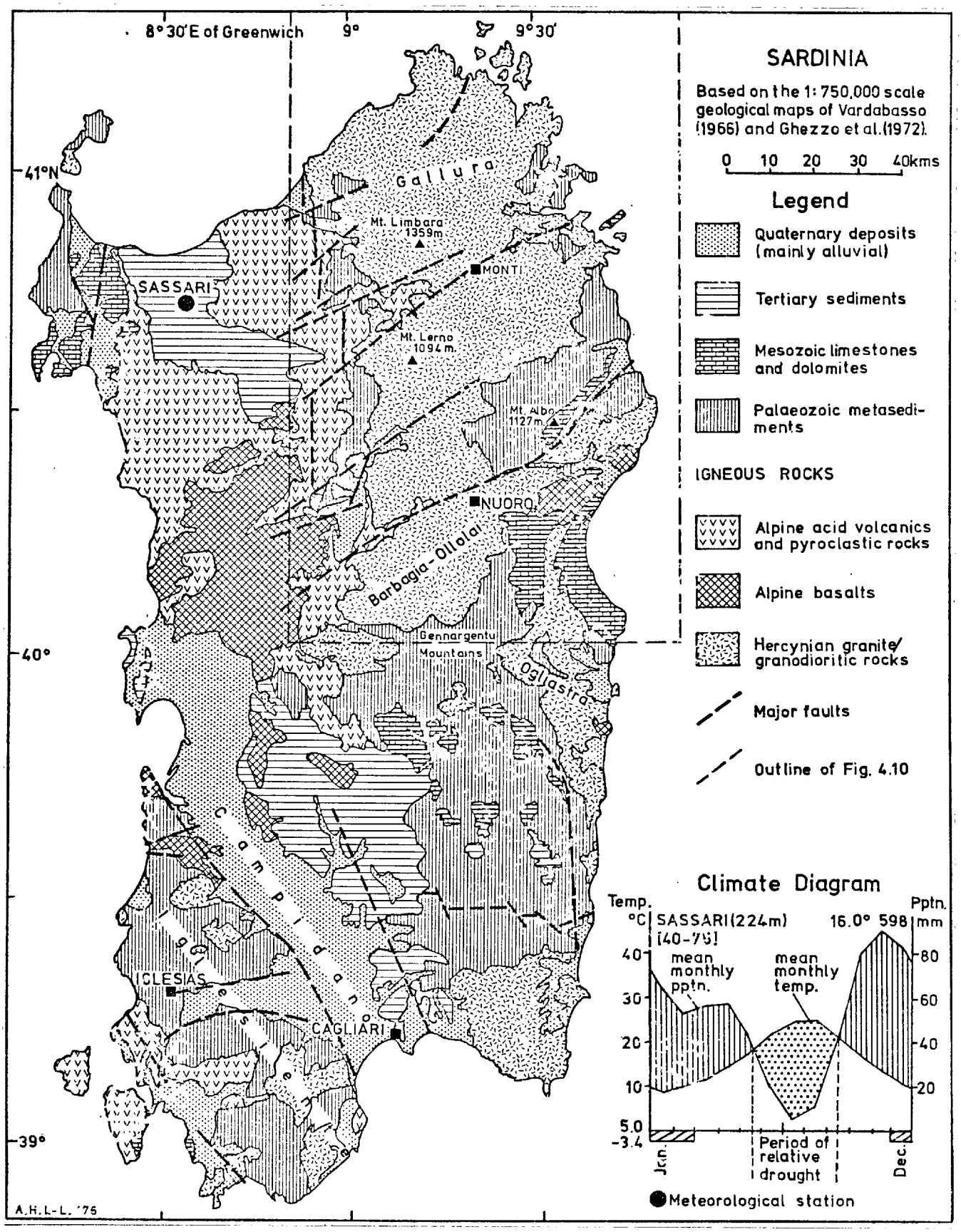


Fig.4.9 Geological sketch map of Sardinia (Scale 1:1,250,000 approx).

Topography and communications

The terrain of the granitic batholith is mountainous(Mt. Limbara 1,359 metres) and heavily dissected, especially in the north. The drainage in detail is sub-dendritic but is broadly radial away from the centre of the batholith towards coastal outlets. The granite is cut by a number of canyons related to Tertiary rift faulting, and it is along these that many of the main roads and railways are located.

Superficial deposits

Brown mediterranean soils are developed widely over the granite mass and locally lithosols are found on the steeper slopes. The soils, which normally have a fully developed profile, are light and well drained. They are easily cultivated but are not as productive as the brown soils developed over most of the other rocks of the island.

Vegetation

There are two main natural vegetation zones covering the region which are:-

1) Zone of sclerophyllous(hard-leaved) shrub formations
(from 0-500 metres elevation approximately)

This zone which is more or less confined to the coastal regions is represented by maquis and garrigue - thick secondary shrub formations mainly of evergreen species. This plant community also commonly includes heather, gorse and broom.

2) Zone of montane mediterranean forests
(from 500-1,200 metres elevation approximately)

Xerophile(i.e. adapted to hot dry conditions) oak forests occupy the upland regions of the hinterland. These contain evergreen

Quercus ilex mixed with deciduous oaks such as Q. suber(cork oak) and Q. pubescens. These forests commonly degrade into bushy formations where tree felling has taken place.

The granitic batholith

The batholith is a multiple intrusion which was generated by the emplacement of minor amounts of basic magma, and culminated with the production of the main granitic phase. Ghezzo et al. (1972) have distinguished three main groups of rocks within the batholith which are:-

1) Minor gabbros, diorites and tonalitic quartz diorites, generally enclosed within the larger granitic intrusions.

2) Medium grained equigranular quartz diorites and granodiorites, mainly in the western part of the batholith.

3) Medium to coarse grained granites and granodiorites, often inequigranular, forming the main intrusive mass of the batholith.

Dark magmatic xenoliths are abundant in rocks of group 2 and are present to a lesser extent in those of group 3. These xenoliths have mainly been derived from the basic rocks of group 1. Quartz dioritic stocks containing many schlieren(particularly at the margins) and small bodies of microgranites can be seen in the central part of the region(Ghezzo et al., 1968). Further, it has been observed that the batholith has a "compositional polarity", with more acid rocks outcropping towards the north-east(Ghezzo et al., 1972).

Late stage magmatic activity was responsible for the injection of a number of minor intrusions both into the batholith itself and into the country rock. These included quartz veins, quartz porphyries, aplites and lamprophyric dykes. Thermal metamorphism and mineralization of the adjacent palaeozoic metasediments took place as a result of the intrusion of these veins and dykes.

Geological background

Palaeozoic metasediments of varying metamorphic grade surround the granite. The age of the metamorphism of this basement is presumed to be Hercynian, but older than the date of emplacement of the batholith. The intrusive character of the granite is generally shown by its sharply discordant contacts with the country rocks. It has been suggested that in north-eastern Sardinia there may have been Caledonian intermediate pressure metamorphism, which has since been overprinted with Hercynian greenschist facies metamorphism(Ricci, 1972).

Dolomites of Jurassic age outcrop in the south-east of the study region and have been faulted by Tertiary rift faults. To the west of the batholith there are extensive areas of Tertiary and Quaternary volcanic rocks.

Structure

Although the granitic batholith is a post-tectonic intrusion its emplacement may well have been controlled by pre- or syn-tectonic structures. The dominant axial trend of the main Hercynian fold structures has been observed in south-west Sardinia to be N-S(Moore, 1969). In addition a number of major N-S faults cut the Tertiary rocks to the west of the batholith, testifying to a deep seated zone of dislocation. The Ogliastra-Gallura granite is itself elongated

in a N-S direction and it is probable that this configuration was imposed by these persistent structures. The N-S orientation of the granite has been subsequently modified by block-faulting caused by NE-SW Tertiary rift faults.

4.5.2 Photointerpretation

Image quality

LANDSAT-1 frame 1020-09341 was taken at the height of the dry mediterranean summer in August, 1972. The NASA quality rating was fair for MSS bands 4,5 and 6 and good for band 7. However in the writer's opinion none of these bands could be described as more than fair in quality. Three main factors have contributed to the degradation of the quality of these images which are:-

1) Poor definition overall which may have been due to imperfect atmospheric transmission, probably caused by scattering of the reflected radiation by suspended dust particles.

2) Strong reflection of summer vegetation and light toned soils in the IR bands. This produced light toned prints of rather low contrast.

3) Blurring of the western part of the frame by some unknown factor causing poor definition on all four MSS bands.

Geomorphology

An examination of the satellite imagery of the Ogliastra-Gallura region allows the identification of three main morphological units within the exposed part of the batholith. These lie in three zones from north to south which are:-

1) A northern zone within the Gallura region of the northern part of the island. This has topography which is rugged, strongly affected by fracturing and heavily dissected.

2) A central zone, lying south of a major NE-SW rift fault which passes close to the town of Monti. This region has a less rugged appearance than the northern zone and forms hilly rather than mountainous scenery.

3) A southern zone, occupying the district of Barbagia-Ollolai lies to the south of another major NE-SW rift fault, which passes just north of the provincial capital of Nuoro. This zone is mountainous but not as highly fractured as the northern zone.

Within the central zone there are a number of curved scarp features like 1 on Fig. 4.10. These can be identified under the stereoscope, using another image from an adjacent orbit, as being the edges of some tabular formations. Stratification as a result of sheet jointing in the granite may be the cause of these tabular bodies. This has been observed in the Hercynian Dartmoor granite of south-west England, where sheet jointing follows the topography(Edmonds et al., 1969).

Erodibility

The granitic rocks of Sardinia generally form positive resistant massifs and are less easily eroded than the adjacent metamorphic rocks. This is in contrast to the situation normally encountered in desert regions(see Section 4.1) where the granites disintegrate at a faster rate than the other rocks. The dolomitic limestones at 2 on Fig. 4.10 also stand out as a strongly resistant plateau.

Drainage features

The drainage pattern within the northern zone of the batholith is dominantly dendritic and moderately fine textured, but is frequently modified by fractures. Thus many of the valleys have straight stretches giving the overall pattern an angulate dendritic character. The metasediments at 3 on Fig. 4.10 have a finer dendritic drainage pattern than the granites. There is also an absence of the straight, steep-sided valleys characteristic of the well jointed granitic rocks. The individual drainage channels are not easily distinguished on any of the MSS bands except where they are fracture controlled. This is either because of low contrast on the negatives(MSS bands 6 and 7) or because dense, dark-toned vegetation cover on the valley sides obscures the central channels(MSS bands 4 and 5).

Soil factors and land use

The balance between areas of natural vegetation and agricultural land in Sardinia is closely related to topography. The widespread development of relatively fertile brown mediterranean soils has encouraged extensive cultivation where slopes are not too steep. The granite in general forms rather rugged terrain unsuitable for cultivation, but over the more subdued topography of the central zone of the batholith, light tones on all MSS bands indicate widespread cultivation. An examination of a Skylab true colour photograph of the northern part of the island shows that the light tone is due to the light brown colour of the soils. Thus light coloured brown soils rather than the crops growing on them appears to be the dominant influence on the overall hue of these cultivated areas, when viewed from orbital altitudes.

Vegetal features

The steeper slopes and mountain tops are covered by oak forests and thick secondary shrub formations. MSS bands 4 and 5 show these naturally vegetated zones in dark tones, whilst the same areas are light toned on bands 6 and 7. It is interesting to note that although much of the forest cover is of evergreen species it reflects reasonably well in the IR, unlike evergreen pine forests. MSS bands 4 and 5 are especially useful for showing up lineaments caused by boundaries between naturally vegetated and cultivated areas. Some of these lineaments are of geological significance like parts of the rift fault shown at 4 on Fig. 4.10.

Tones

Tone tends to vary as a function of factors such as land use, topography, rock type and vegetation in this region. The strongest tonal contrasts are found on MSS bands 4 and 5 where the tones vary from medium to dark. The tones on MSS bands 6 and 7 are much more uniform and vary from medium to light.

Textures

The texture of the granitic batholith varies depending on the degree of dissection of the terrain. The highly fractured northern zone is divided into angular sub-units. Whilst in the central zone the outlines of the granitic hills are often wavy and ragged or even have a saw-toothed appearance as at 5 on Fig. 4.10. The latter is probably due to dissection of scarp edges by rivers running off the plateaux. Another feature of the granitic areas is the rounded form of the interfluves compared with those of the metamorphic areas, which are generally sharper.

Rock boundaries

Rock boundaries of the batholith with adjacent formations cannot generally be drawn with much certainty on any of the MSS bands. Where the granite is covered with Quaternary alluvium, as at 6 on Fig. 4.10, then there is a clear boundary line. Generally though the imagery is not sharp enough to show up precisely the change in texture between granitic and metamorphic areas.

Structural units

The granitic rocks of north-east Sardinia are the products of a series of magmatic events, and are related to a number of intrusive centres. The main structural event to have affected these rocks since their emplacement has been rift faulting of the Alpine orogenesis. Consequently it is now convenient to consider the structure of the Ogliastra-Gallura region as being composed of three major fault blocks separated by two NE-SW trending rift faults.

These three morphotectonic units coincide with the morphological zones described earler and are from north to south:-

1) The northern block which is highly fractured and forms the heavily dissected scenery of the Gallura region. This is suggestive of an uplifted fault block undergoing rapid erosion.

2) The central block south of the Monti fault, where the topography is more subdued. Fracturing is not well developed in this zone.

3) The southern block of Barbagia-Ollolai, which is separated from the central block by the Nuoro fault, which appears to

downthrow to the north. The sense of movement of this fault appears to be indicated by the Mesozoic dolomites of Mount Albo at 2 on Fig. 4.10. They are found immediately north of this fault, and being younger stratigraphically than the adjacent granite and metasediments suggest a northwards downthrow for the fault.

This structural sub-division of the batholith is based mainly on the evidence presented by the satellite imagery, and the lithological information shown on the 1:750,000 scale geological map of Sardinia(Vardabasso, 1966). The three morphotectonic units are shown on Fig. 4.10c.

Circular features

A number of circular features from 5 to 10 km. across can be seen on the imagery within the granitic areas and these are indicated on Fig. 4.10b. These are best observed under the stereoscope using a similar MSS band from an adjacent orbit. It is thought that some of these may represent intrusive centres. Further it is possible that one or two of these could be equated with the description in the abstract of a paper by Ghezzo et al.(1968), where they mention that in middle northern Sardinia as well as a "granito principale" there are also some quartz dioritic and granodioritic stocks.

Lineaments

The most notable feature of the lineament pattern within the granitic batholith is the contrast between the highly fractured northern block and the relatively unfractured central block. The minor lineaments of the northern block have a persistent NNE-SSW trend whilst other longer fractures vary between NE-SW and N-S. There is also an important ENE-WSW fault shown

on the imagery at 7 on Fig. 4.10 which has not previously been mapped. All these lineaments form deep negative features in the land surface. Contrastingly there is a NW-SE set of lineaments, which include 8 on Fig. 4.10, with a different appearance. These lineaments though persistent along their length do not form continuous negative features and do not modify the topography in the way of the first described lineaments. Perhaps they represent a younger set of fractures or some resistant dykes. Extended lineaments with subdued topographic expression have also been noted in north-east Scotland, where they coincide with magnetic anomalies on the aeromagnetic map(see Section 4.6 page 144).

The lineaments of the central block are more uniform than the northern block and have a dominantly NE-SW trend. This direction coincides with the trend of the Tertiary rift faulting and the strike of quartz veins and lamprophyric dykes of this zone(Pecorini, 1971). The structural character of this block as described previously is markedly different from the northern block. The area appears to be weakly fractured and it has characteristic rounded tabular massifs. It should not be overlooked that the apparent lack of fracturing of the block may be partly due to a thicker soil cover and more subdued topography than the northern zone.

The southern block appears to have been affected by a rather different tectonic regime. There are only a few major fractures and these generally trend either NE-SW or NNW-SSE. One curving fault at 9 on Fig. 4.10 strikes N-S. The sharp curve of this fault suggests that

FIG. 4.10

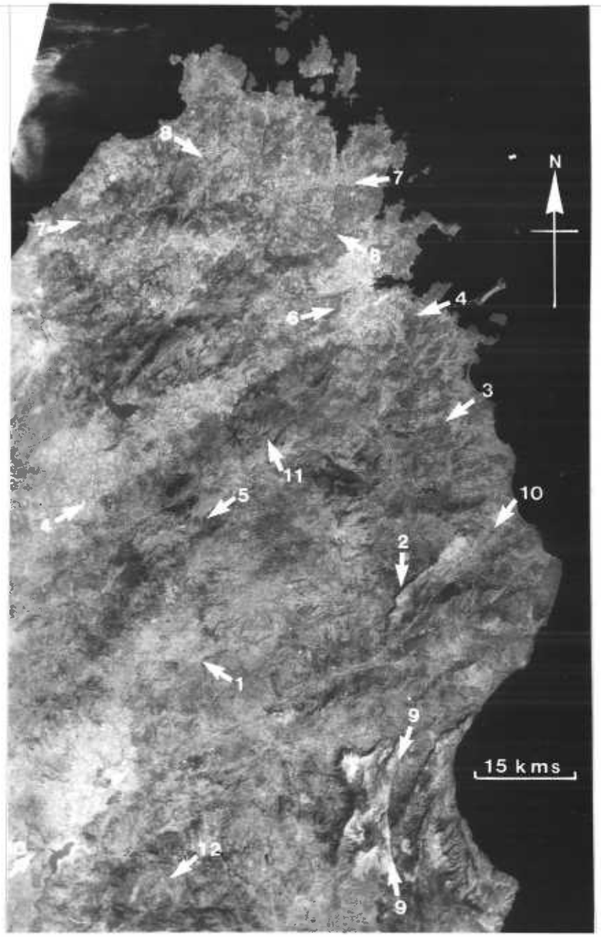


Fig.4.10a MSS band 5 of part of LANDSAT-1 scene 1020-09341 covering north-east Sardinia (Scale 1:850,000 approx).

1-edge of tabular formation, 2-dolomitic limestone plateau, 3-drainage pattern of metasediments, 4-Tertiary rift fault, 5-saw-toothed scarp edge of granite, 6-boundary between granite and alluvium, 7-major fracture, 8-fault line scarp, 9-curving ?thrust fault, 10-Tertiary rift fault, 11 and 12-circular structures within granite batholith.

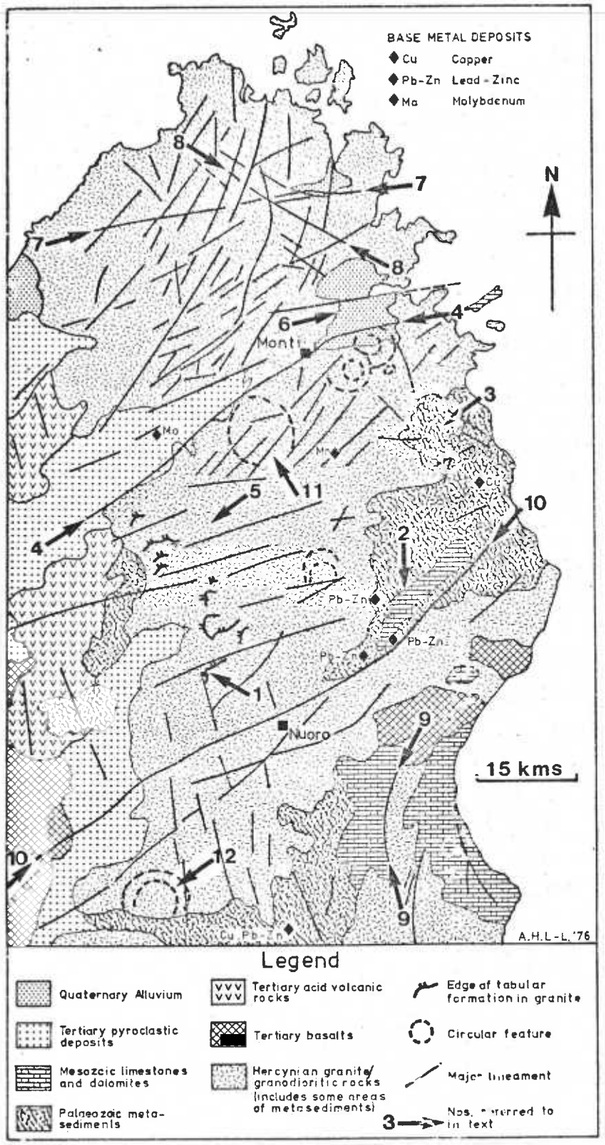


Fig.4.10b Photogeological outline of Fig.4.10a. Location of area is shown on Fig.4.9. (Scale 1:850,000 approx).

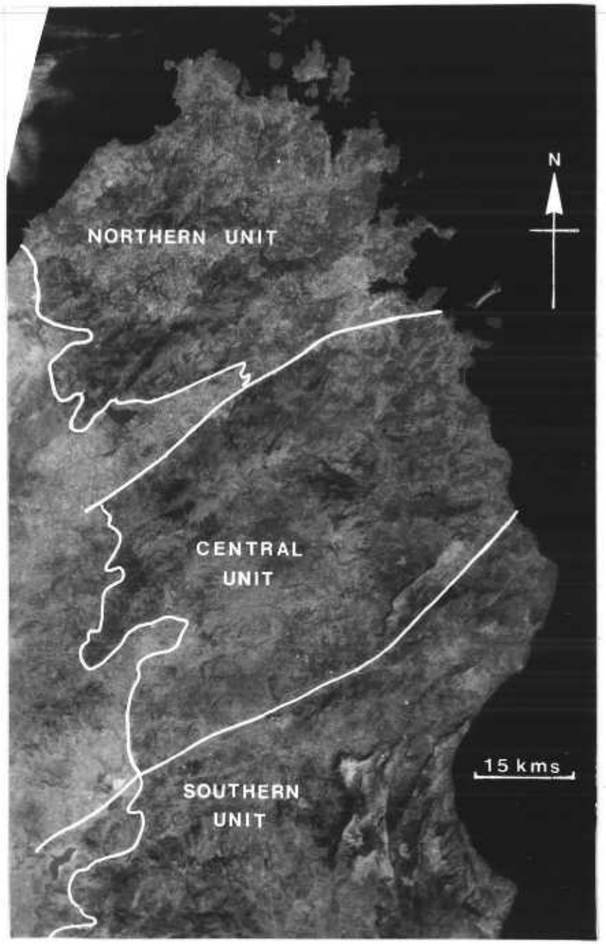


Fig.4.10c The morphotectonic units of the north-eastern part of the Sardinian granite batholith.

it is probably a thrust fault. The change from a dominantly NE-SW fracture pattern to one partly affected by NNW-SSE fracturing marks a change to the NW-SE trending structural domain of the southern part of the island. The major structure of that region being the broad Tertiary rift valley of the Campidano in the south-west of the island(Fig. 4.9).

4.5.3 Usefulness of the imagery

General geology

The LANDSAT imagery studied shows on one frame the major part of the outcrop of one of the largest granitic blocks of the European Hercynide mobile belt. This synoptic view has enabled the writer to distinguish three main structural zones within the granite based on texture, fracture patterns and morphology. At the same time a number of previously unmapped circular features were observed which may well represent the centres of individual intrusions within the batholith. A summary of the main points of photogeological interest relating to the batholith are given below:-

1) The identification of three morphotectonic zones within the granitic batholith.

2) The observation of a number of circular features within the batholith, possibly representing individual intrusive centres.

3) Identification of the location of the major rift faults and subsidiary fractures.

4) Identification of the main lineament directions and types within the different zones of the batholith.

5) Observation of certain tabular formations in the central zone of the batholith.

6) MSS bands 4 and 5 were useful for showing up geological lineaments coincident with boundaries between cultivated and naturally vegetated areas.

7) Observation of the angulate dendritic nature of the drainage pattern of the granite in the northern zone, which contrasts with the more nearly dendritic character of the drainage over the metamorphic rocks.

8) Observation of the outline of the Jurassic dolomitic limestones in the eastern part of the region.

Economic geology

Following the intrusion of the Hercynian granite in Sardinia there was a phase of hydro-thermal alteration of the rocks. At that time metal-bearing magmatic volatiles and residual fluids penetrated both the granite and the country rocks along faults, fractures and rock boundaries. This produced a number of replacement deposits of copper, zinc, lead, tungsten, antimony, molybdenum, iron minerals along with fluorite and barite(Moore, 1972). Economically workable quantities of these minerals have been found in south-west Sardinia associated with grano-dioritic stocks.

Two molybdenum prospects are located to the south of Monti(Fig. 4.10b). One lies within an area of Tertiary pyroclastic deposits and the other within the Hercynian granite batho-lith. An interpretation of the satellite imagery suggests that both prospects may be associated with NE-SW lineaments. Other base

metal deposits, lead, zinc and copper, occur within Palaeozoic metasediments adjacent to the batholith as shown on Fig. 4.10b.

Moore(1969) has observed that the hydrothermal replacement deposits of Iglesiente in south-west Sardinia are located within radial and tangential fractures cutting some granodioritic stocks. The former he regarded as due to the initial intrusion of the stocks, whilst the tangential fractures, which resemble ring fractures, are due to slight post-intrusion subsidence. A number of circular features thought to represent granodioritic stocks have been observed on the satellite imagery within the main part of the batholith and these have been plotted on Fig. 4.10b. It could be that some of these are similar to the granodioritic stocks of Iglesiente. If this were the case they would provide future prospecting targets for further base metal exploration in north-east Sardinia. In particular where circular structure 12 on Fig. 4.10b comes into contact with Palaeozoic metasediments along its southern extremity would seem to be a likely site for mineralization of the replacement type mentioned above.

4.6 Caledonian granites of the Grampian Highlands of Scotland - temperate environment

4.6.1 Introduction

General

This last case study is concerned with the "newer" granites of the Grampian Highlands of Scotland. These rocks comprise an extensive group of late- to post-tectonic acid intrusions, and they belong to a widespread suite of basic to acid plutonic and volcanic rocks. The granites form major mountain blocks such as the Cairngorms and Lochnagar as well as numerous smaller bodies. The regional distribution of these intrusions is shown on Fig. 4.11. Radiometric dating of the granites puts their age at around 400 m.y.(Siluro-Devonian). The individual dates of intrusion cover a fairly broad time span, but they are generally considered to be younger than the main Caledonian folding and metamorphism and older than the Middle Old Red Sandstone group.

Climate

The climate of this part of Scotland varies enormously. At any one location it depends mainly on altitude but also on topographic situation. The moderating effects of warm air currents accompanying the Gulf Stream, which flows around the Scottish coastline are felt for considerable distances inland. Much of the region can be described as one of short cool summers with long cold winters. The increase in annual precipitation(rain and snow) with altitude is a well established maxim. Conditions vary from the warm moist climate of the Spey valley to the extremely cold and permanently water-logged environment found on

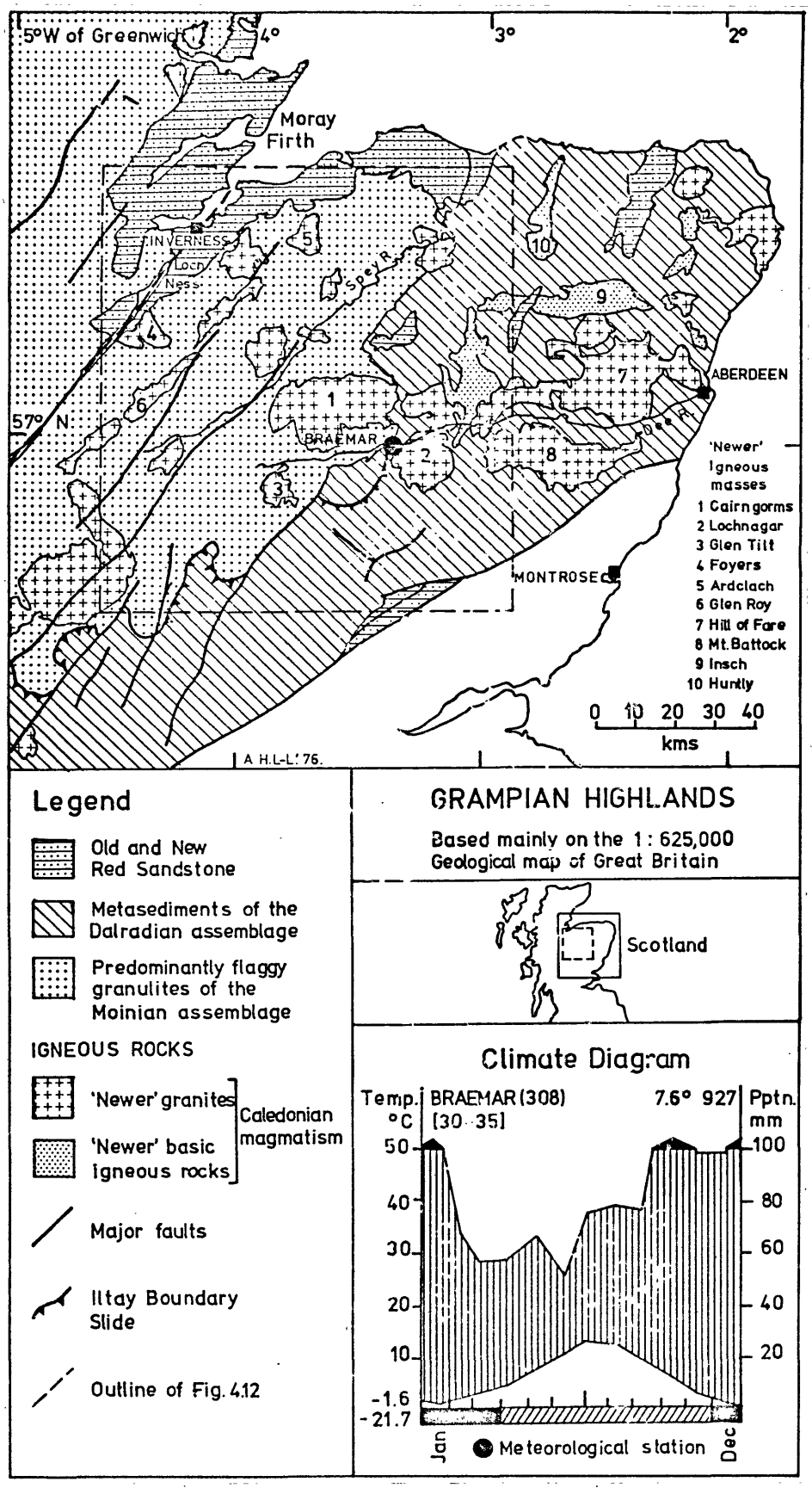


Fig.4.11 Geological sketch map of part of the Grampian Highlands of Scotland (Scale 1:1,600,000 approx).

the higher parts of the Cairngorms. The latter are just below the permanent snow line as it would be drawn at this latitude. The climate diagram on Fig. 4.11 shows that at Braemar the average annual temperature is only 7.6° C, and for four months of the year the mean daily temperature frequently drops below zero. Braemar lies just within the upland zone of climate and soil type outlined by Glentworth(1966) and described in detail under the section on superficial deposits.

Topography

The major part of the region studied has been carved from an ancient peneplain of Miocene-Pliocene age. This "Highland Peneplain" has two physiographically distinct domains. Most of the region studied has considerable areas of the country between 600 and 900 metres, which represents a poorly dissected part of the peneplain. Whilst in the extreme south-west of the study region and further to the west the peneplain is well dissected, with only the highest points on the watersheds reaching heights of 600 to 900 metres. The extensive effects of glaciation are readily observed in the well dissected part of the peneplain in the form of deep U-shaped valleys and elongated lochs.

The topography of the Cairngorms which lie in the poorly dissected part of the peneplain is predominantly pre-glacial in origin. This has been established by Sugden(1965) and others. Sugden observed that the granite is widely affected by sheeting or pseudo-bedding. Examination of the sheeting revealed that it is typical of the sort of structure which is normally induced under arid climatic conditions. The sheeting is commonly parallel to the smooth

slopes and has only been interfered with by ice action on a limited basis. Where this has happened the sheeting is abruptly truncated by the steep walls of glacial troughs and corries.

Superficial deposits

Glacial till(boulder) clay is widespread over the lowland areas of the region and accumulations may be tens of metres thick. However this cover thins out fairly rapidly on the higher ground to much less than a metre. Glentworth(1966) has recognised in Scotland three main altitudinal soil zones and these give a reasonable impression of the type of soil cover affecting the granitic rocks of the region. These zones are described below:-

1) Montane - above 750 metres

This is a zone of arctic alpine vegetation. Frost action is the dominant weathering process, with the production of boulder fields, scree slopes and bare outcrop. Montane podzol, alpine humus or ranker soils(soils with a high organic content in the A-horizon) are developed under these severe conditions.

2) Upland - 300 to 750 metres

Peat podzol soils derived from granitic and glacial till are widely developed in this wet zone. There is sometimes a development of a thin layer rich in iron(iron pan) which roots and water cannot penetrate. Under these poor drainage conditions there may be accumulations of peat of up to three metres. Peat moor, moss and bog develop in that order with increasing wetness.

3) Lowland - below 300 metres

Here there is a greater range of soils although peat podzols are still present. Sandy loams developed on the medium steep slopes may be suitable for agriculture. The land of the valley floors is widely cultivated on soils developed over glacial till.

Vegetation

The vegetation developed over the granites is acidophilous and rather monotonous, being broadly controlled by climate and topography. There are two main regional vegetation types within the study region. Heather moors cover the highland granites of the central and eastern parts of the region. Whilst granites of lower relief in the west, which include the Foyers, Ardclach and Glen Roy intrusions(4,5 and 6 on Fig. 4.11), are covered with acid grassland complexes. Minor local variations in the physical and chemical properties of the soil may affect the varieties of plant species to be found within these communities. Ferreira (1959) found that in the Cairngorms basiphilous plant species were encountered along fractures due to concentration of lime derived from some hornblendic rocks. The tree line on the Cairngorms is between 300 and 500 metres. Above 750 metres arctic-alpine stunted plant communities are encountered which include species of moss, heather and crowberry.

The "newer" granites

The "newer" granites are predominantly calc-alkaline rocks and according to Mercy(1965) 80% of their outcrop is in fact granodiorite or adamellite. Certainly they are not generally uniform bodies, and are commonly zoned from the outside towards the centre i.e. the youngest

members of the intrusive series are at the centres of the massifs. The Lochnagar granite has recently been the subject of a detailed study by Oldershaw(1974). He has shown that this body is a ring complex consisting of nine concentric and crescentic masses of adamellite and granodiorite. The later members of the suite have been intruded up through ring fractures resulting from cauldron subsidence. Harry(1965) has revealed that at the western end of the Cairngorms there are two main rock units. These consist of a "main granite" and a "porphyritic granite" of which the latter occupies the centre of the massif. The Foyers granite is also a differentiated intrusion with a succession of phases from tonalite - granodiorite - adamellite(Marston, 1971).

The mode of emplacement of the granites is variable, and there is the additional complication that they are now exposed at different structural levels. Roof phenomena(stoping) can be seen over parts of the Foyers and Glen Tilt intrusions. They are all however generally considered to be forceful intrusions, which according to Read(1961) solved the space problem by "shoving aside" their country rocks. Harry(1965) now regards the Cairngorms as a stock-like intrusion, whereas it was formerly considered to be a typical laccolith. Lochnagar, as outlined above, is an example of polyphase intrusion by cauldron subsidence in successive stages. The outer margins of the granites i.e. the earlier phases are often foliated. Contact with the country rocks is generally either sharp and transgressive or veined and sheeted.

Geological background and structure

The region is mainly underlain by late Precambrian/lower Palaeozoic paraschists of the Moinian and Dalradian assemblages. The older Moinian assemblage comprises a monotonous series of originally shallow water sediments, whilst the Dalradian rocks are more varied in composition. The two units were involved in the Caledonian orogeny and are now generally separated structurally by the north-east striking Iltay Boundary Slide(IBS). North-west of the IBS there is a "northern nappe zone" of Moinian rocks with north-west closing structures. South-east of the IBS the predominantly Dalradian rocks form the huge recumbent anticline of the Tay Nappe, which closes to the south-east.

There are three main groups of igneous rocks associated with the Caledonian orogeny(Johnstone, 1966) and the "newer" igneous rocks are the youngest of the three groups. The three groups are summarized below:-

1) <u>The older igneous rocks</u>(pre- or early-tectonic)

A few outcrops of basic rocks and some acid intrusions.

2) <u>Syntectonic migmatites</u>

Composite gneisses which developed during the main phases of folding and metamorphism.

3) <u>The "newer" igneous rocks</u>(late- to post-tectonic)

These include basic and acid plutonic, hypabyssal and volcanic rocks.

Structurally the "newer" granites and their minor intrusions were emplaced after the main phase of Caledonian folding, and in some cases they cross-cut major structures like the Iltay Boundary Slide. Most of the major faults and fractures of the region are probably related to the NNE-SSW sinistral wrench faults of the Great Glen system. Pitcher(1969) considered that the main phase of fault movements took place between the early and middle Devonian periods. Minor movements have taken place from time to time, notably during the Carboniferous, and in certain cases both the interiors and margins of the granites have been faulted.

4.6.2 Photointerpretation

Image quality

The remarkably sharp and clear imagery used for this study(LANDSAT-1 ID No. 1233-10564) was taken during a period of good atmospheric conditions in late winter. Cloud and considerable areas of snow cover affects parts of the scene, but the latter does not always hamper interpretation. Where the snow cover was thick then the underlying features are masked out, but where it was thin it has in many cases enhanced geological lineaments such as fractures and strike ridges. It is possible to detect features through a greater thickness of snow cover on MSS band 7(Fig. 4.12b) than on band 5(Fig. 4.12a). The result of this is that the two images show features not detectable on the other. So that the sum of interpreted features was much greater than if only a single band had been used for interpretation.

This winter scene has provided an excellent example of low sun angle imagery, as the sun

elevation was only 27°. The low angle of illumination produced strong dark shadows away from the sun azimuth(N 154° E) on the IR MSS bands. This has given the elevated parts of the region a remarkable three-dimensional appearance on the imagery. A comparison of this imagery with an MSS band 6 image taken in August during the summer(LANDSAT-1 ID No. 1035-10552) shows the latter to be distinctly inferior. The greater sun angle(39°), resulting in weaker shadows and the lack of enhancement of ridges by snow cover, has made this image much less useful for morphological interpretation.

Geomorphology and erodibility

The "Highland Peneplain" was composed of crystalline rocks of rather uniform hardness. Erosion of the peneplain by ice action and fluvial processes has on the whole not been very selective. This means that the granites do not necessarily form elevated ground. Large blocks like the Cairngorms do however show the characteristic rounded margins and steep sided valleys of a granitic massif. Another granite is elongated parallel to the major NNE-SSW regional fault direction, whilst many are almost submerged beneath a thick cover of glacial till. The latter are not differentiable from the enclosing metamorphics on the satellite imagery.

Drainage features

The most distinctive single granitic block in the region is the Cairngorms mountains. This is the second largest granite outcrop in the United Kingdom, with an area of over 400 sq. kms. A glance at a considerably enlarged LANDSAT image of this block(Fig. 4.13a) shows that geomorphologically it is not a uniform body. The western end of the massif has a rather smooth rounded appearance with a fairly coarse drainage texture. Its smooth rolling character can be



Fig.4.14a True colour photograph taken from ground based observation platform at the western end of the Cairngorms, showing smooth rolling topography

Fig.4.14b True colour ground photograph of the western end of the Cairngorms mountains, showing angular drainage channels



seen on the ground photographs Figs. 4.14a and b. Contrastingly the eastern end of the mass has a finer drainage texture and much thinner superficial cover. This variation in drainage density from east to west cannot easily be appreciated from the Ordnance Survey one inch map of the Cairngorms. This is because there has been a tendency on the part of the cartographer to keep the drainage density uniform.

Soil factors

Soils as mentioned in the introduction tend to be altitudinally zoned in Scotland. Strongly acidic soils form on the mountains whilst neutral to acid soils develop over glacial till of the lowlands. The latter being generally very fertile have been extensively cultivated, and can be clearly seen on MSS band 7 around the Moray Firth.

Vegetal features

Vegetation boundaries are best shown on MSS band 5, where the contrast between improved land and moorland is strongest. The cultivated land of the low lying areas is medium to light toned and contrasts strongly with the very dark tones of the heather moorland areas. Once again MSS band 7 shows the greatest detail of field patterns in the extensively cultivated areas, but the distinction between cultivated and moorland areas is not as strong as on band 5.

Tones

The granite outcrops are generally medium to dark toned on MSS band 7 and dark toned on MSS band 5. The dark tones are mainly due to the poorly reflective nature of the damp, peaty heather moorlands. Where coniferous forest is developed on the less mountainous slopes the tones are exceptionally dark on both MSS bands 5 and 7. A light covering of snow considerably

lightens the tones of parts of the area. This enables details of topography to be picked out in what would otherwise be almost black areas of the image. The lower relief granites covered by grasslands are generally medium toned on MSS band 7 and show more spectral variation than the mountainous granites. This is probably due to the greater variation in the composition of the superficial materials and the extent of land improvement.

Structural units

The region is bounded in the north-west by the Great Glen fault(1 on Fig. 4.12b) and Loch Ness. The structural grain of the Dalradian rocks in the north-east of the region also follows the NNE-SSW Great Glen trend. The Cairngorms granite in the centre stands out clearly on the imagery as the dominant morphological feature of the region. Fracturing of diverse trends has affected the rocks, but it is difficult to assess the relative ages of these faults as many have been active during more than one period. To the south of the Cairngorms the curvilinear suture of the Iltay Boundary Slide can be easily picked up.

Circular features

Two circular features about 4 kms. across can be seen on the imagery to the west of the centre of the Lochnagar granite at 1 on Fig. 4.13, and at the eastern end of the Cairngorms mass at 2 on Fig. 4.13. The former lies within the position of the known ring complex/cauldron subsidence feature described by Bailey(1960) and Oldershaw(1974), and may be related to it. The latter is as yet unexplained, but on the same image it can be seen to be at the centre of a much larger set of ring structures(see 3 on Fig. 4.13). Perhaps this is once again a

manifestation of polyphase intrusion similar to that of Lochnagar. The remote and inaccessible eastern end of this mountain block is certainly worthy of further ground investigation. It would now appear that the early interpretation of the Cairngorms as a simple laccolith should almost certainly be discarded, in the light of recent field work(Harry, 1965) and the evidence of the satellite imagery.

Lineaments

A number of prominent major faults show up on the LANDSAT imagery of the Grampian Highlands. A notable feature of these faults is that they are commonly marked by deep narrow cuts in the land surface. Six main categories of geological lineaments have been observed on the LANDSAT imagery of the region and these are described below:-

Lineaments of the Grampian Highlands

1) NNE-SSW trending major faults(Great Glen type)

These are very long straight faults which according to Johnstone(1966) are sinistral wrench faults. The Great Glen fault is the greatest of these and is presumed to have displaced the rocks on either side by over 100 kms. The other faults show lateral displacements in the field of up to about 8 kms.(Johnstone, 1966). These fault zones have been the loci of glacial excavation and appear as sharp, deep negative features in the highland topography. Examples of these faults in the study region are faults 1 and 2 on Fig. 4.12b.

2) ENE-WSW trending lineaments

This set of lineaments runs parallel to the trend of the valley of the river Dee, and they appear both as deeply cut valleys and as natural boundaries to major rock units. The latter includes the Dee valley itself(5 on Fig. 4.12b) which marks the southern boundary of the Cairngorms granitic mass. The northern and southern boundaries of the Insch basic mass in Aberdeenshire (9 on Fig. 4.11) also follow this trend. The southern boundary of the Insch mass is a well mapped zone of shearing with intrusive pods of ultrabasic rocks.

3) NNW-SSE trending lineaments

A few lineaments with this trend can be detected in the study region. This trend is the same as that of the Tertiary dyke swarms of the Highlands. These lineaments are not always deeply incised and detection of these may be aided by viewing the satellite image at low angles. MSS band 5 helps to pick out these lineaments where they lie along valleys, as these are light toned relative to the dark tones of the adjacent heather moorlands. One gently curving lineament of this group, 3 on Fig. 4.12a, can be traced intermittently for well over 100 kms. from near Montrose on the east coast to the Moray Firth.

4) Dalradian strike ridges

Within the main Dalradian outcrop zone a number of well marked strike ridges, like 4 on Fig. 4.12b, can be seen. These

represent the beds of more resistant members of the assemblage. Where these beds can be traced they commonly have a NNE-SSW strike.

Lineaments within the Cairngorms and Lochnagar granites

5) Cairngorms fracture pattern

The fracture pattern of the Cairngorms block does not really conform to the regional pattern outlined above. NE-SW fractures appear to be very strong and a number of deep valleys like the Lairig Ghru(4 on Fig. 4.13) traverse the massif from north to south; NE-SW and ENE-WSW fractures are of lesser importance. The N-S direction corresponds more or less to the direction of glacial striae mapped in the Cairngorms, and may in large part be simply of glacial origin.

6) Macro-jointing on the Cairngorms and Lochnagar

Two small areas of densely spaced fractures can be detected on the imagery at the eastern and southern margins of the Cairngorms and Lochnagar massifs respectively(5 and 6 on Fig. 4.13). These can be picked out on LANDSAT-1 image 1233-10564 because of an infilling of snow along these negative features which has enhanced their appearance. The fracture sets on Lochnagar are virtually orthogonal with NNW-SSE and NE-SW orientations. The Cairngorms macro-joints are at 60° to each other with a NE-SW set being the most prominent. This regular array of fractures on such a large scale suggests that they

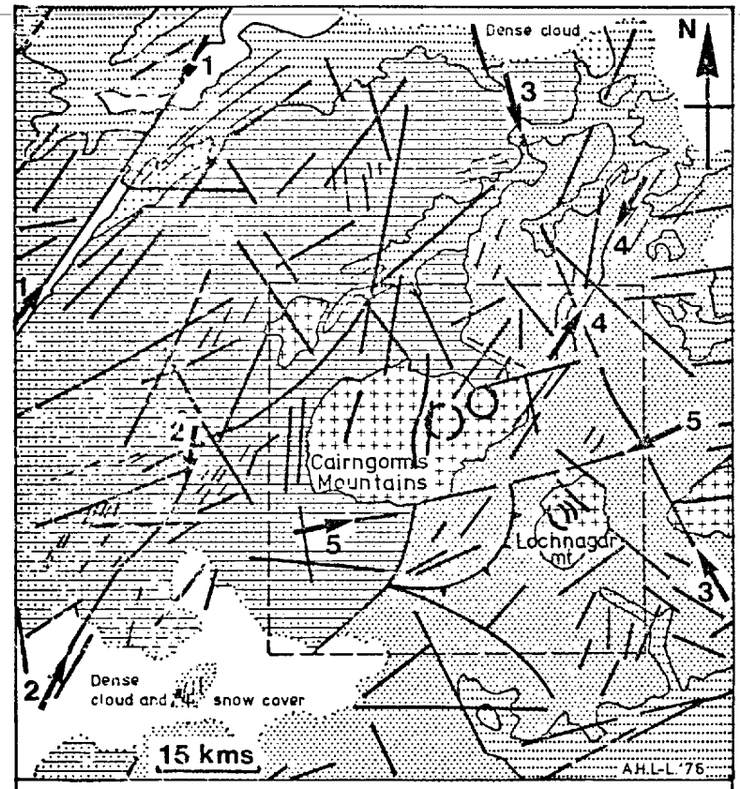
FIG 4.12



Fig.4.12a MSS band 5 of part of LANDSAT-1 scene 1233-10564 covering the north-east Grampian Highlands of Scotland. (Scale 1:1,000,000 approx).

Fig.4.12b MSS band 7 of part of LANDSAT-1 scene 1233-10564.





Legend

- Areas covered with thick glacial till
- Old Red Sandstone
- Predominantly Dalradian metasediments (with some intrusive rocks)
- Predominantly Moinian metasediments (with some intrusive rocks)
- "Newer" granites (Caledonian magmatism)
- Strike ridges of metasediments
- Fractures
- Circular structures within granites
- Iltay Boundary Slide
- 5 Numbers referred to in text
- Outline of Fig. 4.13

Fig.4.12c Photogeological outline of part of LANDSAT-1 scene 1233-10564 (figs. 4.12a and b). Location of the area shown on Fig. 4.11. (Scale 1:1,000,000 approx).

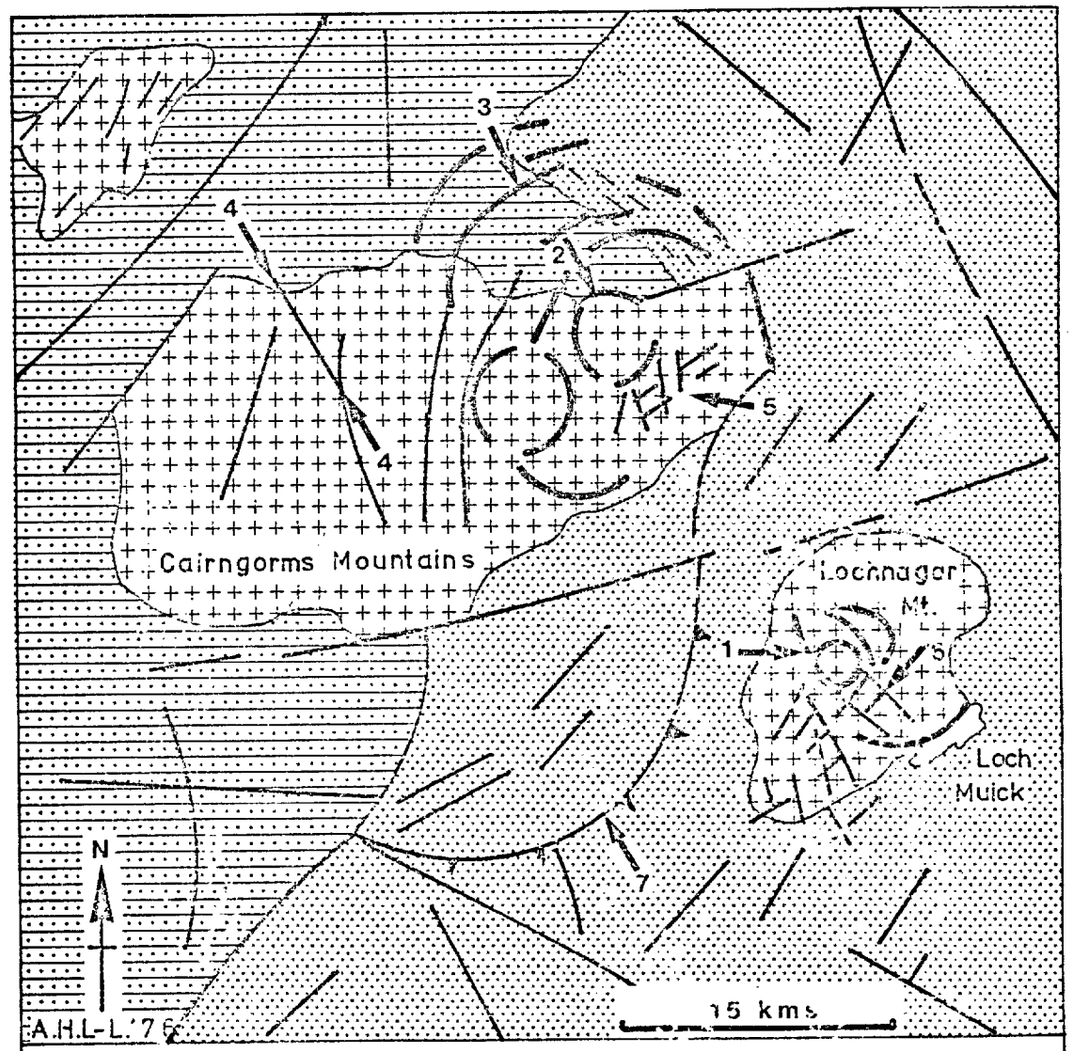
1-Great Glen fault, 2-Glen Markie fault, 3-major NNW-trending lineament, 4-strike ridge of Dalradian metasediments, 5-major lineament of the Dee river valley.

FIG. 4.13



Fig.4.13a MSS band 7 of part of LANDSAT-1 scene 1233-10564. An enlargement of part of the scene covering the Cairngorms mountains (Scale 1:350,000 approx).

1 and 2-circular structures within granite, 3-large diameter ring structure centred on the Cairngorms granite, 4-major fracture followed by the Lairig Ghru valley, 5 and 6-macro-joints within granite.



Legend

- Predominantly Dalradian metasediments
- Predominantly Moinian metasediments
- "Newer" granites (Caledonian magmatism)
- Strike ridges
- Fractures
- Circular structures related to emplacement of granitic intrusions
- Iltay Boundary Slide
- Numbers referred to in the text

Fig.4.13b Photogeological outline of Fig.4.13a. Location of the area is shown on Fig. 4.12c. (Scale 1:350,000 approx).

were formed in a homogeneous body under a very uniform stress field. Conditions for the formation of such fractures seem most likely to have occurred during the primary consolidation phase of the granitic magma.

Thrusts

Major thrusts like the Iltay Boundary Slide can be picked out on the imagery. The IBS is clearly shown by the valley of the Clunie Water at 7 on Fig. 4.13, just to the south of Braemar. The valley appears to have a steep south-east side and a less steep north-west side. This could be an indication of a south-eastwards retreat of the basal notch junction between the over-thrusted rocks and the foreland. However in other places, like just north of Braemar, the IBS is represented by a deep cut in the topography similar to the major faults of the region. Perhaps the real clue to its being a thrust rather than a normal or wrench fault is the sharp curveature of the Clunie section.

4.6.3 Usefulness of the imagery

General geology

The imagery studied provided a first class example of the value of low sun angle imagery for the interpretation of morphology. The advantage of thin snow cover for enhancing linear features was also well demonstrated by this late winter imagery. The imagery has also made a significant contribution to the study of the structure and mode of emplacement of the Cairngorms granitic mass. A summary of the main points of general geological interest obtained from this interpretation follows:-

1) The approximate outline of the Cairngorms mountain block could be discerned, but those granites of lower relief were difficult to distinguish on the imagery.

2) The enlarged image of the Cairngorms mass demonstrated by the variable drainage texture its structural and probable compositional heterogeneity.

3) Strong N-S fracture patterns were easily discerned on the Cairngorms mass.

4) The imagery showed conspicuous circular features on the Cairngorms and Lochnagar mountain blocks, which may indicate centres of intrusion. The former has not previously been recorded, to the writer's knowledge.

5) The imagery showed two areas of cross-hatched macro-joints on the Cairngorms and Lochnagar mountain blocks.

6) Most of the major faults of the region were identified on the imagery, and in addition some others not recorded on the 1:625,000 scale geological map were observed.

7) Parts of the Iltay Boundary Slide were clearly identified on the imagery.

8) The strike of Dalradian metasediments was observed in the north-east part of the region.

9) MSS band 5 distinguished most clearly improved land from heather moorland by the lighter tone of the improved land. In some cases light toned valleys indicated the presence of important fractures.

Economic geology

Dunham(1952) pointed out the general lack of base metal mineralization associated with the Caledonian granites, and considered that much of the Scottish mineralization was of Hercynian age. This opinion has subsequently been confirmed by radiometric age determinations carried out by a number of workers which include Moorbath (1962) and more recently Ineson and Mitchell(1974). Many of the lead-zinc mineralized veins follow the NNE-SSW trend of the Great Glen fault system, although the original date of the faulting is older than the age of the mineralization. Other mineral deposits are associated with multiple fracture directions. It may be therefore that the mineralization took place at weak points in the crust where later fracture sets intersected earlier formed ones.

An examination of the satellite imagery of the study region showed the presence of a major curvilinear lineament with a dominantly NNW-SSE trend of exceptional length(3 on Fig. 4.12). The existence of this rather faint lineament is substantiated by a magnetic anomaly on the 1:625,000 scale Aeromagnetic map of Britain. Further this lineament passes through the valley of the Gairn river where there is a reported lead-zinc vein with a NNW strike lying right on the path of the lineament. The age of this lineament is unknown but it has a similar trend to the Tertiary dyke swarms of the Highlands. It may be that this zone was initiated at an earlier date, and could perhaps be of Hercynian age or older. In the light of this evidence this zone deserves further investigation, along with certain lead and copper prospects known to exist in the vicinity of its northern end. The extent of this zone is shown on a lineament plot of the whole Grampian Highlands region(Fig.

6.3a). This plot also shows the location of the known mineral occurrences.

CHAPTER FIVE

THE GROUND FACTORS WHICH AFFECTED THE APPEARANCE OF ROCKS ON THE IMAGERY

5.1 General

Photogeological investigations are generally undertaken in order to examine general or specific aspects of the lithology and structure of the rocks of a given region. Interpretation is carried out by considering the relative importance and significance of the host of variable factors which have determined the appearance of the landscape. Some, but not all, of these factors will be mainly responsible for the all-important photo-characteristics of tone, texture and pattern observed on the photographic images.

The landforms encountered in any region are broadly the result of climatic activity and tectonic forces which have acted on the rocks of that region over a period of time. The topography is also controlled by the lithology and structure of the underlying rocks. The rocks themselves are generally covered by a mantle of weathered rock debris and soils, which in turn supports a varied vegetation cover.

Identification of lithology and interpretation of structure on conventional aerial photographs is done largely by geomorphological analysis of stereoscopic pairs of photographs. At the present time stereo-coverage of areas by satellite

imagery is rarely available(see Section 3.2). Monoscopic viewing of the imagery is therefore the normal method of investigation. Now although geomorphological interpretation is still of prime importance, the present writer recognises that landforms are not always easy to interpret non-stereoscopically. Therefore in satellite interpretation more use has to be made of indirect factors such as soils and vegetation cover for the elucidation of the geological features of the region.

A summary of the main factors responsible for the appearance of the present landscape is shown in Table 5.1. An explanation for the sub-title "Cainozoic" to the second column of the table, which is headed "Palaeo-events",

Table 5.1 Factors responsible for the appearance of the present landscape

Original rock characteristics	Palaeo-events (Cainozoic)	Present characteristics of rocks and environment
1. Chemical and mineralogical composition of the rocks	4. Climatic variations	9. Nature of climate
2. Lithological features	5. Alteration of the rocks by chemical and mechanical weathering	10. Composition of the weathered rocks
3. Structural features	6. The sculpting of the landscape by various erosion agents associated with different climates	11. Erodibility of the rocks
	7. Tectonic adjustments which have affected the rocks	12. Soil cover
	8. Deposition of alluvial, colluvial eluvial, glacial and duricrust deposits	13. Vegetation cover
		14. Land use and man-made landscape features

should be made at this point. Rates of erosion, even in a weakly erosive environment have been proved sufficient to reduce the level of land by hundreds of feet in relatively short periods of geological time. Holmes(1965) indicated that in southern Africa there is evidence to show that during the last 75 million years over 3,000 feet of Karroo sediments have been removed from above certain kimberlite pipes. Present rates of denudation may be even higher than this. However if a conservative estimate for the geological past of ten metres stripped every million years is considered, it becomes clear that very little of the present topography can be older than 60 or 70 million years. Thornbury(1954) went further to state in one of his "fundamental geomorphological concepts" that most of the present topography is no older than Pleistocene in age. Column two of Table 5.1 is therefore assumed to concern those events which have taken place during the time the rocks of the present landscape have been at or near the surface(i.e. at depths of metres rather than kilometres).

A careful study of Table 5.1 reveals that there are two principal categories of factors which affect the appearance of the landscape. Factors of the first category are related to the fundamental geological character of the rocks and the internal earth processes which have affected them. The second group, and no less important, comprise factors related to climate or change in climatic environment. Consequently the analysis which follows deals both with the geological nature of the rocks examined and also with those factors such as soils and vegetation which are largely the products of climatic influences. The interrelationships between these factors will be discussed in each section.

5.2 Rock Composition

Classification of plutonic rocks

The large sizes of the rock units investigated has meant that they usually contained a great variety of rock types. Classification of the rocks for this study has therefore been based more on tectonic considerations than on actual chemical compositions. The classification that has been adopted is essentially that of the magmatectonic groupings of Eskola(1932), i.e. synorogenic, late-orogenic and post-orogenic. Early-orogenic and eugeosynclinal magmatic rocks have not generally featured in the investigations. The reason being that the former commonly comprise ultrabasics and small amounts of more acid rocks but they are generally of very limited extent, and the latter group are mainly volcanics. Where possible the rocks have been classified on a more chemical basis by the use of Peacock's alkali-lime index classification(1931) e.g. the alkaline and calc-alkaline Burundian granites of eastern Zaire(Section 4.4).

Qualitative estimates of composition

The photogeologist examining satellite imagery with simple equipment must, for the time being, be content with strictly qualitative estimates of rock compositions. There are four main characteristics of the landscape which help in the interpretation of the nature of the underlying rocks of a given region and these are:-

1) Erodibility of the individual rock units.

2) Spatial characteristics of the landforms e.g. structural and drainage features

3) Soil cover

4) Vegetation

The spatial characteristics of landforms and the characteristics of soils and vegetation are commonly of fundamental importance in interpretation and are discussed in Sections 5.3, 5.5 and 5.6 respectively of this chapter. The erodibility, however, of individual rock units or the effects of differential erosion has long been regarded as the first guide to rock identification in photogeology(Miller, 1961). The relative resistance to erosion of the various rock types is commonly a prime factor controlling the topography of a region. Table 5.2 compares the erodibility of the individual rock units of the writer's investigations with the landforms which can be seen on the satellite imagery. The resultant landforms are not always solely dependent on rock composition but have sometimes been influenced by tectonic constraints. These aspects of morphogenesis are considered further in Sections 5.3 and 5.4. The erodibility of plutonic rocks is affected by a number of important parameters, which are now discussed below, and these are:-

1) The mineral content of the rock

2) Rock texture

3) Cohesion of the rock

4) The degree of chemical alteration of the rock minerals

5) The resistance of the chemically altered rock to further chemical and mechanical breakdown

6) The degree of fracturing of the rock

Table 5.2 Erodibility of plutonic(and associated) rocks and the resultant landforms which can be seen on LANDSAT imagery

Climate	Locality	Rock Types	Absolute age of Formation	Alteration of the rock	Erodibility	Landforms observed on LANDSAT imagery
1. Hot desert	Eastern Hoggar mountains Algeria	Alkaline granites	532-482 m.y.	-	Very easily eroded	Very low outcrops, areas of sheetwash deposits and one circular depression in gneiss outcrop
		Syntectonic and post-tectonic granites and granodiorites	650-500 m.y.	-	Granular disaggregation of these rocks appears to have taken place	Subdued forms, mainly flat areas of sheetwash deposits
		Diorites	650-500 m.y.	-	Moderately resistant to erosion	Steep hills and inselbergs
		Suggarian gneisses	2,000 m.y.	-	Resistant to erosion	Mountains, hills and strike ridges
2. Semi-arid	Shoshong-Mokware area Eastern Botswana	Shoshong doleritic sill and associated dykes	?1,950 m.y.	Slight due to low oxidation of ferromagnesian minerals	Highly resistant to erosion	Sill forms rugged tabular mass - dykes show as thin dark lines against light residual soils
		Mokware dioritic sill	?1,950 m.y.	Considerable oxidation of ferromagnesian minerals	Easily eroded and only preserved by flanking quartzites	Smooth, gently sloping hills
		Mahalapye granite	2,600-1,930 m.y.	-	Mainly easily eroded due to granular disaggregation	Peneplain of residual soils with occasional isolated inselbergs
3. Wet-and-dry tropical	Chenene hills area central Tanzania	Syntectonic granites, granitoid gneisses, nebulites and porphyritic granites	2,700 m.y.	-	Exposed rock hard and resistant, but much of area covered by residual granitic soils	Plains with inselbergs, hills and mountains (the latter the result of epeirogenic uplift)
		Greenschist inliers	?3,000 m.y.	-	Moderately resistand to erosion	Elongated low strike ridges surrounded by areas of lateritic soils
4. Wet tropical	S. Maniéma Eastern Zaire	Syn- to post-tectonic calc-alkaline granites	1,300-820 m.y.	Feldspars broken down to clay minerals	Very easily eroded	Low domal forms and irregular masses with fine dendritic drainage
		Rusizian gneisses	2,100-1,800 m.y.	Feldspars broken down to clay minerals	Very easily eroded	Form numerous small scarps parallel to strike direction
5. Mediterranean	N.E. Sardinia	Post-tectonic granites, granodiorites, diorites and gabbros	278 m.y.	Very little alteration	Resistant to erosion	Mountains, hills plateaux and circular features
6. Temperate	Grampian Highlands of Scotland	Late- to post-tectonic calc-alkaline granites, adamellites and granodiorites	400 m.y.	Some alteration of biotite	Moderately to strongly resistant to erosion	Mountains and hills with rounded margins and some circular features

Minerals and rock texture

The plutonic rocks are composed dominantly of silicate minerals, and these when exposed at or near the surface to the conditions of a temperate climate are reasonably stable and resistant to solution and chemical decomposition. The higher ground temperatures encountered in tropical environments however, often give rise to very rapid chemical breakdown of these minerals. The texture of plutonic rocks commonly varies with the size of the pluton, the larger ones which have cooled slowly having the coarsest grained rocks. Coarse grained granites tend to be more susceptible to weathering, but some porphyritic granites are resistant to weathering. It has also been reported that certain coarse grained granites in a temperate environment were more resistant to weathering by frost action than finer grained granites in the same area(Twidale,1971).

Cohesion

The cohesion of rocks is particularly dependent on the degree of chemical alteration of their mineral constituents. It is also controlled by the fabric of the rock i.e. texture(granular relations) and any foliation or cleavages in the rock. Foliated rocks do not necessarily disintegrate at a faster rate than more massive rocks. The Suggarian gneisses of the Hoggar mountains are a case in point(Section 4.1). The gneisses of that arid region form resistant massifs relative to the granites of the area which have largely been planated due to granular disaggregation of their minerals. Garner(1974) suggests that the reason for the relative resistance to erosion of gneisses compared with granites may be due to their fabric. Gneisses commonly have equidimensional mineral grains, which provide a strong physical bond between individual layers. Shearing of certain rocks

occasionally renders them into tougher units which resist erosion. The sheared rocks of the Dodoma hills at 4 on Fig. 4.6 stand out as positive elements of relief on the otherwise flat Dodoma plains.

Chemical weathering

Chemical weathering of the constituent minerals of plutonic rocks is commonly the most significant factor leading to their disintegration in warm climates. This chemical alteration of the rock takes place mainly by the process of hydrolysis - the action of ionised water. The process involves the replacement of metal cations in the silicate lattices by H^+ ions, whilst the ejected cations combine with OH^- ions to form soluble salts which are washed out of the system. Hydrolysis depends particularly on the pH of the groundwater and on ground temperature. It is at its most effective under the warm humid conditions of the wet tropical climate. Heavy leaching and breakdown of feldspars to soft clay minerals results in rapid planation of plutonic rocks in that environment. Ultimately all but the highly stable sesquioxide residues of iron and aluminium(laterite and bauxite) are removed from the system.[1] The Burundian granites of southern Maniéma in eastern Zaire(section 4.4) provide a good example of the effects of this type of weathering. These rocks are covered with a thick regolith of soils and rock waste which gives rise to the typically smooth topography of the region. The situation in temperate environments is rather different. Although ground-water levels are often at or near the surface the ground temperature is not usually high enough to encourage active chemical decomposition of igneous rocks. As a result they commonly form upstanding masses like the Sardinian batholith and the Cairngorms mountains.

1 Under permanently wet tropical conditions the sesquioxides do not bind together to form the laterite which would accumulate if alternate wet and dry conditions prevailed.

It has been found that the relative susceptibility of silicate minerals to alteration is approximately the same as their order of crystallisation from the original silicate melt. That is to say ferromagnesians and plagioclase alter first followed by orthoclase, muscovite and quartz. As a first approximation therefore it can be said that basic igneous rocks weather more rapidly than acid ones. However in practice this order is not always observed, and other factors come into consideration.

Biotite for example is theoretically less susceptible to chemical breakdown than hornblende, but it often weathers more rapidly. This is due to the generally large surface area of biotite grains and to the fact that they are commonly found to be highly fractured. This is probably the main reason for the early disaggregation of many granitic rocks, especially under the extreme conditions of an arid or semi-arid erosional environment. The granitic rocks of the Hoggar mountains(Section 4.1) appear to be an example of the phenomenon of granular disaggregation. In that area even the alkaline granites(traditionally low in ferromagnesians and therefore resistant to chemical weathering) have been eroded away relative to the adjacent gneisses. The appearance of "windows" of sandy deposits within the areas of gneiss outcrops may indicate an underlying granite pluton (e.g. the large sandy area to the north-west of the fold axis 6 on Fig. 4.2).

Alteration of plutonic rocks need not necessarily lead to the rapid destruction of the rock mass, although this is often the case. The Shoshong dolerite and the Mokware diorite(Section 4.2) provide examples of two rock types of fairly

similar chemical composition which have been affected by different degrees of chemical alteration under the same climatic conditions. The Shoshong dolerite forms a relatively unaltered upstanding block due to the low state of oxidation of the ferromagnesian minerals. Oxidation of these minerals has been arrested by the formation of an expanded montmorillonite mineral which has prevented further decomposition. The Mokware diorite on the other hand has been considerably altered and denuded and the remnants of the sill are now only preserved by two resistant flanking quartzite beds.

Fracturing

The presence of numerous fractures in intrusive rocks facilitates the penetration of groundwater and the denudation of these bodies by solution and mechanical agents of erosion. These fractures are mainly related to vertical stresses induced by intrusion, tectonic uplift and the release of pressure due to the removal of overlying rocks.

5.3. Structure

5.3.1 The tectonic classification of plutonic rocks

In recent years three important factors relating to the genesis of the "granitic" rocks have become widely accepted and the tectonic classification of plutonic rocks now adopted hinges on these concepts which are:-

1) The majority of "granitic" rocks have been derived from the melting of pre-existing rocks in the upper crust at depths of 10 to 20 kms. by the process of palingenesis.

2) The type of pluton formed depends on depth of emplacement, and three main categories have been established based on increasing depth - epizonal, mesozonal and catazonal plutons(Grubenmann, 1904 and Buddington, 1959).

3) The type of pluton formed depends on time in relation to orogenic development.

Plutons of the epizone and mesozone have been emplaced by upward migration of magma from the catazone. The most important characteristics of plutonic rocks related to the different depth zones, some of which can be seen on satellite imagery, are outlined briefly in Table 5.3. This table also shows where the various plutonic masses of the writer's investigations fit into the classification. The concept of time and orogeny with respect to the emplacement of plutonic bodies has been embodied in Eskola's magmatectonic classification mentioned in Section 5.2.

Table 5.3 Tectonic classification of plutonic rocks according to depth of emplacement and orogenic movements (after Badgley, 1965)

Epizonal plutons 0 - 9.7 kms. (0 - 6 miles)	Mesozonal plutons 6.5 - 16.9 kms. (4 - 10 miles)	Catazonal plutons 9.7 - 19.3 kms. (6 - 12 miles)
Late to post-tectonic permissive intrusions, frequently with discordant margins e.g. stocks, laccoliths, sills and ring complexes	Late-tectonic forceful intrusions or intrusions formed by magmatic stoping. Usually have sharp contacts with country rocks and development of thermal or regional metamorphism e.g. stocks and batholiths	Syntectonic masses of variable composition with concordant margins. Commonly show signs of post-consolidation deformation e.g. cratonic batholiths and gneiss domes
Case Study Rocks		
1) Alkaline granites of the Hoggar Mts.	1) Sardinian batholith	1) Granite/granodioritic rocks of the Hoggar Mts.
2) Shoshong and Mokware basic sills of E. Botswana	2) Caledonian granites of the Grampian Highlands of Scotland	2) Cratonic batholith of Central Tanzania 3) Burundian granites of E. Zaire

The structural features of plutonic rocks observed on the satellite imagery have been described in the next two sub-sections considering firstly their "genetic" and secondly their "deformational" characteristics. This sub-division has been used for convenience of description and should not be regarded as a rigid classification of the observed features. Genetic and deformational should not be taken as synonymous with the "primary" and "secondary" structures of igneous rocks proposed by Hans Cloos and elaborated by Balk (1937). Balk's primary structures of the "flow stage" were not observed on the imagery and in only one case could fractures which might belong to the so-called "solid stage" be identified(see page 139). Recent work on the rheology of

granites(Pitcher and Berger, 1970) suggest that the primary/secondary division may be an over-simplified classification of the observed structures of plutonic masses. Evidence from model studies on diapiric intrusions, microscopic and field work now suggests that many granites were emplaced in what can only be regarded as a "solid" state, and that their ductility was little different from the country rocks into which they were intruded.

Many of the structural features observed on the imagery are of considerable magnitude and on the basis of scale should perhaps be described as tectonic rather than structural. However since the adjectives structural and tectonic are still ill-defined in geology the writer has frequently used the term structural as being synonymous with tectonic. Table 5.4 summarizes much of the structural data obtained from the satellite imagery of the case study regions.

5.3.2 Genetic characteristics of plutonic rocks

Tectonic control of emplacement

Our present knowledge of earth history has brought us to a realisation that the behaviour of the earth's crust has been changing throughout geological time(Sutton, 1963). It appears however that the crust has always been characterised by zones of instability. During the early Archaean there was widespread instability of the hot, mobile primitive crust, and present day evidence shows that there were few zones stable enough to allow deposition of supracrustal sediments. However towards the end of the Archaean there was definite stabilisation of large parts of the crust, though these were separated by zones of great instability(mobile zones). The presence of these zones of

Table 5.4 The structural characteristics of plutonic rocks which can be seen on LANDSAT imagery

Rock Type	GENETIC CHARACTERISTICS				DEFORMATIONAL CHARACTERISTICS		
	Magmatectonic group and form	Tectonic control of emplacement	Shape and attitude of masses	Special Features	Lineaments	Epeirogenic and orogenic features	Morphotectonic units
Alkaline granites of the Hoggar mountains	Post-tectonic stocks and batholiths	Major N-S abyssal faults	Usually rounded sometimes circular	These may be roots of volcanic centres	Affected by N-S NE-SW and NW-SE regional faults	-	-
Granites and granodiorites of the Hoggar mountains	Syn- and post-tectonic batholiths	Partly controlled by major N-S faults	Irregular with poorly defined margins	Poorly exposed due to granular disaggregation	Affected by N-S, NE-SW and NW-SE regional faults	Major block faulting dominantly controlled by N-S faults	1) Western unit of gneisses 2) Eastern ign. met. complex
Diorites of the Hoggar mountains	Syn- and post-tectonic masses	-	Small fault-bounded blocks	-	Affected by N-S NE-SW and NW-SE regional faults	Commonly observed as fault bounded blocks	-
Shoshong dolerites of Eastern Botswana	Post-tectonic sills and dykes	Sills and dykes emplaced along WNW-ESE lineaments	Shoshong sill forms gently dipping mass	Sill is highly fractured and forms rounded outcrops	NW-SE regional lineaments	-	-
Mokware diorite of Eastern Botswana	Post-tectonic sill	-	Crescentic gently dipping mass	Interbedded with quartzites	ENE-WSW regional lineaments	-	-
Granites, granitoid gneisses, nebulites and porphyritic granites of Central Tanzania	Syntectonic cratonic batholith	-	Eastern margin of batholith has rounded shape	Inliers of greenstone rocks	1) WNW-ESE and ENE-WSW shear zones 2) NNW-SSE shield disjunction zone	Block faulting of the region along NW-SE and NE-SW faults	1) The Chenene Hills forms a tilted horst block 2) Plains with inselbergs
Calc-alkaline granites of Eastern Zaire	Syn- and post-tectonic batholiths	-	Low domes and irregular masses with rounded margins	-	Few major lineaments seen. One granite has NW-SE lineaments (?shear zones)	-	-
Granite/granodioritic rocks of N.E. Sardinia	Post-tectonic batholith	N-S elongation of batholith controlled by ancient crustal features	Indistinct boundaries with adjacent rocks	Batholith is a multiple intrusion with many circular intrusive centres	1) NE-SW Tertiary rift faults 2) NNE-SSW faults in north 3) NNW-SSE faults in south	Batholith is divided into three morphotectonic units by two NE-SW Tertiary rift faults	1) Fractured uplifted northern block 2) Central block with plateaux 3) Southern block
Calc-alkaline granites, adamellites and granodiorites of the Grampian Highlands of Scotland	Late- to post-tectonic stocks and batholiths	Controlled by NNE-SSW wrench faults and possibly also by ENE-WSW fractures	Circular intrusions and masses with rounded margins. Some elongated along faults	1) Ring fractures 2) Cross-hatched "primary" macro-joints	1) Major NNE-SSW wrench faults 2) ENE-WSW ?abyssal faults 3) NNW-SSE lineaments	-	-

instability has persisted up to the present time as one of the remarkable behavioural characteristics of the earth's crust. Khain and Muratov(1969) suggested that the reason for these zones of instability is that the earth's crust is subjected to periodic movements, which are probably related to disturbances within the mantle. During the late-Archaean (ca. 2,500 m.y.) these movements caused the first rigid crust to be cut up into blocks separated by deep abyssal faults which penetrated the entire crust and part of the upper mantle[1]. Many of these faults have probably survived to the present day as zones of weakness in the crust. They have in some cases been extended and intersected by other major faults, produced by subsequent tectonic disturbances probably related to plate movements of the continental masses.

We know that many dykes, ring complexes and diatremes were emplaced along or at the intersection of fractures in the crust. The present writer considers that deep-seated fractures may have controlled the emplacement of many larger intrusive masses. The elongated disposition of the Glen Roy Caledonian granite, 6 on Fig. 4.11, was almost certainly controlled by a major fracture. The N-S meridional faults and to some extent the major NE-SW faults of the eastern Hoggar mountains have exercised structural control on the emplacement of the late-Precambrian granites of that region. Indeed the N-S meridional faults of the Hoggar massif

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1 Khain and Muratov were probably referring to the tectonosphere which comprises the tectonically significant outer layers of the earth (it includes the crust and upper mantle down to a depth of about 400 kms.).

have been of great significance throughout the Phanerozoic. They extend far to the south into the Air mountains and Nigeria, where they almost certainly affected the emplacement of the Jurassic tin-bearing alkaline granites of the Jos plateau[1].

Less obvious fracture control of pluton emplacement is shown by the dominant N-S elongation of the Sardinian batholith. There is some evidence to suggest that this may be related to a plate boundary collision(Ghezzo et al. 1972). Hint of an ENE-WSW fracture control of the disposition of the Cairngorms granite (Section 4.6) is given by a set of lineaments on the satellite imagery with that trend. The most important of these lineaments lies along the valley of the river Dee(5 on Fig. 4.12b), whilst another coincides with the southern dislocated margin of the Insch basic mass(9 on Fig. 4.11).

Evidence for fracture control of epizonal and mesozonal plutons therefore appears to be not entirely lacking, but what of the granites of the deeper catazone? It is unlikely in this highly mobile setting that individual fractures or even groups of fractures controlled pluton emplacement. The Burundian granites of eastern Zaire(Section 4.4) are products of the catazone, and in this case a huge part of the basement was sufficiently remobilised to move bodily upwards to form steep walled domes.

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1 Chukwu-Ike(personal communication) has in fact observed on LANDSAT imagery of the Jos plateau region a major meridional lineament passing through a group of alkaline granite intrusions which are aligned in a N-S direction.

Hickman(1974) proposed an interesting model to explain the disposition of the mantled granitic domes of the Pilbara craton of western Australia. It seems to the present writer that Hickman's model might usefully be applied to explain the structure of the Tanzania craton. Evidence of doming is not obvious in the latter case but the presence of supracrustal greenschist inliers is similar to the Pilbara craton. According to Hickman's model the rafts and xenoliths of supracrustal greenschists(Dodoman formation) in the Dodoma area of the batholith are the only remaining indicators of presumed intradomal regions. The lack of large tracts of supracrustal rocks in the Dodoma area suggests that the granite is exposed at a deep structural level, and the originally highly mobile granite has invaded and assimilated much of the former greenschist supracrustal rocks. Contrastingly the granite of northern Tanzania is probably exposed at a higher structural level, as large synclinal keels of supracrustal greenschists (Nyanzian formation) have been preserved as triangular areas within the granite craton.

Shape and attitude of plutons

The salient points to emerge from the research regarding the shape and attitude of plutonic masses are as follows:-

1) Most of the plutonic bodies have rounded margins.

2) Some of the plutons are elongated parallel to major faults.

3) Some of the plutons are bounded by faults.

4) Generally only epizonal plutons have sharp clearly defined boundaries on satellite imagery.

Point 4 deserves further consideration. It might be assumed that the reason for this is that many epizonal plutons are relatively young geologically. Although this is an important factor in many cases it is not the whole answer. The main reason for the sharp boundaries in the present writer's opinion is that epizonal plutons have sharp contacts with the country rock and have not affected the latter to any great extent either thermally or dynamically. This commonly results in strongly contrasting topographic levels for the intrusion and country rock based on differential erosion. Examples of this are the circular depression indicating the position of the Adrar Tiguluras alkaline granite in the Hoggar mountains(point 1 Fig. 4.2) and the up-standing tabular mass of the Shoshong dolerite in Eastern Botswana(Fig. 4.4).

Mesozonal plutons also commonly have sharp contacts in the field, but they do affect the adjacent rocks for some distance from the pluton margin. Thermal metamorphism may produce hornfelsing of the country rock for variable distances from pluton margins. Again hydrothermal alteration of the margin of the pluton and its envelope may produce an irregular zone of altered rock. Cataclastic effects due to forceful intrusion will cause fracturing of the country rock. These effects all tend to extend the influence of the pluton on topography beyond its actual margin. Because the country rocks are not necessarily homogeneous they may react differentially to these influences thus producing an aureole of very variable extent and physical properties. What appears as the mappable unit on the satellite image is not the actual pluton itself but a mass which includes the pluton and part of its envelope. The boundary of such a unit is generally obscure and

is related to the effect of some or all of the contact phenomena described above on the country rock.

Composite intrusions

The research has emphasized that many batholiths are composite intrusions, and that many have been formed from the coalescence of magma emanating from a number of separate intrusive centres. Evidence of multiple intrusion can be gained directly from a study of the satellite imagery in many cases. It is however generally difficult to detect compositional differences between the various rock types within a single batholith. The presence of a number of circular features within the main mass of the Sardinian batholith(Fig. 4.10) clearly testifies to individual intrusive centres. Similarly circular features on the LANDSAT imagery of the Cairngorms mountain block(Fig. 4.13) indicates that this can no longer be described as a simple laccolith, as suggested early on by Barrow et al.(1913). Even Harry's(1965) interpretation that the Cairngorms appears to be a discordant stock-like intrusion may be too simple. The satellite imagery suggests that three or more distinct intrusions were involved in the formation of the whole batholith. Work by Oldershaw(1974) on the Lochnagar granite certainly seems to suggest that the emplacement history of these Caledonian granites was very complex.

"Primary" fractures

The association of three mutually perpendicular sets of joints in granitic intrusions related to vertical stress was first recognised by Cloos. There are commonly two vertical sets which he termed cross joints and longitudinal joints. The former being at 90° to the flow lineation of the granite and the latter parallel to it.

These in turn are commonly intersected by a third near-horizontal set which Cloos called primary flat joints. Evidence of the presence of two intersecting joint sets is clearly visible on the satellite imagery of the Cairngorms area due to an accident of weather, as depicted on the late-winter scene examined. These can be seen at points 5 and 6 on Fig. 4.13, where an infilling of snow picks out two areas of regularly spaced macro-joints. Whether these represent primary cross joints and longitudinal joints is a matter for conjecture, but their even close spacing is quite unlike any fracture patterns the present writer has seen on satellite imagery of areas of regionally metamorphosed schists and gneisses.

Inliers

Variations in composition within plutons are not generally easy to detect on LANDSAT imagery, unless they are represented by strong differences in soil type and vegetation and/or topography. However one feature which does show up well on the imagery are the greenstone[1] inliers within Archaean cratonic granites like the Tanzania craton(see point 9 on Fig. 4.6). Viljoen and Viljoen(1973) have also examined the distribution of similar greenstone inliers on LANDSAT imagery of southern Rhodesia, where they have been able to define the limits of a granite-greenstone "geotectonic domain" relative to the Limpopo mobile belt. These granite-greenstone provinces have elicited considerable interest in recent years, and LANDSAT imagery appears to be an ideal tool for mapping their distribution. In view of their commonly sheared margins and association with gold mineralisation the distribution of these greenstone inliers is of considerable economic interest(see also Section 7.2).

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1 Originally a field term to describe slightly altered basic igneous rocks, now used to describe belts of basic low grade supracrustal schists found within the Archaean cratons.

5.3.3 Deformational characteristics of plutonic rocks

Lineaments

The appearance on LANDSAT imagery of numerous linear features, many of which are of geological significance, is probably the most important contribution of the imagery to the field of geological mapping and tectonic analysis. Many of these lineaments are of considerable length, up to hundreds of kilometres long, and a great number have not previously been recorded either by ground mapping or from aerial photographs. The extent of some of these major lineaments suggests that they represent deep-seated zones of disjunction within the crust and it would appear that there is commonly a direct relationship between their length and depth. Makarov et al.(1974) working on LANDSAT imagery proposed as a general rule that "as the degree of generalization of an image increases(i.e. as the scale becomes smaller), structural elements of ever deeper levels appear".

The present writer has been able to distinguish four main orders of lineaments on LANDSAT imagery based on a study of the maximum lengths of lineaments from 23 groups of these features. The four orders are shown in Table 5.5 with examples of each category taken from the writer's case study regions. The length limits of each category are not intended to be precise and overlap may occur in different regions. However genetically the four orders appear to have some significance.

The longest lineaments designated geotectonic lineaments, represent major global fractures extending up to hundreds of kilometres in length. Outstanding examples of these lineaments are the main branches of the East African Rift System,

Table 5.5 The orders of lineament lengths observed on LANDSAT imagery with examples from the case study regions of the writer's investigations

Lineament category	Length limits	Examples from the case study regions
1. Geotectonic lineaments	>150 kms.	1. NNE-SSW sinistral wrench fault of the Great Glen Scotland. 2. N-W 8°30' meridional fault of the eastern Hoggar mountains Algeria
2. Major regional lineaments	80-150 kms.	1. NE-SW Tertiary rift faults of N.E. Sardinia 2. NW-SE fault line scarp of the Chenene mountains Tanzania
3. Regional lineaments	20-80 kms	1. ENE-WSW lineaments of the Grampian Highlands of Scotland 2. NE-SW and WNW-ESE faults shear zones and dykes of the Shoshong-Mokware region eastern Botswana
4. Local tectonic lineaments	<20 kms.	1. NE-SW and NW-SE macro-joints of the Cairngorms granite Scotland 2. NNE-SSW minor lineaments of the Sardinian batholith

the Red Sea Rift and the San Andreas strike-slip fault. Major regional lineaments, often directly related to the geotectonic lineaments, include fractures such as the subsidiary branches of the East African Rift System and the ancillary sinistral wrench faults of the Great Glen fault system of Scotland. Both geotectonic and major regional lineaments can be classed as planetary or global lineaments. These abyssal fractures generally penetrate far into the crust and probably affect parts of the upper mantle. An important characteristic of these lineaments

is that they are commonly associated with considerable vertical and/or horizontal displacements of rock masses.

Umbgrove in his book "Pulse of the Earth"(1947) concluded that the earth was cut by two sets of major fractures orientated along the cardinal directions and their bisectors i.e. N-S, E-W, NE-SW and NW-SE. V.E. Khain later proposed that the two systems of planetary lineaments should be referred to as orthogonal and diagonal lineaments. This proposal has been extensively studied by Katterfeld and Charushin(1973) who carried out statistical studies on 250,000 lineaments of the Earth, Mars and the Moon. These studies confirmed that there are four prominent major lineament trends formed on the earth which can be grouped into two genetic systems which are:-

1) A N-S and E-W orthogonal system of lineaments resulting from tensional and compressive stresses.

2) A NE-SW and NW-SE diagonal system of lineaments resulting from shear stresses.

Deformation of experimental models shows that the orientation of linear fractures developed on a rotating spherical shell conform more or less to these four directions. Similar deformation of the earth's lithosphere could have been caused by a change in the planet's shape or in its rotation rate. Alternatively the lineaments may be the result of internal processes within the mantle such as local disturbance or convection currents. Whatever the cause it seems almost certain that they were formed by forces generated outside the crust itself.

Table 5.6 Examples of planetary lineaments (between 80 and 600 kms long) observed on LANDSAT imagery of the case study regions

Orientation	Description*
1. NNE-SSW	Sinistral wrench faults of the Great Glen fault system Scotland
2. N-S	Meridional faults of the Hoggar mountains Algeria
3. NNW-SSE	Curvilinear lineament traversing the Grampian Highlands of Scotland from the N.E. coast to the Moray Firth
4. NW-SE	Major crustal fracture followed by the course of the Lualaba river E.Zaire
5. NE-SW and NW-SE	Major faults of the eastern Hoggar mountains Algeria
6. NNW-SSE	Major zone of disjunction along the eastern margin of the Tanzania batholith
7. NE-SW	Tertiary rift faults of N.E. Sardinia

* Lineaments are listed approximately in order of decreasing length

Regional lineaments are generally much shorter than planetary lineaments, although they may still be related to the same stress systems which produced the latter. The straight NE-SW regional faults of Neogene age in the Dodoma region(section 4.3) of central Tanzania are generally less than 50 kms. long, but they belong to the geotectonic stress field of the East African Rift System. Like planetary fractures regional fractures commonly cut across a number of different formations, but the vertical and horizontal displacements of the rocks intersected by these faults can be measured in hundreds rather than thousands of metres. Some regional faults are deep enough to have partly controlled the emplacement of mesozonal plutons as discussed in Section 5.3.2.

However relatively minor tectonic adjustments within discrete blocks of the lithosphere are responsible for most regional lineaments, compared with the major movements of crustal blocks and plates associated with the abyssal planetary fractures. Table 5.7 gives examples of the regional lineaments which were encountered in the writer's case study regions.

Table 5.7 Examples of regional lineaments (between 20 and 80 kms. long) observed on LANDSAT imagery of the case study regions

Orientation	Description*
1. ENE-WSW	Major fractures associated with the NNE-SSW wrench faults of Grampian Highlands
2. NE-SW and NW-SE	Faults, shear zones and dykes of the Shoshong-Mokware area eastern Botswana
3. NE-SW	Neogene faulting of central Tanzania (subsidiary faults of the East African Rift System)
4. ENE-WSW	Major fracture traversing the Gallura region of northern Sardinia
5. NW-SE	Major fractures cutting across the northern part of the Sardinian batholith

* Lineaments are listed approximately in order of decreasing length

Local tectonic lineaments are the shortest structures which appear as significant linear features on satellite imagery. The origin of these features is diverse and their orientation is much more variable than that of regional lineaments. Indeed they often show little agreement with the trend of regional lineaments. These lineaments together with numerous shorter linear features make up the bulk of the raw data used for regional fracture trace studies carried out by photogeologists on conventional aerial photography. The

larger faults commonly observed in sedimentary rocks belong to this category of lineaments. Such faults, unless directly related to underlying basement structure, are rarely longer than about 15 kms. Almost all the faults marked on the 1 inch to 1 mile Geological map

Table 5.8 Examples of local tectonic lineaments (< 20 kms. long) observed on LANDSAT imagery of the case study regions

Orientation	Description*
1. NE-SW NW-SE and NNE-SSW	Large fractures transecting the Shoshong dolerite eastern Botswana
2. NE-SW	Fractures up to 20 kms. long within the outcrop of the Sardinian batholith
3. ENE-WSW	Shear zones within the Tanzania craton
4. NE-SW and N-S	Fractures up to 13 kms long within the Cairngorms granite
5. NNE-SSW	Minor fractures of the Sardinian batholith
6. WNW-ESE	Shear zones parallel to the Dodoman greenschist inliers within the Tanzania craton
7. NNE-SSW	Strike ridges of Dalradian metasediments of N.E. Scotland
8. NW-SE	Strike ridges of Rusizian gneisses in eastern Zaire
9. NW-SE	?Shear zones within the Burundian granites of southern Maniéma eastern Zaire
10. NNW-SSE and NE-SW	Macro-joints within the Cairngorms granite Scotland
11. WNW-ESE	Strike ridges of Usagaran metasediments in the Kiboriani mountains central Tanzania

* Lineaments are listed approximately in order of decreasing length

sheets of south-eastern England were found by the writer to belong to this group. Bott(1971) implies that in the case of sedimentary rocks such faults are the result of passive deformation of the sedimentary cover which has adjusted to accommodate movements in the stronger underlying basement rocks. Local tectonic lineaments related to plutonic rocks include "primary" post-consolidation macro-joints, post-consolidation shear zones and shear zones resulting from the updoming of gneiss domes. Many of these lineaments represent the results of pervasive fracturing rather than discrete faults. Table 5.8 shows the main groups of local tectonic lineaments encountered in the case study regions.

Epeirogenic and orogenic features

The plutonic rocks investigated mainly acted as rigid blocks during phases of post-consolidation diastrophism. Consequently the most significant structural features affecting the plutonic rocks, which can be observed on satellite imagery, are related to fracturing of the rocks. Folding of the country rocks adjacent to intrusions is a familiar feature of lensoid diapiric plutons and mantled gneiss domes, but such features are mainly related to initial intrusion. The post-consolidation deformational phenomena associated with plutonic rocks, which were observed on the imagery, included examples of block-faulting, strike-slip faulting, zones of fracturing, zones of shearing and major thrust zones.

Block-faulting

Block-faulting, resulting mainly from vertical movements, appears to be an important factor affecting extensive regions of the crust. Large batholiths such as the Tanzania craton and the Sardinian batholith are themselves cut up into fault-bounded blocks by major faults. These fault systems include both planetary and regional

fractures. Many of these faults are of relatively young geological age(Tertiary to Recent) and in Russia a study of these fractures has resulted in a new branch of tectonics called "neotectonics". Undoubtedly such fractures have not necessarily been confined to the most recent geological era as shown by the major N-S faulting of the Hoggar mountains, which was initiated as far back as the Cambrian or even earlier. However geomorphologically it is the young faults(or the most recently reactivated faults) which are of greatest significance, as they have played an important part in the formation of the present landscape. Uplifted blocks of country often show signs of heavy dissection by rivers and provide the photogeologist with a detailed exposition of the texture and structure of the underlying rocks. Such regions are particularly suitable for fracture trace analysis studies. Study of the major faults may also be of importance indirectly in mineral exploration planning, as they sometimes expose individual parts of plutonic bodies at different structural levels, as in the case of the Sardinian batholith.

Strike-slip faulting

The Highlands of Scotland provides a classic region for the study of rocks affected by strike-slip faulting. The region is characterized by a rhombic system of fractures of Caledonian age. The two fracture sets comprise the major NNE-SSW wrench faults of the Great Glen fault system and a set of shorter but persistent regional ENE-WSW lineaments. This fracture system extends right across the Highlands and can even be picked up on the satellite imagery through a cover of thick glacial deposits in N.E. Scotland. Auden(1954) appreciated the vast scale of this network and he was able to show that many of these faults and fractures follow recognizable topographic features. It therefore seemed logical to the writer to

extend Auden's work on north-west Scotland to cover the whole of the Grampians as well. This was done by mapping in all the major lineaments, most of which are controlled by topographic features, shown on the satellite imagery of the region(see Fig. 6.3a). Evidence for sinistral movements along the Great Glen Fault system can be obtained from two sources on the satellite imagery which are:-

1) There appears to be a southwards deflection of the strike of the Old Red Sandstone rocks to the east of the Great Glen fault in the Inverness area(see Fig. 6.3a).

2) A number of more north-easterly feathering fractures tail off both the Great Glen fault and some of the other wrench faults e.g. the fracture following Glen Moriston to the west of the Great Glen fault, and the Laggan fault which is related to the larger Glen Markie fault(see Fig. 6.3a).

Fracture zones

In most areas of well exposed crystalline rocks one is nearly always aware of numerous fractures and shatter planes which intersect the outcrop. Whilst the writer was working for an open-cast mining company in west Africa, frequent visits to the mining cuts revealed that the basement rocks(Birrimian pelites) were cut by a number of shatter belts. These belts had a very persistent ENE-WSW strike and were depicted by stringers of quartz veins and heavily jointed rocks. These belts represented tensional and compressive features and the quartz veins were probably related to a late-magmatic phase of the nearby Winneba granite. The fact that such pervasive structures do not indicate either horizontal or vertical displacements of the rocks has meant that in the

past they have been virtually unrecognised during regional geological mapping projects. Satellite imagery has made it abundantly clear that there are a large number of major fractures which show no signs of having displaced the rocks on either side. Nevertheless it is becoming clear that a study of such fractures is essential to the wider understanding of the palaeo-stress systems which have affected the rocks of individual areas.

Shear zones

Deformation of brittle rocks such as granite commonly results in the formation of fracture and shear zones within plutons. The Tanzania craton has been affected by such deformation and it is traversed by zones of granulation and shearing. The zones of granulation generally result in negative features on the land surface, whilst the sheared rocks are sometimes harder and more resistant to weathering than the unsheared granite. This has given rise to lines of hills which are clearly identifiable on the satellite imagery. The shear zones are of importance in the prospecting of gold which may be found in tensional quartz veins associated with large shear zones, as at Madengi hill near Dodoma(Section 4.3.3 and Fig. 4.6b).

Thrust zones

Thrust zones are not easily identified on satellite imagery without prior knowledge of their existence. However part of the Iltay Boundary Slide of the Grampian Highlands which separates Moinian rocks from the Dalradian sequence can be clearly seen on the imagery at point 7 on Fig. 4.13.

Morpho-tectonic units

Regions of basement rocks are generally characterized by landforms which are the result of diastrophism. Many of these landforms are what

the geomorphologist would refer to as "structural" landforms i.e. they have developed by erosion of the original structure of the rock mass. Such landforms include arcuate fold belts, circular igneous intrusions and gently dipping sills such as the Shoshong dolerite. The study of groups of such landforms leads one on to the wider field of "morphotectonics" which includes the study of both the external form and internal structure of major topographic units(Hills, 1961).

The synoptic views of the earth's surface provided by satellite imagery have in certain regions revealed large-scale tectonic units with a characteristic morphological and tectonic style. These units have been termed "morphotectonic units" by the present writer. Individual morphotectonic units may include numerous structural landforms but they usually form only a small part of a "geotectonic domain"(Viljoen and Viljoen, 1973). These morphotectonic units are mainly related to relatively recent vertical movements of large blocks of the crust. The delineation of these units is not possible in all areas but in many cases they can be delineated by a few major faults. The units are defined by a consideration of some or all of the following aspects of the landscape:-

1) Lithology

2) Structural styles e.g. fracture and fold patterns

3) Topography

4) Drainage patterns

These units do not necessarily have to be

elevated or depressed blocks but may be stable zones adjacent ~~or~~ to uplifted blocks.

The tripartite division into morphological zones of the main part of the Sardinian batholith(Section 4.5.2) provides a good example of what is meant by morphotectonic units. The whole region, in that case, is one of relatively uniform lithology("granite") which has been transected by two Tertiary rift faults. These faults form the boundaries between the units. The morphotectonic units of the batholith are defined mainly on the basis of topography and the type and density of the fractures as they appear on the imagery. Another example is in the eastern Hoggar mountains area(Section 4.1). In the area investigated a western unit of openly folded Suggarian gneisses is separated from a highly fractured eastern igneous/metamorphic complex by the major $8^{\circ}30'$ meridional fault.

Morphotectonic units as described above may appear to correspond closely with the units of some land classification schemes. But the main difference is that they are based mainly on geological factors and to a lesser extent on physiography. The advantages of a knowledge of these units for a particular region could be considerable in the fields of hydrogeology, engineering geology as well as in mineral exploration.

5.4 Geomorphology

5.4.1 The landforms of plutonic rocks

The research showed that there were two main categories of landforms found in the study regions, which are:-

1) Landforms resulting from planation of the landsurface by erosion and also from the dissection of previous erosion surfaces.

2) Tectonically uplifted landforms related to epeirogenic movements.

Examples of these landforms are shown in Table 5.9. The table shows that it is possible to encounter a variety of "granite" scenery even in one region. The granite of the Tanzania craton in the Chenene mountains region illustrates this point. In that area the horst block of the Chenene mountains forms an uplifted and tilted block of rugged granite which to the south-west degenerates into a zone of pediments and tors and further south passes into the tectonically undisturbed region of the Dodoma plains area of residual soils and isolated tors. The Sardinia batholith is another example, where the northern and southern blocks of the main part of the batholith appear to represent uplifted blocks separated by rift faults from a central zone of relative stability. The gentle topography of the central zone and the presence of several tabular masses, perhaps even representing the remnants of an erosion surface, suggest that it has acted as a relatively stable zone.

Table 5.9 Planated and uplifted landforms encountered in the case study regions

PLANATED LANDFORMS	
1. The Shoshong and Mokware hills in E. Botswana. The summit plains form part of the early Tertiary erosion surface of southern Africa.	3. The Dodoma plains and tor region of the Tanzania cratonic batholith
2. The plain underlain by the Mahalapye granite, E. Botswana. This gently sloping plain forms part of the late Tertiary erosion surface of southern Africa.	4. The Maniéma region of eastern Zaire which is underlain by the Burundian granites.
	5. The Grampian Highlands of Scotland which have been carved from the Tertiary "Highland Peneplain".

UPLIFTED LANDFORMS	
Description	Latest taphrogenic movements
1. The igneous/metamorphic complex of the eastern Hoggar mountains, Algeria.	Quaternary
2. The horst block of the Chenene mountains which form part of the Tanzania cratonic batholith.	Neogene(Alpine rift faulting)
3. Certain blocks of the Sardinian granite batholith	Tertiary(Alpine rift faulting)

The view expressed in the introduction to this chapter that most landforms are no older than Tertiary in age was confirmed by the writer's investigations. Further a re-examination of the process of landscape evolution as embodied in the classical views of W.M. Davis and Walther Penck would now appear to be in order. What appears to remain from the original theories is that planated surfaces are commonly formed as the result of denudation, whether by a process of "wearing down" or "wearing back". However in the past it was assumed that these surfaces on the continental platforms were

rejuventated by intermittent isostatic uplift, consequent on removal of material by erosion. Geophysical evidence has shown that isostatic balance is very delicately maintained as rocks are eroded and that sudden uplifts are unlikely from this process. The evidence from satellite imagery and many other sources indicates that widespread sudden vertical movements have taken place in the not too distant geological past. The second important contribution of satellite imagery to this problem is the knowledge that the continental platforms are criss-crossed by major fractures. These fractures are lines of weakness in the crust and should stress be set up in these areas they are likely to facilitate vertical displacements of individual blocks of the crust.

Three possible explanations of such vertical movements are now given. The first theory assumes that the earth's crust has been affected by large scale undulatory movements of a periodic nature. In some cases the wavelength of these movements is long resulting in large scale upwarping and downwarping of the crust. King (1967) invoked such a motion to explain the downwarping of the Gondwana erosion surface below sea level off the east African coast. If on the other hand the wavelength of such undulations was short and the amplitude relatively large then closely spaced faulting of the crust would be a probable result. The second theory assumes that the early formed primitive crust was cut by deep faults during the late-Archaean (see also Section 5.3.2) and these faults have been persistently rejuvenated during successive periods of diastrophism(McConnel, 1974). A third possibility suggested by Woolard(1969) is that many basins and swells could have resulted

from the transformation of crustal and mantle material. This would produce changes in the mass distribution and density contrasts between mantle and crustal material resulting in subsidence and uplift.

5.4.2 The drainage networks of plutonic rocks

Drainage patterns

The analysis of drainage patterns as an aid to photogeological mapping is a well established procedure. Howard(1967) has provided an excellent summation of the types and patterns of the various drainage patterns encountered. Drainage analysis from satellite imagery is not always easy. Firstly because stereoscopic images are generally not available, and secondly because large parts of drainage systems do not show up clearly on the imagery(see Section 6.4.1).

Plutonic rocks are generally characterized by a dendritic drainage pattern in most climatic zones. However this basic pattern is normally modified in a number of ways. Satellite images often depict the large scale character of the drainage pattern. Thus if an area is underlain by a box-of-eggs arrangement of granite domes, such as the Burundian granites of Maniéma in E. Zaire, then the drainage pattern will be broadly curvilinear(see Fig. 4.8b). Curvilinear patterns may also be induced by zones of shearing and granulation as in the case of the Tanzania cratonic granite(see point 5 Fig. 4.6). Radial drainage patterns can be observed on the imagery of large granite batholiths such as the Sardinian batholith and the Cairngorms mountains. Major and minor fracturing of the rocks is the most common factor modifying

the drainage pattern. Major fractures may induce a parallel drainage pattern as in the case of the Neogene faults affecting the Chenene mountains region of the Tanzania craton(Fig. 4.6a). Minor fractures related to the initial intrusion of plutons commonly impart an angulate dendritic character to the drainage pattern.

Drainage textures

Drainage texture or the spacing of drainage lines is an important parameter in the drainage analysis. The writer along with others has used loosely the terms "fine", "medium" and "coarse" textured as qualitative guides to drainage texture. Ideally such terms should be defined with regard to specific drainage line spacings for a particular scale of imagery. However this was not deemed vital for satellite image studies as the most useful aspect of drainage texture to emerge from the research was its variation within individual plutonic bodies. In several cases the character and number of identifiable drainageways altered with a change in the degree of fracturing or the topography. This factor was most helpful in the attempt to define morphotectonic units. The advantages of using satellite imagery over aerial photographs or topographic maps for this type of interpretation should be stressed. This is because large scale subtle changes in drainage texture can often be taken in at a glance on satellite imagery, whereas they may go almost unnoticed on aerial photographs even if mosaics are studied.

5.5 Soil Cover

General

Interpretation of solid geology from space imagery is especially concerned with the nature of the soil and vegetation cover of a region. The opportunity to observe individual outcrops on space imagery is rare, except perhaps on images of arid terrain. It is the character of the soils and vegetation cover together with the tectonic and morphological aspects of the landscape which influence the photo-characteristics of the imagery and provide the clues to the underlying geology.

Factors influencing soil type

The most important factors which influence soil type are parent material, topography, climate (including past climatic variations) and vegetation. The value of residual soils as guides to underlying bedrock is commonly quite considerable in arid and semi-arid terrain. But the value of soils as indicators of underlying geology diminishes with increasingly moister climates. Soils developed under humid conditions tend to be related mainly to climatic and vegetation zones, and are said to be zonal soils.

Parent material

The parent material of soils, especially in the drier climates, is an important factor affecting the surface characteristics of the landscape. It is these characteristics which are capable of detection and recognition by interpreters on remotely sensed imagery. The chemical and physical properties of soils exert a great influence on the surface environments of landscapes. André and Anderson(1961), working in the semi-arid region of northern California, confirmed

earlier views that it was the physical properties of soils(e.g. colloid to moisture ratio and dispersion ratio) rather than the chemical properties which largely affected the cohesion of soils and hence their erodibility. Erodibility in turn affected the type and density of vegetation growing on the surface. Thus granitic soils which are generally sandy, freely drained soils are much more easily eroded than for example soils developed over basalts, and tend to have a thinner vegetation cover.

The colour of soils is not necessarily a reliable guide to parent material, as the addition of a small percentage of certain minerals may be sufficient to radically alter the overall colour of the soil. For arid and semi-arid environments however certain generalisations can be made. Granitic soils are normally low in clay minerals and have a light colour due to the abundance of light coloured or nearly transparent mineral grains such as quartz and feldspar. This makes the soils highly reflective on all MSS bands of LANDSAT imagery, where they are not covered by vegetation (see Section 6.2.1). The soils developed over basic rocks in tropical terrains tend to be high in iron oxides and red-earths are developed. Such soils are easily picked out on the LANDSAT imagery in the vicinity of the Dodoman greenschist inliers within the Tanzania batholith.

Soils and topography

The detailed classification of soils for agricultural purposes is based on the soil profile, which is a description of the various soil horizons of the regolith or soil mantle. Normally the soil is divided into three main horizons - an A horizon(an eluviated or leached zone), a B horizon(of illuviated material) and a C horizon

of weathered parent rock. Soils of the humid regions generally have fully developed profiles, although individual horizons may be attenuated on the steeper slopes. In the drier regions of the world variations in topography greatly affect the drainage conditions at a site and a variety of soil types may be derived from a single parent rock within a small area. Milne (1935) working in East Africa noticed that as one moved from the top to the bottom of a typical concave hillslope of the region that a complete sequence of soils was crossed. These ranged from well-drained red loams on the hilltops to black or grey clays in the swampy hollows at the bottom. Milne proposed the term catena(Latin, a chain) for this association. Later it was observed that the soil divisions within the catena also corresponded to changes in vegetation. In retrospect it is now clear that the catenary classification, on a smaller scale, pre-empted the type of classification which is now being used for mapping soil units on satellite imagery. The soil units of satellite image studies have been called soil associations.

Soil associations

Soil associations have been defined by Dudal et al.(1966) as being "composed of soils which are geographically associated in the landscape, occurring in sequences bound to the topography and the composition of bedrock". This definition aptly covers the grouping together of soils into larger units for presentation on small-scale maps. Soil associations as they appear on satellite imagery however are better described by the definition given by Hunt(1972), where he indicates that a soil association is composed of "...one or more types(of soil) that occur together in a characteristic pattern in a given area, providing a repetitive appearance to the

ground". Hunt's mention of patterns and repetitive appearance anticipates the appearance of soil associations on satellite imagery. That is that such units will appear as areas of uniform tonal values. This has been found to be true in many cases and is of great significance to the photogeologist, because these units may indicate the extent of underlying geological formations.

A useful concept related to soil associations was introduced by the United States Department of Agriculture(USDA). They suggested that a soil association represented a particular type of surface landscape. Westin(1973) indicated that these landscapes are characterized by a particular surface geometry defined by parameters such as drainage density or the percentage of bare soil areas. Vegetation and hydrology are also used to define surface landscapes.

The writer has encountered a number of soil associations on LANDSAT imagery during the course of research. The most important of these have been outlined in Table 5.10, where the main soil types have been given together with descriptions of parent rocks, topographical situation and vegetation cover. Research showed that in the drier climates the most important characteristics defining soil associations are soil colour, vegetation cover and drainage patterns. Whilst in the more humid regions land use patterns and vegetation cover are the most important parameters defining soil associations on the satellite imagery.

Climate and soils

The character of soils depends on the interaction of various physical, chemical and biotic factors. Climate plays an important part in regulating

Table 5.10 Major soil associations related to plutonic and associated rocks which were observed on the LANDSAT imagery

Climate and Location	Soil Associations seen on LANDSAT imagery	Parent Rock	Topography	Vegetation	Notes
1. Arid Hoggar Mts. Algeria	Light toned residual granitic soils	Alkaline granites, granites and grano-diorites	Generally subdued	Occasional xerophytes or non-existent	This soil association occupies low lying areas between outcrops of metamorphic rocks
2. Semi-arid Shoshong area E. Botswana	Black and red-brown lithosols	Doleritic and dioritic sills	Gently dipping plateaux	Fairly dense tree savannah	Red-brown soils over diorite form thick smooth surface, black soils over dolerite are thin and landsurface texture rough
	Ferruginous reddish-brown and grey-brown sandy loams	Synorogenic granite	Very gently sloping plain	Open tree savannah	Drainage channels have minutely dissected the thick easily eroded soils of this plain
3. Wet-and-dry tropical Central Tanzania	Grey sandy residual granitic soils	Synorogenic granite	Level plain with isolated tors	Bushland and thicket	The thicket frequently thins out and the soils have a high albedo
	Ferruginous red-earths	Greenschist enclaves within granite	Low hills and pediments	Bushland and thicket	The soils are distinguished on IR images by their lower albedo due to their higher moisture content c.f. granitic soils
4. Wet tropical S. Maniéma E. Zaire	Ferralitic soils	Various, including granites, gneisses and sediments	Low dome shaped hills and broad valleys	Dense equatorial forest	These are poorly drained soils forming a thick regolith
	Lateritic soils	Various, including granites, metasediments and Karroo sediments	Low hills and gently sloping plains	Broad-leaved tree savannah	These soils dry out temporarily during the year thus favouring the formation of laterite
5. Mediterr-anean N.E.Sardinia	Brown mediterranean soils(derived from granite)	Granites and granodiorites	Mountains and hills	Oak forests and secondary shrub(maquis)	Secondary shrub and forest cover grow on the steeper slopes. Zonal soils with fully developed profiles.
	Brown mediterranean soils(derived from pyroclastic rocks)	Tertiary pyroclastic deposits	Lowland plains and valleys	These fertile soils are heavily cultivated	The soils show up on LANDSAT imagery due to their high albedo related to extensive areas of dry bare soil
6. Temperate Grampian Highlands of Scotland	Podzolised soils, organic soils and lithosols	Granites and metamorphic rocks	Uplands and mountains	Heather moorlands	These poorly drained soils covered with heather and peat are very dark toned on LANDSAT imagery
	Dominantly organic soils and some podzolised soils	Granites, metamorphics and Devonian sediments	Hill scenery	Acid grasslands	These are poorly drained soils
	Sandy loams and peat podzols	Glacial till and Devonian sediments	Valleys and lowlands	Generally heavily cultivated	These show up on LANDSAT imagery by their much lighter tone c.f. heather moorlands

the degree to which each of these factors affect the soil forming process. The soils of arid regions, where there are few plants and insufficient humus to encourage the activity of micro-organisms, are mainly raw mineral soils. Whilst in humid tropical regions the high organic content of the soil produces acids which help further breakdown the mineral particles of the soil(see also Section 5.2, rock weathering). The variation in rainfall in tropical regions often has a marked effect on soil processes and on the type of vegetation which the soils support.

The two major soil associations of southern Maniéma in eastern Zaire defined by Sys(1960) are almost entirely related to differences in annual rainfall. The hygro-kaolisols represent ferralitic soils developed under permanently wet conditions, whilst the hygro-xerokaolisols further south show that a significant dry season has altered the type of zonal soil formed. This has allowed deposition of iron oxides in the upper layers of the soil in sufficient quantities to form laterite. The area of the ferralitic soils almost exactly coincides with the equatorial forest cover and the lateritic soils are covered with the more open vegetation of the broad-leaved tree savannah(Fig. 4.8a).

Land use patterns, particularly in temperate climates, are often a guide to the underlying soils and to their parent material. In Scotland all the cultivated areas are lowland areas i.e. at heights of less than 300 metres above sea level. This is because climatic conditions above that height produce acid soils unsuitable for growing crops. Thus in the Cairngorms area an examination of an MSS band 5 LANDSAT image (Fig. 4.12a) shows that the boundary between the

steep, dark toned, heather covered hills and mountains and the cultivated soils of the lowlands is remarkably sharp. The latter being developed over thick glacial till in the intervening valleys, whilst the former are normally underlain by basement rocks.

Cultivated areas in Sardinia show up as light toned areas on MSS band 5 LANDSAT imagery. This is because what has been imaged was essentially bare dry soils rather than the much smaller area of the crops growing on them. This was found to be a most useful criterion for distinguishing areas of soils developed over acid pyroclastic deposits(very fertile and highly cultivated) from soils developed over granites(less fertile and less intensively cultivated), see Fig. 4.10.

Finally climate exerts a strong influence on the type of natural vegetation of a region and the character of the soils in turn is strongly affected by this vegetation cover. The nature of this vegetation cover is commonly one of the prime factors responsible for the tones and textures observed on LANDSAT imagery. As such its effect on photointerpretation deserves serious attention by the photogeologist.

5.6 Vegetation

General There are five main factors relating to vegetation which affect the appearance of the satellite imagery and hence the ease with which the geology of a region may be interpreted and these are:-

1) Type of vegetation

2) Distribution of vegetation

3) Density of vegetation

4) The reflectance of the vegetation

5) Seasonal variations in vegetation

The type of vegetation cover, its distribution and density are factors which are almost inextricably linked, and are dealt with together in this account. It is a well established fact that most green vegetation reflects a significantly higher proportion of solar radiation in the infrared part of the spectrum compared with the visible part. This is one of two important factors[1] contributing to variations in tone between the visible and IR bands of MSS imagery. Seasonal variations in plant growth may considerably affect the reflectivity of various plant communities. This sometimes dramatically shows up areas of contrasting vegetation, soils and underlying rock in the drier climates.

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1 Moisture content of the soil is the other important factor causing variations in tone between the IR and visible bands of MSS imagery.

Type distribution and density of vegetation

The factors affecting the types and distribution of vegetation species in an area are very closely linked with those determining the distribution of soil types. There is therefore often a strong affinity between vegetation and soil associations, although a direct correspondence to areas of parent rock is not necessarily to be found in the more humid climates where zonal conditions are dominant. Walter(1973) regards the following as the main factors influencing the habitat of vegetation:-

1) Heat

2) Water

3) Chemical factors

4) Mechanical factors

The species and numbers of the various plants in a given environment, developing under natural conditions, are generally in a state of dynamic equilibrium. That is to say that normally each plant is in competition with neighbouring plants for the available space, light, moisture and nutrients. In semi-arid climates grass, shrubs and trees are the commonest forms of vegetation. Walter(1973) points out however that grass and woody species are antagonistic plant types which to some extent are mutually exclusive. Grasses have a finely branched intensive root system which thoroughly permeates the top layer of the soil, thus retaining and utilising most of the rain which falls in the drier climates. At the end of the rainy season the grass dries up and all but the roots and apical meristem(leading shoot) die. Woody species on the other hand have an extensive root system with an open

branching structure which penetrates the soil in all directions. Woody species however will not survive a lengthy dry season unless there is a modicum of water left in the soil at the end of the rainy season with which to replace water losses.

In the very arid regions such as the Hoggar mountains only a few plants can survive the conditions of extreme drought. Under those conditions it is adaptation to the climate rather than the ability to compete with other plants that is the important factor determining survival. Thus hard-leaved halophytic species are the only plants which are found. However when the annual rainfall reaches about 100 mms. in hot arid regions then certain tufted grasses can survive to form grasslands. Not until the rainfall reaches about 300 mms. will woody species be found. This occurs when the rain-fall is sufficient for there to be a surplus of moisture retained in the sub-soil at the end of the rainy season. First to appear are species of scrub followed by isolated trees such as baobab or acacia. This mixture of grass and woody species form the true savannah lands of tropical regions.

Although the amount of rainfall is of prime importance in determining the type of plant communities found in a given region, soil type is also very important. For example the rainfall over much of the Kalahari sands of eastern Botswana is between 400 and 500 mms. annually, which is not much less than that falling on the Central Plains area north-east of Mahalapye. However the granitic soils of the Central Plains area retain significantly more moisture than the Kalahari sands. Consequently open-shrub savannah is developed widely over the Kalahari sands whilst

open-tree savannah is the dominant plant association found over the Central Plains area. The isolated hills of Shoshong and Mokware where stony lithosols are developed, provide poor hydrological conditions for the growth of grass and these areas support a fairly dense tree savannah. Similar conditions prevail in the Dodoma region of the Tanzania batholith where tree species grow thickly on the rocky granitic inselbergs. Even where the rainfall is much higher, but the topography is still rocky, as on the Chenene mountains, trees predominate to form "dry forest" (miombo woodland).

Where the ecological balance between grassy and woody species is disturbed by factors such as over-grazing of land or the destruction of less hardy species by bush fires, then more water is available for the growth of woody species. This commonly results in the development of areas of thick scrub which replaces grazing land. These unnatural factors also further complicate the photogeological interpretation of such regions.

The natural vegetation of the more humid regions is dominated by woody species. Where trees grow close enough together to form a complete canopy grass is virtually excluded. The tropical rain forest of southern Maniéma in eastern Zaire forms such a canopy(Fig. 4.8a).

Truly natural vegetation cover is the exception rather than the rule in the more densely populated parts of the northern hemisphere. The natural vegetation cover of Sardinia if left undisturbed by man would be oak forest. However most areas are felled every 20 years and in many cases dense scrub encroaches onto those areas not cleared for agriculture. The lowlands of

England and Wales are dominated by agricultural land which has been stripped of nearly all natural vegetation cover. But in temperate climates poor drainage conditions usually prevail over low lying granitic masses. These lowland granites are generally unsuitable for agriculture and are covered with acid grassland vegetation. The mountain granites of Scotland have very wet surface conditions and the natural vegetation cover is dominated by acidophilous species such as heather, mosses and crowberry.

Vegetation reflectance

The literature contains a wealth of information on the reflectance characteristics of vegetation, and summaries of various investigations are given in the Manual of Remote Sensing(American Society of Photogrammetry, 1975). The vegetation cover of humid regions is generally complete and due to the small scale of satellite imagery differences in vegetation associations are mainly expressed as tonal variations on the imagery. Uneven distribution of vegetation in the drier regions introduces texture as well as tone as a photocharacteristic to be interpreted in relation to vegetation cover.

The most important parameter of vegetation affecting the appearance of multiband imagery is vegetation pigmentation. This commonly results in markedly different tonal values for vegetated areas between the visible and IR bands of the imagery. Images from the visible part of the spectrum generally show areas of green plants in dark tones e.g. the tropical rain forest of southern Maniéma, eastern Zaire on MSS band 5 (Fig. 4.8a). This is due to the absorption of much of the visible radiation. In the near IR chlorophylls and carrotenoids(red or orange coloured plants) are transparent to radiation

of these wavelengths and are highly reflective, producing light toned areas on the images. Experience has shown that contrasts between highly vegetated and sparsely vegetated areas are best shown on the visible bands of the imagery. This is because bare soil(especially granitic soils) tend to reflect significantly more in the visible part of the spectrum but are often only slightly less or slightly more reflective than vegetation in the IR part of the spectrum. The value of MSS band 5 for detecting dark toned vegetated inselbergs on the Dodoma plains area of the Tanzania batholith has already been mentioned. Variations in the colour of vegetation would be most easily detected on the visible image bands. However due to the high absorption of radiation in the visible range by green plants such subtle variations in pigmentation were not detected on the photographic image products investigated by the writer. Poulton(1973) reported that subtle differences in vegetation can be detected using digital tape data derived from the LANDSAT computer tapes.

The above discussion suggests that in savannah terrains the visible MSS bands are more helpful in detecting vegetation anomalies which might be linked to underlying geology. However the IR bands are of considerable help in humid climates as the light tone of the vegetation cover contrasts strongly with physiographic features such as scarp faces. Much of the structural data(mainly lineaments) obtained from the interpretation of the southern Maniéma area came from MSS band 7. Although the general light tone of the forest vegetation produced an image of poor contrast, details of drainage and topography were revealed by the IR images. The shadows on these images were of particular help in picking out the

regional structural grain of the Rusizian gneisses. Similarly in northern Sardinia fracture traces within the dissected granite were in some cases shown up by the IR images. The dark tones of thickly vegetated valleys on MSS band 5 obscured many of the fractures which were clearly visible on the IR bands.

Seasonal changes in vegetation

Vegetation is generally undergoing a continual process of change and growth and variations in the properties of individual plants cause changes in the overall reflectance of the vegetation canopy. Apart from the physiological stresses inflicted on plants by the soil in which they are growing there are several other factors which affect the reflectance of plant canopies. These factors vary with season and with the general maturity of the plant cover. Water is the most important factor affecting growth in tropical climates, whilst in temperate regions it is chiefly changes in temperature and the amount of daylight which affect the growing cycle.

The albedo of a given area of ground is largely determined by the reflectance from the background soils and rocks and from the vegetation cover growing on the soil. The ratio of the areas of soils and plants commonly varies with season. For example the albedo of an area of deciduous wooded country imaged during the winter will be the sum of a high reflectance from the soils and surface deposits and a low reflectance from the leafless trees. However in the summer once a completely leafy canopy has grown the reflectance will be almost entirely from the vegetation. During the growing season changes occur in the size, structure and pigmentation of leafy plants. Variations in the reflectance from leaves in the visible part of the spectrum due to changes

in pigmentation are not easily seen on the MSS imagery as mentioned previously. In the IR region of the spectrum an increase in the amount of water in leaves significantly decreases their reflectivity. Also the change in cellular structure of leaves, from the compact mesophyll of young plants to the more open structure of mature ones with many air spaces, produces a progressive increase in leaf reflectivity. Variations in the cellular structures of different plants therefore produces a variable response on the IR imagery, and this property has been used widely in agricultural surveys using remotely sensed imagery.

Where edaphic factors influence the type and density of vegetation in a particular region there will be vegetation differences between the different soil associations. Although the writer was unable to obtain imagery of different seasons for the case study regions other evidence suggests that images of certain seasons provide significantly more geological information than others. A revealing study carried out by Grootenboer(1974) of a semi-arid region in Namibia(South West Africa) showed that there was considerably more lithological information on a LANDSAT image of the region taken in the middle of the rainy season compared with one taken at the end of the dry season. At the time the dry season image was taken the vegetation was a uniform brown colour and the woody species were leafless. Whereas at the time the rainy season image was taken the region was covered with green grassland and the woody species were in full leaf. Grootenboer regarded the strong tonal variations as due to variations in soil moisture content, atmospheric haze and particular vegetation associations over individual soil associations.

Although detailed studies on the variations of the reflectance from crops have been carried out for monitoring crop growth, it seems that more research is required on changes of image appearance with season of areas of natural vegetation. Knowledge of precisely the right time to image a given region to produce an optimum level of geological information would be of great assistance in future photogeological studies.

CHAPTER SIX

THE PHOTO-CHARACTERISTICS OF PLUTONIC ROCKS ON THE IMAGERY

6.1 General

The photogeological interpretation of remotely sensed imagery is normally a two stage process, which follows the procedure outlined by Ray(1960) for the interpretation of conventional aerial photographs. The first stage involves examination of the imagery and the measurement(usually a mental process) and identification of the features on the imagery. The second stage involves an assessment of the geological significance of these features by deductive and inductive reasoning. A third operation of the interpretation process, and generally an integral part of the work, is the annotation or labelling of the interpreted features of the imagery.

The assessment and identification of image features is carried out by observation of the photo-characteristics or recognition elements of the imagery. The photo-characteristics of LANDSAT imagery which are of prime importance include tone, colour(colour composite images), texture, pattern and shape. Three other important factors which affect interpretation are the size of features to be interpreted, the scale of the imagery and the type of imagery examined.

Variations in tone on LANDSAT imagery give a relative measure of the amounts of reflected solar radiation received by the scanner from

various areas on the ground. These signals will have been attenuated by atmospheric scattering between the ground and the satellite. It may be that varying amounts of water vapour in the air above the different plant and soil associations in semi-arid environments may in fact enhance and accentuate the tonal differences on the imagery. However it is assumed that such effects are much less than the direct reflectance from ground features. Reflectance contrasts between the various ground features represented by tonal differences on the imagery therefore provide the fundamental basis for photointerpretation.

Texture according to Lattman and Ray(1965) is "the aggregate arrangement of minute images expressed by tone, shape, size and pattern". Texture is usually used to describe individual parts of an image where series of closely spaced features have given rise to a characteristic appearance which is described by such terms as mottled, speckled, smooth, rough and even. Both tone and texture are particularly useful in lithological interpretation.

Pattern is probably the most important photocharacteristic of plutonic rocks on LANDSAT imagery. The patterns which have been observed are mainly related to structural elements of the rocks such as fractures, ring structures and morphotectonic units. Patterns manifest themselves on the imagery as a result of orderly arrangements of ground features. It should be remembered that even a single fracture trace on the imagery is an example of pattern. In that case order may be expressed by a plant association which grows preferentially along discrete channels which are aligned in such a

way that they appear as a single lineament on the imagery. The orderly arrangements of lineaments on an image commonly enables the interpreter to decide which are genetically linked.

Shape includes the general outline and the nature of the boundaries of rock units as seen on the imagery. The small scale of satellite imagery may show the outline of a large formation on a single frame, whereas several conventional aerial photographs would have to be examined before the shape became clear.

The size of features detectable on the imagery depends on the resolution of the imagery, and the ease of recognition of such features on the scale of the image examined, i.e. small isolated features are more easily detected on large scale prints, whilst extended features such as major fractures may be more easily seen on small scale images. The type of imagery used for this research project was, as far as possible, a standardized product. The images examined were mainly black and white, 1:500,000 scale, photographic paper prints of the LANDSAT MSS imagery. However the quality of these images varied from scene to scene depending on atmospheric effects, illumination factors and negative quality.

6.2 Tone

6.2.1 Spectral reflectance characteristics of plutonic rocks

Despite the wide range in chemical composition found within individual "granite" batholiths, many plutons appear to be remarkably tonally homogeneous on satellite imagery. This is due to three main reasons which are:-

1) There is a tendency for the majority of the rock mass of individual batholiths to have a particular composition which varies within narrow limits.

2) In arid and semi-arid environments, where residual granitic soils are developed, they have a uniformly high albedo due to the high reflectance from transparent mineral grains(notably quartz and feldspar) which are abundant.

3) The sometimes low tonal contrast of the NASA generated LANDSAT negatives provides poor spectral discrimination between different rock types.

The overall homogeneity of batholiths was confirmed by a statistical analysis of ground observations carried out by Chayes(1950) on a number of different plutons. It is apparent therefore that large scale variations within batholiths are often very subtle and difficult to detect. However laboratory investigations have been carried out by a number of workers to see at least if there was a possibility of

distinguishing between the main categories of igneous rocks by their spectral reflectance, as shown by variation in tone on remotely sensed imagery.

Geologists hoped that multispectral imagery would help to bring out the differences in composition between individual igneous rocks. The hypothetical basis for this was that individual rocks and soils would show either very strong or very weak spectral reflectance at particular wavelengths. If this were the case then a particular image for study could have been selected from the multiband image pack. The image chosen would either have been one with a waveband which showed a distinctive spectral response for the rock type studied or one which showed strong contrasts between the various rock types.

Unfortunately the laboratory tests have shown that there are few abrupt changes in spectral reflectance for the common rocks and soils in the visible and near infrared part of the spectrum. Fig. 6.1(after Salisbury and Hunt, 1974) shows some bidirectional reflectance[1] curves for some of the common igneous rocks. Hunt et al.(1973) explained that the apparent lack of distinct spectral characteristics on the curves was because the principal constituents of igneous rocks are the silicon-oxygen, the aluminium-oxygen and the magnesium-oxygen atomic groupings. All these structures are vibrationally and electronically inert to radiation within the energy range of the visible and near

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1 Bidirectional reflectances are spectral reflectance measurements made for particular angles of illumination and view. The laboratory techniques of Hunt and Salisbury are described in an earlier paper(1970).

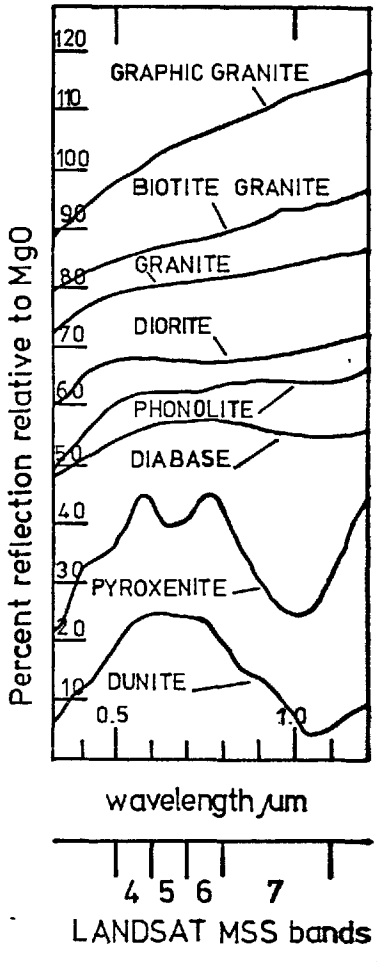


Fig.6.1

Examples of bidirectional reflectance spectra for particulate samples of typical igneous rocks(after Salisbury and Hunt, 1974).

The wavebands covered by the LANDSAT-1 multispectral scanner are also shown.

infrared part of the spectrum. Spectral features(mainly absorption bands) appear as a response to elements in the rock such as iron (electronically responsive) or OH and water which provide vibrational features. Thus intermediate and basic rocks(high in iron and water) are most suitable for discrimination on spectral reflectance grounds. However specialized methods of investigation are required to detect the rather small spectral anomalies which are encountered. It has been found necessary in some cases to use computerized techniques to stretch out part of the contrast range of the image in order to pick out these subtle spectral differences(Rowan et al. 1974).

The lack of variation in spectral response from rocks and soils in arid terrain as observed on the different MSS bands of LANDSAT imagery has been confirmed by the writer's own investigations. An examination was made of two LANDSAT scenes covering the extremely arid, vegetation-free regions of the Hoggar mountains and the Tibesti mountains in the Sahara. The four MSS bands of each of these scenes were found to be almost identical. The main differences are the darker shadows on the IR bands, and the lighter tones of these bands. The latter is probably mainly due to an overall higher reflectance from felsic rocks and soils derived from these rocks on moving into the IR part of the spectrum as shown by the example of a typical granite sample in Fig. 6.1.

Unlike the arid regions however considerable tonal differences can be observed between individual MSS bands of LANDSAT imagery of the slightly wetter regions. Investigations have shown that these variations are related to two important factors which are:-

1) Variation in the reflectance of soils partially or wholly saturated with water.

2) Variation in the reflectance of vegetation.

It is these variations which when related to geological factors ensures that examination of the IR image bands provides additional information to that obtained from the visible bands. These phenomena were discussed more fully in Sections 5.5(p. 183) and 5.6(p. 190).

6.2.2 Tonal characteristics of plutonic rocks on the imagery

The low resolution and small-scale of satellite imagery means that the interpreter is less concerned with the measurement and identification of individual objects than on conventional aerial photography. Instead he becomes more interested in general features of the imagery such as the overall tone or texture of large areas. This factor has already been discussed with regard to the recognition of soil associations(Section 5.5). Tone on the imagery tends to vary as a function of factors such as topography, rock and soil type, vegetation cover and land use. An important indirect factor which greatly affects the tonal contrasts on the imagery is the season at which the imagery was taken as this affects vegetation growth and soil moisture content(see Section 5.6).

The writer's research has brought out a number of general points with respect to tonal contrasts on the LANDSAT MSS imagery. These can best be considered by examining the tonal differences which were observed over the various rock units on the imagery of the case study regions. Estimation of absolute tonal values such as might be made with a densitometer have their value when considering individual areas and form the basis of density slicing or equidensitometry. However such values are difficult to standardize from image to image, and in any case there is commonly quite a considerable variation in tone over one rock unit on the imagery. The writer has used a broad visual estimate of average tonal densities of areas on the imagery in order to semi-quantitatively compare the tones on different LANDSAT scenes. The tones over

individual rock units have therefore been designated as either light, medium or dark toned or combinations of these terms. The estimates of tonal density for the different rock units of the case study regions along with other relevant data are shown on Table 6.1.

The table shows the tonal differences between individual MSS bands of the various plutonic rocks observed on the imagery. Variations in topography and vegetation cover, in some cases, greatly affected the tone of plutonic masses on individual MSS bands. The greatest tonal contrast between MSS bands showed up over the low strike ridges of the greenschist inliers of the Dodoma plains area in Tanzania. These were light toned on MSS band 7 and dark toned on MSS band 5. Strong contrast between MSS bands 5 and 7 were also observed between the rain forested and savannah covered areas of S. Maniéma in eastern Zaire.

The study showed that areas of high relief in arid and semi-arid regions were generally darker toned than the low-lying soil covered areas on most of the MSS bands. Furthermore areas of very considerable relief were even darker toned. This last factor was of some importance in separating morphotectonic units.

Areas of low relief covered with residual granitic soils in the savannah lands of Africa generally appear as mottled toned on the imagery. These tonal variations generally indicate variations in vegetation density which in turn are related to edaphic factors. Such areas often contrast strongly with areas underlain by sedimentary formations which may be very even toned like the Cave Sandstone group(Karroo) at point

Table 6.1 Summary of the tonal values observed on the LANDSAT MSS imagery for the different plutonic masses and associated rocks

Climate and Location	Season of Imagery	Rock Types	Topography	Soil and vegetation cover	Tone MSS BANDS 4	5	6	7
1. Arid Algeria	Dry season	Alkaline granites, granites, and granodiorites	Generally subdued	Thick sandy residual soils virtually devoid of vegetation	L	L*	L	L
		Diorites	Steep hills and inselbergs	Thin lithosols virtually devoid of vegetation	D	D	M/D	M/D*
		Suggarian gneisses	Mountains, hills and strike ridges	Thin lithosols virtually devoid of vegetation	M/D	M/D*	M	M
2. Semi-arid Shoshong-Mokware area E. Botswana	End of the dry season	Shoshong doleritic sill	Rugged tabular mass	Black lithosols covered by fairly dense tree savannah	M	M/D	M/D	M/D*
		Mokware dioritic sill	Smooth gently sloping hills	Thick red lithosols covered by fairly dense tree savannah	M	M/D	M/D	M*
		Mahalapye synorogenic granite	Very gently sloping plain	Thick grey-brown and reddish brown residual soils covered by open tree savannah	M/L	M/L*	M/L	M/L
3. Wet-and-dry tropical Central Tanzania	Middle of the rainy season	Synorogenic granites, granitoid gneisses, nebulites and porphyritic granites	Level plain with isolated tors	Grey sandy residual soils covered with bushland and thicket	N.A.	L*	M	M
			Hills and mountains	Lithosols covered by "dry forest"(miombo woodland)	N.A.	M/D*	M	M
		Greenschist inliers within granite	Low strike ridges	Thin lithosols covered by thicket	N.A.	D*	M	L
			Very gently sloping pediments	Residual red-earths covered by bushland and thicket	N.A.	M	M/D	M/D*
4. Wet tropical S. Maniema E. Zaire	Middle of the rainy season	Syn- to post-tectonic calc-alkaline granites	Low dome-shaped hills	Ferralitic soils covered by equatorial forest	D	D	M	M*
			Low hills	Lateritic soils covered by broad-leaved tree savannah	M	M*	M	L
5. Mediterranean N.E. Sardinia	Dry summer season	Post-tectonic granites granodiorites, diorites and gabbros	Mountains and hills	Oak forest and secondary shrub formations over brown Mediterranean soils	M/D	M/D*	M	M/L
6. Temperate Grampian Highlands of Scotland	Late winter	Late- to post-tectonic calc-alkaline granites, adamellites and granodiorites	Uplands and mountains	Heather moorlands over organic and podzolised soils	D	D	D	M/D*
			Hill scenery	Acid grasslands over organic and podzolised soils	M/D	M/D	M/D	M*

Key to MSS BANDS L - Light toned M - Medium toned D - Dark toned
N.A. - image not available for study * - indicates the MSS band which was most useful for the interpretation of the particular rock unit

3 on Fig. 4.4(an MSS band 7 image of the Shoshong-Mokware area E. Botswana). MSS band 5 images taken in the rainy season were found to bring out the greatest tonal contrasts between individual rock units of these low-lying areas.

The tonal variations on the imagery of mountainous regions in temperate zones depend mainly on the nature and attitude of individual slopes. Soil moisture content, shadows and preferential growth of vegetation all affect the tone of the imagery. Slopes facing away from the sun are dark toned on the IR bands due to dense shadows and also to the higher soil moisture of such slopes. Areas of low relief in temperate climates are commonly more variegated tonally as they are often areas of intense cultivation and appear as mottled tones on the imagery.

6.3 Texture

General

Texture on remotely sensed imagery lies somewhere between flat tone and pattern in the range of photo-characteristics. Most photogeologists are however familiar with the transition from pattern to texture to tone of ground features as ever smaller scales of imagery are examined. Generally texture is used to describe arrangements of tones which are individually small in area but nevertheless together have a distinctive appearance.

The textures observed on LANDSAT imagery over the plutonic rocks are of four main types:-

1) Textures related to the surface form of outcrops(outcrop texture).

2) Textures related to fracturing of plutonic masses(fracture texture).

3) Textures related to tonal variations within areas of residual soils(soil/vegetal texture).

4) Textures related to the degree of dissection of outcrops(erosional texture).

One other use of the word texture in photogeology which should be mentioned is drainage texture(see Section 5.4.2). The usage of the term texture in that case is however rather different to the categories of texture given above, as it refers to the spacing of the drainage lines of a drainage network. The appearance of drainage on satellite imagery is mainly

discussed in terms of pattern and is considered further in the next section of this chapter (Section 6.4.1).

Outcrop textures

Granitic rocks commonly display rounded outcrop forms, and in arid and semi-arid regions a rounded lumpy surface texture can often be observed on the satellite imagery. The rounded character of the weathering profile of granites can also be observed on the grander scale of extensive areas of mountain granites. The texture produced by the rounded smooth interfluves between deep valleys contrasts strongly with the texture of metamorphic rocks in mountain areas. The latter have sharp interfluves producing a distinctive stellate texture on the imagery. Compare the appearance of the Chenene mountains (granite) with the Kiboriani mountains(gneisses and schists) of Central Tanzania on Fig. 4.6a.

Fracture texture

A fine cross-hatched texture of criss-cross fracturing is sometimes to be observed over outcrops of plutonic rocks on the satellite imagery. Generally such textures will be best observed on the IR bands of LANDSAT imagery as the fractures tend to be accentuated by dark shadows due to their negative relief. Intense fracturing of epizonal and mesozonal plutons due to the vertical stresses of intrusion is not uncommon, and may produce a distinctive texture of macro-joints which can help the interpreter to pick out such bodies on the imagery. Examples of fracture texture observed on the imagery can be seen over the Shoshong dolerite(Fig.4.4a) and more unusually the texture produced by the snow-filled macro-joints of the Cairngorms and Lochnagar granites at points 5 and 6 on Fig. 4.13a.

Soil/ vegetal texture

Planated areas covered with residual soils and underlain by granites in areas of savannah vegetation commonly have a mottled texture on the imagery. This is due to the irregular development of patches of woody vegetation, which are generally darker toned on the imagery than the intervening grass-covered areas. Examples of mottled textures are the Dodoma plains area underlain by the Tanzania cratonic granite(Fig. 4.6a) and the Central Plains area of E. Botswana underlain by the Mahalapye granite(Fig. 4.4a). These textures are caused by virtually two-dimensional textures compared with the three-dimensional aspects of textures related to outcrop forms. In the more humid climatic zones where vegetation is thicker and more uniform such textures are not generally seen on the scale of satellite imagery as those landscapes appear as areas of uniform tone. The tones and textures of cultivated areas where the reflectance from soils is once again directed towards the satellite sensor may give the clue to underlying geology. So far few criteria have been produced regarding the textures of cultivated areas in relation to underlying geology on satellite imagery. This may well prove to be a fruitful field of research for future investigators, especially in view of the improved resolution imagery expected from forthcoming space missions.

Erosional texture

Textures related to the degree of dissection of terrain are referred to as erosional textures. The value of erosional texture is that it is a relative parameter and it commonly varies depending on lithological and tectonic factors. Variation in the degree of dissection of the "Highland Peneplain" illustrates the variations of erosional texture as seen on a LANDSAT mosaic of the Grampian Highlands of Scotland(Fig. 6.3b).

The mosaic(MSS band 6 imagery) shows that the boundary between the well dissected part of the peneplain and poorly dissected part of the peneplain can almost be drawn in on the mosaic. The well-dissected part of the peneplain in the west and south-west is characterized by deeply cut valleys with elongated lochs. Contrastingly the eastern poorly-dissected part of the peneplain, although equally mountainous, has relatively few deeply cut valleys and the latter are much narrower.

Erosional texture may be simply related to the erodibility of rock units or it may be linked to vertical displacements of blocks of country related to tectonic uplift. The writer found this latter aspect of erosional texture particularly useful in delineating morphotectonic units, such as those suggested for the Sardinian batholith(Section 4.5.2).

6.4 Pattern

6.4.1 Drainage

General

Drainage channels are commonly difficult to discern on LANDSAT MSS imagery, even of areas with perennial rivers, where one might have expected to pick out rivers by their black tone on IR imagery(due to the low reflectivity of water for IR radiation). The reason for the poor discrimination of drainage channels is mainly that the resolution of the satellite imagery is less than the width of most drainage channels(ground resolution of LANDSAT-1 MSS imagery is ca. 78 metres). Alternatively in some cases there may be insufficient reflectance contrasts between drainage channels and adjacent land to show up on the imagery. In mountainous areas where drainage channels are numerous but narrow few show up clearly on LANDSAT MSS imagery. Almost the only conspicuous indications of fresh water on the IR imagery of northern Sardinia are in fact man-made reservoirs, not a single river can be clearly distinguished.

Structural control

Even if fully integrated drainage maps cannot generally be produced from LANDSAT photographic image products, several characteristics of the drainage can be observed which are of use in photogeological interpretation. One of the most significant aspects of drainage analysis to emerge from this study of LANDSAT imagery is that much of the drainage of the study regions appears to be structurally controlled. In particular fracture control of drainage over plutonic rocks is very widespread and could be observed on the imagery of all but the most

densely vegetated regions. Further it was observed that frequently it is only those parts of the drainage network which are fracture controlled which are clear on the imagery(this factor may be important for automated optical image processing for fracture trace analysis studies). Thus in many cases a plot of discernible drainage channels will be little different from a lineament plot taken from the same image. In mountainous areas fracture controlled drainage lines are generally best seen on the IR image bands. This is because these lines are accentuated by the strong shadows of IR imagery which often produces strong tonal contrasts between opposite flanks of deeply cut valleys.

Drainage in arid and semi-arid regions

The plutonic rocks of arid and semi-arid regions are generally characterized by one of three main types of landforms. Each of these landforms has a drainage network which has distinctive features on LANDSAT imagery. The three types of landforms are:-

1) Exhumed resistant, rounded masses of hard crystalline rocks forming corestone inselbergs and isolated fragmented masses surrounded by areas of residual soils.

2) Planated areas covered by residual soils and underlain by plutonic rocks.

3) Uplifted mountain blocks undergoing rapid erosion.

The highly fractured nature of plutonic rocks is responsible for the fragmented appearance of many outcrops as seen on the imagery. The fractures are rapidly exploited by erosive agents and this results in the outcrop being divided

into separate blocks. The drainage network developed between the blocks lacks preferred orientation and is poorly integrated. Such units are generally easy to pick out on the imagery by the darker tone of the outcrops compared with the lighter tone of the interstitial network of sand rivers and residual soils. MSS band 5 is generally the most useful image band for the recognition of this type of outcrop/drainage system, as the contrast between darker outcrops and light toned soils is generally greater than on IR imagery.

Depending on the thickness and texture of residual soils a more or less fully integrated, coarse-textured drainage pattern can usually be observed on the LANDSAT imagery of low lying areas underlain by plutonic rocks. Such drainage systems may be broadly dendritic but they are frequently modified by regional fractures, which may impart a degree of parallelism to the drainage pattern. Most of the drainage channels will be seasonal and sand-filled. These will show up as very light toned lines on the imagery if they are wide enough, and if there is sufficient spectral contrast with the adjacent land. These drainage lines are best observed on MSS bands 4 or 5. MSS band 4 was found to be particularly useful for picking out fault-controlled wadis in the sand covered area to the east of the Hoggar mountains.

Sometimes the drainage courses will be medium to dark toned on all MSS bands if imaged in the dry season, which is probably due to the development of leafless woody species along the water course banks. Contrastingly if they are imaged in the rainy season MSS band 5 will show these drainage courses as dark toned lines due to

absorption of much of the visible radiation by the green pigment of the green leaves of the woody species.

The drainage of very flat areas may be characterized by areas of seasonal swamps. These will show up as dark toned areas on MSS band 7 images. Such areas in Tanzania(mbugas) are frequently large and elongate and are often bounded on one margin by a major fracture.

The drainage of uplifted blocks of granitic rocks is commonly characterized by heavily incised drainage channels. This factor together with the rounded appearance of the interfluves, shown by the lack of sharp tonal contrasts are often sufficient to differentiate granitic rocks from other rocks on the imagery e.g. the drainage of the Chenene mountains in central Tanzania(Fig. 4.6a).

Drainage of the humid regions

The concept of drainage texture as expressed by the terms "fine", "medium" and "coarse" cannot always be applied meaningfully in the photo-interpretation of satellite imagery. This point is illustrated by the area underlain by the Burundian granites and Rusizian gneisses of S. Maniéma in E. Zaire, where on the imagery the drainage density appears to vary but in reality is rather uniform. The reason for this is vegetation cover. The northern part of Fig. 4.8a is covered by equatorial rain forest(almost black toned on this MSS band 5 image) and only the characteristic curvilinear drainage of the main tributaries crossing this area of crystalline basement can be discerned. This "coarse" texture is shown by the clearings developed along the banks of the rivers(lighter toned on MSS band 5).

Contrastingly further south, where thick forest has given way to broad-leaved tree savannah, a fine-textured dendritic drainage pattern can be seen developed over similar granites and gneisses. This pattern shows up exceedingly well on MSS band 5, as dark toned lines of trees follow the drainage network(see point 2 on Fig. 4.8a). This network stands out strongly against the light toned background covered by savannah vegetation.

In spite of these variations in drainage texture, the broadly curvilinear pattern of the forested region together with the appearance of the fine textured dendritic drainage of the "savannah granites" provide sufficient evidence to deduce that much of the area north of the Lualaba river is underlain by crystalline basement, even though this has been affected by deep tropical weathering.

Variations in drainage texture over an area of uniform vegetation cover however may be of critical importance in photointerpretation. These may indicate lithological variations or help to define morphotectonic units and should be regarded as drainage anomalies of possible tectonic significance(e.g. the variations in the drainage texture over the Cairngorms mountains shown on Fig. 4.13a).

One final aspect of drainage on LANDSAT imagery which can be of use to the photogeologist is the value of valley alluvium for drainage analysis. In many regions of low relief the main rivers meander through wide flood plains. Although the river channels themselves may not be visible on the imagery the extent of the valley alluvium often shows up very clearly. Glacial till fills many of the major valleys of Scotland and these

have provided soils suitable for intensive agricultural development. The patterns of cultivation show up as light toned areas on MSS band 5 and contrast strongly with the darker toned heather-clad mountains. Thus a dendritic pattern of valley alluvium can sometimes be made out on the imagery.

6.4.2 Lineaments

General

The linear arrangements of ground features which constitute lineaments and are frequently related to subsurface geological phenomena, are commonly the most readily observed pattern elements of LANDSAT imagery. The majority of these lineaments represent simple fractures and normal faults, whilst a smaller percentage represent less common tectonic features such as shear zones, fault scarps and thrusts. The geological causes of geological lineaments observed on the LANDSAT imagery are listed below in Table 6.2.

Table 6.2 Nomenclature of the types of geological lineaments observed on LANDSAT imagery in areas of plutcnic rocks

FRACTURES and FAULTS	
1. Geotectonic and major regional(planetary fractures > 80 kms. long)	
2. Regional fractures(20 - 80 kms. long)	
3. Local tectonic fractures(< 20 kms. long)	
MISCELLANEOUS LINEAMENTS	
Certain	**Uncertain**
1. Shear zones	6. Unclassified lineaments (of presumed geological significance)
2. Fault scarps	
3. Thrusts	7. Zones of disjunction
4. Dykes	
5. Strike ridges	

Following the procedure established in Section 5.3.3 for classifying lineaments according to their length, the appearance of fractures on the imagery will be described in three groups, planetary, regional and local tectonic. Several lineaments belonging to the miscellaneous categories of the lower half of Table 6.2 were observed on the imagery and a description of some of these is given at the end of this section(see also Table 6.6).

Planetary fractures

There are three important types of recognition elements with respect to planetary fractures, and indeed also to many of the shorter fractures, which can be observed on LANDSAT imagery and these are:-

1) The photo-appearance of the fracture line

2) Associated landscape features

3) The shape of the fracture line

The appearance of planetary fractures on the imagery is variable and they may appear as negative, positive, broad and shallow, diffuse or sharp features. The major faults transecting the eastern Hoggar mountains assume several of these habits and are described in the top half of Table 6.3. Planetary fractures of the more humid regions however commonly form negative features in the landsurface.

Fractures may often be picked out by observation of associated natural features such as rivers and elongated lakes which show up well on IR imagery. They may also be picked out by the lighter tone of valley alluvium, especially if the alluvial soils are under cultivation.

Table 6.3 The photo-characteristics of planetary fractures observed on LANDSAT imagery

Climate and Location	Season of Imagery	Fractures	Rocks Affected	Photo-characteristics of fractures	Text Figure References
Arid Hoggar Mts. Algeria	Dry season	Major N-S meridional faults	Precambrian gneiss and plutonic rocks	Sinuous, diffuse, medium toned lines against light toned sandy desert soils on MSS band 5. The 8°30' meridional fault has a fairly well integrated fault line on the imagery which truncates part of the outcrop line of the Hoggar mountains which runs obliquely to the fault.	5 on Fig. 4.2
		Major NE-SW and NW-SE faults	Precambrian gneiss and plutonic rocks	1. Follow wadis and show as light toned lines relative to the surrounding areas on MSS band 5 and vice versa.	9 on Fig. 4.2
				2. Ridges of indurated rock follow fault lines and show as conspicuous dark toned lines on all MSS bands.	10 on Fig. 4.2
				3. Light toned wadis show they follow faults by their straightness in the outcrop areas as they contrast strongly with the darker toned outcrops on MSS band 5.	11 on Fig. 4.2
				4. Chains of tiny dark toned outcrops spaced out along wadis denote fault lines(MSS 5).	12 on Fig. 4.2
Wet tropical S. Maniema E. Zaire	Middle of the rainy season	Major NW-SE crustal fracture	Precambrian basement and Permo-Carboniferous (Karroo) sediments	This lineament is defined by a remarkably straight stretch of the Lualaba river (over 100 kms long). It shows well on all MSS bands but especially on MSS band 7 where it is obvious because of the black tone of the river water.	Fig. 4.8b
Mediter-anean N.E. Sardinia	Dry summer season	Major NE-SW rift faults	Granite batholith and many pre-Tertiary rocks	1. Continuous deep negative feature on MSS band 7 partly followed by road which shows as very light toned on MSS band 5.	10 on Fig. 4.10
				2. Shown by fault scarp where contrast between light toned soils of the rift valley and darker toned bush covered hills is sharp on MSS band 5.	4 on Fig. 4.10
Temperate Grampian Highlands of Scotland	Late winter	Major NNE-SSW sinistral wrench-faults	Precambrian basement and Caledonian granites	1. Very continuous narrow deeply cut negative feature. Fault line often followed by elongated lochs(MSS band 7).	2 on Fig. 4.12b
				2. The Great Glen fault shows up well where a light toned S.E. facing valley slope contrasts strongly along a sharp line with the darker toned moorland on the hilltops to the west(MSS band 7).	1 on Fig. 4.12b

Strong tonal contrasts between steep valley sides and flatter ground, due to differences in illumination, may by their linearity indicate the presence of a fracture(often well shown on MSS band 7). Where rift fault scarps are present tonal contrast is generally strong between the valley floors(generally light toned) and the scarp face(darker toned). Sharp linear truncation of outcrop may in some cases show that a fracture is in fact a fault.

Some of the major fractures appear to be decidedly sinuous or curvilinear on the imagery, but the photogeologist should be on the look out for sharp changes in direction of curvilinear lineaments. Such changes in direction may represent an intersection of two major fractures or alternatively the bifurcation of one major fracture into two subsidiary or one major and one minor fracture. The sharply curving lineament may in that case represent the result of a process rather akin to river capture, in which the lineament is composed of segments of two different fractures e.g. the intersection of the NE-SW Ad Azeteite fault(10 on Fig. 4.2) with the $8^{\circ}30'$ meridional fault(5 on Fig. 4.2) of the Hoggar mountains. Very straight fractures, like the Great Glen fault, appear to be associated with strike-slip faulting though these may bifurcate like the normal faults described above.

Regional fractures

Many of the characteristics of planetary fractures can also be observed in regional fractures. Details of the photo-characteristics of some of the regional fractures observed on the LANDSAT imagery of the case study regions are given on Table 6.4. The table shows that fractures distinguished on the basis of tonal contrasts related to soil/vegetation factors are generally

Table 6.4 The photo-characteristics of regional fractures observed on LANDSAT imagery

Climate and Location	Season of Imagery	Fractures	Rocks Affected	Photo-characteristics of fractures	Text Figure References
Semi-arid Shoshong-Mokware area E. Botswana	End of the dry season	NW-SW and WNW-ESE faults and shear zones	Basic and acid plutonic rocks	1. Straight water courses follow fractures and appear as faint light toned lines on MSS band 5 but are less distinct on MSS band 7.	4 on Fig. 4.4
				2. Straight watercourses follow fracture but there is also a strong tonal contrast between soils on opposite sides of the fracture(MSS bands 5 and 7).	5 on Fig. 4.4
Wet-and-dry tropical Central Tanzania	Middle of the rainy season	NE-SW faults (Neogene)	Precambrian basement and plutonic rocks	1. Very straight wide shallow channels crossing flat area of residual granite soils. Medium/light toned on MSS band 5 and 7. Show best on MSS band 7 due to lower background albedo of residual soils.	7 on Fig. 4.6
				2. Deep fractures cutting the mountain granite show up well on MSS band 5 due to the alternation of tones on opposite flanks of the valleys.	6 on Fig. 4.6
Wet tropical S. Maniema E. Zaire	Middle of the rainy season	N-S and NNE-SSW fractures	Permo-carboniferous sediments (Karroo)	Very straight broad shallow channels which are medium toned on MSS band 5 contrasting with the lighter tone of the adjacent savannah lands. Also show as narrow dark toned channels on MSS band 7.	6 and 7 on Fig. 4.8b
Mediterranean N.E. Sardinia	Dry summer season	ENE-WSW regional fracture	Hercynian granite batholith	Very straight, long(over 40 kms.) deeply cut negative feature seen on MSS band 5 where it shows up due to the lighter tone of the valley floor c.f. the adjacent bush covered slopes.	7 on Fig. 4.10
Temperate Grampian Highlands of Scotland	Late winter	ENE-WSW regional fractures	Precambrian basement	Show mainly as broad deep valleys such as the river Dee which show well on MSS band 7 as dark toned lines and as broader medium toned tracts of alluvium on MSS band 5.	5 on Fig. 4.12a

best seen on MSS band 5, whilst fractures distinguished on the basis of topography are generally more clearly seen on MSS band 7(mainly due to shadow enhancement). The study has also shown that many fractures can be picked up by the persistent linearity of broad shallow watercourses on LANDSAT imagery. Such channels when examined on single aerial photographs do not necessarily suggest fracture control.

Local tectonic fractures

Local tectonic fractures are relatively short fractures which are mainly observed over areas of hilly and mountainous terrain on the satellite imagery. Table 6.5 shows that they generally appear as negative features in the landscape and are usually best seen on the IR MSS image bands, due to the dark shadows produced by their negative relief. Many of the longer fractures belonging to this category appear as groups of lineaments with a persistent parallel trend, and these may be genetically linked to some of the regional fractures. Such lineaments may be numerous on the imagery and can impart a structural grain to part of a plutonic mass e.g. the NNE-SSW grain of the northern part of the Sardinian batholith shown on Fig. 4.10a. Other local tectonic fractures are very short and although they may show locally as very regular networks of lineaments, like the macro-joints of the Cairngorms granite, they are not persistent over larger areas. These minor fractures are sometimes merely related to a local stress field associated with an individual intrusive centre, which itself may form only a small part of a large composite intrusion like the Sardinian batholith.

Table 6.5 The photo-characteristics of local tectonic fractures observed on LANDSAT imagery

Climate and Location	Season of Imagery	Fractures	Rocks Affected	Photo-characteristics of fractures	Text Figure References
Semi-arid Shoshong-Mokware area E. Botswana	End of the dry season	NE-SW, NNE-SSW and NW-SE macro-joints	Shoshong dolerite	These fractures are denoted by dark lines where they cut outcrop and also by light toned lines where they separate individual blocks of the main outcrop(MSS band 7).	Fig. 4.4a
Mediterranean N.E. Sardinia	Dry summer season	NNE-SSW minor fractures	Hercynian granite batholith	Numerous parallel short fractures in the heavily dissected northern part of the Sardinian batholith. They show as medium to dark toned negative features on MSS band 5.	Fig. 4.10a
		NNW-SSE minor fractures	Hercynian granite batholith	Parallel fractures cutting many of the other lineaments. They appear as definite negative features in the landscape of the granite of the southern part of the study region. They are pervasive and relatively evenly spaced, approx. 7 kms.(MSS band 5).	Fig. 4.10a
Temperate Grampian Highlands of Scotland	Late winter	NE-SW and N-S fractures	Caledonian granite batholith	Very deep negative features cutting the Cairngorms massif which have probably been deepened by ice action. Due to the depth of excavation they appear as broad medium toned tracts on the imagery as all that can be seen are the valley flanks(MSS band 7).	4 on Fig. 4.13
		NNW-SSE and NE-SW macro-joints	Caledonian granite batholiths	Cross-hatched, nearly orthogonal arrangement of fractures infilled with snow clearly visible on the flanks of the Cairngorms and Lochnagar granites(MSS band 7).	5 and 6 on Fig. 4.13

Miscellaneous lineaments

The appearance of lineaments on satellite imagery, as has been shown, is very variable and unequivocal designation of the type and origin of individual lineaments is the exception rather than the rule in photointerpretation. However as with fractures there are a few pointers which may help to pick out some of the other types of geological lineaments which may be encountered on satellite imagery. Examples of some of these lineaments and their photo-characteristics are given in Table 6.6.

Shear zones

Perhaps the most common type of lineament on the imagery next to fracture and bedding traces are produced by shear zones. Unfortunately there are no definite criteria by which these may be identified on the imagery as they often appear to be virtually identical to fracture traces on the imagery. However some general points arising from this study which may be of help when searching for shear zones on the imagery are given below:-

1) Shear zones commonly occur as very straight features on the imagery which do not change direction.

2) They frequently appear as diffuse zones on the imagery rather than sharp lines.

3) They are sometimes manifest by straight lines of mylonitised outcrops.

4) In semi-arid regions they may be picked out by their dark tone on IR imagery due to the presence of moisture along the shear zone (this also applies to fractures to some extent).

Table 6.6 The photo-characteristics of several miscellaneous lineaments which were observed on the LANDSAT imagery

Climate and Location	Season of Imagery	Lineaments	Rocks Affected	Photo-characteristics of Lineaments	Text Figure References
Wet-and-dry tropical Central Tanzania	Middle of the rainy season	NNW-SSE major zone of disjunction	Runs along the margin of the Tanzania craton	Broad, diffuse mottled zone of residual soils following the edge of the Tanzania craton. Shows up well on MSS band 5 as it is slightly darker toned than the adjacent light toned residual soils. The zone is very straight and can be traced on the imagery for over 100 kms.	10 on Fig. 4.6
		ENE-WSW Shear zones	Archaean granite batholith	Straight channels on the Dodoma plains with a similar appearance to the NE-SW Neogene faults of the region. Sometimes shown by lines of outcrops of sheared rocks as at 8 on Fig. 4.6. These show up well on MSS band 5 due to the darker tone of the outcrops c.f. the residual soils.	8 on Fig. 4.6
		WNW-ESE Shear zones	Archaean granite batholith	Not easily observed on the imagery except where shown by elongated outcrops of sheared greenschist inliers as at 9 on Fig. 4.6. One diffuse darker toned NW-SE line south of the greenschist inliers at 9 may be a shear zone. This line is best seen on MSS band 7 where it probably shows up as a darker line due to the higher moisture content of the soil along this line.	9 on Fig. 4.6
Wet tropical S. Maniema E. Zaire	Middle of the rainy season	NW-SE ?shear zone	Burundian granites	Numerous short lineaments constitute a very broad zone of fracturing and/or shearing. Visible only on IR MSS bands where the tiny lineaments appear as darker toned negative features in the equatorial forest region.	5 on Fig. 4.8b
Mediterranean N.E. Sardinia	Dry summer season	Major NW-SE lineament (?fault scarp)	Hercynian granite batholith	A dark toned diffuse line crosses the image but does not form a negative feature(MSS band 5). Under the stereoscope it appears to be a fault scarp with the dark tone being due to the steep slope of the scarp.	8 on Fig. 4.10
Temperate Grampian Highlands of Scotland	Late winter	NNW-SSE major curvilinear lineament	Precambrian basement and Palaeozoic rocks	This is a gently curving lineament which is generally a negative feature and strikes intermittently for over 100 kms. Parts of it are best seen on MSS band 5 by the light tone of valley alluvium and where it crosses mountainous country it is best seen on MSS band 7.	3 on Fig. 4.12a
		Major thrust fault	Precambrian basement	The Iltay Boundary Slide is shown up principally by the very sharp curveature of its line at 7 on Fig. 4.13 and by its SE'ly retreating notch junction which has left a broad valley which is well seen due to the light toned alluvium which fills it on MSS band 5.	7 on Fig. 4.13

Shear zones may be narrow or very wide and in the latter case may be more appropriately designated as zones of disjunction by the photogeologist. Such a zone was observed by the writer at 10 on Fig. 4.6 which runs for over 100 kms. just to the east of the margin of the Tanzania craton.

Fault scarps

Fault scarps representing relatively young faults are generally easily identified by their straightness where rift valleys are formed on the downthrow side of the fault, e.g. the Tertiary rift fault at 4 on Fig. 4.10 which cuts the Sardinian granite batholith. However in many cases extensive Cainozoic faults may only be indicated by a faint line on the imagery, or sometimes a dark zone where a fault scarp has developed as at 8 on Fig. 4.10. Such faults may be of especial interest in mineral exploration as they may be related to the emplacement of relatively young mineral deposits such as the porphyry copper ores of the North and South American cordilleras. These faults can be distinguished on the imagery by a number of factors of which the following is a summary:-

1) The faults are generally very long.

2) They commonly cross-cut most of the other fractures.

3) They may appear as dark toned lines(or zones) where a fault scarp has developed.

4) The faults often do not form negative features as due to their relative youth there has not yet been time for erosive processes to impress these into the landscape.

Thrusts — Low angle thrusts such as the Moine thrust and the Iltay Boundary Slide(IBS) of the Highlands of Scotland may occasionally be identified on satellite imagery by the sinuosity of their line. The IBS is well seen on the satellite imagery at 7 on Fig. 4.13 where it is traced by the sharply curving valley of the Clunie Water.

Dykes — Most dykes are generally too narrow to be observed on satellite imagery unless there is exceptional spectral contrast between the dyke and the adjacent rocks or soils. These conditions are most likely to be satisfied in arid and semi-arid regions where basic dykes like dolerites appear as dark toned features against the light tone of residual soils.

6.4.3 Circular features

Tanzania craton — A semi-circular feature about 13 kms. across can be seen at the margin of the Tanzania craton just to the north of Msagali on Fig. 4.6. This ring structure is clearly shown on MSS band 7 by the light tone of the peripheral sand river and the darker tone of the soils and rocks within the ring compared with those outside. This ring structure lies directly on a major NNW-SSE zone of disjunction. Ancient basic metamorphosed dykes approximately follow this zone which was initiated in the early Archaean and probably rejuvenated during a period of late-Mozambiquian deformation.

Sardinian batholith — A number of circular features were observed on the imagery covering the Sardinian batholith. These structures are from 5 to 10 kms. across and it is considered by the writer that they represent individual intrusive centres within the batholith. The circular structures appear

to belong to one of two types which are:-

1) Heavily dissected rather dark toned masses with deeply cut valleys with steep wooded sides(dark toned on MSS band 5). Outlines are rather ragged and they may be circular or elliptical(e.g. 11 on Fig. 4.10).

2) Strongly circular ring structures which may be shown by a broad ring feature within the main structure or by a dark toned peripheral annular drainage channel on MSS band 5(e.g. 12 on Fig. 4.10).

It is suggested that those rocks of category one represent homogeneous late-phase acidic intrusions, whilst those of category two may represent ring fractured, possibly composite intrusions.

Caledonian granites

Polyphase intrusion accompanied by successive phases of cauldron subsidence was a feature of the genesis of some of the Caledonian granites of Scotland. This has resulted in annular, crescentic, circular and elliptical outcrops of varying composition within a single pluton. The Lochnagar ring complex is one such intrusion and the satellite imagery shows an elliptical feature about 4 kms. across at the centre of this mass(1 on Fig. 4.13). This feature is picked out on the imagery by a steep dark toned corrie at the southern end and by two convex stream courses to the north. Although this feature does not exactly coincide with any mapped rock unit of the complex it is almost certainly related to the annular structure of the intrusion. The circular form of this pluton is echoed by the strong curve of Loch Muick around the southern perimeter of the batholith.

Moving north-westward on Fig. 4.13 on to the mass of the Cairngorms granite yet another circular feature of about 4 kms. diameter is encountered at point 2. This feature is shown by a curving drainage-way, and the curving line of steep cliffs and corries, with their attendant dark shadows on this IR image. Furthermore on this enlarged print it is possible to see that this ring lies at the centre of a much larger set of rings, which are shown up principally by an annular drainage system. On the MSS band 5 image(Fig. 4.12a) where snow enhances these circular features another possible ring structure can be seen just to the south-west of the original innermost ring. It seems therefore likely that the Cairngorms is a composite intrusion of some complexity composed of two, three or even more intrusive centres.

6.4.4 Morphotectonic units

Definition

Morphotectonic units as observed on satellite imagery are individual landscapes uniquely defined by distinctive tonal, textural and pattern elements, resulting from the integration of certain lithological, structural, topographical and drainage characteristics. These units are often separated by major faults, related to vertical tectonic displacements.

Hoggar mountains

Two distinct morphotectonic units were observed on the LANDSAT imagery of the eastern Hoggar mountains(Fig. 4.2). A western unit is underlain by folded Suggarian gneisses which have a striated outcrop texture and are medium toned on MSS band 5. Fold closures are clearly visible on this well exposed unit and the drainage is partly controlled by the major folds and

partly by fractures. The western unit is separated from an eastern unit of mixed metasedimentary and magmatic rocks(referred to by this writer as the igneous/metamorphic complex) by the geotectonic $8^{o}30'$ meridional fault. The scenery of the eastern unit is rugged and consequently much darker toned on the imagery than the western unit(due to the presence of numerous steep slopes). This strong tonal difference between the two units is one of the most striking differences between them. The outcrop texture of the eastern unit is predominantly lumpy and a fine fracture texture is developed over parts of the unit. Island patterns of outcrops, in areas of residual soils around the periphery of this unit, emphasize the fracture control and poor integration of the drainage system of this dominantly plutonic unit.

Tanzania craton

The granite of the Tanzania cratonic batholith is divided into two morphotectonic units in the Chenene Hills region of central Tanzania(Fig. 4.6). The larger unit is a broad flat plain of light toned residual soils with isolated dark toned tors of exhumed granite corestones (MSS band 5). To the north-east the tectonically uplifted block of the Chenene mountains forms a NW-SE elongated range of granite hills. This unit is much darker toned than the plains area on MSS band 5 due to the denser vegetation cover and rougher topography. The valleys of the mountain block are deeply cut and steep-sided being largely controlled by NE-SW fractures. The northern boundary of the mountain block is sharp with a smooth, rounded or straight boundary line representing a steep fault scarp. Whilst to the south-west the mountains grade gradually into the plains area suggesting that the mountain block has been tilted to the

south-west. The irregularities of the northern fault scarp appear to be due to displacement of individual blocks of granite along NE-SW Neogene faults.

Sardinian batholith

The tripartite division of the north-east part of the Sardinian granite batholith has been described at length in Section 4.5.2 and has been cited as typical examples of what is meant by morphotectonic units. The photo-characteristics of these three units are now summarized below(reference may also be made to Fig. 4.10c):-

1) The northern block to the north of the NE-SW Monti rift fault has a well dissected erosional texture. Much of the drainage is fracture controlled and these channels are well displayed on MSS band 5 where they show as dark toned lines.

2) The central block south of the Monti fault is less mountainous and generally lighter toned on MSS band 5. Rounded tabular massifs are common with ragged scarp edges due to the numerous rivers which flow off these plateaux.

3) The southern block is mountainous and has a fairly well dissected erosional texture, but the drainage is not markedly fracture controlled.

6.5 The shape of plutons

The ease with which plutons may be recognised and their boundaries traced on satellite imagery varies according to such factors as rock composition, mode of emplacement and structural level exposed at the surface. Many epizonal plutons (those emplaced at the shallowest depths) have circular outlines representing horizontal sections across diapiric(inverted, tear drop shaped) intrusions. Such circular features may also be found within larger plutonic masses where polydiapirism has taken place as in the case of the Sardinian batholith(Section 6.4.3). However the overall shape of the larger plutons of the mesozone and catazone, which have featured prominently in this research project, are commonly irregular though rounded margins are typical.

The boundaries between rock units in peneplaned regions in both humid and arid zones are often obscure. In arid and semi-arid regions boundaries may however sometimes be inferred from tonal and textural differences on the satellite imagery between rock units. But in the humid tropics the widespread development of zonal soils and uniform vegetation cover often make it difficult to interpret more than just the main areas of crystalline and sedimentary rocks. The granites of temperate regions are generally much less chemically weathered than those of the tropical regions, and consequently may stand out as positive elements of relief which can be delineated on the imagery e.g. the Cairngorms granite massif Fig. 6.2a.

Fracture control of pluton emplacement and post-consolidation fracturing may produce fault-bounded blocks or elongated bodies of magmatic rocks. Where marginal faults are present these may show up well on the satellite imagery due both to the linearity of the fault and to strong tonal differences between the pluton and the adjacent rocks.

Catazonal plutonic masses sometimes occur as updomed structures, though such domes have generally been planated. However the presence of such units may be indicated on the satellite imagery by curving inliers of originally mantling sediments like the Dodoman greenschist enclaves at 9 on Fig. 4.6 within the Tanzania craton. At shallower structural levels such plutons may show up as vast arena structures surrounded by an almost continuous belt of metasedimentary rocks.

6.6 Size and scale

The size and types of geological features which can be observed on satellite imagery are fundamentally controlled by two basic characteristics of the image production process. These are the resolving power of the imaging system(the MSS, data feedback system and image processing in the case of LANDSAT) and the scale of the final image used for interpretation. Two further, more subjective elements affecting interpretation are the detectability and recognizability of features on the imagery and these were discussed in Section 2.2.3.

The calculated ground resolution of the photographic image products produced from the LANDSAT MSS data is in the region of 70 - 80 metres. In practice narrower lineaments may show up on the imagery if there is a strong reflectance contrast between the observed feature and the adjacent part of the scene. However for practical purposes the ground resolution figures given above can be used as a working guide to the limitations of the imagery in terms of detectable features.

Although the size of plutonic bodies varies enormously from minor dykes occupying narrow fissures to vast areas of cratonic granites covering thousands of square kilometres it is important to remember, that as far as the interpretation of plutonic rocks on LANDSAT imagery is concerned, only those bodies of near batholithic proportions will appear as really significant entities. A body of 100 sq. kms., the size of body arbitrarily laid down by Daly as

the minimum size for a batholith, even so only covers four square centimetres of a 1:500,000 scale LANDSAT scene(approximately 1% of the scene area).

The useful range of scales which can be used for interpretation of LANDSAT imagery is considerable, ranging from mosaics constructed at the contact scale of the original negatives received from NASA(approx. 1:3,000,000 scale) up to about 1:250,000 scale. At larger scales than 1:250,000 blurring of detail becomes excessive and for general purposes severely limits the usefulness of the imagery. At smaller scales than 1:3,000,000 the imagery becomes very generalized and only major features show up. Such mosaics are of some value but imagery of less than 1:5,000,000 scale is of little more value than imagery received from the higher altitude weather satellites.

The writer after examining a number of different scales of imagery found that 1:500,000 scale prints provided considerable detail without being excessively large and unwieldy. Consequently prints at this scale(size 37.0 x 36.2 cms.) were used almost exclusively throughout this study. Fig. 6.2a shows part of an MSS band 6 image covering the Cairngorms mountains of Scotland at a scale of 1:500,000.

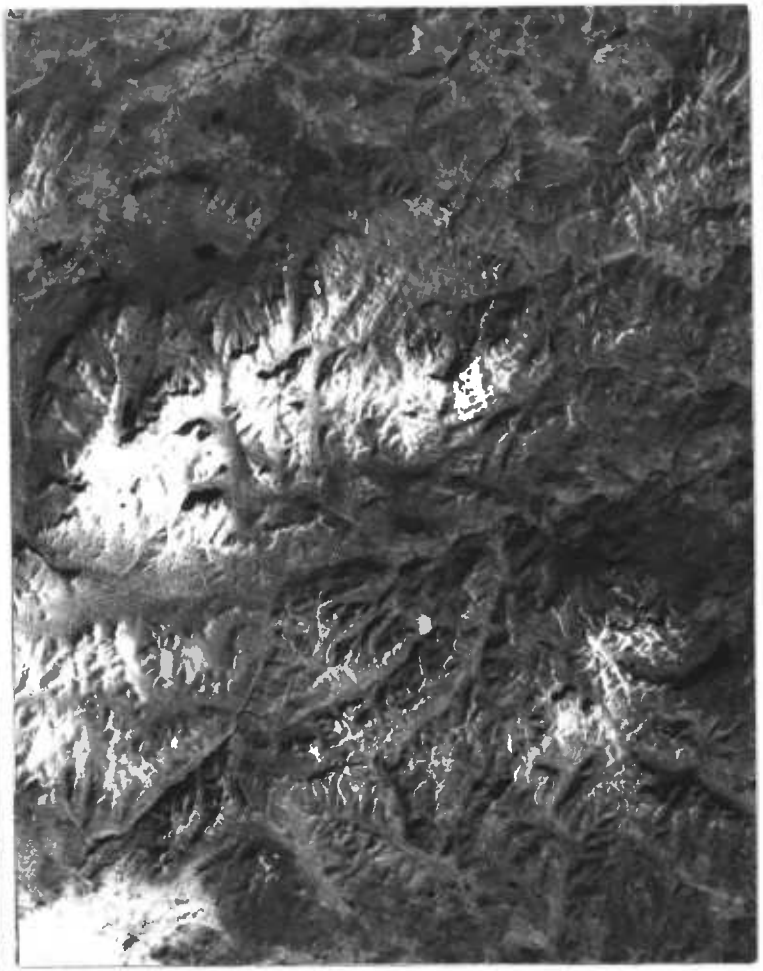
Although 1:500,000 scale imagery was mainly used for interpretation in this project a small amount of work was carried out at both smaller and larger scales. Fig. 6.2b shows an enlargement of part of Fig. 6.2a with the dominating Cairngorms mountain block occupying a large part of the print area. On this enlargement the outline of circular structures within the

Fig.6.2a(left)

MSS band 6 of part of LANDSAT-1 scene 1233-10564 covering the Cairngorms mountains (Scale 1:500,000)

Fig.6.2b(right)

MSS band 6 of part of LANDSAT-1 scene 1233-10564 (Scale 1:350,000 approx).



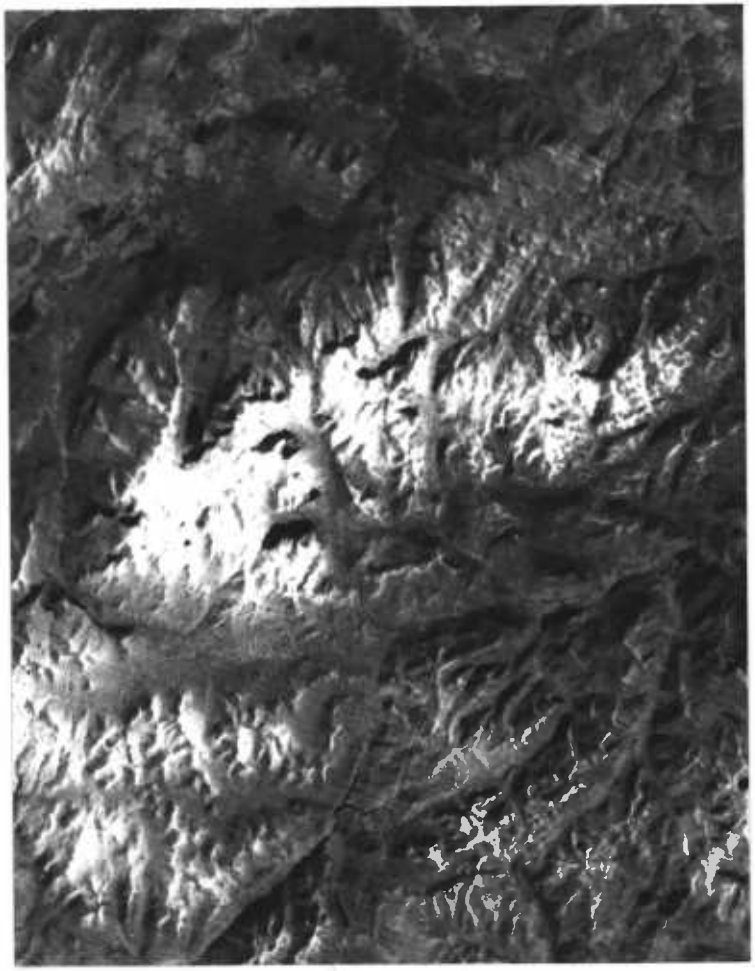


FIG.6.3

Fig.6.3a

Lineament plot of Fig.6.3b.
A LANDSAT-1 mosaic covering the Grampian Highlands of Scotland (Scale 1:1,350,000 approx).
Mineral localities taken from Gallagher et al. 1971.

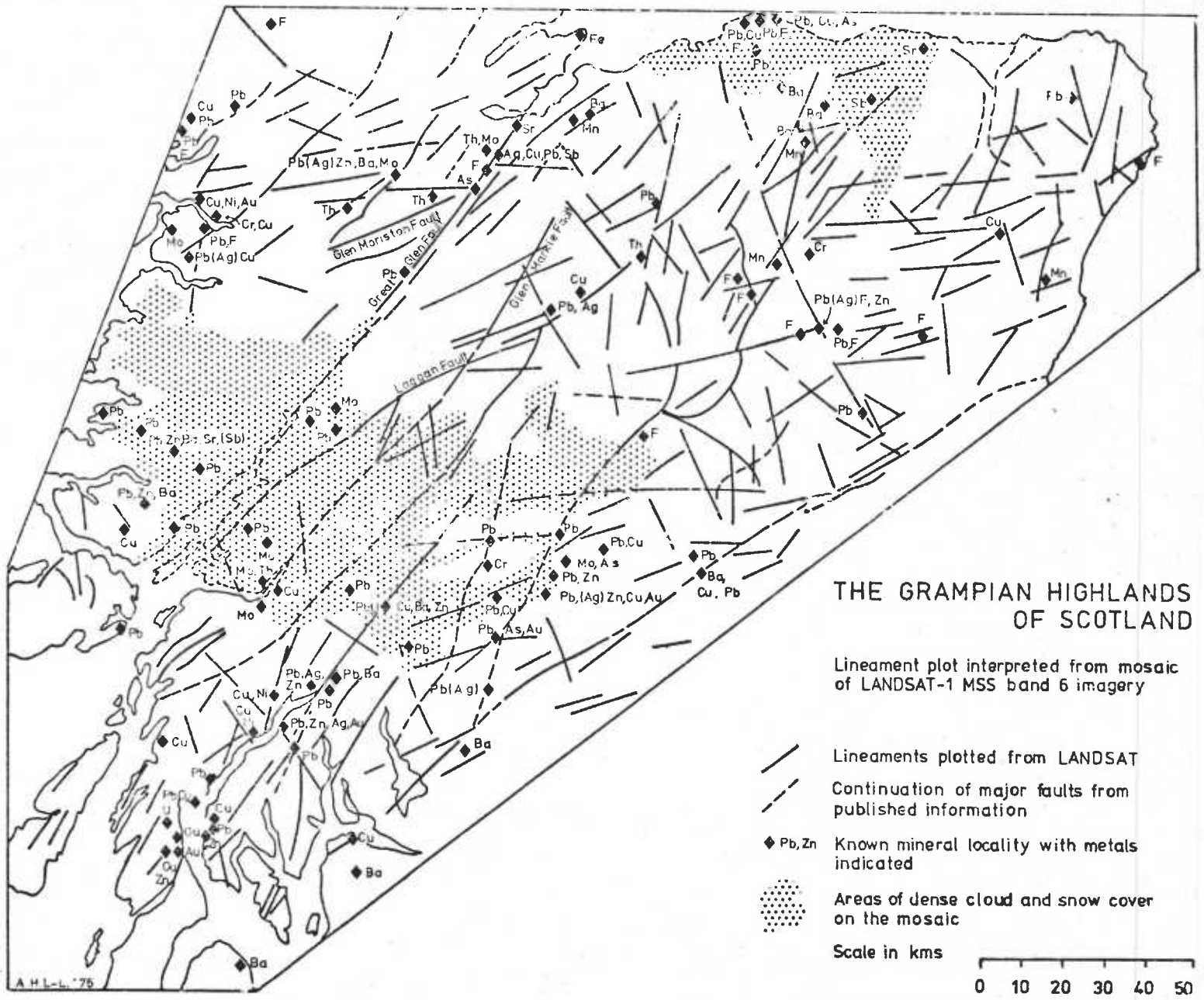
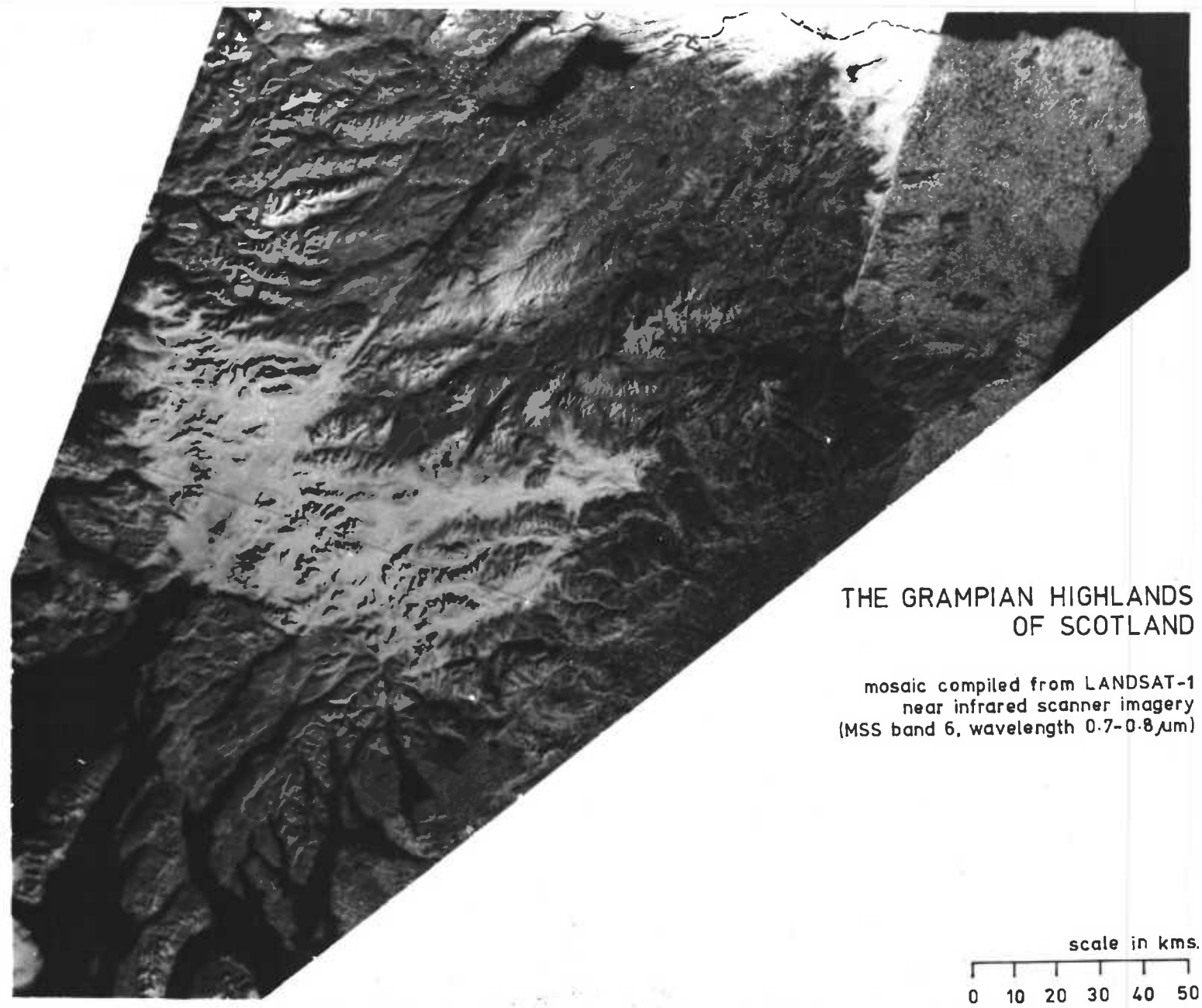


Fig.6.3b

MSS band 6 mosaic of LANDSAT-1 imagery covering the Grampian Highlands of Scotland (Scale 1:1,350,000 approx).



Cairngorms massif are more readily discerned, and it is also possible to see more clearly the variation in drainage texture over the whole mountain block. Fig. 6.3b shows a mosaic of the whole Grampian Highlands and in the NW of the area shown it is possible to see the dominant rhombic pattern of the major faults in that region. The outline of the Cairngorms massif

Table 6.7 Examples of the types of features related to plutonic rocks which can be seen on enlarged prints of LANDSAT scenes and those which can sometimes be more readily observed on smaller scale prints including mosaics

SINGLE SCENES (Scales 1:250,000-1:1,000,000)	SINGLE SCENES and MOSAICS (Scales 1:1,500,000-1:3,000,000)
1. Regional lithological variations(tones and textures).	1. Major rock groups e.g. the ability to distinguish between sedimentary basins and areas of crystalline basement.
2. Outcrop boundaries of plutons larger than 10 sq.kms.	2. Outcrop boundaries of batholiths(i.e.masses>100 sq.kms)
3. Outcrop texture.	3. Erosional texture of major rock units.
4. Dykes, sills, inliers, stocks and batholiths.	4. Major batholiths and cratonic blocks.
5. Regional drainage patterns and textures.	5. Major continental rivers.
6. Local tectonic and regional lineaments.	6. Major regional lineaments and geotectonic lineaments.
7. Shear zones.	7. Major strike-slip faults and rift valleys.
8. Morphotectonic units.	8. Morphotectonic units.
9. Structural style of plutons	9. Structural style of cratons.
10. Structural control of pluton emplacement.	10. Structural control of the emplacement of several related plutons.
11. Regional structural setting of mineralization	11. Regional structural setting of mineralization

also shows up clearly as the boundary irregularities have been simplified at this small scale.

The three scale examples illustrated show that there is a variation in the density and types of information which can be obtained from different scales of imagery. Table 6.7 gives a summary of the types of features related to plutonic rocks which can be obtained using different scales of imagery. Investigators planning photogeological projects using satellite imagery should therefore at an early stage decide what type of geological information is required from the study. They should then choose the scale of imagery which will readily enable the photointerpreters to obtain this information.

6.7 Type of Imagery

General

The imagery used for this study was in the main system corrected(bulk) MSS images which were obtained from the EROS Data Center as 70 mm format negatives. These negatives have a limited density range which is less than the original LANDSAT negatives. However they were adequate for making the paper prints which were largely used for interpretation. In fact the bromide papers used for printing have an even narrower density range than the bulk negatives.

6.7.1 Image quality - black and white imagery

This writer found that the factors which affected the image quality of black and white imagery were of two main types - factors related to image processing, and those related to natural phenomena at the time the images were taken. The majority of the image processing factors were a hindrance to interpretation, whilst the effects of various natural phenomena at the time of imaging were in some cases advantageous to the interpreter.

The following defects of image processing were encountered on some or all of the LANDSAT frames examined:-

1) Scan lines were too prominent.
2) Scratch lines at right angles to the scan direction.
3) Small bubble-like grey marks on some prints.
4) Areas of Newton's rings on some negatives.
5) Blurring of parts of the negatives.
6) Dense negatives producing low contrast prints.

The majority of these defects were inherent in the negatives received from the Data Center and there was little that could be done to compensate for them during the final print making process.

The types of natural phenomena which influenced image quality were:-

1) Cloud cover
2) Snow cover
3) Atmospheric scattering
4) Seasonal phenomena
5) Sun angle at time of imaging

Cloud cover

Images with less than 10% cloud cover were selected for this project from the NASA LANDSAT catalogues. However the NASA estimates of cloud cover were not always reliable and some negatives proved unusable due to cloud cover in excess of the estimated percentages.

Snow cover

Snow cover commonly affects the appearance of the imagery of the higher regions of northerly climatic zones in winter. Clouds can usually be distinguished from snow cover by their attendant shadows on the imagery. Moderate snow cover proved to be an aid to the interpretation of parts of the Grampian Highlands area as it picked out circular structures, strike ridges and fractures. The writer also observed that there was greater penetration of snow cover on IR imagery than on the visible band imagery. Examination of individual bands therefore produced more information than if only a single band had been used for interpretation.

Atmospheric scattering

Scattering of reflected radiation takes place in the atmosphere by interaction with the gas molecules of the atmosphere, haze or dust particles (particulates) and clouds of liquid or solid

water. Molecular scattering is of some importance in the visible part of the spectrum but is negligible beyond 1 μm. Haze or dust particles are important in remote sensing. The dense Saharan haze of the mediterranean summer months was probably responsible for the murky appearance of the LANDSAT scenes of Sardinia examined. Although variation in the density of particulates does not greatly affect the degree of attenuation of reflected radiation the degree of humidity does. High humidity in the lower atmosphere will cause water vapour condensation on particulates which may severely attenuate the reflected radiation. In planning remote sensing projects it is important to order imagery taken not only on a cloud free day but also at a time when the relative humidity was low. Clouds are generally optically opaque and cause complete obliteration of the ground in the 0.3 to 3.0 μm. waveband.

Seasonal phenomena

The imagery of arid and semi-arid regions is most useful for photogeological interpretation when taken during the rainy season. The reasons for this are firstly that during the dry season vegetation is generally dormant and there is little variation in reflectance between vegetated and bare soil areas, and secondly the soil moisture content varies during the wet season depending on the soil texture and these differences can be picked up on IR imagery.

Sun angle

Low sun angle imagery can be a great advantage in satellite image interpretation where stereoscopic cover is not generally available. Low sun angles lengthen shadows and produce an accentuation of relief on the imagery. The greater part of the mosaic of the Grampian Highlands(Fig. 6.3b) was taken with the sun at

an elevation of 27°. Hackman(1967) concluded that a sun angle of 20-30° was the most useful for the interpretation of geological features on aerial photographs. The disadvantages of low sun angle imagery is that there may be increased atmospheric scattering and also a loss of tonal values accompanying increased shadow enhancement. However, in view of the commonly weak tonal differences between rock types on satellite imagery, enhancement of relief differences may be of more use to the interpreter than good tonal discrimination: especially when much of the useful geological information gained from satellite imagery is related to linear patterns rather than to tonal or textural aspects of areas.

6.7.2 Colour composite images

Colour composite prints made from three individual MSS bands of LANDSAT imagery(normally MSS bands 4,5 and 7) were unavailable from the EROS Data Center for all but one of the writer's case study regions. The technical difficulties and expense of producing high quality colour composite prints are considerable, and in addition higher quality starting negatives have to be obtained from the Data Center(N-4 negatives). The writer felt that on the whole the versatility of black and white paper prints of individual MSS bands outweighed the advantages of using poor quality colour composite prints. Consequently only a very limited amount of work was carried out on colour composite material.

The standard type of colour composite prints produced by the Data Center are made in such a way that the false colours depicted on the images

resemble as nearly as possible those produced on Kodak Ektachrome colour infrared(CIR) film. In fact the three MSS bands 4,5 and 6 correspond exactly to the sensitivity ranges of the three emulsion layers of CIR film. In practice MSS band 7 is used to make the LANDSAT colour composites rather than MSS band 6 as it gives a higher contrast between water and vegetation (McEwan and Schoonmaker, 1975).

CIR film was developed during the Second World War for camouflage detection. The false colour convention used on this film allows easy interpretation of vegetation, water and cultural features. This convention has been adhered to over the years because increasing numbers of civilian interpreters have found it to be the most satisfactory for general purposes. From the geological standpoint this CIR film convention is not always helpful. Colour composite images of temperate regions are commonly saturated by a red colouration which is due to the strongly reflective nature of ubiquitous green plants in the infrared part of the spectrum. Colour composite prints are most useful in the semi-arid regions. The colour composite print of the Shoshong-Mokware area(Fig. 4.4c) helped to differentiate sparsely vegetated soil associations from more vegetated ones, by the pinker tones of the latter. Further examples of the value of colour composite imagery are shown by the excellent prints in the review on the applications of LANDSAT imagery in geology and mineral exploration by Viljoen et al(1975).

CHAPTER SEVEN

CONCLUDING OBSERVATIONS

7.1 General

The aim of this research was to ascertain what value multiband satellite imagery might have for photogeological investigations. This was realised by examining the appearance of plutonic rocks and related features on a number of LANDSAT-1 satellite images from different climatic zones. The positive results of this survey were then described in terms of possible criteria which could be used to identify certain features of plutonic rocks on the imagery (Chapter 6).

The general lack of variations in spectral response from areas of bare rocks and soils of plutonic rocks in the range of the LANDSAT MSS wavebands(0.5 - 1.1 μm), anticipated by the writer from laboratory studies(Salisbury and Hunt, 1974) were confirmed by the present investigation. However the considerable tonal differences between visible and IR MSS bands related to variations in soil moisture and vegetation cover compensated for this deficiency in many cases. These variations were commonly found to be related to geological factors and enabled lithological and structural features to be interpreted on the imagery. Rainy season imagery with the new season's vegetation showing clearly is generally superior to dry season imagery for photogeological interpretation of semi-arid regions.

It therefore appears to the writer that LANDSAT does have a contribution to make to the photo-interpretation of plutonic rocks and some of the important features recognized on the imagery are listed in Table 7.1.

Table 7.1 Important features of plutonic rocks which were observed on the LANDSAT imagery

MISCELLANEOUS	
1. Outcrop boundaries	6. Areas underlain by basement rocks
2. Circular epizonal plutons	7. Areas of residual soils underlain by granite
3. Granitic morphology of hill regions	8. Morphotectonic units
4. Dykes, sills, stocks and batholiths	9. Erosional texture
5. Greenstone inliers within an Archaean craton	10. Fracture texture

LINEAMENTS	
1. Major zone of disjunction	5. Fractures
2. Rift Faults	6. Shear zones
3. Faults	7. Macro-joints
4. Fault scarps	8. Strike of metasediments

The features listed were not all observed with equal facility on the imagery of the various regions examined. Outcrop boundaries were most readily drawn around inselbergs and hill masses of plutonic rocks in the arid and savannah regions. Circular epizonal plutons were generally readily observed in both humid and arid environments. The considerable number of circular structures within some of the larger batholiths emphasized the composite nature of such bodies. The granites of hilly regions were characterized by deeply cut valleys and rounded interfluves in both humid and arid

climates. These generally contrasted strongly with areas of metasediments which have sharper crests to the interfluves.

Dykes could only generally be distinguished on the imagery of semi-arid regions where there was a strong tonal contrast between the narrow outcrops and the surrounding residual soils. Areas underlain by crystalline basement in the rain forested, wet tropical regions of eastern Zaire were distinguished from sedimentary basins by the broad curvilinear drainage pattern of the former compared with the parallel drainage pattern of the latter.

Fracture texture was useful for locating plutons in all climatic zones as intense fracturing is often associated with epizonal and mesozonal plutons. Variations in erosional texture helped to define morphotectonic units. The concept of morphotectonic units developed by the writer as a result of the synoptic views afforded by LANDSAT is one of the unique contributions of the imagery to tectonic studies.

The lineaments observed on LANDSAT proved to be the greatest single addition to the geological knowledge of most of the areas examined. The writer's four fold length classification of lineaments into geotectonic($>$150 kms.), major regional(80 - 150 kms.), regional(20 - 80 kms.) and local tectonic($<$20 kms.) attempts to aid studies of pluton emplacement and the control of mineralization.

The lack of stereoscopic imagery for almost all the regions examined was a drawback to accurate interpretation of the observed features. This handicap may be overcome in the future by the

use of a new digital image processing technique. The technique aims at creating a stereoscopic mate from a given image by introducing parallax as a linear function of terrain at each picture point.

Imagery of the highest quality is required for interpretation: this means imagery with zero cloud cover and imagery virtually unaffected by the effects of atmospheric scattering.

7.2 LANDSAT imagery in mineral exploration

The writer was not directly concerned with the value of LANDSAT imagery for mineral exploration. However the research suggested that it could be of value for this work, especially where background information and/or data from ground studies is available. Like most tools of the exploration geologist its main use is to suggest where to look, rather than to pinpoint actual mineral deposits. Three types of features were observed on the imagery by the writer which may be associated with mineralization and these are:-

1) Greenstone belts within an Archaean craton are sometimes sheared and associated with gold mineralization(Tanzania craton).

2) Circular structures were observed in the main part of the Sardinian granite batholith. They appear to represent diapiric intrusions within the main granite. The writer considers that these may be related to some granodioritic stocks in S.W. Sardinia which are associated with hydrothermal replacement deposits containing base metals.

3) Lineaments representing dykes, shear zones and faults providing loci for mineralization or for mineralization along associated tensional fractures were observed in various areas.

Greenstone belts

Gold mineralization of economic value is concentrated within the greenstone inliers(Nyanzian formation) of the northern part of the Tanzania

craton around Lake Victoria. The abundance of greenstone tracts in that region is due to their higher level within the batholith compared with those around Dodoma(Dodoman formation) in the central part of the batholith(Read and Watson, 1975). Viljoen et al. (1970) expressed the view that the gold of similar greenstone belts in southern Africa was introduced during their formation. The gold was subsequently concentrated into workable deposits by crustal processes accompanying mobilisation and emplacement of granitic material. Gold has been found in both the northern and central Tanzania greenstone belts even though the enclosing granite is exposed at different structural levels. Viljoen's hypothesis therefore suggested to the writer that originally gold was probably disseminated throughout all the Tanzania greenstone rocks. Therefore although the greenstone belts of central Tanzania are fewer in number than those of the north, due to their lower structural level, there is still the possibility that a workable concentration of gold may be located there(small concentrations have already been found).

LANDSAT imagery was particularly useful for picking out the greenstone belts in the Dodoma region. This was due to the dark tone of such belts on MSS band 5 related to dense vegetation over the lime-rich soils derived from amphibolitic rocks. The writer suggests that a LANDSAT survey carried out over a wide, poorly mapped, NW-SE tract of the Tanzania batholith centred on the town of Tabora would pick out more greenstone belts. In addition the mapping of fractures and shear zones could be carried out, which, together with any newly

mapped greenstone belts, could provide further information relevant to gold prospecting.

Circular structures

The central zone of the main part of the Sardinian batholith contains several quartz dioritic and granodioritic stocks as well as numerous dykes, the products of late-stage magmatic activity. The satellite imagery of this region shows a number of circular features of several kilometres diameter. These may well be an indication of the granodioritic stocks referred to above i.e. a manifestation of "diapirism within diapirs" or the phenomenon of polydiapirism(Stephansson, 1975). Such stocks could be similar to the mineralized granodioritic stocks of south-west Sardinia where workable concentrations of base metals have been located. The writer suggests that if further photogeological and ground studies were carried out in this central zone of the batholith it might lead to the discovery of economic base metal deposits. In view of the rather feeble relief of this zone a regional geochemical soil survey might also help in the location of sources of base metals.

Lineaments

Simple lineament plots examined in the light of knowledge of the type of mineralization in a given area may suggest additional targets for mineral exploration. The writer found that lineaments were of value in locating mineral deposits in five different situations which are outlined below:-

1) Mineralization is sometimes found where an igneous dyke intersects a rock of a particular composition. The dolerite dykes of the Shoshong-Mokware region in

E. Botswana are associated with a NW—SE set of lineaments on the imagery. Where the dykes intersect limestone chrysotile asbestos has been formed in some cases. Ground prospecting of the NW—SE lineaments might reveal further deposits of asbestos.

2) Major zones of disjunction can be picked out on the imagery, either as broad diffuse zones of marked linearity or as zones of several parallel lineaments. Such zones represent ancient lines of crustal weakness and may have provided loci for the intrusion of ultrabasic bodies. Minerals often associated with such intrusions include nickel, platinum and diamonds.

3) Igneous dykes associated with the late-stage magmatic activity of granite provinces may contain minerals such as tin, copper and silver. If the strike of some already located mineralized dykes is known then lineaments on the satellite imagery with the same trend will provide targets for further prospecting.

4) A comparison of a lineament plot from the imagery with a plot of known mineral localities for a region may show that some of the lineaments pass through one or more mineral localities. If the strike of mineralized veins is known for each locality and these are found to coincide with the trend of the lineaments passing through them, it can reasonably be postulated that the vein and lineament are genetically related. Such a lineament then becomes a target for further ground prospecting.

5) Polyphase mineralization is not an uncommon phenomenon, as in the Highlands of Scotland where base metal mineralized veins follow a number of strike directions. Mineral deposits in such circumstances may be located where a younger fracture intersects a more ancient and established fracture. A plot of lineament intersections will suggest possible sites for additional mineral localities.

One final aspect of LANDSAT imagery in mineral exploration is the possible use of morphotectonic units in locating epigenetic mineral deposits. Morphotectonic units can be used to define relative differences in structural level of block-faulted regions. It may be that economic mineralization associated with intrusive igneous masses are confined to particular structural levels within the plutons. If a few surface showings or even borehole samples of these minerals are known, then it may be that the morphotectonic unit which includes these samples could define the limits of further mineralization belonging to the same structural environment.

7.3 In conclusion

The procedure adopted for this study was to examine the LANDSAT imagery of reasonably well mapped areas to discover which geological features could be picked up and to note their appearance on the imagery. The images were also examined for additional features not shown on published maps. The additional features noted included circular structures, fractures, faults, a fault scarp, macro-joints, morpho-tectonic units and a major zone of disjunction. The photogeologist examining imagery of unknown areas can expect to pick out a number of the features listed in Table 7.1. His ultimate success in interpretation will depend on an understanding of the limitations and advantages of working on imagery of particular climatic zones as discussed in this thesis.

It would now seem to the writer that multiband satellite imagery does have a definite role to play in future photogeological and mineral exploration projects.

APPENDIX

Background data on the LANDSAT imagery referred to in this thesis

Text Fig. Ref.	Location	Coords. of scene centre points	Scene ID No.	Date Imaged	MSS bands	Sun elev.	Sun azim.
Fig. 4.2a	E. Hoggar mountains Algeria	23°12'N 08°58°E	1071-09221	2nd Oct. '72	5	51.9°	131.2°
Figs. 4.4a & c	Shoshong-Mokware area E. Botswana	22°59'S 26°29'E	1069-07405	30th Sept. '72	5 & colour composite	50.0°	65.0°
Fig. 4.6a	Central Tanzania	5°44'S 36°24'E	1155-07133	25th Dec. '72	5	51.9°	121.1°
Figs. 4.8a & b	E. Zaire	4°25'S 26°43'E	1054-07524	15th Sept. '72	5 & 7	55.4°	78.2°
Figs. 4.10 a & c	N.E. Sardinia	40°42'N 9°53'E	1020-09341	12th Aug. '72	5	54.7°	128.9°
Figs. 4.12a & b 4.13a 6.2a & b	Grampian Highlands of Scotland	57°10'N 4°07'W	1233-10564	13th March '73	5,6 & 7	27.3°	154.7°
Fig. 6.3 b	Mosaic of the Grampian Highlands	57°10'N 4°07'W 55°46'N 4°59'W 57°16'N 1°14'W	1233-10564 1233-10570 1231-10451	13th March '73 13th March '73 11th March '73	6 6 6	27.3° 28.4° 26.4°	154.7° 153.5° 154.8°

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