SATELLITE IMAGERY (LANDSAT) FOR
RECONNAISSANCE SCALE NATURAL RESOURCE MAPPING
IN WESTERN SUDAN

Being a thesis presented by David E. Parry, in accordance with the regulations governing the award of the degree of Doctor of Philosophy of the University of Aston in Birmingham.

August, 1979.

SATELLITE IMAGERY (LANDSAT) FOR RECONNAISSANCE SCALE NATURAL RESOURCE MAPPING IN WESTERN SUDAN

David E. Parry Ph.D 1979

SUMMARY

This study examines the potential usefulness of multi-spectral imagery obtained from the LANDSAT 1 earth orbiting satellite, as a base for reconnaissance scale natural resource mapping in the Sahelian and Savanna zones of Western Sudan. The study is carried out in two parts and covers two adjacent areas of Southern Darfur Province.

The first part is a comparative analysis of the accuracy of a land system, geomorphology and soils map, compiled from the manual interpretation of bulk processed colour composite LANDSAT imagery, with that of a similar thematic map of the same area compiled from the interpretation of medium scale aerial photography and ground survey. Methods of image interpretation, data collection and map compilation for both maps are presented, and the objectives of reconnaissance survey and methods of measuring map accuracy are reviewed.

Accuracy is measured by comparing the areas occupied by similarly classified mapping units using a standard technique, and by examination and measurement of boundary shape and coincidence using two new methods. Measurements are carried out by manual and digital means. LANDSAT image characteristics of various natural resource features and their equivalent characteristics on aerial photographs are examined in detail.

In the second part of the study, reconnaissance scale resource maps of 55,000 km^2 of Darfur were compiled from the interpretation and ground checking of LANDSAT imagery in one year. A practical methodology was devised for using satellite imagery in the field that was tailored to the needs and resources generally available in the African Sahelian and Savanna regions.

Key Words: LANDSAT
Remote Sensing
Sudan
Reconnaissance Soil Survey
Land Systems

ACKNOWLEDGEMENT

There are many people whom I would like to thank in connection with the preparation of this thesis, and without whose help and advice much of the work would not have been possible.

In particular I would like to thank Dr. W.G. Collins of the University of Aston, in his capacity of research supervisor, for his continued help and guidance. Professor A. Young of the University of East Anglia as joint supervisor, for his encouragement and technical advice. Dr. P. Thomson for compiling the computer program and Miss G. Thomas for running the programs and proof reading the manuscript.

I am indebted to Hunting Technical Services Limited for financial support during the study and for access to confidential data, including reports, aerial photographs and satellite imagery.

I would also like to thank Mrs. Ann Philips for the cartography and Mrs. Marguerite Revell for the typing.

Finally, I should like to thank my wife Patricia, for her encouragement and patience.

CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND TO THE PRESENT STUDY

The unprecedented growth in world population during the twentieth century has enormously increased man's demand for land and water resources and with it, the need for the quantification and rational management of those resources. Nowhere is the need more urgently felt than in the developing countries of the third world, and in particular, in those countries of the African Sahelian and Savanna zones between latitudes 8°N and 14°N. The Sahelian drought of 1968-73 focussed attention on the chronic problems of human survival and development in these regions. Foremost amongst these is an expanding rural population, burdened with poverty, hunger, disease and water shortage, that is competing for a diminishing supply of natural resources, the distribution and quantities of which are largely unknown.

Indigenous governments, international agencies and private consultants concerned with development strategies in the Sahelian zone, agree that any rise in the standard of living of the rural population and cessation of the very obvious processes of ecological decline, requires integrated planning within a regional context. However, to ensure that regional planning is effective much more information is required on the human, animal and physical resources of these areas.

The present study is primarily concerned with natural resources. It presents an evaluation of the use of data obtained from the LANDSAT earth orbiting satellite programme for mapping natural resources at reconnaissance scale in areas of the African Sahelian and Savanna zones, with particular reference to the mapping of soils and geomorphology in the Western Sudan.

1.2 NATURAL RESOURCE MAPPING

Systematic collection of natural resource data is well advanced in Europe and North America. Most countries within these continents have quantified and mapped their physical resources at national, regional and often at local level. This is not the case in many of the developing countries in the tropics where the size, remoteness, lack of adequate internal communications, particularly an efficient road and railway network, have often precluded the systematic collection of such data. Yet, as Christian and Stewart (1968) observe:

'It is these newly developing countries that are very largely dependent on the utilisation of natural resources for their immediate advancement.'

It is generally accepted that the mapping of resources and their development possibilities is best carried out by some method of integrated survey. A further quote from Christian and Stewart (op.cit.) admirably summarises the concept.

'Information about individual resource factors in isolation is of little value and balanced information which may be about all resource features in each subdivision of the landscape is necessary. Thus, integrated regional surveys are a prerequisite for optimal utilisation and conservation of a developing country's resources.'

Ground survey methods of data collection are time consuming and expensive. However, post-World War II developments in the use of remote sensing techniques, namely methods for obtaining information about objects whilst still at some distance from them, have revolutionised natural resource survey. In particular, the widespread use of medium scale aerial photography for the interpretation and mapping of geology, soils, geomorphology, hydrology, vegetation and land use, has enabled the earth scientist to map larger areas more quickly, cheaply and accurately than was possible using more conventional terrestrial survey techniques.

Aerial survey costs will vary in relation to the size of the area to be surveyed, type and scale of photography required, and type of survey aircraft used. In general, the cost of aerial surveys is still sufficiently high to prevent complete coverage of a developing country being obtained at one scale or at one time. However, for regional studies, even if medium scale (1:25,000 - 1:60,000) aerial photography was readily obtainable, the logistical problems in terms of data handling and interpretation would be formidable when covering large areas. For example, to give vertical aerial photographic coverage, with a 60 per cent forward overlap and 15 per cent side overlap, of 80,000 km^2 of terrain at 1:50,000 scale would require approximately 1,800 nine inch square contact prints. To cover an area of 2,506,825 km^2, the size of the Republic of Sudan, at the same scale and specification, requires in the region of 55,700 prints. However, developments in the last decade, in the use of photographic and non-photographic imagery taken at altitudes of 500 km or more above the earth's surface by manned and unmanned spacecraft and satellites, offer scope for the solution of some of these problems.

It is now possible for the user to obtain from space satellites sequential imagery of large areas of the earth's surface between latitudes 82° north and south, in a short period of time and at a relatively low cost per unit area. The earth scientist is thus presented with a unique perspective of a large part of the earth's surface on one image. In addition, this imagery is acquired under uniform conditions of lighting and exposure and has near orthographic map properties.

LANDSAT is the current name for a series of satellites formerly known as ERTS (Earth Resources Technology Satellite), and developed by the United States National Aeronautics and Space Administration (NASA). To date, three such satellites have been put into orbit:

LANDSAT 1 in July 1972
LANDSAT 2 in January 1975
LANDSAT 3 in March 1978

The satellites and their sensors are briefly described in Chapter 2. Although the use of LANDSAT imagery has reduced data handling by providing, in one frame, aerial coverage of approximately 34,000 km^2, it has also compounded the problem. More information is now available in digital and photographic display form of the visible and infra-red spectral properties of the earth's surface than can be adequately analysed by either manual or currently available automated methods. Nonetheless, the advantages of regional perspective and near orthography possessed by satellite imagery, suggest that it could be used on a cost effective basis for regional natural resource mapping in Sahelian and Savanna Africa where conventional photography is lacking, incomplete, outdated or of an unsuitable scale.

1.3 THE PROBLEM

Since the launching of the LANDSAT satellites a great deal of literature has been published on the value of satellite imagery for the mapping and monitoring of natural resources. Much of this work has been carried out by Principal Investigators appointed by NASA and the results published in NASA Symposia Proceedings. However, between 1972 and 1976 the majority of these investigations were carried out in the United States and, with the exception of Thailand, Indonesia, Philippines, India, Iran and some South American countries, relatively few studies were undertaken in the developing countries of the third world. This is particularly true of the countries of the African Sahelian and Savanna zones, regions which the National Academy of Sciences Report (1977) claim are still inadequately mapped, and where remote sensing technology, particularly LANDSAT imagery, is likely to have the greatest impact. The significance of synoptic images in these areas may actually be more important than in developed nations which are better mapped and more thoroughly explored, particularly in such fields as agriculture, land use planning and mineral exploration. Since 1976 the use of LANDSAT imagery for mapping the natural resources of developing countries has increased as the study by the National Academy of Sciences (op. cit.) shows, but there are still large gaps in the data base of many countries.

To evaluate LANDSAT imagery for mapping the natural resources of a developing country it is necessary to compare resource maps compiled from satellite imagery with maps of the same area compiled from aerial photographs and terrestrial survey. Few such studies have been carried out and the following criticism made by Colwell (1968) with reference to pre-LANDSAT orbital imagery and its value for natural resource inventory, is applicable in large measure to the use of LANDSAT imagery in today's developing world, particularly in the Sahelian regions of Africa.

'The present situation would seem to call for the employment of more vigorous efforts and more vigorous procedures as we seek to determine the usefulness of space photography for natural resource inventory. There is very little direct evidence that natural resource inventory can indeed be made from space photography. From the voluminous literature to date none described a systematic method to determine the usefulness of space photography and neither have authors attempted to determine the extent to which more detailed information of the type needed for resource management might be extracted from space photographs.'

The present study, the broad objectives of which are summarised in Section 1.4, is an attempt to answer the criticism of Colwell (op.cit.).

1.4 OBJECTIVES

(a) An evaluation of LANDSAT imagery for mapping natural resources at a reconnaissance scale in the African Sahelian-Savanna zone with particular reference to mapping of soils and geomorphology in Western Sudan.

(b) The development and application of a methodology for the interpretation of LANDSAT imagery and the compilation of thematic maps, that is tailored to the needs and resources generally available in most developing countries.

(c) The compilation of land system, soils and geomorphological maps from LANDSAT imagery of some 55,000 km^2 of the Sahelian-Savanna zone in Western Sudan (Area B, Figure 1.1).

1.5 THE STUDY AREAS

In 1971 the Sudanese Government, in association with the United Nations Food and Agriculture Organisation (F.A.O.) and the Overseas Development Administration (O.D.A.) of the Foreign and Commonwealth Office, London, began two integrated land use planning studies in Western Sudan. The studies were carried out in the two adjacent areas of Southern Darfur Province, shown as A and B in Figure 1.1, and covered an area of approximately 80,000 km^2 where both sahel and savanna conditions occur.

Southern District (Area A):

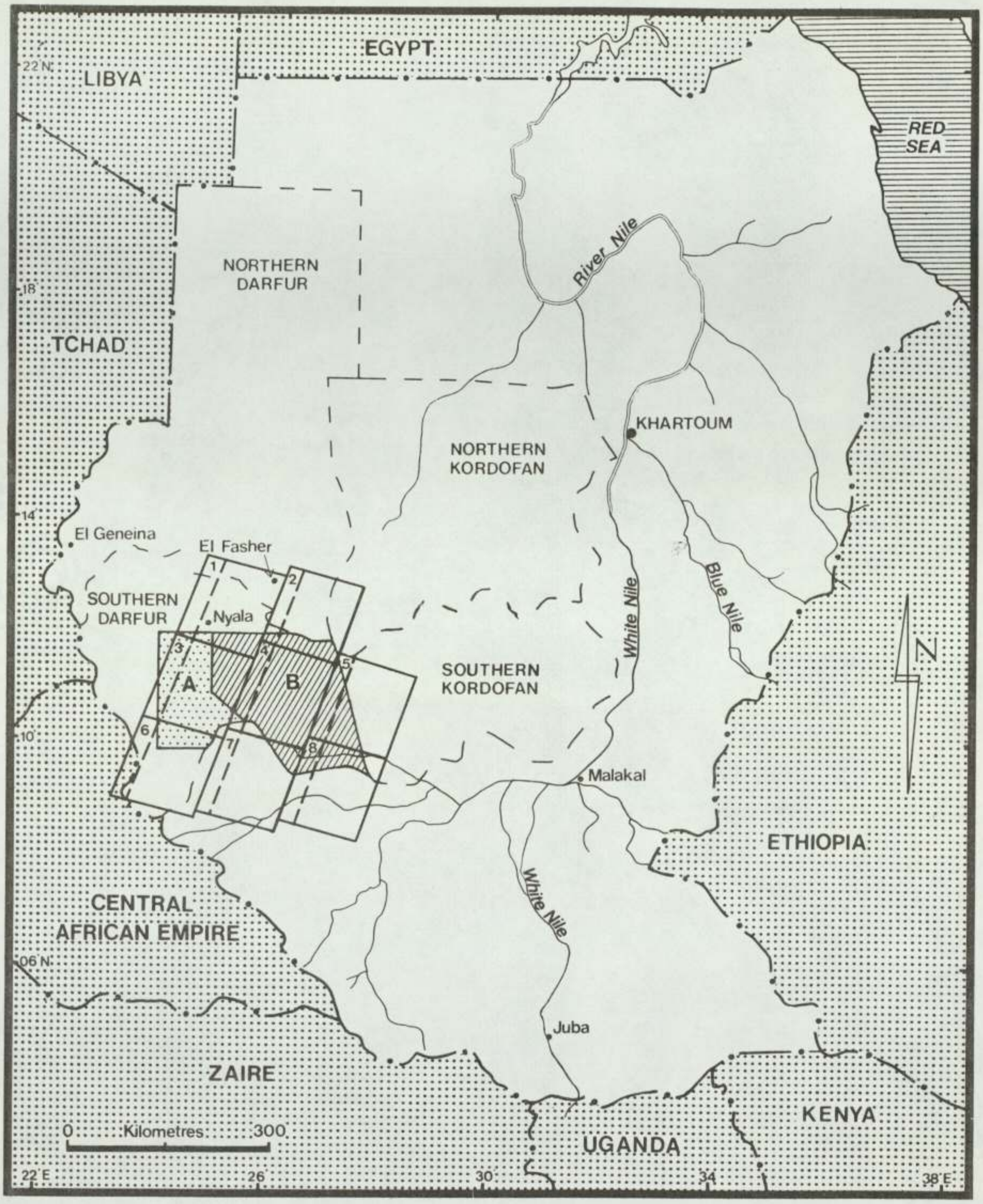
The Southern Darfur Land Use Study area marked 'A' in Figure 1.1 is hereafter referred to as the Southern District Survey or Area A. It was carried out under assignment to the O.D.A. by Hunting Technical Services Limited, a British firm of Agricultural and Land Use Consultants. The survey covered some 25,000 km^2 and came within the boundary of Southern District Council. It was completed between January and June 1972 using aerial photographs, mosaics and terrestrial survey methods. LANDSAT imagery of the area was not available until October 1972, by which time resource mapping and compilation were completed. The results of this survey provide the basic data for the comparative analysis with resource maps subsequently compiled from LANDSAT imagery.

Eastern District (Area B):

The first phase of the F.A.O. financed Savanna Development Project was carried out by F.A.O. personnel and the second phase by Hunting Technical Services Limited. The second phase covered 57,500 km^2 of the Eastern District Council, marked 'B' in Figure 1.1. The area hereafter is referred to as Eastern District or Area B. Natural resource maps of some 57,500 km^2 of the Sudan Sahelian zone were compiled from colour composite LANDSAT imagery using manual interpretation methods. In addition, a practical methodology was devised for ground checking topographic and thematic detail.

These surveys in Areas A and B presented an opportunity to evaluate the resource mapping potential of LANDSAT imagery in a developing country and develop a practical methodology for compiling resource maps from that imagery.

Figure 1.1
LANDSAT Imagery covering Study Area



LANDSAT FRAMES WITH LESS THAN 10% CLOUD COVER.

No.	1972	1973	QUANTITY
1.	Oct,Nov.	Jan+,Feb,May,July.	6.
2.	Nov,Dec.	Jan+,Feb,June.	6.
3.	Oct,Dec.	Jan+,Feb,May,July.	7.
4.	Nov,Dec.	Jan+,Feb,June.	6.
5.	Nov.	Feb,Mar,June.	4.
6.	Oct,Dec.	Jan+,Feb.	5.
7.	Nov,Dec.	Jan,Feb,Jun.	5.
8.	Nov.	May,June.	3.

More than one image available for the preceding month. . . . . +

Southern District Survey Area . . . . . . A

Eastern District Survey Area . . . . . . B

Source: LANDSAT INDEX ATLAS OF DEVELOPING COUNTRIES OF THE WORLD. Pub. by World Bank, March 1976.

1.6 CONSTRAINTS

Most research programmes are subject to various kinds and degrees of constraint, and the present study proved no exception. The logistics for living in and travelling around an extensive, remote and often highly inaccessible region such as Southern Darfur are formidable, time consuming and unproductive in terms of natural resource survey. Further delays to the field programme were caused by early rains towards the end of the dry season in 1972 which made many tracks impassable even with four-wheel drive vehicles.

The large size of the study areas and the relatively short time allocated for data collection dictated that access to the region had generally to be confined to the limited network of major tracks and this introduced considerable sampling bias. Although every effort was made to obtain ground data of all photo-interpreted mapping units, time constraints precluded random ground sampling within these units. However, for surveys of a reconnaissance nature such random sampling is thought unnecessary in order to achieve the desired level of accuracy. The methods and objectives of reconnaissance scale mapping and the problems associated with the definition and measurement of map accuracy are discussed in Chapter 3.

Perhaps the most serious constraint for the purposes of the present study was the lack of complete satellite coverage of the area during any one month of the same year, or even of the same season. This was caused by the poor image quality, or the high cloud cover present on many frames, and thus the best images of the area were selected from a number of overpasses of different dates. The areas covered by each frame and date of the overpass are shown in Figure 1.1.

These constraints, or similar ones, are likely to persist for a considerable time wherever natural resource surveys are carried out in the more remote parts of the developing world. In addition, the use of less conventional remotely-sensed data, particularly satellite imagery, as an aid to mapping natural resources is likely to increase. Thus an attempt to evaluate LANDSAT imagery against the background of the constraints outlined above is deemed justifiable.

CHAPTER 2

REMOTE SENSING

2.1 INTRODUCTION

Remote sensing is defined in its broadest sense by the American Society of Photogrammetry (1975) as:

> 'the measurement or acquisition of information of some property of an object or phenomenon, by a recording device that is not in physical or intimate contact with the object or phenomenon under study'.

The technique employs such devices as the camera, multi-spectral scanner, lasers, radio frequency receivers, radar systems, sonar, seismographs, gravimeters, magnetometers and scintillation counters. With the exception of geophysical measurements of the earth's magnetic and gravitational fields, the majority of sensors used in the mapping of natural resources measure electromagnetic radiation, with wavelengths between ultra-violet and radio regions.

The aerial camera is the most widespread of these sensors currently in use and provides, through its product, the aerial pnotograph, one of the foremost tools for resource mapping. The use of non-photographic sensors (i.e. sensors without a lens system) that operate both within and beyond the visible spectrum is increasing. Two such systems are the multi-spectral scanners (MSS) on board LANDSAT 1, 2 and 3, and side-looking airborne radar systems (SLAR) now being used commercially. However, the dominance of the conventional aerial photograph and the fact that data obtained by non-photographic sensors are, in most cases, ultimately reproduced in photographic form for the purposes of interpretation, necessitates an understanding by the earth scientist of the basic principles of electromagnetic radiation, the photographic process and aerial photographs.

2.2 THE ELECTROMAGNETIC SPECTRUM

Electromagnetic radiation in the form of photons generated by the sun is propagated through space at the speed of light as a series of waves of varying frequency. This dynamic form of energy is made manifest only by its interaction with matter. When this occurs, the energy will be either absorbed, emitted, scattered or reflected. For example, in its passage through the atmosphere some of the radiation will be scattered or absorbed while the remainder continues to the earth's surface. The latter is continually reflecting, absorbing and emitting energy. The ordered array of known electromagnetic radiations, the electromagnetic spectrum, and the regions covered by the different remote sensors are shown in Figure 2.1. This energy can be detected by a variety of sensors. By recording radiation changes due to material interactions, the sensors provide the earth scientist with information about the properties of the matter with which the energy has interacted. It can be seen from the transmission graph in Figure 2.2 that the atmosphere has well defined 'windows' which only permit the passage of certain wavelengths, whilst others are totally absorbed by atmospheric gases. Thus, sensors are designed to respond selectively to radiation from different parts of the electromagnetic spectrum.

The visible and infra-red regions of the spectrum (0.4-10 μm) are the most widely used 'windows' for earth resource mapping. Cameras and photochemical emulsions on film are used to capture reflected energy from the sun or some artificial source and display it as a photograph. Specific wavelengths within the visible - infra-red region can be selected by the use of appropriate filters. Today there exists a wide variety of camera systems and film filter combinations for ground, aerial and space photography. However, compared with any other sensor, vertical aerial photography taken within the visible region of the spectrum still provides the most accurate information on the shape, size and relative position of objects (Parker and Wolff, 1965).

2.3 AERIAL PHOTOGRAPHS

Aerial photographs are photographs taken from the air with the camera, in most instances, pointing vertically downward from an aircraft or other aerial platform. As Estes (1977) so rightly emphasises, aerial photography is the oldest form of what has come to be referred to as remotely sensed data. Vertical aerial photographs, taken in a series of independent overlapping exposures with a single lens camera, are the corner-stone of topographic and natural resource mapping. Van Genderen (1975) considers that about 90 per cent of the photo-interpretation in the earth sciences is carried out on vertical aerial photographs. Other types of aerial photograph taken at oblique angles are available but have a more restricted application.

For the majority of surveys aerial photographs are exposed on a roll of panchromatic film nine inches wide (22.9 cm) and sensitive to the visible portion of the spectrum between 0.4 and 0.7 μm.. For more specific survey requirements such as detecting diseased crops or trees, radiation from the near infra-red and infra-red portions (0.7 to 1.1 μm) of the spectrum will be sensed.

Figure 2.1 The Electromagnetic Spectrum

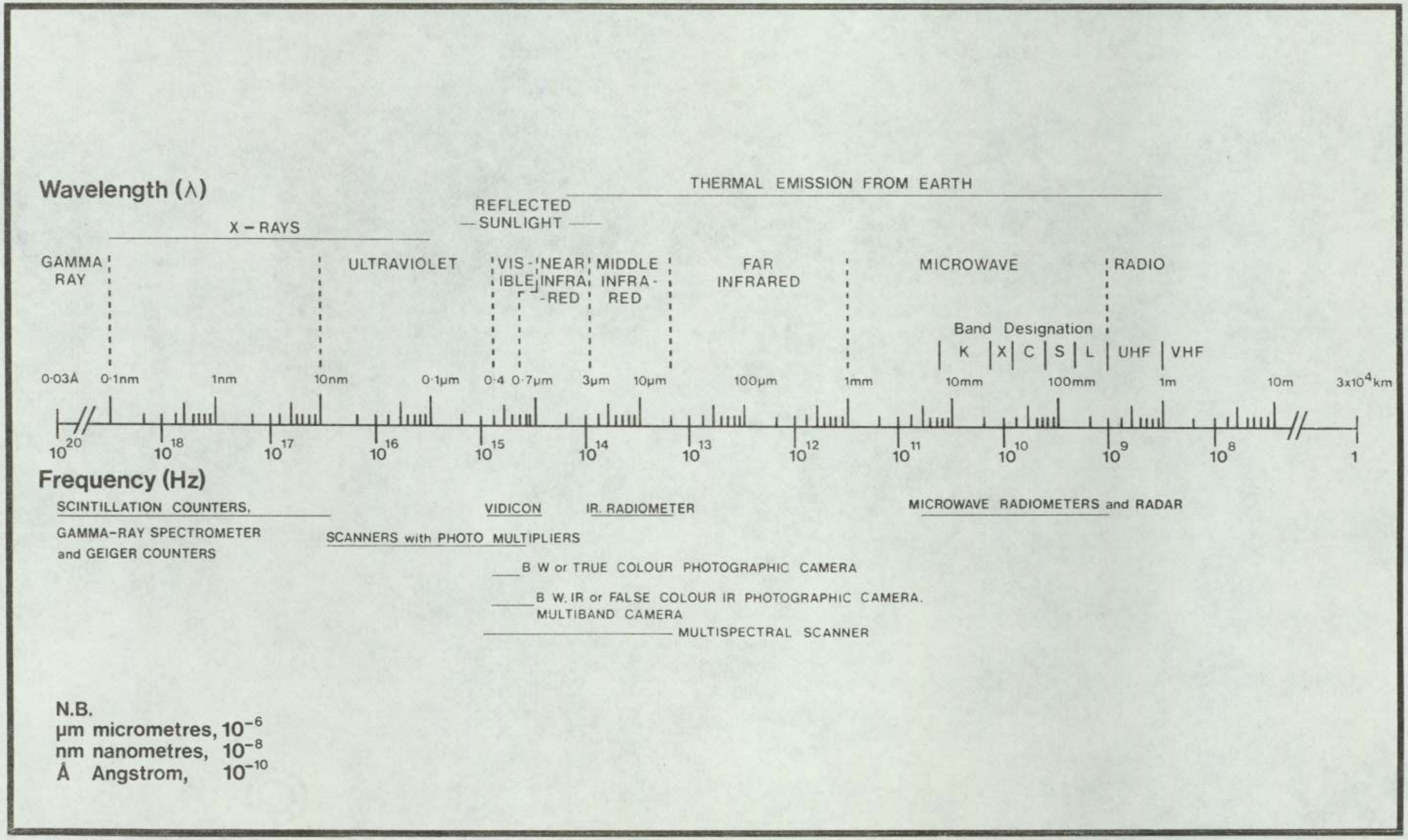
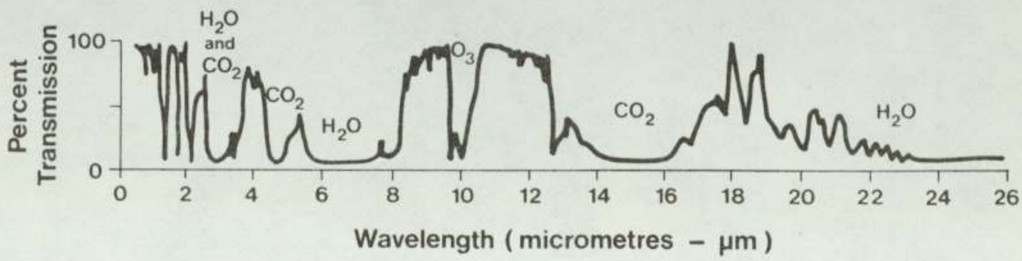


Figure 2.2
Transmission Graph (after Parker and Wolff, 1965)



Atmospheric absorption of electromagnetic radiation is almost complete in the ultraviolet region of the spectrum to about 0.3μm. The visible region (0.4 - 0.7μm) is relatively free from absorption but considerable atmospheric scattering occurs. In the infra-red region out to 25μm there are many absorption bands including water vapour, carbon monoxide, nitrous oxide and ozone. Water vapour virtually closes the atmosphere between 25μm and 1.0mm, the beginning of the microwave region.

Photography of selected spectral bands may be acquired with either a single lens or multiple lens system. The basic concept of the multi-lens or multi-spectral system is the taking and viewing of simultaneously exposed black and white photographs having identical formats, through filters which divide, into several intervals, the light reflected from the terrain. The recorded light is usually the visible spectrum plus the near infra-red. This type of aerial photography has considerable potential in resource survey studies but a basic knowledge of target signatures and careful choice of filter sets are of prime importance in obtaining a final image with maximum enhancement of the required features.

The multi-spectral data obtained since July 1972 by the earth orbiting LANDSAT satellites, although collected by non-photographic sensors, nonetheless represents the largest amount of multi-spectral data on earth resources ever amassed, covering the spectral region from the visible to the infra-red (0.4-1.1 μm).

Conventional colour film and colour infra-red film are also used in aerial photography. The latter is particularly useful for the classification and recognition of vegetation types and the detection of diseased and damaged (stressed) vegetation. There is little doubt that the extra criterion of colour is of value in earth science photo-interpretation but for most purposes the increase in interpretative data content compared with black and white photography is generally out of all proportion to the cost of colour photography. The flying, exposure and processing conditions are more stringent for colour than for black and white film and the cost prohibitive for general resource survey purposes.

2.4 INTERPRETATION OF AERIAL PHOTOGRAPHS

The interpretation of aerial photographs or any other remotely sensed imagery is concerned with the examination of images for the purposes of identifying objects or conditions and deducing their significance.

Morain and Campbell (1974) give a succinct description of the process:

> 'Conventional photo-interpretation performed on vertical aerial photographs involves a complex process of evaluating a number of image characteristics such as size, shape, texture, tone, shadow and stereo-parallax. The analysis of the factors combined with the additional power of the human brain (i.e. subjective reasoning, intuition, convergence of evidence, past experience, etc.) allows the interpreter to recognise, identify and deduce the significance of objects or conditions seen on the photographs.'

Since aerial photography is the oldest and most widespread of what is currently termed remotely sensed data, its interpretation remains the lynch-pin of remote sensing. Many of the interpretative techniques developed for use with 'more advanced' or 'less conventional' imagery, much of which is generated by non-photographic means, are essentially extensions of aerial photographic interpretation methods. Thus an understanding of the methods developed for the interpretation of aerial photographs and the incorporation of these methods in the visual interpretation of other types of remotely sensed data is fundamental to the evaluation of the latter's role in natural resource mapping.

Recent advances in the application of digital and analogue computers to the collection and analysis of remotely sensed data has added a new dimension to the science and given greater flexibility in the presentation of data. However, even if data are collected in a digital mode, the most widespread end product for the resource scientist, particularly one engaged in regional studies, is in the familiar photographic form. After numerous digital corrections and enhancements have been performed the final image in photographic form may be very different from the original, but the visual interpretation of the image will be carried out essentially along the lines established for the interpretation of aerial photographs.

The literature on the interpretation of aerial photographs for natural resource survey is extensive. Only a brief summary of the types of aerial photographic interpretation is given here. Of the more general references, the Manual of Remote Sensing (American Society of Photogrammetry, 1975), is probably the most comprehensive. References more specific to the interpretation of soil and geomorphology data include Goosen (1967), Buringh (1960) and Vink (1968).

Several authors (Smith, 1943, Buringh, 1960, Lueder, 1959, Vink, 1968) recognise various phases of photo-interpretation. The first phase is commonly called recognition and identification or 'photo-reading', and consists of the recognition and identification of individual features, such as roads, railways and buildings. The terrain characteristics that can be identified directly on aerial photographs include landform, drainage, vegetation structure and soil tone. Schwaar (1970) has compared the method with that of reading a topographic map; the photo-interpreter uses the detail of the aerial photograph in the same way as a map reader uses the conventional map symbols.

Vink (op. cit.) introduces the importance of the interpreters level of reference for each observation and identification is done in comparison with a reference level. This level consists of a knowledge of various objects and processes and depends on the background knowledge and training of the interpreter. Recognition and identification of cultural or physical features on aerial photographs can be carried out by anyone providing the features are within the confines of general human knowledge and experience. But for special purposes, such as the identification of landforms in the dry tropics, a more specific reference level is needed.

Photo-analysis, the next stage of air photo-interpretation, involves the separation and distinguishing of an object's component parts. A geomorphologist may interpret and measure slopes; a hydrologist may analyse drainge patterns. The analysis should be of directly visible and measurable elements and patterns, although a degree of deduction often plays a role in the analysis. In soil survey, element analysis of aerial photographs as developed by Buringh (op. cit.) is based upon the fact that most features of the earth's surface are connected with soil conditions in some way.

Deductive interpretation is the most advanced and difficult phase of interpretation. Deductions are made about the nature of the terrain characteristics that cannot be directly interpreted from image characteristics that are identified during the phase of photo-reading and analysis. Landscape elements are not considered as separate individuals but as interrelated phenomena which constitute the physiographic regions of Goosen (1967) or the land systems of Christian (1958). The interpretation of these physiographic units requires a wide knowledge on the part of the photo-interpreter of the earth sciences, in particular a knowledge of soils, geology, geomorphology and vegetation. In the present study the land systems approach was used to interpret both the aerial photographs and the satellite images.

2.5 THE DEVELOPMENT OF SPACE IMAGERY

The acquisition of terrestrial imagery obtained from space, defined by Lowman (1965) as 50 miles or higher above the surface of the earth, began in earnest in the United States after World War II with the use of small cameras carried by V-2 sounding rockets. Since then, numerous space flights have been made by a variety of sounding rockets, ballistic missiles, unmanned spacecraft, manned spacecraft, and satellites, fitted with a range of remote sensors. With the exception of the U.S. weather satellites launched during the nineteen sixties, the majority of the early space flights between 1949 and 1969 obtained photographs of the earth using a variety of camera, film and filter combinations.

Systematic earth orbital observations began in 1960 with the launching of TIROS I, the first meteorological satallite, which carried television and infra-red sensors. In 1961, the first orbital terrain photography was obtained using an automatic 70 mm camera mounted in the MA-4 Mercury space-craft. The geological sketch maps of large areas of the Sahara compiled by Morrison and Chown (1965) from the Mercury photographs clearly demonstrated the value of orbital photography to the geological sciences. Although most interpreters of space imagery stressed the geological value of orbital photography, the potential for landform, land-use, vegetation, forestry, hydrologic, oceanographic and ice-pack studies was noted by Morrison and Chown (op. cit.) and Lowman (1965), amongst others.

The interest generated in the use of Mercury orbital photography for geological and other resource evaluations led to the development of a more ambitious terrestrial photographic programme for the Gemini space flights. The first formal geological photography experiment was carried out in June 1965 on the Gemini GT-4 mission. Further experiments were carried out on the Gemini GT-5 and GT-7 missions in August and December 1965. Although a great deal of the Mercury and Gemini orbital photographs were of poor quality these early space photographs led to the formulation by the U.S. Geological Survey of a set of performance specifications and a general plan for repetitive surveys of the Earth for resources and environment investigations (Fischer and Robinove, 1968). This contributed to the development of the NASA Earth Resources Technology Satellite (ERTS-1), later renamed LANDSAT.

The Apollo space programme produced further advances in orbital terrain photography, the most significant of which was the SO65 Multi-spectral Terrain Photography Experiment carried out by the Apollo-9 crews in 1969. The aim of the experiment was to determine the feasibility and value of multi-spectral orbital photography for earth resources studies. The wave bands used were approximately those planned for the NASA ERTS-1 satellite.

2.6 LANDSAT SATELLITES

In July 1972 the first NASA Earth Resources Technology Satellite, ERTS-I, was launched by Delta rocket into a sun synchronous polar orbit at an altitude of approximately 920 km (575 ml). Prior to being closed down in early 1978, the satellite made 14 orbits a day (103 minutes per orbit). Its coverage of any specific point on the earth's surface was repeated at about 0930 hours local time every eighteen days using return beam vidicon cameras (RBV) and a multi-spectral scanner (MSS). These sensors provided film positives and contact prints on a worldwide basis, for the user community at low cost. The satellite, subsequently renamed LANDSAT-I in January 1975, was the first orbital imaging system specifically designed for the mapping and monitoring of the earth's resources.

On January 22nd 1975 a second satellite, LANDSAT 2, an exact replica of the first satellite, was placed in orbit at ninety degrees to the inclination of LANDSAT 1. The satellite imagery used in the present study was obtained from LANDSAT 1 because LANDSAT 2 images of Eastern District (Area B) were unobtainable at the time, and for the comparative study of Southern District (Area A) LANDSAT imagery obtained in 1972, the same year as the aerial photography, was considered to be preferable.

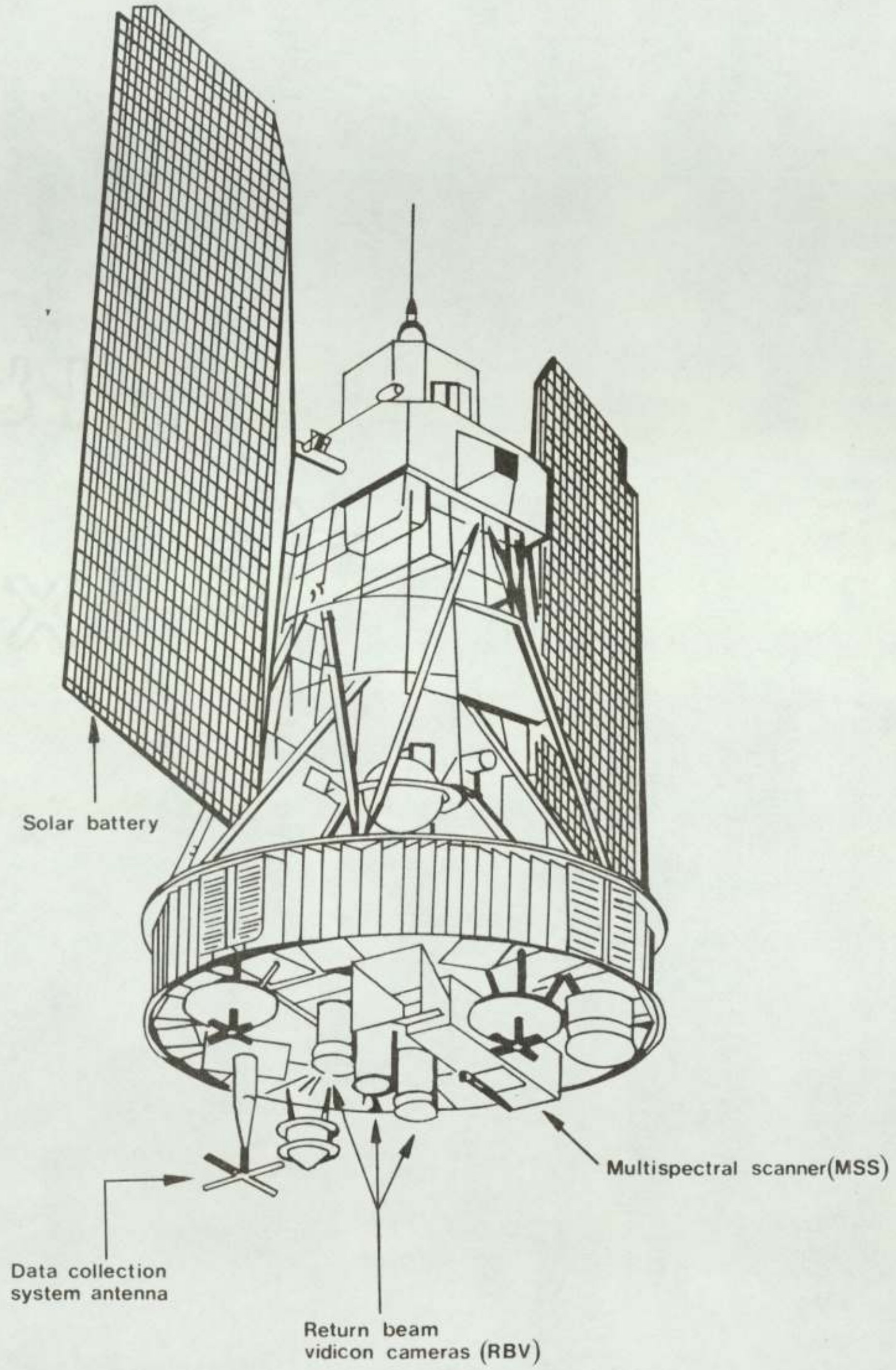
LANDSAT 2 is a 950 kg satellite, 3 m high and 4 m wide when its two independent solar panels are extended (Figure 2.3). The solar panels are connected to storage batteries and provide power for the control, sensing, recording and transmitting equipment on board. The batteries are required for the period when the satellite is on the dark side of the earth.

On each satellite pass, a strip of terrain 185 km wide is viewed by the sensors. A day later the satellite passes over a point at the equator 170 km west of that same strip and senses an adjacent strip of 185 km. This provides a 14 per cent overlap at the equator so that at least 15 km at the edge of each strip are always viewed twice on consecutive days in each 18 day cycle. The image overlap increases with latitude giving 19 per cent overlap at 20 degrees and 34 per cent overlap at 40 degrees.

The two space-craft have recorded over 450,000 scenes providing nearly complete coverage of the world's land areas and repeated coverage for many areas. Most of this coverage has been with the multi-spectral scanner and very little use has been made of the return beam vidicon cameras because of malfunctions in the system. The sensors on board LANDSAT 1 have now been shut down and another satellite, LANDSAT 3, was launched into an identical orbit in April 1978. LANDSAT 3 is producing RBV imagery of a very high quality (Allan, 1978).

The multi-spectral scanner (MSS) on board each of the satellites is a four channel radiometer which scans the earth's surface by means of a rotating mirror and measures the intensity of energy reflected by features and objects on the surface in four separate wave bands of the electromagnetic spectrum. The image spectral bands are:

Figure 2.3
LANDSAT spacecraft and sensors



Source: LANDSAT USERS HANDBOOK

Band 4	Wavelength	500 - 600 nanometres	(green)
Band 5	Wavelength	600 - 700 nanometres	(lower red)
Band 6	Wavelength	700 - 800 nanometres	(upper red/lower infra-red)
Band 7	Wavelength	800 - 1100 nanometres	(near infra-red)

The radiation signals acquired by the scanning mirror are translated into an electrical signal and ultimately reproduced on the LANDSAT imagery as one picture element or pixel representing an area of approximately 80 m square or 0.64 hectares.

The level of intensity of the composite signal emanating from each pixel area will depend upon the nature of that area and the wavelengths reflected by its various components. The recording and analysis of these different levels and their identification with the features and areas they represent on the ground provide the basis for the interpretation and mapping of earth resources using remotely sensed data. Further details of the multi-spectral scanner and the return beam vidicon cameras are given in Appendix A.

2.7 DATA PROCESSING

Signals acquired by the sensors on board the satellites are sent to ground receiving stations where they are converted to digital form and recorded onto magnetic (video) tape. A station can receive telemetry from LANDSAT while the space-craft is within its line of sight, or for an approximate radius of 3,000 km. There are three ground receiving stations in the United States and one each in Brazil, Canada and Italy. Other stations are planned or under construction in Zaire, Iran, Chile, Norway, Upper Volta, India, Japan and Australia.

The video tape of LANDSAT imagery undergoes a process of annotation, correction and conversion to the desired form of data product. These may be black and white prints, colour composite prints or computer compatible tapes (CCT). Black and white images generated at this initial or 'bulk processing' stage are corrected for geometric distortion and radiometric balance. Selected frames can be precision processed by an alternative system to give images of much higher accuracy but this entails extensive and expensive computer processing to correct the images to measured ground control.

Four different black and white corrected images on film of each 185 km square scene are produced, each image corresponding to the data registered on one MSS band.

However, the 64 levels of intensity on the original tape are reduced in a black and white film to between 10 and 15 grey levels, which are about as many as the human eye can distinguish.

The 'false colour composite' image of a LANDSAT scene is another product which has been designed to take advantage of the fact that the human eye, unlike its limitations with respect to the grey scale, can distinguish many hundreds of colour variations. The colour composite is a single image in which the original grey tone variations are expressed as different colours or variations in colour tone. The colours employed are not the same as the colours of the features seen by the human eye. Established usage is that natural green is shown as blue, red as green, and near infra-red as red. Vegetation, for example, appears in 'false colour' composites in variations of magenta, orange, and red. It is generally accepted that colour composites are superior to single band products for most types of thematic mapping.

To extract the full data value from the 64 density levels, the most effective product is the computer compatible tape (CCT). The original video tape data are first converted into intermediate High Density Digital Tapes (HDDTs) by one processing subsystem and then converted by another subsystem into CCTs. These can then be fed into computers for digital analysis of the spectral properties of each pixel and subsequent automatic classification of surface features. The capability and accuracy of digital classification methods for mapping natural resources have been the subject of much controversy amongst resource scientists since the beginning of the LANDSAT programme. A summary of the results of applying automatic classification methods to the mapping of natural resources is included in Appendix B.

2.8 POTENTIAL OF LANDSAT IMAGERY FOR MAPPING NATURAL RESOURCES

Prior to the launching of the LANDSAT space-craft, evaluations of space imagery for mapping natural resources were carried out mainly on photography obtained from the Mercury, Gemini and Apollo missions. Lowman (1964, 1965) and van Zuidam (1971) give a comprehensive review of the results. Most investigators agreed that space photography had a valuable role to play in the mapping and evaluation of the earth's resources at a regional, reconnaissance, or exploratory level. However, image distortion, variable image geometry caused by camera tilt, colour distortion, contrast attenuation and loss of resolution caused by the effects of atmospheric scattering, and incomplete global coverage, precluded the use ofthese photographs for systematic resource evaluation.

Nonetheless, despite these imperfections pre-LANDSAT space imagery had certain unique capabilities compared with conventional aerial photography. Foremost amongst these was the perspective view of a large area of the earth's surface afforded by the great altitude of the orbiting space-craft over which photographic tones or colours are comparable. Earth scientists now had the advantage of regional observation over large geological, geomorphological and biogeographical features that was superior to anything currently available from conventional aerial photography. The area covered by one photograph depends on the altitude of the space-craft and the orientation of the camera. An oblique Gemini XI Mission photograph of the Lower Indus Basin in Pakistan interpreted by Parry (1971) covered an area of approximately 73,400 km^2 compared with 34,000 km for the current generation of LANDSAT images. The results of the Mercury, Gemini and Apollo terrain photographic missions contributed significantly to the development of the LANDSAT Space Programme.

Since the beginning of image acquisition in 1972, LANDSAT 1 and 2 have obtained some 450,000 frames of the earth's surface. Evaluation of some of these data are contained in a voluminous literature composed of scientific journal papers, symposia proceedings and books. It is the consensus of opinion that LANDSAT imagery can provide a valuable data base for small scale thematic mapping in areas where no previous maps existed, and can be used for updating existing topographic and thematic maps. The unique advantages possessed by orbital imagery, namely, a synoptic view, uniform conditions of illumination, speed of image acquisition, high planimetric accuracy and repetitive coverage, lend themselves ideally to small scale mapping. Such mapping is essential in the developing world, much of which, the National Academy of Sciences (1977) consider, is still inadequately mapped. In spite of this, the use of LANDSAT imagery to fulfil this role throughout the developing world and particularly in Africa, has been somewhat tardy as the figures quoted in Section 2.9 show.

2.9 THE USE OF LANDSAT IMAGERY FOR RESOURCE SURVEYS IN DEVELOPING COUNTRIES

The following quote from Howard (1974) expresses the early promise LANDSAT held for many as a tool for the mapping and subsequent management of the natural resources in developing countries.

'As many developing countries are inadequately mapped and frequently rely on outdated maps, LANDSAT imagery is considered to provide a wide spectrum of valuable data. LANDSAT data are seen as providing developing countries with relatively inexpensive information as a basis to regional surveys, management surveys and local and regional planning activities'.

Unfortunately this ideal is only now beginning to be realised. During the first four years of the LANDSAT Programme, 1972-1976, the majority of the research and evaluation of the imagery for mapping natural resources was carried out on imagery of the North American continent or Europe. Of the 424 LANDSAT resource evaluations published by the National Aeronautics and Space Administration (NASA) in three separate symposia (NASA, 1972, 1973, 1976) only 37 or 9 per cent referred to developing countries. An analysis of some 2,369 abstracts contained in 141 weekly bulletins published by the National Technical Information Service (NTIS) on significant results obtained from LANDSAT imagery, revealed an even greater bias towards the developed world. Only 97 or 4 per cent were concerned with resource appraisal in developing countries and the majority of these were of an exploratory nature, seeking to define resource objectives for orbital imagery and suggesting possible interpretation procedures.

In the past two years the use of remotely sensed data in general, and LANDSAT imagery in particular, for resource mapping in the countries of the Third World has greatly increased (National Academy of Sciences, 1977). This trend was confirmed at the Twelfth Symposium on Remote Sensing of Environment held in April 1978 in the Philippines. Out of a total of 227 papers presented at the symposium, 82 or 36 per cent were concerned with remote sensing projects in the developing world and of these 82 studies, 76 were wholly or partially dependent on LANDSAT imagery. However, when one examines the geographical distribution of the studies there is a large bias towards South America and the Far East. Only 6 of the 82 papers on the application of LANDSAT imagery in developing countries referred to studies on the African continent. The situation has improved recently as the National Academy of Sciences (op. cit.) analysis on remote sensing activities in Africa shows, 14 of the 45 African countries listed are using LANDSAT imagery on a project basis and a further 14 propose to use it.

In the field of soil and geomorphological mapping in developing countries the use of LANDSAT imagery is still very much in its infancy. Most of the work on soil mapping that has been carried out by Principal Investigators for the National Aeronautics and Space Administration (NASA) and summarised by the American Society of Photogrammetry (1975), is concerned with soil mapping in the United States. Many valuable conclusions have been drawn from these studies. The work of Westin (1973) and Westin and Frazee (1975) on the delineation of soil associations in South Dakota is particularly illuminating.

However, caution is necessary when extrapolating results obtained in the United States to the countries of the Third World where climate and land-use may be very different, and the availability of base maps and collateral information on the environment, limited or non-existent. The National Academy of Sciences (op. cit.) foresee a significant use of LANDSAT imagery for land and soil reconnaissance level surveys in the developing world but to date, there are only a few examples of this potential being realised in these areas. A selection of these examples are reviewed below.

In East Java, Suroto and Malingreau (1975) were able to recognise and delineate on LANDSAT imagery most of the soil units mapped on the 1:1,000,000 scale soils map of Java. On the island of Sulawesi the same authors found that the ground resolution of LANDSAT imagery was too poor for accurate soil mapping at 1:50,000 scale. However, most of the soil units delineated on the 1:50,000 scale aerial photographs of the area could be recognised but not mapped from the satellite imagery because the boundaries between the low contrasting features were too diffuse.

In Mexico, Klingebiel and Myers (1974) prepared soil maps mainly from LANDSAT imagery at a scale of 1:1,000,000 to show the location and extent of the country's potentially arable soil resources. Two sets of LANDSAT colour transparencies for most of the country, one taken in the Autumn wet season and the other in the February-March dry season, provided the basis for the mapping project.

Elbersen (1974) in his interpretation of LANDSAT imagery of a savanna area of eastern Columbia, concluded that the most important units of an existing 1:250,000 scale reconnaissance soil map could be extrapolated successfully into an unknown but similar area using LANDSAT imagery in conjunction with sample strips of aerial photography. Small scale mapping from LANDSAT imagery of major soil and geomorphological units has been carried out in Bolivia by Brockman (1974). Nixon (1974) was able to map the geomorphology of Lesotho from satellite imagery which, because of its unique perspective, provided an overview infinitely superior to anything that could be obtained using more conventional aerial photography. The overview greatly facilitated the recognition of recurrent landform patterns and deductions concerning their evolutionary development. In the Sudan, Mitchel (1975) also found that the interpretation of LANDSAT imagery strengthened geomorphic theorizing.

In an evaluation of LANDSAT imagery for natural resource mapping in the Central Afar region of Ethiopia, Parry (1974) concluded that exploratory scale soil, vegetation and land-use maps and a reconnaissance scale geological map could be rapidly compiled from the satellite colour composite imagery. In this instance satellite imagery was a valuable addition to conventional aerial photography for agricultural studies but would have been inadequate by itself for soil and land-use mapping at the scale of 1:20,000 required by the Ethiopian Government.

More recent work on reconnaissance soil and landscape mapping from LANDSAT imargery has been carried out in the Sudan by Moore (1978) and Worcester and Moore (1978) in the Sudd region of Southern Sudan. The survey covered 160,000 km^2 and occupied fourteen LANDSAT frames. Characteristic patterns of soil-landscape units relating to topography, soils and vegetation were identified on the LANDSAT imagery and checked against conditions occurring on the ground. The results of the studies revealed that LANDSAT data can be effectively used for rapidly acquiring resource data over a large region in a timely manner.

CHAPTER 3

RECONNAISSANCE SURVEYS AND MAP ACCURACY

3.1 RECONNAISSANCE SURVEYS

In any natural resource survey an appreciation of the constraints imposed by the mapping scale is crucial if misunderstandings are to be avoided regarding the maps utility. In soil survey the terms exploratory, reconnaissance, semi-detailed, detailed and very detailed are used to describe surveys of increasing intensity (i.e. those with a greater number of sample sites per unit area). An indication of the mapping scale used in various kinds of soil survey and the density of observation sites required is shown in Table 3.1.

TABLE 3.1 MAP SCALE AND RELATED OBSERVATION SITE DENSITY

Map Scale	Type of Survey	Area represented by 1 cm^2 of Map	Sampling Density
1:5,000	Very detailed	0.25 ha	1/0.5 ha
1:10,000	Very detailed	1.00 ha	1/2.0 ha
1:20,000	Detailed	4.00 ha	12/km^2
1:25,000	Detailed	6.25 ha	8/km^2
1:50,000	Semi-detailed	25.00 ha	2/km^2
1:100,000	Reconnaissance	1 km^2	1/2km^2

Source: FAO/IBRD (1968)

Exploratory Soil Surveys generally have a mapping scale of between 1:250,000 and 1:1,000,000.

The different objectives and methods used for each type of soil survery are succintly reviewed by Young (1973). However, the overall objective of all soil surveys irrespective of scale, is basically the same, namely, to delimit areas of soils that do not contain significant differences and separate areas of soils that are significantly different. As Webster and Beckett (1968) observe, the soil surveyor hopes that the soils within his mapping units are less variable than over the landscape at large, and that precise statements can be made about particular parts of the soil landscape that could not be made about the whole.

The essential difference between the soil units demarcated on a detailed soils map and those delineated on a reconnaissance map is the degree of precision concerning statements which can be made about the soil within the mapping units. In detailed surveys the pedologist is mapping at a very low categoric level soil properties such as depth, stoniness or pH. Soil series, types or phases are usually mapped at this scale as discrete units within which the variation in soil properties is very low. In statistical terms, the pedologist will wish to achieve the maximum reduction in the within-class variance compared with the variance within the classes of previous maps or within the area unclassified if no previous map exists (Webster and Beckett op. cit.).

In reconnaissance soil survey the mapping units are generally at the higher taxonomic levels of great soil group or sub-order. These may be grouped into compound units, such as soil associations or complexes, if mapping scale or environmental complexity preclude the separation of discrete units. Thus each mapping unit may include a larger number of significantly different soils than are permitted in more detailed surveys. Statistically, the within-class variance of reconnaissance maps is greater than for detailed or semi-detailed maps.

This apparent lack of precision in reconnaissance maps does not negate their usefulness but merely sets limits on the type of data that can be obtained from the map. The specific objectives of a reconnaissance soil survey may be summarised as follows:

(a) The delineation of soil groups or associations and related landforms.

(b) The description of the morphological and analytical properties of the soils within each classified unit.

(c) The selection of areas which merit more detailed study.

Reconnaissance maps are urgently required in developing countries, where large areas remain wholly lacking in thematic and topographic coverage or are inadequately recorded (National Academy of Sciences, 1977). Clearly, the specific objectives of a reconnaissance soil survey are very different from those of more detailed surveys. These differences are reflected in the methods of map compilation and sampling procedures adopted for the two types of survey.

3.2 USE OF AERIAL PHOTOGRAPHS IN RECONNAISSANCE SOIL MAPPING

The use of aerial photographs for plotting soil boundaries is one of the major advances in post-war soil survey. The work of Simonson (1950), Buringh (1960) and Vink (1968), amongst others, has firmly established the use of aerial photography as an integral part of most soil surveys. The advantages of air-photo interpretation for soil surveys may be summarised as follows:

(a) Soil boundaries can be placed with more precision onto base maps by generating a stereoscopic model of the terrain from a pair of overlapping aerial photographs and carrying out photo-reading, photo-analysis and deductive interpretation.

(b) The areas can be studied in advance of field work and the field programme rationalised, thus saving time and increasing survey efficiency.

(c) Mapping confidence increases and in many cases, the observation density may be lessened with minimal loss of map accuracy.

(d) The lower cost of soil surveys which utilise aerial photographs has created possibilities for investigating large, quite unproductive and thinly populated areas.

Numerous studies have shown that, as a general rule, the interpretative and mapping value, as against the locational value, of aerial photographs in soil survey, increases as the map scale decreases. In other words for mapping soil boundaries, aerial photographs are of greater value in reconnaissance surveys than they are in more detailed studies. This conclusion would appear to be valid for reconnaissance soil mapping from LANDSAT imagery. This can best be illustrated by considering the manner in which soil appears on aerial photographs and satellite imagery.

The soil surface is very rarely seen on aerial photographs or satellite images, except in arid or semi-arid environments. The soil profile, the usual basis for classification, is nerver visible. Differences in soils are generally distinguished on aerial photographs and multi-spectral images because there is a relationship between soil type and those of its surface characteristics that affect the photographic tone, texture and pattern, and visible features, such as landform, geology, land-use, vegetation and drainage. In areas such as

Southern Darfur, where these well established environmental relationships are particularly marked, the soil scientist can rapidly and accurately map large areas of similar soils, similar groups of soils or related heterogenous soil groups prior to field checking. This method of deductive image interpretation (discussed in Section 2.4), is particularly well suited to reconnaissance scale mapping and forms the basis of the Land Systems method of landscape analysis developed by Christian (1958), and the similar method of Physiographic Analysis used by Goosen (1967). These methods of landscape analysis, initially developed for work on aerial photographs, have been applied in the present study to resource mapping from multi-spectral satellite (LANDSAT) imagery.

3.3 SAMPLING METHODS AND MAP ACCURACY

In detailed soil studies the number of observation sites is calculated and their location plotted according to the principles of statistical sampling in order to reduce to an acceptable minimum the sampling error or the within-class variance of the mapping units. Such a statistical approach to sampling is both desirable and practical when mapping a small area in great detail, particularly in areas where soil changes have very little surface expression and therefore may not be visible on aerial photographs. However, this method is both unnecessary and impractical at a reconnaissance scale where large areas, such as the 80,000 km^2 of Southern Darfur, have to be mapped rapidly and for the first time, to a level of accuracy commensurate with a reconnaissance survey designed to be used as a basis for regional land-use planning. The fulfilment of the three basic objectives of reconnaissance survey outlined in Section 3.1 provides the quality and quantity of data required providing maximum use is made of aerial photographs and satellite imagery as the present study demonstrates.

Clearly, the third objective, that of the selection of areas which merit more detailed study, is crucial for the implementation of a regional plan. It is in these areas which, for example, may contain soils of agricultural potential, that detailed studies are required based on a statistically valid sampling procedure. In detailed soil studies a grid survey technique is generally used in which observation sites are located at the intersection of an evenly spaced grid of points on a map or aerial photograph. The selection of sampling points may be done on a systematic basis by:

(i) sampling at every grid intersection point or

(ii) on an entirely random basis, the only universally certain way of avoiding bias.

Random, as Yates (1965) points out, does not mean haphazard selection. A random sample can be obtained only by the adherence to some proper random process, such as the drawing of lots or the use of a table of random numbers.

In reconnaissance survey the preliminary interpretation of the landscape on aerial photographs or satellite images serves as the primary strata for mapping and subsequent field sampling. The selection of observation sites within each of the interpreted units is generally carried out at the discretion of the soil scientist. Steur (1961) and Buringh et al (1962) proposed the term 'free survey' to distinguish this somewhat subjective method of survey from the more rigorous grid sampling procedure. But this subjectivity is acceptable at the reconnaissance level and, as Young and Stoeckler (1956) observe, time consuming and expensive sampling is not justified for reconnaissance soil mapping where boundary delineations by photo-interpretation are frequently more accurate than boundary lines located by field survey alone. However, this does not imply that the free survey method is a substitute for field work or that the two methods are mutually exclusive, a misunderstanding that is apparent in some of the literature. More recent work by Guinard (1974) on random sample surveys over large areas underlines the basic problem of selecting a suitable minimum sample size for reconnaissance scale mapping that is capable of implementation within the time allotted for the survey. Experience to date seems to suggest that, in practical terms, the soil surveyor's time is better spent in producing a reconnaissance map by 'free survey' techniques linked to physiographic analysis of remotely sensed data, rather than attempt a random sampling procedure which will give results of a very low precision.

The location of soil boundaries is particularly accurate on aerial photographs or satellite images where the boundaries have a clear external expression and are related to landforms or vegetation types with an equally definitive and visible boundary. In such instances, Burrough et al (1971), in comparing the utility of soil maps produced by different survey procedures, found that maps produced by a free survey method were superior to those prepared by grid survey for boundary location at scales considerably larger than 1:250,000.

The soil scientist's understanding of the interrelationships between the soils, geomorphology, geology and vegetation, as well as the complexity of the soil pattern will largely determine the number and location of his observation sites in a reconnaissance survey. The accuracy of the final reconnaissance soil map, by whatever means it is measured, will be determined by the following:

(a) The complexity of the area surveyed.

(b) The skill of the soil scientist at interpreting and comprehending the ecological relationships of the area.

(c) The design of the sampling programme.

(d) The choice of map legend.

The variable skill of soil scientists to carry out reconnaissance surveys is summed up by the Soil Survey Staff (1951) of the United States Department of Agriculture in the following quote:

> "Excellent soil scientists for some kinds of research, including detailed soil surveys, fail utterly in reconnaissance mapping. They may be unable to visualise large and complex patterns or become mentally harassed by indecision in the face of vague and apparently conflicting evidence."

Nonetheless, Webster and Beckett (1968) amongst others, consider that some quantitative criteria of map quality is required as a measure of success or comparison. Many such assessments have been made to determine the quality or utility of a soil map in terms of the accuracy of boundary location or the soil variability within mapped units (i.e. the degree of purity of the unit) using a variety of statistical measures combined with field checks. These evaluations are reviewed in terms of their applicability to the present study in the following section.

3.4 A REVIEW OF THE QUANTITATIVE ASSESSMENTS OF SOIL MAP ACCURACY

In the numerical assessment of the accuracy of soil maps prepared by photo-interpretation, conventional ground survey and a combination of both techniques, two basic approaches have been used:

(1) Measurement of the purity of a mapping unit.

(2) Measurement of the accuracy of soil boundary delineation.

Webster and Beckett (1968) favour the former approach and suggest the criteria of within-class variance as a possible measure of accuracy and the establishment of maximum threshold values for this property in soil maps. They further suggest that a statement of the mean and modal values of the properties of each class, together with their variance and standard deviations would be of great value to the map user in assessing the overall quality of the map. However, soils data in the Southern Darfur Surveys were obtained by 'free survey' methods and not by a random sampling programme, the model on which most statistical theory rests. The data collected in Area A for comparative analysis were therefore unsuited to such statistical analysis.

In another study using mapping 'purity' as the criteria of excellence, Bie and Beckett (1973) compare four soil maps of 19 km^2 of Cyprus compiled from airphoto-interpretation by four independent soil scientists. They conclude that the four interpretations differed considerably in the purity of their mapping units and that purity appeared to be inversely related to the number of profile classes. The purity was measured as the percentage of random sites at which the map would have correctly predicted the class to which the soil profile belongs. In this area of Cyprus it seemed that the quality of soil surveys by airphoto-interpretation was more sensitive to the soil scientist's choice of classes and mapping units than his skill in locating boundaries. However, the survey area chosen was very small, a common constraint in many of these quantitative assessments, and in marked contrast to the soils of Southern Darfur, the Cyprus soils were relatively homogeneous and lacked a clear expression or 'signature' on the air photographs.

The second approach, that of measuring by some method the accuracy of boundary delineation, was used by Pomerening and Cline (1953). They produced a map compiled from all available data including field checking and used this as a 'standard' against which to compare the accuracy of five soil maps compiled using various methods that made use of aerial photography. Map accuracy was determined by measuring the area of each mapping unit on each map, comparing it with the equivalent area measured on the 'standard' map and calculating the areas of agreement and disagreement. These values were divided by the total area of the mapping unit on the 'standard' map and expressed as per cent agreement or disagreement for that unit. Valentine et al (1971) used a similar method when assessing the accuracy of soil maps obtained from black and white, colour and infra-red aerial photographs.

Bie and Beckett (1973) argue that such test criteria are rather subjective as boundary agreement has been assessed in relation to the 'standard' or 'Best' Map which biases the result in favour of maps which share the mistakes of the Standard Map. However, in areas where no previous soils map or other soils data exist such as Southern Darfur, and where in addition, further field data cannot be gathered to check quantitatively the purity of the original map, the latter becomes and remains the only possible standard for comparison with maps of the same area compiled by other means. Bearing in mind the objectives and methods of compiling reconnaissance soil maps outlined in Section 3.1, some degree of bias is inevitable and acceptable within the framework of reconnaissance survey.

A numerical procedure for testing the accuracy of soil boundary location plotted from aerial photos rather than the purity *per se* of mapping units was tested by Webster and Wong (1969). The interpreted boundaries of an area approximately 24 km^2 were checked in the field by sampling at 20 m intervals along a 6 km line transect which cut across part of the area. The objective was to establish where on the transect the points of maximum rate of change lay and to what extent these corresponded with the points where the transect bisected the interpreted boundary. By using principal components analysis to combine many soil properties into a single variate that expresses a large proportion of the available information, the rates of maximum or minimum lateral change between soils were determined statistically. However, the statistically determined boundaries were generally in very close agreement with the interpreted boundaries, particularly where changes in landform occurred. On flat land the soil changes were not interpreted until after field checking but nonetheless were apparent on the photographs.

The transect method of boundary checking is more suited to detailed surveys in areas where a rapid lateral variation in soil occurs without any marked surface expression. A further factor to be considered and one not mentioned by Webster and Wong (op. cit.) is the number of transects required to give a statistically valid assessment of accuracy along the length of the soil boundary.

The foregoing examples demonstrate the value of air photo-interpretation in soil survey backed by field studies, for accurately delineating major soil boundaries. They also serve to illustrate the impracticality of using random sampling techniques and principal components analysis of transect data for checking the accuracy of a reconnaissance map. This is particularly true in a developing country like the Sudan where soils data outside the Nile valley are scarce or non-existent, and where major soil boundaries may be hundreds of kilometres in length.

It is clear that a quantitative assessment of the accuracy of a reconnaissance map presents considerable difficulties in areas such as the present Study Areas, where:

(a) No previous soil maps or other soil data covering the study area exist with which to make comparisons.

(b) The original survey was carried out using a free survey technique and therefore a biased sampling method, based on the interpretation of aerial photographs or satellite imagery.

(c) Additional field data for the purposes of checking the original map cannot be obtained.

Thus, for the comparative analysis of soil units mapped in Southern District (Area A) from air-photo-interpretation and 'free survey', with those units mapped by interpretation of LANDSAT imagery of the same area, no numerical assessment of the former or 'best' map can be given. In the absence of other soil maps the former must be considered the 'Standard' map against which the accuracy of the LANDSAT map is compared numerically.

In this comparative study a quantitative assessment of map accuracy has been used, based on the areal measurement of mapping units and similar to the methods employed by Pomerening and Cline (1953) and Young and Stoeckler (1956). In addition, qualitative and quantitative methods of assessing boundary coincidence have been developed and tested. These methods and results of these analyses are discussed in Chapters 6, 7 and 8.

CHAPTER 4

STUDY AREA ENVIRONMENT

4.1 INTRODUCTION

The first systematic resource survey in Southern Darfur Province was started in 1958 and since then five major regional studies have been completed. These are shown in Figure 4.1. However, prior to the Southern Darfur Land-use Planning Study (Hunting Technical Services Ltd., 1974a), very little was known of the physical resources of those parts of Darfur within the boundaries of Southern and Eastern District Councils (Areas A and B). Those studies that had been carried out were mainly isolated traverses through the areas made by government officers, itinerant geographers or small expeditions collecting flora and fauna. The latter were generally en route for the more spectacular and ecologically rewarding environment of the 3,000 m volcanic massif of Jebel Marra in Western Darfur. The history of botanical exploration in Darfur is summarised by Wickens (1977).

The following summaries and maps of the physical resources of Southern and Eastern Darfur are, with the exception of climate and geology, derived from the interpretation and ground checking of aerial photographs and satellite (LANDSAT) multi-spectral imagery by the author. Field work was carried out between January and July 1972 and between January 1975 and May 1976.

4.2 CLIMATE

The climate of the area, classified by Meigs (1965) as 'hot semi-arid', is dependant upon the seasonal movement of the sun and the associated Inter-Tropical Convergence Zone (ITCZ). During the winter months from October to January the ITCZ moves south of the equator and Southern Darfur is in a zone of dry north-easterly 'harmattan' winds. The mean daily temperature at this time of year is about 24°C. Air temperatures rise to a mean maximum of 38°C in April and May as the ITCZ moves northward.

Rainfall is seasonal, occurring on 40-50 rain days during July, August and September. It reaches a single peak in late July or early August when a moist maritime south-westerly air stream moves towards the ITCZ, then at the northern limit of its annual migration. The average annual rainfall (1941-1970) of the area ranges from approximately 500 mm along the Darfur Railway, to over 800 mm at the Bahr el Arab. The isohyets for the period 1941-1970 are shown on the Land Systems map in Figure 4.2.

Figure 4.1
Resource Surveys in Southern Darfur

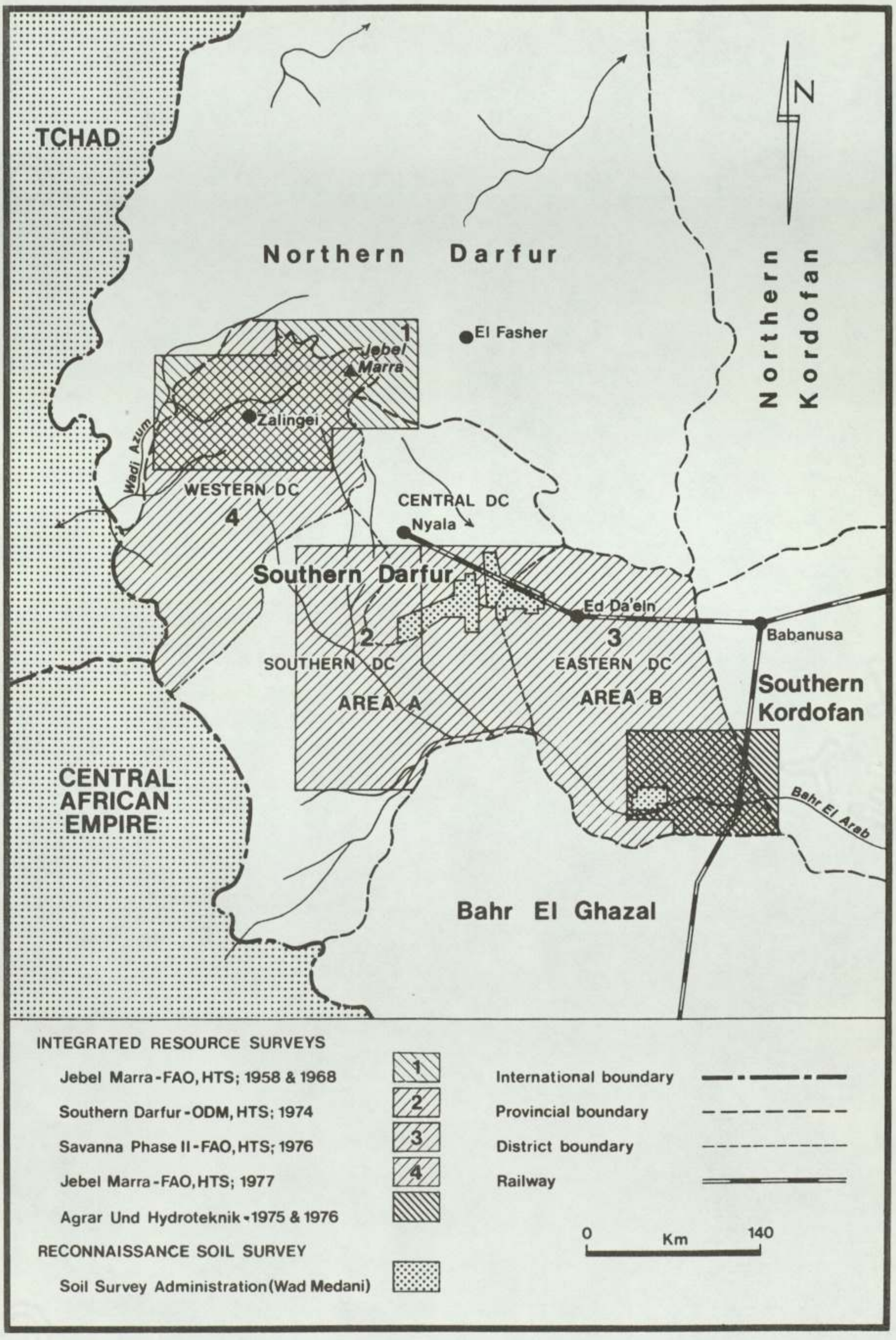
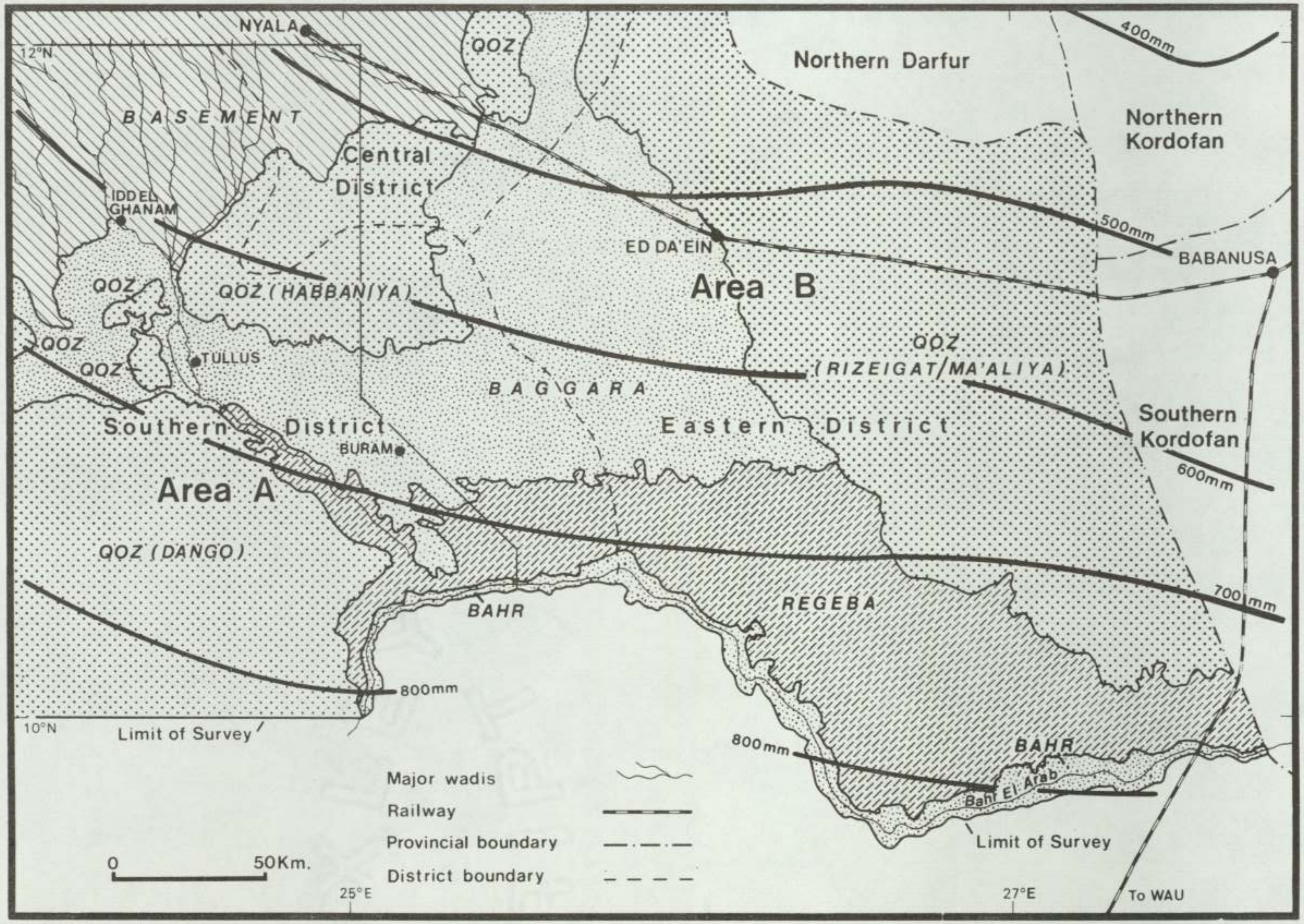


Figure 4.2
Land systems and isohyets (1941-70) in Southern Darfur



SOURCE: Land systems from interpretation of aerial photography, LANDSAT imagery and field work by D.E. Parry.
Isohyets from data supplied by Sudan Meteorological Department

Although prolonged and widespread rainfall occasionally occurs in mid-season, isolated thunder storms associated with the atmospheric instability of the ITCZ, are the main source of rainfall.

The present day climate in Darfur and its short term oscillations, as exemplified by the 1968-1974 drought, has largely controlled the formation and distribution of the various landforms, soil surface materials and vegetation. Interpretation of satellite imagery and examination of the deeper soil mantle in relation to drainage morphometry and landforms have suggested that major long term climatic changes have occurred in the not too distant past. These episodes are tentatively correlated with the major Sudanese late Pleistocene and Holocene climatic changes referred to by Grove (1972) and Williams and Adamson (1974) for the Central Sudan.

4.3 GEOLOGY

The Study Area forms part of a large sedimentary basin within the Basement Complex formation. It is located between the volcanic massif of Jebel Marra to the north west, and the Nuba mountains, and upland area of Basement complex rocks to the south east in South Kordofan Province. Recent geophysical surveys and borehole drilling programmes have shown that the basin in Southern Darfur and South Kordofan is fault controlled and very deep, exceeding several thousand metres in places.

Three main sedimentary formations have been deposited within the basin; superficial deposits, Umm Ruwaba Series and Nubian Series. The Superficial deposits of Pleistocene to Holocene age cover the majority of the Project Area and provide the dominant soil parent materials.

4.4 GEOMORPHOLOGY AND LAND SYSTEMS

In essence, the area consists of a level to gently undulating pediplain in the north west which is cut across Basement Complex rocks at approximately 600 m a.m.s.l. The pediplain is broken in places by inselbergs which are rarely more than 50 m above the surrounding plain. The pediplain slopes towards the south and south-east and gradually disappears beneath a level to very gently undulating sedimentary mantle of aeolian and fluvial deposits between 550 m and 420 m a.m.s.l.

The landscape has been classified by Hunting Technical Services Ltd. (1974b) into five major elements called Land Systems after Christian (1958), each with a recurring pattern of geomorphology, geology, soils and vegetation.

The five land systems, Qoz, Baggara, Regeba, Basement and Bahr, are shown in Figure 4.2. The boundaries of these land systems drawn on 1:1,000,000 scale satellite images covering areas A and B are shown in Figures 4.3, 4.4 and 4.5.

4.5 SOILS

Very little has been published on the soils of Southern Darfur. Jewitt (1950) analysed and compared two soil profiles on the Qoz soils; one at El Fasher and the other at Sungikai in Kordofan. General references to the Qoz sands are made by Tothill (1948), Edmonds (1942), Grabham (1935) and Andrew (1948). Smith (1949) discusses the dynamic aspects of sheet wash slope formation, and the development of the typical non-cracking surface of the naga'a soils in Darfur in terms of rainfall run-off relationships and vegetation succession but does not consider the three-dimensional soil profile. Harrison and Jackson (1958) refer in very general terms to the topo-sequence of sands and heavier textured soils in the special areas of low rainfall woodland savanna in Darfur designated Baggara and Regeba Repeating Patterns. But these are considered as part of a regional vegetation classification and no formal soil studies appear to have been carried out in these areas.

The majority of the observations above come from isolated traverses across Darfur and were made without the aid of aerial photographs or satellite imagery. They are too scattered, too few in number and contain insufficient detail of the chemical, physical and morphological properties of the soils. It was not until the nineteen fifties and sixties that any systematic regional and sub-regional natural resource surveys, that included soil and geomorphological studies, were carried out in Darfur by the Wad Medani Soil Survey Administration and teams of visiting foreign consultants. These surveys are shown in Figure 4.1.

The soils in Areas A and B have been classified by the author on the basis of their physical and chemical characteristics and their geomorphological position into taxonomic units (Hunting Technical Services Limited, 1974b, 1976a). For the purposes of the present study these soils are grouped together and briefly described under the following three headings: aeolian soils; alluvial soils; residual and polygenetic soils. Their distribution is illustrated in Figure 4.6.

The aeolian soils include the deep sands of the Qoz land system and the shallower sands found on the dunes and sand mantle in the Baggara and Basement Land Systems.

Figure 4.3
Land systems boundaries. Southern District (Area A)

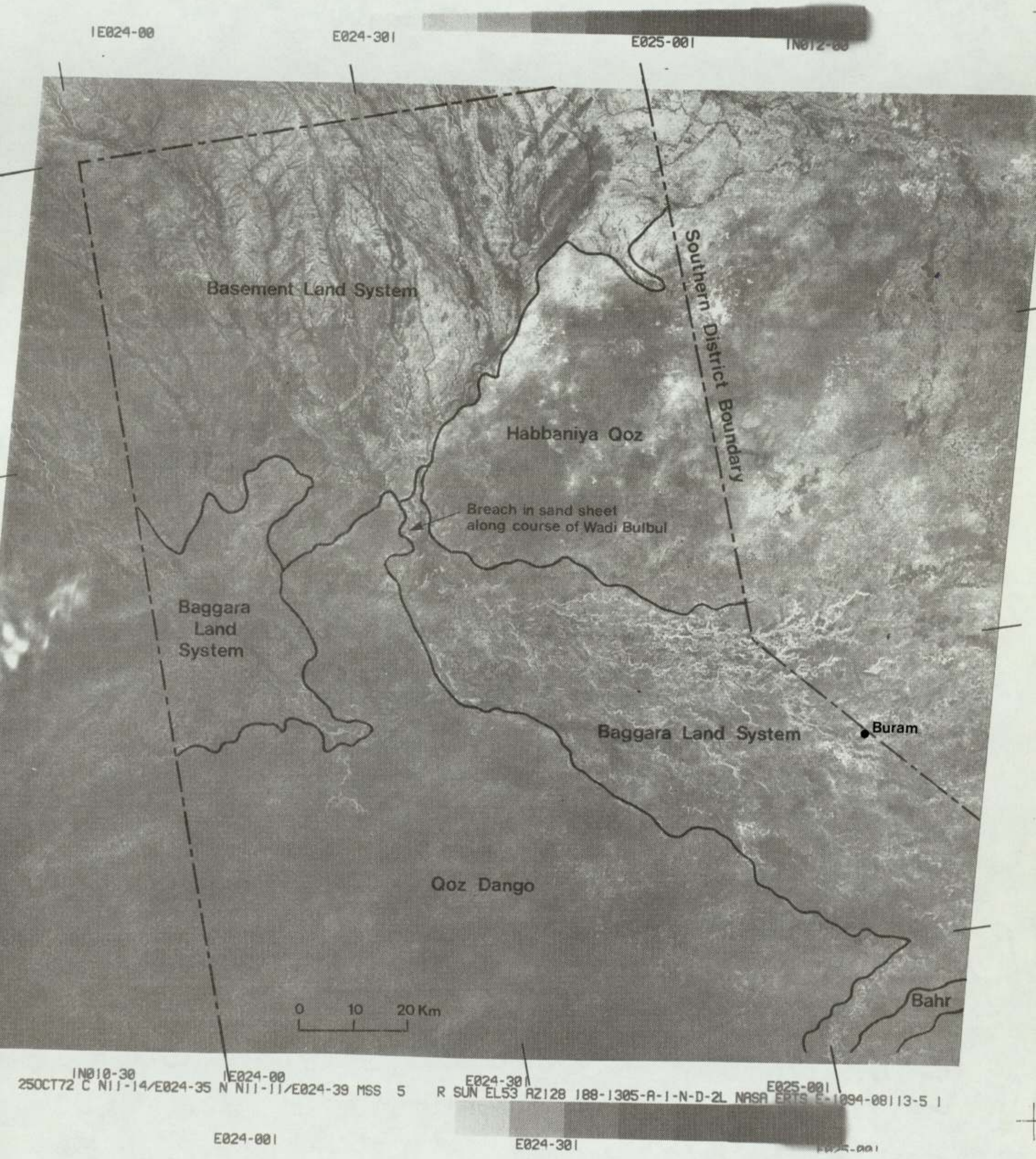


Figure 4.4
Land systems boundaries. Eastern District (Area B, North part)

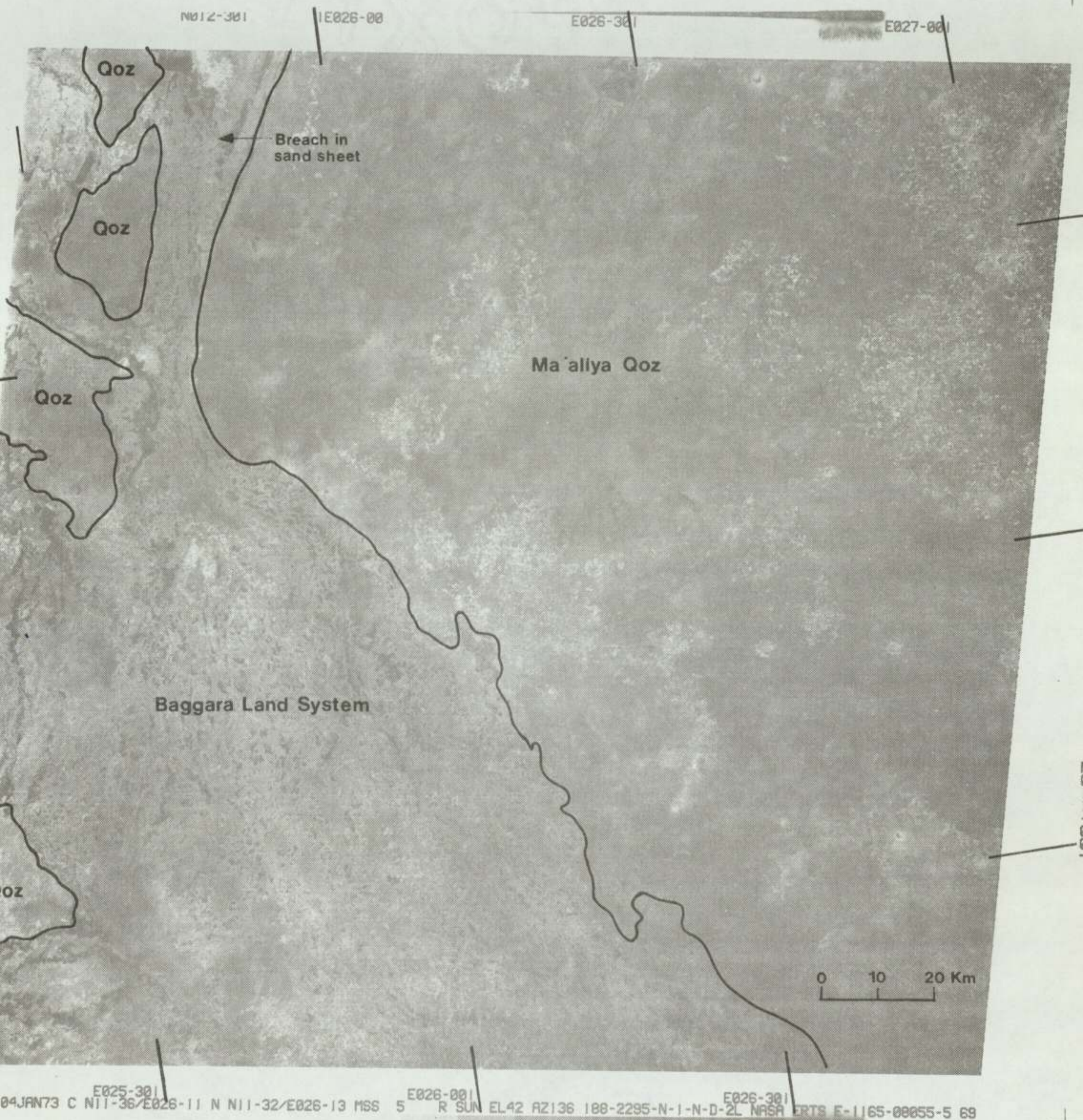


Figure 4.5
Land systems boundaries. Eastern District (Area B, South part)

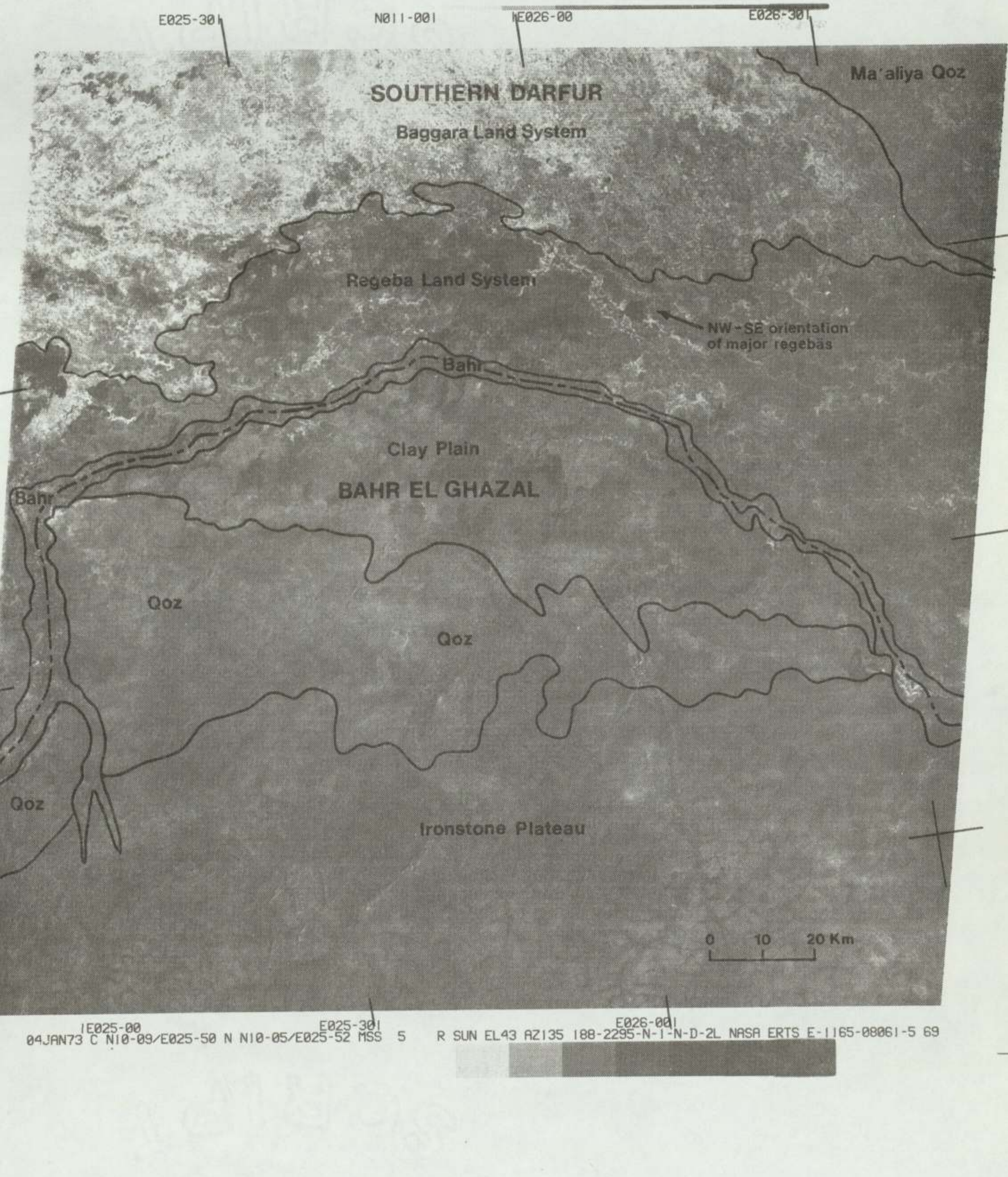
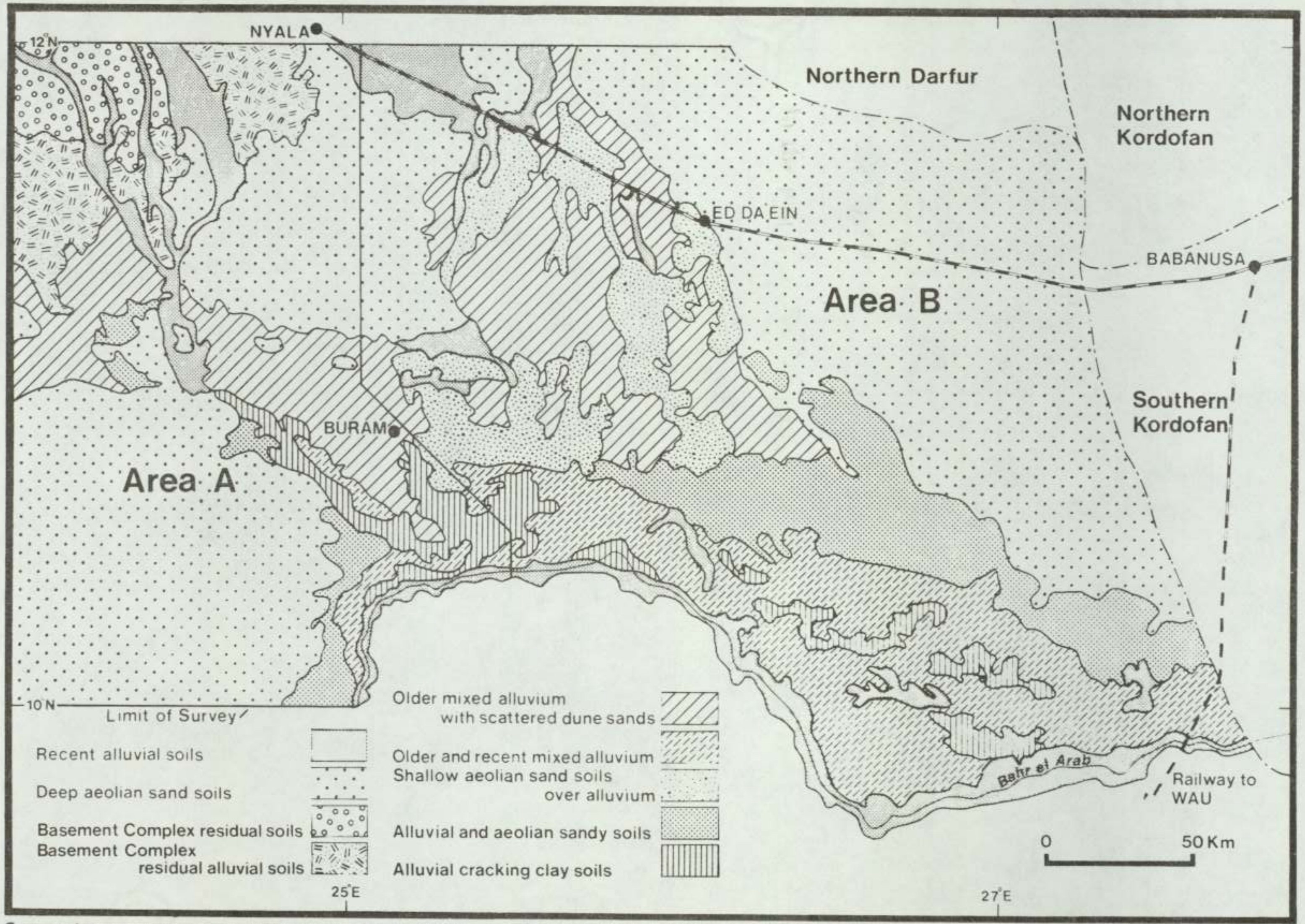


Figure 4.6
Soils of Southern Darfur



Source: Interpretation of aerial photography, LANDSAT imagery and field work by D.E.Parry

The poor analytical properties of the sands are partially offset by the excellent root penetration and the ease with which they are cultivated using traditional hand implements. These sands are the most widespread agricultural soils in Southern Darfur.

The alluvial soils are found throughout the Study Areas but are dominant in the Baggara, Regeba and Bahr land systems where fluvial processes have dominated landscape evolution and soil formation. In other land systems the alluvial soils are generally confined to narrow floodplains and terraces on either side of the major drainage channels (wadis). The soils are a heterogeneous group ranging from deep, uniform, dark grey cracking clays or vertisols in depressions, to complex stratified alluvia of mixed textural composition and pedogenesis on levees and sheet wash slopes.

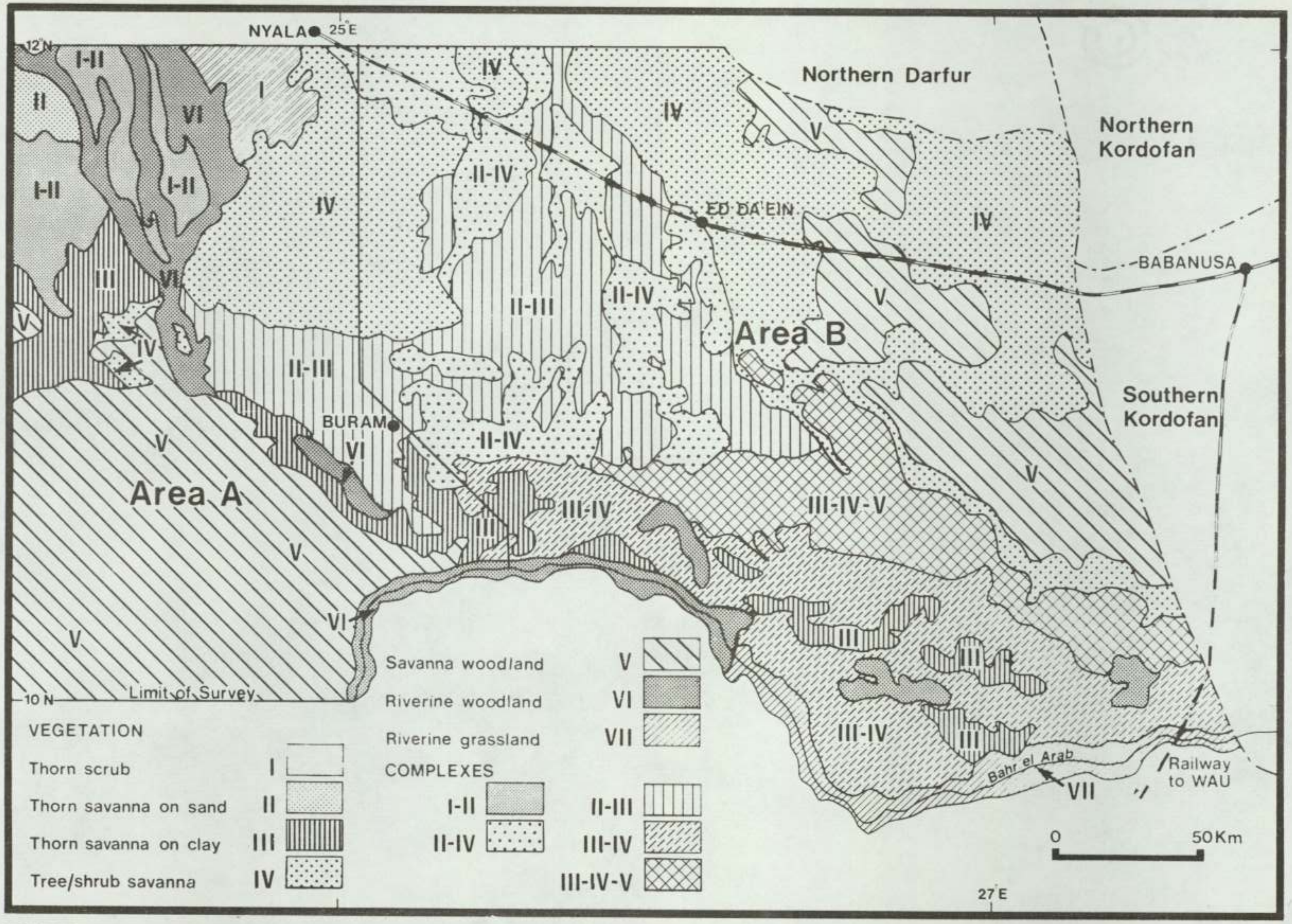
Interpretation of the drainage patterns within these land systems using aerial photographs and satellite imagery combined with subsequent field work, indicated that the alluvium is derived from the weathering of Basement Complex rocks to the north west,and Jebel Marra Volcanics to the north.

Residual and polygenetic soils occur in the Basement Land system wherever the deeper aeolian or alluvial mantle is absent. Variations in geomorphology, topographic position and lithology have created complex catenas of polygenetic soils. In the middle and upper slope positions and on interfluves and pediments, residual clays derived from the weathering of Basement Complex rocks occur. These frequently have a colluvial and alluvial mantle. The proportions of residual, alluvial and colluvial material will vary according to topographic position, depth and type of bedrock. Lithosols and skeletal soils occur on rock outcrops and pediments and are derived from *in situ* weathering Basement Complex rock.

4.6 VEGETATION

The vegetation of Southern Darfur was classified by Harrison and Jackson (1958) as Low Rainfall Woodland Savanna Formation-type. It was further mapped and classified by Hunting Technical Services Ltd. (1974b and 1976a) into formations, sub-formations and associations. The system of classification followed was that used the the United Nations Kordofan Special Fund Project (F.A.O., 1964) and the United Nations Special Fund Jebel Marra Project (F.A.O., 1969), modified where necessary to cater for variations in the flora of Southern Darfur.

Figure 4.7
Vegetation of Southern Darfur



SOURCE: Interpretation of aerial photography, LANDSAT imagery and field work by D.E. Parry, P. Hekstra and S. Hashim

In the northern part of the area thorny species, mainly Acacia, are predominant. Towards the south, as rainfall increases, a greater variety of broad-leaved deciduous species occurs, although some thorny species are still present. Within this latitudinal climatic gradient, soil texture and the biotic influences of agriculture and grazing are major factors determining the physiognomic form and floristic composition of the vegetation. The distribution of the main physiognomic vegetation types is shown in Figure 4.7.

CHAPTER 5

DATA COLLECTION AND MAPPING: SOUTHERN DISTRICT (AREA A)

5.1 INTERPRETATION AND MAPPING 'STANDARD MAP'

5.1.1 Introduction

A reconnaissance level survey of the physical resources of some 25,000 km^2 of the Southern District Council Administrative Area of Southern Darfur Province, Sudan, hereafter called Area A, was carried out between January and December 1972 by Hunting Technical Services Ltd. The physical resources examined included the soil, geomorphology, geology, vegetation, surface hydrology and groundwater. For the purposes of the present study only the mapping of the regions land systems, soils and geomorphology carried out by the author, are considered.

5.1.2 Base Map Compilation

The existing 1:2,000,000 to 1:100,000 scale topographic maps covering Area A were outdated, were not compiled from aerial photography and contained insufficient topographic and hydrologic detail to serve as a suitable mapping base for the reconnaissance survey. In the absence of good topographic maps the base map for Area A, on which thematic data were later superimposed, was compiled from newly flown aerial photography.

Hunting Surveys flew black and white aerial photography at 1:40,000 scale between January and February 1972 and the Sudan Survey Department compiled sets of 1:50,000 and 1:100,000 scale mosaics from this photography. The base map and thematic maps constructed in the field from the 1:100,000 scale mosaics were photographically reduced to a scale of 1:250,000 for publication with the Report (Hunting Technical Services Ltd., 1974a) and further reduced photographically to 1:500,000 scale for the purposes of this Study.

5.1.3 Land Systems Mapping

The existence of a strong association between the soils, geology, geomorphology and vegetation of the region suggested in the Appraisal Report (Hunting Technical Services Ltd., 1971), in addition to the large size of the area, indicated that a survey method similar to that of the land systems approach developed by Christian (1958) would be the most suitable. Using this approach and the methods of aerial photographic interpretation outlined in Chapter 2, the landscape was broken down into four distinct units or land systems within which there was a recurring pattern of soils, geology, geomorphology, hydrology and vegetation. Each land system was then sub-divided into its component soil and geomorphological sub-systems using the deductive method of air-photo interpretation. These interpreted units provided the framework for subsequent field studies.

5.1.4 Soils and Geomorphology Mapping

A reconnaissance soil and geomorphology survey of Area A was carried out in the field between January and June 1972 by the author. During the survey 200 soil bores and 40 soil pits were examined in detail to depths of 150 cm and 200 cm respectively where conditions permitted. A 'free survey' technique was used in which the location of soil observation sites was left to the discretion of the soil scientist, following pre-field air-photo interpretation of the Area. Slope angle, aspect and shape were also recorded at each soil observation site in addition to notes on the general geomorphology. Numerous other sites were examined in the field but not in detail. Chemical and physical analyses were carried out on 167 soil samples taken from 36 soil pits. For details of the analytical and morphological properties of the soils in Area A, reference should be made to the relevant report (Hunting Technical Services Limited, 1974b).

Ground traverses were carried out along all major tracks using a four-wheel drive vehicle. Where necessary, offsets were made on compass bearings in order to sample areas of particular pedological or geomorphological interest. Most detailed observations were made at sites considered by the pedologist to be typical or representative of a land system or sub-system and related soil type. Sites considered atypical were also sampled in order to aid understanding of the past and present regional pedogenic and geomorphic processes. The range of soil and geomorphic properties was determined by considering the catenary ralationships between soils and slopes over relatively short distances (up to one kilometre). A section of a 1:100,000 scale mosaic with a soil interpretation overlay covering parts of the Qoz and Baggara land systems is illustrated in Figure 5.1.

In the Soils and Geomorphology Map (Map 1 Appendix E) both discrete soil mapping units and soil complexes are coded in the denominator of a fractional coding system. The land systems and geomorphic sub-units are coded in the numerator. This map serves as the 'standard'or best map against which the accuracy of the map compiled from LANDSAT imagery is compared. A scaled down, simplified version of Map 1 is shown in Figure 5.2 and a simplified legend in Table 5.1.

Figure 5.1
Part of 1:100,000 scale mosaic and interpretation overlay (Area A)

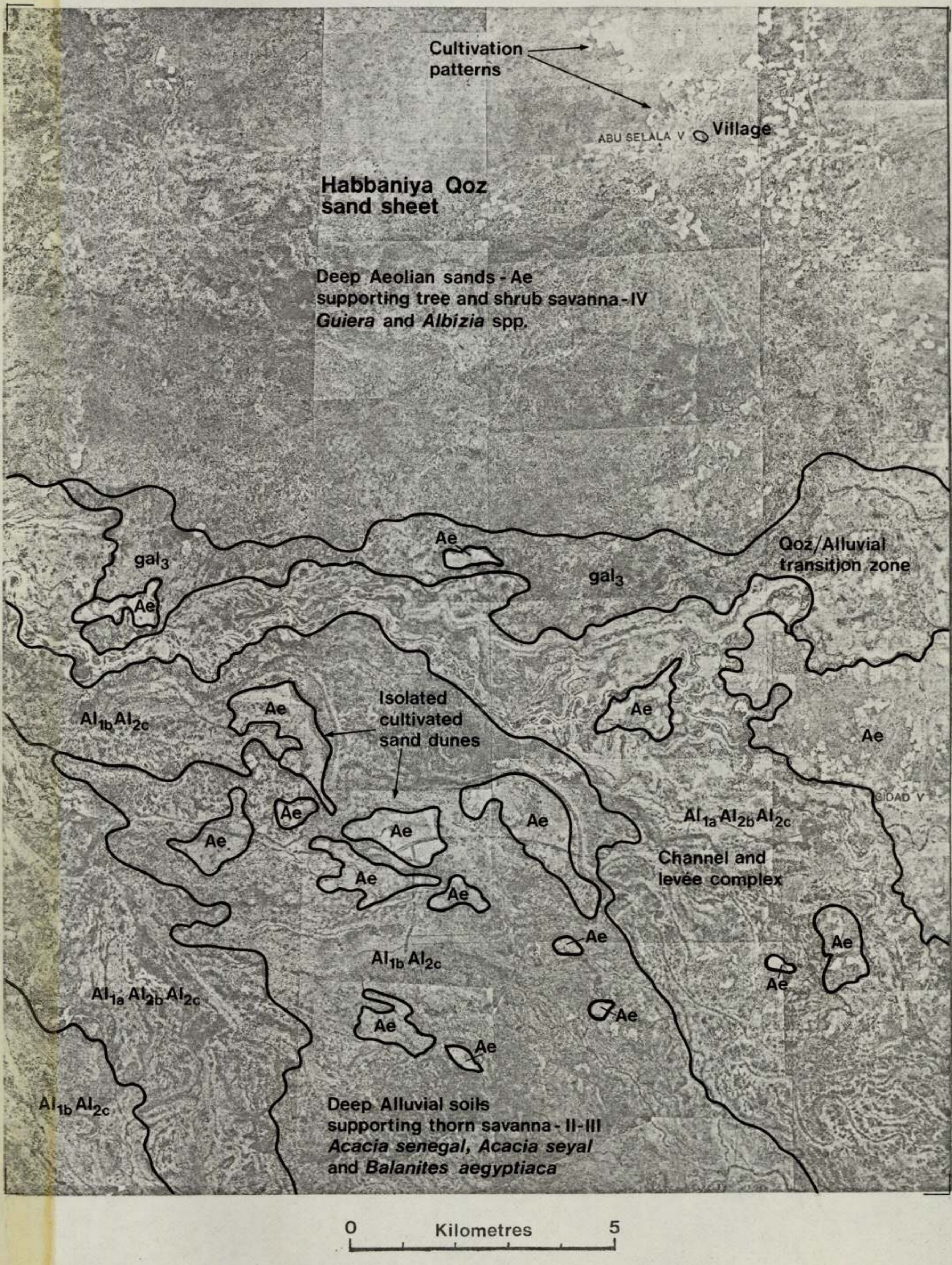


Figure 5.1
Part of 1:100,000 scale mosaic and interpretation overlay (Area A)

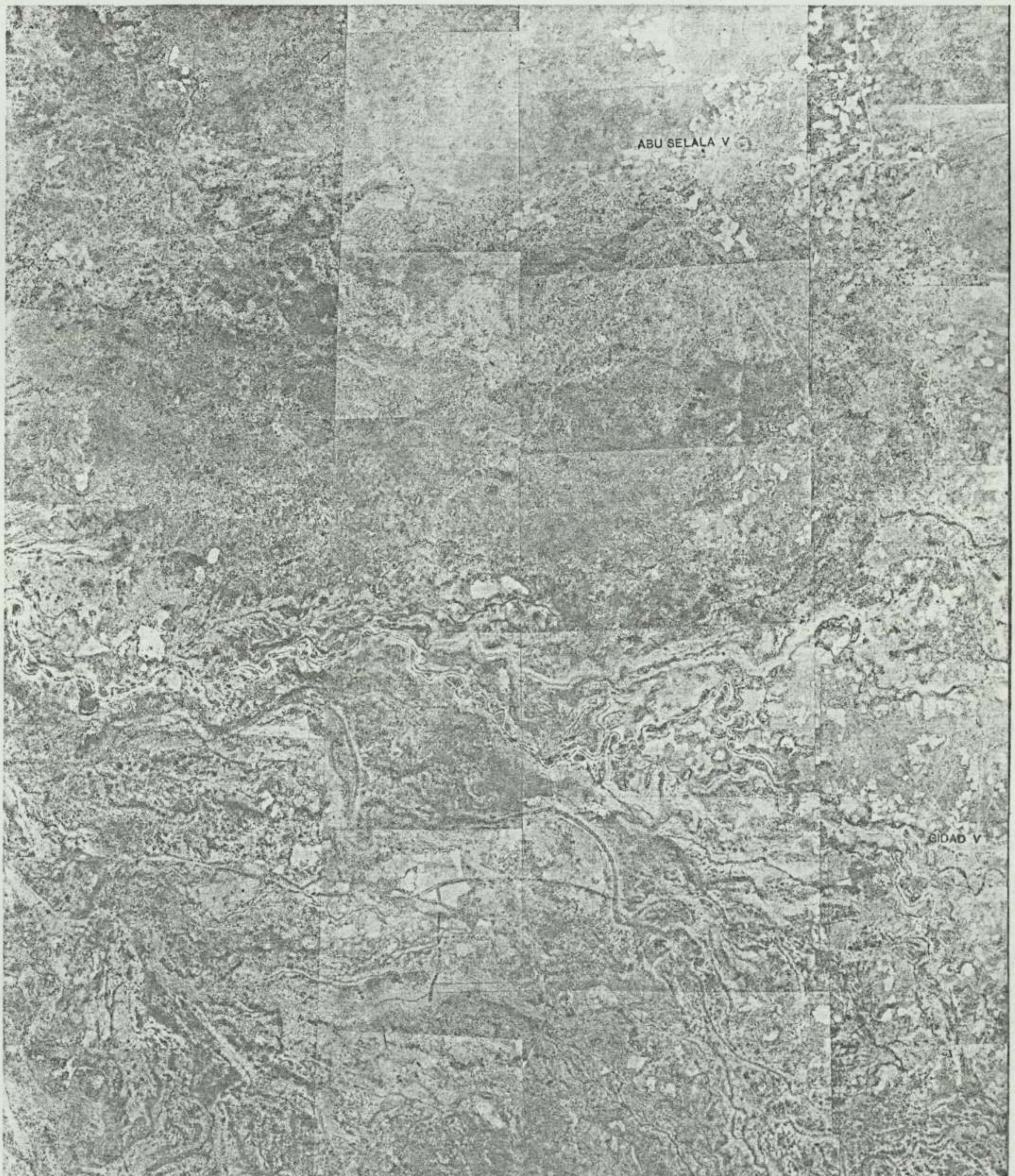


Figure 5.2 Southern District (Area A). Soils and land systems. Aerial photography and ground survey.

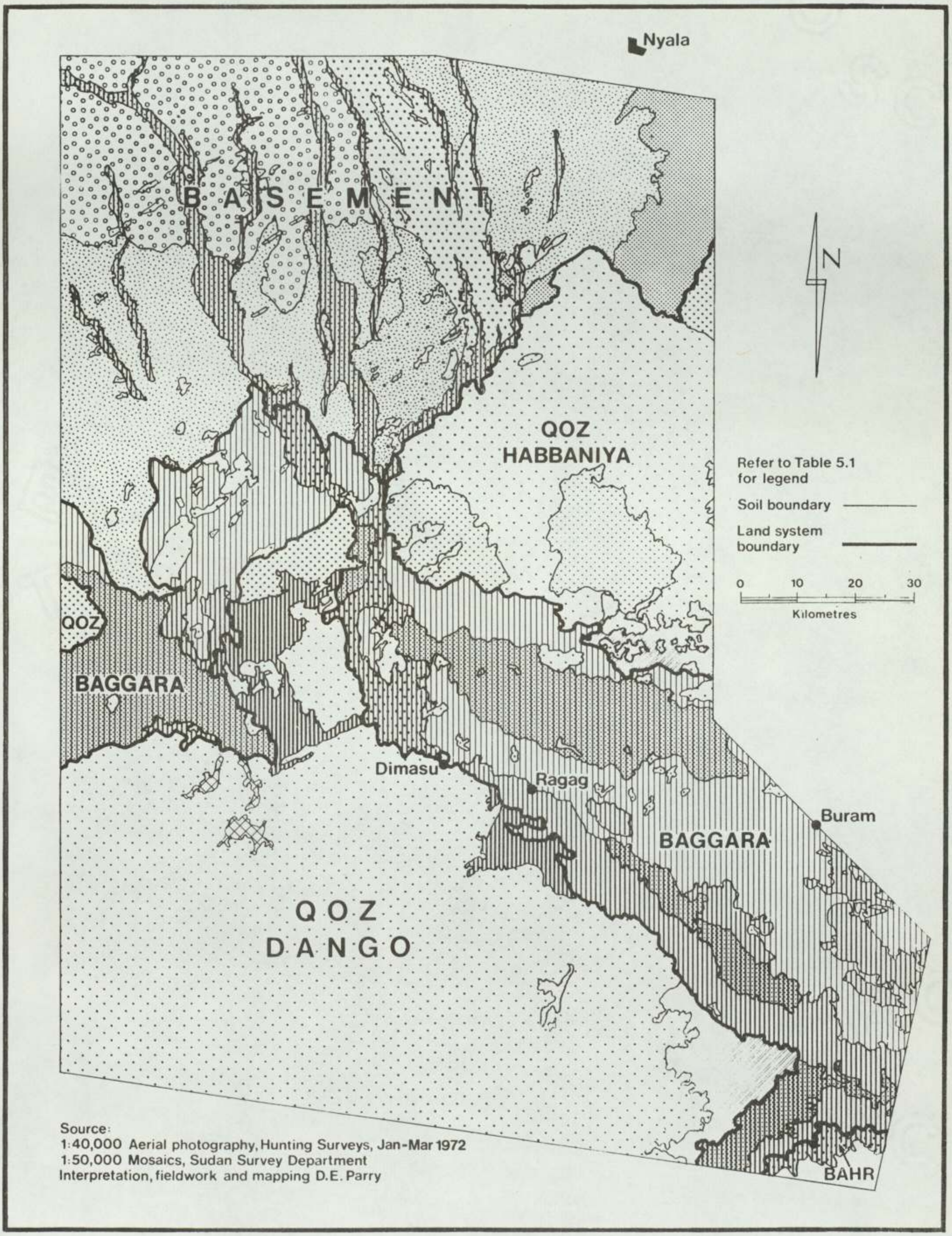


TABLE 5.1 SOIL AND LAND SYSTEMS LEGEND SOUTHERN DISTRICT (AREA A)

Soil Unit	Parent Material	Soil Description
Ae	Aeolian sands	150 cm of brown and reddish brown fine and medium sands, loamy sands and sandy loams
bs Ae	Colluvium and alluvium from Basement Complex schists, gneisses, granites and quartzites; aeolian sand	Dark brown to dark greyish brown clay loams, sandy clay loams and sandy clays; often calcareous; many quartz fragments on surface in association with Ae soils
Nua	Aeolian sand from Nubian sandstone	Red fine and medium loamy sands, sandy loams and loams
Nur Nua	Residual and aeolian sand from Nubian sst.	As above but with some gravelly clay loams
Ae Nua		See relevant soil unit
Al_{2c}	Fine textured micaceous and non-micaceous alluvium	Dark grey cracking clays; frequently calcareous
gal_3	Aeolian sand over alluvium	Brown fine and medium sands and loamy sands over massive, mottled sandy loam, sandy clay loam; frequently calcareous
Al_{1b} Al_{2b} Al_{2c}	Mixed micaceous and non-micaceous alluvium	Complex of sandy loams, clay loams, sandy clay loams and clays
Al_{1b} Al_{2c}	Mixed micaceous and non-micaceous alluvium	Clay loams, sandy clay loams and clays
Al_{2a} Al_{2b}	Stratified micaceous and non-micaceous alluvium	Stratified coarse and medium sands, sandy loams, loams, silt loams, clay loams; occasionally calcareous
Al_{2a} Al_{2b} Al_{2c}	Stratified micaceous and non-micaceous alluvium	As above but with cracking clays
Al_{2a} Al_{2c}	Stratified micaceous and non-micaceous alluvium	Stratified coarse and medium sands, sandy loams and clays
Al_{2b} Al_{2c}	Stratified micaceous and non-micaceous alluvium	Stratified silt loams, clay loams and clays
gal_3 Al_{2b}	Aeolian sand and stratified alluvium	See relevant soil unit
gal_3 Al_{2c}	Aeolian sand and stratified alluvium	See relevant soil unit
bs	Colluvium and alluvium from Basement Complex	See relevant soil unit
bsr	Residual weathering of Basement Complex rocks	Bare rock and shallow red brown sandy loams, clay loams and gravelly loams; frequently micaceous

5.2 INTERPRETATION AND MAPPING LANDSAT MAP

5.2.1 Introduction

The interpretation of satellite imagery for resource mapping by manual methods is essentially an extension of the conventional techniques of aerial photographic interpretation familiar to the geologist, soil scientist, geographer, forester and other resource scientists. It involves the evaluation by the interpreter of a number of image characteristics such as tone, or colour, texture, size, shape, pattern, contrast and shadow in order to recognise, identify and deduce the significance of the total image and its component parts. However, when interpreting LANDSAT imagery, the interpreter familiar with aerial photograph interpretation must recognise and make allowances for the following, before proceeding to the deductive phase of satellite image interpretation:

(1) The interpreter must adjust his scale perspective from that of aerial photography (1:5,000-1:60,000) to that of orbital imagery (1:250,000-1:3,000,000).

(2) The interpreter must be aware of the spectral responses from earth resource features in each of the four spectral bands imaged by the LANDSAT multi-spectral scanner, singly and in a false colour combination.

A great deal is known about the multi-spectral response from orbital altitudes of various earth resource features in the North American and European environments. This information is summarised in Table 5.2. Much less is known about the spectral responses in the semi-arid African Sahelian and Savanna zones. As a result, the reliability of the deductive phase of the interpretation exercise is frequently low. This fact puts a very high premium on field verification of satellite interpretation in these zones.

5.2.2 Land Systems and Soils Interpretation and Mapping

Land system and soil boundaries were manually interpreted from a 1:500,000 scale colour composite print (MSS bands 4, 5 and 7) of LANDSAT image E-1094-08113, onto a clear 'Melanex' overlay. A clear film overlay was found to be superior to the more opaque tracing films for interpretation. The LANDSAT frame was taken on October 25th 1972 and covered 90 per cent of the Southern District Study Area.

The colour composite print was made using the Cibachrome colour printing process P-18 (Ilford, 1976) after the 70 mm positive transparencies of the three bands had been registered and projected through appropriate colour filters on an International Imaging

TABLE 5.2
APPROPRIATE LANDSAT MSS BANDS FOR IDENTIFYING RESOURCE FEATURES

FEATURE	MSS band				FEATURE	MSS band			
	4	5	6	7		4	5	6	7
Airfields		X			Metamorphic rocks			X	
Air pollution	X				Rivers			X	X
Burned rangeland				X	Roads	X	X		
Chlorophyll (seawater)			X	X	Serpentine outcrop				X
Cloud penetration				X	Shallow water	X			
Cloud-snow difference			X		Shoals	X			
Clouds (thin cirrus)	X	X			Shores			X	X
Crop differentiation				X	Small lakes				X
Defoliation		X		X	Snow detection	X			
Eddies		X			Snow lines	X		X	
Floodplains				X	Soil associations		X	X	
Forests		X			Soil moisture	X			
Geological features			X		Stream channels		X		
Grass fires				X	Surface water			X	X
Growth state	X			X	Tectonic features			X	X
Haze	X				Topography		X		
Ice	X				Turbidity	X	X		
Igneous rocks			X		Urban areas	X	X		
Iron (ferric)	X	X			Water boundaries			X	X
Irrigated fields				X	Water depth	X	X		
Jet contrails	X	X			Water pollution	X	X		
Landform features		X			Water sediment	X	X		
Large bridges			X		Wet lands			X	X
Large horizontal concrete structures		X			Wooded areas	X	X		
Lithology		X							

SOURCE: LANDSAT Data Users Handbook

Systems (I^2S) colour additative viewer. In the present case, Band 4 (blue-green) was projected through a blue filter; band 5 (red) through a green filter; and Band 7 (infra-red) through a red filter. The end product, a Xerox colour copy of which is shown at the reduced scale of 1:1,000,000 in Figure 5.3, depicts healthy vegetation in shades of red. This is due to the high reflectance of infra-red radiation from vegetation containing a high chlorophyll content to which Band 7 is sensitive. Other colours in the image represent a variable proportion of dormant vegetation (some of which has been burnt), bare soil of various types, cultivation, settlements, drainage lines and bare rock.

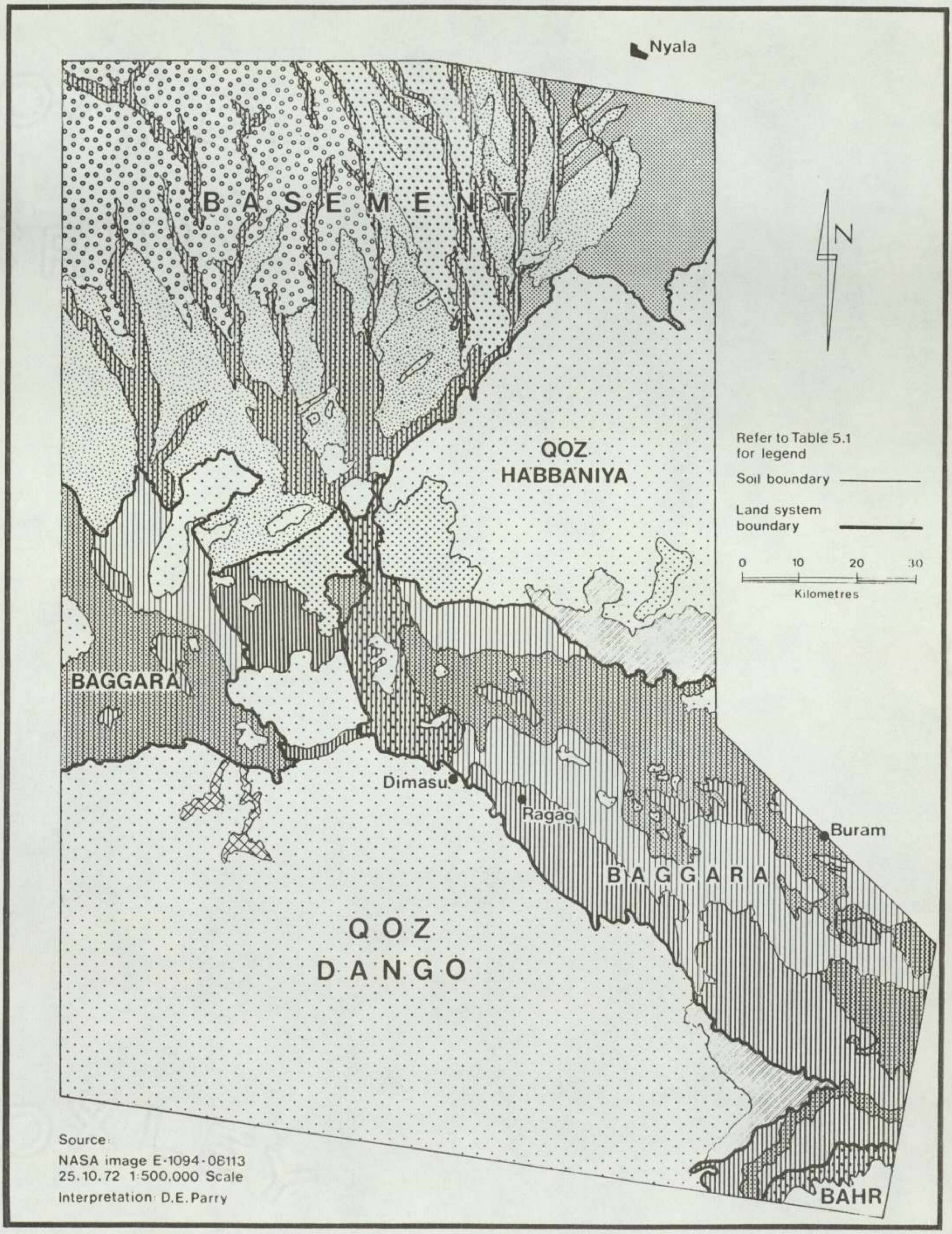
A land system, soils and geomorphology map was compiled from the interpretation overlay and is shown at a reduced scale in Figure 5.4. Details of interpretation criteria and the spectral properties of resource features are discussed in detail in Chapter 6. The simplified legend in Table 5.1 is also applicable to Figure 5.4. The 1:500,000 scale versions of the two maps shown in Figures 5.2 and 5.4 are included in Appendix E. These two maps provided the basic data for the comparative analysis of map accuracy in Area A.

Figure 5.3
LANDSAT colour composite image of Southern District (Area A)

Colour xerograph copy obtained from 1:1000 000 colour composite prints (MSS bands 4,5 and 7) using a Xerox 6500 colour copier.

0 Kilometres 50

Figure 5.4 Southern District (Area A). Soils and land systems. LANDSAT interpretation



CHAPTER 6

COMPARATIVE ANALYSIS SOUTHERN DISTRICT (AREA A)

6.1 INTRODUCTION

The 1:500,000 scale Land Systems, Soils and Geomorphology map (Map 1 Appendix E) compiled from the interpretation of aerial photography and field work in Area A by the methods described in Section 5.1, was used as the 'standard' map for comparison with a map of the same area (Map 2 Appendix E) compiled from the manual interpretation of a LANDSAT 1 colour composite image at the same scale. The quantitative methods employed in the present study to measure the accuracy of Map 2 in relation to Map 1 are described below.

6.2 METHODS OF ASSESSING MAP ACCURACY USED IN PRESENT STUDY

Manual Area Measurement

The area of each mapping unit on the 'standard' map (Map 1) and the LANDSAT map (Map 2) were measured using a planimeter and a dot grid with 49 (7 x 7) dots to the square centimetre. The latter was generally used for measuring areas of less than approximately 3 cm^2. At 1:500,000 scale one dot represented 0.49 km^2. In addition to measuring the individual mapping units, the total areas of each map were measured by planimetering the survey boundary as a check on the cumulative totals.

The areas of each land system and soil type for the two maps were compared by taking the 'standard' map (Map 1) and calculating the areal percentage error of the equivalent unit on the LANDSAT map (Map 2).

Transparent 'Melanex' overlays were superimposed on Maps 1 and 2 and all mapping unit boundaries transferred in etching ink. Land system boundaries were drawn in a line of double thickness. Each mapping unit was numbered and the area of each numbered unit calculated using a planimeter and a dot grid with 7 x 7 dots to the square centimetre. Photocopies of the 1:500,000 scale overlays for Maps 1 and 2 are included in Appendix E. Figures 6.1 and 6.2 are photographically reduced copies of these overlays. The area measurements in square kilometres for each numbered unit on both maps are given in Table 6.1.

Digital Area Measurement

The areas of the various soil mapping units on Maps 1 and 2 were also calculated

Figure 6.1
Map 1 (Standard map) numbered mapping units

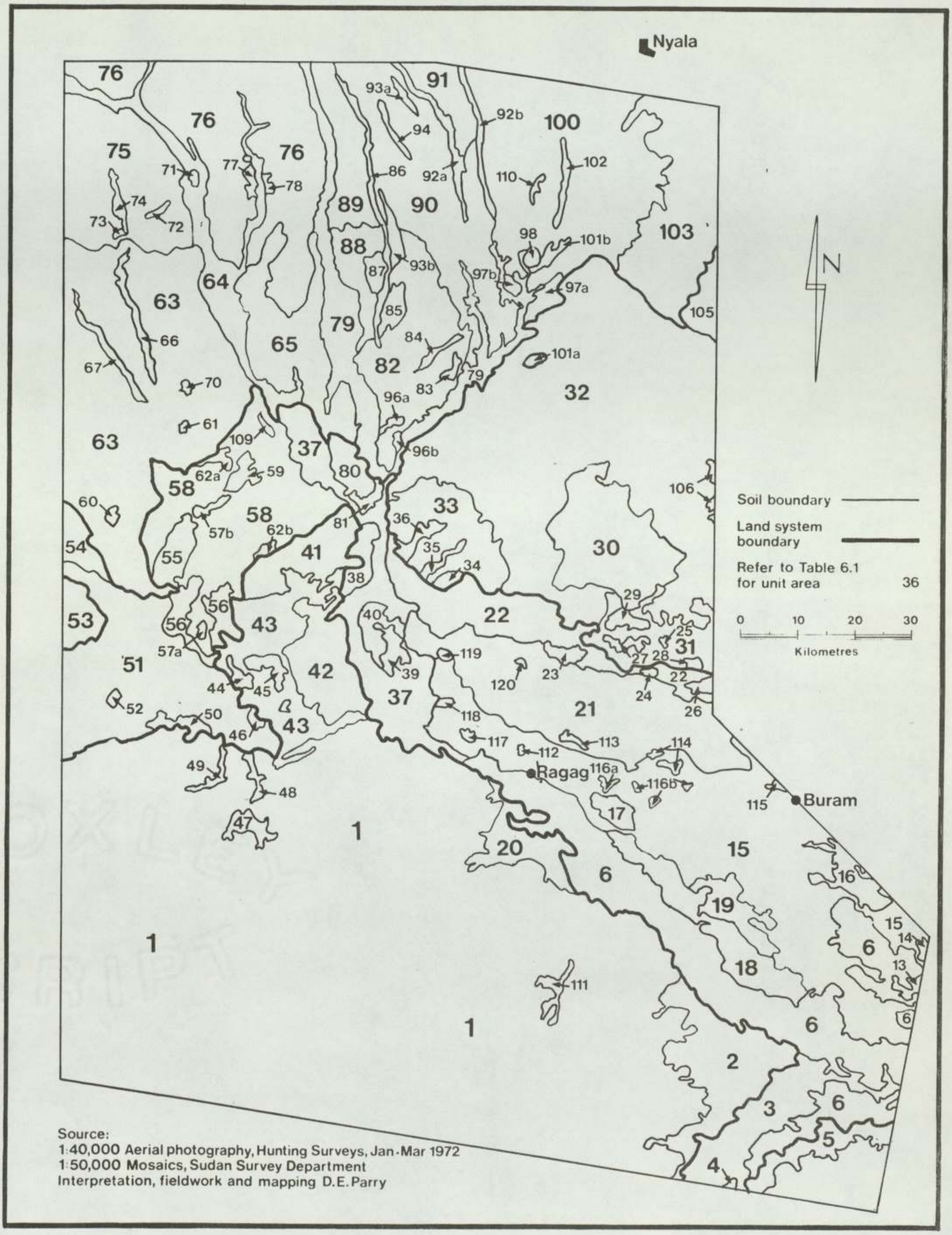
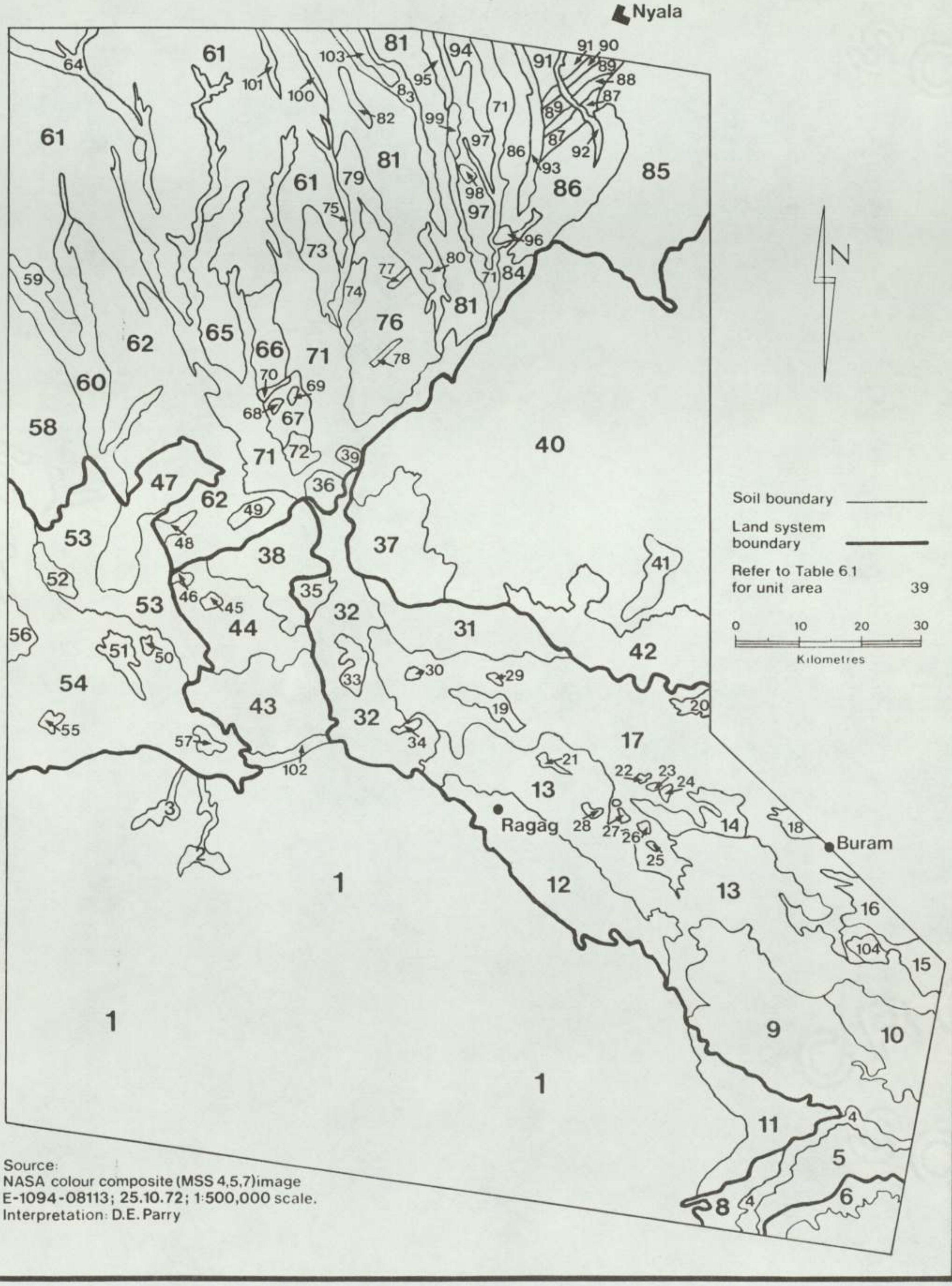


Figure 6.2
Map 2 (LANDSAT map) numbered mapping units



Source:
NASA colour composite (MSS 4,5,7) image
E-1094-08113; 25.10.72; 1:500,000 scale.
Interpretation: D.E. Parry

TABLE 6.1 AREA MEASUREMENTS: PLANIMETER AND DOT GRID

STANDARD MAP

Unit No.	Soil	Land System	Geomorphology	Area km^2
1	Ae		sd	5,915.49
25	Ae		sd	1.47
32	Ae		sd	1,865.24
42	Ae		sd	200.00
44	Ae		sd	10.78
45	Ae		sd	7.35
46	Ae		sd	18.62
28	Ae		sd	3.43
29	Ae	Q	sd	15.19
27	Ae		sd	11.27
34	Ae		sd	7.84
35	Ae		sd	11.27
36	Ae		sd	18.62
Sub-Total				8,086.57
31	gal_3	O	alt	120.79
2	gal_3		alt	292.50
Sub-Total				413.29
20	gal_3 Al_2b		alt	132.50
43	gal_3 Al_2b		alt	253.88
111	gal_3 Al_2b		alt	2.45
Sub-Total		Z		388.83
47	gal_3 Al_2c		vx	23.52
48	gal_3 Al_2c		vx	8.82
49	gal_3 Al_2c		vx	9.80
Sub-Total				42.14
33	Nur Nua		nsp	240.00
30	Nur Nua		sd	312.50
106	Nur Nua		sd	8.33
Sub-Total				560.83
53	Nua		sd	70.56
41	Nua		sd	165.00
101a	Nua		sd	6.86
105	Nua		sd	61.94
Sub-Total				304.36
Total				9,796.02
5	Al_2a Al_2b Al_2c	BAHR	mx	70.00
Sub-Total				70.00
Total				70.00

LANDSAT MAP

Unit No.	Soil	Land System	Geomorphology	Area km^2
1	Ae		sd	6,190.66
40	Ae		sd	2,234.04
43	Ae	Q	sd	275.00
45	Ae		sd	6.86
46	Ae		sd	8.82
56	Ae		sd	40.18
Sub-Total				8,755.56
11	gal_3		alt	185.00
42	gal_3	O	alt	300.00
Sub-Total				236.56
44	gal_3 Al_2b		alt	208.14
102	gal_3 Al_2b		alt	28.42
Sub-Total				236.56
2	gal_3 Al_2c		vx	23.03
3	gal_3 Al_2c	Z	vx	24.01
Sub-Total				47.04
41	Nur Nua		nsp	50.96
37	Nur Nua		nsp	220.00
Sub-Total				270.96
38	Nua		sd	155.00
Sub-Total				155.00
Total				9,950.12
6	Al_2a Al_2b Al_2c	BAHR	mx	72.03
Sub-Total				72.03
Total				72.03

TABLE 6.1 (Cont.) AREA MEASUREMENTS: PLANIMETER AND DOT GRID

STANDARD MAP

Unit No.	Soil	Land System	Geomorphology	Area km²
63	bs		wdp	1,191.00
100	bs		wdp	822.55
65	bs		wdp	320.00
88	bs		wdp	105.00
85	bs		wdp	22.54
91	bs		wdp	85.26
94	bs		wdp	10.29
93b	bs		wdp	20.58
93a	bs		wdp	6.86
Sub-Total				2,584.08
90	Al_2a Al_2b		fpx	535.35
Sub-Total				535.35
64	Al_2a Al_2c		fpx	390.00
79	Al_2a Al_2c	B	fpx	442.50
97a	Al_2a Al_2c		fpx	5.88
92b	Al_2a Al_2c		fpx	22.54
102	Al_2a Al_2c	A	fpx	16.70
74	Al_2a Al_2c		fpx	13.23
66	Al_2a Al_2c		fpx	24.50
67	Al_2a Al_2c	S	fpx	20.58
86	Al_2a Al_2c		fpx	24.50
92	Al_2a Al_2c		fpx	27.44
Sub-Total		E		987.87
103	Ae Nua		psd	430.52
97	Ae Nua		psd	25.00
98	Ae Nua	M	psd	6.86
Sub-Total				462.38
87	bs Ae		wdps	18.62
82	bs Ae	E	wdps	385.89
Sub-Total				404.51
71	bsr		sdpj	3.92
75	bsr		sdpj	456.38
76	bsr	N	sdpj	749.45
89	bsr		sdpj	145.04
Sub-Total				1,354.79
101b	Ae	T	sd	8.33
96a	Ae		sd	8.05
96b	Ae		sd	6.82
97b	Ae		sd	3.37
83	Ae		sd	6.86
84	Ae		sd	7.84
61	Ae		sd	3.92
70	Ae		sd	3.92
110	Ae		sd	3.92
72	Ae		sd	3.43
73	Ae		sd	1.96
77	Ae		sd	3.92
78	Ae		sd	3.43
60	Ae		sd	4.96
Sub-Total				70.73
Total				6,399.71

LANDSAT MAP

Unit No.	Soil	Land System	Geomorphology	Area km²
58	bs		wdp	320.00
59	bs		wdp	52.92
62	bs		wdp	530.00
65	bs		wdp	125.00
66	bs		wdp	69.58
67	bs		wdp	51.45
73	bs		wdp	63.21
74	bs		wdp	31.36
79	bs		wdp	58.80
82	bs		wdp	14.70
88	bs		wdp	19.60
90	bs		wdp	17.64
94	bs		wdp	51.45
98	bs	B	wdp	4.90
99	bs		wdp	14.90
103	bs		wdp	25.97
86	bs	A	wdp	331.66
Sub-Total				1,783.14
81	Al_2a Al_2b		fpx	530.00
Sub-Total		S		530.00
60	Al_2a Al_2c		fpx	207.50
64	Al_2a Al_2c		fpx	77.42
71	Al_2a Al_2c	E	fpx	687.50
75	Al_2a Al_2c		fpx	35.77
80	Al_2a Al_2c		fpx	31.36
83	Al_2a Al_2c	M	fpx	67.13
92	Al_2a Al_2c		fpx	15.19
93	Al_2a Al_2c		fpx	42.63
95	Al_2a Al_2c	E	fpx	22.54
100	Al_2a Al_2c		fpx	11.76
101	Al_2a Al_2c		fpx	12.25
Sub-Total				1,211.05
84	Ae Nua	N	psd	32.34
85	Ae Nua		psd	622.72
91	Ae Nua		psd	25.48
Sub-Total		T		680.54
76	bs Ae		wdps	272.16
97	bs Ae		wdps	102.60
Sub-Total				374.76
61	bsr		sdpj	1,630.08
Sub-Total				1,630.08
68	Ae		sd	2.94
69	Ae		sd	3.43
70	Ae		sd	6.37
72	Ae		sd	23.02
77	Ae		sd	5.88
78	Ae		sd	6.86
96	Ae		sd	12.25
48	Ae		sd	17.64
49	Ae		sd	18.13
36	Ae		sd	32.83
39	Ae		sd	12.74
Sub-Total				142.09
Total				6,351.66

TABLE 6.1 (Cont.) AREA MEASUREMENTS: PLANIMETER AND DOT GRID

STANDARD MAP

Unit No.	Soil	Land System	Geomorphology	Area km²
54	Al_1b Al_2c		sw	57.82
58	Al_1b Al_2c		sw	529.23
80	Al_1b Al_2c		sw	51.25
40	Al_1b Al_2c		sw	37.73
22	Al_1b Al_2c		sw	340.00
15	Al_1b Al_2c		sw	1,208.07
13	Al_1b Al_2c		sw	10.29
109	Al_1b Al_2c		sw	4.90
Sub-Total				2,239.29
56	Al_2c		bs	82.50
50	Al_2c		bs	21.07
17	Al_2c		bs	28.91
16	Al_2c		bs	53.80
4	Al_2c	B	bs	2.45
19	Al_2c		bs	12.50
6	Al_2c		bs	871.48
Sub-Total		A		1,077.71
18	Al_2b Al_2c		lbx	182.50
3	Al_2b Al_2c		lbx	217.06
Sub-Total		G		399.56
37	Al_2a Al_2b Al_2c		lbx	387.50
Sub-Total				387.50
51	Al_1b Al_2b Al_2c	G	opx	600.59
38	Al_1b Al_2b Al_2c		opx	36.26
21	Al_1b Al_2b Al_2c		opx	651.67
Sub-Total				1,288.52
115	Ae	A	sd	5.88
112	Ae		sd	3.43
52	Ae		sd	4.41
62	Ae	R	sd	6.12
81	Ae		sd	15.68
39	Ae		sd	22.54
26	Ae	A	sd	10.78
23	Ae		sd	18.62
120	Ae		sd	4.82
119	Ae		sd	3.92
117	Ae		sd	3.92
118	Ae		sd	4.90
116b	Ae		sd	8.57
114	Ae		sd	12.85
24a	Ae		sd	2.94
62b	Ae		sd	4.90
116a	Ae		sd	6.43
55	Ae		sd	48.02
59	Ae		sd	20.05
57b	Ae		sd	3.45
Sub-Total				218.64
Total				5,611.22

LANDSAT MAP

Unit No.	Soil	Land System	Geomorphology	Area km²
13	Al_1b Al_2c		sw	885.46
16	Al_1b Al_2c		sw	59.29
18	Al_1b Al_2c		sw	15.68
31	Al_1b Al_2c		sw	205.00
53	Al_1b Al_2c		sw	247.50
Sub-Total				1,412.93
8	Al_2c		bs	61.25
5	Al_2c		bs	177.50
9	Al_2c		bs	555.00
12	Al_2c		bs	352.00
14	Al_2c		bs	58.31
19	Al_2c		bs	30.38
51	Al_2c		bs	32.83
52	Al_2c	B	bs	24.50
55	Al_2c		bs	8.33
104	Al_2c		bs	18.86
Sub-Total		A		1,318.96
4	Al_2b Al_2c		lbx	83.30
10	Al_2b Al_2c		lbx	195.00
15	Al_2b Al_2c	G	lbx	59.78
Sub-Total				338.08
32	Al_2a Al_2b Al_2c		lbx	336.63
Sub-Total		G		336.63
17	Al_1b Al_2b Al_2c		opx	979.29
35	Al_1b Al_2b Al_2c		opx	36.26
54	Al_1b Al_2b Al_2c		opx	740.22
Sub-Total		A		1,755.77
21	Ae		sd	6.86
22	Ae		sd	2.45
23	Ae	R	sd	1.96
24	Ae		sd	3.92
25	Ae		sd	1.96
26	Ae	A	sd	3.43
50	Ae		sd	4.90
57	Ae		sd	13.72
27	Ae		sd	3.43
28	Ae		sd	5.39
29	Ae		sd	2.45
30	Ae		sd	3.92
33	Ae		sd	30.87
34	Ae		sd	5.39
20	Ae		sd	14.21
20	Ae		sd	14.21
47	Ae		sd	175.00
Sub-Total				279.86
Total				5,442.23

60.89

digitally using a computer program written in Fortran ICL by Dr. P. Thomson and run on the ICL 1906 computer at Aston University. In addition, a sampling program was carried out on Map 1 to determine the minimum size of a random dot sample that would give an acceptable level of mensuration accuracy.

The comparison of the manual and digital area measurements on Maps 1 and 2 and the results of the sampling program on Map 1 are discussed in Chapter 7. The computer output sheets are included in Appendix C.

Boundary Displacement

For the purposes of a reconnaissance survey the areas of the various mapping units are important for planning at the regional level. However, respective boundary coincidence between similarly classified mapping units is another important and related parameter of map accuracy. Good areal agreement between a taxonomic unit on one map and its equivalent on the other may disguise gross differences in the shape and geographical location of each. Such discrepancies could make ground location of that unit boundary in certain directions difficult, as the hypothetical example in Figure 6.3 demonstrates.

Differences in the shape of thematic boundaries of the same resource feature on two separate maps compiled from different data sources are basically caused by the following, singly or in combination:

(a) Uniform displacements due to scale differences between the two maps being compared.

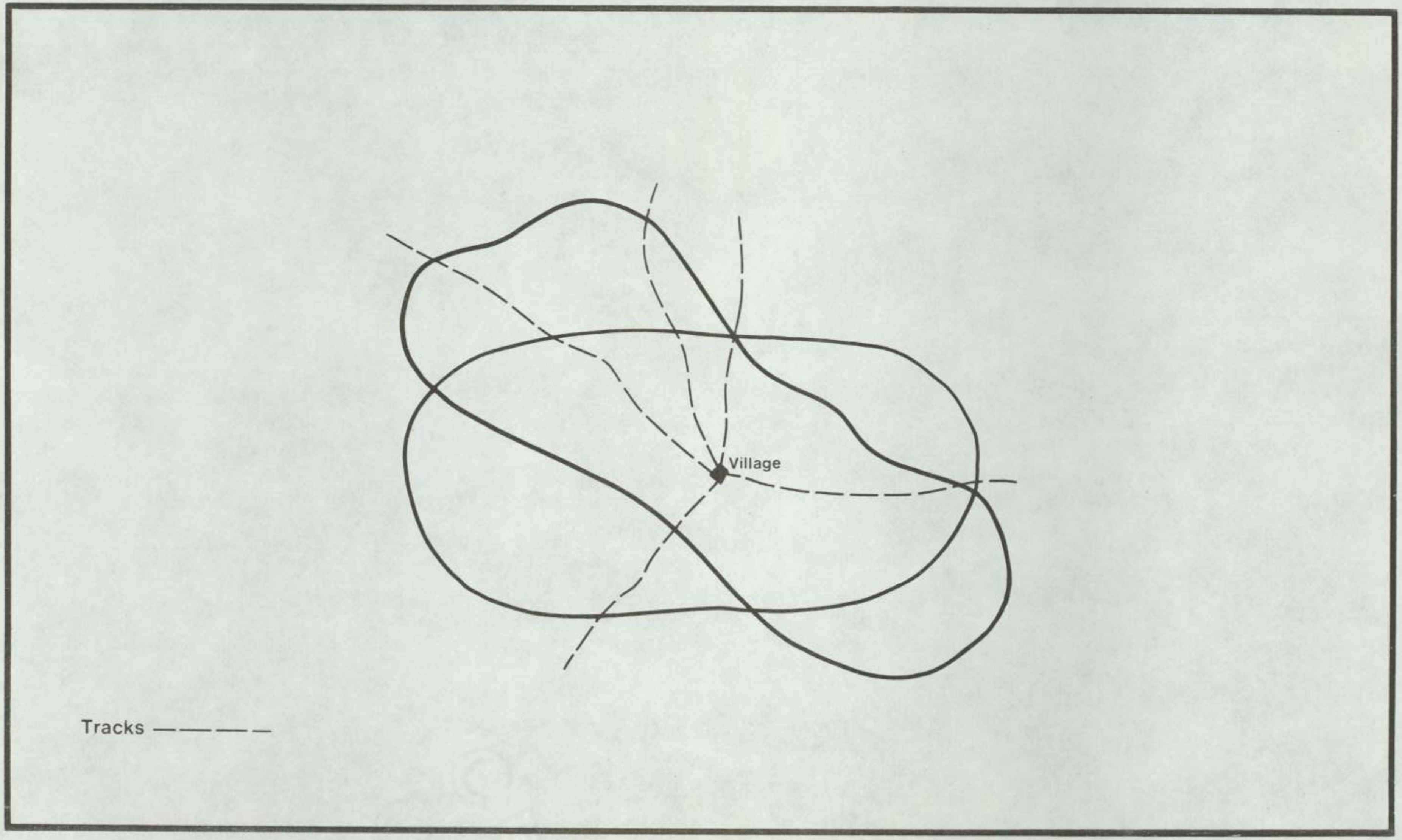
(b) Irregular displacements due to differences in interpretation.

(c) A real change in the field situation.

In the present study all significant differences in the placement and shape of boundaries are due to differences in the interpretation of the primary data sources; conventional aerial photography and satellite imagery.

Boundary displacements caused by scale differences between the 'standard' map and the map compiled from satellite imagery are minimal and do not significantly affect the area calculations. As Tables 6.1 and 6.2 show, the areal difference the two maps amounts to 61 km^2 or less than 0.3 per cent of the total Study Area. At a reconnaissance level

Figure 6.3 Equal area boundary displacement



such an error is considered insignificant and it was felt unnecessary to adjust the area figures on the LANDSAT map in order to make the total area figures for the two maps tally exactly.

This small scale difference in area between the two maps is caused by minor mosaicing errors in the south eastern quadrant of the 'standard' map. In an area of predominantly low relief such as Southern Darfur the map compiled from the LANDSAT image will have greater planimetric accuracy than the 'standard' map which was compiled from semi-controlled mosaics.

In the present study one qualitative and two quantitative methods of assessing boundary coincidence have been used. These methods and the results of applying them to Maps 1 and 2 are discussed in detail in Chapter 8.

6.3 COMPARATIVE ANALYSIS BY AREA OF LAND SYSTEMS AND SUB-SYSTEMS

The land system boundaries on Map 1, the 'standard' map, were compared with those of Map 2 by expressing the areal differences of each land system in terms of the percentage error of the same land system on Map 1. Table 6.2 gives the comparative areas and percentage error for each land system.

No land system interpreted from the satellite imagery has an areal difference of more than +/- 3 per cent compared with its equivalent on the 'standard' map. This level of accuracy is adequate for a reconnaissance level survey. The reasonable agreement in areas between the two maps at land systems level disguises some large areal discrepancies between the various geomorphic and related soil sub-systems (Table 6.3). The greatest discrepancies occur within the Basement and Baggara land systems, particularly where they are adjacent. Image interpretation in these areas is difficult because of the low image contrast. This reflects the similarity of the soils, the general geomorphology (although not the geomorphic history) and vegetation of the Baggara sheet wash plains (sw) and the Basement weakly dissected pediplain (wdp). In the satellite interpretation (Map 2) much of the area mapped as sheet wash plain (sw) on Map 1, the 'standard' map, was excluded from this category on the former and included in the Basement land system, and vice versa. The differences that exist between these particular sub-units are too subtle to be confidently and unambiguously interpreted from the bulk processed colour composite LANDSAT imagery. Even on aerial photographs the positioning of the boundary between these two units is of doubtful validity and would require more detailed soil studies and geomorphological measurements to locate it accurately.

TABLE 6.2 LAND SYSTEM AREAS PERCENTAGE ERROR

Land System	Standard Map (1) Area km^2	LANDSAT Map (2) Area km^2	Difference km^2	Error %
Qoz	9,796	9,950	+154	+2
Baggara	5,611	5,442	-169	-3
Basement	6,400	6,352	-48	-0.75
Bahr	70	72	+2	+3
Totals	**21,877**	**21,816**	**-61**	**-0.28**

The least measure of agreement on Map 2 between geomorphic units within a land system occurs in the Basement, where the error ranges from -31 per cent for the weakly dissected pediplain (wdp) to +100 per cent for the isolated sand dunes. Of the sub-systems within the Basement land system only the weakly dissected pediplain with shallow sand cover (wdps) was mapped to within a 10 per cent level of accuracy. The more extensive areas of sand have very clear image characteristics in marked contrast to the non-sandy pediplains.

The valleys and floodplains (fpx) also have very distinctive shapes and colours on the LANDSAT imagery. The dendritic patterns are highlighted in red tones on the colour composite imagery because of the high infra-red reflectance from the dense riverine tree vegetation, although mapping accuracy was only +14 per cent.

The best agreement between sub-units within a land system occurs in the Qoz where the percentage error ranges between +/- 3 and 13 per cent on Map 2. Each geomorphic sub-unit within the Qoz has a very distinctive signature on the LANDSAT imagery.

The lack of major surface drainage in the sand sheet and dune complex (sd) separate it from the Qoz/Alluvial transition zone (alt) in which a series of ill-defined discontinuous sand choked channels can be interpreted from the satellite imagery with difficulty.

The Nubian scarps (nsp) and pediments are visible on the LANDSAT imagery although the extent of their influence as a soil parent material is difficult to determine on both the satellite and aerial imagery.

TABLE 6.3 LAND SYSTEMS AND SUB-SYSTEMS AREA PERCENTAGE ERROR

Land System	Sub-System	Standard Map (Map 1) Area km^2	LANDSAT Map (Map 2) Area km^2	Difference km^2	Error %
	sd	8,712	8,911	+199	+2
Qoz	alt	802	721	-81	-10
	nsp	240	271	+31	+13
	vx	42	47	+5	+12
Totals		**9,796**	**9,950**	**+154**	**+2**
	sw	2,239	1,413	+ 286	-37
	bs	1,078	1,319	+241	+22
Baggara	lbx	787	675	-112	-14
	opx	1,289	1,756	+467	+36
	sd	219	280	+61	+28
Totals		**5,612**	**5,443**	**-169**	**-3**
	wdp	2,584	1,783	-801	-31
	fpx	1,523	1,741	+218	+14
Basement	psd	462	681	+219	+47
	sdpj	1,355	1,630	+275	+20
	wdps	405	375	-30	-7
	sd	71	142	+71	+100
Totals		**6,400**	**6,352**	**-48**	**-0.75**
Bahr	mx	70	72	+2	+3
Total		**21,878**	**21,817**	**-61**	**-0.28**

The Valley complex (vx) within the Qoz Dango is the only large, well-defined valley system within the sand sheet and is easily interpreted from the LANDSAT imagery. The 12 per cent error between these units on Maps 1 and 2 only represents an areal difference of 5 km^2. These valleys were identified in the original survey as areas requiring more detailed resource studies. By identifying and mapping such small areas from the satellite imagery one of the basic objectives of reconnaissance survey has been achieved and the 12 per cent error is considered to be an acceptable level of accuracy.

The boundary between the Qoz land system, particularly between the Habbaniya Qoz and the Basement land system to the west, and the Baggara land system to the south, is readily interpreted from the satellite imagery because of the very high image contrast between the Qoz and the other land systems. The lack of surface drainage within the sand sheet, combined with the high reflectivity of the cultivated areas and overgrazed aureoles around boreholes accounts for much of this contrast. For the purposes of regional planning, this boundary, which can be mapped so accurately from the LANDSAT imagery, represents one of the most important resource boundaries in the Study Area. It separates the sandy arable soils, used by the traditional sedentary farmers, from the non-cultivated alluvial and colluvial soils. The latter support the highly palatable annual grasses favoured by the cattle of the Baggara nomads.

The Bahr land system was mapped to a +3 per cent accuracy on Map 2. In October, the time of image acquisition, the seasonal river, the Bahr el Arab is full of water. This continuous stretch of water in the extreme southeast of the Study Area is clearly visible on the MSS infra-red band 7 as a black sinuous line which appears as blue on the colour composite image. The pattern of cut-offs and basins on either side of the river in the present floodplain are clearly defined and mark the boundary of the land system. The older, larger channel between five and ten kilometres to the north, is a broad, shallow, discontinuous channel locally called a regeba. The water in it does not flow and the channel is choked with aquatic grasses and shrubs hence infra-red reflectance is primarily from the vegetation, and on the colour composite shows as a bright red sinuous line. As a defunct drainage channel it is excluded from the Bahr land system and included in the adjacent Baggara land system.

6.4 COMPARATIVE ANALYSIS BY AREA OF SOIL UNITS

Map 1 has 114 soil mapping units compared with 102 on Map 2. Thus 12 soil units were not recognised on the map interpreted from the satellite image. These omissions occurred for the most part in the Qoz land system. The delineation of soil boundaries on both the satellite imagery and the aerial photography of Southern District was based mainly on geomorphic criteria because of the known strong association between the geomorphology and soils of the region (Hunting Technical Services, 1971). Thus the figures for the areal percentage error between the soil major units of Maps 1 and 2 and shown in Table 6.4 are very similar to those of the land system units given in Table 6.3. The differences between the two tables are caused for the most part by the occurrence of particular soil types in more than one geomorphic unit. The areal percentage error in Table 6.4 has a range of +47 to -52 per cent. This level of accuracy for mapping the soil units on the satellite imagery is unacceptable even by reconnaissance standards. However, when the mapping units are combined into genetic and agricultural classes (Tables 6.4 and 6.5) the accuracy improves considerably.

TABLE 6.4 MAJOR SOIL UNITS PERCENTAGE ERROR (PLANIMETERED)

Genetic Group	Major Soil Units Code	Standard Map (1) km^2	LANDSAT Map (2) km^2	Difference km^2	Error %
	Ae	8,376	9,178	+802	+10
	bs Ae	405	375	-30	-7
Aeolian	Nua	304	155	-149	-49
Soils	Nur Nua	561	271	-290	-52
	Ae Nua	462	681	+219	+47
	Sub-Total	**10,108**	**10,660**	**+552**	**+5**
	Al_2c	1,078	1,319	+241	+22
	gal_3	413	485	+72	+17
	Al_1b Al_2b Al_2c	1,289	1,756	+467	+36
Alluvial	Al_1b Al_2c	2,239	1,413	-826	-37
Soils	Al_2a Al_2b	535	530	-5	-1
	Al_2a Al_2b Al_2c	458	409	-49	-11
	Al_2a Al_2c	988	1,211	+223	+23
	Al_2b Al_2c	400	338	-62	-16
	gal_3 Al_2b	389	237	-153	-39
	gal_3 Al_2c	42	47	+5	+12
	Sub-Total	**7,831**	**7,745**	**-86**	**-1**
Residual and	bs	2,584	1,783	-801	-31
Polygenetic Soils	bsr	1,355	1,630	+275	+20
	Sub-Total	**3,939**	**3,413**	**-526**	**-13**
	TOTAL*	**21,878**	**21,818**	**-60**	**-0.28**

* *The totals in Table 6.4 differ from those in Table 6.3 by 1 km^2. This is due to rounding up the area figures given to two places of decimals in Table 6.1 and does not affect the overall percentage error.*

TABLE 6.5 SOIL AGRICULTURAL POTENTIAL CLASSES PERCENTAGE ERROR

Potential	Mapping Units	Standard Map (1) km²	LANDSAT Map (2) km²	Difference km²	Error %
Sandy soils cultivated	Ae	8,376	9,178	+802	+10
and suitable for	bs Ae	405	375	-30	-7
cultivation using	Nua	304	155	-149	-49
traditional hand	Nur Nua	561	271	-290	-52
tillage methods	Ae Nua	462	681	+219	+47
	Sub-Total	**10,108**	**10,660**	**+552**	**+5**
Alluvial soils suitable	Al_1b Al_2c	2,239	1,413	-826	-37
for mechanised	Al_1b Al_2b Al_2c	1,289	1,756	+467	+36
agriculture	Al_2c	1,078	1,319	+241	+22
	gal_3	413	485	+72	+17
	gal_3 Al_2b	389	237	-153	-39
	gal_3 Al_2c	42	47	+5	+12
	Sub-Total	**5,450**	**5,257**	**-193**	**-3.5**
Alluvial soils in major	Al_2a Al_2c	988	1,211	+223	+23
wadis suitable for	Al_2a Al_2b Al_2c	458	409	-49	-11
irrigation	Al_2a Al_2b	535	530	-5	-1
	Al_2b Al_2c	400	338	-62	-16
	Sub-Total	**2,381**	**2,488**	**+107**	**+4.5**
Non-arable soils	bsr	1,355	1,630	+275	+20
	bs	2,584	1,783	-801	-31
	Sub-Total	**3,939**	**3,413**	**-526**	**-13**
	TOTAL	**21,878**	**21,818**	**-60**	**-0.28**

The areas of the three main groups of arable soils (Table 6.5) interpreted from the satellite imagery agree with those on the 'standard' map to within +5 to -3.5 per cent, an acceptable level of accuracy for a reconnaissance survey. But the agreement between groups must be viewed with caution because of the large within group variation between similarly classified soil units. This variation is expressed in Tables 6.6 and 6.7 by calculating the cumulative difference for each genetic soil group and agricultural potential class. This value expressed in km^2 and as a percentage of the total area, is the sum of the area overestimates (+) and underestimates (-) for each mapping unit on the LANDSAT interpretation map. The sign is therefore ignored in the calculation and the value obtained by adding the figures (km^2) in the difference columns in Tables 6.4 and 6.5, respectively. The two values give an indication of the area within each group or class that has been wrongly classified. The figures in Tables 6.6 and 6.7 show that the aeolian soils, which are suitable for cultivation using hand tillage methods, and those alluvial soils suitable for irrigation, have less area variations between their component mapping units than other soil groups.

TABLE 6.6 AREA VARIATION BETWEEN GENETIC SOIL GROUPS

Genetic Group	Map 1 km^2	Map 2 km^2	Difference km^2	Error %	Cumulative Difference km^2	Error %
Aeolian	10,108	10,660	+552	+5	1,490	15
Alluvial	7,831	7,745	-86	-1	2,103	27
Residual/ Polygenetic	3,939	3,413	-526	-13	1,076	27
Totals	**21,878**	**21,818**	**-60**	**-0.28**	**4,669**	**21**

The within group variation is particularly marked in the case of the alluvial soils. The total area difference between Maps 1 and 2 for this genetic group amounts to 86 km^2 or 1 per cent of the total Study Area. However, the cumulative difference between the areas of alluvial mapping units on the two maps is 2,103 km^2 or 27 per cent of the total class area (Table 6.6). In other words, overestimates and underestimates of the extent of these soils as interpreted from the satellite imagery amount to 2,103 km^2. A similar magnitude of error occurs with soil agricultural class B, alluvial soils suitable for mechanised agriculture (Table 6.7). The total area difference is 193 km^2 or 3.5 per cent of the total class area but the cumulative difference is 1,763 km^2, equivalent to 32 per cent of the class area.

The following conclusions emerge with regard to the accuracy of the LANDSAT Map (Map 2):

(1) No land system interpreted from the satellite imagery has an areal difference

greater than plus or minus three per cent compared with its equivalent on the 'standard' map (Map 1). This level of accuracy is adequate for a reconnaissance level survey.

(2) The good areal agreement at land systems level between the two maps disguises large variations in area between the geomorphic and related soil sub-units. These variations are greatest within the Basement and Baggara land systems.

(3) A misleading impression of accuracy is obtained by classifying the soil mapping units into larger groups based upon genetic or agricultural suitability criteria and comparing the combined area totals. To obtain a more realistic measure of comparative accuracy it is essential to compare the variation of area totals within the major groups. Using this criterion, the most widespread agricultural soils, the aeolian sands, and those alluvial soils with irrigable potential are mapped more accurately than other soil groups from the LANDSAT imagery.

(4) The error of 1 per cent between the total area of alluvial soils on Maps 1 and 2, compared with the 27 per cent cumulative error difference, indicates that gross boundary discrepancies occur between soil mapping units within the Baggara land system; the land system in which the majority of the alluvial soils occur. (Methods of measuring these boundary discrepancies are examined in Chapter 8).

(5) The total cumulative error for Map 2 amounts to 4,669 km^2 or 21 per cent of the total Project Area (21,878 km^2) and therefore some 21 per cent of Map 2 is incorrectly classified. This level of accuracy is unacceptable even by reconnaissance scale standards. However, within this 4,669 km^2 of misclassified soil there are certain soil units which only account for a few square kilometres of this cumulative error for example, bs Ae, gal_3, Al_2a Al_2b, Al_2a Al_2b Al_2c, Al_2b Al_2c and gal_3 Al_2c. At the other extreme are soil units which contribute substantially to this cumulative error. These include Ae, Al_1b Al_2c, and bs soil mapping units each of which has an error of greater than 800 km^2 on Map 2. The reasons for these large variations in the accuracy of the soil units interpreted from the satellite imagery are examined in the following section.

TABLE 6.7 AREA VARIATION BETWEEN SOIL AGRICULTURAL CLASSES

Class	Map 1 km²	Map 2 km²	Difference km²	Error %	Cumulative Difference km²	Error %
A	10,108	10,660	+552	+5	1,490	15
B	5,450	5,257	-193	-3.5	1,763	32
C	2,381	2,488	+107	+4.5	339	14
D	3,939	3,413	-526	-13	1,076	27
Totals	**21,878**	**21,818**	**-60**	**-0.28**	**4,668**	21

Class A: *Sandy soils cultivated and suitable for cultivation using traditional hand tillage methods.*

Class B: *Alluvial soils suitable for mechanised agriculture.*

Class C: *Alluvial soils in major wadis suitable for irrigation.*

Class D: *Non-arable soils.*

6.5 SOIL MAPPING UNITS AND IMAGE CHARACTERISTICS

Aeolian Soils

The soils of this genetic group are characterised by a very high wind-borne sand content derived from both local and regional weathering of arenaceous rocks.

Ae, Nua, Nur Soils

These soils occur in the major sand sheets (Qozes) and as isolated sand dunes within the Baggara and Basement land systems. Reference to Table 6.8 indicates that the main sources of error on the map derived from LANDSAT imagery occurs in the Habbaniya Qoz and the dune sands of the Basement and Baggara land systems. In the former, the error is primarily due to the inclusion on Map 2 of some 262 km^2 of Nur Nua soils. This area, located in the centre of the Habbaniya Qoz and mapped as unit 30 on Map 1 (Figure 6.1), occupies 312 km^2. On Map 2 (Figure 6.2) only part of this unit covering 51 km^2 was interpreted, the remainder being classified as part of the Ae soil unit. In terms of the soils agricultural potential the error is of little consequence, despite its magnitude, since the Nubian (Nua) soils which form the dominant part of the Nur Nua complex are very similar in their morphological, chemical and physical properties, to the Ae soils of the Habbaniya Qoz.

The genesis, morphology and agricultural potential of the residual Nubian sandstone soils (Nur) is very different from that of the sand sheet aeolian (Ae) soils. The Nur soils occupy a very small part of the mapping unit and they only occur on and in the immediate vicinity of the rock outcrops. These outcrops or jebels are readily interpreted from the satellite imagery although they are generally too small to be mapped as discrete units at the scale of 1:500,000.

TABLE 6.8 AEOLIAN SOILS AREA PERCENTAGE ERROR BY LAND SYSTEM

Land System	No. of Soil Mapping Units	Map 1 km^2	No. of Soil Mapping Units	Map 2 km^2	Difference km^2	Error %
Qoz (Habbaniya)	1	1,865	1	2,234	+369	+20
Qoz (Dango)	1	5,915	1	6,191	+276	+5
Baggara	20	219	16	280	+61	+28
Basement	14	71	11	142	+71	+100
Totals	**36**	**8,070**	**27**	**8,847**	**+777**	**+10**

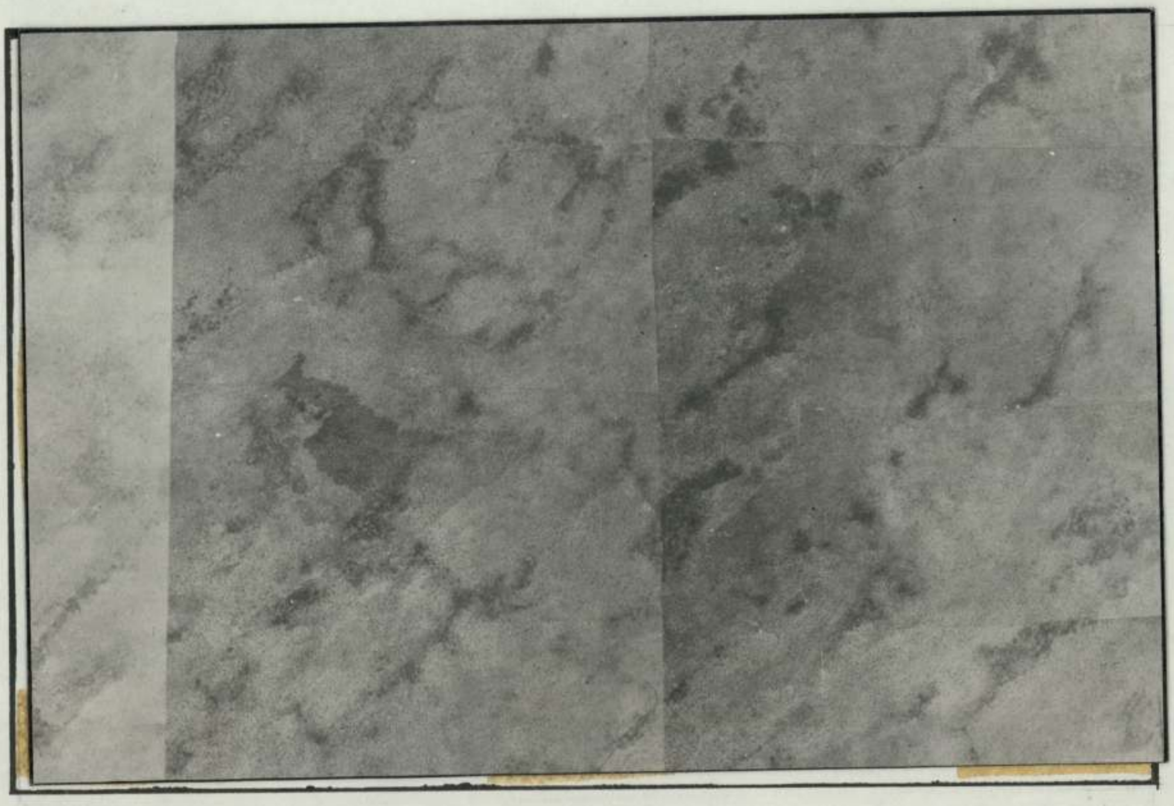
The range of colours occurring on the LANDSAT image within the area of Habbaniya Qoz, and the fact that the majority of the area is mapped as one soil unit may seem something of a contradiction. However, it is the lack of a well developed surface drainage pattern that provides the major clue to the nature of the soils and their degree of uniformity. The colour differences represent various densities of vegetation in different stages of vigour, combined with cleared land under shifting cultivation and showing varying degrees of degradation. Even where the soil is subject to severe wind erosion, as is the case around many of the wateryards where overgrazing is acute and reflectance from the soil surface very high, the differences between the morphology and chemistry of these soils and their non-degraded equivalents is minimal.

The aeolian soils of the Qoz Dango were mapped to within 5 per cent of their area on the 'standard' map. Image contrast in the Qoz Dango is less than it is in the Habbaniya Qoz because there is less cultivated land and a much denser cover of relatively even-aged, mature savanna woodland. The differences in red tones represent the varying levels of chlorophyll present in leaves at different stages of maturity. The dark green and black tones are burning patterns. The type of soil and the degree of uniformity is indicated by analysis of the indistinct drainage pattern which is visible on both the satellite imagery and the aerial photographs (Figure 6.4). The pattern consists of discontinuous dune hollows orientated north east-south west which are connected at breakthrough points to form a broken trellis pattern. This pattern is more apparent in the less disturbed environment of the Qoz Dango on both types of imagery than it is in the cultivated and grazed regions of the Habbaniya Qoz.

Of the remaining Ae soils, those occurring as isolated sand dunes (Atmur) in the Baggara land system have been mapped from the satellite imagery to a 28 per cent level of

Figure 6.4
Drainage pattern in the Qoz Dango

A. Colour composite LANDSAT image: Scale 1:500,000



B. Mosaic of aerial photographs: Scale 1:100,000

accuracy. Sixteen dunes were interpreted from the satellite image (Map 2) compared with twenty on Map 1. The largest part of this difference is accounted for by unit 47 on Map 2 (Figure 6.2). This unit was interpreted from the LANDSAT image as a continuous stretch of dune sand occupying 175 km^2 (Table 6.1). In reality, as Figure 6.1 shows, the area is occupied by four separate sand dunes (units 55, 57b, 59 and 62a). These cover a total area of 78 km^2 and are separated by alluvium.

The remaining dunes within the Baggara land system are much smaller and more widely scattered than unit 47 on Map 2 or the four equivalent sand dunes on Map 1. The light textures, excellent root penetration and the ease with which they are cultivated make the sand dune soils the most sought after agricultural soils in the Baggara land system. The soils usually support crops of millet, sorghum and vegetables but in October, the month in which the interpreted LANDSAT frame was taken, the crops had been harvested. The light tones on the satellite imagery, so typical of these cultivated dune soils, are caused by the reflected radiation from the bare, very light brown sandy surface and dry crop stubble. In this condition these dunes are easily recognised on the satellite imagery since they contrast strongly with the surrounding darker areas of smooth Naga'a non-cracking alluvial soils on the sheet wash plains, and the almost white tones of the levee soils. The narrow sinuous shapes of the latter prevent the interpreter confusing the levee soils with the light toned sand dune soils.

In the wet season the delineation of sand dune soils with a standing crop in the field would be more difficult; the increased infra-red reflectance from the crop would make it very difficult to distinguish these sandy soils from the adjacent alluvium carrying a dense cover of *Acacia* spp. thicket. Even a moderate cover of bush on the sand dunes in the Basement land system on the dry season image precluded their accurate delineation. If the four larger sand dunes referred to above are omitted, the other 16 in the Baggara land system on Map 1, the 'standard' map cover as Table 6.1 shows, 141 km^2 (219-78 km^2). Similarly, if unit 47 is omitted on Map 2, the LANDSAT map, the remaining 15 sand dunes occupy 105 km^2 (280-175 km^2). The former range in size from 3 to 23 km^2 and have a mean size of 8 km^2. The latter have a range of between 2 and 31 km^2 with a mean size of 7 km^2. Of these 15 smaller sand dunes interpreted from the LANDSAT imagery, 13 occur in the same geographical location as their equivalent units on the 'standard' map.

The 36 km^2 gross difference in area between the smaller dunes on the two maps is due to the difficulty of delineating small units accurately and in a consistent manner when interpreting and mapping at very small scales. For example, at 1:500,000 scale, the scale used in the present study, an interpretation line of 0.2 mm thickness is equivalent to 100 m on the ground.

With such small units the ability to use LANDSAT imagery to interpret individual sand dunes in the same geographical location as that in which each occurs on the 'standard' map, is of greater significance for reconnaissance scale survey than a high degree of accuracy in the areal measurement of each dune.

The sand dunes in the Basement land system were very inaccurately mapped from the LANDSAT image, with an additional 71 km^2 interpreted, equivalent to an error of 100 per cent (Table 6.3). The large boundary discrepancy between the Basement and Baggara land systems accounts for some of this error, in so far as some sand dunes included in the Basement land system on Map 1 are excluded from the same land system on Map 2. Many of the dunes in the Basement land system lack the distinct light toned signature of the Baggara land system dunes because the former are not presently cultivated and support a moderately dense bush fallow vegetation. The vegetation cover masks the highly reflecting surface of bare sand and thus the contrast with the darker toned bare clay soils or dense thickets of *Acacia mellifera* scrub is less obvious.

Clearly, when mapping soils from satellite multi-spectral imagery, which includes an infra-red channel, in areas subject to seasonal changes in the vigour and cover of natural vegetation and land use, the time of image acquisition is of paramount importance. Multi-temporal imagery is the ideal but where, as in the present case, this was not available late dry season imagery would appear to be preferable for mapping the small areas of cultivated sand dune soils in Southern Darfur. For mapping the extent of uncultivated sand dunes the bulk processed colour composite LANDSAT image used in the present study was inadequate. Precision processed LANDSAT imagery with its higher resolution and data content would have been preferable.

Alluvial Soils

These soils are derived from heterogeneous alluvial deposits ranging in texture from coarse sands through silts to clays. They include the discrete vertisol mapping units, Al_2c and the following complex mapping units: Al_1b Al_2c, Al_1b Al_2b Al_2c, Al_2a Al_2b, Al_2a Al_2b Al_2c, Al_2a Al_2c, Al_2b Al_2c, gal_3 Al_2b, gal_3 Al_2c.

Al_2c Soils

The discrete areas of dark grey cracking clay soils were overestimated on the satellite interpretation by 241 km^2 or 22 per cent of the total area occupied by these soils on the 'standard' map (Table 6.5). These soils occur in low lying areas and are rarely cultivated because of flooding and tillage problems. They support a variable cover of *Acacia Seyal* thorn woodland. Where this cover is dense and the trees are in leaf a strong infra-red response is obtained on the LANDSAT image. However, this particular image was taken at the end of the wet season when many other tree and shrub species, not exclusively found in low lying areas, were in full leaf. Thus, it was not possible to separate consistently the infra-red response or 'signature' of *Acacia seyal* from that of other species on the edges of the depressions, and in nearby drainage channels.

A further factor preventing the accurate delineation of the vertisols on the LANDSAT imagery was the occurrence of burning patterns in both areas of cracking and non-cracking clays. The dark green/grey tones associated with grass burning also correlated with unburnt areas of non-cracking alluvial soils (Al_1b) in the sheet wash plains of the Baggara land system.

Al_1b Al_2c Complex

This, the largest area of alluvial soils mapped, correlates with the very smooth and level areas of sheet wash plain occurring between the shallow, meandering channels in the Baggara land system. These areas and their associated soil complex were underestimated on the LANDSAT map by 826 km^2, an error of 37 per cent (Table 6.5). This error is due mainly to the difficulty of interpreting boundaries on the satellite imagery between the cracking clay soils (Al_2c), the complex of soils in the overflow plain (Al_1b Al_2b Al_2c) and the Al_1b Al_2c complex in the south eastern part of the Baggara land system.

The juxtaposition of areas with high infra-red reflectance and dark grey/green tones caused a gross overestimate of the Al_2c soils in this part of the land system and consequent underestimate of the Al_1b Al_2c soil complex.

Al_2a Al_2b, Al_2b Al_2c, Al_2a Al_2b Al_2c, Al_2a Al_2c Soil Complexes

The boundaries of these four soil complexes are associated with marked differences in vegetation and geomorphology and correlation between the two maps is reasonably good. The soil complexes occur in the major wadis and floodplains of the Basement and Baggara land systems and possess a very distinctive sinuous bright red signature on the satellite image. This is caused by the high infra-red reflectance from the dense riverine vegetation. These soils have considerable potential for small scale irrigation using shallow groundwater and as Table 6.9 shows, were mapped from the satellite imagery within an accuracy range of 1-23 per cent, had a total error of 4.5 per cent and a cumulative error of 14 per cent.

TABLE 6.9 ALLUVIAL SOILS OF MAJOR WADI SYSTEMS: AREA PERCENTAGE ERROR

Soil Complex	No. of Map Units	Map 1 km²	No. of Map Units	Map 2 km²	Difference km²	Error %	Cumulative Difference	Error %
Al_2b Al_2c	2	400	3	338	-62	-16	-	-
Al_2a Al_2c	10	988	11	1,211	+223	+23	-	-
Al_2a Al_2b Al_2c	2	458	2	409	-49	-11	-	-
Al_2a Al_2b	1	535	1	530	-5	-1	-	-
Totals	**15**	**2,381**	**17**	**2,488**	**+107**	**+4.5**	**339**	**14**

gal_3, gal_3 Al_2b, gal_3 Al_2c Soil Complexes

The gal_3 soils and the gal_3 Al_2b soil complex occur around the edges of the major sand sheets in the Qoz/Alluvial transition zone (alt) where fluvial processes have reworked the aeolian sand deposits. The gal_3 Al_2c soil complex is confined to the few valleys that occur in the Qoz Dango. The interpretation of all three units on both the aerial photographs and the satellite image was based primarily on landform and drainage pattern criteria rather than image tone or texture. The drainage pattern in the major valleys of the Qoz Dango is very distinctive and is picked out in very light tones on the satellite image, in marked contrast to the surrounding red tones representing savanna woodland on deep aeolian (Ae) soils. The soils in these valleys (gal_3 Al_2c) were mapped from the LANDSAT image to a 12 per cent level of accuracy (Table 6.10).

TABLE 6.10 QOZ/ALLUVIAL SOIL COMPLEXES: AREA PERCENTAGE ERROR

Soil Complex	No. of Map Units	Map 1 km²	No. of Map Units	Map 2 km²	Difference km²	Error %	Cumulative Difference	Error %
gal_3	2	413	2	485	+72	+17	-	-
gal_3 Al_2b	3	389	2	237	-153	-39	-	-
gal_3 Al_2c	3	42	2	47	+5	+12	-	-
Totals	**8**	**844**	**6**	**769**	**-76**	**-9**	**230**	**27**

The interpretation of the soil units in the Qoz/Alluvial Transition zone from the LANDSAT image was made difficult by the lack of contrast. The areas on the edge of the sand sheets carried a similar vegetation cover to that of the interiors and thus a similar range of colours occurred on the satellite image. Separation of these units from the main sand sheets was based on drainage pattern differences. The transition zones generally possessed a more active drainage system which could be picked out on the satellite image but not with the same degree of accuracy as was possible on the aerial photographs.

Residual and Polygenetic Soils

The residual and polygenetic soil units (bs, bsr) have a percentage error on Map 2 of -31 and +20 per cent respectively (Table 6.11). This is somewhat surprising in view of the fact that the two soil mapping units in this genetic group have, for the most part, very distinctive signatures on the LANDSAT imagery and occur exclusively in the Basement land system; a land system with well defined geomorphic and soil boundaries on the satellite image, with the notable exception of the southern part where separation from the adjacent Baggara land system was very inaccurate.

TABLE 6.11 RESIDUAL AND POLYGENETIC SOILS: AREA PERCENTAGE ERROR

Soil Unit	No. of Map Units	Map 1 km^2	No. of Map Units	Map 2 km^2	Difference km^2	Error %	Cumulative Difference	Error %
bs	9	2,584	17	1,783	-801	-31	-	-
bsr	4	1,355	1	1,630	+275	+20	-	-
Totals	**13**	**3,939**	**18**	**3,413**	**-526**	**-13**	**1,076**	**27**

bs Soils

The colluvial/residual Basement soils occur in the weakly dissected pediplain (wdp) geomorphic sub-unit. These dark grey sandy clay loam, sandy clay and clay soils support a variable density of *Acacia mellifera* scrub vegetation. Reflected energy in the visible and near infra-red bands of the spectrum is low and the tonal signature of the LANDSAT image ranges from dark grey/green to dark purple. The soils are easily separated from their truly residual counterparts in the more dissected parts of the Basement land system by marked tonal and pattern contrasts. However, in the southern part of the land system on the satellite image the bs soils appear to merge imperceptibly with the morphologically similar alluvial soils of the Baggara sheet wash plains. This major boundary discrepancy is largely responsible for the 801 km^2 underestimate of these soils on Map 2 (Table 6.11).

A further misclassification contributing to this large error is found in the extreme north eastern part of the Basement land system where alternate bands of light and dark tones orientated north-east-south-west, the direction of the prevailing dry season north-east trade winds, occur. The contrast between the dark and lighter patches is so clear cut on the satellite imagery that the former were mapped as bs soils and the latter as Ae soils. On Map 2 the whole area was mapped as a bs soil unit.

The striping pattern on the satellite image is far more pronounced than it is on the aerial mosaics due in large measure, to a processing error (over exposure) on one run of aerial photographs. For the image interpreter this area is highlighted by the wider perspective provided by the LANDSAT scene in a way that is not possible using aerial photographs and mosaics. The high tonal contrast between the alternating stripes, combined with the orientation, strongly suggested that the lighter tones represented sand dune soils. Field work revealed that a thin sand 'skim' overlying the bs soils was indeed present but that its depth rarely exceeds a few centimetres. Where the thin sand cover was absent, the light tones were due to the presence of a light brown sandy/silty alluvial layer which was deposited on the level bs soils following rain by the process of sheet wash. In this instance it was not possible to infer the depth of the aeolian and alluvial cover from the satellite image.

bsr Soils

The areas of soil derived from the *in situ* weathering of Basement complex rocks are found in the strongly dissected pediplain and jebels (sdpj) geomorphic sub-unit. Severe soil erosion in these areas has created a large number of gullies and sheet wash slopes devoid of vegetation. These constitute highly reflective surfaces and have a very clear light toned signature on the satellite image. In areas where erosion is less severe and the soils support patches of thorn savanna and savanna woodland, the light yellow tones are mixed with red and light blue tones. These areas stand out in marked contrast to the dark toned level pediplains with bs soils supporting thickets of *Acacial mellifera* scrub, further to the south and west of the Basement land system.

The well defined dense dendritic drainage pattern on the image, combined with the distinctive range of tonal characteristics associated with the soils and vegetation of this mapping unit and the contrasting tones of adjacent units, should enable the interpreter to confidently delineate the unit. But, as Table 6.11 shows, the area of these soils interpreted from the LANDSAT image is overestimated by 275 km^2, equivalent to an error of +20 per cent (Table 6.11). In this particular case the contrast between this unit and others is greater on the satellite image than it is on the aerial photographs and these differences are enhanced by the space-craft's synoptic view of the area. In this instance the LANDSAT map most probably gives a more accurate estimate of the area occupied by the bsr soils than that obtained from interpreting the aerial photographs.

6.6 CONCLUSIONS

In general, the aeolian soils are readily interpreted on the satellite imagery. The interpreter relies primarily on an analysis of such image characteristics as shape, pattern and tone to determine the extent of aeolian geomorphological features and related soils. In the interiors of larger sand sheets where cultivation is minimal, the surface of the aeolian sand soils is rarely exposed. In this situation the interpreter relies on other image characteristics such as the lack of a surface drainage system to deduce the presence of aeolian sand soils. The smaller and more widely scattered sand dunes, particularly those in the Baggara land system, are easily identified on the LANDSAT image because the field crops had been harvested at the time of image acquisition. The combination of dry crop stubble and the pale brown sandy surface creates high surface reflectivity, in marked contrast to the surrounding areas of dark grey alluvium with low reflective properties.

The size of most of the sand dunes (6-7 km^2) precludes accurate delineation of their boundaries on a 1:500,000 scale bulk processed LANDSAT colour composite image. However, the fact that 13 of the 15 dunes interpreted from the satellite image occupy the same geographical co-ordinates as their counterparts on the 'standard' map is considered to be of greater significance for a reconnaissance survey than precise boundary delineation.

In the Basement land system many of the sand dunes have reverted to bush fallow and the image characteristics are very similar to those of the non-aeolian soils which support *Acacia* spp. bush and thicket. As a result, the dunes in this land system are not accurately mapped from the LANDSAT image.

When attempting to interpret the extent of the alluvial soils on the LANDSAT image the interpreter relies on the known association between the alluvial soils and their related vegetation and geomorphology. In a complex depositional environment such as that of Southern Darfur, an analysis of image patterns, particularly those depicting the drainage, provided the primary criteria for the discrimination of soil and geomorphological complexes. Occasionally it was possible to map discrete units within the areas of alluvium. For example, dark grey cracking clays generally occurred in association with dense *Acacia seyal* woodland in depressions. Infra-red reflectance from this woodland was high and was recorded in bright red colours on MSS band 7. Where the interpreter had correctly predicted the areas of depressional topography and mapping accuracy of this discrete soils unit (Al_2c) was high. However, other alluvial soils not exclusively found in low lying areas also support a dense vegetative cover with a high infra-red reflectance thus consistent identification of the cracking clays was not possible. Where alluvial soils occur in unambiguous geomorphological situations (major wadi valleys and floodplains) the agreement between the two maps is reasonably good.

In the southern part of the Basement land system the interpretation of the residual and polygenetic soils presented some problems. The area merges almost imperceptibly with the northern part of the Baggara land system, an area which is environmentally very similar. This similarity is reflected in the almost identical image characteristics of the two regions and accounts for the inaccuracies on the LANDSAT map.

CHAPTER 7

DIGITAL AREA MEASUREMENT AND SAMPLING PROGRAM

7.1 INTRODUCTION

Manual methods of area calculation using such techniques as planimetering and dot counting are extremely laborious and time consuming. This is particularly so when dealing with a large number of intricately shaped mapping units such as those occurring on Maps 1 and 2. Speed of area computation is particularly important in the development planning context and therefore the viability of an alternative method of area calculation using a digital technique on Maps 1 and 2 was explored. In addition, a digital sampling program was carried out in an attempt to establish the minimum sample size required to give an acceptable level of mensuration accuracy.

7.2 DIGITAL AREA MEASUREMENT METHODOLOGY

Each fifteen minute grid square on Maps 1 and 2 was indexed according to the map coordinates of the south-west corner and each of the soil categories in the map legends numbered serially 1-22. An 11 x 11 dot grid was superimposed on each grid square and the frequency of occurrence of each soil unit at each point recorded on prepared forms on a line by line basis. These data were then transferred to computer punch cards. At the present scale of 1:500,000 each dot represented 6.25 km^2 and approximately 3,500 dots were used to calculate the total area for each map.

The computer program was written by Dr. P. Thomson in Fortran and run on the Aston University ICL 460 computer. The program was designed to give the total amount of each soil unit in each grid square and to sum the totals. These data in the computer print out format are included in Appendix C. The results of the comparative manual and digital area calculations of Maps 1 and 2 are discussed in the following section.

7.3 RESULTS AND CONCLUSIONS

Bearing in mind the scale and complexity of the two maps, the use of an 11 x 11 dot grid for each fifteen minute grid square was considered to be an adequate dot density for the initial digital area calculations. The 3,487 dots covering the entire Study Area, with each dot representing 6.25 km^2 on the ground, are of course sample points and the accuracy of the area calculations must be measured against the values obtained manually using the total area calculation methods; planimetering and dense dot grid sampling (one dot representing 0.49 km^2) for the very small mapping units.

In Table 7.1 the manual and digital area calculations for Maps 1 and 2 are compared. Areal differences, expressed as percentage error for the 17 soil categories mapped have a range of between -22 and +19 per cent for Map 1 (the 'standard' map) and a range of between -4 and +47 per cent for Map 2 (the LANDSAT map). However, digital calculations of 15 and 13 of the 17 categories on Maps 1 and 2 respectively, are within +/- 10 per cent of the manually computed values. In addition, 8 soil categories on Map 1 and 10 categories on Map 2 are measured digitally to within +/- 5 per cent of the planimetered values. In the present study a 10 per cent error is generally considered to be acceptable for the purposes of a reconnaissance survey although in some instances the use of percentage error alone can be misleading. For example, those soil categories with an error in digital measurement of greater than 10 per cent (gal_3 Al_2c, Al_2a Al_2c, bs Ae, Nua, Ae Nua) occupy relatively small areas and the percentage error tends to exaggerate the discrepancy between the two area calculations. This is clearly demonstrated in the gal_3 Al_2c unit, which has a 19 per cent error on Map 1 and a 47 per cent error on Map 2. In terms of areas these values represent 8 and 22 km^2 respectively. Bearing in mind that even with approximately 3,500 dots, the digital method of area calculation is still a sampling as against a total method of area calculation, and that each dot represents 6.25 km^2, it is apparent that the regularly spaced array of 3,487 dots was too small a sample to cope with the small size and boundary complexities displayed by some mapping units. The errors are reduced to 1 per cent and less when the soils are grouped in their genetic classes.

The manual method of area measurement was chosen initially so that a valid comparison could be made between the accuracy of Maps 1 and 2 based upon total area measurements. In the absence of manual total area measurements the map user would have to rely entirely on the digital area calculations. It is therefore instructive to see what effect, if any, reliance on digital area measurements based in the 3,487 dot sampling program, would have had on the comparative study. The digitally computed values for Maps 1 and 2, with the difference (in km^2) and percentage error calculated, are set out in Table 7.2.

The results compare reasonably well with their planimetered counterparts; 7 of 17 soil categories are calculated to within +/- 5 per cent of the manually derived values; 5 to within +/- 5-10 per cent; 2 to within +/- 10-15 per cent and 3 have an error greater than +/- 15 per cent. The sign remains the same for both calculations except in the bs Ae and gal_3 Al_2c soil units. Both are relatively small units with complex boundaries.

TABLE 7.1 SOIL MAPPING UNITS MANNUAL AND DIGITAL AREA CALCULATIONS

Soil Unit	Computer Code	STANDARD MAP 1 Manual km²	Digital km²	Difference km²	Error %	LANDSAT MAP 2 Manual km²	Digital km²	Difference km²	Error %
Ae	10	8,376	8,463	+87	+1	9,178	8,919	-259	-3
bs Ae	12	405	375	-30	-7	375	438	+63	+17
Nua	7	304	275	-29	-10	155	181	+26	+17
Nur Nua	22	561	538	-23	-4	271	269	-2	-1
Ae Nua	19	462	488	+26	+6	681	756	+75	+11
Sub-Total		10,108	10,139	+31	+0.3	10,660	10,563	-97	-1
Al_2c	6	1,078	1,163	+85	+8	1,319	1,313	-6	-1
gal_3	9	413	450	+37	+9	485	475	-10	-2
Al_1b Al_2b Al_2c	13	1,289	1,288	-1	-0.1	1,756	1,719	-37	-2
Al_1b Al_2c	14	2,239	2,225	-14	-0.6	1,413	1,363	-50	-4
Al_2a Al_2b	15	535	575	+40	+7	530	544	+14	+3
Al_2a Al_2b Al_2c	16	458	456	-2	-0.4	409	437	+28	+7
Al_2a Al_2c	17	988	775	-213	-22	1,211	1,225	+14	+1
Al_2b Al_2c	18	400	406	+6	+2	338	356	+18	+5
gal_3 Al_2b	20	389	413	+24	+6	237	219	-18	-8
gal_3 Al_2c	21	42	50	+8	+19	47	69	+22	+47
Sub-Total		7,831	7,801	-30	-0.4	7,745	7,720	-25	-0.3
bs	1	2,584	2,463	-121	-5	1,783	1,919	+136	+8
(bs)bsr	(02)11	1,355	1,394	+39	+3	1,630	1,631	+1	+0.1
Sub-Total		3,939	3,857	-82	-2	3,413	3,550	+137	+4
Total		21,878	21,797	-81	-0.4	21,818	21,833	+15	+0.1

Notes:-

(a) The soil mapping units represented by the computer code numbers 3, 4, 5 and 8 never appear as discrete units on the maps.

(b) Soil unit bsr was incorrectly classified on the LANDSAT map as (bs)bsr(11) when the computer program was originally run. This error was corrected on the map and makes no difference to the computed values since (bs)bsr is equivalent to bsr.

TABLE 7.2 SOIL MAPPING UNITS PERCENTAGE ERROR (COMPUTED)

Genetic Group	Soil Unit	Standard Map (1) km²	LANDSAT Map (2) km²	Difference km²	Error %	Error Planimetered %
	Ae	8,463	8,919	+456	+5	+10
Aeolian	bs Ae	375	438	+63	+17	-7
Soils	Nua	275	181	-94	-34	-49
	Nur Nua	538	269	-269	-50	-52
	Ae Nua	488	756	+268	+55	+47
	Sub-Total	**10,139**	**10,563**	**+424**	**+4**	**+6**
	Al_2c	1,163	1,313	+150	+13	+22
	gal_3	450	475	+25	+6	+17
	Al_1b Al_2b Al_2c	1,288	1,719	+431	+33	+36
Alluvial	Al_1b Al_2c	2,225	1,363	-862	-39	-37
Soils	Al_2a Al_2b	575	544	-31	-5	-1
	Al_2a Al_2b Al_2c	456	437	-19	-4	-11
	Al_2a Al_2c	775	1,225	+450	+58	+23
	Al_2b Al_2c	406	356	-50	-12	-16
	gal_3 Al_2b	413	219	-194	-47	-39
	gal_3 Al_2c	50	69	+19	+38	-12
	Sub-Total	**7,801**	**7,720**	**-81**	**-1**	**-1**
Residual and	bs	2,463	1,919	-544	-22	-31
Polygenetic	bsr	1,394	1,631	+237	+17	+20
Soils						
	Sub-Total	**3,857**	**3,550**	**-307**	**-8**	**-13**
	Total	**21,897**	**21,833**	**+36**	**+0.2**	**+0.03**

7.4 DIGITAL SAMPLING PROGRAM

In sampling, by definition, no number of dots will give the right answer. The problem is one of deciding how large the errors can be before they matter. In the present study an acceptable level of accuracy is one that is judged to provide area calculations within +/- 10 per cent of their true value. The results discussed in Section 7.3 show that 15 and 13 of the 17 soil categories on Maps 1 and 2 respectively are mapped to this level of accuracy using a sample of approximately 3,500 dots. Errors in the digital calculation of greater than 10 per cent would probably be reduced if the sample size was increased and the point location randomised to prevent sampling bias.

TABLE 7.3 DIGITAL SAMPLING PROGRAM RESULTS

Computer Code	Soil Unit	Planimetered km^2	3487x1 km^2	Error %	2000x20 $\bar{x}$ km^2	Error %	1500x20 $\bar{x}$ km^2	Error %	1000x20 $\bar{x}$ km^2	Error %	500x20 $\bar{x}$ km^2	Error %	250x20 $\bar{x}$ km^2	Error %	100x20 $\bar{x}$ km^2	Error %	25x20 $\bar{x}$ km^2	Error %
10	Ae	8,376	8,463	+1	8,467	+1	8,447	+1	8,420	+0.5	8,399	+0.3	8,508	+2	8,816	+5	8,282	-1
	σ	-	-	-	124	+0.05	199	+0.2	312	-0.5	344	-0.8	560	+0.5	1,318	+4	1,920	-2
12	bs Ae	405	375	-7	381	-6	369	-9	372	-8	373	-8	336	-17	305	-24	349	-14
	σ	-	-	-	36	+2	52	-2	55	-1	133	-1	133	-10	211	-19	427	-7
7	Nua	304	275	-10	271	-11	267	-12	268	-12	268	-12	283	-7	349	+15	305	+0.3
	σ	-	-	-	43	-1	41	-3	66	-3	106	-3	193	+3	270	+27	416	+11
22	Nur Nua	561	538	-4	543	-3	532	-5	539	-4	593	+6	545	-2	512	-9	567	+1
	σ	-	-	-	44	+1	57	-1	73	+0.2	144	+10	263	+1	325	-5	744	+5
19	Ae Nua	462	488	+6	473	+2	471	+2	450	-3	482	+4	484	+5	447	-3	262	-43
	σ	-	-	-	54	-3	52	-3	62	-8	180	-1	274	-1	280	-8	399	-46
	Aeolian Sub-Total	10,108	10,139	+0.3	10,135	+0.3	10,086	+0.2	10,049	-0.6	10,115	+0.01	10,156	+0.5	10,429	+3	9,765	-3
						-0.04		-0.5		-0.9		-0.2		+0.2		+3		-4
6	Al_2c	1,078	1,163	+8	1,136	+5	1,123	+4	1,171	+9	1,133	+5	1,216	+13	1,177	+9	1,177	+9
	σ	-	-	-	73	-2	88	-3	120	+0.7	246	-3	225	+5	484	+1	966	+1
9	gal_3	413	450	+9	443	+7	467	+13	451	+9	427	+3	436	+5	403	-2	174	-58
	σ	-	-	-	44	-2	54	+4	80	+0.2	106	-5	177	-3	340	-10	445	-61
13	Al_1b Al_2b Al_2c	1,289	1,288	-0.1	1,272	-1	1,300	+0.1	1,299	+0.8	1,292	+0.2	1,482	+15	1,188	-8	1,526	+18
	σ	-	-	-	87	-1	74	+0.1	133	+0.8	174	+0.2	229	+15	438	-8	989	+18
14	Al_1b Al_2c	2,239	2,225	-0.6	2,199	-2	2,203	-2	2,255	+0.7	2,216	-1	2,175	-3	2,081	-7	2,223	-0.7
	σ	-	-	-	92	-1	143	-1	232	+1	263	-0.4	357	-2	566	-6	1,217	-0.1
15	Al_2a Al_2b	535	575	+7	574	+7	581	+9	565	+6	573	+7	615	+15	687	+28	436	-18
	σ	-	-	-	57	-0.2	76	+1	73	-2	120	+0.3	169	+7	426	+19	703	-24
16	Al_2a Al_2b Al_2c	458	456	-0.4	470	+3	438	-4	423	-8	484	+6	501	+9	381	-17	436	-5
	σ	-	-	-	48	+3	45	-4	79	-7	155	+6	200	+10	307	+16	516	-4
17	Al_2a Al_2c	988	775	-22	791	-19	812	-18	785	-21	787	-20	728	-26	741	-25	654	-34
	σ	-	-	-	52	+2	66	+2	96	+1	174	+2	263	-6	304	-4	866	-15
18	Al_2b Al_2c	400	406	+2	411	+3	432	+8	401	+0.3	392	-2	405	+1	392	-2	741	+85
	σ	-	-	-	38	+1	52	+6	92	-1	116	-3	168	-0.2	313	-3	744	+82
20	gal_3 Al_2b	389	413	+6	420	+8	391	+0.5	437	+12	421	+8	357	-8	294	-24	305	-22
	σ	-	-	-	46	+2	50	-5	71	+6	125	+2	151	-13	231	-29	499	-26
21	gal_3 Al_2c	42	50	+19	53	+26	52	+24	52	+24	50	+19	52	+24	65	+58	0.00	-100
	σ	-	-	-	13	+6	20	+4	33	+4	40	0.0	70	+4	121	+30	0.00	-100
	Alluvial Sub-Total	7,831	7,801	-0.4	7,769	-0.8	7,799	-0.4	7,839	+0.1	7,775	-0.5	7,967	+2	7,409	-5	7,672	-2
						0.4	-	-0.03	-	+0.5	-	-0.3	-	-1	-	-5	-	-2
1	bs	2,584	2,456	-5	2,490	-4	2,502	-3	2,487	-4	2,550	-1	2,306	-11	2,451	-5	2,920	+13
	σ	-	-	-	88	+1	128	+2	170	+1	308	+4	345	-6	624	-0.2	1,241	+19
2	bsr	1,355	1,394	+3	1,401	+3	1,408	+4	1,420	+5	1,353	-0.1	1,364	+0.7	1,504	+10	1,438	+6
	σ	-	-	-	81	+0.5	95	+1	181	+2	194	-3	309	-2	430	+8	966	+3
	Residual Polygenetic Sub-Total	3,939	3,850	-2	3,891	-1	3,910	-0.7	3,907	-0.8	3,903	-0.9	3,670	-7	3,955	+0.4	4,358	+10
						+1	-	+2	-	+1	-	+1	-	-5	-	+3	-	+13
	Total	21,878	21,790	-0.4	21,795	-0.4	21,795	-0.4	21,795	-0.4	21,793	-0.4	21,793	0.4	21,793	-0.4	21,795	-0.4
		-	-	-	-	+0.02	-	+0.02		+0.02	-	+0.01	-	+0.01	-	+0.01	-	+0.02

Note: Error % top figure with regards to planimetry - bottom figure with regards to 3,487 sample

In the present study the use of a sample of approximately 3,500 dots is considered to give an acceptable level of accuracy for the purposes of reconnaissance survey. It remained to be seen whether a smaller sample of dots located at random would also provide an acceptable level of accuracy.

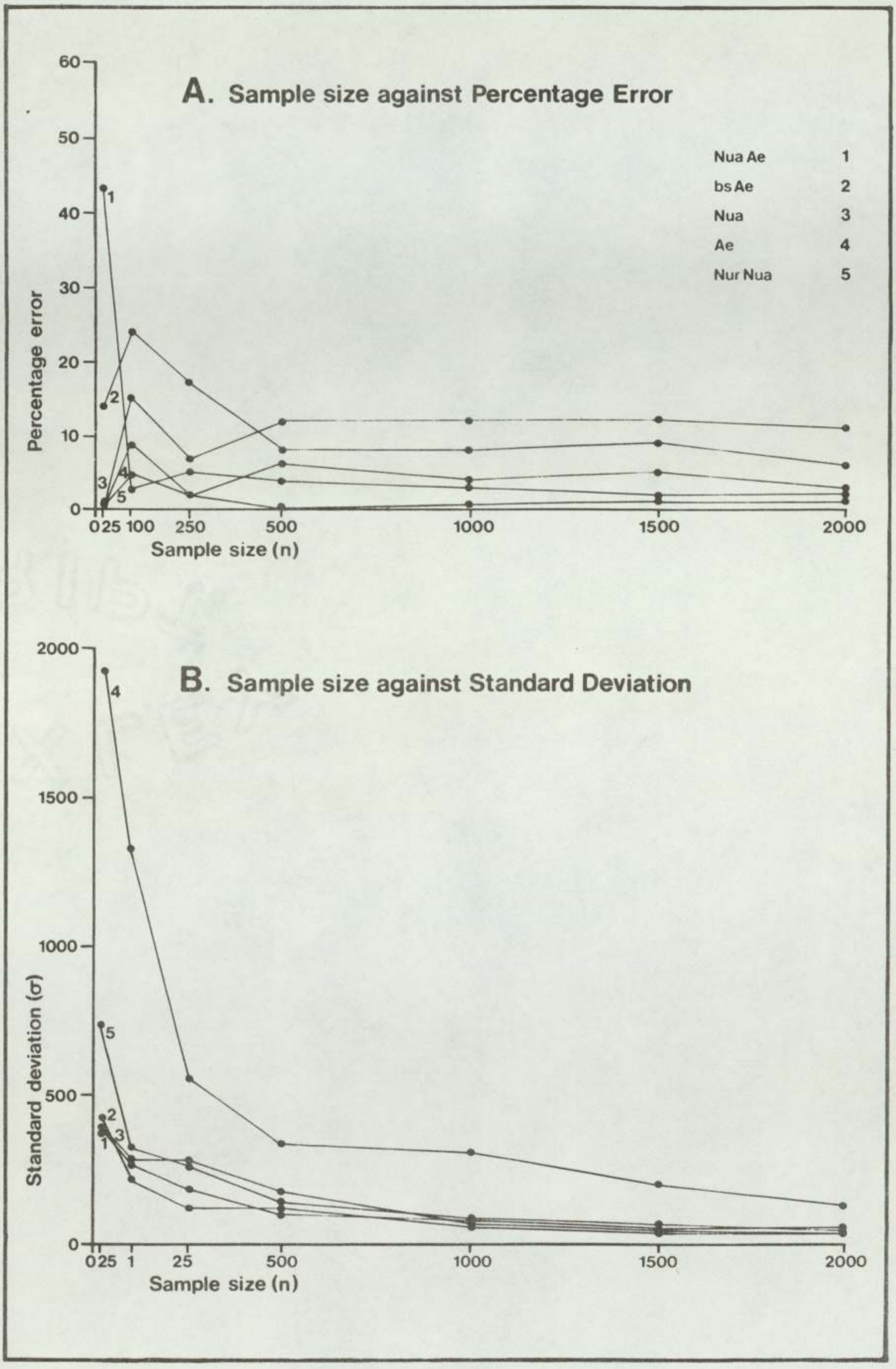
The digital sampling program was only carried out on Map 1, the 'standard' map. The objective of the exercise was to determine the minimum sample size that would provide a +/- 10 per cent level of accuracy for area calculations of the soil mapping units. To achieve this a series of 2,000, 1,500, 1,000, 500, 250, 100 and 25 sample points were randomly selected from the entire data set of 3,487 points on Map 1. The area programs were run on the computer and repeated twenty times for each sample size. The mean values and standard deviations of the twenty runs for each sample size were also calculated. These data are presented in full in Appendix C and summarised in Table 7.3 alongside the percentage error for each mapping unit within each sample. This area error for each unit was calculated as a percentage of the equivalent planimetered area and area calculated using the 3,487 dot sample. The coefficient of variation (V) value of each mapping unit per sample has also been calculated. These figures are presented in Table 7.4.

7.5 RESULTS AND CONCLUSIONS

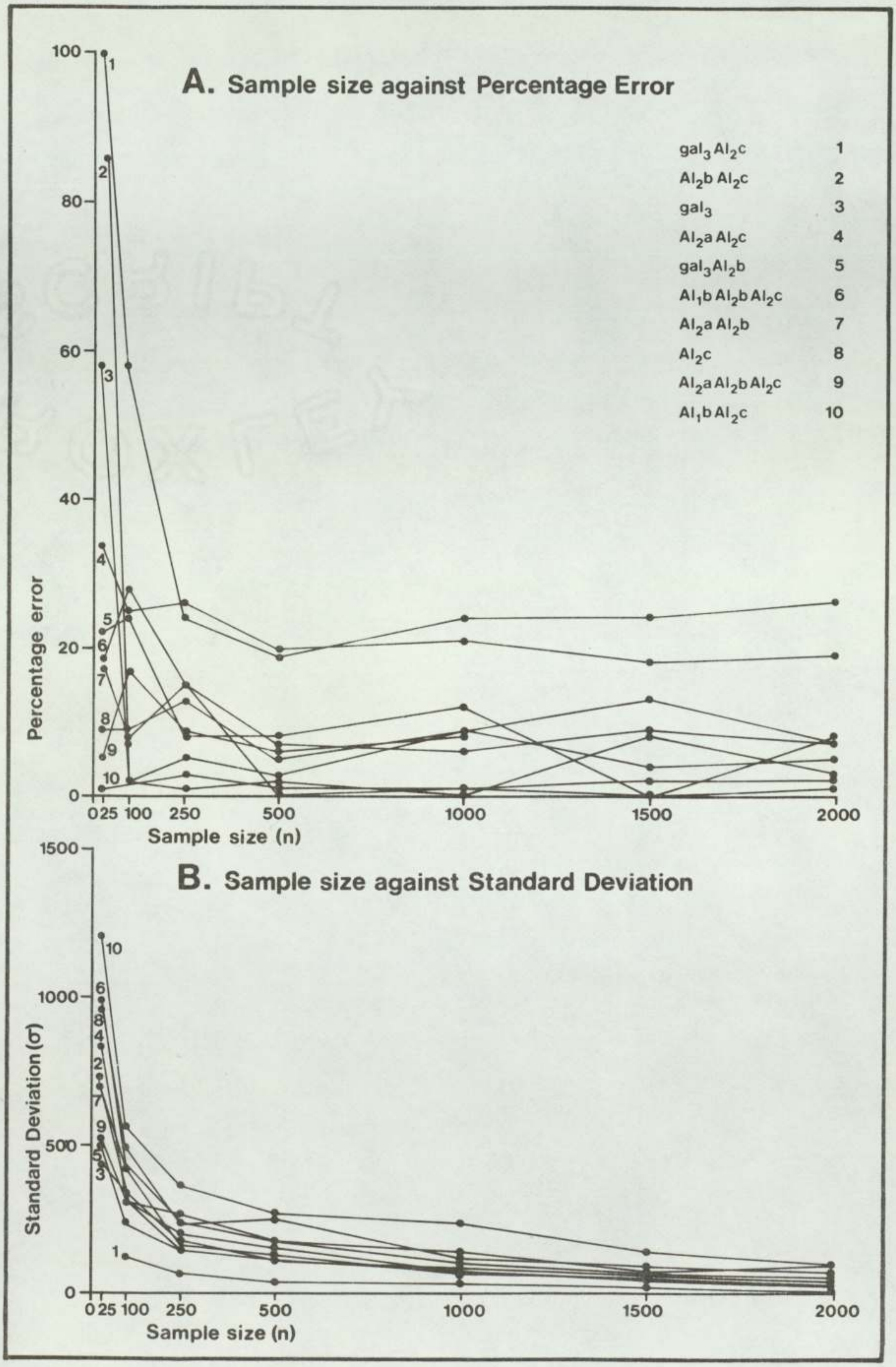
The percentage errors shown in Table 7.3 do not significantly exceed the +/- 10 per cent threshold with regards to the 3,487 sample or with regards to the planimetered values, until the 250 dot sample. Using the 500 dot sample, no soil group has an error of greater than 10 per cent when compared with the areas derived from the 3,487 dot sample, and only three groups have errors larger than 10 per cent (Nua -12 per cent, Al_2a Al_2c -20 per cent and gal_3 Al_2c +19 per cent) when compared with their planimetered equivalents. In the latter case these three soil groups have errors in excess of 10 per cent in the 2,000, 1,500 and 1,000 dot samples. The percentage errors of the various sample sizes, calculated using the planimetered values as the standard, are presented graphically in Figures 7.1a-7.3a for the three genetic soil groups.

To obtain a measure of the reliability of the mean area values for the twenty runs at each dot density, the standard deviation (σ) was calculated for each mapping unit. These σ values, given in Table 7.3 and presented graphically against sample size in Figures 7.1b to 7.3b, increase in magnitude as the size of the sample decreases and indicate loss of accuracy. The curves shown in Figures 7.1b-7.3b flatten out at the 1,000 dot sample and this superficially suggests that the 1,500 and 2,000 dot samples are redundant. However, there is considerable variation in the magnitude of the standard deviations for each soil group within each dot sample as well as between the same soil group in different samples.

Figures 7.1A&B Sample size against percentage error and standard deviation: Aeolian soils



Figures 7.2A&B Sample size against percentage error and standard deviation: Alluvial soils



Figures 7.3A&B Sample size against percentage error and standard deviation: Residual and Polygenetic soils

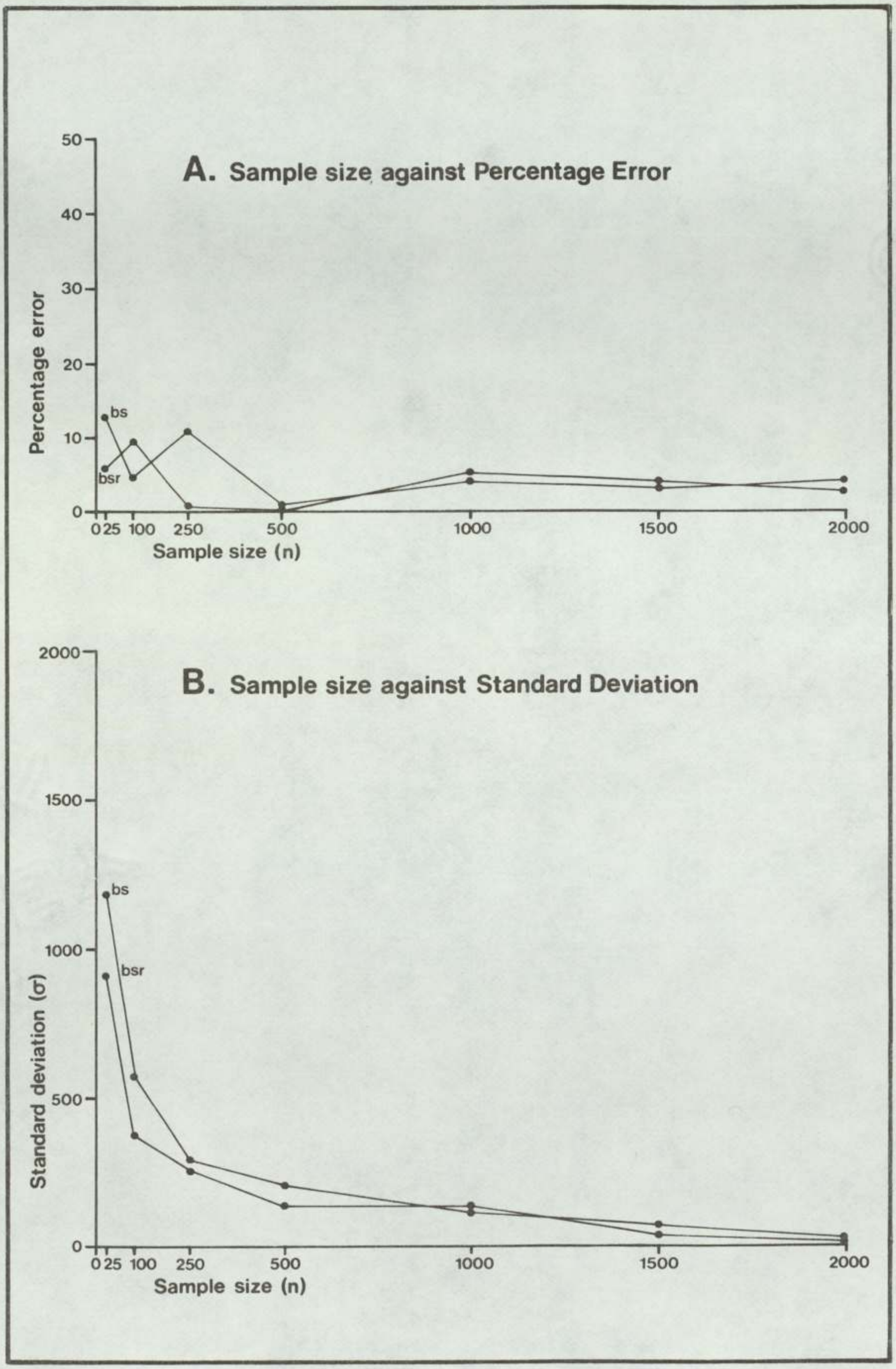


TABLE 7.4 SAMPLING PROGRAM COEFFICIENT OF VARIATION (V) VALUES

	Sample Size						
	2,000	1,500	1,000	500	250	100	25
Ae	1.46	2.36	3.70	4.09	6.58	14.95	23.18
bs Ae	9.45	14.09	14.78	35.66	39,58	69.18	122.30
Nua	15.86	15.36	24.63	39.55	68.20	77.36	136.39
Nur Nua	8.10	10.71	13.54	24.28	48.26	63.48	131.22
Nua Ae	11.42	11.04	13.78	37.34	56.61	62.64	152.29
Al_2c	6.43	7.84	10.25	21.71	18.50	41.12	82.07
gal_3	9.93	11.56	17.74	24.82	40.60	84.37	255.78
Al_1b Al_2b Al_2c	6.84	5.69	10.24	13.48	15.45	36.87	64.81
Al_1b Al_2c	4.18	6.49	10.29	11.87	16.41	27.20	54.75
Al_2a Al_2b	9.93	13.08	12.92	20.94	27.48	62.01	161.24
Al_2a Al_2b Al_2c	10.21	10.27	18.68	32.02	39.92	80.58	118.35
Al_2a Al_2c	6.57	8.13	12.23	22.11	36.13	41.03	132.42
Al_2b Al_2c	9.25	12.04	22.94	29.59	41.48	79.85	100.40
gal_3 Al_2b	10.95	12.79	16.25	29.69	42.30	78.57	163.61
gal_3 Al_2c	24.53	38.46	63.46	80.00	134.62	186.15	00
bs	3.53	5.12	6.84	12.08	14.96	25.46	42.50
bsr	5.78	6.78	12.77	14.34	22.65	28.59	67.18

Coefficient of variation (V) calculated from formula (Gregory, 1963):

$$\frac{\text{standard deviation } (\sigma)}{\text{mean } \overline{x}} \times 100\%$$

In general, the standard deviation of soil mapping units occupying 750 km² or more becomes unacceptably large (>10 per cent of the mean value), even by reconnaissance standards, with samples of less than 1,000 dots. For example, the mean value for bs soils using the 1,000 dot sample is 2,487 km² +/-170 and for the 500 dot sample the mean is 2,550 km² +/-308. Thus there is a 95.45 per cent probability that the true mean value in the former case will be between 2,147 and 2,827 km² (i.e. between plus and minus two standard deviations) a tolerable level of accuracy. In the latter case it will be between 1,934 and 3,166 km², clearly a very low level of accuracy.

The standard deviation for the Ae soils is larger than that of the other units because of the large areas occupied by these soils. This has resulted in a larger standard deviation for the mean area value for the sampling runs. By calculating the coefficient of variation (V), the influence of the magnitude of this large mean is removed. The values for V presented in Table 7.4 show a considerable increase between the 1,000 and 500 dot samples for the majority of the soil groups.

In the smaller soil units and those with particularly complex boundary configurations (e.g. Al_2a Al_2c), the standard deviation is high in the samples with less than 1,500 dots. In a few instances, for example in the gal_3 Al_2c and Al_2a Al_2b mapping units, the value for σ exceeds 10 per cent of the mean ($\overline{x}$) value in the 2,000 dot sample.

The overall complexity of the map as measured by the number of classes and mapping units is another factor which influences the accuracy of a sampling technique. In point sampling, Robertson and Stoner (1970) found that the best results are generally obtained when there are only a few classes and when the areas under consideration are large. These conditions are rarely fulfilled in the present study where Map 1, the 'standard' map, contains 22 soil classes and 114 mapping units. These vary from 2 km^2 to 5,915 km^2 (units 73 and 1 in Table 6.1 Chapter 6) in size and their boundary shapes are often very complex.

The results of the digital sampling program indicate that a sample of at least 1,500 dots is required to give tolerable levels of accuracy (+/- 10 per cent) for area measurement of the mapping units. To achieve a similar degree of accuracy for soil units gal_3 Al_2c and Al_2a Al_2c would require a sample larger than 2,000 dots to be run 20 times and 3,487 dots run once. Smaller dot samples of between 1,000 and 250 dots give a reasonable degree of accuracy where the soil class contains large mapping units. The Ae and Al_1b Al_2c soil classes each contain at least one mapping unit 1,000 km^2 or more in area (Table 6.1) and have percentage errors of below 10 per cent even with a 25 dot sample, although the standard deviations of such low intensity sampling are unacceptable. In the case of the Ae soil class, the largest unit occupies 5,915 km^2 and the second largest 1,865 km^2. With mapping units of this size the probable errors in digital low dot sampling of the 42 soil units is the Ae class, with individual areas of less than 20 km^2, make little impact on the overall accuracy of area calculation for the soil class.

Thus a digital sampling method can provide a reasonably accurate estimate of class areas on a complex thematic map although the choice of sample size is critical. However, in the context of development planning within the Third World the use of such time consuming and expensive techniques of mensuration must be viewed with extreme caution when manual methods of total area calculation (planimetry, dot counting, cutting and weighing) can be carried out cheaply and accurately in a field situation.

CHAPTER 8

DISPLACEMENT OF THEMATIC BOUNDARIES

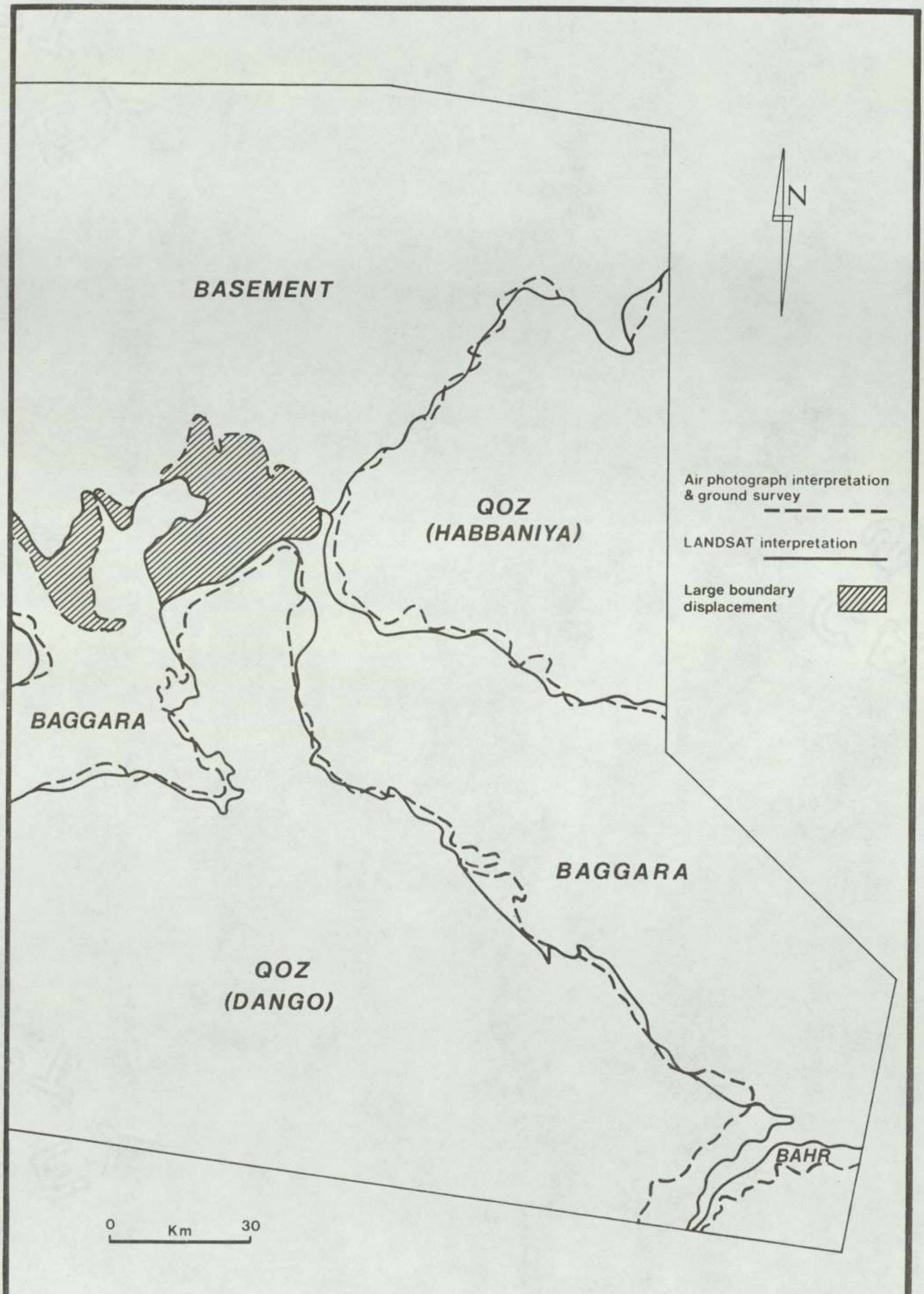
8.1 INTRODUCTION

The degree of boundary coincidence between similarly classified mapping units is an important parameter of map accuracy. Good areal agreement between a unit on one map and its equivalent on another, may disguise gross differences in the shape and geographical location of each. By reference to the comparative analysis of mapping unit areas on the 'standard' and LANDSAT maps, and visual inspection of the boundaries, it is apparent that there is considerable variation in area and boundary shape of similarly classified units. In the present study three methods have been used to determine the degree of land system and soil boundary displacement or coincidence on the LANDSAT map. One of the three methods, namely sieve mapping, is an established geographical technique (Monkhouse and Wilkinson, 1974) although it has been modified for the purposes of the present study to provide a qualitative estimate of boundary coincidence and a rapid guide to those areas of gross boundary discrepancy. The other two methods are quantitative. They have been developed in an attempt to refine the measurement of accuracy on the LANDSAT map as determined by areal comparison of similarly classified units on the 'standard' map and sieve mapping.

8.2 SIEVE MAPPING

Sieve mapping is generally used in geographical studies to select areas that are suitable or unsuitable for a specific type of land-use. This is achieved by superimposing isopleths representing various factors and eliminating or 'sieving out' those areas which do not fulfil the required criteria. The method is thus increasingly selective in response to additional data and the results are presented in terms of areas. For the purposes of the present study, further comparisons of accuracy, expressed as differences in area, were considered unnecessary since these data were already available from the manual and digital mensurations and they tell us little about boundary similarities. However, by superimposing a transparent overlay of the LANDSAT map onto a transparent overlay of the 'standard' map, a simple and rapid assessment of boundary coincidence can be obtained in those areas of the map where boundary agreement is either very good or very bad. The agreement between the land systems boundaries, shown in Figure 8.1, is particularly good except in the shaded area between the Baggara and Basement land systems. In this instance the sieve map gives a clear visual impression of boundary coincidence because the number of boundaries being compared is small and the contrast between those boundaries with high

Figure 8.1
Land system boundaries. Sieve map



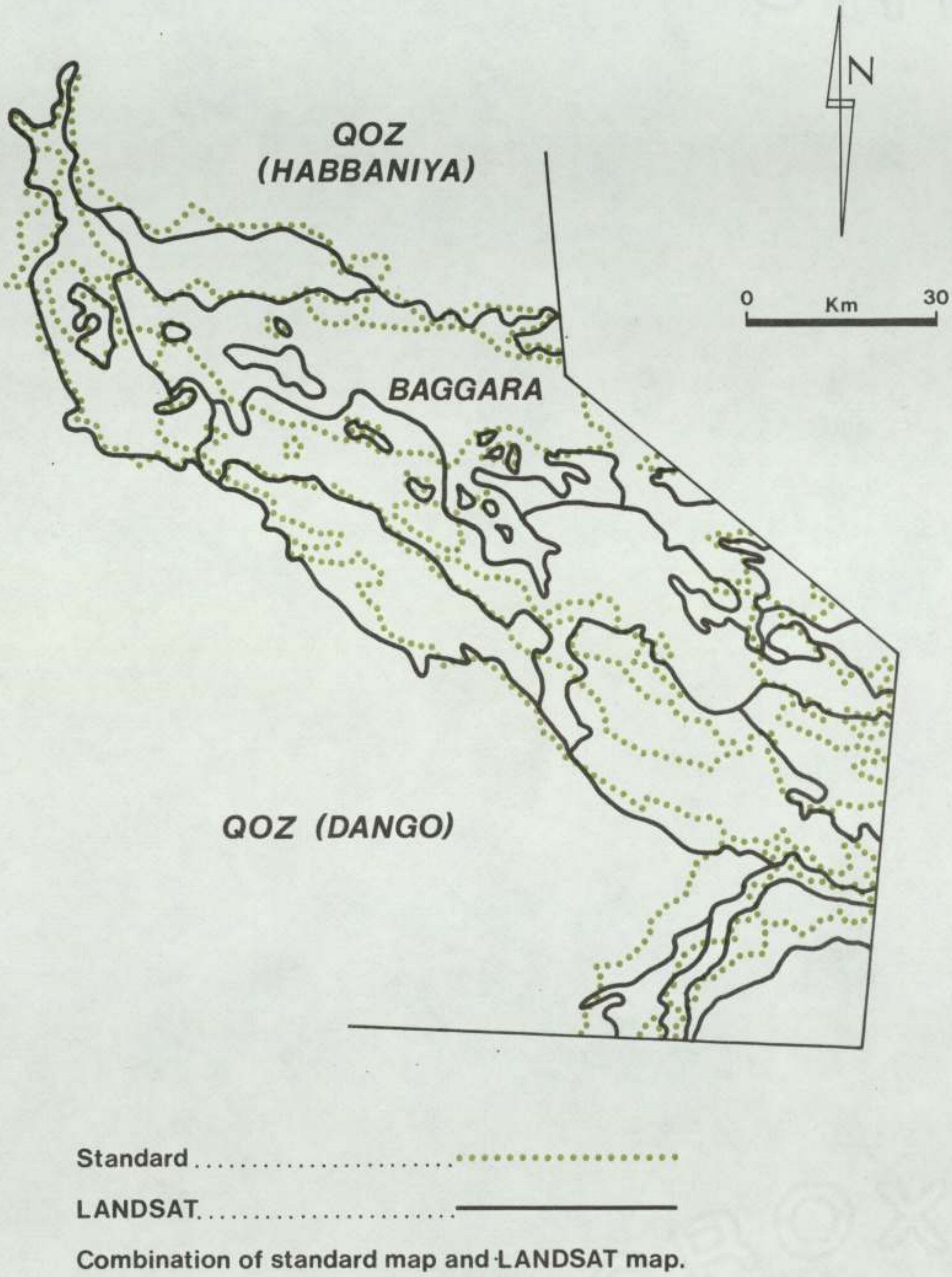
and low degrees of coincidence is so great. However, when a large number of mapping units with varying degrees of boundary coincidence are examined by this method the end result can be visually confusing, as Figure 8.2 demonstrates.

8.3 MEASUREMENT OF BOUNDARY DEVIATION

For the map user an approximate measure of the boundary reliability on the LANDSAT map would be preferable to a qualitative statement concerning the similarity of boundaries. For example, at any point how far is the boundary interpreted from the LANDSAT image likely to deviate from the true boundary, namely that shown on the 'standard' map? To provide an approximate measure of boundary deviation between boundaries representing the same class of phenomena, the areas of mismatch and agreement along the lengths of the boundaries were sampled linearly using north-south and east-west transects, and the results expressed in kilometres of deviation from the 'standard' map boundary.

For the land systems boundaries a 3 mm grid was superimposed on the Land Systems Sieve map as shown in Figure 8.3. The grid size can be variable and is determined by the magnitude of boundary displacements. In the present case a 3 mm grid was considered adequate to cope with the degree of boundary deviation. Taking each transect in turn, the distance between the 'standard' boundary (broken line) and the LANDSAT boundary (solid line) was measured along the transects at scale and converted to kilometres. Thus in Figure 8.3, north-south transect 2 cuts the LANDSAT boundary between the Basement and Qoz (Habbaniya) land systems in the three places marked $2d_1$, $2d_2$ and $2d_3$. The same transect crosses the 'standard' map boundary between the two land systems at the points marked $1d_1$, $1d_2$ and $1d_3$. The deviation of the LANDSAT boundary along that particular transect is calculated by measuring the distances in mm between $1d_1$ and $2d_1$, $1d_2$ and $2d_2$ and $1d_3$ and $2d_3$. The deviation between $1d_1$ and $2d_1$ is 3 mm or approximately 3 km at 1:1,000,000 scale. At $1d_2$ and $2d_2$ the boundaries coincide and therefore the deviation is zero and the deviation between $1d_3$ and $2d_3$ is 4 mm or approximately 4 km. The deviations were measured in this manner along each of the north-south and east-west transects covering the Basement-Qoz (Habbaniya) land system boundary. The deviations along the boundary were then summed and the mean and standard deviations calculated. This was repeated for each pair of land system boundaries, with the exception of that between Basement and Baggara land system, and the results are presented in Table 8.1. These results confirm the overall visual impression given by the sieve map, that the land system boundaries on the LANDSAT map are, with one notable exception, very similar in shape to those on the 'standard' map.

Figure 8.2
Soil boundaries. Sieve map



Combination of standard map and LANDSAT map.
Soil overlays for part of the Baggara land system.

Figure 8.3
Land system boundary coincidence. Deviation transect sampling

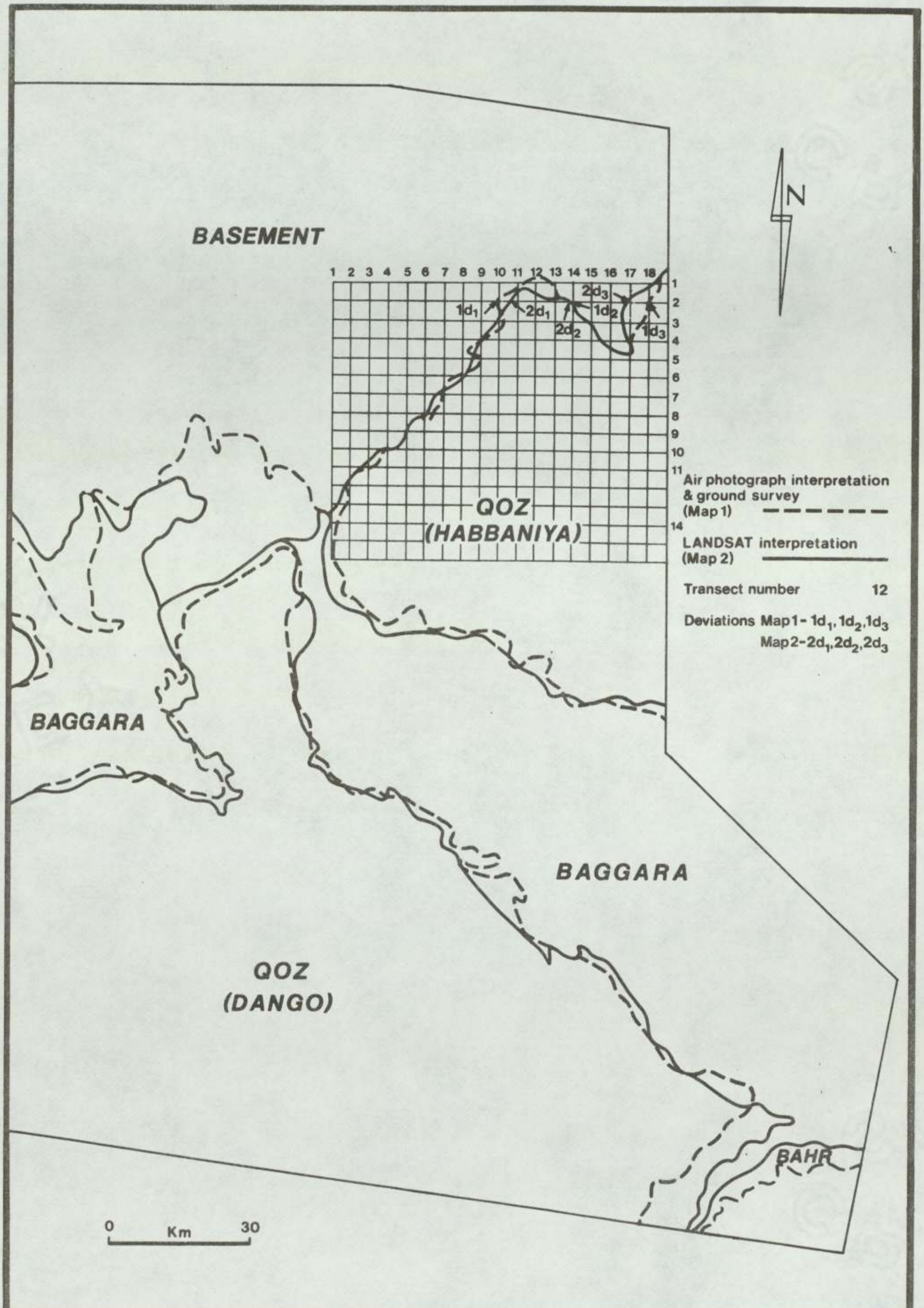


TABLE 8.1 DEVIATION OF LAND SYSTEM BOUNDARIES ON LANDSAT MAP

Land System Boundary	East-West Transects			North-South Transects			Combined Transects		
	Sample No. n	Mean $\bar{x}$ km	Std. Devn. σ +/- km	Sample No. n	Mean $\bar{x}$ km	Std. Devn. σ +/- km	Sample No. n	Mean $\bar{x}$ km	Std. Devn. σ +/- km
Basement - Habbaniya Qoz	17	1.6	1.3	18	1.4	1.7	35	1.5	1.5
Baggara - Habbaniya Qoz	13	2.3	1.3	20	2.1	1.7	33	1.9	1.5
Baggara - Bahr	-	-	-	-	-	-	-	-	-
Qoz Dango - Bahr	7	6.7	2.2	8	5.8	2.4	15	6.2	2.3
Qoz Dango - Baggara	59	2.8	2.5	51	2.4	2.5	110	2.6	2.5

Sample No. n - number of times transect cuts a boundary.

There is very little difference between the mean and standard deviations in either transect direction. The combined transect mean and standard deviation values for the boundaries between the Basement and Qoz (Habbaniya), the Baggara and Qoz (Habbaniya) and the Baggara and Qoz (Dango) land systems are low, with values of 1.5 km +/-1.5 km, 1.9 km +/-1.5 km and 2.6 km +/-2.5 km repsectively. These levels of accuracy are considered to be well within the acceptable limits for a reconnaissance survey. The boundary between the Qoz (Dango) and Bahr land systems is less accurately mapped on the LANDSAT map and has a combined transect mean error of 6.2 km +/-2.5 km. Much of this error can be attributed to the small scale differences that exist between the south eastern corners of the 'standard' map and the LANDSAT map.

The results suggest that the mean difference between two boundaries can be expressed as a linear measure and the main direction of error stated if one is comparing like with like. If necessary, the transects can be orientated at right angles to the main direction of error which will be indicated on a sieve map. However, the method does not work when boundary combinations between the two maps differ. This situation occurs on the land systems map with the boundary between the Baggara and Basement land systems. On the LANDSAT map the boundary is linked with that of the Qoz (Dango) thus creating a land system boundary that does not occur on the 'standard' map. The boundary discrepancies in this area (shaded in Figure 8.1) and discussed at length in Chapter 6, are extreme. In this situation, where boundary errors between the two maps are large and are clearly shown on a sieve map, quantification is not really necessary since the magnitude of the map's unreliability in those areas has been clearly indicated. A similar argument precludes the use of this method for deriving the deviation of the LANDSAT map soil units in the Baggara land system (Figure 8.2). This part of both maps is too complex and some soil units that occur on one do not occur on the other. Thus the method is inappropriate if more than two mapping units are being compared and cannot cope with additional or omitted mapping units. Another quantitative method, described in Section 8.4, was developed which was sensitive to these criteria.

8.4 INDEX OF BOUNDARY COINCIDENCE (i)

As previously stated, one of the main problems encountered when comparing mapping units interpreted from the LANDSAT image with those on the 'standard' map is that one is not always comparing like with like. The classification of the same geographical area may not be the same on the two maps. In some instances additional units will be mapped from the LANDSAT imagery and in others, units mapped on the 'standard' map will not be apparent on the satellite imagery. The following method takes this into account and provides a quantitative measure of boundary coincidence over the whole map and within a land system stratum by relating the number of mapping units, expressed as the number of transect bisects, to the proportion of a mapping unit boundary correctly classified. In addition, this measure of boundary coincidence, hereafter referred to as the boundary coincidence index (i) will discriminate between two similarly classified mapping units of equal area but with gross differences in boundary shape.

Using a table of random numbers and centimetre squared paper, fifteen randomly located linear transects were drawn on the 1:500,000 scale 'standard' map (Map 5, Appendix E). The same transects were also drawn on the LANDSAT 1:500,000 scale map (Map 6, Appendix E). These randomly located transects are reproduced on 1:1,000,000 scale (approx.) reductions of Maps 5 and 6 in Figures 8.4 and 8.5.

A straight edge of white paper or card was laid along each transect on both maps and tick marks put at the beginning and end of the transect, and at each point where the transect crossed a thematic boundary. The number of boundaries bisecting the transect line on each map was noted (n_1 and n_2 respectively), the distance between each pair of bisects measured in mm (1_1 and 1_2) and the classification between transect bisects (1_1 and 1_2) was recorded. The length of boundary between 1_1 and 1_2 that was correctly classified on the LANDSAT map (1_3) was calculated and the values summed to give $\Sigma 1_3$. To calculate the coincidence index (i), the fraction of correctly classified boundary $\frac{\Sigma 1_3}{\Sigma 1_1}$ was multiplied by the bisect fraction $\frac{n_2}{n_1}$. On the few occasions that n_2, the number of bisects recorded on the LANDSAT map, exceed n_1, the number recorded on the 'standard' map, the former value was used so that the index would never exceed unity. Thus, the boundary coincidence index(i) is calculated from the formula:

$$i = \frac{\Sigma 1_3}{\Sigma 1_1} \cdot \frac{n_2}{n_1}$$

where: $\Sigma 1_3$ is the total length between boundary bisects on the transect that is correctly classified on the LANDSAT map.

$\Sigma 1_1$ is the length of the transect

n_1 is the number of times a thematic boundary bisects the transect on the 'standard' map.

n_2 is the number of times a thematic boundary bisects the transect on the LANDSAT map.

Figure 8.4
Standard map: Random transects

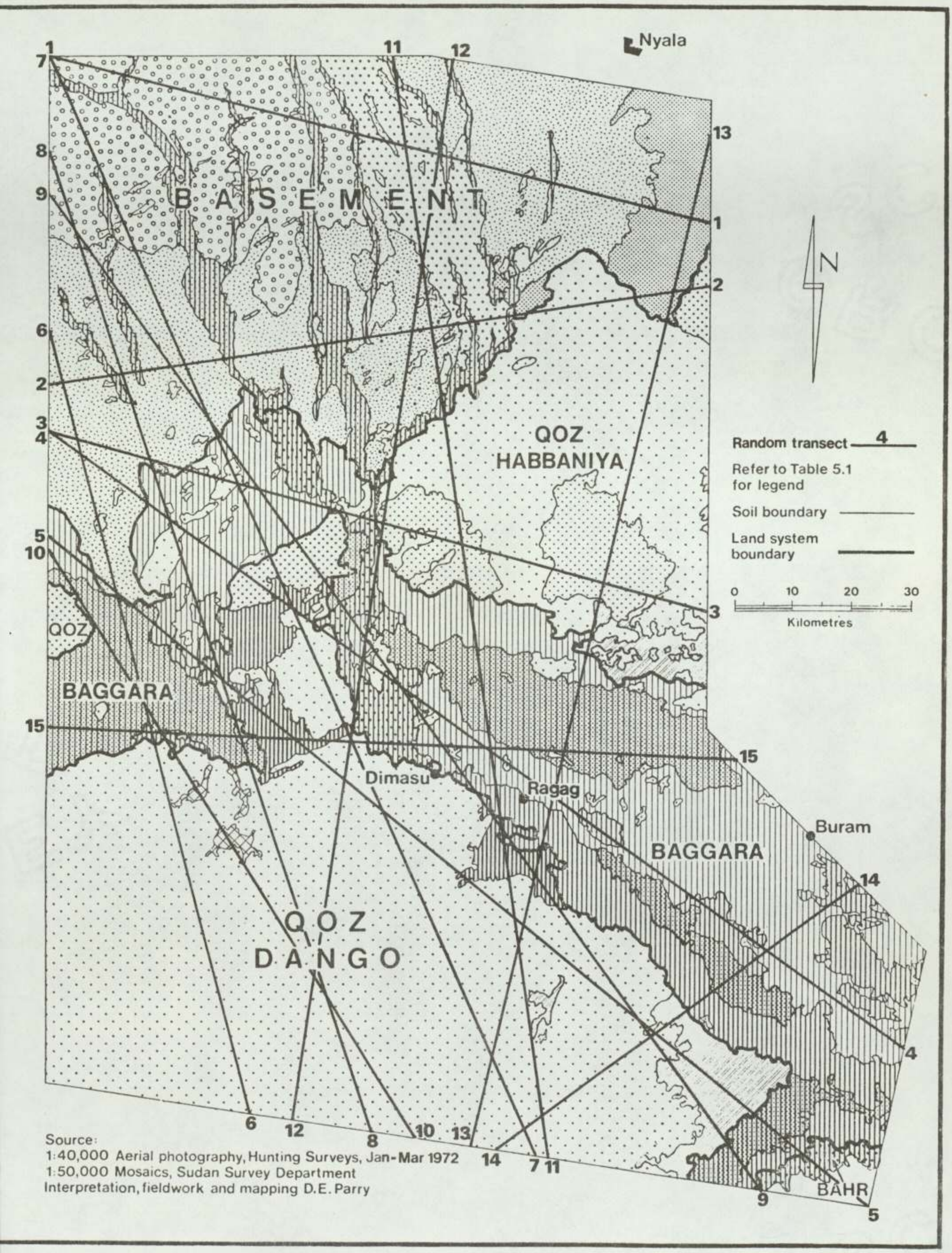
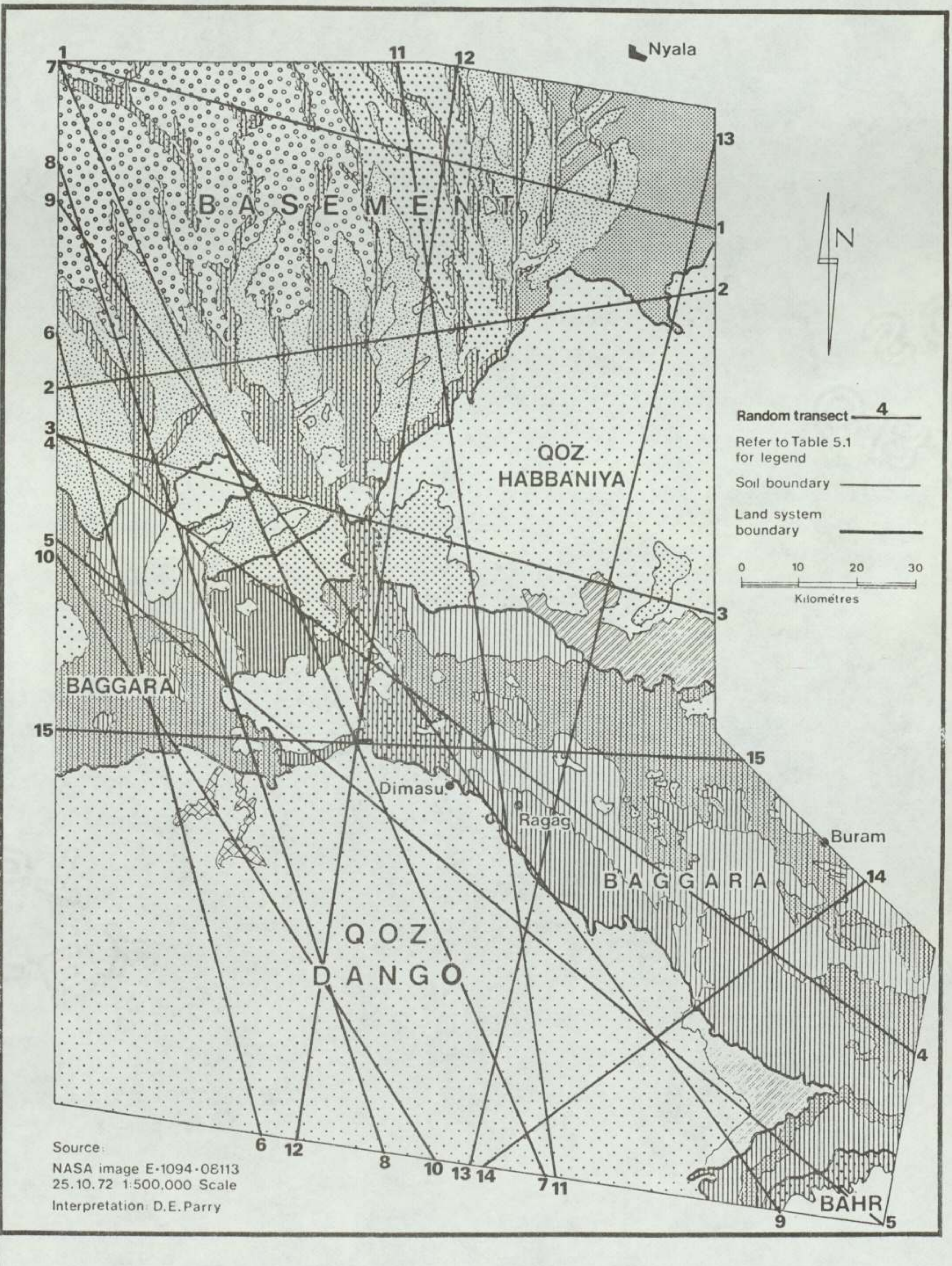


Figure 8.5
LANDSAT map: Random transects



In Figures 8.6 to 8.9 a range of hypothetical comparative map situations demonstrates the use of the method. The transect data and calculations for the fifteen randomly located transects used on the 1:500,000 scale copies of the 'standard' map and LANDSAT map, have been photographically reduced and are included in Appendix D. The boundary coincidence index (i) calculated for each of the 15 transects randomly located on the 1:500,000 scale LANDSAT map, is given in Table 8.2 with a descriptive rating alongside. The class intervals for these ratings are as follows:

Boundary Coincidence Index (i) Class Interval	Rating
1.0 - 0.09	Excellent
0.89 - 0.80	Very good
0.79 - 0.70	Good
0.69 - 0.60	Fair
0.59 - 0.50	Poor
>0.50	Very poor

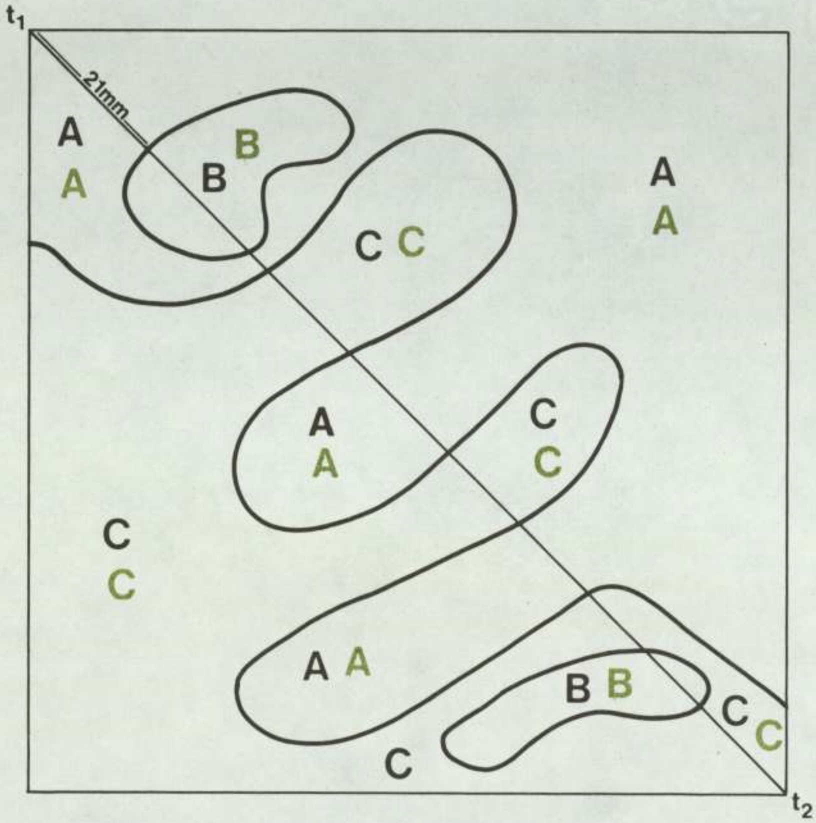
The indices clearly reflect the variations in the accuracy of the LANDSAT Soil map that the comparison of area measurements revealed. The index ranges from 0.45 (very poor) to 0.90 (excellent) and has a mean value of 0.69 (fair) +/-0.12.

To test further the sensitivity of this comparative method of measuring map accuracy, a sub-sample was selected from within an area of obvious soil boundary discrepancy and the coincidence indices calculated. The southern part of the Baggara land system illustrated in Figure 8.2 was chosen.

Using a table of random numbers and millimetre squared graph paper, 15 transects were plotted at random onto a transparent overlay and superimposed on part of the 'standard' map Baggara land system. An identical set of transects was superimposed on the LANDSAT map Baggara land system (Figures 8.10 and 8.11). The boundary coincidence index (i) for each transect was calculated in the manner described above. A summary of the results is shown in Table 8.3 and details of the transect calculations are included in Appendix D.

The value for i had a wide range of between 0.26 (very poor) and 0.87 (very good) and a mean value of 0.59 (poor) +/-0.21. Eight of the fifteen transects have a rating of very poor or poor (i.e. 0.59 or less). These values for i confirm the overall visual impression of a low degree of boundary coincidence in this part of the Baggara land system that is given by the sieve map, Figure 8.2.

Figure 8.6
Boundary coincidence. Perfect match



traverse t: length $t_1 - t_2$ = 140mm n_1=9 n_2=9

Standard map l_1 (Black)

t_1	A	B	A	C	A	C	A	C	B	C t_2
	21	19	4	15	18	13	13	10	11	16

Other map l_2 (Green)

t_1	A	B	A	C	A	C	A	C	B	C t_2
	21	19	4	15	18	13	13	10	11	16

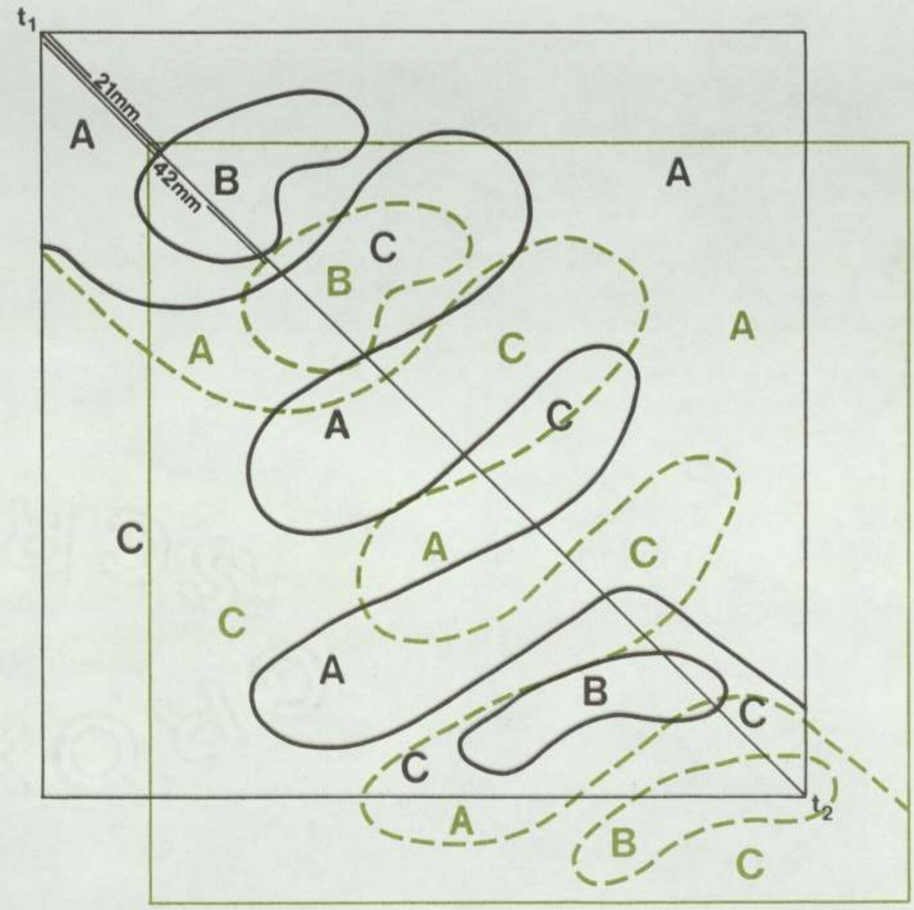
Standard map $l_1$mm		
A	B	C
21	19	15
4	11	13
18		10
13		16
Σ 56	30	54 = 140

Other map $l_2$mm		
A	B	C
21	19	15
4	11	13
18		10
13		16
Σ 56	30	54 = 140

	Σl_1	Σl_2	Σl_3
ΣA	56	56	56
ΣB	30	30	30
ΣC	54	54	54
	140	140	140

$$i = \frac{\Sigma l_3}{\Sigma l_1} \times \frac{n_2}{n_1} = \frac{140}{140} \times \frac{9}{9} = 1.0$$

Figure 8.7
Boundary coincidence. Regular displacement



traverse t: length $t_1 - t_2$ = 140mm

$n_1 = 9$ $n_2 = 8$

Standard map l_1 (Black)

t_1	A	B	A	C	A	C	A	C	B	C	t_2
	21	19	4	15	18	13	13	10	10	17	

Other map l_2 (Green)

t_1	A	B	A	C	A	C	A	C	B	t_2
	42	18	4	17	17	16	11	11	4	

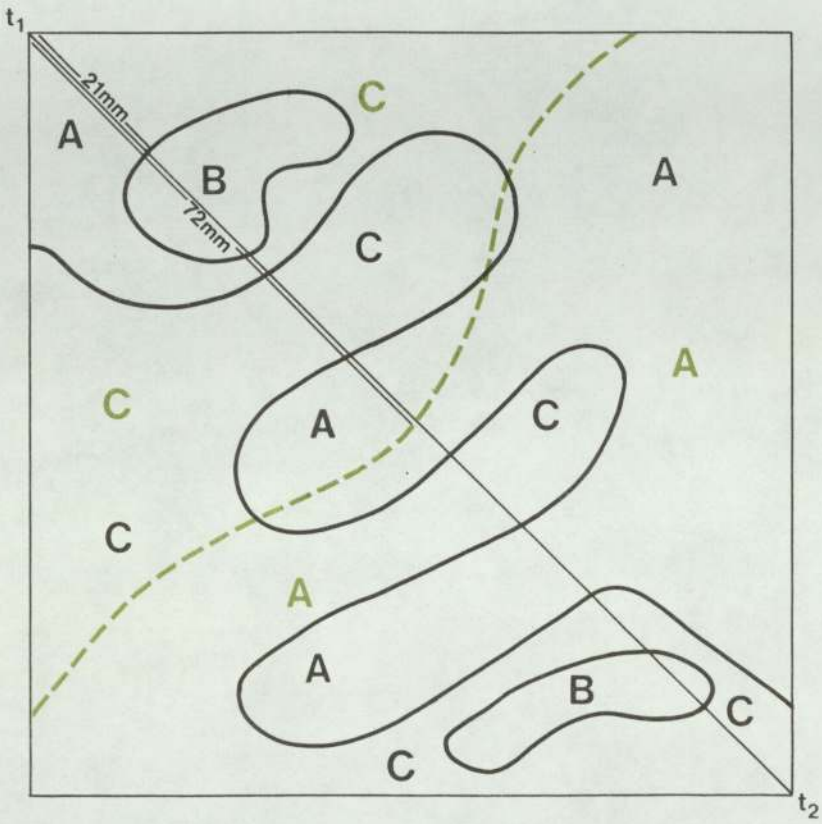
Standard map $l_1$mm			
A	B	C	
21	19	15	
4	10	13	
18		10	
13		17	
Σ 56	29	55	140

Other map $l_2$mm			
A	B	C	
42	18	17	
4	4	16	
17		11	
11			
Σ 74	22	44	140

	Σl_1	Σl_2	Σl_3
A	56	74	56
B	25	22	22
C	55	44	44
	140	140	122

$$i = \frac{\Sigma l_3}{\Sigma l_1} \times \frac{n_2}{n_1} = \frac{122}{140} \times \frac{8}{9} = 0.77$$

Figure 8.8
Boundary coincidence. Extreme displacement



traverse t: length $t_1 - t_2 = 140$ mm $n_1 = 9$ $n_2 = 1$

Standard map l_1 (Black)

t_1	A	B	A	C	A	C	A	C	B	C	t_2
	21	19	4	15	18	13	13	10	11	16	

Other map l_2 (Green)

t_1	C	A	t_2
	72	68	

Standard map l_1 mm

	A	B	C
	21	19	15
	4	11	13
	18		10
	13		16
Σ	56	30	54 = 140

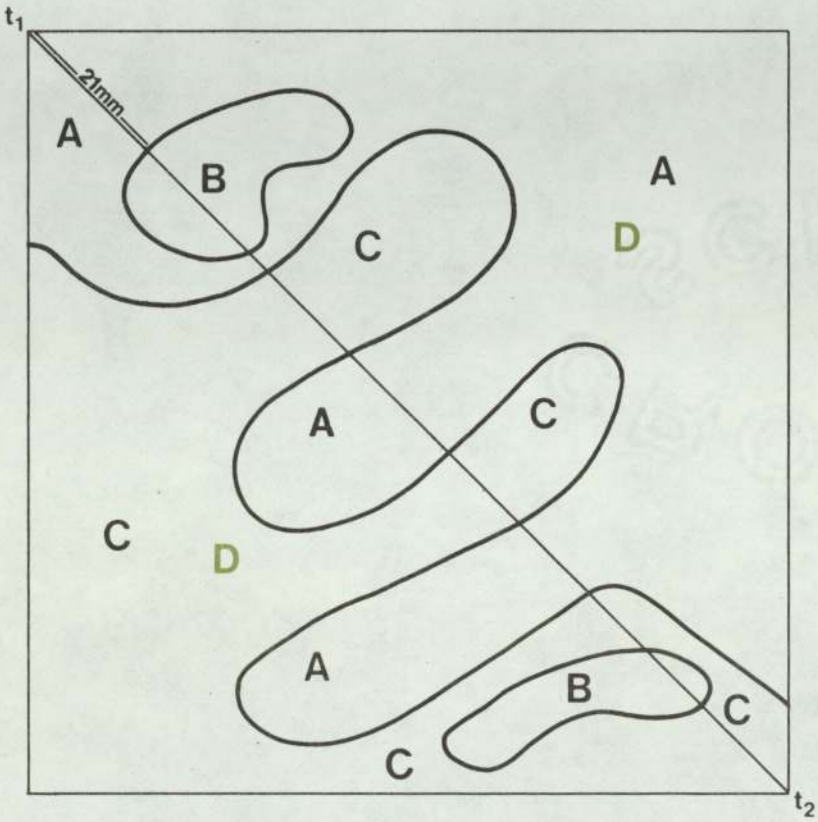
Other map l_2 mm

	A	B	C
	68	0	72
Σ	68	0	72 = 140

	Σl_1	Σl_2	Σl_3
A	56	68	56
B	30	0	0
C	54	72	54
	140	140	110

$$i = \frac{\Sigma l_3}{\Sigma l_1} \times \frac{n_2}{n_1} = \frac{110}{140} \times \frac{1}{9} = 0.09$$

Figure 8.9
Boundary coincidence. Perfect mismatch



traverse t: length $t_1 - t_2$ = 140mm $n_1 = 9$ $n_2 = 0$

Standard map l_1 (Black)

t_1	A	B	A	C	A	C	A	C	B	C t_2
	21	19	4	15	18	13	13	10	11	16

Other map l_2 (Green)

t_1	D	t_2
	140	

Standard map $l_1$mm		
A	B	C
21	19	15
4	11	13
18		10
13		16
Σ 56	30	54 = 140

Other map $l_2$mm
D
140
Σ 140

	Σl_1	Σl_2	Σl_3
A	56	0	0
B	30	0	0
C	54	0	0
D	0	140	0
	140	140	0

$$i = \frac{\Sigma l_3}{\Sigma l_1} \times \frac{n_2}{n_1} = \frac{0}{140} \times \frac{0}{9} = 0$$

Figure 8.10 Random transects across soil units in part of Baggara land system (Standard map)

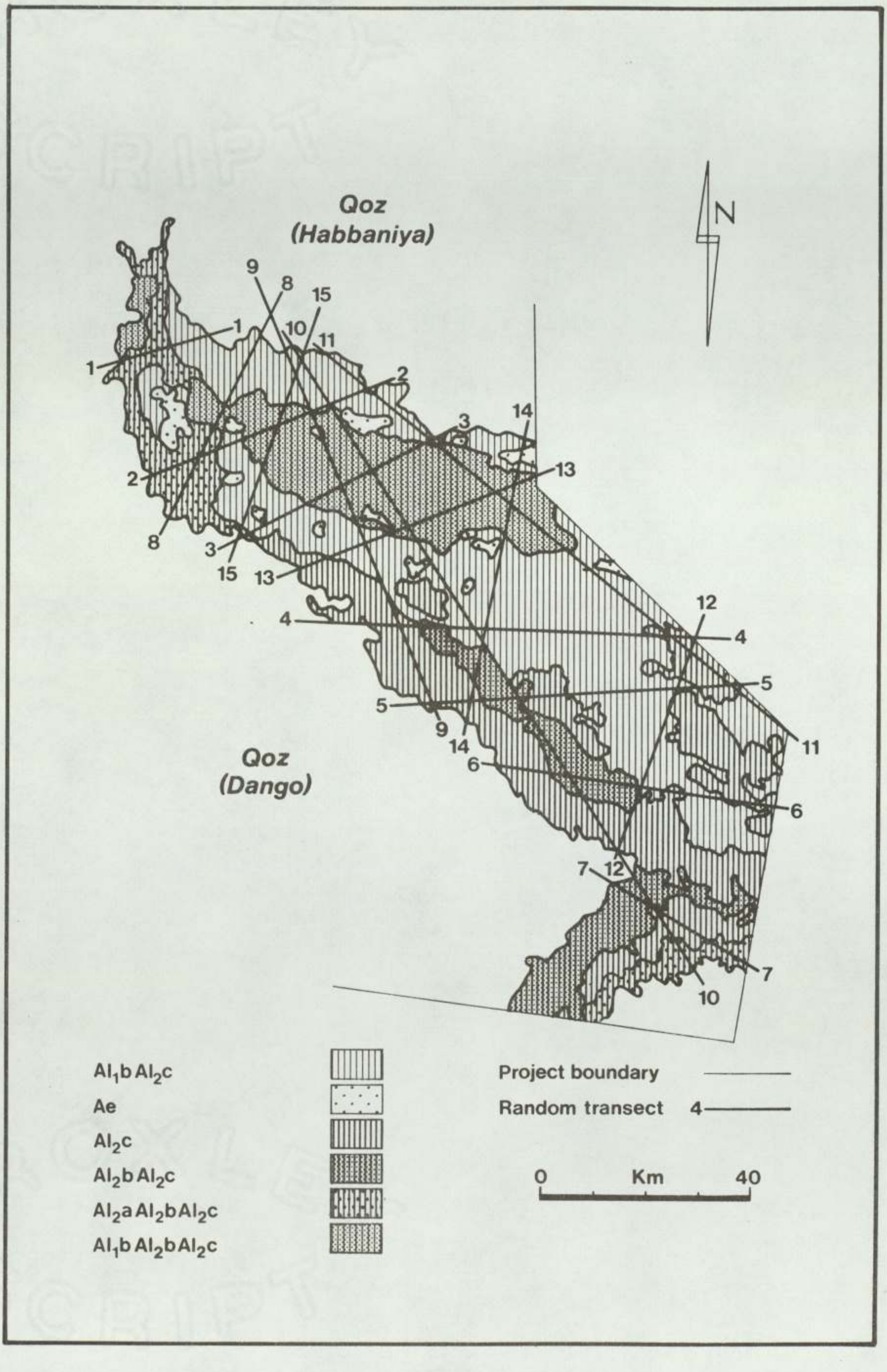


Figure 8.11 Random transects across soil units in part of Baggara land system (LANDSAT map)

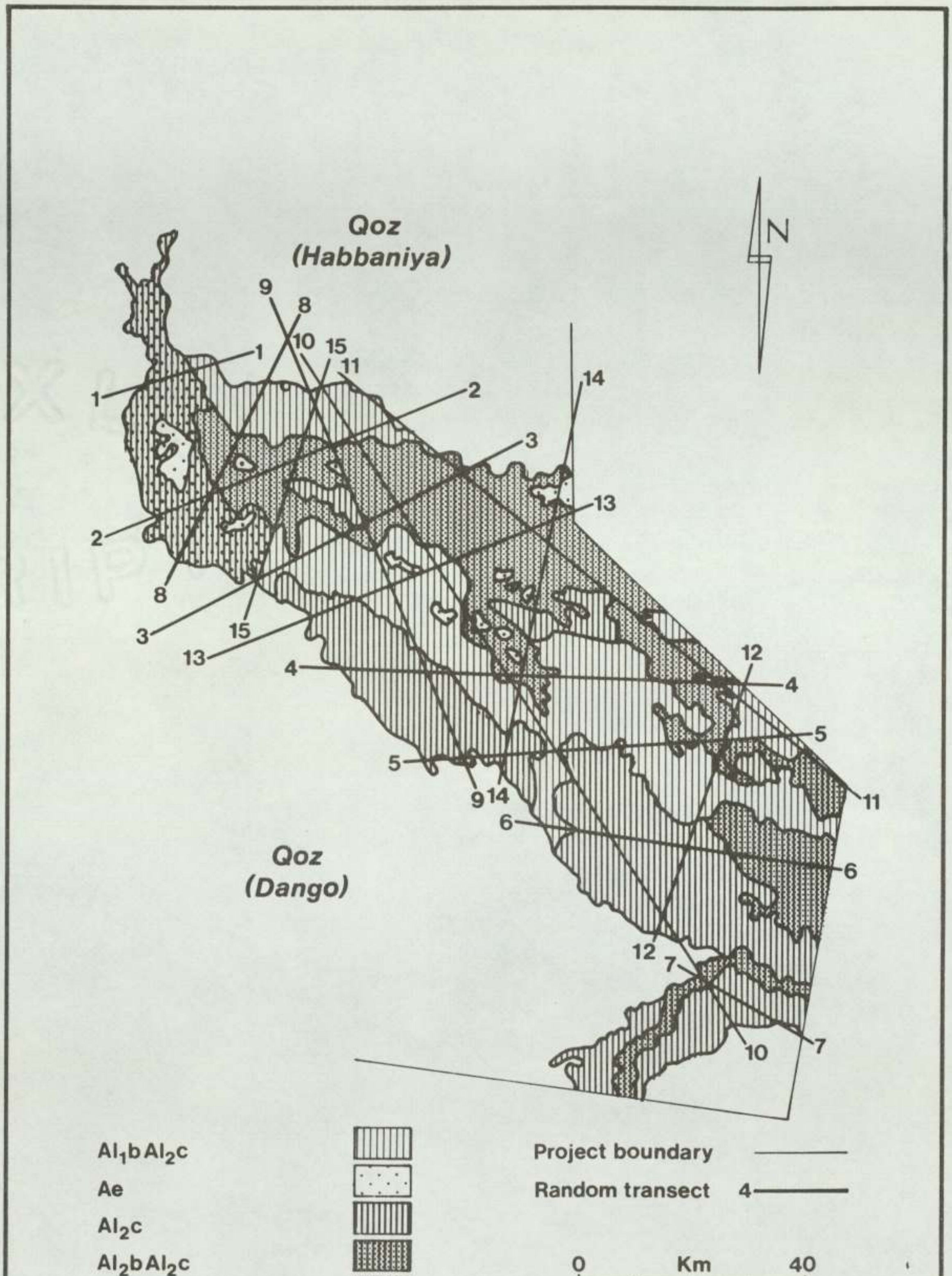


TABLE 8.2 BOUNDARY COINCIDENCE INDEX FOR SOIL UNITS ON LANDSAT MAP: TOTAL AREA

Transect number	No. bisects n_1	No. Bisects n_2	$\Sigma 1_1$ km	$\Sigma 1_3$ km	Coincidence Index i	Rating
1	17	27	110.5	79.5	0.45	Very poor
2	18	19	111.0	90.5	0.77	Good
3	19	14	115.0	88.5	0.57	Poor
4	24	24	176.0	139.5	0.79	Good
5	15	14	167.0	124.0	0.69	Fair
6	5	5	135.0	122.0	0.90	Excellent
7	15	11	202.5	179.5	0.65	Fair
8	12	13	174.0	135.5	0.72	Good
9	27	27	206.0	140.5	0.68	Fair
10	9	5	118.0	101.5	0.48	Very poor
11	17	14	188.0	160.0	0.70	Good
12	20	18	181.0	160.0	0.80	Very good
13	14	12	173.5	146.5	0.72	Good
14	7	6	76.0	62.5	0.70	Good
15	14	12	115.0	85.0	0.63	Fair

Mean value	**0.68**
Standard deviation	**+/-0.12**

On balance, the index for boundary coincidence provides an approximate measure of boundary similarity between two maps. The method takes into account additional or omitted mapping units and is sensitive to major boundary distortions in similarly classified units of equal area and with an equal number of bisects, as the hypothetical example in Figure 8.12 demonstrates. However, the index (i) cannot be converted into a valid linear measure of boundary coincidence as it is possible to do by calculating the boundary deviation. Nonetheless, analysis of the transect data does provide valuable linear quantitative data on comparative map accuracies on a discrete basis.

8.5 CONCLUSIONS

Each of the three methods used in the present study to compare boundary similarity or coincidence between two maps have their strengths and weaknesses. It is unlikely that any one method will prove entirely satisfactory for a comparative study and a combination of methods would be preferable.

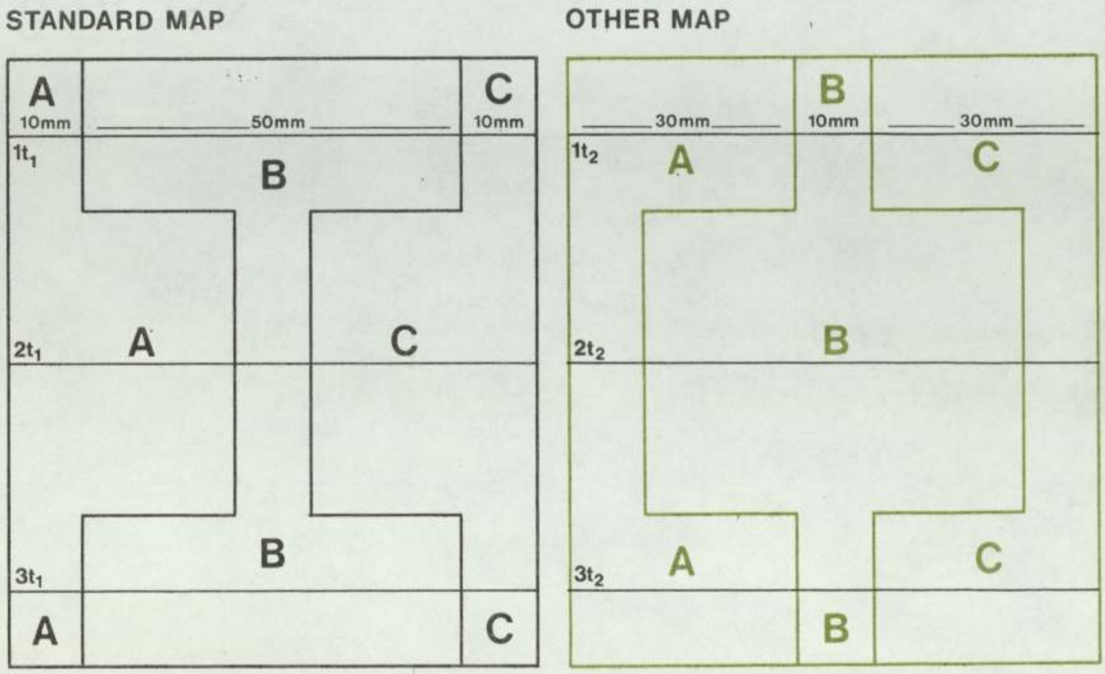
The sieve map has much to commend it when a rapid non-quantitative appraisal is required of maps with a small number of units. The method is simple to execute and clearly identifies those areas where boundary agreement is particularly good or particularly bad. If quantification is required, the method of calculating the average linear deviation of a thematic boundary on the other map, with its equivalent boundary of the 'standard' map, can be used. However, the compilation of a sieve map is a prerequisite for this method. The technique has the advantage over sieve mapping *per se* of providing a measure of average boundary deviation in kilometres or metres although it can only be usefully applied on a relatively simple map.

When boundaries on complex maps, such as those compiled in the present study, are compared, the calculation of the boundary coincidence index provides a reasonable means of assessing boundary similarity. The index is sensitive to differences in the shape of a boundary, the area it encompasses and the inclusion or omission of mapping units on one of the maps being compared.

TABLE 8.3 BOUNDARY COINCIDENCE INDEX: SOIL UNITS IN PART OF BAGGARA LAND SYSTEM

Transect No.	n_1	n_2	$\Sigma 1_1$ km	$\Sigma 1_3$ km	Coincidence Index i	Rating
1	1	1	16	13	0.81	Very good
2	4	2	40	37	0.69	Fair
3	3	3	37	29	0.78	Good
4	3	5	56	46	0.49	Very poor
5	5	11	54	46	0.43	Very poor
6	5	2	48	40	0.33	Very poor
7	2	2	27	15	0.28	Very poor
8	3	2	37	28	0.76	Good
9	5	5	67	58	0.87	Very good
10	12	8	128	95	0.49	Very poor
11	8	8	104	64	0.62	Fair
12	5	5	38	22	0.58	Poor
13	2	2	44	38	0.86	Very good
14	6	6	50	27	0.54	Poor
15	3	6	34	18	0.26	Very poor
					Mean 0.59 +/-0.21	

Figure 8.12
Equal area, equal bisects, different boundary shape



Transects t	Standard Map			Other Map			$l_3$mm
	n_1	mapping units	$l_1$mm	n_2	mapping units	$l_2$mm	
1	2	A	10	2	A	30	10
		B	50		B	10	10
		C	10		C	30	10
			Σ70			Σ70	Σ30
2	2	A	30	2	A	10	10
		B	10		B	50	10
		C	30		C	10	10
			Σ70			Σ70	Σ30
3	2	A	10	2	A	30	10
		B	50		B	10	10
		C	10		C	30	10
			Σ70			Σ70	Σ30

1 $\quad i = \frac{\Sigma l_3}{\Sigma l_1} \times \frac{n_2}{n_1} = \frac{30}{70} \times \frac{2}{2} = 0.43$

2 $\quad i = \quad " \quad = \frac{30}{70} \times \frac{2}{2} = 0.43$

3 $\quad i = \quad " \quad = \frac{30}{70} \times \frac{2}{2} = 0.43$

CHAPTER 9

INTERPRETATION AND MAPPING EASTERN DISTRICT (AREA B)

9.1 INTRODUCTION

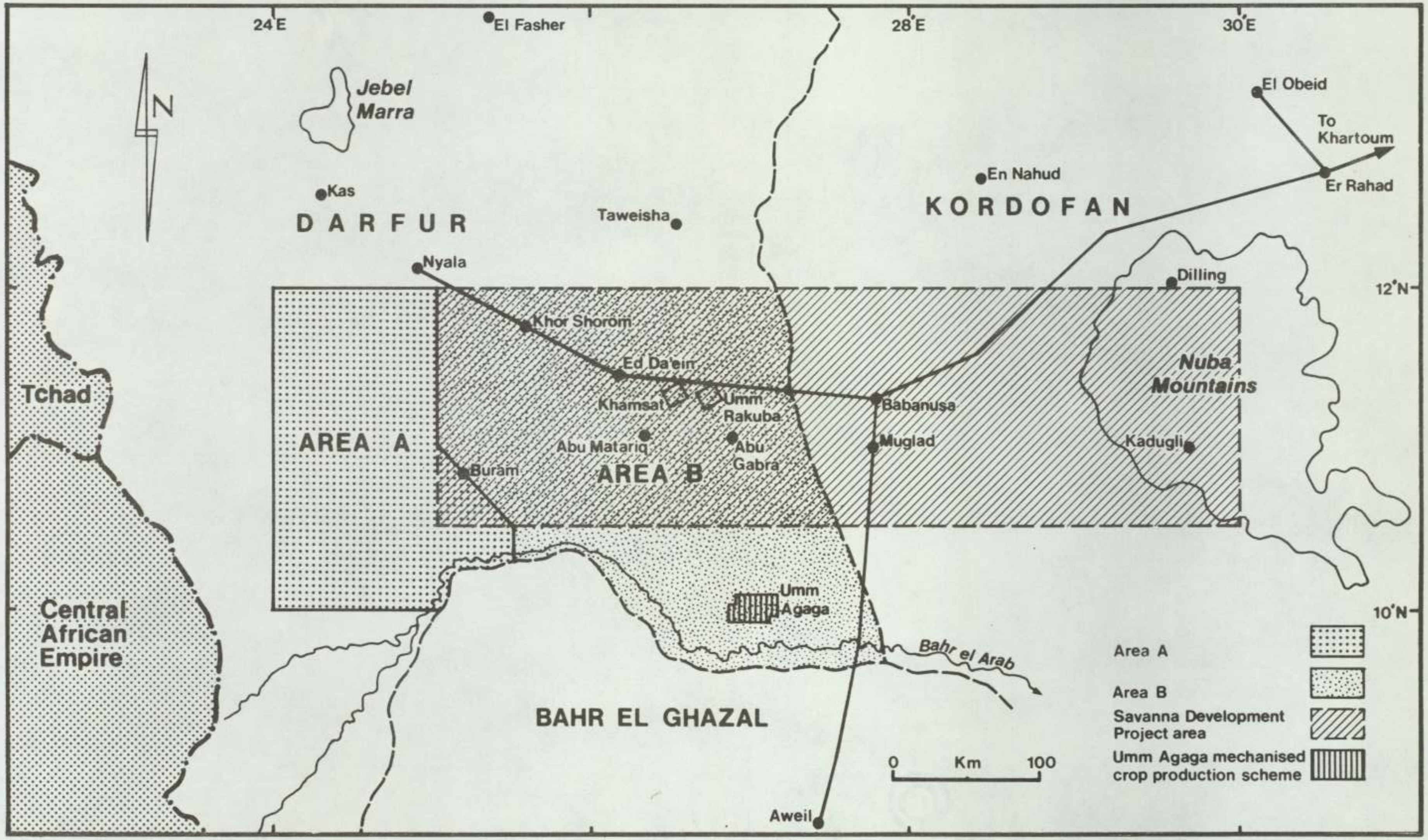
In the previous chapters the accuracy of a land systems, soil and geomorphology map of a part of Southern Darfur (Area A), derived from the manual interpretation of LANDSAT imagery, was compared in qualitative and quantitative terms with an equivalent 'standard' map of the area, derived from the interpretation of aerial photography and ground survey. The opportunity to use the LANDSAT imagery in the field, either to complement the more conventional aerial photography or as a possible alternative, did not arise in the Southern District survey (Area A) because satellite imagery of the area was not available at the time. However, with the inception of the adjacent Eastern District survey (Area B), the opportunity presented itself of testing, in a project situation, the viability of using manually interpreted LANDSAT imagery as a topographic and thematic map base for reconnaissance scale resource mapping. This chapter reviews the background to that study, the methods adopted and results achieved. It is not a comparative study as there were no reliable thematic maps of Area B at a comparable scale with which to make comparisons.

9.2 PHASE 1 STUDY

In 1971 the Food and Agricultural Organisation (F.A.O.) of the United Nations began Phase 1 of the Savanna Development Study, a large resource survey which covered that part of Eastern District (Area B) north of latitude 10°N and most of South Kordofan Province (the latter being excluded from the present study). Panchromatic aerial photography at 1:40,000 scale and mosaics of 1:50,000 scale were available for the area north of latitude 10°30'N but not for the southern region of Area B (Figure 9.1). F.A.O. proposed to assess the usefulness of LANDSAT 1 imagery for integrated resource survey in the area covered by the Savanna Development Project.

The Phase I soil and geomorphological study (Gaddas, 1973) covered that part of the Eastern District Council (Area B) north of latitude 10°30'N, and was essentially a photo-interpretation exercise. Specific information on soil types and properties was lacking and terminology on the map legends confusing. Due to distortions in the mosaics the maps, compiled from 1:50,000 mosaics and reduced to 1:250,000 scale by pantograph, provided a very poor topographical base for thematic mapping.

Figure 9.1 Location diagram Area B



Six one to a million scale monochrome diapositives of LANDSAT frames covering part of the area but excluding Area B, were initially interpreted in Khartoum by Eggeling and Gaddas (1973). Cloud free imagery, in the form of monochrome diapositives in all four MSS bands of the whole area at one to one million scale was subsequently evaluated by Mitchell (1973 and 1975). Despite the very limited ground control available, the lack of colour composite imagery and the short duration of both these studies, Mitchell (op. cit.) believed that the imagery would be valuable for correcting and updating topographic maps for broad scale geological and land systems mapping and for monitoring changes in drainage networks.

9.3 PHASE II STUDY

Manpower and other logistical problems prevented the collection of field data and the completion of the resources survey and LANDSAT evaluation in Eastern District by F.A.O. In 1974 Hunting Technical Services Limited were appointed sub-contractors to F.A.O. to complete the survey, including the LANDSAT evaluation, and compile an integrated development plan for the District. Thus, at the beginning of the Project the survey team were faced with a resource mapping problem that is depressingly common in the developing countries of the Third World; the resources of a large, remote and relatively unknown area have to be mapped and a report compiled within a very short time span (in the present case one year) in the face of a formidable array of logistical and technical constraints. In the present study it was the technical constraints which presented the greatest problems. These were:

(i) The photo-interpreted soil and geomorphology maps compiled by F.A.O. during the first phase of the study only covered part of the area and were subject to gross errors due to serious distortions in the original mosaics.

(ii) The 1:250,000 scale topographic maps covering the area and produced by the Sudan Survey Department were outdated and contained insufficient detail to serve as an adequate mapping base. In some cases they were also grossly inaccurate. Analysis of LANDSAT imagery of the area and subsequent ground checking confirmed that on the topographic map the administrative centre of Abu Matariq was placed 12 km to the west of its true position.

(iii) There was no aerial photographic cover for the region below latitude 10°30′N.

(iv) No satellite imagery of Eastern District (Area B) had been interpreted and field checked.

These constraints, particularly the lack of a suitable base map or the means of acquiring one in the allotted time using conventional techniques, meant that a new base map had to be compiled using LANDSAT imagery, the only alternative available. The base map was compiled from 1:500,000 scale LANDSAT 1 colour composite imagery and then photographically enlarged to 1:250,000 scale by the Sudan Printing Office. Thematic detail was interpreted from 1:250,000 scale colour composite enlargements. The latter were acquired some months after the smaller scale imagery.

9.4 INTERPRETATION AND MAPPING FROM LANDSAT IMAGERY

As previously stated (Section 5.2.1), the interpretation of satellite imagery for resource mapping by manual methods is essentially an extension of the conventional techniques of aerial photographic interpretation. The scale differences between an aerial photograph and a satellite image pose an initial adjustment problem of perspective for the interpreter. In the present study topographic features, land system and soil boundaries were initially interpreted from 1:500,000 scale colour composite images and drawn onto clear Melanex plastic overlays. This preliminary interpretation formed the basis for subsequent field checking and sampling.

At the outset of the study it was readily apparent that the use of low resolution NASA bulk processed imagery, combined with the poor image registration between MSS bands on some frames covering the Study Area, posed several locational problems for topographic and thematic mapping. The lack of time and funds precluded computer enhanced LANDSAT imagery of the area, with its greater data content and higher resolution, being used to provide a mapping base. The maps had to be compiled from data currently available in the Sudan.

For the purposes of a reconnaissance survey, the Universal Transverse Mercator (UTM) grid superimposed on the LANDSAT images by NASA, was considered an adequate base on which to plot directly topographic and thematic detail derived from the interpretation and field checking of the near orthographic images. With satellite imagery, a relatively new source of data that presents the resource scientists with a unique perspective of the earth's surface, the value of ground checking interpreted phenomena cannot be over-emphasised. In a relatively unknown area such as Southern Darfur, field checking occupied at least 80 per cent of the study time.

In any mapping exercise that uses remotely sensed imagery, the ability to locate on the ground those features identified on the imagery is essential. In Area B a number of widely spaced features with distinctive LANDSAT image characteristics or 'signatures' were selected during the preliminary interpretation phase. These provided a framework of reference points for the compilation of the base map and the thematic maps. The features were then located on the ground, where possible, and described in detail.

In the northern part of Area B, the Nyala-Khartoum railway line, the stations, the surrounding areas of cultivated land, and the aureoles of overgrazed land around boreholes in the Qoz (Ma'aliya), have very distinctive signatures on the LANDSAT imagery (Figure 9.2). These features were easily located on the ground and formed the framework for topographic and thematic mapping in this northern area. In the southern part of Area B, pattern complexity and low image contrast made the location of interpreted features more difficult, although the larger regebas (broad, shallow meanders) and the mechanised crop production scheme at Umm Agaga (for which a soils map, prepared by the Soil Survey Administration, Wad Medani, was available) provided suitable starting points (Figure 9.3). The lack of aerial photography as an aid to navigation and ground location was a further constraint.

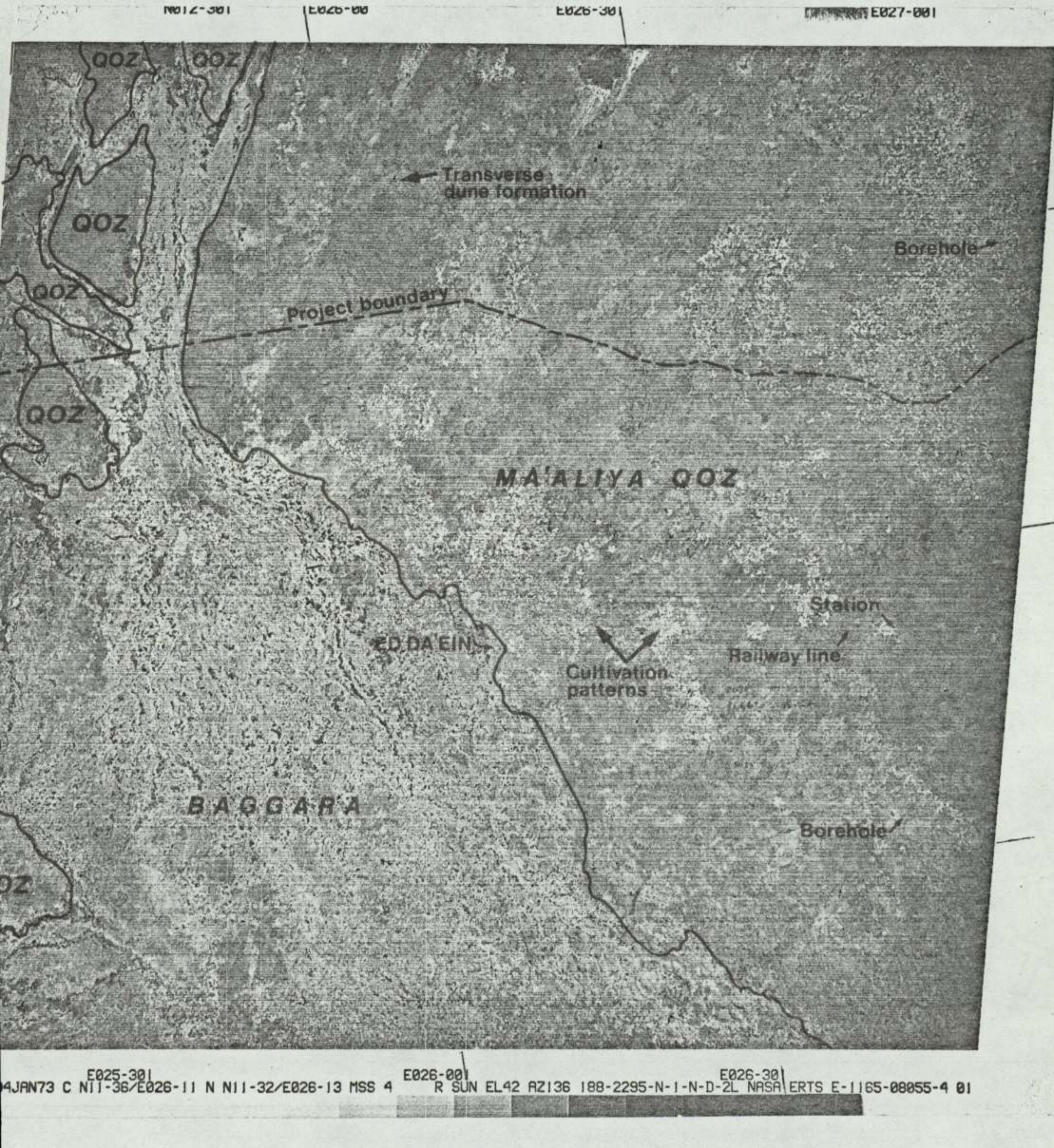
It is impractical to lay down hard and fast rules for the interpretation and subsequent field checking of LANDSAT imagery. Clearly, the ease with which each interpreted mapping unit or topographic feature is located on the ground will depend on a large number of variables, including the type and complexity of the environment in terms of such image characteristics as resolution and contrast. However, based on the experience gained in Area B the following general conclusions were drawn:

(a) Boundaries that contained an easily identifiable irregularity or were near a topographical feature such as a hill, meander or borehole were generally easy to plot on the image and locate on the ground.

(b) The boundaries of mapping units with high contrast were readily located on the ground because the differences in image contrast were usually related to marked differences in soil, geology, geomorphology, vegetation or land use.

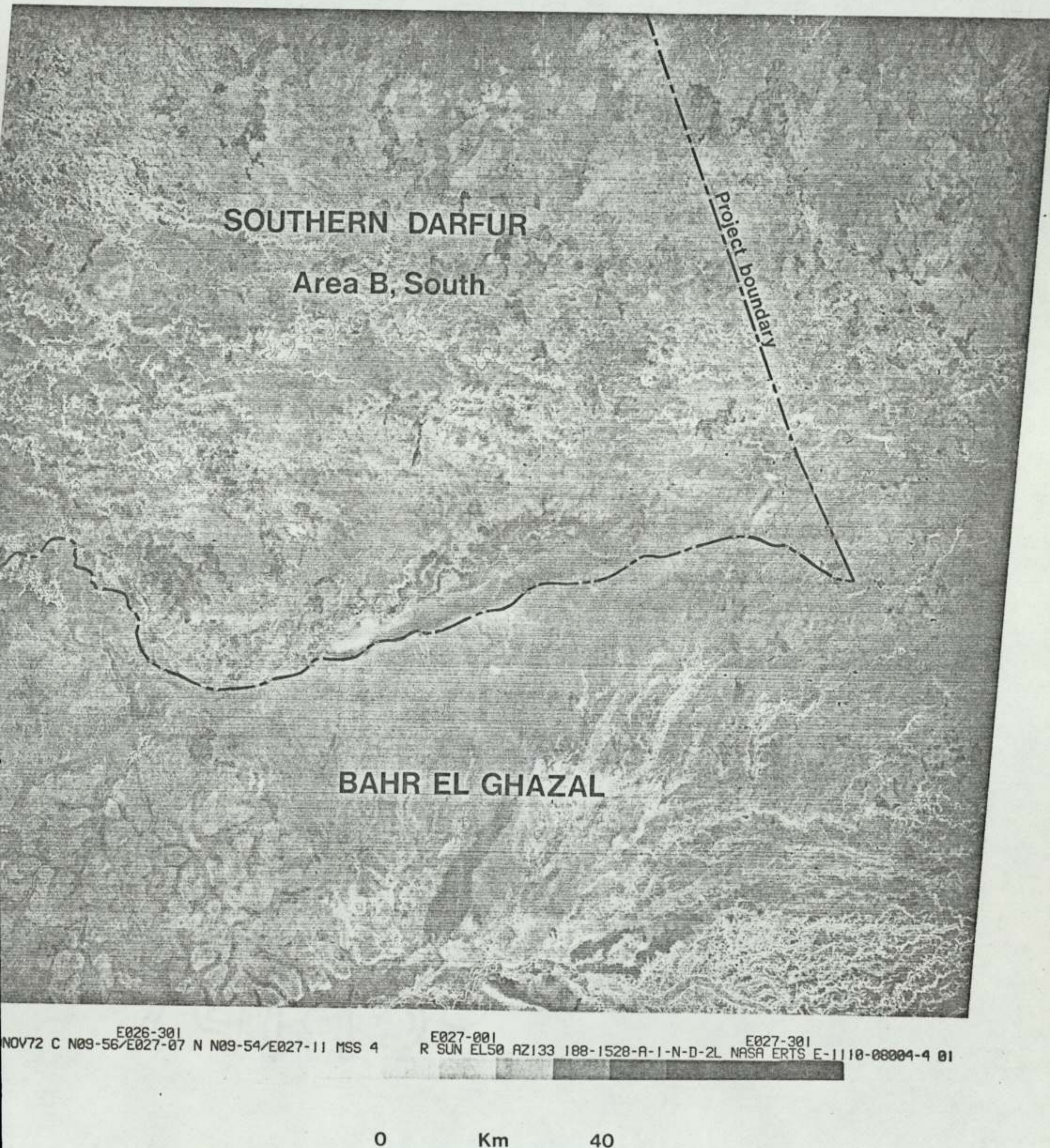
(c) Natural resource boundaries and topographic features in the higher rainfall areas of Southern Darfur were more difficult to interpret and locate because of the lower contrast. This was caused for the most part by the increased

Figure 9.2 Eastern District (Area B, North). Land system boundaries on LANDSAT image



NOTE: The railway line is not visible in the Baggara land system on the 1:1million MSS 7 print. However, sections of it are clearly visible on the 1:250,000 scale colour composite image from which the original map was compiled

Figure 9.3 LANDSAT image (MSS 4) of part of Area B without air-photography cover



vegetative cover and the saturating effect the infra-red MSS band 7 has on the colour composite image.

(d) Ground location was extremely difficult in areas in which land use changes had occurred between the dates of image acquisition and field checking.

Once a feature on the LANDSAT image was positively identified on the ground, compass traverses were made from that point to other known points and topographic and thematic detail between the reference points collected. Traverses using a light aircraft were used to supplement information obtained on the ground. Details of these two traverse techniques are given in the following section.

9.5 RAPID RECONNAISSANCE GROUND AND AIR TRAVERSES

Compass traverses were made from known reference points along all major tracks in the Study Area using four-wheel drive vehicles. During these traverses information on all aspects of the physical environment was recorded on miniature tape recorders and changes noted to the nearest one tenth of a kilometre. Detailed site descriptions were also carried out along traverses at the discretion of the field scientist. Field notes were written up together with compass headings and distances and the data plotted onto clear Melanex overlays. In this manner an index was acquired of the image characteristics of the various resource and topographic features. Where reference points were widely spaced the inherent inaccuracy of a method based on car compass headings and speedometer/odometer distance readings became apparent. In these instances plotting was resumed from another reference point, or series of points, surrounding the area of uncertainty in an attempt to provide corroborative data. The method is thus basically one of narrowing down the magnitude of plotting error between known reference points.

Three aerial reconnaissance flights were made in a light high-wing aircraft, to check and refine map detail and observe the few areas which were inaccessible on the ground. The method entailed flying on fixed headings, predetermined to cross resource features of particular interest, at as constant an air-speed as possible. Using a stop watch and tape recorder, timed observations were made by the observer as the aircraft passed over a particular feature. In addition, easily recognisable features such as large channels or the railway line were frequently followed and a number of offsets made at intervals on an *ad hoc* basis. The data on the tape recorders were later correlated with the LANDSAT image characteristics and plotted onto Melanex clear overlays in the manner described for the transference of data from the ground traverses.

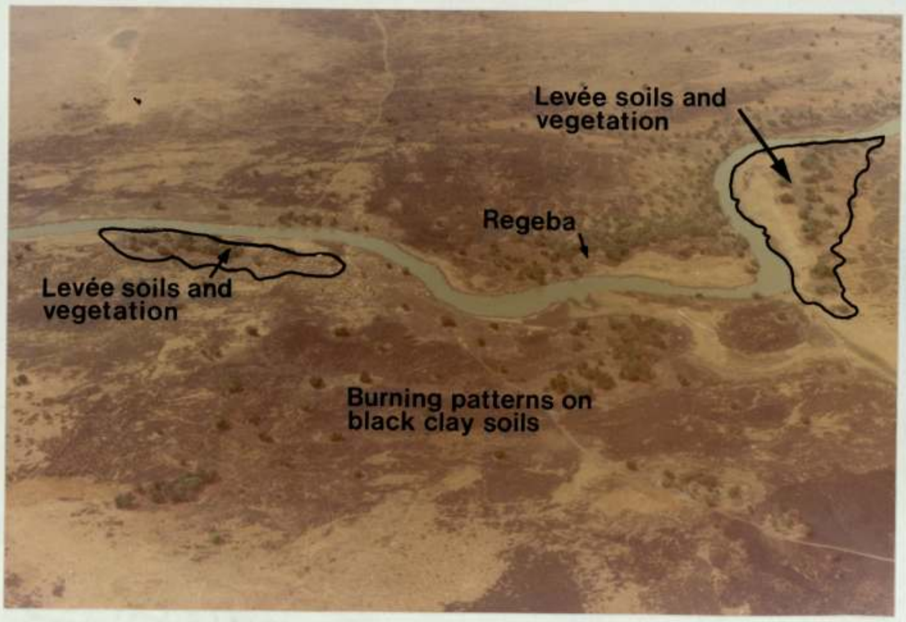
Clearly, the accuracy of a method is highly suspect, which relies on the constant air-speed of a light aircraft in an environment subject to considerable clear air turbulence and as a total mapping method its inherent errors are intolerable even by reconnaissance standards. However, as a supplement to ground derived information and the identification of features with distinct characteristics on the satellite image, the method proved to be of immense value in constructing the topographic base map and in identifying some vegetation and soil units. It was particularly useful for locating wateryards in areas of broad-leaved savanna woodland or thorn woodland, where the lack of an adequate track network made ground location extremely difficult and time consuming. The final soil, geomorphology and land system maps of Area B were compiled from the interpretation of 1:250,000 colour composite imagery and ground checked using these rapid traverse techniques.

9.6 THEMATIC MAPPING

Field checking of the land system, soils and geomorphology boundaries identified on the LANDSAT imagery during the preliminary interpretation phase was carried out over the 57,500 km^2 of Area B between February and June 1975. As in Area A, ground traverses were completed along all major tracks and at the discretion of the field scientist offsets made on compass bearings to ensure as complete a coverage of soils and landforms as time would permit. A total of 300 soil bores and geomorphological site descriptions and 25 soil pits were examined in detail to depths of 150 cm and 200 cm respectively and are described in the relevant report (Hunting Technical Services, 1976a). Information on all aspects of the physical environment between detailed observation sites, was recorded on tape and compiled in field notebooks. An extract from a field notebook of a traverse along the railway line between Nyala and Khor Shorom (Figure 9.1) is given in Table 9.1. These data were invaluable for plotting each traverse onto the relevant LANDSAT image and enabled a list of the image characteristics for various resource features to be compiled. The variability in image processing and different dates of the five LANDSAT images covering Area B occasionally meant that the same feature had a variety of colours.

In addition to ground traverses, three aerial reconnaissance flights were made in a Cessna 185 light aircraft to check map boundaries and refine map detail by the method described in Section 9.5. Oblique 35 mm colour aerial photographs were also taken as an aid to the identification of complex resource features, particularly channel patterns, on the satellite imagery, and their subsequent location on the ground. A selection of annotated 35 mm colour aerial photographs taken over the Regeba and Qoz land systems are shown in Figures 9.4a and 9.4b.

Figure 9.4a
Area B : Aerial reconnaissance photographs



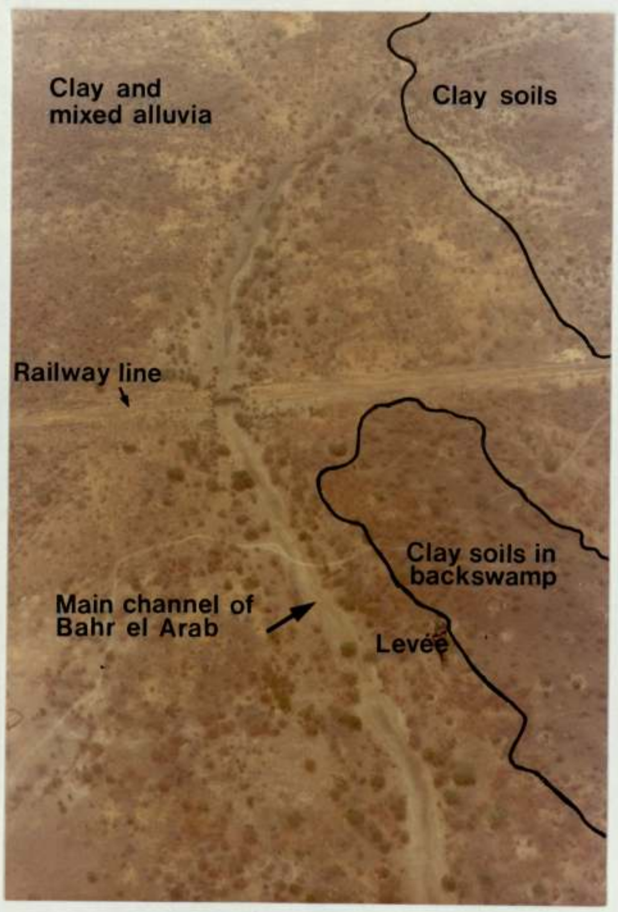
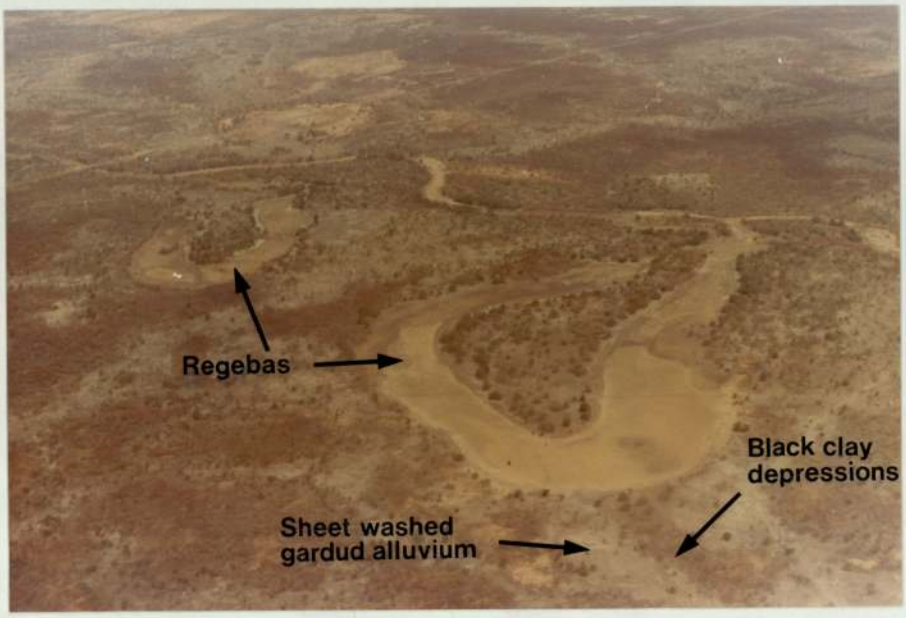


Figure 9.4b
Area B: Aerial reconnaissance photographs



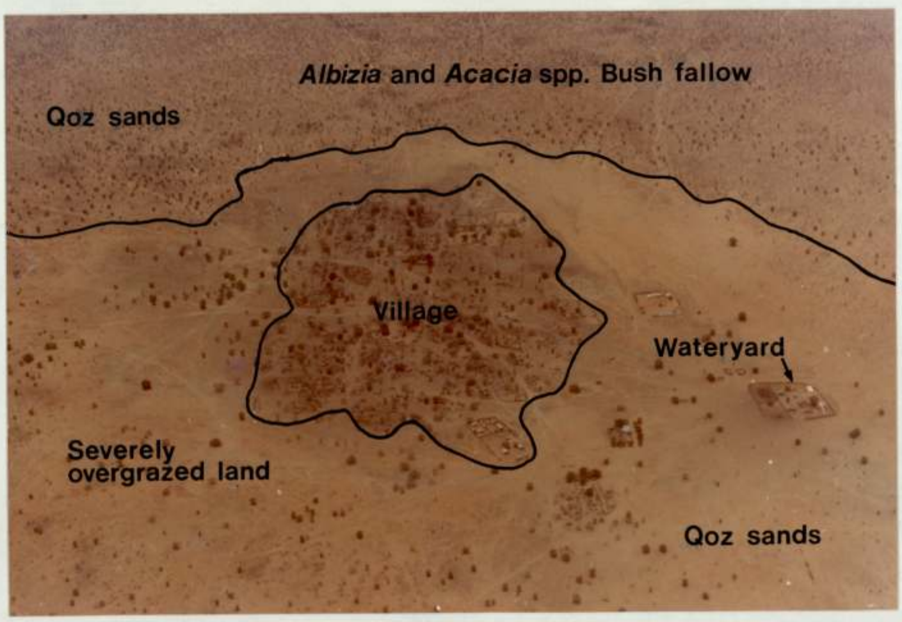
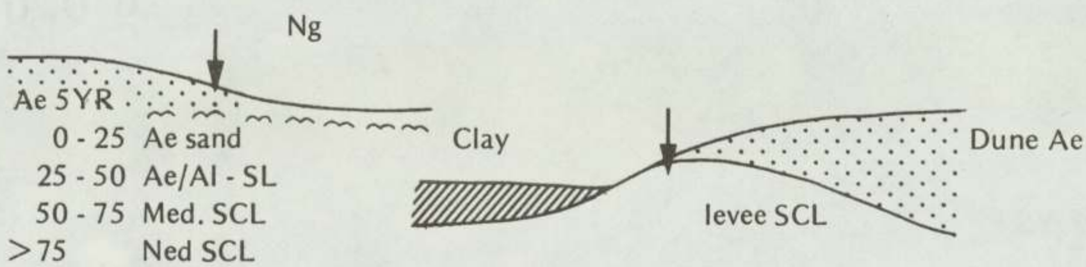


TABLE 9.1 EXTRACT FROM FIELD NOTEBOOK OF RAPID RECONNAISSANCE GROUND TRAVERSE BETWEEN NYALA AND KHOR SHOROM

TRAVERSE: **Nyala - Tor Taan - Khor Shorom** **Date: 21.6.75**

km	Description
872	1,318 km post Nyala stn. - S.E. along rly line - Wadi Nyala alluvium-scatt. Dom palm, *Balanites* (Bal), *Ziziphus* (Zi) + cultn.
873	Light brown silty and sandy stratified alluvium (al) Ng and At soils - open + cultn. and young Dom.
875	Open degraded dune-scatt. young Dom - poss. some old al - reflectance predom. from soil in seif and vegn. during Khareif.
876	Mod. dense *Ac. mellifera* in flower - quartz stones and gravel on surface - pediment/ pediplain - bs soils extensive unit.
890	Bileil stn. km post 1301 (dist. from Khartoum).
892	Ng soil with mod. dense *Ac. mell.* scrub - At soil.
893	Ng + coarse sand (cs) and gravel on surface.
898	SDR 287 - cs and gravel on surface + few quartz stones - open Naga'a patches with scatt. *Ac mell.* and *Ac. nilotica* - rare Boabab, *Ac. tortilis* and *Cordia ovalis* - area surrounded by mod. dense and dense *Ac. mell.* and scatt. *Capparis tormentosa* - some small *Ac. albida* and *Ac. senegal* - mixed floodplain al and colluvium - high cs and sand content over wadi channel al - sand sample taken from 125-150 cm - bs floodplain - open and dense patches.
905	*Ac. mell.* just before Jebel Umm Kardous Halt - km post 1282 - SDR 228 - cleared area surrounded by dense *Ac. mell.* Bt soil - 140 cm clay over sandy loam (sl).
906	Mod. dense and dense *Ac. mell.* and *Ac. nubica* scrub + open patches - floodplain.
909	*Ac. senegal, mell.* and *nubica.*
912	Swale parallel with railway line - *Anogeissus, Ac. seyal, Balanites, Ac. mell.* - mod. dense to dense - red brown soil surface typical of Naga'a - not pale brown of bs floodplain - open Ng + dense patches of *Ac. mell.* - good track on a s. side of railway.
914	Ng + Ngs - open and dense *Ac. mell.* and *Ac. nubica* assocn.
920	Tor Taan station - dune sand N of stn. + village cracking clay to S - mod. dense *Ac. mell.*
922	SDR 289 Ng soil - mod. dense *Ac. mell.* - mod. open - mod. dense + scatt. *Boscia senegalensis* and *Cadaba farinosa* - soil (Ng(m) - Ng (Hy) - non-micaceous - no mottling. Probe at base of dune.



km	Description
935	Khor Shorom stn.

SDR 289 Detailed soil bore description to 150 cm.

For the purposes of the present study the original maps, compiled at a scale of 1:250,000, have been photographically reduced to 1:500,000 scale and are included in Appendix E, Maps 7 and 8. Figures 9.5 and 9.6 in the text are 1:1,000,000 scale (approximately) reductions of the maps. This scale reduction meant that some simplification of the original maps and accompanying legend (Table 9.2) were necessary in these text figures to ensure clarity.

9.7 RESULTS AND CONCLUSIONS

Composite reconnaissance land system, soil and geomorphology maps covering 55,000 km^2 of a part of Southern Darfur Province, Sudan were compiled from the interpretation of LANDSAT imagery over a period of one year. The study area, Area B, was not covered by reliable topographic or thematic maps, and aerial photography was available for the northern part of the area only. In the absence of such data LANDSAT imagery, with its unique perspective and near orthographic properties, appeared to offer the only viable means of map compilation. The methods developed during the study for compiling the maps utilised the cheapest bulk processed imagery, and relied on manual methods of image interpretation followed by ground and air verification using a rapid reconnaissance traverse technique.

The accuracy of the final maps (Maps 7 and 8, Appendix E) cannot be quantified in the manner of the Southern District (Area A) maps, since no other thematic maps of the area exist at a suitable scale or degree of reliability. However, by using the experience gained in the comparative study in Area A, a region of marked ecological similarity, it is possible to draw some general conclusions regarding the accuracy and reliability of the Area B maps. All land system boundaries, with the exception of the one separating the Regeba and Baggara land systems, are clearly defined on the satellite imagery of Area B and are readily linked with their counterparts in Area A. It is therefore reasonable to assume that the overall accuracy of land system boundaries in Area B is commensurate with the accuracy of the similarly derived land system boundaries in the adjacent Area A (+/- 5 per cent).

The accuracy of land system boundary location can be tested along the boundary separating Areas A and B by calculating the coincidence index (i) using the total length of the boundary as a transect. The calculation, shown in Table 9.3(a) gives an index (i) of 0.62 (fair), a much lower index than expected. However, this is caused by the omission of the Regeba land system in Area A and its inclusion in area B, thus affecting the number of transect bisects.

Figure 9.5 Eastern District (Area B, West).
Soils and land systems. LANDSAT interpretation

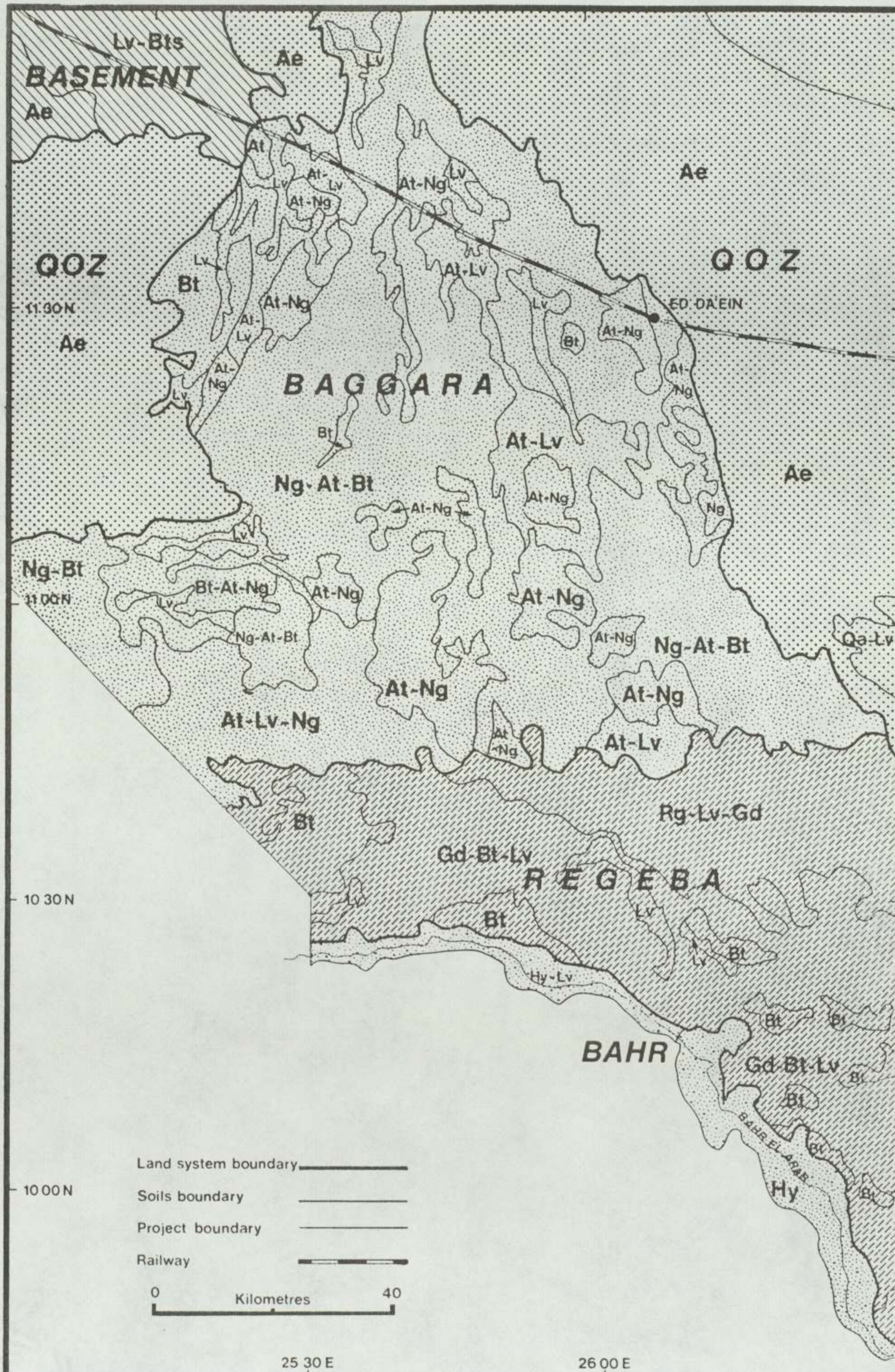


Figure 9.6 Eastern District. (Area B, East). Soils and land systems. LANDSAT interpretation

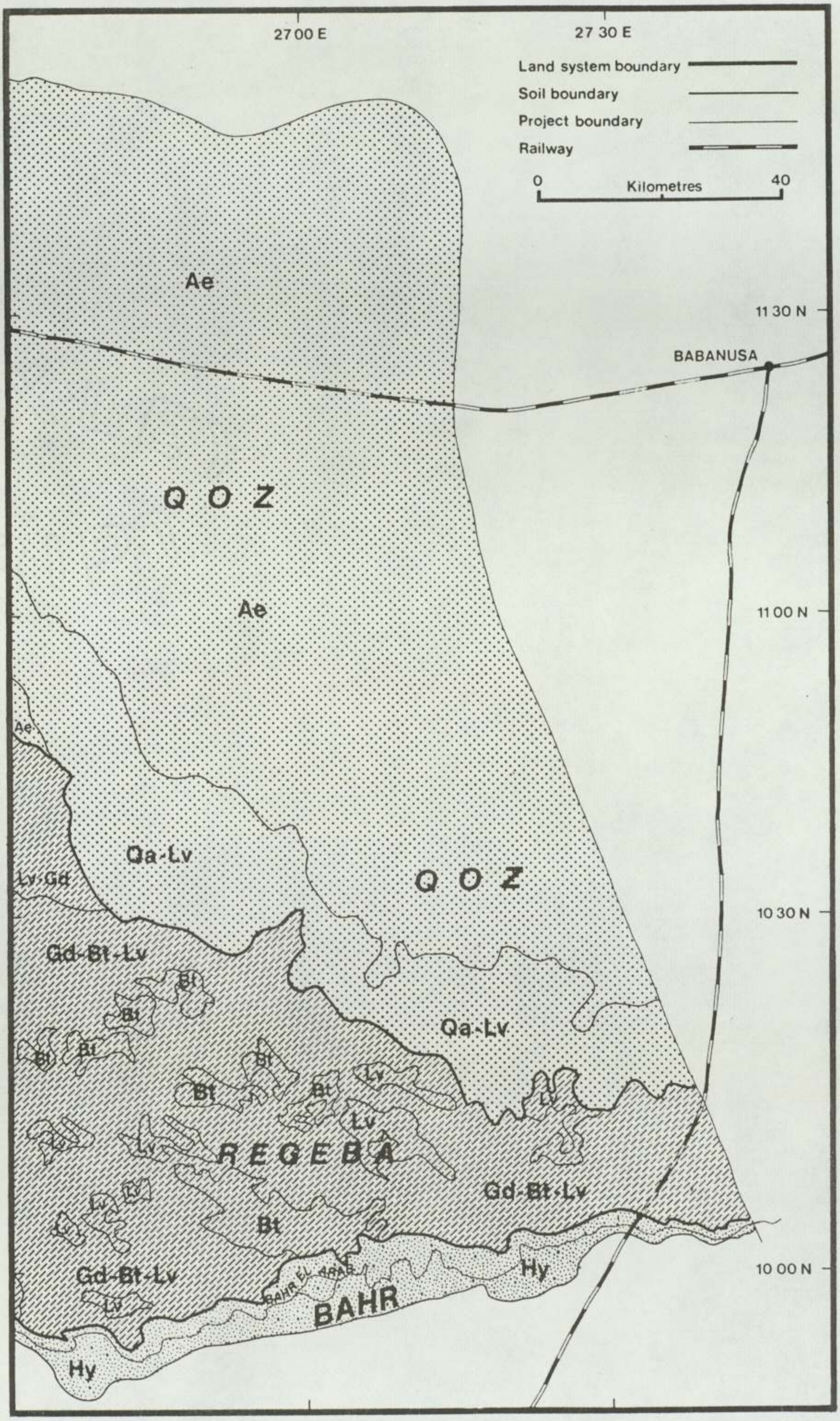


TABLE 9.2 SOIL AND LAND SYSTEMS LEGEND EASTERN DISTRICT

SOILS

Code	Parent Material	Soil Description
Ae	Aeolian sands	150 cm of red and yellowish red sands and loamy sands.
At	Aeolian sands and reworked aeolian sands	50-150 cm of brown and yellowish red sands and loamy sands.
Ng	Medium and fine textured, micaceous and non-micaceous alluvium with a thin aeolian sand cover	Dark greyish brown non-cracking soils with 50 cm of aeolian sand; frequently micaceous, stratified and calcareous.
Gd	Stratified and non-stratified alluvium overlying reworked aeolian sand below 2 m	Greyish brown and olive brown non-cracked silty clay loams and clays; frequently calcareous.
Bt	Fine textured alluvium	Dark grey cracking clays; frequently calcareous.
Bts	Micaceous fine textured alluvium	Dark grey cracking clays; frequently calcareous.
Hy	Medium and fine textured alluvium	Dark grey hydromorphic clays and silts.
Lv	Stratified fine, medium and coarse textured alluvium	Stratified sands, silts and clays.
Br	Stratified coarse textured micaceous alluvium	Stratified, micaceous sands, loamy sands and sandy loams.
Qa	Reworked aeolian sands over alluvial sediments	Brown sands and loamy sands over massive, mottled sandy loams and sandy clay loams; frequently calcareous.

LAND SYSTEMS

Screen	Land System	Landform Units
	Qoz	Sand sheet, degraded dunes, inter-dune hollows, relic drainage channels.
	Baggara	Sheetwash plain (Baga'a) basin, sand dunes (Atmur), channels, levees.
	Regeba	Sheetwash plain, meander channels, ox-bow (Regebas), backswamps, levees.
	Basement	Pediments, jebels, shallow sand sheet and dunes, braided channels.
	Bahr	Meanders, incised channel, levees, floodplain.

The Regeba land system was not recognised during the Area A Study on either the aerial photographs or the LANDSAT imagery. The recurring pattern of major landforms and associated soils and vegetation characteristic of the Regeba land system only occurred in the extreme south eastern corner of Area A, and at the time of map compilation these patterns were considered to be an atypical part of the Baggara land system. Indeed, in this area the two land systems have very similar characteristics, and with hindsight, are probably best considered as part of a transition zone. The problem for the interpreter is analogous to that posed in Area A when separating the southern part of the Basement land system from the northern part of the Baggara land system, an area where environmental similarity combined with low image contrast made any such decision somewhat arbitrary. In the present Study, the unique characteristics of the Regeba land system, its full extent in Area B and its limited occurrence in Area A, was appreciated only after the interpretation of LANDSAT imagery covering Area B had been carried out and ground verification studies made.

The similarity of the soils and landforms and related agricultural potential along this part of the boundary indicates that the separation of the Baggara and Regeba land systems is somewhat unnecessary and certainly has no significance for regional land-use planning - the raison d'être of the mapping exercise. The other boundaries between land systems along the transect, namely between the Basement and Qoz, the Qoz and Baggara and the Baggara and Bahr, have great significance for land-use planning and show an excellent measure of agreement. Thus, if the dubious Regeba land system boundary is omitted from the calculation of the coincidence index, the value for i improves dramatically to 0.97 (excellent) as Table 9.3(b) shows.

The comparison of boundary coincidence between soil mapping units along the boundary between Areas A and B is not possible because the units are not entirely comparable. Some of the taxonomic units recognised on the LANDSAT imagery of Area B differ slightly from those in Area A and the soil complexes tend to be more generalised. This is a reflection of the greater amount of soil data that can be consistently interpreted from aerial photographs compared with satellite imagery. This is particularly true of the Baggara and Regeba land systems although at the present scale of mapping much of the detail visible on aerial photographs cannot be shown.

A large proportion of Area B is occupied by the Qoz land system and mapped as one soil unit (Ae). Although the sandy Ae soils are very uniform over large areas, more detailed soil studies carried out at the Umm Rabuka and Khamsat development farms (Figure 9.1), revealed a considerable variation in the clay content of these soils. These

TABLE 9.3 LAND SYSTEM COINCIDENCE INDEX BETWEEN AREA A STANDARD MAP AND AREA B LANDSAT MAP

(a)

Land System		$\Sigma 1_1$ mm	$\Sigma 1_2$ mm	$\Sigma 1_3$ mm
Basement	Bs	62	58	58
Qoz	Qz	147	142	142
Baggara	Bg	187	128	128
Regeba	Rg	0	65	0
Bahr	B	8	6	6
		404	**399**	**334**

$n_1 = 3 \quad n_2 = 4$

$i = \frac{1_3}{1_1} \cdot \frac{n_1}{n_2}$* since n_2 is the greater

$$\frac{334}{404} \times \frac{3}{4} = 0.62$$

(b)

Land System		$\Sigma 1_1$ mm	$\Sigma 1_2$ mm	$\Sigma 1_3$ mm
Basement	Bs	62	58	58
Qoz	Qz	147	142	142
Baggara	Bg	187	193	187
Bahr	B	8	6	6
		404	**399**	**393**

$n_1 = 3 \quad n_2 = 3$

$$i = \frac{1_3}{1_1} \cdot \frac{n_2}{n_1} = \frac{393}{404} \times \frac{3}{3} = 0.97$$

where: 1_3 is the total length between boundary bisects on the transect that is correctly classified on the LANDSAT map.

1_1 is the length of the transect.

n_1 is the number of times a thematic boundary bisects the transect on the 'standard' map.

n_2 is the number of times a thematic boundary bisects the transect on the LANDSAT map.

differences in clay content, which varied between 5 and 50 per cent, were related to slope position and formed part of a catenary sequence. The heavier textured sandy clays which generallyoccurred at the base of slopes and in the inter-dune hollows, often supported flora of greater density or of a different species composition. Occasionally these soil and vegetation differences within the Qoz could be interpreted from the bulk processed colour composite LANDSAT imagery but generally, the areas were too small and the differences in image characteristics too subtle to be interpreted with confidence. The presence of burning patterns and the lack of topographic reference points away from the immediate vicinity of the deep boreholes were additional factors precluding a more detailed breakdown of the soils and geomorphology in the Qoz land systems of Area B. However, within the context of a reconnaissance soil survey, such a breakdown is unnecessary since the mapping of the Qoz soils from LANDSAT imagery has fulfilled the objectives of a reconnaissance survey by delineating broad areas of similar soils and indicating the range of soil variability that occurs over small areas. Such variability can only be shown in map form after more detailed surveys (using medium and large scale aerial photography) have been completed.

Within the context of land-use planning in a developing country such as the Sudan, land systems constitute natural planning units and form the framework for regional development planning. Thus, the mapping of the land systems can be considered of greater importance than the mapping of the soil units within these land systems. The actual mapping of discrete soil units or complexes is subordinate to the task of establishing the range of soils, or for that matter, any other natural resource features, within the confines of the various land systems. Such data can only be obtained by extensive ground studies such as those used in the present study.

Land systems containing areas with development potential will require more detailed resource studies but these would, in all probability, be based upon survey methods which utilise medium and large scale aerial photography. In Area B those regions within land systems containing soils with agricultural potential can be identified and broadly located from the LANDSAT map. However, environmental complexity, combined with a moderately dense vegetative cover which is subject to burning, and the low resolution of the satellite imagery, precludes the extraction of more detailed soils data from the bulk processed LANDSAT imagery used in the present study.

The existence of medium scale aerial photography for the northern part of Area B proved to be a valuable asset but not an essential one for interpretation and field location. Providing image contrast is high and reference points can be located on the ground, reconnaissance land systems and soils mapping can be carried out to an acceptable level of accuracy from the interpretation of colour composite LANDSAT imagery backed by extensive ground studies, in an African Sahelian - Savanna environment.

CHAPTER 10

RESULTS AND CONCLUSIONS

10.1 Outline of Study

The present study evaluates the use of satellite imagery (LANDSAT) as a mapping base for the compilation of reconnaissance scale land system, soils and geomorphology maps to be used for development planning in Southern Darfur Province, Western Sudan. In common with many other areas in the African Sahelian and Savanna zones, Western Sudan is a large, remote area with a very poor system of internal communications. These factors have acted as serious constraints to the collection of natural resources data using both remote sensing and terrestrial survey techniques. The advent of the LANDSAT programme, and with it the world-wide availability of low cost orbital imagery possessing a unique perspective and near orthographic properties, appeared to offer a solution to this problem of data acquisition.

Many authorities believed that LANDSAT imagery would provide, at the very least, a remotely sensed source of data that could be used to supplement data obtained from terrestrial survey and the more conventional remote sensing techniques such as aerial survey. Others thought the satellite imagery might provide an alternative source of information. The results of the present study support in general both these views, but with a number of reservations.

The Study was carried out in two parts in two adjacent areas of Southern Darfur, designated Areas A and B. The first part of the Study, carried out in Area A, was a comparative analysis of the accuracy of a land systems and soils map compiled from the interpretation of bulk processed colour composite LANDSAT imagery, with that of a similar thematic map of the area compiled from the interpretation of medium scale aerial photography and ground survey.

The objectives of reconnaissance survey and methods of measuring map accuracy were reviewed. The inadequacy of applying many of the established methods in the present study necessitated the development of new techniques. In the comparative study accuracy was measured, using a standard technique, by comparing the areas (in km^2) occupied by similarly classified mapping units, and by using two new methods for the examination and measurement of boundary shape and coincidence. Areal measurements were carried out by both manual and digital methods.

In the comparative analysis, LANDSAT imagery of Area A was interpreted as a desk exercise and the imagery was not used in the field. In the second part of the study, LANDSAT imagery of Area B, an adjacent and environmentally similar part of Southern Darfur, was used in the field for the compilation of reconnaissance scale topographic and thematic maps covering 55,000 km^2 from the manual interpretation of colour composite LANDSAT imagery and ground survey. The area was not covered by reliable topographic or thematic maps and aerial photography was available for the northern part of the area only. In the absence of such data, LANDSAT imagery appeared to offer the only viable means of map compilation. Mapping was carried out using the cheapest bulk processed imagery and relied on manual methods of image interpretation. The interpretation was followed by ground and air verification using a rapid reconnaissance traverse technique developed during the course of the study.

The accuracy of the Area B maps cannot be quantified in the manner of Area A maps since no other thematic or topographic maps of Area B existed at a suitable scale or degree of reliability. However, by using the experience gained in the comparative study it was possible to draw some general conclusions regarding the accuracy and reliability of the Area B LANDSAT derived maps.

10.2 Summary of Results

The results of the areal comparative study in Area A, using manual methods of calculation showed that no land system interpreted from the satellite imagery had an areal difference greater than ± 3 per cent compared with its equivalent on the 'standard' map (Map 1). This level of accuracy is adequate for a reconnaissance level survey. However, the good areal agreement at land systems level between the two maps disguise large variations in area between the geomorphic and related soil sub-units. These variations were greatest within the Basement and Baggara land systems.

Because of the large within-group variation between similarly classified units a misleading impression of accuracy was obtained by classifying the soil mapping units into larger groups (based upon genetic or agricultural suitability criteria) and comparing the combined area totals. To overcome this, the cumulative difference between similarly classified units was calculated. This value gave an indication of the area within each group or class that had been wrongly classified. Using this criterion, the most widespread agricultural soils, the aeolian sands, and those alluvial soils with irrigable potential, were mapped more accurately than other soil groups from the LANDSAT imagery.

The error of 1 per cent between the total area of alluvial soils on Maps 1 and 2, compared with the 27 per cent cumulative error difference, indicates that gross boundary discrepancies occur between soil mapping units within the Baggara land system; the land system in which the majority of the alluvial soils occur. The total cumulative error for Map 2 amounts to 4,669 km^2 or 21 per cent of the total Project Area (21,878 km^2) and therefore some 21 per cent of Map 2 was incorrectly classified.

The differences between the two maps were usually the result of errors in the interpretation of the LANDSAT image. There errors were caused, for the most part, by the low resolution of the bulk processed LANDSAT imagery and the saturating effect that the infra-red channel (MSS 7) has on the image of areas with dense vegetation cover.

In general, the aeolian soils are readily interpreted on the satellite imagery. The interpreter relies primarily on an analysis of such image characteristics as shape, pattern and tone to determine the extent of aeolian geomorphological features and related soils. In the interiors of larger sand sheets where cultivation is minimal, the surface of the aeolian sand soils is rarely exposed. In this situation the interpreter relies on other image characteristics such as the lack of a surface drainage system to deduce the presence of aeolian sand soils. The smaller and more widely scattered sand dunes, particularly those in the Baggara land system, are easily identified on the LANDSAT image because the field crops had been harvested at the time of image acquisition. The combination of dry crop stubble and the pale brown sandy surface creates high surface reflectivity, in marked contrast to the surrounding areas of dark grey alluvium with low reflective properties.

The size of most of the sand dunes (6-7 km^2) precludes accurate delineation of their boundaries on a 1:500,000 scale bulk processed LANDSAT colour composite image. However, the fact that 13 of the 15 dunes interpreted from the satellite image occupy the same geographical co-ordinates as their counterparts on the 'standard' map is considered to be of greater significance than precise boundary delineation for a reconnaissance survey because of the agricultural importance of the sand dunes in Southern Darfur.

In the Basement land system many of the sand dunes have reverted to bush fallow and the image characteristics are very similar to those of the non-aeolian soils which support *Acacia* spp. bush and thicket. As a result, the dunes in this land system are not accurately mapped from the LANDSAT image.

When attempting to interpret the extent of the alluvial soils on the LANDSAT image the interpreter relied on the known association between the alluvial soils and their related vegetation and geomorphology. In a complex depositional environment such as that of Southern Darfur, an analysis of image patterns, particularly those depicting the drainage, provided the primary criteria for the discrimination of soil and geomorphological complexes. Occasionally it was possible to map discrete units within the areas of alluvium. For example, dark grey cracking clays generally occurred in association with dense *Acacia seyal* woodland in depressions. Infra-red reflectance from this woodland was high and was recorded in bright red colours on MSS band 7. Where the interpreter had correctly predicted the areas of low topography, mapping accuracy of this discrete soils unit (Al_2c) was high. However, other alluvial soils not found exclusively in low lying areas also support a dense vegetative cover with a high infra-red reflectance, thus consistent identification of the cracking clays was not possible. Where alluvial soils occur in unambiguous geomorphological situations (major wadi valleys and floodplains) the agreement between the two maps is reasonably good.

In the southern part of the Basement land system the interpretation of the residual and polygenetic soils presented some problems. The area merges almost imperceptibly with the northern part of the Baggara land system, an area which is environmentally very similar. This similarity is reflected in the almost identical image characteristics of the two regions and accounts for the inaccuracies on the LANDSAT map.

For the comparison of areas using digital methods a computer program was written which used a regular array of approximately 3,500 dots to calculate the soil unit areas on the two maps. By using the 'standard' map planimetered values as a check, it was found that 15 and 13 of the 17 soil categories on Maps 1 and 2 respectively were measured digitally to within +/- 10 per cent of their true areas. Errors of greater than 10 per cent would probably have been reduced if the sample size had been increased above the 3,500 level and sample point location randomised.

Random point location was used in the sampling program to determine the minimum sample size that would provide a 10 per cent level of accuracy for the area calculations. The results of the digital sampling program indicate that a sample of at least 1,500 dots would be required to achieve the 10 per cent level of accuracy for most mapping units, although some units would require much larger samples. Smaller dot samples of between 100 and 250 dots give a reasonable degree of accuracy where the soil class contains large mapping units ($> 1{,}000\ km^2$) although the standard deviations of such low dot sampling are unacceptably large. But the use of digital sampling techniques must be viewed with caution in the context of development planning in the Third World where cost effectiveness is a primary concern. The manual methods of area calculation used in the present study are undoubtedly cheaper than digital methods and can be carried out in the field.

The degree of boundary coincidence between similarly classified mapping units is an important parameter of map accuracy. It was found that a good areal agreement between similarly classified mapping units in Area A often disguised gross differences in the shape and geographical location of boundaries. Three methods were used in the present study to measure thematic boundary displacement and coincidence. One of these methods, namely sieve mapping, is an established technique although modified for the purposes of the present study. The other methods were developed in an attempt to refine the areal measurements of map accuracy. Each method has advantages and disadvantages although in a complex map situation such as that in Area A, the calculation of the boundary coincidence index gives the most realistic measure of boundary coincidence since it is sensitive to differences in boundary shape, area and to the inclusion or omission of mapping units on one of the maps being compared.

In Area B all land system boundaries, with the notable exception of the one separating the Regeba and Baggara land systems, were clearly defined on the satellite imagery of Area B and were readily linked with their counterparts in Area A. It is therefore reasonable to assume that the overall accuracy of land system boundaries in Area B is commensurate with the accuracy of the similarly derived land system boundaries in the adjacent Area A (+/- 5 per cent).

The Regeba land system recognised in Area B was not mapped in Area A although it was subsequently found to occur in the extreme south-eastern corner of Area A. However, the unique characteristics of the land system, which are faithfully recorded on the LANDSAT imagery, and its limited occurrence in Area A were appreciated only after the interpretation of Area B satellite imagery and ground verification.

The accuracy of the soil and geomorphic units in Area B interpreted from the LANDSAT imagery is probably as variable as it was in Area A, despite field checking. Clearly, within the time constraints of a reconnaissance survey it is not feasible to cover the whole length of an interpreted boundary and much of Area B had image characteristics similar to those occurring on the LANDSAT frame of Area A. However, it was possible to refine some ambiguous boundaries in areas of low image contrast by ground checking using the rapid reconnaissance traverse technique. This was not possible in the desk interpretation of Area A LANDSAT imagery.

10.3 Conclusions

The synoptic properties of satellite imagery dictate its use in the initial stages of regional resource studies in the Sahelian and Savanna zones of Africa: areas where conventional aerial photographic cover is frequently lacking and where the costs of obtaining complete regional cover are prohibitive. The LANDSAT imagery can be used effectively to identify rapidly those areas with agricultural or other resource potential which should be photographed from an aerial platform and subject to more detailed ground surveys.

The complexity and ambiguity of some spectral responses on LANDSAT imagery of the African Sahelian and Savanna zones emphasises the need for comprehensive field verification of any interpretation.

The field checking of the LANDSAT imagery underlined the importance of accurate ground location for the correlation of LANDSAT image characteristics with natural resource features. The ground and aerial traverse techniques developed during the present study provided a practical means of field location wherever a framework of easily identifiable features occurred. The accuracy of the method deteriorated in areas of low image contrast or dense vegetation cover and thus was more suited to the drier northern and central parts of the area.

The existence of medium scale aerial photography of the northern half of the area proved to be a valuable asset, but not an essential one, in view of the high image contrast and large number of easily identifiable reference points in the area. Aerial photography of the more humid southern part would have considerably improved the accuracy of the soil and geomorphological mapping. It is unlikely to have made very much difference to the land systems mapping since satellite imaging, with its synoptic view is admirably suited to this kind of mapping.

Within the context of land-use planning in a developing country, such as the Sudan, land systems constitute natural planning units and form the framework for regional development planning. Thus, the mapping of the land systems can be considered of greater importance than the mapping of the soil units within those land systems. The actual mapping of discrete soil units or complexes is subordinate to the task of establishing the range of soils, or for that matter any other natural resource features, within the confines of the various land systems. Such data can be obtained only by extensive ground studies such as those used in the present study. Satellite imagery, or any form of remotely sensed image, cannot yet provide such data.

The 80 m ground resolution of the current bulk processed LANDSAT imagery supplied by NASA precludes the more detailed mapping of earth resources using manual techniques. The use of digital methods which process the original data tapes for more detailed mapping has yet to be evaluated in the Sahelian and Savanna zones. These methods, which are still the subject of extensive research, are extremely expensive. Thus, at the 'present-state-of-the-art' the more detailed resource mapping is best carried out using medium and large scale aerial photography.

REFERENCES

ALLAN, J.A. (1978). Better Resolution from LANDSAT. Nature Vol. 273. pp. 189-190.

AMERICAN SOCIETY OF PHOTOGRAMMETRY (1975). Manual of Remote Sensing Volumes I and II Falls Church, Virginia.

ANDREW, G. (1948). Geology of the Sudan. Chapter Six in Agriculture of the Sudan, edited by J.D. Tothill, Oxford University Press.

BIE, S.W. and BECKETT, P.H.T. (1973). Comparison of four independent soil surveys by air-photo-interpretation, Paphos area (Cyprus). Photogrammetria, 29: pp.189-202.

BROCKMAN, C. (1974). Earth Resources Technology Satellite Data Collection Project ERTS - Bolivia. In: 3rd ERTS Symposium on significant results obtained from ERTS-1, Vol. 1, Section A, NASA. pp. 559-577.

BURINGH, P. (1960). The applications of aerial photographs in soil surveys. Man. of Photogr. Interpr., Washington D.C., pp. 633-666.

BURINGH, P. STEUR, G.G.L., and VINK, A.P.A. (1962). Some Techniques and Methods of Soil Survey in the Netherlands. Neth. J. Agric. Sci. 10, pp. 157-72.

BURROUGH, P.A., BECKETT, P.H.T. and JARVIS, M.G. (1971). The relation between cost and utility in soil survey (I-III), J. of Soil Sci., Vol. 22, No.3.

COLWELL, R.N. (1968). Determining the usefulness of space photography for natural resource inventory. In: Proc. of the 5th Int. Symp. on Remote Sensing of Environment, Ann Arbor, Michigan, pp. 249-289.

CHRISTIAN, C.S. (1958). The concept of land units and land systems. Proc. 9th Pacific Science Cong., Vol.20, pp. 74-81.

CHRISTIAN, C.S. and STEWART, G.A. (1968). Methodology of Integrated Surveys, in: Proceedings of the Toulouse Conference Aerial Surveys and Integrated Studies, UNESCO, pp. 233-280.

EDMONDS, J.M. (1942). The Distribution of Kordofan Sand in the Anglo-Egyptian Sudan. Geol. Mag. Vol.79, pp. 111-113.

EGGELING, M.D., and GADDAS, R.R. (1973). Preliminary report on ERTS I imagery in the Sudan. SUD/372/AGS-AGP.

ELBERSEN, G.W.W. (1974). Interpretation of ERTS-MSS Images of a Savanna Area in Eastern Columbia. In: 3rd ERTS Symposium on Significant Results obtained from ERTS-I, Vol.1, Section A, NASA, pp. 105-120.

ESTES, J.E. (1977). A Perspective on the State of the Art of Photographic Interpretation. In: Proceedings of the Eleventh International Symposium on Remote Sensing of Environment, Vol.1, ERIM, Ann Arbor, Michigan, pp.161-177.

F.A.O. (1964) Land and Water Use Survey in Kordofan Province of the Republic of the Sudan. Report on Survey of Geology, Geomorphology and Soils, Vegetation and Land Use. Government of Sudan.

F.A.O. (1969) Land and Water Resources Survey of the Jebel Marra Area, Reconnaissance and Semi-detail Soil Surveys. PA: SF/SUD 17, Rome.

FAO/IBRD (1968) Comparison of Sampling Density, Rate of Progress and Scale of Systematic Soil Survey (with some use of Air-Photo Interpretation). Misc. Paper.

FISCHER, W.A. and ROBINOVE, C.J. (1968). A Rationale for a general purpose Earth Resources Observation Satellite: Proc. of the Remote Sensing Symp. Univ. of Wash. 6p.

GADDAS, R.R. (1973). Photo-interpretation of selected areas of the Sudan savanna belt, geomorphology, soils, and present land use. FAO Savanna Development Project Phase I, SUD 25.

GENDEREN, J.L. van (1975). Visual Interpretation of Remote Sensing Data and Electronic Image Enhancement Techniques. Remote Sensing Data Processing, Pub. for Remote Sensing Society by University of Sheffield, pp. 19-51.

GOOSEN, D. (1967). Aerial Photo-Interpretation in Soil Survey. Soil Bulletin No. 6, F.A.O., Rome.

GRABHAM, G.W. (1935). The Anglo-Egyptian Sudan from Within. J.A. de Hamilton, Faber, pp. 257-281.

GREGORY, S. (1963). Statistical Method and the Geographer. Longmans, London.

GROVE, A.T. (1972). Climatic change in Africa in the last 20,000 years, In I.G.U. Colloque, Ouargla, 1951, Les Problèmes de développement du Sahara Septentrional, 2. Institut de Géographie, Alger.

GUINARD, A. (1974). Assessment of Potential Land Resources through random sample surveys. World Crops, May/June, pp. 127-129.

HARRISON, M.N. and JACKSON, J.K. (1958). Ecological Classification of the Vegetation of the Sudan. Min. of Agr. Rep. of Sudan. For. Bull. 2.

HOWARD, J.A. (1974). Concepts of Integrated Satellite Surveys in: Third ERTS-I Symposium, Vol.1, NASA, Washington, D.C., pp. 523-537.

HUNTING TECHNICAL SERVICES LTD. (1971). Southern Darfur Land Use Planning Survey. Preliminary Appraisal, Government of Sudan.

HUNTING TECHNICAL SERVICES LTD. (1974a). Southern Darfur Land Use Planning Survey,Development Plan, Government of Sudan.

HUNTING TECHNICAL SERVICES LTD. (1974b). Southern Darfur Land Use Planning Survey, Annex 1, Soils and Vegetation, Government of Sudan.

HUNTING TECHNICAL SERVICES LTD. (1976a). Savanna Development Project Phase 2, Annex 1, Soils and Vegetation, Government of Sudan.

ILFORD, (1976). Technical Booklet No.25 EN January, 1976.

JEWITT, T.N. (1950). Goz Soils of the Anglo-Egyptian Sudan. Trans. 4th Int. Cong. of Soil Science, pp. 285-288.

KLINGERBIEL, A.A. and MYERS, V.I. (1974). Soil Study of Tampico and Isthmus Areas of Mexico using ERTS imagery to determine potential land use. Washington, D.C. World Bank (unpublished).

LOWMAN, P.D. (1964). A Review of Photography of the Earth from Sounding Rockets and Satellites. NASA Technical Note D-1868.

LOWMAN, P.D. (1965). Space Photography - A Review. Photogrammetric Engineering Vol.31, pp.76-86.

LUEDER, D.R. (1959). Principles and Applications of Aerial Photographic Interpretation. McGraw-Hill, New York.

MEIGS, P. (1965). World Distribution of Arid and Semi-arid Homoclimates: Rev. Res. on Arid Zone Hydrology., UNESCO, Paris, pp. 203-210.

MITCHELL, C.W., (1973). The Application of ERTS-1 Imagery to the FAO Sudan Savanna Project, FAO, Khartoum.

MITCHELL, C.W. (1975). The Applications of LANDSAT I Imagery to the Sudan Savanna Project. Journal of the British Interplanetary Society, Vol.28, Nos. 9 and 10, pp. 659-672.

MOORE, D.G. (1978). Methods for using LANDSAT in Large-Areas Resource Inventories. In: Summaries Twelfth International Symposium on Remote Sensing of Environment, Environmental Research Institute of Michigan, Ann Arbor, Michigan, p.42.

MORAIN, S.A. and CAMPBELL, J.B. (1974). Radar Theory applied to Reconnaissance Soil Surveys. Soil Sci. Soc. Amer. Proc., Vol.38, pp. 818-826.

MORRISON, A. and CHOWN, M.C. (1965). Photographs of the Western Sahara from the Mercury MA-4 Satellite. Photogrammetric Engineering, March, pp.350-362.

MONKHOUSE, F.J. and WILKINSON, H.R. (1974). Map and Diagrams. University Paperback, p.282.

NASA (1972) Earth Resources Technology Satellite 1 Symposium Proceedings.

NASA (1973). Third Symposium on Significant Results Obtained from the Earth Resources Technology Satellite-1. Vol.1, Sections A and B, Goddard Space Flight Centre, Maryland.

NASA (1976). NASA Earth Resources Survey Symposium. Vols. 1A-1D, National Aeronautics and Space Administration, Lyndon B. Johnson Space Centre.

NATIONAL ACADEMY OF SCIENCES (1977). Resource Sensing from Space, Prospects for Developing Countries. Washington, D.C.

NIXON, P.H. (1974). Use of ERTS imagery for Natural Resources Research and Development in Lesotho. Final Report, Sept. 1972-May 1974, Department of Mines and Geology, Masem, Lesotho.

PARKER, D.C. and WOLFF, M.F. (1965). Remote Sensing. International Science and Technology, July 1965, pp.v-xvi.

PARRY, D.E. (1971). An analysis of existing space imagery with particular reference to the GEMINI-NASA Photograph 12.11.54. of the Lower Indus Region, West Pakistan. Paper presented at Seminar on Applications of Earth Resource Satellites to Mapping, The Experimental Cartography Unit. Imperial College, London, Oct. 22nd.

PARRY, D.E. (1974). A Natural Resource Evaluation of ERTS-I Imagery of the Central Afar Region in Ethiopia. Photogrammetric Record, 8(43), pp.65-80.

POMERENING, J.A., and CLINE M.G. (1953). The accuracy of soil maps prepared by various methods that use aerial photograph interpretation. Photogramm. Eng. 119: pp. 809-817.

ROBERTSON, V.C. and STONER, R.F. (1970). Land Use Surveying: A case for reducing the costs. The World Land Use Survey, Occasional Paper No.9.

SCHWAAR, D.C. (1970). Air-photo and air-photo interpretation in soil survey. Report SSR 83. UNSF, F.A.O., Kingdom of Thailand, Soil Survey Division.

SIMONSON, R.W. (1950). Use of Aerial Photographs in Soil Surveys. Photogramm. Eng., 16: pp. 308-15.

SMITH, H.T.U. (1943). Aerial Photographs and their Application. New York. Appleton-Century-Crofts.

SMITH, J. (1949). Distribution of tree species in the Sudan in relation to rainfall and soil texture. Ministry of Agriculture. Bull. 4.

SOIL SURVEY ADMINISTRATION (1975). Reconnaissance Soil Survey and Land Capability Classification of Umm Agaga Area. Wad Medani.

SOIL SURVEY STAFF (1951). Soil Survey Manual, Agriculture Handbook No.18, United States Department of Agriculture, Washington, D.C.

STEUR, G.G.L. (1961). Methods of Soil Survey in Use at the Netherlands Soil Survey Institute. Boor Spade 11, pp. 59-77.

SUROTO, A. and MALINGREAU, J.P. (1975). Applications of Remote Sensing Techniques to Soil Investigations. Paper given at UN-FAO Training Seminar, Jakarta, Indonesia.

TOTHILL, J.D. (1948). A Note on the Origin of the Soils of the Sudan from the Point of View of the Man in the Field, p. 131, from Agriculture of the Sudan, edited by J.D. Tothill, (1948), Oxford University Press.

VALENTINE, K.W.G., LORD, T.M., WATT, W. and BEDWANY, A.L. (1971). Soil mapping accuracy from black and white,colour and infra-red aerial photography. Canadian J. Soil Sci. 51: 461-69.

VINK, A.P.A. (1968). Aerial photographs and the Soil Sciences. In: Aerial Surveys and Integrated Studies, Proceedings of the Toulouse Conference UNESCO, Paris, pp. 81-141.

WEBSTER, R. and BECKETT, P.H.T. (1968). Quality and Usefulness of Soil Maps. Nature, Vol.219: 680-82.

WEBSTER, R. and WONG, I.F.T. (1969). A numerical procedure for testing soil boundaries interpreted from aerial photographs. Photogrammetria, 24: 59-72.

WESTING, F.C. (1973). ERTS-I MSS imagery: Its use in delineating soil associations and as a base map for publishing soils information. In: Third ERTS-I Symposium, Vol.1, Section A, pp. 183-204.

WESTIN, F.C. and FRAZEE, C.J. (1975). LANDSAT-I Data, its use in a soil survey program. In: NASA Earth Resources Survey Symposium, Technical Session Presentations, Vol. 1-A, Houston, Texas, pp. 67-97.

WICKENS, G.E. (1977). The Flora of Jebel Marra (Sudan Republic) and its Geographical Affinities. H.M.S.O., London.

WILLIAMS, M.A.J. and ADAMSON, D.A. (1974). Late Pleistocene desiccation along the White Nile. Nature, 248, pp. 584-586.

WORCESTER, B.K. and MOORE, D.G. (1978). Delineation of Soil Landscapes in the Sudd Region of Sudan on LANDSAT imagery. In: Summaries Twelfth International Symposium on Remote Sensing of Environment, Environmental Research Institute of Michigan, Ann Arbor, Michigan, pp.138-139.

YATES, F. (1965). Sampling Methods for Censuses and Surveys. Griffin. London.

YOUNG, A. (1973). Soil Survey Procedures in Land Development Planning. Geographical Journal, Vol.139, Part 1, pp. 53-64.

YOUNG, H.E. and STOECKLER, E.G. (1956). Quantitative evaluation of photo-interpretation mapping. Photogramm. Eng., 22, pp.137-143.

ZUIDAM, R.A. van (1971). Orbital photography applied to natural resources survey. Series B, Number 61, International Institute for Aerial Survey and Earth Sciences (ITC). The Netherlands.

APPENDIX A

LANDSAT SENSORS

MULTISPECTRAL SCANNER (MSS)

The MSS scanning device is a mirror tilted at a 45 degree angle from the earth and which rotates about 2.9 degrees and scans the earth's surface from east to west within a 185 km north-south strip on each orbit, as shown in Figure A.1. Each sweep of the scanning mirror takes in reflected radiation signals from six parallel lines of landscape and feeds these lines of signals through a pair of fixed mirrors and a set of fibreoptic bundles to the detectors. The signals from one scanned geographic line being directed to one of the six detectors in each of the four spectral bands. The detectors convert the radiation signals into electrical signals that can be recorded onto magnetic tape on board the space-craft or telemetered back to ground receiving stations.

When the mirror returns for the next sweep, the satellite has advanced about 474 metres. Each continuous line of signals acquired by the scanning mirror is divided into 3,200 separate signals each of which is translated into an electrical signal by the detector and is ultimately reproduced on the LANDSAT imagery product as one picture element or pixel representing an area of approximately 80 m square or 0.64 ha.

The level of intensity of the composite signal emanating from each pixel area will depend upon the nature of that area and the wavelengths reflected by its various components. The intensity level of the signal will be recorded differently in each of the four MSS bands. These data are transmitted as 64 distinct intensity levels to ground receiving stations. It is the recording and analysis of these different levels of intensity, and their identification with the feature and areas that they represent on the ground, that provide the basis for the interpretation and mapping of earth resources from LANDSAT data.

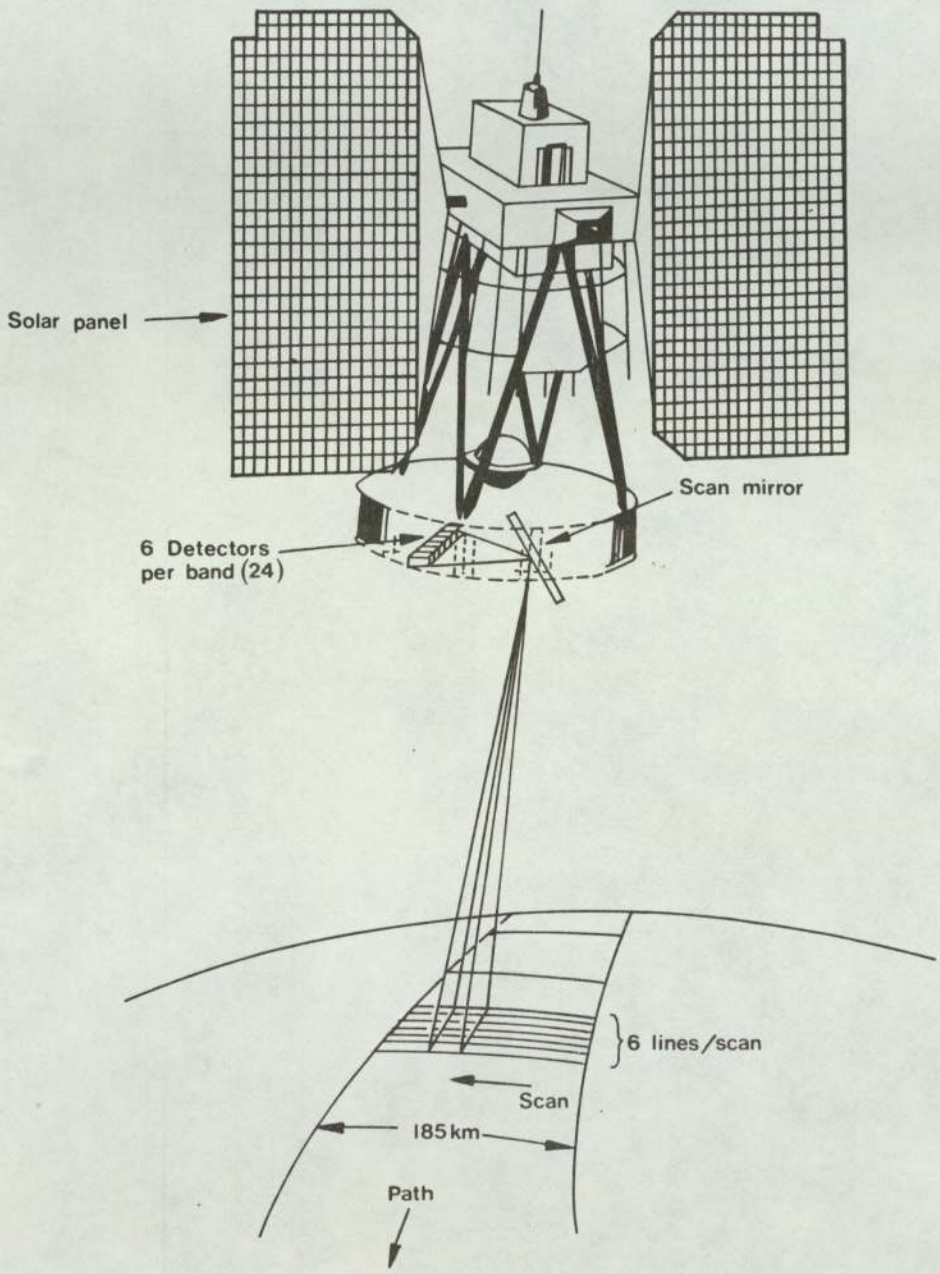
THE RETURN BEAM VIDICON CAMERA (RBV)

Three television cameras simultaneously photograph the same portion of the earth in three different spectral bands as follows:

Band 1 (green)	460 - 600 nanometres
Band 2 (red)	570 - 680 nanometres
Band 3 (near infra-red)	660 - 820 nanometres

When operating the cameras photograph an area 185 km square (34,000 km^2) every 25 seconds. Each television picture has 4,125 lines (compared with the 625 lines of the standard European television systems) and 4,000 picture elements per line. The complete image has over 16 million pixels - equivalent to that of the MSS system.

Figure A.1
LANDSAT multispectral scanner (MSS) system



Source: NASA/GSFC

In the early orbits of LANDSAT 1, the RBV system generated data of excellent quality. However, due to a circuit malfunctioning a few weeks after launch, the RBV system ceased to operate. The RBV system on LANDSAT 2 is in working order but has been operated primarily for equipment testing purposes and is being held in reserve for possible special or emergency use. LANDSAT 3 is currently producing RBV imagery of a very high quality.

APPENDIX B

AUTOMATIC DATA PROCESSING AND CLASSIFICATION

INTRODUCTION

The rapid developments in the use of orbital remote sensors during the last decade has been accompanied by the parallel development of techniques for digital image processing, analysis and classification. The Computer Compatible Tapes (CCTs) on which LANDSAT data are recorded can be digitally processed by a computer to produce images with a range of formats, and with varying degrees of geometric and radiometric excellence. These images may then be interpreted manually or digitally by earth resource scientists. A variety of computer programs or algorithms are available that will automatically classify an image into its component spectral classes. The advantages of image processing and enhancement prior to interpretation are well documented and recognised by users of LANDSAT imagery. The merits of automatic classification methods are still the subject of considerable research and controversial debate.

In the present study bulk processed, fourth generation, LANDSAT imagery was used. The imagery has undergone some minor geometric corrections but was not subjected to the more sophisticated forms of computer processing. Neither time nor money permitted the purchase of the CCTs covering the Southern Darfur Project Areas. Clearly, in a study of this nature it would have been desirable to compare thematic maps compiled by conventional means, with maps compiled by manual and digital methods of classification using bulk processed and computer processed imagery respectively.

Thus, the purpose of this appendix is to review the methods used in automatic data processing and their applications in natural resources survey, with a view to assessing how valuable they might have been in the present study.

IMAGE PRE-PROCESSING AND ENHANCEMENT

During pre-processsing LANDSAT images are spatially and spectrally rectified and mutually registered before release to the user. Imagery is made available from NASA in the bulk or precision processed mode. The bulk processed imagery has the following routine geometric corrections applied:

(a) scale rotation;

(b) earth rotation skew correction;

(c) frame rotation to obtain north orientated images.

Frames can be precision processed to further improve radiometric balance and planimetric accuracy.

The precision processed imagery requires the use of nine accurately located ground control points which can be recognised on each image. The precision processed imagery has a cartographic accuracy of about 100 metres but the application of the corrections is a very expensive and time-consuming process.

The multi-spectral and multi-temporal nature of LANDSAT data present the interpreter with a vast data set for a particular scene and application. To extract the relevant information from such a large data set will be exceedingly time-consuming for the interpreter if he has to examine each image individually. Furthermore, as Custance et al (1977) observe, the interpreter's appreciation of each image's complementary information in relation to the other images becomes exceedingly difficult when he has more than three or four images to interpret. It is at this stage that digital processing of remotely sensed data, either through image enhancement or automatic analysis, can contribute greatly to the interpretation. Image enhancement techniques are generally chosen when the human interpreter makes the final visual interpretation.

The object of enhancement is to extract information from the imagery that cannot be extracted by direct visual examination of the imagery in its normal format. This may be done by electronic manipulation of the image, and different features, some of which may not be visible to the naked eye, emphasised or highlighted. Van Genderen (1975) grouped image enhancement techniques into the two broad categories of photographic and electronic methods. The first category includes such techniques as photographic enlarging, contrast printing and photographic density slicing. In the second category, a large number of electronic methods have been developed and are currently available from the NASA EROS Data Centre and a host of commercial organisations, for the enhancement of LANDSAT multi-spectral imagery. The methods include: band ratioing, intensity normalisation, principal components analysis, hue, saturation and intensity enhancement, edge enhancement, cumulative distribution function data stretch, colour enhancement, density slicing and contouring. Details of these methods are summarised by Klass (1977).

AUTOMATIC CLASSIFICATION

Automatic classification refers to computer processes that result in the production of a map by a computer rather than an enhanced image to aid human visual interpretation.

There are two basic categories of automatic classification: unsupervised and supervised. In unsupervised methods the computer divides the image data into a number of spectrally similar areas by means of a clustering algorithm which groups or clusters similar measurement vectors. The clusters are built up point by point by the classifier with each sample being tested to see if it lies close to or within a present cluster (Smedes et al., 1971). If not, it is either rejected or kept as the possible starting point for a new cluster. The compactness of clusters can be determined by statistics which measure the separation of clusters to their internal dispersion.

In supervised methods the computer is trained by supplying it with spectral information for certain pre-determined areas of 'training sets' and from which the spectral signatures are determined. The training sets are measurement vectors taken from a collection of areas for which ground data are available and which should contain all the classes to be identified. A pattern classifier is then constructed by dividing measurement space into decision regions, each region being one of the training set spectral clusters. During classification unknown data points are tested to see into which decision region they fall.

SPATIAL PROCESSING

The application of the spectral signature approach for the automatic classification of earth resources data using LANDSAT imagery poses a number of fundamental problems in addition to those related to changes in illumination intensity over the scene. These include the classification of image texture, shape, size and pattern and their bearing on the classification of resource features. Texture, which may be defined as the spatial variation in the spectral signature of pixels surrounding the one being processed is thus created by tonal repetitions in groups of objects which are too small to be discerned as individual objects. It is subjectively described by the human interpreter in terms of image 'roughness' or 'smoothness' but nonetheless provides valuable information to the interpreter.

Research into automatic textural classification of remotely sensed data has tended to concentrate on methods which compute power spectra using Fourier transform methods. These methods are described by Gramemopoulos and Corbett (1973). More recently, Stanley (1978) has attempted to quantify image texture using first and second order statistical methods. Both these methods are still in the experimental stage and much more research is required before textural algorithms are accepted on a commercial basis by the user community concerned with the mapping of natural resources.

The problem of the automatic recognition and subsequent classification of shape, size and pattern for the mapping of natural resources is in its infancy. These are fundamental characteristics of any image which the human interpreter, using the brain/eye mechanism, combined with subjective reasoning, intuition, convergence of evidence, past experience and the like, identifies and analyses in seconds. For example, the shape or form of some objects is so distinctive that they may be identfied from this criterion. Size is another important element. As Estes (1977) observes, an interpreter by measuring the size of an unknown object on an image can eliminate from consideration whole groups of possible identifications.

Pattern or repetition is a characteristic of many man-made and natural features. It is however, very scale dependent. For example, an orchard which may exhibit a pattern on a low altitude aerial photograph may constitute textural information on smaller scale imagery, appearing as a coarse textured phenomenon on a high altitude aerial photograph, and a smooth textured feature on a satellite image, depending on the focal lengths and associated resolution capabilities of the sensor systems employed.

Association provides a further clue to the identification of features and currently defies automatic analysis. Estes (op.cit.) quotes the example of schools which usually have associated playgrounds and athletic fields while churches do not. Bond and Atkinson (1972) cite association, or 'context-dependent exclusion relationships' as they call it, as one of the main types of error encountered when comparing automatic land-use classification with human photo-interpretation of the same area. For example, a particular type of land-use will preclude the presence of another type. The classification of strips of land between airport runways as agricultural land is an example of such a classification error.

AUTOMATIC CLASSIFICATION AND MAPPING OF NATURAL RESOURCES

The majority of automatic classifications of LANDSAT MSS data for the mapping of earth resources have been concerned with land-use mapping in the United States. The large fields in the agricultural areas of the mid-west and western states, which have well defined angular boundaries and grow one or two crops each season, are well suited to automatic classification using a spectral approach. The accuracy of automatic classification techniques in such areas frequently exceeds 90 per cent.

Mapping of vegetation resources in the United States has also been carried out using automated methods. In the Bucks Lake Forestry test site, California, Krumpe et al. (1973) selected 400 km^2 for automatic classification using a supervised method. The accuracy of the seven main vegetation and land-use classes delineated by the computer, as measured against those recognised by interpretation of high altitude aerial photography and ground survey, ranged from 31 to 100 per cent and had an overall accuracy of 79 per cent. These results were equivalent to the level of accuracy obtained by the manual interpretation of LANDSAT imagery of the area.

Thie (1976) working on supervised land classification in northern Canada achieved a best result of 70 per cent accuracy but concluded that automated classification did not generate useful information in the study area because the final legend was too broad to be of value. Nonetheless, the application of automatic classification methods to land-use and vegetation mapping in North America has proved reasonably successful and classification algorithms are used commercially for land-use mapping. But this success is attributable in large measure to the relatively unambiguous nature of the spectral responses from cropped land and forest and the existence of excellent ground data. In addition, many of the areas mapped cover only a small part of the total LANDSAT scene and could not be considered as regional mapping exercises.

The application of automated classification to the mapping of land-use and natural resources in the developing world is in an embryonic stage. Although a number of countries in the third world including Indonesia, Thailand, the Philippines, India, Iran, Bolivia and Brazil have the capability to perform automatic data processing, its use in an operational mode is very limited. The high cost of required instrumentation and lack of trained personnel are partially responsible for this situation but even where these constraints do not apply, the intensity and heterogeneity of land-use and ground cover over small areas, particularly in the Far East, pose serious obstacles for automated mapping at both local and regional levels.

Some success was achieved by Kalensky et al. (1978) in mapping the land-use and land-cover of Lombok Island, Indonesia from multi-temporal LANDSAT images using a supervised classification method. Computer assisted mapping of forest types has been carried out in the Philippine Islands by Lachowski et al. (1978) and in north eastern and southern India by Madhavan Unni (1978). In the former study, a synoptic view of the nation's total forest resources was obtained from digital data of 30 selected frames of the Philippine Islands taken between 1972 and 1976. Broad forest categories were defined using an interpreter and computer in an interactive mode. The forest maps will serve as a baseline for more intensive forest management studies in the Philippines.

The application of automated methods of analysis to LANDSAT multi-spectral data of the African continent is at a much lower level of development than in the Far East and South America. Computer processed LANDSAT imagery of Upper Volta at 1:100,000 scale was manually interpreted by Wispelaere and Waksman (1977) as part of a range land study in the African Sahel. They concluded that satellite imagery used in this mode provides a valuable means of monitoring range conditions over vast areas of the drought prone Sahel but that satellite image interpretation requires a total approach through synthetic units (range land units) which combine soil and vegetation characteristics. Such an approach is similar to the land systems concept and lends itself least of all to automatic classification methods.

Baumgardner (1974) carried out a computer based analysis of the natural resources of 1,450 km^2 in Kordofan Province, Sudan. Non-supervised and supervised methods were used and the data from a LANDSAT Computer Compatible Tape (CCT) were reformatted for compatibility with the LARS Software System (LARSYS) at Purdue University. The results of the study were marred by processing errors and inadequate ground truth. However, one very significant conclusion emerged, namely, the inability of a spectral classification to separate areas of bare ferruginised sandstone from areas of poorly vegetated dark cracking clay soils, when both had the same spectral signature. The human interpreter could easily discriminate between these two classes by using shape and related spatial and contextural information.

The application of automated classification methods to the mapping of land systems, soils and geomorphological features has not met with the same degree of success achieved in mapping land-use and vegetation in either the developed or developing world. Land systems by definition, are integrated land units containing a number of related physical features including soils, vegetation, geology, geomorphology, drainage and land-use. They tend to be regional mapping units and are delineated on an image on the basis of pattern, size, shape and texture analysis, combined with evidence of association, rather than on pure spectral properties. The Qoz land system in the present study provides convincing proof of this statement. A spectral map of the Habbaniya and Dango Qozes would, in all probability, identify at least six separate spectral classes for each Qoz. Yet, at the present scale of mapping, the sandy soils occupying both areas are physically and chemically identical. The landform units likewise are very similar. The spectral differences are caused for the most part by burning patterns, land-use patterns, which reflect the bush fallow system of cultivation prevalent in southern Darfur, and, to a lesser extent in the Qoz Dango, differences in floristic composition, density and phenology of the relatively undisturbed, broad leaved, savanna woodland.

The burning patterns are particularly confusing for automated methods of classification based on spectral analysis because similar spectral signatures are recorded for features unrelated to burning. In Southern Darfur such features include rock outcrops, exposed areas of dark grey cracking clays and the polygenetic soils of the Basement Complex land system which support a variable cover of *Acacia mellifera* scrub vegetation.

The clear cut boundaries generally associated with burning patterns, frequently the result of the fire ending along a path or road wide enough to prevent burning on the opposite side, and the orientation of burn patterns in the direction of the prevailing winds, enables the human interpreter rapidly to separate burnt areas from features with a similar spectral response.

In the present study image texture and the lack of a well defined drainage pattern in the Qoz areas were the main image characteristics used to determine the boundaries of the Qoz land systems. Although no digital analysis was carried out on the LANDSAT frames of Southern Darfur, the current capability of spatial processing methods would suggest that automated methods of land system analysis in these regions would be unsuccessful.

Robinove (1977) carried out experimental automated land systems mapping on part of a LANDSAT frame of southwestern Queensland, Australia. Clustering algorithms were used to classify spectral classes which were then compared with land systems of the area. The land systems were mapped from the interpretation of aerial photography backed by ground survey. The results showed that many land systems were recognised as distinct spectral classes or as acceptably homogeneous combinations of several spectral classes. However, the recognition that these combinations of spectral classes constituted a land system, and the subsequent delineation of that land system was carried out by the photo-interpreter, and not by spectral classifier.

Available evidence suggests that land systems mapping is best carried out by the human interpreter using computer processed imagery with its higher information content. Automated classification methods that rely on a spectral approach cannot convey sufficient information on the all important spatial aspects of the image, and spatial processing algorithms are presently inadequate for the task. The non-applicability of the spectral approach may not apply in some relatively simple, high contrasting environments of the arid tropics. However, spectral land system mapping in the more vegetated parts of the semi-arid, sub-humid and humid tropics seems less likely to succeed.

The automated mapping of soils and landforms from digital LANDSAT data is subject to the same constraints that apply to the automated classification of land systems, in that, so much of the information relating to soil and landform properties is contained in the spatial image characteristics. Inferences concerning soils and landforms are made by analysis of these spatial data in association with spectral data and context related information. From the limited number of automated soil mapping studies carried out, it is apparent that the utility of a spectral classification will be largely determined by the ground conditions and in particular, by what proportion of the reflected energy is from bare soil. The paucity of vegetation cover in the arid tropic means that a spectral approach to soil mapping may yield useful results although other factors, such as the state of tillage and moisture content of the soil, will affect the surface reflectance and hence the automated classification. The work of Kirschner et al. (1977) clearly demonstrates the potential of automated methods of soil mapping when the soil surface is exposed and the tillage and moisture status are known. Digital analysis of LANDSAT MSS data was used to prepare a spectral soil map for a 430 ha area in Clinton County, Indiana. Using a clustering algorithm fifteen spectral classes were defined, representing twelve soil and three vegetation classes. The twelve soil classes were grouped into four moisture regimes based upon their spectral responses and the spectral map compared with a conventionally prepared soil map of the area. Results showed that the spectral map contained the same soil units delineated on the conventional soil map and that in addition, it identified inclusions within each mapping unit that had different drainage characteristics from those designated on the conventional map. Field checks on a major portion of the questionable areas revealed the spectral classification to be correct. In this instance digital classification of LANDSAT data provided data on soils that were not readily discernible through visual interpretation.

The success of the above study must be viewed in perspective when considering the applicability of digital classification and mapping of soils in regions of the Third World. The Indiana study was carried out over a very small area under ideal field conditions and was able to rely on total ground verification. These conditions rarely exist in the developing countries, particularly those of the African Sahel and Savanna zones where the need for rapid regional mapping of soils is acute. For, as the National Academy of Sciences (1977) observes, one must be very cautious in extrapolating from the results of remote sensing studies in the United States to the potential net benefits such systems might produce in other parts of the world. To date, the majority of soil mapping from LANDSAT imagery in the Third World countries has relied on manual methods of interpretation. This situation is likely to remain for the foreseeable future until the regional soil mapping requirements are completed, spatial processing methods are considerably improved and the net benefits of these very expensive methods of analysis proven beyond reasonable doubt.

CONCLUSIONS

It is generally accepted by resource scientists that a digital capability is essential to handle and extract the maximum amount of information from the vast quantities of LANDSAT data available. Digital processing permits an investigator to exploit the total information content of the original satellite data, unlike the film and print output, which loses information content with each successive processing of the same scene. This demand for digital processing will increase over the next decade as more space platforms become available for imaging the earth's surface.

The fundamental issue seems to be the relative emphasis that should be placed on digital pre-processing using man and computer in an interactive mode to produce 'hard copy' imagery for manual interpretation, vis à vis digital processing followed by automated methods of classification and mapping.

Automated classification methods are still in a state of flux. The spectral approach using both supervised and unsupervised techniques has potential for local land-use, vegetation, and to a lesser extent, soil mapping in certain agro-climatic conditions. The American mid-west and parts of California provide ideal conditions for automated detailed land-use mapping. Large scale irrigation schemes concentrating on one or two major crops a year, in both the dry tropics (Gezira in the Sudan and Lower Indus Project, Pakistan) and the wet tropics (rice growing in the Far East) cloud cover permitting, may also be mapped and regularly monitored using a spectral signature approach.

For the majority of resource mapping problems in the developing world, particularly the regional mapping of soils, geology, geomorphology and vegetation, experience to date suggests that manual interpretation of digitally pre-processed imagery, using interpreter and computer in an interactive mode, is preferable. A spectral approach to such regional mapping problems cannot classify the spatial properties of size, shape and pattern which are so valuable to the human interpreter. The development of spatial algorithms capable of performing these tasks to the required standard lies somewhere in the future. Indeed, one may argue that precisely because the eye/brain mechanism copes so well with spatial problems and context related data, that these facets of image analysis are best left to the human interpreter. Automated methods may then be concentrated on refining the spectral classification techniques for those applications considered appropriate.

When interpreting a pictorial image the human interpreter is to a varying degree subjective, imprecise, spectrally unreliable and lacking in rapid numeracy compared with a computer based system. However, the human eye/brain mechanism can scan an image and deduce significant information from that image, commensurate with the interpreter's reference level, of a nature, and at a speed and cost, currently beyond the capabilities of automated systems.

REFERENCES

BAUMGARDNER, M.F. (1974). Identifying and Mapping Earth Surface Features in Sudan's Kordofan Province by Computer Assisted Analysis of ERTS-1 Multispectral Data. Unpublished Report, FAO, Rome.

BOND, A.D. and ATKINSON, R.J. (1972). An Integrated Feature Selection and Supervised Learning Scheme for Fast Computer Classification of Multispectral Data. Proc. Earth Resources Observation and Information Analysis System Conference, University of Tennessee Space Institute, p. 645.

CUSTANCE, N.D.E., O'HAGAN, M. and SERLE, P.P.O. (1977). Earth Resource Surveys and their Interpretation - an Introduction. Systems Technology No.26 pp. 9-14.

ESTES, J.E. (1977). A Perspective on the State of the Art of Photographic Interpretation. In: Proceedings of the Eleventh International Symposium on Remote Sensing of Environment, Vol.1, ERIM, Ann Arbor, Michigan, pp.161-177.

GENDEREN, J.L. VAN (1975). Visual Interpretation of Remote Sensing Data and Electronic Image Enhancement Techniques. Remote Sensing Data Processing. Published for Remote Sensing Society by University of Sheffield, pp.19-51.

GRAMENOPOULOS, N. and CORBETT, F. (1973). Diffraction Analysis of ERTS-1 Images. Technical Report of ERTS-1 Investigation.

KALENSKY Z.D., DARMOYUWONE, K. and POTTS, T.F. (1978). Thematic Map of Lombok Island from LANDSAT Computer Compatible Tapes. In: Summaries Twelfth International Symposium on Remote Sensing of Environment, Manila, Philippines. ERIM, Ann Arbor, Michigan. pp. 163-164.

KIRSCHNER, F.R., KAMINSKY, S.A., HINZEL, E.J., SINCLAIR, H.R. and WEISMILLER R.A. (1977). Quantification of Soil Mapping by Digital Analysis of LANDSAT Data. In: Proceedings of the Eleventh International Symposium on Remote Sensing of Environment, Ann Arbor, University of Michigan, pp. 1567-1573.

KLASS, J. (1977). New Techniques Spur LANDSAT Data Use. Aviation Week. October 17, pp. 48-65.

KRUMPE, P.F., NICHOLS, J.D. and LAUER, D.T. (1973). ERTS-1 Analysis of Wildland Resources using Manual and Automatic Techniques. In: Symposium Proceedings, Management and Utilisation of Remote Sensing Data, American Society of Photogrammetry, Sioux Falls, South Dakota. pp. 50-66.

LACHOWSKI, H.M., DIETRICH, P.L., UMALI, R., AQUINO, E. and BASA, V. (1978). LANDSAT assisted Forest Inventory of the Philippine Islands. In: Summaries Twelfth International Symposium on Remote Sensing of Environment, Manila, Philippines, ERIM, Ann Arbor, Michigan. pp. 170-171.

MADHAVAN UNNI, N.V. (1978). Computer Classification and Delineation of Types Using LANDSAT-1 Data in two areas of Tropical Forests of India. In: Summaries Twelfth International Symposium on Remote Sensing of Environment, Manila, Philippines, ERIM, Ann Arbor, Michigan, p.182.

NATIONAL ACADEMY OF SCIENCES (1977). Resource Sensing from Space, Prospects for Developing Countries. Washington, D.C.

ROBINOVE, C.J. (1977). Experimental Land System Mapping with Digital LANDSAT Images. In: Proceedings of the Eleventh International Symposium on Remote Sensing of Environment, Ann Arbor, University of Michigan, p.1241.

SMEDES, H.W., LINNERUD, H.J., WOOLAVER, L.B. and HAWKS, S.J. (1971). Digital computer mapping of terrain by clustering techniques using colour films as a three-band sensor. In: Proceedings of the Seventh International Symposium on Remote Sensing of Environment, Ann Arbor, University of Michigan, pp. 2057-71.

STANLEY, D.J. (1978). Digital Analysis of Radar Imagery for Vegetation Detection in Nigeria. In: Remote Sensing Applications in Developing Countries. Pub. by Remote Sensing Society, pp. 63-74.

THIE, J. (1976). An evaluation of remote sensing techniques for ecological (biophysical) land classification in northern Canada. Ecological (Biophysical) Land Classification in Canada, Ecological Land Classification Series, No.1, edited by J. Thie and G. Ironside, Lands Directorate Environment Canada, pp.129-147.

WISPELAERE, G. de and WAKSMAN, G. (1977). Contribution du traitement des images - satellite à la cartographie des pâturages sahéliens. Institut d'Elevage et de Médecine Vétérinaire de Pays Tropicaux, 30(4): pp. 407-424.

APPENDIX C

COMPUTER DATA SHEETS

```
:EVS8025,BASICS

#LISTING OF :EVS8025.BASICS(1/8180) PRODUCED ON  4JAN79 AT 15.31.18

#GP.62T AT ASTON    IN ':EVS8025.BASICS' ON  4JAN79 AT 15.31.22 USING  U14

DOCUMENT     :EVS8025.BASICS(/8180)

STARTED :EVS8025,BASICS, 4JAN79 15.25.48 TYPE: BACK  10 : STREAM A : PRIORITY 1 : ENTERED WELL  4JAN79 15.24.59
15.25.48+ JOB :EVS8025,BASICS,JD(JT60,MZ40K)
15.25.48 JOB IS NOW FULLY STARTED
15.25.49+ BASICS
15.25.49+ UAFORTRAN OWNPD
ENTERING :MACROS.UAFORTRAN(206/)
15.25.50+   ,    TA AB,CM,JL

UAFORTRAN: STATUS REPORT NUMBER 3  DATE 25 FEB  77

FORTRAN COMPILATION BY #XFIV MK 3B     DATE  04/01/79  TIME  15/26/04

          LIST(LP)
          PROGRAM(FPCT)
          INPUT 5=CR0
          OUTPUT 6=LP0
          COMPRESS INTEGER AND LOGICAL
          COMPACT
          TRACE 0
          END

          MASTER BASICS
          DIMENSION IUNIT(11,11),ISEQ(11),SQUARE(22),TOTAL(22)
          DATA TOTAL/22*0.0/
          STEP=6.25
          DO 100 ISQARE=1,33
          DO 10 I=1,22
          SQUARE(I)=0.0
       10 CONTINUE
          READ(5,21) JY1,JY2,JX1,JX2,(IUNIT(J,1),J=1,11),ISEQ(1)
          DO 20 I=2,11
          READ(5,21)      IY1,IY2,IX1,IX2,(IUNIT(J,I),J=1,11),ISEQ(I)
       21 FORMAT(4I2,12I3)
          IF(IY1.NE.JY1.OR.IY2.NE.JY2.OR.IX1.NE.JX1.OR.IX2.NE.JX2) GO TO 901
       20 CONTINUE
          DO 25 I=1,11
          IF(ISEQ(I).NE.I) GO TO 901
       25 CONTINUE
          DO 30 I=1,11
          DO 30 J=1,11

          IF(IUNIT(I,J).EQ.0) GO TO 30
          IF(IUNIT(I,J).GT.22) GO TO 902
          K=IUNIT(I,J)
          SQUARE(K)=SQUARE(K)+STEP
          TOTAL(K)=TOTAL(K)+STEP
       30 CONTINUE
          WRITE(6,31) IY1,IY2,(SQUARE(I),I=1,11),IX1,IX2,(SQUARE(I),I=12,22)
       31 FORMAT(1H0,I2,1X,I2,2H N,11F10.2/  2(1X,I2),2H E,11F10.2)
      100 CONTINUE
          WRITE(6,90) TOTAL
       90 FORMAT(7H0ENTIRE ,1X,11F10.2/5H AREA ,3X,11F10.2)
          STOP
      902 WRITE(6,802) ISQARE,I,J
      802 FORMAT(23H0INVALID DATA IN SQUARE ,I2, 5H ROW ,I2, 8H COLUMN ,I2)
          STOP
      901 WRITE(6,801) ISQARE
      801 FORMAT(29H0DATA OUT OF ORDER FOR SQUARE ,I2)
          STOP
          END

END OF SEGMENT, LENGTH   230, NAME  BASICS

          FINISH

END OF COMPILATION -  NO ERRORS

     S/C SUBFILE  :    10 BUCKETS USED

CONSOLIDATED BY XPCK 12H     DATE     04/01/79    TIME 15/27/06

     *SHORTLIST

     *IN ED (FORTSEMICOMP)

     *LIB ED (SUBGROUPSRF4.SUBROUTINES)

     *WORK ED (FORTWORKFILE)

     ****

PROGRAM FPCT
COMPACT DATA (15AM)
COMPACT PROGRAM (DBM)
CORE          3072

ALLOT     *CR0     N
0.09: MONITOR
ALLOT     *LP0     N
0.10: MONITOR
15.31.15 FREE *CR0 ,363 TRANSFERS
15.31.15 FREE *LP0 ,69 TRANSFERS
0.18 :DELETED , 00
15.31.15 0.18 DELETED,CLOCKED 0.08
DISPLAY: UAFORTRAN: NORMAL EXIT
15.31.17 0.19 FINISHED : 2 LISTFILES
15.31.17 JOBTIME USED 19 ; MAXIMUM CORE USED 32576
15.31.17 JOB UNITS 41
```

*EVS8025.BASICS **Map 1**

#LISTING OF :WORKFILE.AAA00010301(1/) PRODUCED ON 9JAN79 AT 09.47.52

#G0,62T AT ASTON IN ':EVS8025.BASICS' ON 9JAN79 AT 09.52.15 USING U14

DOCUMENT 1

11 45 N	0.00	656.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24 0 E	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00
11 45 N	6.25	506.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	31.25	0.00
24 15 E	0.00	0.00	0.00	118.75	0.00	93.75	0.00	0.00	0.00	0.00	0.00
11 45 N	406.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.75	0.00
24 30 E	0.00	0.00	0.00	256.25	0.00	56.25	0.00	0.00	0.00	0.00	0.00
11 45 N	337.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24 45 E	0.00	0.00	0.00	0.00	0.00	31.25	0.00	256.25	0.00	0.00	0.00
11 30 N	537.50	112.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.50	0.00
24 0 E	0.00	0.00	0.00	0.00	0.00	93.75	0.00	0.00	0.00	0.00	0.00
11 30 N	350.00	118.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24 15 E	75.00	0.00	0.00	0.00	0.00	212.50	0.00	0.00	0.00	0.00	0.00
11 30 N	93.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	125.00	0.00
24 30 E	206.25	0.00	0.00	200.00	0.00	100.00	0.00	31.25	0.00	0.00	0.00
11 30 N	75.00	0.00	0.00	0.00	0.00	0.00	56.25	0.00	0.00	431.25	0.00
24 45 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	193.75	0.00	0.00	0.00
11 15 N	512.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	62.50	0.00
24 0 E	0.00	0.00	168.75	0.00	0.00	6.25	6.25	0.00	0.00	0.00	0.00
11 15 N	81.25	0.00	0.00	0.00	0.00	0.00	50.00	0.00	0.00	75.00	0.00
24 15 E	25.00	12.50	343.75	0.00	118.75	50.00	0.00	0.00	0.00	0.00	0.00
11 15 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	500.00	0.00
24 30 E	68.75	0.00	6.25	0.00	0.00	31.25	0.00	0.00	0.00	0.00	150.00
11 15 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	587.50	0.00
24 45 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	168.75
11 0 N	62.50	0.00	0.00	0.00	0.00	81.25	68.75	0.00	0.00	31.25	0.00
24 0 E	0.00	418.75	93.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11 0 N	0.00	0.00	0.00	0.00	0.00	18.75	100.00	0.00	0.00	225.00	0.00
24 15 E	0.00	43.75	56.25	0.00	93.75	0.00	0.00	0.00	218.75	0.00	0.00
11 0 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	131.25	0.00
24 30 E	0.00	225.00	256.25	0.00	68.75	0.00	0.00	0.00	0.00	0.00	75.00
11 0 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	137.50	225.00	0.00
24 45 E	0.00	150.00	93.75	0.00	0.00	0.00	0.00	6.25	0.00	0.00	143.75
10 45 N	0.00	0.00	0.00	0.00	0.00	6.25	0.00	0.00	0.00	625.00	0.00
24 0 E	0.00	118.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.25	0.00
10 45 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	562.50	0.00
24 15 E	0.00	56.25	0.00	0.00	6.25	0.00	0.00	0.00	87.50	43.75	0.00
10 45 N	0.00	0.00	0.00	0.00	0.00	75.00	0.00	0.00	0.00	387.50	0.00
24 30 E	0.00	25.00	137.50	0.00	56.25	0.00	0.00	0.00	75.00	0.00	0.00
10 45 N	0.00	0.00	0.00	0.00	0.00	143.75	0.00	0.00	0.00	12.50	0.00
24 45 E	0.00	206.25	343.75	0.00	0.00	0.00	31.25	0.00	18.75	0.00	0.00
10 45 N	0.00	0.00	0.00	0.00	0.00	18.75	0.00	0.00	0.00	12.50	0.00
25 0 E	0.00	31.25	506.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 30 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	756.25	0.00
24 0 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 30 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	756.25	0.00
24 15 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 30 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	756.25	0.00
24 30 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 30 N	0.00	0.00	0.00	0.00	0.00	175.00	0.00	0.00	50.00	468.75	0.00
24 45 E	0.00	0.00	6.25	0.00	0.00	0.00	43.75	0.00	12.50	0.00	0.00
10 30 N	0.00	0.00	0.00	0.00	0.00	318.75	0.00	0.00	31.25	6.25	0.00
25 0 E	0.00	0.00	300.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00
10 30 N	0.00	0.00	0.00	0.00	0.00	93.75	0.00	0.00	0.00	6.25	0.00
25 15 E	0.00	0.00	112.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 15 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	256.25	0.00
24 0 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 15 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	387.50	0.00
24 15 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 15 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	500.00	0.00
24 30 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 15 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	75.00	506.25	0.00
24 45 E	0.00	0.00	0.00	0.00	0.00	0.00	31.25	0.00	0.00	0.00	0.00
10 15 N	0.00	0.00	0.00	0.00	0.00	156.25	0.00	0.00	156.25	6.25	0.00
25 0 E	0.00	0.00	0.00	0.00	93.75	0.00	187.50	0.00	0.00	0.00	0.00
10 15 N	0.00	0.00	0.00	0.00	0.00	75.00	0.00	0.00	0.00	0.00	0.00
25 15 E	0.00	0.00	0.00	0.00	18.75	0.00	6.25	0.00	0.00	0.00	0.00
ENTIRE	2462.50	1593.75	0.00	0.00	0.00	1162.50	275.00	0.00	450.00	8462.50	0.00
AREA	375.00	1287.50	2225.00	575.00	456.25	775.00	406.25	487.50	412.50	50.00	537.50

:EVS8025.BASICS **Map 2**

#LISTING OF :WORKFILE.AAAD00004474(1/) PRODUCED ON 4JAN79 AT 15.31.15

#G0.02T AT ASTON IN ':EVS8025.BASICS' ON 4JAN79 AT 15.31.16 USING U14

DOCUMENT 1

11 45 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	681.25
24 0 E	0.00	0.00	0.00	0.00	0.00	75.00	0.00	0.00	0.00	0.00	0.00
11 45 N	43.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	518.75
24 15 E	0.00	0.00	0.00	93.75	0.00	100.00	0.00	0.00	0.00	0.00	0.00
11 45 N	181.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24 30 E	93.75	0.00	0.00	293.75	0.00	156.25	0.00	0.00	0.00	0.00	0.00
11 45 N	168.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24 45 E	0.00	0.00	0.00	0.00	0.00	37.50	0.00	412.50	0.00	0.00	0.00
11 30 N	368.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	243.75
24 0 E	0.00	0.00	0.00	0.00	0.00	143.75	0.00	0.00	0.00	0.00	0.00
11 30 N	343.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	187.50
24 15 E	12.50	0.00	0.00	0.00	0.00	212.50	0.00	0.00	0.00	0.00	0.00
11 30 N	50.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.50	0.00
24 30 E	262.50	0.00	0.00	156.25	0.00	131.25	0.00	143.75	0.00	0.00	0.00
11 30 N	37.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	518.75	0.00
24 45 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	200.00	0.00	0.00	0.00
11 15 N	406.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	106.25	0.00
24 0 E	0.00	43.75	106.25	0.00	0.00	93.75	0.00	0.00	0.00	0.00	0.00
11 15 N	243.75	0.00	0.00	0.00	0.00	0.00	56.25	0.00	0.00	112.50	0.00
24 15 E	18.75	0.00	0.00	0.00	37.50	225.00	0.00	0.00	0.00	0.00	12.50
11 15 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	537.50	0.00
24 30 E	50.00	0.00	0.00	0.00	0.00	50.00	0.00	0.00	0.00	0.00	118.75
11 15 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	750.00	0.00
24 45 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.25
11 0 N	12.50	0.00	0.00	0.00	0.00	68.75	0.00	0.00	0.00	81.25	0.00
24 0 E	0.00	450.00	137.50	0.00	0.00	0.00	0.00	0.00	6.25	0.00	0.00
11 0 N	12.50	0.00	0.00	0.00	0.00	0.00	125.00	0.00	0.00	212.50	0.00
24 15 E	0.00	37.50	37.50	0.00	137.50	0.00	0.00	0.00	187.50	0.00	6.25
11 0 N	0.00	0.00	0.00	0.00	0.00	25.00	0.00	0.00	18.75	118.75	0.00
24 30 E	0.00	237.50	175.00	0.00	87.50	0.00	0.00	0.00	0.00	0.00	93.75
11 0 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	275.00	225.00	0.00
24 45 E	0.00	206.25	18.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	31.25
10 45 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	556.25	0.00
24 0 E	0.00	175.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.00	0.00
10 45 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	618.75	0.00
24 15 E	0.00	50.00	0.00	0.00	18.75	0.00	0.00	0.00	25.00	43.75	0.00
10 45 N	0.00	0.00	0.00	0.00	0.00	125.00	0.00	0.00	0.00	400.00	0.00
24 30 E	0.00	31.25	125.00	0.00	75.00	0.00	0.00	0.00	0.00	0.00	0.00
10 45 N	0.00	0.00	0.00	0.00	0.00	162.50	0.00	0.00	0.00	31.25	0.00
24 45 E	0.00	293.75	268.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 45 N	0.00	0.00	0.00	0.00	0.00	31.25	0.00	0.00	0.00	0.00	0.00
25 0 E	0.00	162.50	150.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 30 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	756.25	0.00
24 0 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 30 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	756.25	0.00
24 15 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 30 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	756.25	0.00
24 30 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 30 N	0.00	0.00	0.00	0.00	0.00	162.50	0.00	0.00	12.50	506.25	0.00
24 45 E	0.00	0.00	75.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 30 N	0.00	0.00	0.00	0.00	0.00	400.00	0.00	0.00	12.50	0.00	0.00
25 0 E	0.00	31.25	206.25	0.00	0.00	0.00	106.25	0.00	0.00	0.00	0.00
10 30 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25 15 E	0.00	0.00	62.50	0.00	0.00	0.00	143.75	0.00	0.00	0.00	0.00
10 15 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	306.25	0.00
24 0 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 15 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	400.00	0.00
24 15 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 15 N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	506.25	0.00
24 30 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 15 N	0.00	0.00	0.00	0.00	0.00	6.25	0.00	0.00	6.25	600.00	0.00
24 45 E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 15 N	0.00	0.00	0.00	0.00	0.00	287.50	0.00	0.00	150.00	50.00	0.00
25 0 E	0.00	0.00	0.00	0.00	75.00	0.00	75.00	0.00	0.00	0.00	0.00
10 15 N	0.00	0.00	0.00	0.00	0.00	43.75	0.00	0.00	0.00	0.00	0.00
25 15 E	0.00	0.00	0.00	0.00	6.25	0.00	31.25	0.00	0.00	0.00	0.00
ENTIRE	1918.75	0.00	0.00	0.00	0.00	1312.50	181.25	0.00	475.00	8918.75	1631.25
AREA	437.50	1718.75	1362.50	543.75	437.50	1275.00	356.25	756.25	218.75	68.75	268.75

```
STARTED :EVJ0025,SAMPLING, 9FEB79 12.03.23 TYPE: BACK 13 : STREAM 6 : PRIORITY 1 : ENTERED WELL 9FEB79 12.02.11
12.03.24= JOB :EV,B025,SAMPLING,JD(JT300,MZ40K)
12.03.25 JOB IS NOW FULLY STARTED
12.03.26= SAMPLING
12.03.26= U:FORTRAN BOURN,LIB HAGE
ENTERING :MACROS,XAFORTRAN(2967)
12.03.26=          TA AR,CH,JL

UAFORTRAN: STATUS REPORT NUMBER 3  DATE 25 FEB 77

FORTRAN COMPILATION BY #XFIV MK 3A    DATE 09/02/79  TIME 12/07/04


                     LIST(LP)
                     PROGRAM(FACT)
                     INPUT 5=CR0
                     OUTPUT 6=LP0
                     COMPRESS INTEGER AND LOGICAL
                     COMPACT
                     TRACE 0
                     END


                     MASTER SAMPLING
                     DIMENSION INIT(3003),ISEL(3003),SAMPL (22),SUM1(22),SUM2(22)
                     READ(5,1) INIT
                   1 FORMAT(6X,11I3)
                     NTOT=0
                     DO 40 I=1,3003
                     IF(INIT(I).EQ.0) GO TO 40
                     NTOT=NTOT+1
                     INIT(NTOT)=INIT(I)
                  40 CONTINUE
                     NSAM=NTOT
                     NREPT=1
                     GO TO 12
                  10 READ(5,11,END=60) NSAMP,NREPT
                  11 FORMAT(2I5)
                  12 DO 15 I=1,22
                     SUM1(I)=0.0
                     SUM2(I)=0.0
                  15 CONTINUE

                     STEP=NTOT*0.25/NSAMP
                     DO 20 IREPT=1,NREPT
                     DO 21 I=1,22
                     SAMPL (I)=0.0
                  21 CONTINUE
                     CALL SAMPLE(NSAMP,NTOT,ISEL)
                     DO 25 I=1,NTOT
                     IF(ISEL(I).EQ.0) GO TO 25
                     K=INIT(I)
                     IF(K.EQ.0) GO TO 25
                     SAMPL(K)=SAMPL(K)+STEP
                  25 CONTINUE
                     DO 27 I=1,22
                     SUM1(I)=SUM1(I)+SAMPL(I)
                     SUM2(I)=SUM2(I)+SAMPL(I)**2
                  27 CONTINUE
                  20 CONTINUE
                     DO 30 I=1,22
                     SUM1(I)=SUM1(I)/NREPT
                     SUM2(I)=SQRT(SUM2(I)/NREPT-SUM1(I)**2)
                  30 CONTINUE
                     WRITE(6,32) NSAMP,NREPT
                  32 FORMAT(////' SAMPLE OF ',I4,' POINTS TAKEN ',I4,' TIMES')
                     WRITE(6,34) (SUM1(I),I=1,11),(SUM2(I),I=1,11),(SUM1(I),I=12,22),
                    1            (SUM2(I),I=12,22)
                  34 FORMAT('0',11F10.2/1X,11F10.2)
                     GO TO 10
                  60 STOP
                     END

END OF SEGMENT, LENGTH  245, NAME  SAMPLING

                     SUBROUTINE SAMPLE(NS,MAX,IS)
                     DIMENSION IS(MAX),CRAND(4001),KRAND(4000)
                     INTEGER GUSSZF
                     DATA MAXSET/0/
                     IF(MAX.EQ.MAXSET) GO TO 5
                     IF(MAX.GT.4000) STOP 'TOO BIG'
                     MAXP1=MAX+1
                     CALL G05AFF(1,MAX,MAXP1,CRAND,KRAND,MAX+1,MAX)
                     MAXSET=MAX
                   5 IF(NS.GT.MAX) STOP 'OVERSIZE SAMPLE'
                     IF(NS.GT.MAX/2)          GO TO 6
                     MAJOR=0
                     KR=NS
                     GO TO 7
                   6 MAJOR=1
                     KR=MAX-NS
                   7 MINOR=1-MAJOR
                     DO 1 I=1,MAX
                     IS(I)=MAJOR
                   1 CONTINUE
                     DO 2 I=1,KR
                   3 J=G05EZF(MAXP1,CRAND,KRAND,MAX)
                     IF(IS(J).NE.MAJOR) GO TO 3
                     IS(J)=MINOR
                   2 CONTINUE
                     RETURN
                     END


END OF SEGMENT, LENGTH  117, NAME  SAMPLE

                     FINISH

END OF COMPILATION - NO ERRORS

     S/C SUMFILE :    13 BUCKETS USED

CONSOLIDATED BY XPCK 12A    DATE   09/02/79   TIME 12/17/05

         *SHORTLIST

         *IN ED (FORTSEMICOMP)

         *LIB ED (SUBGROUPNAGF,SUBROUTINES)

         *LIB ED (SUBGROUPSRF4,SUBROUTINES)

         *WORK ED (FORTWORKFILE)

         ****

PROGRAM FACT
COMPACT DATA (15AM)
COMPACT PROGRAM (DBM)
CORE            23036

ALLOT       *CR0    0
0.1K: MONITOR
ALLOT       *LP0    0
0.1K: MONITOR
13.13.07 FREE *CR0 ,371 TRANSFERS
13.13.08 FREE *LP0 ,73 TRANSFERS
1.49 :DELETED : 0?
13.13.09 1.49 DELETED,CLOCKED 1.3?
DISPLAY: UAFORTRAN: NORMAL EXIT
13.13.13 1.49 FINISHED : 2 LISTFILES
13.13.13 JOBTIME USED 11? : MAXIMUM CORE USED 32576
13.13.13 JOB UNITS 242

*.VVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVV
*VVVVV.VV
*VVVVVVVV        NUMBER OF PAGES    3
*VVVVV.VV
```

:EVS8025.SAMPLING **Map 1**

#LISTING OF :WORKFILE.AAAD0000136(1/) PRODUCED ON 9FEB79 AT 13.13.08

#G8.62T AT ASTON IN ':EVS8025.SAMPLING' ON 9FEB79 AT 13.13.11 USING U14

DOCUMENT 1

SAMPLE OF 3407 POINTS TAKEN 1 TIMES

2456.25	1393.75	0.00	0.00	0.00	1162.50	275.00	0.00	450.00	8462.50	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
375.00	1287.50	2225.00	575.00	456.25	775.00	406.25	487.50	412.50	50.00	537.50
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

SAMPLE OF 2000 POINTS TAKEN 20 TIMES

2489.04	1401.34	0.00	0.00	0.00	1136.00	270.79	0.00	442.96	8466.87	0.00
87.75	61.36	0.00	0.00	0.00	73.49	42.80	0.00	43.76	124.39	0.00
380.35	1271.67	2193.59	574.27	469.66	700.57	410.81	472.92	420.07	52.85	543.21
36.33	67.39	92.63	56.95	48.48	52.09	38.30	54.20	45.91	12.56	43.76

SAMPLE OF 1500 POINTS TAKEN 20 TIMES

2501.92	1407.83	0.00	0.00	0.00	1123.10	267.34	0.00	467.11	8447.26	0.00
127.79	94.60	0.00	0.00	0.00	83.03	41.45	0.00	53.83	199.24	0.00
369.04	1299.63	2202.02	581.17	438.05	812.18	431.52	470.74	390.83	51.58	531.77
52.06	74.15	143.27	75.50	44.01	66.41	51.59	51.86	49.68	19.75	57.28

SAMPLE OF 1000 POINTS TAKEN 20 TIMES

2486.67	1419.86	0.00	0.00	0.00	1171.41	268.06	0.00	451.13	8420.02	0.00
169.03	160.54	0.00	0.00	0.00	120.34	66.14	0.00	80.40	312.29	0.00
371.53	1298.91	2234.50	584.46	424.80	784.58	401.00	450.04	436.96	52.30	539.40
55.34	133.17	232.44	73.23	79.00	95.99	92.05	61.75	70.78	32.62	72.90

SAMPLE OF 500 POINTS TAKEN 20 TIMES

2549.87	1353.39	0.00	0.00	0.00	1133.27	268.06	0.00	427.16	8399.31	0.00
308.38	194.13	0.00	0.00	0.00	246.18	106.12	0.00	106.41	344.07	0.00
372.67	1292.37	2218.42	573.18	483.32	786.75	392.29	481.64	420.62	50.13	592.79
132.55	173.95	263.97	110.59	154.66	173.52	116.14	180.49	125.02	39.65	143.51

SAMPLE OF 250 POINTS TAKEN 20 TIMES

2365.78	1304.29	0.00	0.00	0.00	1216.09	283.32	0.00	435.87	8508.28	0.00
344.64	308.53	0.00	0.00	0.00	224.76	192.72	0.00	176.52	559.82	0.00
335.62	1461.97	2175.02	614.53	501.26	727.91	405.36	483.82	357.42	52.30	544.84
133.00	228.99	356.75	160.76	200.46	263.37	168.31	273.56	150.74	69.74	262.79

SAMPLE OF 100 POINTS TAKEN 20 TIMES

2451.83	1503.77	0.00	0.00	0.00	1176.86	348.70	0.00	403.18	8815.57	0.00
1023.66	429.84	0.00	0.00	0.00	484.39	270.45	0.00	339.56	1317.53	0.00
1305.11	1167.76	2031.30	688.50	381.59	740.99	392.29	446.77	294.22	65.38	512.15
211.39	438.46	566.11	428.37	307.25	303.55	312.80	279.73	231.41	121.34	325.27

SAMPLE OF 25 POINTS TAKEN 20 TIMES

2920.36	1438.39	0.00	0.00	0.00	1176.86	305.11	0.00	174.35	8281.67	0.00
1241.29	965.83	0.00	0.00	0.00	065.83	415.80	-0.00	444.51	1919.83	0.00
348.70	1525.56	2222.96	435.87	435.87	653.81	740.99	261.52	305.11	0.00	566.64
427.97	989.16	1218.55	702.83	513.73	866.28	743.55	399.49	498.88	0.00	743.55

APPENDIX D

BOUNDARY COINCIDENCE INDEX TRANSECT DATA

RANDOM TRANSECT DATA: TOTAL AREA

Transect No.	Soil Unit	$\Sigma 1_1$ km	$\Sigma 1_2$ km	$\Sigma 1_3$ km	n_1	n_2	i
	bsr	46.0	37.5	37.5	17	27	
	Al_2a Al_2c	8.5	26.0	8.5			
	Al_2a Al_2b	11.0	14.5	11.0			79.5 x 17
1	bs	36.5	14.0	14.0			110.5 27
	Ae Nua	8.5	16.0	8.5			
	bs Ae	-	1.0	-			=0.45
	Ae	-	1.5	-			
	Totals	**110.5**	**110.5**	**79.5**			
	bs	45.0	34.5	34.5	18	19	
	Al_2a Al_2c	12.0	22.0	12.0			
	bs Ae	13.0	13.5	13.0			90.5 x 18
	Al_2a Al_2b	8.5	7.5	7.5			111 19
	Ae Nua	11.0	5.5	5.5			
	Ae	18.0	28.0	18.0			= 0.77
	Nua	3.5	-	-			
	Totals	**111.0**	**111.0**	**90.5**			
	bs	22.5	29.5	22.5	19	14	
3	Al_2a Al_2b Al_2c	6.0	6.0	6.0			88.5 x 14
	Ae	33.0	43.5	33.0			115 19
	Al_1b Al_2c	22.5	-	-			
	Nua	4.0	4.0	4.0			= 0.57
	Nur Nua	22.0	18.0	18.0			
	gal_3	5.0	14.0	5.0			
	Al_2a Al_2c		4.0	-	-		
	Totals	**115.0**	**115.0**	**88.5**			
	bs	21.0	19.0	19.0	24	24	
	Al_1b Al_2c	87.0	63.5	63.5			
	Ae	19.0	10.5	10.5			
	Nua	7.0	4.5	4.5			139.5 x 24
4	gal_3 Al_2b	3.0	19.0	3.0			176 24
	Al_2a Al_2b Al_2c	12.0	18.0	12.0			= 0.79
	Al_2c	19.5	23.5	19.5			
	Al_2b Al_2c	7.5	18.0	7.5			
	Totals	**176.0**	**176.0**	**139.5**			
	Al_1b Al_2c	13.0	4.5	4.5	15	14	
	bs	7.0	8.0	7.0			
	Al_1b Al_2b Al_2c	6.0	22.5	6.0			124 x 14
	Al_2c	11.0	9.0	9.0			167 15
5	Ae	85.0	110.5	85.0			
	gal_3	33.0	7.5	7.5			= 0.69
	Al_2b Al_2c	7.0	1.5	1.5			
	Al_2a Al_2b Al_2c	5.0	3.5	3.5			
	Totals	**167.0**	**167.0**	**124.0**			
	Ae	70.0	66.5	66.5	5	5	
	Al_2c	2.5	5.0	2.5			
6	Al_1b Al_2b Al_2c	22.5	22.5	22.5			122 x 5
	bs	41.0	30.5	30.5			136 5
	Al_1b Al_2c	-	11.0	-			= 0.90
	Totals	**136.0**	**135.5**	**122.0**			
	Ae	103.0	99.0	99.0	15	11	
	gal_3	8.5	15.0	8.5			
	Nua	3.5	6.5	3.5			179.5 x 11
7	Al_1b Al_2c	17.5	-	-			202.5 15
	bs	34.0	43.5	34.0			
	bsr	30.0	34.0	30.0			= 0.65
	Al_2a Al_2c	6.0	4.5	4.5			
	Totals	**205.5**	**205.5**	**179.5**			
	Ae	80.0	79.5	79.5	12	13	
	Al_1b Al_2b Al_2c	8.0	9.0	8.0			
	gal_3	5.0	3.0	3.0			135.5 x 12
	Al_2c	8.5	-	-			174 13
8	Al_1b Al_2c	18.0	24.5	18.0			
	bs	36.0	8.5	8.5			=0.72
	Al_2a Al_2c	2.0	21.5	2.0			
	bsr	16.5	28.0	16.5			
	Totals	**174.0**	**174.0**	**135.5**			
	bsr	10.5	13.0	10.5	27	27	
	bs	36.0	42.5	36.0			
	Al_2a Al_2c	3.0	10.0	3.0			
	Al_1b Al_2c	38.5	6.5	6.5			
	Nua	8.5	8.5	8.5			140.5 x 27
9	gal_3	22.0	3.0	3.0			206 27
	Al_1b Al_2b Al_2c	1.5	6.5	1.5			
	Ae	59.5	82.5	59.5			=0.68
	Al_2a Al_2b Al_2c	17.5	3.0	3.0			
	Al_2c	3.0	4.0	3.0			
	Al_2b Al_2c	6.0	86.5	6.0			
	Totals	**206.0**	**206.0**	**140.5**			
	Ae	74.5	75.5	74.5	9	5	
	gal_3 Al_2c	4.0	6.0	4.0			
	Al_2c	4.0	-	-			101.5 x 5
10	Al_1a Al_2b Al_2c	23.0	36.5	23.0			118 9
	Nua	8.5	-	-			= 0.48
	Al_2b Al_2c	4.0	-	-			
	Totals	**118.0**	**118.0**	**101.5**			
	Al_2c	6.5	12.0	6.5	17	14	
	Ae	76.0	93.0	76.0			
	gal_3 Al_2b	8.0	-	-			
	bs	5.0	2.0	2.0			
	Al_1b Al_2c	18.0	18.0	18.0			160 x 14
11	Al_1b Al_2b Al_2c	13.5	9.5	9.5			188 17
	Nur Nua	13.0	-	-			
	Al_2a Al_2c	6.0	6.0	6.0			= 0.70
	Al_2a Al_2b	34.5	36.5	34.5			
	bs Ae	7.5	11.0	7.5			
	Totals	**188.0**	**188.0**	**160.0**			
	Ae	85.0	88.5	85.0	20	18	
	gal_3	2.0	2.0	2.0			
	Al_2a Al_2b Al_2c	12.0	19.5	12.0			
	Al_1b Al_2c	14.0	-	-			160 x 18
12	Nur Nua	7.5	11.0	7.5			181 20
	Al_2a Al_2c	5.0	10.0	5.0			
	bs Ae	20.0	21.5	20.0			= 0.80
	Al_2a Al_2b	24.5	24.0	24.0			
	bs	11.0	4.5	4.5			
	Totals	**181.0**	**181.0**	**160.0**			
	Ae	85.5	106.0	85.5	14	12	
	gal_3	11.0	12.0	11.0			
	Al_2c	6.0	11.5	6.0			146.5 x 12
13	Al_1b Al_2c	11.5	10.5	10.5			173.5 14
	Al_1b Al_2b Al_2c	13.0	12.0	12.0			
	Nur Nua	16.5	-	-			= 0.72
	Ae Nua	30.0	21.5	21.5			
	Totals	**173.5**	**173.5**	**146.5**			
	Ae	36.5	41.5	36.5	7	6	
	gal_3	6.0	-	-			
14	Al_2c	12.0	12.0	12.0			62.5 x 6
	Al_2b Al_2c	4.0	-	-			76 7
	Al_1b Al_2c	17.5	14.0	14.0			= 0.70
	Al_1b Al_2b Al_2c	-	8.5	-			
	Totals	**76.0**	**76.0**	**62.5**			
	Al_1b Al_2b Al_2c	53.0	41.0	41.0	14	12	
	Al_2c	10.0	-	-			
	Ae	13.5	20.0	13.5			85 x 12
15	gal_3	11.0	3.0	3.0			115 14
	Al_2a Al_2b Al_2c	7.5	13.5	7.5			
	Al_1b Al_2c	20.0	37.5	20.0			= 0.63
	Totals	**115.0**	**115.0**	**85.0**			

RANDOM TRANSECT DATA: BAGGARA LAND SYSTEM (PART)

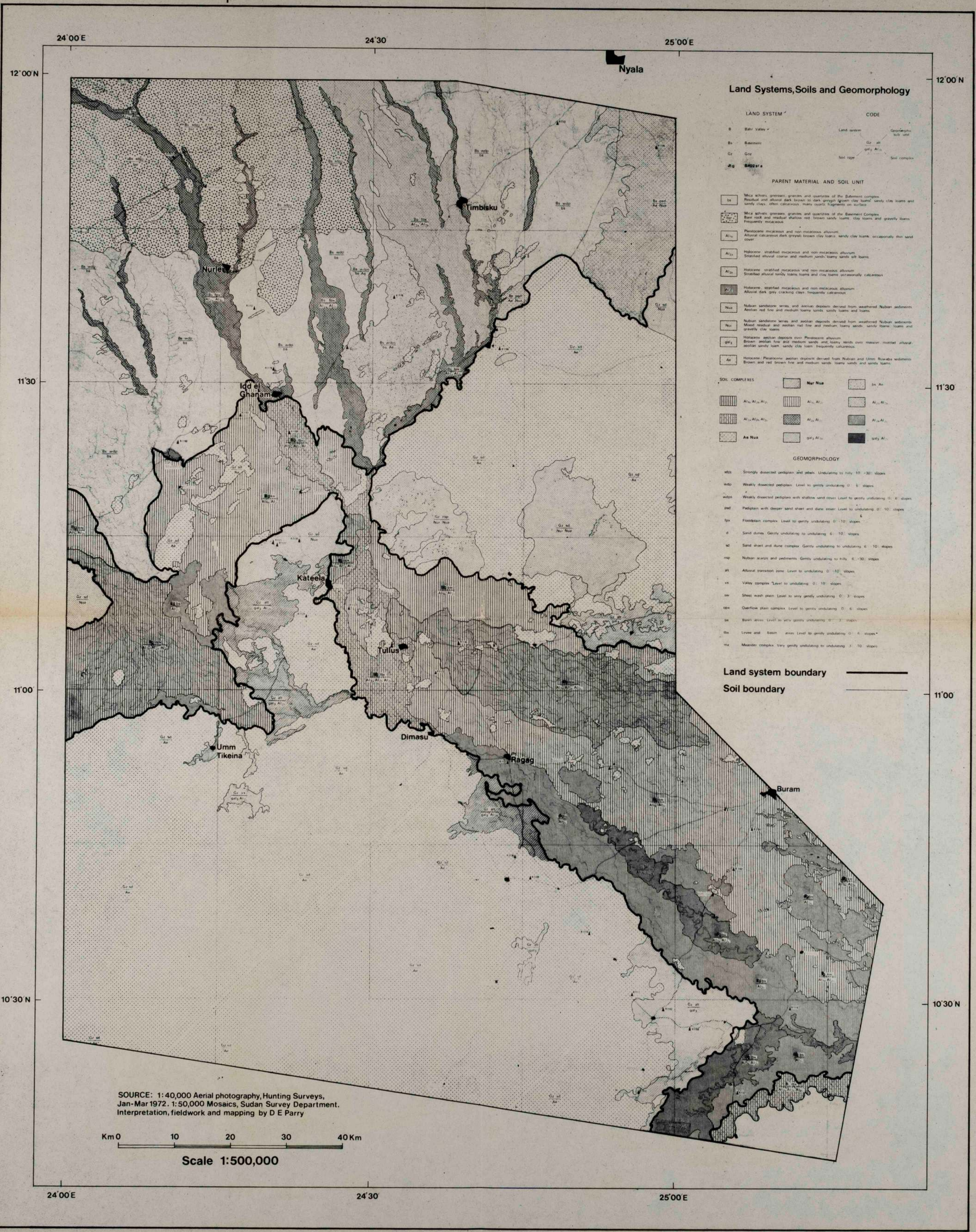
Transect No.	Soil Unit	Σl_1 mm.	Σl_2 mm	Σl_3 mm	n_1	n_2	i
1	Al_2a Al_2b Al_2c	10	8	8	1	1	13 x 1
	Al_1b Al_2c	6	5	5			16 1
	Totals	**16**	**13**	**13**			= 0.81
	Al_2a Al_2b Al_2c	12	12	12	3	2	37 x 2
2	Al_1b Al_2b Al_2c	14	15	14			40 3
	Al_1b Al_2c	14	19	11			= 0.62
	Totals	**40**	**42**	**37**			
	Al_1b Al_2c	24	17	17	3	3	
	Al_2c	0	2	0			29 x 3
3	Al_1b Al_2b Al_2c	12	20	12			37 3
	Al_2a Al_2b Al_2c	1	0	0			= 0.78
	Totals	**37**	**39**	**29**			
	Al_2c	14	17	14	3	5	
	Al_2b Al_2c	5	0	0			46 x 3
4	Al_1b Al_2c	37	32	32			56 5
	Al_1b Al_2b Al_2c	0	15	0			= 0.49
	Totals	**56**	**64**	**46**			
	Al_2c	21	25	21	5	10	
	Al_2b Al_2c	8	0	0			46 x 5
5	Al_1bAl_2c	25	27	25			54 10
	Al_1b Al_2b Al_2c	0	8	0			= 0.43
	Totals	**54**	**60**	**46**			
	Al_2c	20	26	20	5	2	
6	Al_2b Al_2c	15	16	15			40 x 2
	Al_1b Al_2c	13	5	5			48 5
	Totals	**48**	**47**	**40**			= 0.33
	Al_2a Al_2c	15	3	3	2	1	15 x 1
7	Al_2c	12	14	12			27 2
	Totals	**27**	**17**	**15**			= 0.28
	Al_2a Al_2b Al_2c	18	13	13	2	2	28 x 2
8	Al_1b Al_2b Al_2c	14	10	10			37 2
	Al_2c	5	9	5			= 0.76
	Totals	**37**	**32**	**28**			
	Al_1b Al_2c	23	31	23	5	5	
9	Al_1b Al_2b Al_2c	20	19	19			58 x 5
	Al_2c	22	16	16			67 5
	Ae	2	0	0			= 0.87
	Totals	**67**	**66**	**58**			
	Al_1b Al_2c	45	47	45	12	8	
	Al_1b Al_2b Al_2c	27	34	27			95 x 8
10	Al_2b Al_2c	28	2	2			128 12
	Al_2c	21	39	21			= 0.45
	Al_2a Al_2b Al_2c	7	0	0			
	Totals	**128**	**122**	**95**			

Transect No.	Soil Unit	Σl_1 mm	Σl_2 mm	Σl_3 mm	n_1	n_2	i
	Al_1b Al_2c	55	32	32	8	8	
	Al_1b Al_2b Al_2c	29	53	29			64 x 8
11	Al_2c	17	0	0			104 8
	x	3	11	3			= 0.62
	Totals	**104**	**103**	**64**			
	Al_2a Al_2b Al_2c	9	0	0	5	5	
	Al_1b Al_2c	17	15	15			
12	Al_2b Al_2c	5	0	0			22 x 5
	Al_2c	7	19	7			38 5
	Al_1b Al_2b Al_2c	0	8	0			= 0.58
	Totals	**38**	**42**	**22**			
	Al_2c	6	8	6	2	2	
	Al_1b Al_2c	11	17	11			38 x 2
13	Al_1b Al_2b Al_2c	27	21	21			44 2
	Totals	**44**	**46**	**38**			= 0.86
	Al_2c	8	13	8	6	6	
	Al_2b Al_2c	6	0	0			27 x 6
14	Al_1b Al_2c	24	7	7			50 6
	Al_1b Al_2b Al_2c	10	27	10			
	Ae	2	4	2			= 0.54
	Totals	**50**	**57**	**27**			
	Al_2a Al_2b Al_2c	1	3	1	3	6	
	Al_1b Al_2c	21	9	9			18 x 3
15	Al_1b Al_2b Al_2c	12	8	8			34 6
	Al_2b Al_2c	0	8	0			= 0 26
	Al_2c	0	6	0			
	Totals	**34**	**34**	**18**			

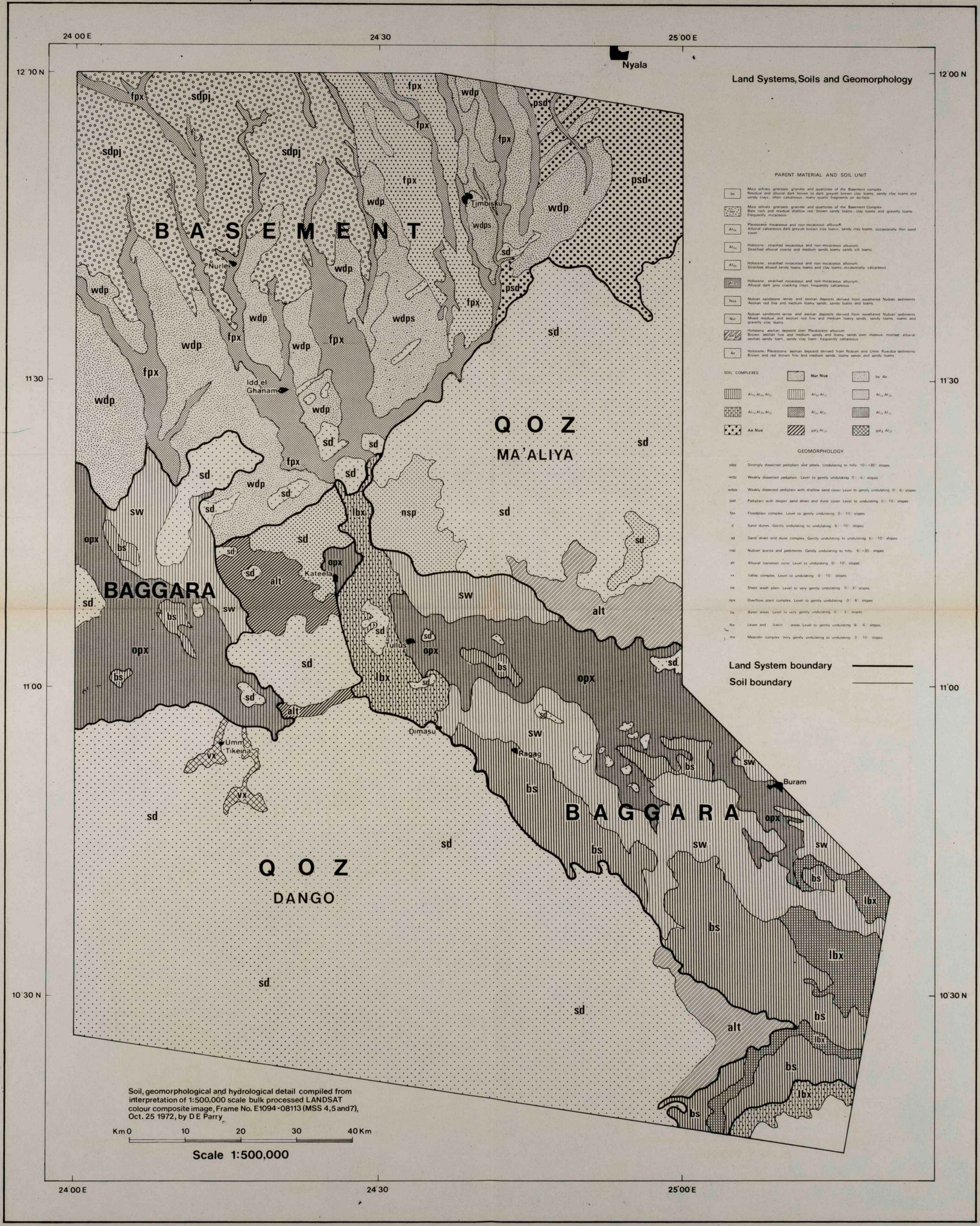
APPENDIX E

MAPS

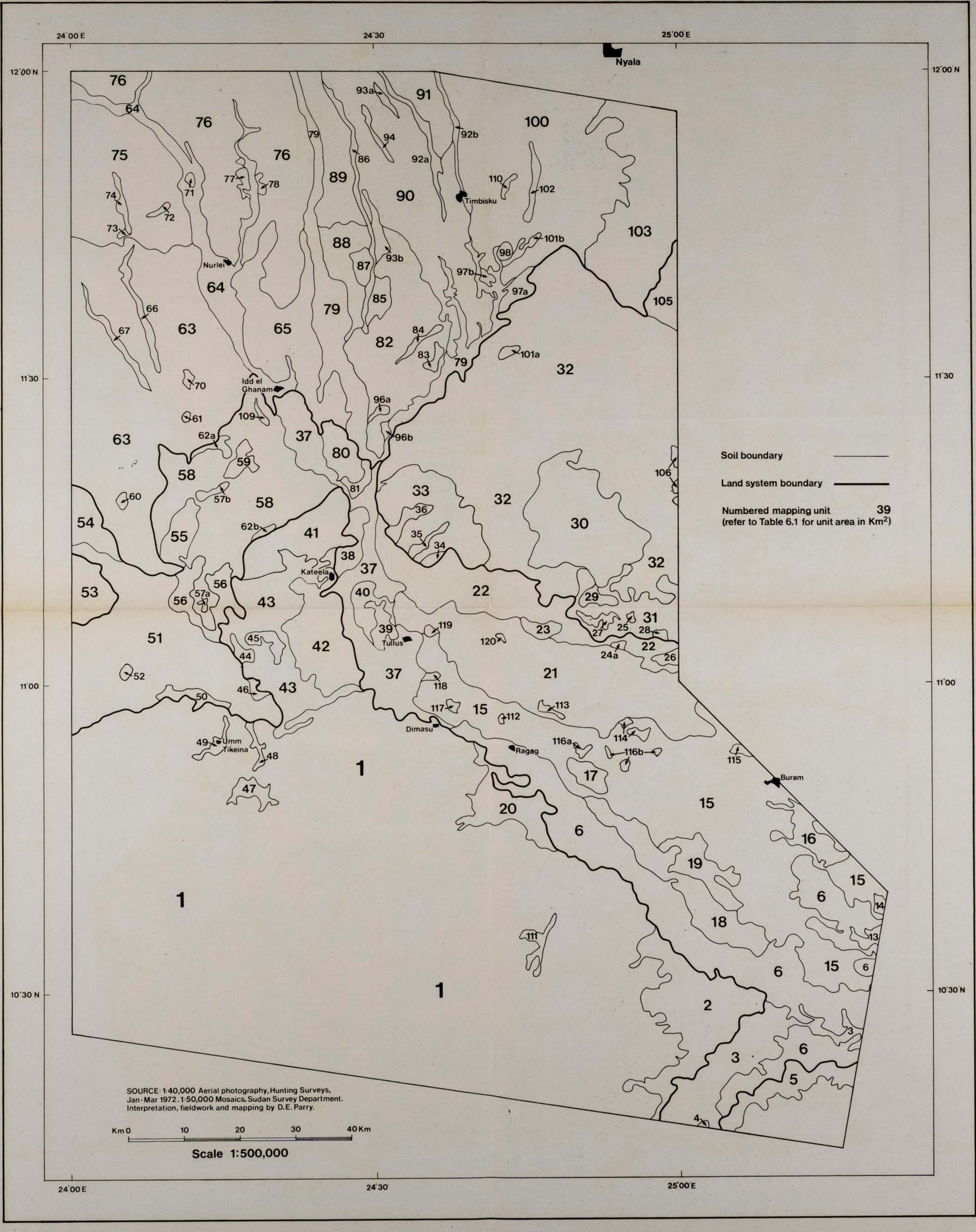
MAP 1 Standard Map



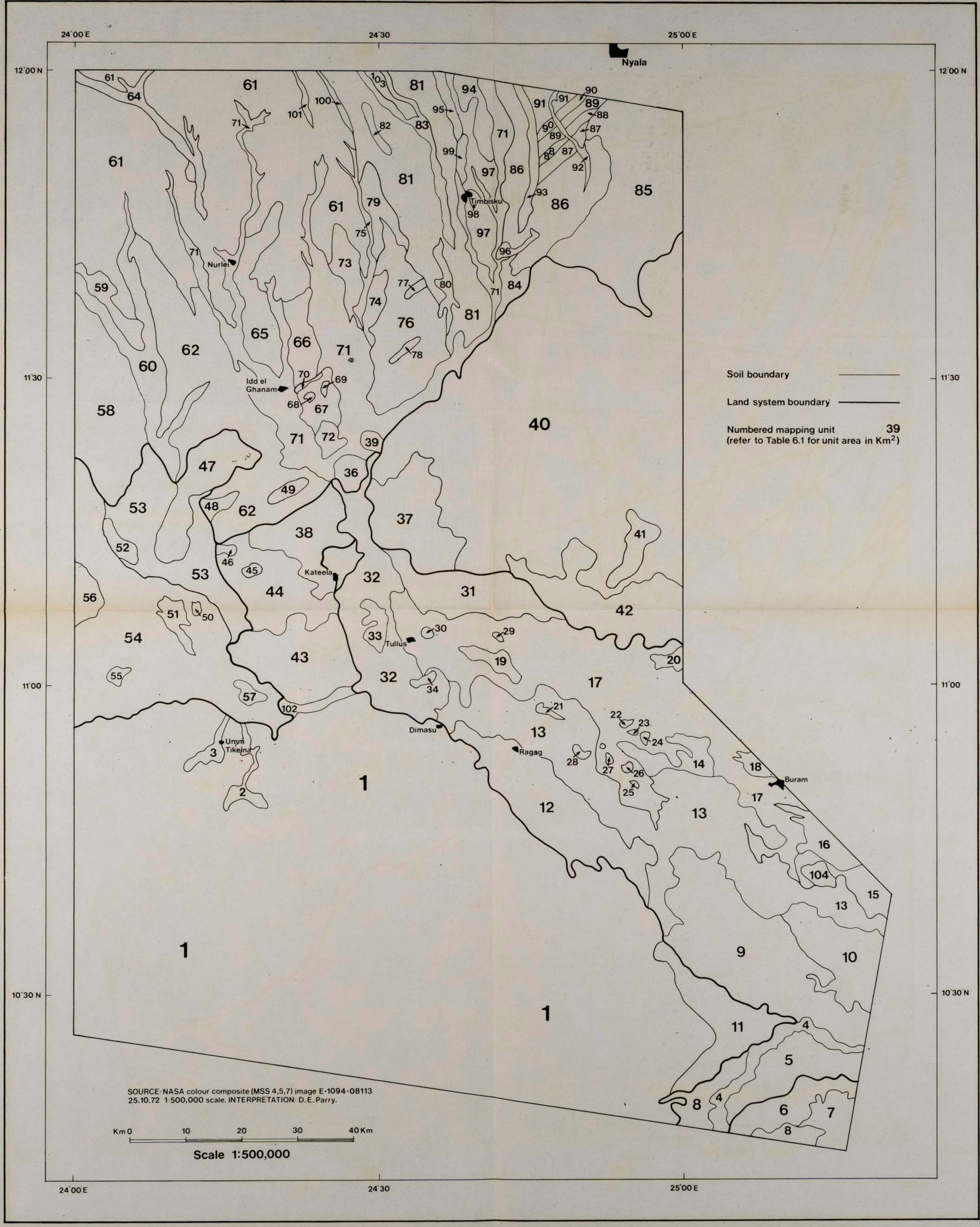
MAP 2 LANDSAT Map



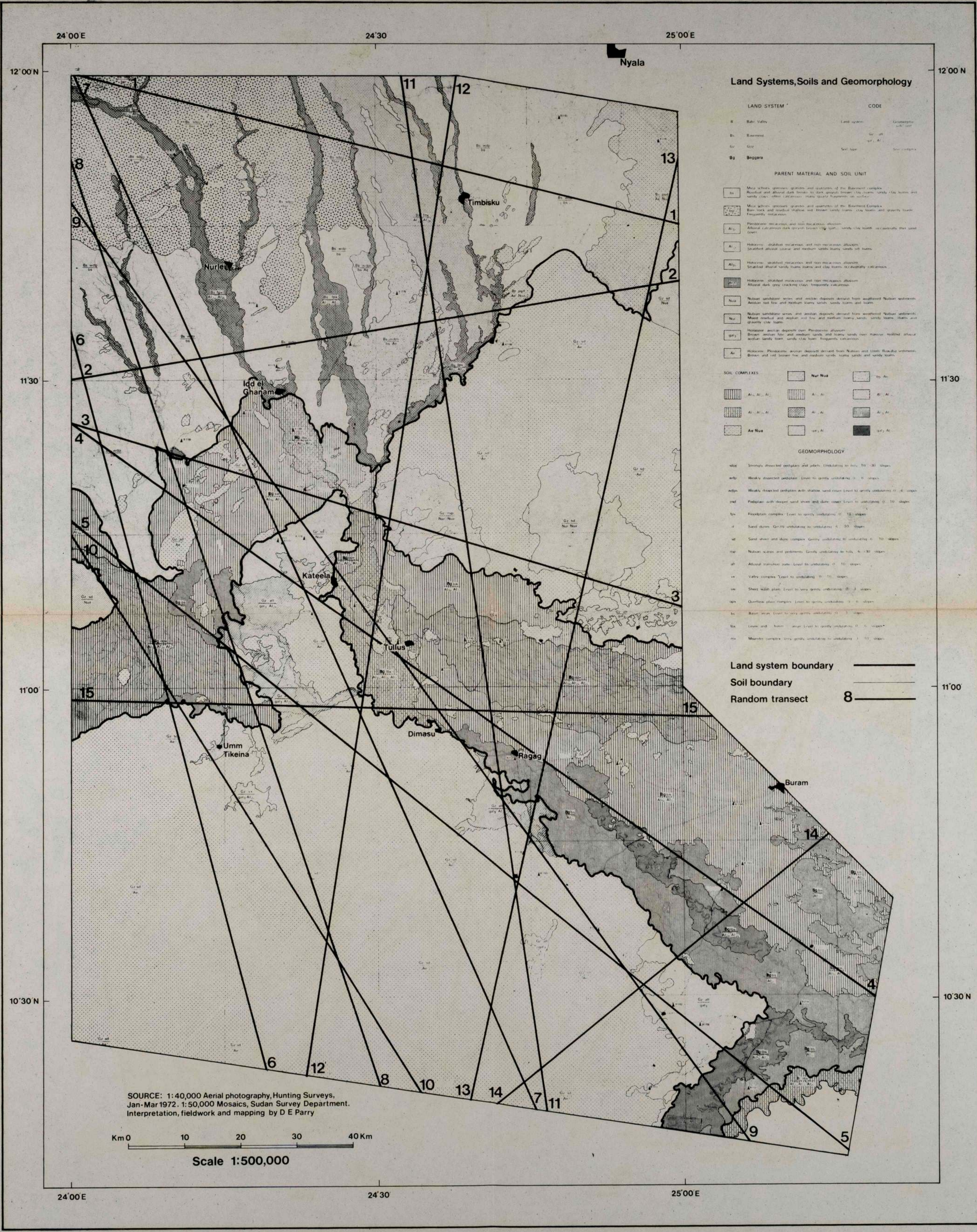
MAP 3 Standard Map Mensuration Overlay



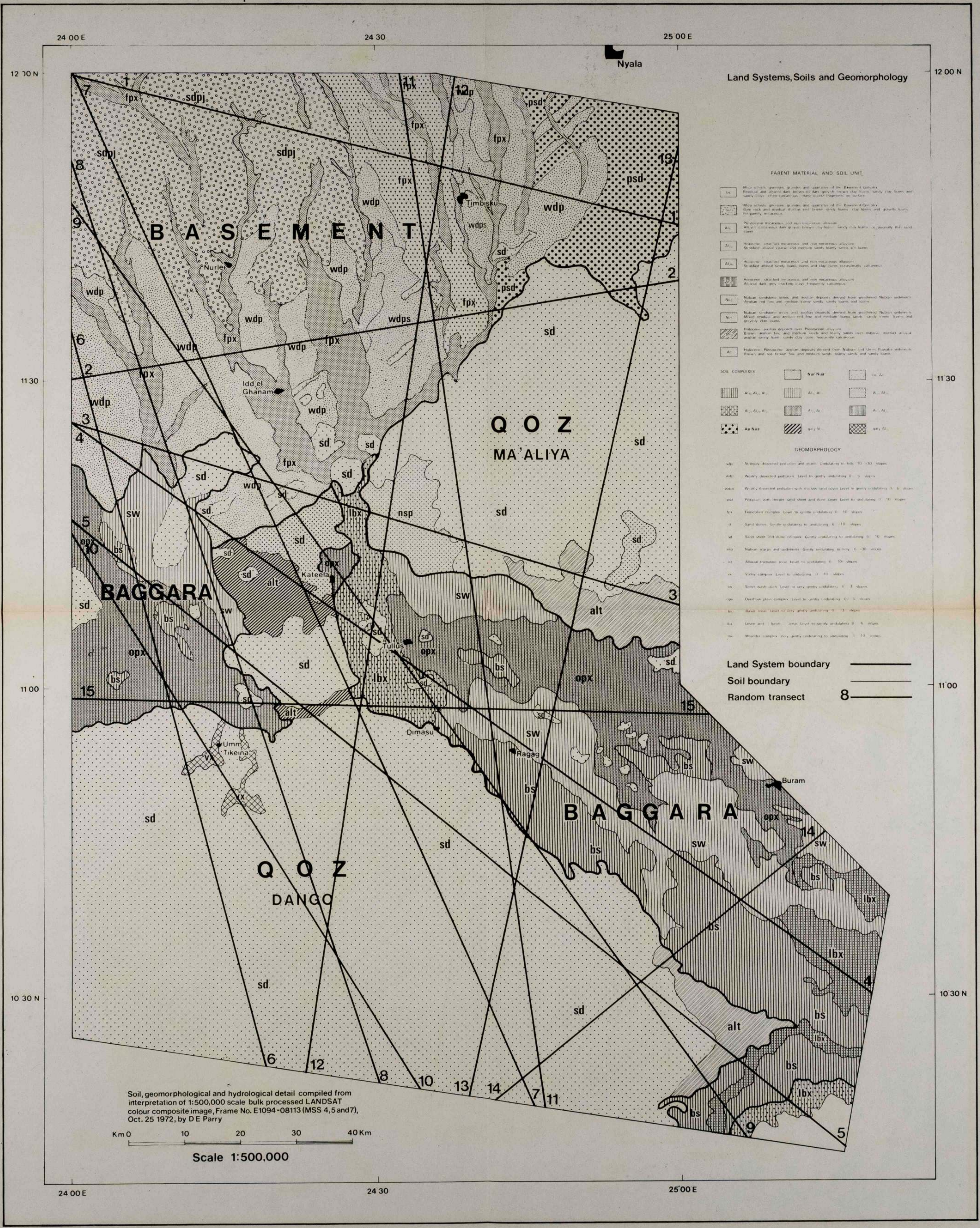
MAP 4 LANDSAT Interpretation Overlay



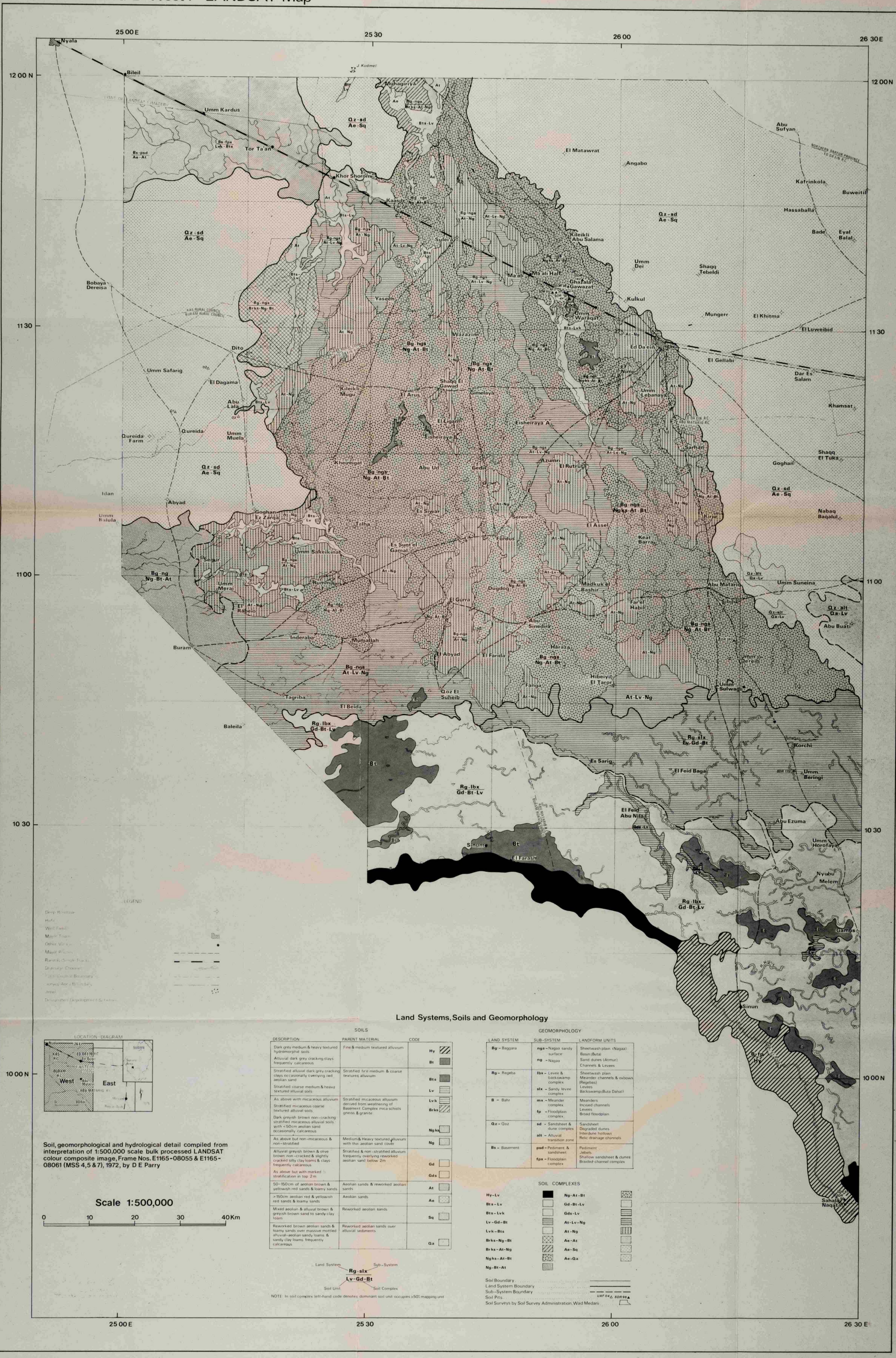
MAP 5 Standard Map and Random Transects



MAP 6 LANDSAT Map and Random Transects



MAP 7 Area B West: LANDSAT Map



Soil, geomorphological and hydrological detail compiled from interpretation of 1:500,000 scale bulk processed LANDSAT colour composite image, Frame Nos. E1165-08055 & E1165-08061 (MSS 4,5 & 7), 1972, by D E Parry

Scale 1:500,000

0 10 20 30 40 Km

Land Systems, Soils and Geomorphology

SOILS

DESCRIPTION	PARENT MATERIAL	CODE
Dark grey medium & heavy textured hydromorphic soils	Fine & medium textured alluvium	Hy
Alluvial dark grey cracking clays frequently calcareous		Bt
Stratified alluvial dark grey cracking clays occasionally overlying red aeolian sand	Stratified fine medium & coarse textured alluvium	Bts
Stratified coarse medium & heavy textured alluvial soils		Lv
As above with micaceous alluvium	Stratified micaceous alluvium derived from weathering of Basement Complex mica schists gneiss & granite	Lvk
Stratified micaceous coarse textured alluvial soils		Brks
Dark greyish brown non-cracking stratified micaceous alluvial soils with <50cm aeolian sand occasionally calcareous		Ngks
As above but non-micaceous & non-stratified	Medium & Heavy textured alluvium with thin aeolian sand cover	Ng
Alluvial greyish brown & olive brown non-cracked & slightly cracked silty clay loams & clays frequently calcareous	Stratified & non-stratified alluvium frequently overlying reworked aeolian sand below 2m	Gd
As above but with marked stratification in top 2m		Gds
50–150cm of aeolian brown & yellowish red sands & loamy sands	Aeolian sands & reworked aeolian sands	At
>150cm aeolian red & yellowish red sands & loamy sands	Aeolian sands	Ae
Mixed aeolian & alluvial brown & greyish brown sand to sandy clay loam	Reworked aeolian sands	Sq
Reworked brown aeolian sands & loamy sands over massive mottled alluvial-aeolian sandy loams & sandy clay loams frequently calcareous	Reworked aeolian sands over alluvial sediments	Qa

Land System — Sub-System: Rg-slx
Soil Unit — Soil Complex: Lv-Gd-Bt

NOTE: In soil complex left-hand code denotes dominant soil unit occupies >50% mapping unit

GEOMORPHOLOGY

LAND SYSTEM	SUB-SYSTEM	LANDFORM UNITS
Bg – Baggara	ngs – Nagaa sandy surface ng – Nagaa	Sheetwash plain (Nagaa) Basin (Buta) Sand dunes (Atmur) Channels & Levees
Rg – Regeba	lbx – Levee & backswamp complex slx – Sandy levee complex	Sheetwash plain Meander channels & oxbows (Regebas) Levees Backswamp (Buta Dahal)
B – Bahr	mx – Meander complex fp – Floodplain complex	Meanders Incised channels Levees Broad floodplain
Qz – Qoz	sd – Sandsheet & dune complex alt – Alluvial transition zone	Sandsheet Degraded dunes Interdune hollows Relic drainage channels
Bs – Basement	psd – Pediment & sandsheet fpx – Floodplain complex	Pediment Jebels Shallow sandsheet & dunes Braided channel complex

SOIL COMPLEXES

Hy-Lv	Ng-At-Bt
Bts-Lv	Gd-Bt-Lv
Bts-Lvk	Gds-Lv
Lv-Gd-Bt	At-Lv-Ng
Lvk-Bts	At-Ng
Brks-Ng-Bt	Ae-At
Brks-At-Ng	Ae-Sq
Ngks-At-Bt	Ae-Qa
Ng-Bt-At	

Soil Boundary
Land System Boundary
Sub-System Boundary
Soil Pits — UAF 04 △ SDR 96 ▲
Soil Surveys by Soil Survey Administration, Wad Medani

MAP 8 Area B East. LANDSAT Map