REMOTE SENSING CENTRE

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USE OF HIGH RESOLUTION SATELLITE DATA FOR SOIL MAPPING
Pilot study in Botswana

Study implemented by GCP/INT/458/FRA
with the assistance of the Government of France

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INTRODUCTION

This report deals with a pilot project carried out in Botswana. It seeks to assess the usefulness of high resolution satellite data, and in particular SPOT data, for soil mapping at 1:250 000 and 1:50 000 scale.

The study was implemented by the FAO Remote Sensing Centre, in conjunction with a "host" FAO project (BOT/85/011) currently being carried out in Botswana by the Land and Water Development Division.

The technical study was subcontracted to CIRAD (International Cooperation Center for Agronomical Research and Development).

The technical and administrative coordination of this project was undertaken through a French Trust Fund project of the FAO Remote Sensing Centre.

The pilot study was performed over a five-month period. The three-week period of field-work in Botswana was organized by the team of soil specialists of the "host" project.

I. GENERAL PRESENTATION OF THE STUDY

I.A. GENERAL CONSIDERATIONS

I.A.1 - Objectives of the study

This study aims at analysing the conditions for using high resolution satellite data, mainly SPOT, in soil mapping projects carried out by FAO. It concentrates on three test sites, and endeavours to show the methodological approach and to analyse the economic advantages of using high resolution satellite data in developing countries.

The project investigates in particular:

- the possibilities offered by visual and digital analysis methods of SPOT data for 1:250 000 and 1:50 000 soil mapping;
- the cost/benefit analysis of using SPOT data for soil mapping as compared to other data such as Landsat TM or MSS, or aerial photographs;
- further suggestions concerning the methodological approach which could prove technically and economically valuable for soil mapping in the framework of FAO projects. In addition, the report contains a number of specific comments concerning the use of SPOT data.

I.A.2 - Introducing Botswana

a) Physical geography :

Botswana is located in southern Africa and is traversed by the Tropic of Capricorn. It stretches over an area of 582,000 km2, a third of which is occupied by the Kalahari desert (Figure 1). The vast majority of the territory is more than 900 m in altitude. The Kalahari basin is surrounded by two high-standing regions: the Ganzi Ridge and the Eastern Ridge. Northwards, it is divided into three sections: the Okavango delta, the Kalahari desert and the Makgadikgadi depression.

b) Geology :

The ancient African land base is mainly a substratum composed of granites, gneiss, amphibolites, etc. Following an early volcanic phase, various sedimentary rocks (sandstone, dolomite, ...) belonging to different systems (Venterdop, Transvaal, Waterberg, Damara, ...) were deposited. At a local level, these formations were subsequently crossed by basaltic rocks (dolerites). Later, a new sediment layer settled closely associated to a volcanic phase, forming an infringement over the existing phases (Karoo system). Finally, since the quaternary, the Kalahari sands have covered a large portion of the country.

c) Climate :

The climate can be described as arid, with annual rains ranging from 200 to 650 mm. The rainy season starts in October and ends in March/April. Average temperatures are around 10 and 15°C in July and go up to 22-26°C in January.

d) Vegetation :

The natural vegetation reflects the climatic conditions. The shrub and tree savannah is mainly made up of xerophile species (dominated by acacias), often mixed and variable in density. It covers the major part of the country, apart from the northernmost extent of the territory where deciduous forests can be found.

e) Soils :

All the large soil groups can be found. Sandy soils are by far the most abundant (Kalahari sands). Cambisoils and luvisoils are also common. Locally, there are vertisoils and salted soils (Makgadikgadi).

f) Human geography

Only 5 percent of the country area is cultivated land. The importance of agriculture (mainly sorghum) does not compare with the outstanding value of cattle raising and mining. The Government is oriented towards the promotion of agricultural potential and, unquestionably, this cannot be carried out without better knowledge and mapping of soils.

I. B. - PRESENTATION OF THE TEST SITES

I. B.1 - Choice of the test sites (plate 1)

Three sites which were representative of the many pedologic conditions found in Botswana were chosen by the FAO Land and Water Development Division and the Remote Sensing Centre: these were the following:

- Gaborone/Molepole site, in the southeast,
- Kanye, in the southeast,
- Nxai Pan, in the northeast.

Soil studies were to be implemented over these areas, within the framework of the main F.A.O. "host" Project, and the work was either already being carried out or about to start.

I.B.2 - GABORONE, MOLEPOLOLE and KANYE sites

The Gaborone and Kanye sites belong to the same geographical region and therefore can be presented jointly.

a) Physical Geography :

Gaborone and Kanye are located in south eastern Botswana, at the eastern border of the Kalahari basin, and are bordered by the Eastern Ridge.

b) Geology :

Most existing geological formations in Botswana can be found in this region. Starting in the southeast and going northeastwards, the substratum (Gaborone granite), Kanye volcanites, Transvaal, Waterberg and Karoo sedimentary rocks, and finally Kalahari sands can be observed respectively. Dolerite sills are often included within the stratified sedimentary formations.

c) Climate :

A feature of the Gaborone and Kanye region is its semi-arid climate with a dry season during which temperatures are so low they can lead to frost, and whose monthly rainfall does not exceed 100 mm. This is better explained by the fact it is located south of the Tropic of Capricorn.

d) Vegetation :

The vegetation growing in this region fits the major landscape units quite well. As an example, the Sandweld, made up of different types of tree and shrub formations, occupies the expanse of Kalahari sands. The Harweld corresponds to tree savannas and forest and covers the soils developed over other geological formations. Lastly, the thin soils of plateaux and hills support dense trees, and depressions allow tree savanna to develop.

e) Soils :

The range of soils encountered in this region is large and varied: they can be luvisoils, acrisoils, vertisoils, arenosols, lithosoils, and regosoils; a few of these soils can occasionally exhibit secondary characteristics, such as a proportion of limestone, iron, etc.

f) Human geography :

The regions of Gaborone, Kanye and Molepolole are principally devoted to agriculture (mainly sorghum and, to a less extent, maize). Housing is concentrated and surrounded by sparse fields. Circulation is easy as numerous large tracks and paths exist.

I.B.3.- NXAI PAN site

a) Physical geography :

Nxai Pan region is located in the northeast corner of the depression of the former Makgadikbadi, which stretches over the lowest part of the Kalahari basin.

b) Geology - geomorphology :

All the surface geological formations in this depression are quite recent and originate from alluvial phenomena: these are either Kalahari sands, already there or re-formed by winds, or alluvial lacustrian and fluvial deposits which can be explained by variations in water levels of the early Makgadikgadi lake (inland sea). Since the quarternary the water level of this lake has considerably decreased. Many successive alluvial deposits were re-formed by hydraulic and wind erosion, causing geomorphological features which can be described as being either desertic (barkanes, dunes, etc.) or coastal (off-shore bar, leading shoot, delta, etc...).

c) Climate :

The Nxai Pan region has a semi-arid climate. It stands at a medium and regular height, and its topography does not cause any climatic variations. Frost occurrences are few.

d) Vegetation :

Vegetation groupings reflect soil and morphological conditions. The boundary of this depression bears mainly shrub and tree formations, typically Northern Kalahari late sandy formations. Towards the center of this depression, the tree savannah turns into herbaceous rangeland in seasonally flooded areas, or humid pastures in frequently flooded areas.

e) Soils :

The soils found over this area in most cases belong to the arenosols group. They very often contain a high limestone content (lacustrian alluvium) and can be salted in the lowest parts of the depression due to flooding.

f) Human geography :

The Nxai Pan region is sparsely inhabited. Wildlife is well developed. The carriageway from Francistown to Maun runs through its southmost area.

I.C.- BASIC PRODUCTS AND DOCUMENTS AVAILABLE

I.C.1 - Satellite and airborne :

a) Selection of remotely-sensed data :

The different SPOT and Landsat images studied had been acquired during the dry season, except for the SPOT image over the Gaborone site, which was acquired at the end of the rainy season. All these products were selected according to availability and image quality criteria.

b) Remote sensing products used over Gaborone site :

* Aerial photographs :

Panchromatic aerial photographs acquired in 1982 (mission 1/81 A) over Gaborone and Kanye areas, available in the form of paper print at 1:50 000 scale.

* SPOT products :

The Gaborone area is the only one over which SPOT data were available in analog and digital form. These are:

- A SPOT multispectral image (XS), processing level 1B, K-J coordinates 127-399, dated 08/04/86, in the form of a standard false color composite paper print at 1:100 000 and in addition, the corresponding digital data supplied in a Computer Compatible Tape.

- A stereoscopic pair of images, made up of two SPOT panchromatic scenes (P), processing level 1B, K-J coordinates 127-399, acquired on 23/03/86 and 29/04/86, and provided in the form of a B&W paper print at 1:100 000 scale.

* LANDSAT products :

- One Landsat Thematic Mapper TM standard scene, dated 20/06/84, (a) in the form of a color composite paper print at 1:250 000 scale (bands 4/5/3, respectively on R/G/B), and (b) the corresponding Computer Compatible Tape.

- Important Remark

Unfortunately, the Landsat TM data analysis had to be reduced because of technical problems found by the supplier. Therefore, the digital data were received very late, almost at the end of the current project, and the corresponding 1:100 000 scale paper prints proved to be of rather bad quality. For this reason, analysis of SPOT images rather than Landsat TM images, was emphasized in chapter 2 which deals with results.

c) Remote sensing products used over Kanye site :

* aerial photographs :

(see preceding paragraph). These originate from the same mission which covered Gaborone.

* SPOT products

- A SPOT multispectral scene (XS), level 1B, K-J coordinates 126-399, dated 04/06/86, in the form of a standard false color composite paper print at 1:100 000 scale.

* LANDSAT products

- The same scene as the one covering Gaborone site.

d) Remote sensing products used over Nxai Pan site :

* Aerial photographs

- Photograph mosaic at 1:50 000, sheets 1924 D3 and D4.

* SPOT products

- Two SPOT multispectral images (XS), processing level 1B, K-J coordinates 122-390, dated 05/08/86 and 123-390 dated 31/07/86, in the form of a standard false color composite paper print at 1:100 000 scale.

I.C.2 - Basic cartographic products

The following documents were also used:

a) <u>General purpose maps</u> :

- Photo-geological map of Botswana at 1:1 000 000 scale, dated 1978,

- Provisional vegetation map of Botswana, dated 1971;

- Southeast Botswana Vegetation map at 1:500 000 scale

b) <u>Maps covering Gaborone and Kanye sites</u> :

- Topographic maps of Thamanga at 1:50 000 scale (sheets 2425 D1 and D3).;

- Topographic map of Gaborone and Kanye at 1:250 000 scale;

- Geological map of Gaborone at 1:25 000 dated 1980;

- Minutes of soil map of Gaborone at 1:250 000 scale (about to be published), from the Soil Mapping and Advisory Service, Ministry of Agriculture.

c) Maps over Nxai Pan site :

- Topographic map of Nxai Pan and Bushman Pits at 1:250 000;

- Topographic map of Nxai Pan at 1:100 000 scale (sheets 1924 C and D, 1925 C).

I.D - GENERAL METHODOLOGY

This study was carried out in three separate steps :

- An early preparatory step: following the supply of satellite data, preliminary processing was applied to the digital data. This first attempt was designed both to understand and interpret the document in an overall manner. It allowed suitable sites to be identified for field work.

- An intermediate step fieldwork aimed at collecting ground reference data.

- a find step for analysis to clear and exploit the data and to draw a synthesis.

I.D.1- General considerations on soil mapping

a) General definitions of Pedology :

" Whereas soil sciences (i.e. those which soil users and agronomists are used to deal with) are ancient, pedology is a rather new field of investigation. Soils are not a stable and inert medium. On the contrary, they take form and develop. They evolved according to climatic influences and vegetation, at the expense of a given mineral material (geological substratum): as a result, soils are found to be distributed in areas roughly parallel to climatic and vegetation zones, in homogeneous and flat plains. As soils evolve they become deeper and differentiated. Finally soil reaches a relatively stable stage and can be differentiated into distinguishable and individualized layers which together define what is called the soil profile.

Studying the profile and its numerous layers allows one to obtain an abundance of information concerning the stages of soil evolution. In other words, it is a means of understanding the genesis of soils: that is the fundamental idea within pedology.

Pedology involves two major points, which are complementary and inseparable. On one hand, it considers the static side of the soils (studying their components and their peculiar properties). On the other hand, it deals with the dynamic evolution of soils (their genesis and the building of the profiles)" Duchaufour (1988).

The genetic classification of soils used in the current study is the FAO classification system, which basically takes into account the combination of the characteristics of given sample layers, precisely defined by their morphological, physical and chemical characteristics: these layers are known and used as "diagnosis" layers. This terminology was created by Dudal (1973) when building the legend of the World Soil Map for FAO-UNESCO. It discriminated 26 soils, but it was subsequently revised in 1986 and 5 new classes were added to it.

b) Traditional mapping methods :

Soil mapping aims at defining the soil units found in a given region and at accurately drawing their respective geographical extent. It requires a synthetic approach its goal is to locate each soil unit in the landscape, then endeavour to stress the existing relationships between the various soil types and their environment, and lastly, to identify the existing interactions between adjoining soils.

Soil maps are indispensable when implementing land resource planning and development projects, whatever the scale or the area under consideration.

Small scales, e.g. 1:250 000 scale (reconnaissance), are better used for global maps, as they enable the influence of environmental factors on soil genesis to be stressed. The soil units represented are often soil associations.

1:50 000 scale maps, that is to say medium scale soil maps, allow one to derive indications of the potential of different soil types on a regional basis and to draw the major orientation lines for a land development project.

b.1) Systematic prospection

Where Soils are characterized by layers and profiles, traditional mapping concentrates the existing information into three dimensions. Traditionally, the soil scientist studies the layers during his field work subsequent to the analysis of soil surface, existing outcrops and surrounding vegetation. In the same way, a grid of variable density is set up to allow regular observations to be carried out. This can be done either by means of drills or pedological pits. The density and organization of the observations depends very much upon the complexity of the landscape, the accuracy required, the scale of the map (transect, regular grid,...), and also the accessibility of the area under study.

The data collected in a three dimensional space enable the soil specialist to define pedological units, and to delineate them after extrapolating the results between a few given observation points. Contours are then transferred onto a topographic map to yield a two dimensional soil map.

b2) Using aerial photographs :

Data acquired by airborne (and spaceborne) vectors provide coverage of the earth's surface from a given height; consequently, only two dimensional restitution is possible. When considering pedological interpretation, the third dimension (depth) cannot be dealt with.

Nevertheless, use of aerial photographs permits a reduction in the number of ground observation points (drills or pits), but in no case can they be completely eliminated. The soil specialist locates the different soil units on the aerial photograph and draws the boundaries of each unit when possible. A ground checking procedure enables him to check the identity of the layers (which exist and which do not) and of the profile (which kind it is), and subsequently, to observe to which area it extends. As a result, he is in a position to confirm the unit limits, in close correlation with the limits drawn through the aerial photograph interpretation. After being drawn at the same scale, the tracing-papers bearing the limits are transferred to a topographic map together with the data collected over the sampled soil areas from the ground survey. These are merged with the existing documents and lead to the writing-up of a pedological minute.

However, use of aerial photography has certain shortcomings. Working over an area at a reduced scale inevitably requires the manipulation and interpretation of a large number of photographs. Furthermore, the existing photographic coverage is usually too old or of bad quality.

I.D.2 - Methodology for satellite data analysis : the hierarchical approach (diagram 1)

a) Advantages :

Compared to aerial photography, satellite imagery offers a number of advantages :

- it provides synoptic coverage, in that it covers a vast extent of territory in one block, thereby giving an undistorted view of large natural units, according to a known and homogeneous geometrical pattern.

- it is capable of repetitive coverage, due to the continuous coverage cycle of the satellite, which returns to the vertical of a given point on earth every 18 days for Landsat, and 26 days for SPOT 1 (SPOT 1 repetitivity can be improved by up to 3 days when using lateral viewing capabilities).

- it is possible to observe the transformations affecting soils (erosion, farming systems), and permits timely monitoring and assessement of the modifications in soil boundaries.

As in the case of aerial photographs, satellite imagery does not provide us with a three-dimensional view of the pedological units: it remains impossible to infer any measure of soil depth (profile) from the imagery.

Traditional soil mapping methodologies are mainly based on profile analysis. These prove tedious and time-consuming. It therefore appeared necessary to develop further methods in order to to reduce the number of pedological pits to be dug: integrating satellite derived information concerning the natural environment related directly to pedological processes is a solution. The methods have been integrated through a specific so-called hierarchical (descending and ascending) approach, which can be summarized as follows:

b) Descending approach

This consists of analysing the geological background, which provides information about the repartition of the bed-rock from which the soils originated and about the geomorphology which gives information on the soil genesis processes: this is best done through studying the morphology of the terrain and the surface hydrology, which can be easily interpreted on a satellite image.

Studying both geology and geomorphology together with pedological pits enables one to draw a morpho-pedological map, which includes the soils themselves, and often soil associations. These maps are generally drawn at a reconnaissance scale (1:250 000). They prove very useful in guiding the detailed field work which is required when drawing pedological maps at large scale (1:50 000 and larger).

c) Ascending approach

In addition, to the descending approach, in which the many components gathered to define soil were analysed (geology, geomorphology), it also appears interesting to ascertain the numerous characteristics from which the presence of a soil type can be inferred (vegetation, land use, farming systems). These characteristics can be deducted from satellite imagery by using a so-called ascending methodology.

These two approaches are not always applicable when mapping at a small scale (inferior to 1:250 000), because the integration of details can become a critical task.

I.D.3.- Methodological aspects concerning pilot projects

a) The different study cases : (cf. plate 1)

Each study site was examined in a separate way, as far as the availabilitiy of data or the ease of access was concerned. The study conditions can be summarized as follows :

a1) at 1:250 000 scale:

- Gaborone site

  Gaborone test site had already been partly studied before the field-work and is easily accessed: a topographic map of the area exists and is of reasonable quality, there are also geological maps and a newly drawn detailed pedological minute. In addition, a network of pedological pits exists. A fair amount of remote sensing data is available from the pilot study framework.

- Kanye site

- Kanye region was not as well studied as Gaborone, but it is easily accessed. Its geomorphology can be described as varied. The existing topographic maps are more or less reliable. There is no thematic map available for this region at present, and the pedological field surveys for the host project were about to commence at the time of the pilot project.

- Nxai Pan site :

- Nxai Pan site is neither well known nor easily accessible. There are almost no maps for this region and the few existing ones are unreliable. However, the geology and the geomorphology are rather homogeneous over this site.

a2) at 1:50 000 scale :

The two sub-zones which were analysed at 1:50 000 scale belong to the Gaborone sites of Dimawe and Molelopole, where a large number of maps and satellite data were available.

b) Data analysis methods

b1) Visual analysis :

The visual interpretation of satellite images is carried out in very much the same way as in classical aerial photograph interpretation, that is to say, by bringing into play the texture (organization of pixels) together with edge perception, and taking into account hue and shapes, uniform segments and the relationships existing between all the units.

- the photo-interpretation work must be done by the soil specialist, who will carry out the ground reference data collection.

- the quality of the visual analysis depends very much on the experience of the photo-interpreter.

The visual interpretation was done on small scale (1:250 000 scale) and large scale (1:50 000 scale) paper prints. These were generated on the one hand from standard photographic products, and on the other, from photographic restitutions of digitally enhanced images (printer output and screen photograph).

b2) Digital analysis :

(i) Hardware and software :

Two types of hardware and software were used for the current study;

- the Pericolor 1000 system at the CIRAD premises in Montpellier, supporting the HYPERCUBE image processing software package.

- the HACIENDA system at the CNUSC premises in Montpellier, supporting the STIMDI image processing software package (Discrete Image Processing System)

(ii) Image enhancement :

- Two separate image enhancement procedures were tested on the SPOT scene of Gaborone using the STIMDI and HACIENDA software package :

- Intensity, Hue, Saturation (I/H/S) transformation, on the 3 bands, leading to 3 new bands containing respectively 16 Intensity levels, 64 Hue levels and 4 Saturation levels. This transform function, rather classical in image enhancement procedures, consists of building a new 3-band color composite image. The new bands are the result of a linear combination of the original bands computed through the I/H/S transform.

- Principal Components (PC) Analysis followed by Intensity/Hue transform

- In the above procedure, the I/H/S transform is applied to the first two components obtained when applying the Principal Components Analysis to the three bands of the original image.

The images resulting from the processing described above were further enhanced by applying interactively a distinct linear stretch to each band.

Finally, the enhanced images were printed at 1:250 000 scale for the whole Gaborone scene, and at 1:50 000 scale for the two so-called Gaborone sub-sites, DIMAWE and MOLEPOLOLE.

(iii)- Digital classifications :

Two attempts were made to produce digital classifications over the test-sub-site of MOLEPOLOLE at a scale of 1:50 000, using the Pericolor system supporting the HYPERCUBE software package:

1) Three supervised classifications using the box classification algorithm on the following band combinations:

-1 . SPOT channel 1 and the Normalized Difference Vegetation Index (3-2/3+2)
-2 . the first two principal components resulting from the PC Analysis.
-3 . a combination of these last four bands.

2) A semi-automatic classification was carried out using the original SPOT band 2 and band 3. It divides the two-dimensional space formed by the two channels into 17 radiometric classes. Colors were chosen so that the resulting image provided a natural color image, which is better interpreted by the human eye (brown to green for increasing values in band 3, and dark to light for increasing digital values in band 2).

c) Ground checking procedures :

All the ground reference data collection work was carried out in close collaboration with the soil specialists undertaking the field work for the FAO "host" project. The observations were made in addition to the visual interpretation of the imagery. Many problems and hypotheses were raised during this preliminary stage. Nevertheless, it was not possible to investigate all these hypotheses and questions, as the three-week period allocated for the work was too short to cope with the difficulties in accessing the sampled areas.

The field work consisted, on the one hand, of carrying out a series of visual observations and characterisations of the actual geomorphology, landscapes, soils and vegetation. On the other hand, many drills and pits were sunk; this prospection work was carried out without any gridding, since this was not possible within the period of time period allocated.

II TEST SITES : RESULTS OF THE ANALYSIS OF SPOT DATA

As indicated when introducing the methodology, SPOT data were the only kind it was possible to analyse fully from the beginning of the pilot study over the test sites. For this reason, the technical results presented in this chapter are limited to SPOT data only.

II.A - REMOTE SENSING SOIL MAPPING AT 1:250 000 SCALE.

II.A 1 - Results over Gaborone test site (plate 3 to 6)

The Gaborone test site was one where a great deal of information was available. In fact, there was a pedological minute being written in the framework of the FAO "host" project. This minute was used as an additional source of reference data for the soil study.

Soil mapping was attempted from the analysis of SPOT multispectral standard images and digitally enhanced imagery (I-H-S or PCA/I-H) and from a standard SPOT panchromatic stereo pair.

The approach used for mapping soils on the SPOT images can be described as hierarchical, that is to say both descending and ascending.

a) Descending approach :

a1) Geological analysis (Plate 3,4,5) :

Transferring contours from the geological map at 1:250 000 scale was more satisfactory on multispectral images (Pl. 5). One can observe that a large majority of geological units fit very well into the visual shapes inferred from the SPOT images. This is particularly true in the contact area between Kalahari sands, Gaborone Granites, red sand stones, Waterberg quartz and feldspath sand stones, and dolerite discharges.

Correcting errors and uncertainties in the geological map became possible, as well as extrapolating a few unit limits, although not drawn on the maps available, particularly in the western area of Molepolole.

The geological interpretation was considerably facilitated on the multispectral image as a large number of rocks could be associated to colour units on the SPOT image. For example, it was found that red sand stones were elongated in shape, granite inselbergs appeared circular, and felsite outcrops were distinguishable through their association of dark rounded shapes within a lighter network.

a2) Morpho-pedological units analysis :

As a second stage of the interpretation, the interpreter looks for possible subdivisions in the geological units, based on the morphology and drainage network. SPOT multispectral data prove very helpful at this stage. It should be noted that a few difficulties were found on the multispectral images in the analysis of the relief, and particularly in the evaluation of slopes. However, these could easily be overcome when using a SPOT stereo pair (cf. plate 4). After being defined, the physiographic units are then subdivided, or more precisely characterized in function of their pedological characteristics. These relationships are very often quite straight-forward, when soils happen to follow a topo-sequency, e.g. the feldspathic sand stone hills, which include the hill top with ferric arenic luvisoils, and arenosols on the slopes. Such a distribution in the form of a topo-sequence is not always the case, and under other conditions, the allocation of units could be made more complex (association of soils in the form of extension of another soil), which calls for more intensive ground checking.

b) Ascending approach :

In a few cases, geo-morphological or morpho-pedological units can be further subdivided into smaller units due to the information provided by the analysis of a few land-cover elements (vegetation, farming system, etc.) which are directly correlated to a given soil type extent.

In this way, it has been observed that the cropped areas located in Gaborone zone corresponding to rather rich soils can be characterized by specific shapes where colours vary on the different kinds of multispectral imagery processed (e.g.: reddish on the SPOT standard false colour composite, blue on the SPOT I-H/PCA image and a rather more subtle blue on the I-H-S enhanced image).

As an example, in the southwest area of this same scene, around Thamaga, villages are made up of houses spread out and built on bare, smooth and eroded soils, little cultivated and covered by sparse vegetation. They can be identified on the colour composites as light circular areas, where the reflection remains high in all the three channels.

Northwestwards, lowlands could be singled out on the SPOT panchromatic image, as they appeared elongated in shape, whereas forested hills appeared globe-shaped. Both belong to a series of areas variable in hue in the enhanced I-H-S SPOT image, and purple in the I-H/PCA enhanced SPOT image.

The analysis of these sub-units is implemented by following a so-called ascending method. As a consequence, the soil specialist is able to guide his field work and to establish a reliable connection between ground observations and land-use inferred from the imagery as associated with particular soil units.

c) Final morpho-pedological synthesis map :

Plate 6 shows the result of the soil mapping procedures at 1:250 000 scale: this was obtained from the interpretation of a SPOT panchromatic stereo pair in combination with a 1:100 000 multispectral image. The final legend has been specially developed and detailed. It includes 30 distinct associated or individualized soil units, such as cambic arenosols, lithosoils, arenic luvisoils, pellic vertisoils, regosoils, etc.

As presented in the table containing the legend, each pedological unit can be associated with a land form, which relates itself to a lithological unit. These units are known as morpho-pedological units, derived from much larger geological units, which are in turn grouped into vast land units. This legend illustrates quite well the hierarchical approach used in the current study (mainly descending in this particular case).

It should be noted that the map, which originates directly from the visual interpretation of SPOT images (PA + XS stereoscopic coverage) can be favourably compared to the existing 1:250 000 scale pedological minute, which had been mainly prepared from available aerial photographs and very intensive ground survey.

d) Remarks on the choice of multispectral products

Comparison of the three enhanced images, namely the SPOT Standard false color composite, the I-H-S image and the I-H/PCA image led, in this particular case, to the following comments:

- Generally speaking, processed images (I-H-S and I-H/PCA images) do not convey a significant improvement in comparison to the standard image.

- The I-H/PCA image is better contrasted. This was achieved through the color assignation carried out on the second component; nevertheless, interpreting it is a more complex task insofar as artificial colorations are introduced, which do not always refer to well identified interpretation keys.

- The I-H-S natural color image is easily interpreted as far as land units are concerned, though less contrasted.

II.A.2 - Results over Kanye test site (Plates 7 and 8)

There was no 1:250 000 scale pedological minute available for this site, as there was for the Gaborone area. The ground reference data collection had to be limited in time (a few days only) due to logistical factors; nevertheless, it was sufficient to enable the team to draw a reliable map, following once again the above-mentioned hierarchical approach.

a) Descending approach :

An in-depth study of the 1:100 000 standard SPOT scene made it possible to delineate quickly the major geomorphological units. These could then in some cases be further subdivided into sub-morpho-pedological units (Plates 7 and 8).

In this way, three large units could be deduced through visual interpretation of the image respectively in the western, eastern and southern regions:

* A first western region, which includes the whole Kalahari area. Soils are very sandy, and are subject to few variations (cambic arenosols). They stand out clearly among the other units on the SPOT image (this could not be observed on the Landsat TM image available).

  . The hydrographic network is made up of wide and discontinuous, even unorganized low-land areas. The Kalahari plateau surface shows multiple colors ranging from light to very dark yellow. From quick ground observation, it seems that these various hues do not correspond to differences in soils.

  . Karoo formations were incorporated with this large unit, mainly composed of coarse sands, barely discriminated from Kalahari sands, which look similar (ferralitic arenosols).

* Westwards, the second unit corresponds to sedimentary Waterberg formations, and can be further divided from north to south in many morpho-pedological units. These are as follows:

  . Redsand stones, which form vast outcrops (lithosoils).

  . Other Waterberg formations, which build a series of cuesta-like reliefs, partly smooth, and correspond to hard and thin rocky base support. These rocky levels bear sandy hills, separated one from the other by subsequent depressions where diabases could be found. Therefore, it was possible to map sandy soils (arenosols), rather red in hue (arenic ferric luvisoils or ferralic luvisoils), and more clayish soils born from alkaline rocks (chromic luvisoils and sometimes vertisoils).

* A third large unit in the southern area, in the incision-like formation of Metsemothaba on Gaborone granites, dominated by ferric luvisols (and sometimes petric or petroferric or even arenic), chromic luvisoils and dystric regosoils (thin eroded soils). This button-hole-like

area has been divided into two distinct parts, based on the discrimination of their respective surface water dynamic pattern:

- The northernmost portion is characterized by dark colours in the colour composite. Its hydrographic network is fairly well developed, with shallow channels, and exhibits barrel-like or flat-bottomed valleys.

- In comparison, the southernmost part is easily distinguishable on the SPOT color composite: it appears lighter, often yellowish. The inland waterways network is dense, with deep channels and V-shaped thalwegs. Soils are quite often found to have eroded on the slopes and suffer intense run-off phenomena on the innerbanks of the rivers; these areas are, or at least were, very widely cultivated.

b) Ascending approach

The visual analysis of the information contained on the geomorphological units enabled a few soils and soils associations to be mapped, insofar as they were directly related to land use patterns. A few examples follow:

- Bare soils stand out clearly on the image due to their light hue, and are easily discriminated from dark granitic inselbergs, which correspond to lithosoils.

- The dense accacia tortilis vegetation, in close relation with thin and ferrugineous carapace containing soils (ferric petroferric soils) or in lowlands (ferric, orthic or calcic luvisoils), is often shown in grayish tones on the image.

- Colluvial materials (ferric arenosoils) from the Kalahari plateau are characterized by reddish brown areas on the image.

- In many sites, sheet run-off patterns are clearly identified and if necessary, could even be mapped.

As a conclusion, it has been possible to use SPOT data to draw a soil map at 1:250 000 containing 8 different soil classes, either individualized (e.g.: lithosoils) or associated (e.g.: ferric and chromic luvisoils). Plate 8 and the corresponding table showing the legend clearly demonstrate the existing relationships between soils, morphology, geology and major land form units.

II.A.3 - The results in Nxai Pan site (Plates 9 and 10)

It is hardly possible to investigate this region, since it lacks tracks and reliable maps. The ground reference data collection had to be severely limited, and only the southernmost units of Nxai Pan could be examined. Pedological pits and vegetation were observed with a view to detailing the pedological study.

The visual analysis was carried out using standard SPOT images, in order to delineate the major physiographical units. Consequently, aerial photographs were used to trace the exact boundaries around a few units (Plate 9 and 10).

a) Descending approach :

The large so-called Gidikwe Ridge litoral bar stretches from the northeast to the southwest and the off-shore bar linked to it seems to cut the image into three main zones (Plate 9 and 10) :

- In the southernmost area, a sector not yet identified during the field-trip, was interpreted in close relation to the study carried out in the neighbouring sectors; it could have originated from a former coastal swamp, as part of the western limit of the Makgadikgadi paleolake. It shows a proper structural organisation and looks very much like a dune system (this is to be verified and further investigated).

- South of this bar, an area has been fully checked. It can be divided into two parts:

  - a sandy area, which seems homogeneous when analysed from the ground, but which appears more contrasted on the image;

  - a depression, which is actually a sebkha and partly functional; it is surrounded by sandy ridges (which are actually former lower lake strands). This sebkha shows many low points, covered by salted soils (Na.Cl and Carbonates), flooded during the rainy season, and others at intermediary level, with variable salinity.

- In the north, Nxai Pan depression was studied more in depth, as a result of pedological studies carried out during the field-trip. Six distinct units could be identified along a transect stretching from the on-shore bar and Nxai Pan Basin (Plate 9 and 10) :

  A - Colluvial sand discharge coming from the bar, eutric arenosoils, B - Mixed area, where sandy materials (terraces) alternate with rather shallow or medium-depth calcareous shell soils, arenosols-cambisoils, luvisoils,

C - Calcareous shell soils, shallow or medium-depth, rendzines - (petro)calcic cambisoils/luvisoils,

D - Thick calcareous soils, calcic cambisoils,

and in a less circular pattern :

E - Carbonated sandy soils born on fluvio-lacustrian deltaic formations, calcic arenosoils,

F - Sandy soil zones from fluvio-lacustrian deposits, eutric arenosols.

All these units are to be linked to the various phases and sedimentation types occurring in the depth of the formerly existing lake, followed by a lateral differentiation caused by the drying up. This happened at a time when the calcareous shells including siliceous deposits were formed at the periphery of the basin.

b) Ascending approach :

Final mapping of the above-mentioned units, from A to F was made possible using the ascending approach. This was achieved by analysing the correlation between the various vegetation classes which could be inferred from the SPOT XS images and the soils. In fact, in such an environment where little geological differentiation and low level morphological processes occur, vegetation categories, defined by the species and the canopy density fairly well suited to the soils. Furthermore, in areas of low vegetal density, it has been possible to discriminate various soils by means of their colours on the SPOT image (calcareous shells, sandy soils).

In this way, in the depression, beginning at its very center, the following plant associations can be observed on the image.

- Grass savannah, easily recognizable on the SPOT XS image with its light tones. Acacia bushes are seen as minor reddish brown stains. Both vegetation types are characteristic of the bottom of the former lake bed (lacustrian mud), and can be further likened to unit D.

- Mixed tree savannah made up of various acacia trees, and sometimes mopane, of scarse or medium density, with a light soil background corresponding to calcareous shells described in units B -and C-. Two sub-units were found on the ground to be distinct from unit B as far as their material composition was concerned. They could not be discriminated either on the SPOT image or on the aerial photographs. The whole lot appears grayish on the SPOT image.

- The woodland, very dense, is made up of tall trees which appear as very dark black stains on the SPOT image. This formation is characteristic of part of the former fluvio-lacustrian (terraces) and deltaic formations (typical in shape) already described in units E -and F-. Lighter and yellowish tones correspond to less dense vegetation. Delineating C -and F- was only possible using aerial photographs of Hyphaena palm trees, which mainly occur within unit F and could not be identified only on the photographic prints.

II.A.4. Technical Conclusions on Soil mapping at 1:250 000

It has been demonstrated in existing cases that the high resolution SPOT satellite data are particularly suitable for mapping soils at scales ranging from 1:200 000 to 1:250 000. The hierarchial approach, both descending and ascending, was also proved to be the most adequate method to interpret the imagery.

It was further observed that a large proportion of the information required for soil mapping can be directly obtained from Standard multispectral SPOT imagery visual interpretation. It was also showed that the digital processing of SPOT XS data (principal component analysis, IHS) could not bring any significant improvement compared to the standard XS print (film or paper) provided by SPOT data distributors (eg. SPOT image).

In fact, it appeared that SPOT Standard multispectral images could be used to prepare a quick draft of the pedological situation even in little known areas where there were almost no existing topographic maps or where ground reference data could rarely be collected, such as in Kanye area. In other respects, areas offering little variation in their morphology and little developed geological context, such as occurs in Nxai Pan area, can be fairly well mapped, as far as their soil associations are concerned, from investigations concentrating on vegetation classes. This is of great value in unknown areas which are difficult to reach.

Nevertheless, it remains true that multispectral SPOT data prove to be in several cases insufficient when drawing final high precision pedological maps at 1:200 000 or 1:250 000 scale. They can be further improved by adding stereoscopic coverage data (or at least by using very intensively reliable topographic maps). To this extent, SPOT panchromatic data, either stereoscopic or taken in stereoscopy with multispectral data, prove to be of great value, as was shown when dealing with the Gaborone zone.

II.B - 1:50 000 SOIL MAPPING USING REMOTE SENSING

From the three test sites quoted above, the Gaborone site was the only one which had been covered by different digital satellite and analog data. Two sub-areas, Dimawe and Molelopole respectively, were chosen within the site for the variety of natural situations they could provide.

The objective of this study was to assess the use of SPOT XS and SPOT panchromatic data together with aerial photographs for 1:50 000 scale soil mapping, within these two sub-areas.

II.B.1 - Results in the Dimawe Alveole test site (Plate 11 and 12)

a) Presentation :

The Dimawe region is located west of Gaborone. It can be described as being an alveole within the red sandstone where Gaborone granites and dolerite sill come to the surface.

b) Results of the analysis of Dimawe site :

This study aimed at comparing the soil boundaries drawn from three products: a stereo pair of aerial photographs, a SPOT XS standard image and a screen photographic print of a SPOT XS enhanced I-H-S 1:50 000 scale image.

For mapping morpho-pedological units at 1:50 000 scale, it was found that SPOT XS (standard or enhanced) contains additional information, when compared to the aerial photographs. In this way, the dolerite outcrop located in the center of the alveole contrasts clearly on the SPOT image. This geological unit, which is not only geological but also geo-morphological in nature, can be further sub-divided into two soil types: cromic cambisols where drainage is good, and pellic vertisols in badly drained areas. Such boundaries are not so obvious on the aerial photographs, and to be traced would therefore require consistent additional field survey. It should be noted however that in addition to this general remark a few boundaries in the geomorphological domain appear more obvious under stereoscopic viewing with aerial photographs than on the SPOT print.

II.B.2 - Results in the Molepolole sub-area test site (Plate 13 and 14)

a) Presentation

The Molepolole sub-area test site is southwest of Gaborone. Geological variations are important (refer to the first part) and Karoo and Waterberg outcrops, together with diabase discharges, are remarkable phenomena occurring within this area.

b) Analysis results in the Molepolole site test :

b1) Visual interpretation

As in Dimawe sub-area, a comparison between soil limits obtained from different types of 1:50 000 remote sensing products was carried out using four products: a SPOT XS standard image, an enhanced I-H/PCA processed SPOT image, a stereo pair of panchromatic SPOT images, and lastly, aerial photographs.

- The 1:50 000 scale SPOT multispectral image (Pl. 13) over Molepolole enabled five distinct morpho-pedological units to be mapped (Pl. 14):

  - Unit 1: Soils born on coarse sands (Karoo formation), corresponding to perceptible differences in texture and colours; shrubs and tree savannah

  - Unit 2: Fine to medium sandy soils on convex hills, over feldspathic and quartzitic Waterberg sandstones, easily noticeable by their color associations; dense tree savannah and crops.

  - Unit 3: Diabase discharges in intensively cultivated areas, which appear bluish.

  - Unit 4: Diabase discharge in fallow areas, mainly occupied by Acacia Tortilis, and which appear purple in hue on the image.

  - Unit 5: Narrow white sand slopes, showing in lighter tones; low density tree savannah on bare soil.

- The stereoscopic analysis of the SPOT panchromatic 1:100 000 scale images makes it possible to delineate the above-mentioned 6 units, but discriminating units 3 and 4 remains a difficult task, and units 2 and 3 can be identified only using to stereoscopic vision.

- Reduction into finer subdivisions is not possible using 1:50 000 scale stereoscopic aerial photograph coverage. In fact, if on the one hand, it is possible to delineate both units 1 and 1A, and 2 and 2A, on the other hand, drawing a boundary between units 3 and 4 is not possible. Part of unit 5, along the plateaux, cannot be mapped either.

In conclusion, three definite comments can be made concerning the comparative visual interpretation.

1/ Comparing the three SPOT multispectral products, namely SPOT XS, stereo SPOT panchromatic and aerial photographs demonstrates that SPOT XS data provide a slight additional amount of information for soil mapping purposes as compared to stereo panchromatic coverage. The panchromatic SPOT image stereo pair proved perceptibly superior to the aerial photographs, which were relatively old in the case of this study.

2/ SPOT XS alone are not precise enough for 1:50 000 scale soil mapping. They must be complemented either by intensive ground survey, by the analysis of stereoscopic data such as SPOT PA taken in stereo with SPOT XS, or aerial photography, both being comparable as complementary information.

3/ A more adequate remote sensing product for 1:50 000 mapping seems to be the stereoscopic combination of multispectral and panchromatic imagery. It should nevertheless be borne in mind that comparisons with Landsat TM products could not be undertaken at this scale due to the late delivery of the digital data.

b2) Digital classifications :

Many supervised classification trials of SPOT data were attempted on the Pericolor 1000 supporting the Hypercube Software, in order to map the major units described previously.

Classifications were undertaken on the following channels:

- image 1: band 1 and vegetation index

- image 2: the first two principal components of the PCA analysis of the three original bands.

- image 3: a combination of the two classifications cited above.

The first classified image (band 1 and vegetation index) enabled the medium dense to dense tree savannah to be discriminated from reddish sandy soils over feldspathic and quartzitic sandstone and light soil embankments (sands) bearing sparse vegetation. In comparison, it was not possible to map the two sub-divisions drawn on the field trip, whereas all the diabase discharge sectors could be mapped.

The second classified image (the first two principal components) allows a better discrimination of one of the two existing diabase discharge units. This is achieved by introducing a new class of cropped areas. However, all the reddish sandy soils born on sandstones remain indistinguishable from the other sites over diabase discharges.

A third classification, made on the four channels used in the two previous classifications, was performed in order to map together all the significant and interesting classes of both the first and second classifications.

The findings of this study clearly show that classifications lead to reliable mapping of certain units, i.e. those corresponding either to vegetation classes (savannah types, crops, low density vegetation), or to a few given bare soils (red sands). Nevertheless, the fact remains that digital classifications do not permit automatic soil unit mapping in the way required when drawing a 1:50 000 scale map. Generally speaking, classifications are tedious tasks as compared to visual interpretation, and are not an advisable approach in operational soil mapping.

II.B.3. - Technical conclusions (1:50 000)

These results show that stereoscopic (XS+Panchromatic) SPOT image imagery appears to be the recommended means to use when resorting to visual interpretation of remote sensing-products and methodology for 1:50 000 mapping.

As far as digital classifications are concerned, they are not advisable for soil mapping.

II.C.1 - TECHNICAL CONCLUSIONS ON SOIL MAPPING USING HIGH RESOLUTION SATELLITE DATA

II.C.1.) General conclusions concerning the use of high resolution data

a) Advantages of satellite remote sensing data :

* synoptic coverage

Satellite remote sensing, as compared to aerial photographs, has the advantage of providing synoptic coverage of the areas under study. This allows a quick understanding of large landscape units and therefore:

- guarantees the consistence of the analysis when dealing with vast zones,
- helps in reducing field work requirements, by implementing optimal sampling schemes,
- homogenizes quickly the updating of existing thematic maps (geological maps) used for soil mapping.

* Homogeneous geometry

Satellite images are very homogeneous over large areas in geometrical terms. This greatly facilitates the task of transferring the various pedological and geological data sets. In countries lacking mapped information, satellite data bring a wealth of information which contributes towards a better knowledge of the topography in the areas under study.

b) General methodology: the hierarchical approach :

The global methodology used in the current pilot project for soil mapping can be qualified as a hierarchical approach successively descending and then ascending.

The descending approach attempts to consider the problem from a general to a detailed analysis. It depends on existing and easily interpreted correlations between the geological background (lithology) and the geomorphological and physiographical aspects which finally lead to the mapping of the morphopedological units and to the related soil association units.

The ascending approach, in turn, when it can be applied, is based upon the existing correlation between soils or a group of soils and other given elements which can be identified within each morphopedological unit such as vegetation patterns, land use, soil colors (e.g.: bare soils characterized by specific reddish colors).

II.C.2 - 1:250 000 soil mapping

In actual fact, 1:250 000 soil mapping is equivalent to a detailed morpho-pedological unit mapping, in which only soil associations can be related.

The study of three distinct remote sensing products, namely SPOT XS, SPOT panchromatic stereo pair and aerial photographs (it was not possible to investigate the use of Landsat TM imagery in this chapter because the digital data were delivered too late) led to the following conclusions:

- SPOT XS data gave better results, in all study areas. They allowed the preparation, from a reduced amount of ancillary information, of a geomorphological map which can be used for pedological purposes. Furthermore, within geologically homogeneous and balanced zones, they proved very effective for mapping soil unit which directly related to vegetation cover.

- Stereoscopic data, that is to say SPOT stereo pairs or aerial photographs, are always useful and in several cases are even an essential complement to monoscopic SPOT multi-spectral data for the establishment of the final 1:250 000 geomorphological unit map (exemple of Gaborone study area).

II.C.3 - 1:50 000 scale soil mapping

In overall terms, it appears that, with a rather limited ground survey, digitally enhanced SPOT XS data provide better results than either SPOT stereo panchromatic data or aerial photographs. Nevertheless, SPOT XS data still lack precision for final 1:50 000 scale mapping. Such a problem calls for:

either very much more intensive ground survey,

or a stereoscopic analysis of complementary data (SPOT panchromatic stereo data or aerial photographs).

This is why from a strictly technical standpoint the use of stereoscopic panchromatic coverage is highly recommended and particularly when aerial photographs are of bad quality, unavailable or too old. Information obtained from the stereoscopic pair of SPOT (XS + panchromatic) images was found comparable to that provided by the three images made up of one SPOT XS and a SPOT PA stereoscopic pair.

III. ECONOMIC ASPECTS OF SOIL MAPPING AT 1:200 000 TO 1:250 000 SCALE (FIRST ESTIMATE)

The cost/benefit analysis of the various existing remote sensing methodologies for soil mapping at 1:200 000 to 1:250 000 scale has been studied for other products than those analysed in a detailed manner in the previous chapter. The assessment presented herein is based, on the one hand, upon the analysis of the products available at the end of the project (Landsat MSS and TM), which could be incorporated into Chapter II - Analysis of the results over the test sites -, and on the other hand, the past experience of CIRAD in the field of soil mapping.

The calculation of the cost of the different remote sensing methods for soil mapping took into account data acquisition and data production costs, as well as expenses incurred by the implementation of the different steps of the pedological study (fixed and variable costs).

The respective advantages of the remote sensing techniques for soil mapping were assessed by comparing, for each method, the mapping accuracy, the speed of execution of the work, and the further potential for natural resources studies such as agriculture, forestry and land-use.

The results of both cost and benefit analysis were then represented on a graph in order to propose some recommendations on the most appropriate tool for soil mapping. These conclusions are to be considered as a first global assessment and should be confirmed later on with operational studies.

III.A - COST ANALYSIS

III.A 1 - Basic unit costs

a) Staff expenses :

Employing a soil specialist leads to expenses which can show large discrepancies according to his country of residence: the ratio of the salary of the specialist coming from the developing country itself and that of one who is expatriate ranges from 1 to 10. In the current study, this ratio was kept down to 3. The cost of the field team and the general expenses are less variable. Assessing the price of a soil specialist team comprises a series of costs which are summarized in table II.

b) Remote sensing data

The cost of remotely sensed data varies according to their origin (aerial photographs, SPOT or Landsat satellite images).

b1) Aerial photographs:

In Botswana, the purchase price of an existing aerial photograph is US$ 3.2 per photoprint (1:50 000 scale), that is to say US$ 11.2 per Km². Where there is no existing aerial coverage of the area of interest, the estimated cost of flying a new photographic mission is around US$ 6/Km2. These figures can be US$ 1 per Km² higher if the aircraft has to be brought from Europe.

b2) Satellite data :

From a general point of view, the cost of standard satellite data varies according to the satellite selected (SPOT or Landsat)and, for a given satellite, the sensor chosen (SPOT XS or panchromatic, Landsat MSS or Landsat TM). The price of the satellite data also depends on the data support (photographic film, CCT, floppy disk, paper print).

The price of satellite data was calculated in this study from price listings supplied by distributors (e.g. for Landsat TM, EOSAT; for SPOT, SPOT IMAGE). A general hypothesis was that SPOT XS and Landsat data were already available from the archives (though not processed) and were consequently free of programming charges. However, in the case of SPOT data stereoscopic coverage, the cost of programming one of the two images of the stereoscopic pair was taken into account.

In the case of satellite digital data, the cost of digital processing for enhancement and classification was also considered. The daily rate for digital processing depends on the economic and financial context of the institution in charge of the work (hardware owner, access conditions, leasing). In the case of an EPIC (Public Industrial and Commercial Establishment) such as CIRAD, the cost was evaluated at US$ 200 per day. It would have been higher if the processing had been done by a private commercial company (more than US$ 500 per day).

III.A.2. - Cost of the different 1:250 000 scale soil mapping methods (Table III)

A comparative assessment of the costs involved in 1:250 000 scale soil mapping, using either aerial photographs or satellite data, was made by taking into account the real costs of all the different steps required in soil mapping. Not all criteria could be accurately estimated. The cost assessment of the different methods is directly related to the time required for completing each given step. With a view to facilitating their comparison, these costs were evaluated per 100 km² unit area, and were further subdivided into fixed costs and variable costs as follows:

a) Fixed costs :

Fixed costs are those which relate to expenses independent of the methodology used to carry out the project (either traditional methods, or different aerial and satellite remote sensing methods). These fixed costs cover soil analysis (estimated at US$ 92.2/100 Km^2) and map editing (estimated at US$ 21,3/100 Km^2).

b) Variable costs :

Variable costs involve all those which change according to the different methods compared and mainly correspond to the differences in time, quantity of material and staff requirements (or implementation of the various stages of soil mapping (refer to table III).

b1) Desk study preparation :

This stage involves ancillary data collection and a pre-analysis of remotely sensed data from a geological and land-form point of view.

It can be noticed that using small scale remote sensing aerial photographs is time-consuming, since it requires the handling of large data sets (large amount of photographs, mosaicking).

With the synoptic coverage they offer, satellite data enable the pre-analysis stage to be carried out fairly quickly over large areas. Nevertheless, it should be added that the preparation time is considerably increased when digital processing is required.

b2) Field work :

The intensity and consequently the cost of the field-work depend directly on the quality of the information already contained in the existing cartographic documents. This information is of enormous help when the experts carry out referencing in the field, and within the analysis of the themes related to the soils (thematic interpretation).

* Referencing :

- Using aerial photographs :

  The use of existing and recent 1:50 000 aerial photographs allows fast and accurate positioning on the ground during the field work. This can lead to considerable savings in time (cost of this activity estimated at US$ 76 to 96/100 Km^2).

- Using remote sensing data :

  Ground positioning based only on satellite data can lead to errors in object location and consequently to an increase in field work expenditure (cost estimated at US$112 to 173/100 Km² according to the data used).

* Thematic interpretation from 1/250,000 scale:

- Using aerial photographs :

  1:250 000 scale is usually adopted for large areas requiring a great number of aerial photographs which can be quite difficult to handle during the field work. Also, aerial photos present a considerable number of details not always interesting and lacking in synoptic view, which could lead the soil specialist to make a number of useless observations (costs amounting to US$ 389/100km²).

- Using high resolution imagery (SPOT and Landsat TM) :

  Due to their large coverage, high resolution imagery at 1:250 000 scale are easy to handle during the field work. Furthermore, they provide a good global view of the essential elements, as well as a quantity of finer details at reduced scale and help to save time (estimated costs for this activity evaluated at US$ 189 to 259/100 Km², according to the data used). This cost decreases when using satellite data in conjunction with aerial photographs (product synergy), with a resulting cost estimated at US$ 190-200/100 Km².

- Using Landsat MSS images :

  The use of Landsat MSS images for orienting the field work appears to be more costly especially when complementary aerial photographs are lacking (US$ 415/100 Km²).

c) Data analysis (refer to table III) :

- The data analysis stage mainly covers the definition of the final legend and the mapping of the boundaries of the soil units. In fact, as the soil unit prospection work advances, the soil specialist is able to put the ground observations into good order, as if composing a puzzle. He is able to draw the physiographic and morpho-pedological boundaries accurately over a topographic map (when available). This, in turn, becomes the basic document for writing the pedological minutes.

- At 1:250 000 scale, using the traditional methodology based on the observation of pedological pits and without resorting to remote sensing, drawing the boundaries is done by SVR interpolations on a grid. This often proves a very tedious task, time-consuming and consequently expensive; furthermore, the final result is not accurate. This method was not taken into account in the comparison presented in table III.

- Using aerial photographs requires mosaicking of the photos which are then used for transferring soil limits to a topographic map. All these tasks are rather time-consuming. They lead to errors and an increase in the time required for writing up the cartographic minutes (cost estimated at US$ 173/100 Km^2).

- The use of satellite images such as SPOT and Landsat TM greatly guides and facilitates the implementation of the various stages leading to the drawing of maps. Satellite data compensate for the lack of valuable topographic information and help to avoid problems when handling a large number of aerial photographs. As a consequence, the time and money spent in elaborating the pedological minutes considerably decrease as compared to previous methods (US$ 83 to 93/100 Km^2).

III.A 3 - Conclusions on cost analysis

Table III makes it possible to compare the costs involved in the different phases previously described, according to the different methodologies considered for soil mapping at 1:250 000 scale.

The methodologies shown between brackets were not studied within the current exercise. They were simply assessed on the basis of past experience. In addition, the costs of the respective phases were calculated on the basis of the financial conditions of CIRAD, which is a Public Industrial and Commercial Establishment (EPIC).

The analysis of this table helps to put forward four main categories of methodologies; these are the following (in increasing order of cost):

1. Economical methods, the costs of which range from US$ 626 to 661/100 Km^2. All of these use high resolution multispectral data in combination with stereoscopic remote sensing data, as follows:

   - SPOT stereopair (PA+XS), with or without aerial photographs.

- SPOT XS data + aerial photographs,

- Landsat TM data + aerial photographs

2. Methods whose costs range from US$ 662 to 675/100 Km², are principally based upon the analysis of high resolution imagery (SPOT or Landsat TM), without resorting to aerial photograph coverage.

3. Higher cost methods (ranging from US$ 705 to 762/100 Km²), which use either a SPOT panchromatic stereo pair, or digital processing of high resolution data, or MSS data in combination with aerial photographs.

4. "Expensive" methods, (amounting to US$ 870 to 1.589/ 100 Km², which concentrate on aerial photograph interpretation without making use of satellite images, or just MSS images without aerial photographs. It must be noted that all methods which require specially flown aerial photographs are very expensive.

Comparing costs cannot be done without comparing advantages, and both analyses must be brought into contact in order to provide better guidance in the choice of the most suitable method.

III B BENEFIT ANALYSIS

As compared to traditional soil mapping methods, the use of remote sensing data has many outstanding advantages, which can be summarized as follows:

III.B.1 - Accuracy of the results

From a general standpoint, it can be said that the larger the number of documents brought into play (different types of satellite data), the better the mapping accuracy (detail and boundary accuracy).

The following products were assessed in terms of mapping accuracy :

- Aerial photographs,

- Standard SPOT XS images,

- SPOT panchromatic stereo pair,

- One SPOT panchromatic and one SPOT XS taken in stereo

- Landsat TM image (delivered at the end of the study).

Firstly, a comparison of the different SPOT products was made at the end of the pilot study from results obtained over the Gaborone site test. SPOT and Landsat TM products were compared on the basis of the results of the morpho-pedological map over Kanye area. Nxai Pan site test was used for the comparison of SPOT images with aerial photographs.

For each of the above-mentioned documents, accuracy was assessed by means of a notation system, with marks ranging from 0 (very bad), to 3 (good accuracy). What was actually judged was the ability of a given document to map accurately the different morpho-pedological units. The final mark given to each document is the mean of the marks relating to each soil unit, scaled as a percentage.

In conclusion (refer to Table IV), 1:250 000 scale mapping is more accurately achieved when using the SPOT (XS + PA) stereoscopic coverage. SPOT XS data alone lead to better results than SPOT panchromatic, which yield good results in terms of accuracy index. Accuracy is slightly decreased when using Landsat TM images.

III.B.2 - Speed of implementation

The speed of implementation of the work was assessed by measuring the time required to carry out the different phases of the soil mapping methodology, that is to say:

- the preparation phase,
- the field-work,
- the data analysis stage.

The remote sensing products tested remain the same as those previously quoted. In order to facilitate their comparison, the respective timing for drawing cartographic documents using each method was noted. The fastest method was given the mark 100, and the others were referenced in the same scale system (table V).

As a conclusion, the fastest methods seem to be those using SPOT data (>80%), the best (100%) being the method which requires SPOT stereo coverage (XS+panchromatic) in combination with existing aerial photographs. Landsat TM data also proved especially good when used in conjunction with aerial photographs (88%).

III.B.3 - Pluridisciplinary interest

A satellite derived document used for soil mapping can also be utilized when drawing other thematic maps at 1:250 000 scale in the field of renewable resources.

All the remote sensing products previously quoted were compared in order to assess their potential use in map drawing for other multidisciplinary applications (refer to table V) such as :

- land use mapping,
- topographic mapping,
- forest inventories and monitoring,
- inventorying and monitoring of water resources,
- land capability studies.

It was deduced that the best results are those obtained when using either specially acquired aerial photographs or SPOT stereo data (XS + panchromatic).

As is the case with soil mapping, one should notice the good results obtained by allying high resolution data with available aerial photographs (93% for SPOT and 87% for Landsat TM). Lastly, it appears that Landsat MSS data do not provide good results, even when used with aerial photographs (46 to 60%).

III.B.4.- Case where 1:250 000 scale mapping is carried out prior to 1:50 000 scale mapping forecast in the medium term

It should be borne in mind that the choice of the data and the methods to be used must be made with, when possible, full knowledge of surveys likely to be implemented in the near future, such as soil mapping or any other thematic mapping (land use), at 1:50 000 scale. In fact, renewable resources inventories usually tend to be reexecuted at a more precise scale after a medium or long period. From this standpoint, of all the methods studied, the only ones which can be considered for future 1:50 000 mapping are those based either on specially acquired aerial photographic coverage, or SPOT data, and particularly the SPOT (XS+P) stereoscopic data.

III.C - CONCLUSIONS ON COST/BENEFIT ANALYSIS AND RECOMMENDATIONS (DIAGRAM VII)

The detailed analysis of respective costs and benefits for the different methodologies makes it possible to distinguish two categories of approaches:

III.C.1.- Methods offering little advantages

These are methods which are not advisable from the cost/benefit standpoint: they can be further subdivided as follow:

a) <u>Remote sensing products which offer less attractive costs and whose advantages are less interesting than any other products under study:</u>

- Standard Landsat MSS data, with or without aerial photographs (always higher in price and lower in advantages than SPOT or Landsat TM);

- Historical aerial photographs, the use of which is expensive, considerably time-consuming and tedious, and which are less advantageous for other applications.

b) Satellite derived products, "not justified" because they prove less interesting from a technical standpoint than other very similar products, and present higher acquisition constraints:

- Digitally enhanced high resolution data (SPOT, Landsat TM), less interesting than the corresponding standard false color composites (almost similarly advantageous and considerably more expensive).

- Panchromatic SPOT stereoscopic coverage, less attractive in economic terms and advantages than the SPOT (one XS + one PA) stereo pair.

c) Remote sensing products whose cost is very high and whose advantages over other products do not justify their use, such as with specially acquired aerial photographs (cost estimated to be US$ 1.569,7/ 100Km²).

III.C.2 - Recommended products : High resolution satellite data

Once all the disadvantageous products have been eliminated, there is still a group of products all of which are worth considering according to specific study conditions. These are :

- SPOT (XS+P) stereo pair, either with or without (historical) aerial photographs

- SPOT XS either with or without aerial photographs

- Landsat TM, either with or without aerial photographs.

Optimising the choice of one of these products is better done through the decision tree shown in diagram VII. The main parameters to be considered are:

- the availability of fair quality aerial photograph coverage,

- the feasibility of acquiring SPOT (XS+P) stereo coverage within a reasonable deadline;

- the existence of severe budgetary constraints (tolerance lower than US$ 0,3/ Km²);

- the likelihood that 1:50 000 scale mapping of the area under study will be required within a medium term (5 to 6 years time);

- the additional programmation cost for acquisition of SPOT data (special or not, according to the case).

Finally, the following are recommended (refer to diagram VII):

1. SPOT (XS+P) stereo coverage: where aerial photographs are not available and acquisition of stereoscopic data cannot be obtained within a reasonable deadline.

2. SPOT (XS+P) + aerial photographs, should there be lower budgetary constraints (tolerance US$ >0,3/Km^2).

3. - Standard SPOT XS products - when aerial photographs are not available, stereoscopic data cannot easily be obtained and the SPOT programming price is high.

4. Standard Landsat TM data, - for the reasons previously quoted for SPOT XS, and when the SPOT programming price is high (e.g.: Special programmation acquisitions pending).

5. Standard SPOT XS + aerial photographs - in the case of more severe budgetary constraints, when soil mapping at 1:50 000 scale is foreseen in the medium term, or even not foreseen at all, and when existing SPOT data are mostly already archived (though not processed).

6. Standard Landsat TM products + aerial photographs - where budgetary constraints are severe, 1:50 000 scale mapping is not anticipated in the medium term, and when SPOT data must in part be programmed (normal or special acquisition).

FINAL CONCLUSIONS (Executive Summary)

The current pilot study, aimed at investigating 1:250 000 and 1:50 000 scale soil mapping using high resolution satellite data, was implemented within the framework of projects carried out by F.A.O.

This study was two-fold:

- An analysis aimed at assessing the most suitable techniques (visual or digital interpretation) for soil mapping, concentrating on SPOT data (Landsat TM data was unfortunately not made available before the end of the study).

- A cost/benefit analysis which compared the use of several remote sensing tools (Landsat MSS, Landsat TM, SPOT, aerial photographs) and which resulted in a series of recommendations for operational application projects dealing with soil mapping.

From a general standpoint, it has been demonstrated that the use of high resolution satellite data (Landsat TM and SPOT) offers the various following technical advantages:

- Synoptic coverage, which allows for fast analysis and comprehension of soil genesis phenomena over large natural areas

- Homogeneous geometrical characteristics which greatly facilitate the transfer of cartographical information ;

- High resolution pixels, which bring a wealth of information about landscape elements.

The best results are those obtained through visual analysis of the images when using a so-called hierarchical approach, both descending and ascending :

The descending approach consists of extracting main land forms, then dividing these into geological units, which are in turn broken down into a number of geomorphological units, and identifying the numerous morpho-pedological units. Within these latter units, soil associations or pure soils can finally be mapped.

The ascending approach consists of analysing, as a second stage, the land use closely associated to certain underlying soils. The final mapping exercise is the integrated result of the soils units identified both in the descending and the ascending approach. Such a methodology still relies on rather intensive ground survey.

The technical assessment of using specifically high resolution data for soil mapping was made from analysis of SPOT multispectral and panchromatic data over three test sites for 1:250 000 scale soil mapping and over two test sites for 1:50 000 scale soil mapping.

It was shown that, whatever the mapping scale considered, SPOT XS data gave better results than other products such SPOT PA stereopair or even available old and medium quality aerial photos.

At 1:250 000 scale, SPOT XS allows preparation from reduced amount of ancillary information, of a geomorphological map which can be used for pedological purposes. Furthermore, in geologically homogeneous and balanced zones, they proved very effective for mapping soil units which directly related to vegetation cover. In any case, stereoscopic data (SPOT stereo pair or aerial photographs) are always useful and in several cases even essential to complement the monoscopic SPOT multispectral data for the establishment of the final soils association unit map (eg. Gaborone).

At 1:50 000 scale, it was demonstrated that, with a rather limited ground survey, digitally enhanced SPOT XS provides a good performance but, nevertheless, still lacks precision for final soil mapping. From a technical standpoint, it is highly recommended to complement them with a stereoscopic pair of SPOT data (preferably XS + PA taken in stereo) or eventually with good quality recent aerial photographs.

A cost/benefit analysis of 1:250 000 soil mapping was undertaken in an attempt to judge 12 distinct remote sensing approaches, each one characterized by products and product combinations (Landsat MSS, Landsat TM, aerial photographs, SPOT panchromatic). This study was based on estimates and showed that methods using SPOT (or Landsat TM data) were by far the most cost effective, thanks mainly to the time saved by these products in map preparation and ground survey. Consequently, all the methods which use Landsat MSS and/or recent or specially acquired aerial photographs were not advisable.

It was also shown that the total cost of soil mapping (i.e. the management of the project, purchase and analysis of high resolution remote sensing data, field-work, soil sample analysis and map edition) ranged from US$ 6 to 7/Km^2, for the most cost-effective methods.

From an operational point of view, a list of recommendations on the best remote sensing products to be used was drawn up, in relation to the various conditions to be considered in a 1:250 000 soil study (Diagram VII): thus, it was noticed that, according to the study conditions, a SPOT (XS+P) stereo pair, SPOT XS or Landsat TM color composite is advisable. The final choice is governed by a group of considerations on programmation costs, availability of images or future studies at 1:50 000 scale. In all cases, it was observed that the use of aerial photographs, when available and of good quality, in conjunction with high resolution satellite data is always cost-effective.

The current study is only a first assessment and its results should be through operational projects.

In conclusion, the use of high resolution satellite images permits faster and more efficient soil surveys. There is not doubt that they are useful new tools, not only technically but also from the economic point of view for soil mapping projects in developing countries.

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TAB I:

HIERARCHICAL APPROACH
(descending and ascending)

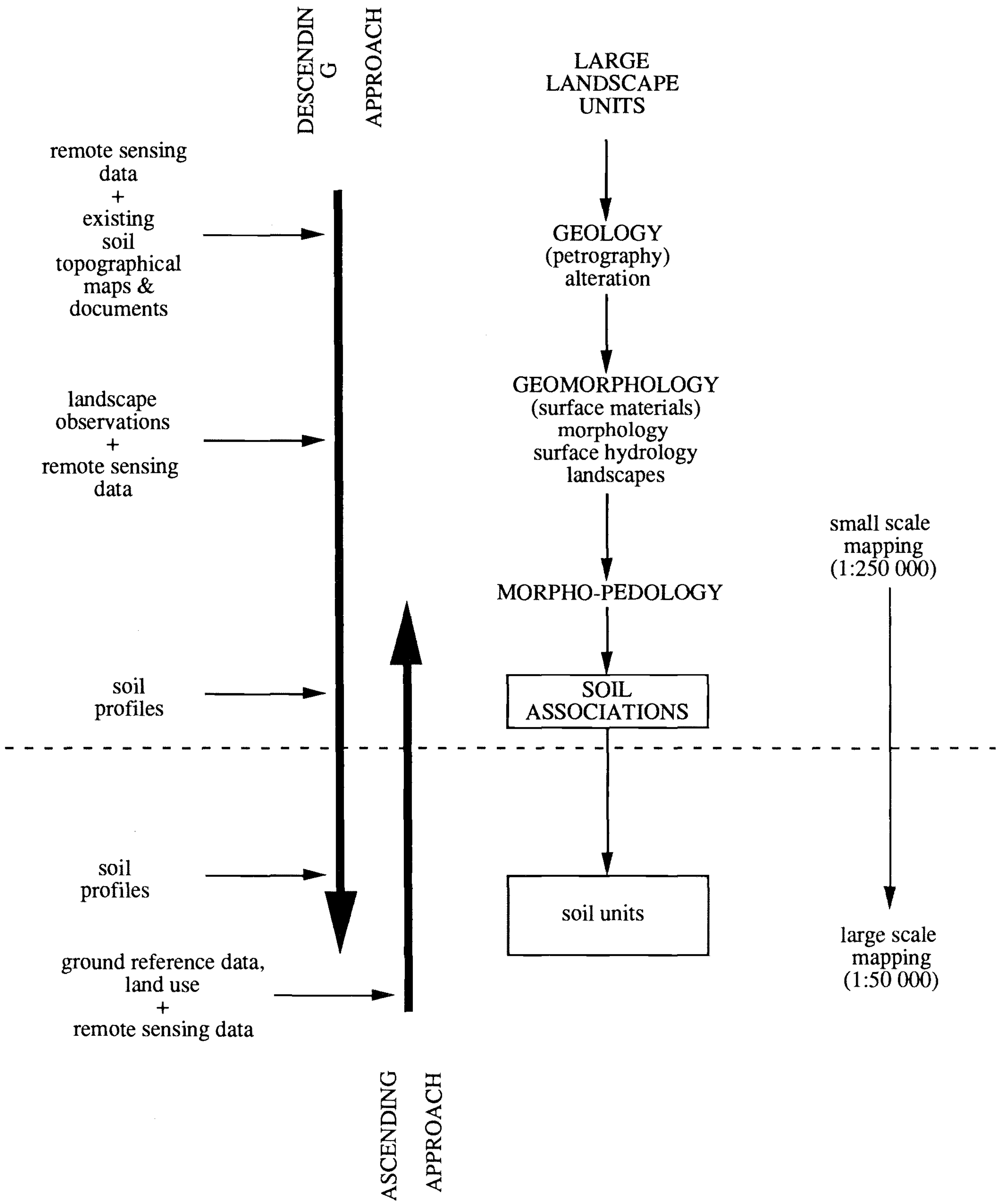


Table II

ESTIMATES OF UNIT COSTS

ANUAL AVERAGE COST FOR SOIL MAPPING

EXPATRIATED SPECIALIST	100.000	TO	140.000 $
NATIONAL SPECIALIST	10.000	TO	50.000 $
TEAM LEADER NATIONAL	4.000	TO	8.000 $
DRIVER	3.000	TO	6.000 $
3 TO 5 WORKERS	3.000	TO	10.000 $
4 WD VEHICLE	15.000	TO	25.000 $
MISSION EXPENDITURES	5.000	TO	10.000 $

ESTIMATES VARIABLE COSTS FOR DIFFERENT PHASES (PER MONTH)

- OFFICE PREPARATORY WORK 11 000 USD
- FIELD WORK 15 000 USD
- ANALISYS, MAPPING 12 000 USD

Table III

SUMMARY OF COST ASSESSMENT FOR IMPLEMENTING REMOTE SENSING SOIL MAPPING AT 1/250.000 SCALE

ESTIMATED COSTS IN US $ / 100 km2										
ALLOCATION OF MAPPING COSTS / MAPPING METHODS	BASIC DATA		VARIABLE COSTS					FIXED COSTS		TOTAL
	Raw data	Digital processing	Office preparatory work	Field-work: referencing	Field-work: inter-pretation	Field-work: total	Analysis report mapping.	Map edition	Soil analysis	
1. AERIAL PHOTOGRAPHS										
11. already existing	11,2	-	127,0	96,0	389,0	485,0	173,0	21,3	92,2	909,7
12. special acquisitions	711,0		127,0	76,0	389,0	465,0	173,0	21,3	92,2	1569,5
2. SATELLITE IMAGES ONLY										
21. SPOT										
a - standard XS	44,0		76,0	130,0	216,0	346,0	83,0	21,3	92,2	662,5
b - digital XS	64,8	6,9	95,0	130,0	216,0	346,0	83,0	21,3	92,2	709,2
c - stereo P	123,0		76,0	112,0	259,0	371,0	87,0	21,3	92,2	770,5
d - stereo. P et XS	112,6		72,0	106,0	189,0	295,0	77,0	21,3	92,2	670,1
22. LANDSAT TM										
a - standard	12,8		63,0	147,0	246,0	403,0	93,0	21,3	92,2	675,3
b - digital	13,0	11,5	95,0	147,0	246,0	403,0	93,0	21,3	92,2	719,0
(23. LANDSAT MSS)	1,6		73,0	173,0	415,0	588,0	104,0	21,3	92,2	880,1
3. COMBINATION OF AERIAL PHOTOGRAPHS AND SATELLITE IMAGE										
31. PA + SPOT XS	55,2		95,0	86,0	190,0	276,0	90,0	21,3	92,2	629,7
32. PA + LANDSAT TM	24,0		82,0	86,0	210,0	296,0	111,0	21,3	92,2	626,5
(33. PA + LANDSAT MSS)	12,8		82,0	86,0	346,0	442,0	111,0	21,3	92,2	751,3
34. PA + SPOT (XS + PA)	123,8		95,0	86,0	152,0	245,0	77,0	21,3	92,2	647,3

P.S.1 : This cost/benefit analysis has been calculated within the financial framework of a French Industrial and Commercial Public Establishment Legal Status.
P.S.2 : The data mentionned between brackets (LANDSAT) are estimation figures based on the consultant experience and do not relate directly to the current field study. .
* with access to topographic maps

Table IV

ANALYSIS OF THE MULTIDISCIPLINARY INTEREST (SOIL MAP AT 1:250 000 SCALE)

	REMOTE SENSING APPROACH											
Mapping Applications	**Ph.a**	**Ph.b**	**S.XS**	**N.XS**	**S.P + S.P**	**S.P + S.XS**	**S.TM**	**N.TM**	**S.MSS**	**Ph + S.XS**	**Ph + S.TM**	**Ph + S.MSS**
Land Use Map	1	3	3	3	2	3	3	3	2	3	3	2
Topographic Map	1	3	2	2	3	3	2	2	1	2	2	1
Inventories, forest Monitoring	2	3	2	2	2	3	2	2	1	3	3	2
Inventories, water resources monitoring	2	3	3	3	2	3	3	3	2	3	3	2
Environment potentialities assessment	2	3	3	3	2	3	3	3	1	3	3	2
TOTAL	8	15	13	13	11	15	13	13	7	14	14	9
Percentage	53	100	87	87	73	100	87	87	46	93	93	60

Table IV

Analysis of mapping accuracy (in %)
(1/250,000 scale soil map)

	Remote Sensing Approach		
Mapping Unit	SPOT XS standard	SPOT Panchro stereo standard	SPOT XS et P stereo standard
1	2	2	3
2	2	3	3
3	3	2	3
4	3	3	3
5	3	2	3
6	2	3	3
7	2	2	3
8	3	2	3
9	3	3	3
10	3	3	3
11	2	2	2
12	3	3	3
13	1	2	2
14	2	3	3
15	2	2	3
16	3	1	3
17	2	2	2
18	2	2	3
19	3	3	3
20	2	2	3
21	2	1	2
22	3	3	3
23	3	2	3
24	2	2	2
25	2	2	2
26	3	2	3
27	3	2	3
28	3	2	3
29	2	2	2
30	2	3	3
	81%	76%	94%

Table V

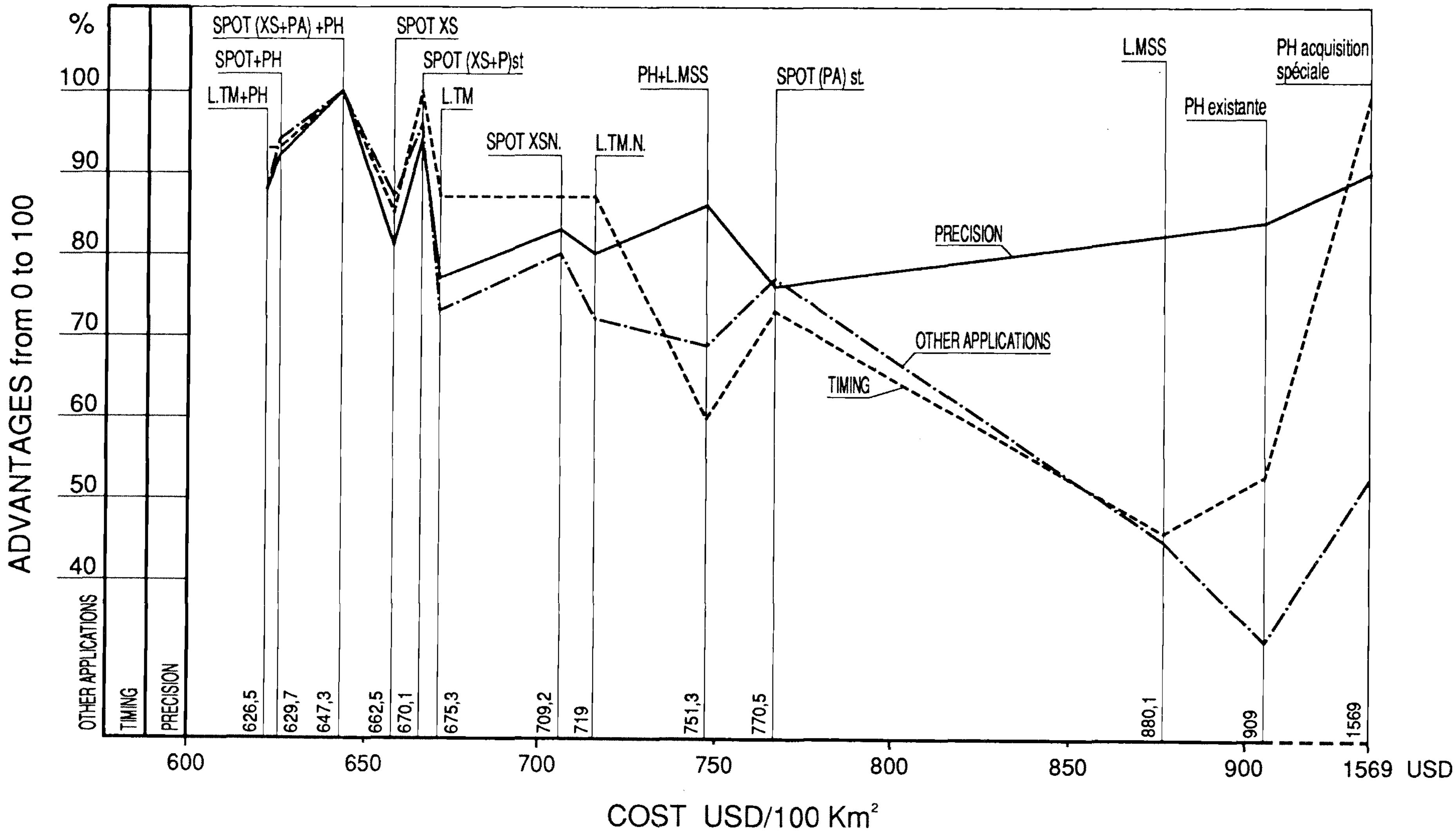
Comparative analysis of various remote sensing methods

(1:250 000 scale soil map)

Remote sensing method	Accuracy	Speed	Pluridisciplinary interest
1. Aerial photographs			
1.1. Already existing	84	33	53
1.2. Special Acquisition	90	53	100
2. Satellite Images			
2.1. SPOT			
a - standard XS	81	85	87
b - digital XS	83	80	87
c - stereo. P	76	78	73
d - stereo. P et XS	94	96	100
2.2. LANDSAT TM			
a - standard	77	73	87
b - digital	80	70	87
2.3. LANDSAT MSS		45	46
3. Aerial photographs and satellite images (standard)			
3.1. PA + SPOT XS	92	94	93
3.2. PA + LANDSAT TM	88	88	93
3.3 PA + LANDSAT MSS	86	69	60
3.4 PA + SPOT (XS+PA)	100	100	100

Marks are rescaled to percentages, and the value 100 means the method is the more performant (accuracy, rapidity or potentialities for other applications).

TABLE VI = COST BENEFIT SYNTHESIS



TAB VII

DECISION TREE
CHOICE OF THE METHODOLOGY
FOR SOIL MAPPING AT 1/250.000 SCALE

(from cost/benefit analysis)

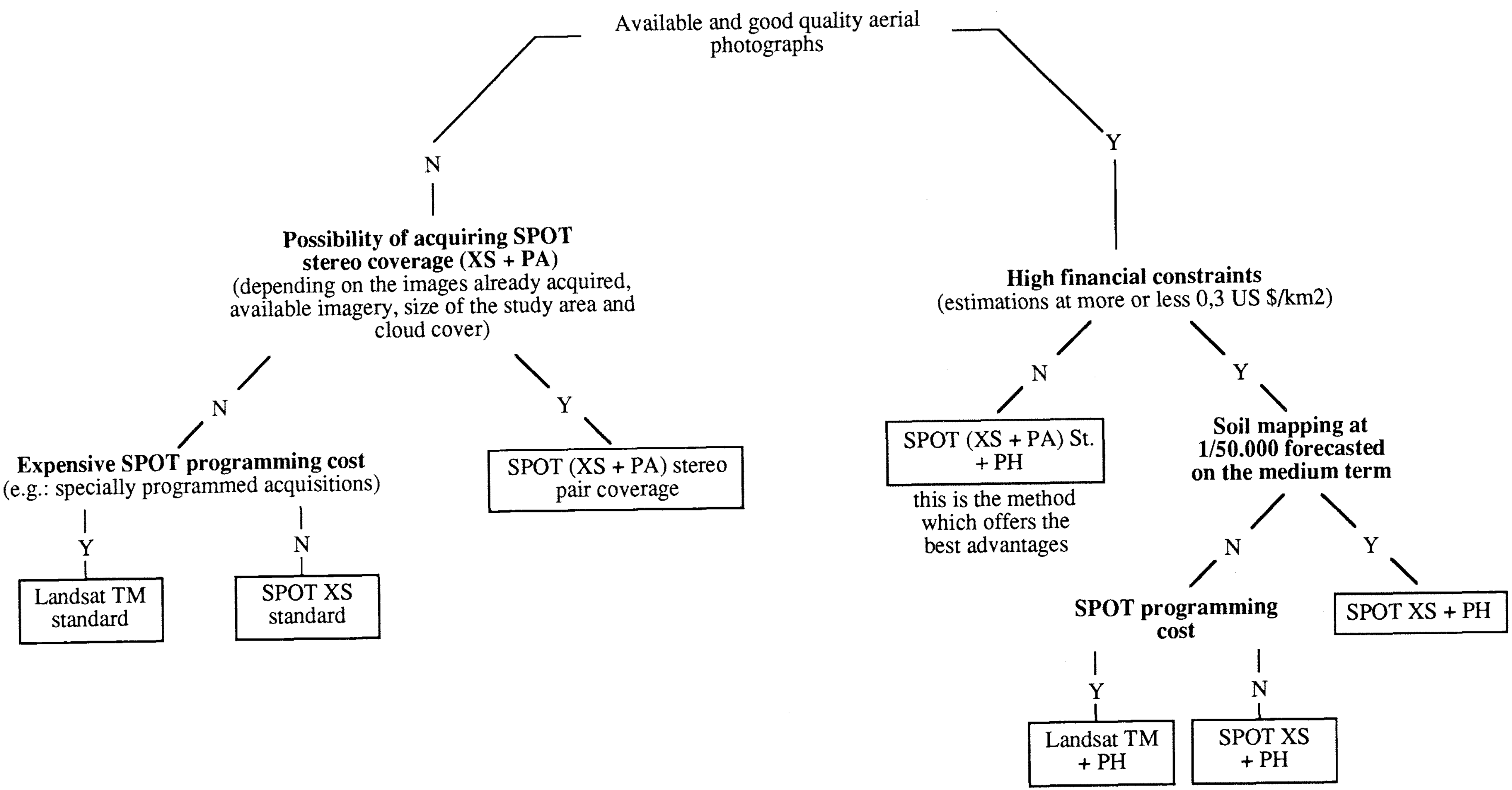


PLATE 1: LOCATION MAP OF STUDY AREAS

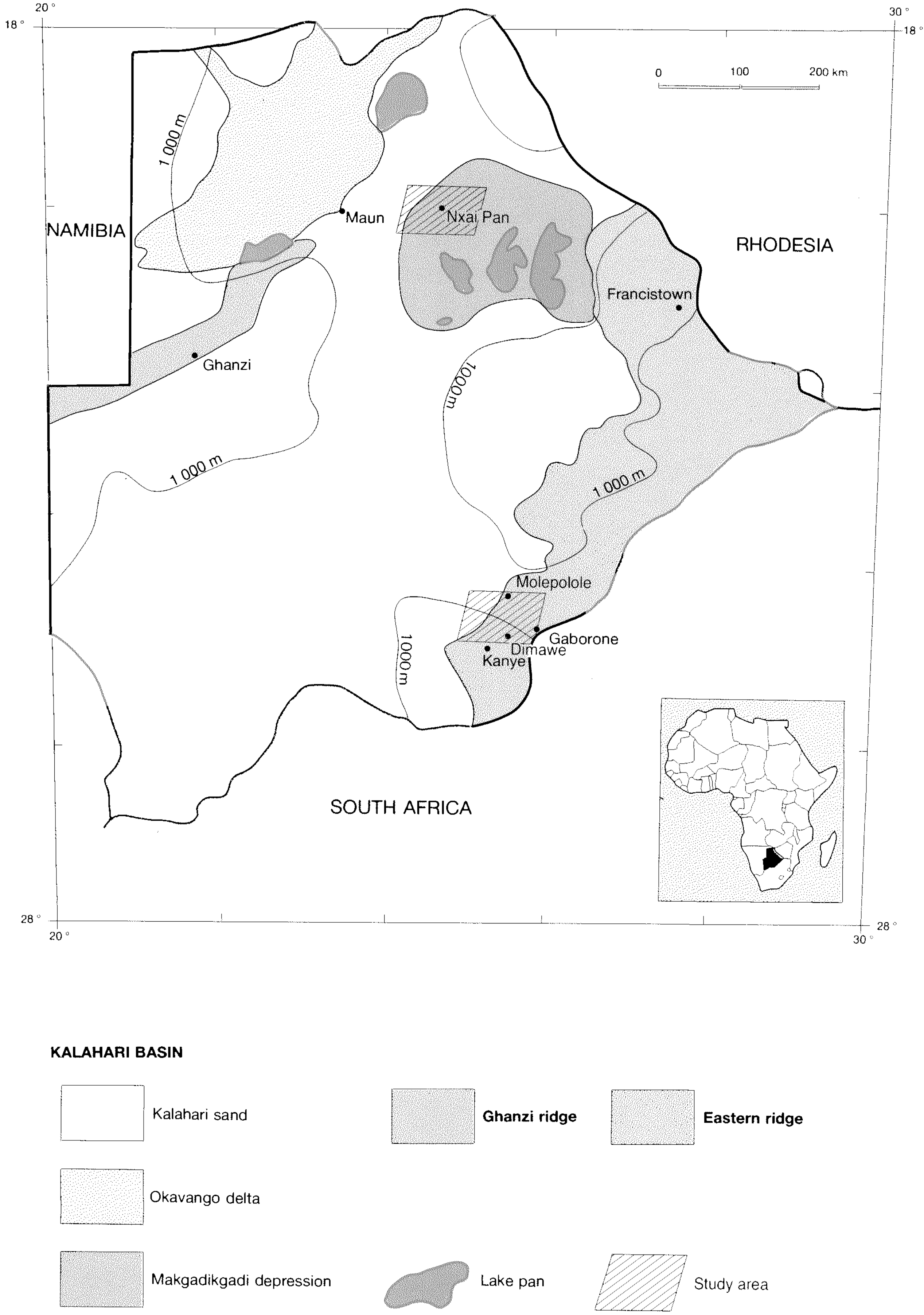


PLATE 2: GROUND PHOTOGRAPHS

PLATE 3: 1/250,000 SPOT XS CO

MPOSITE IMAGE OF GABORONE

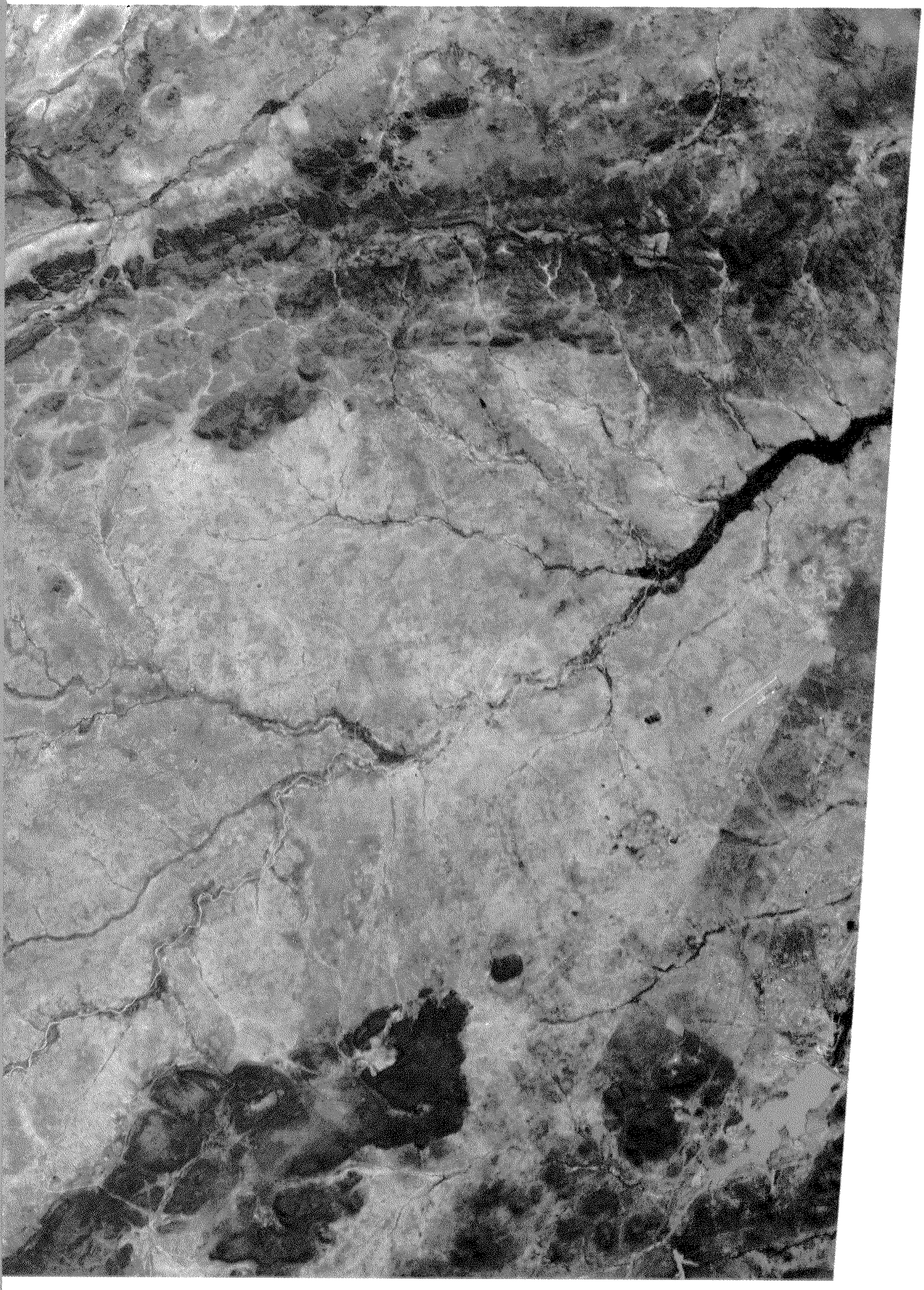


PLATE 4: SPOT PANCHROMATIC 1/250,000 STEREOSCOPIC PAIRS OF WEST OF GABORONE IMAGE

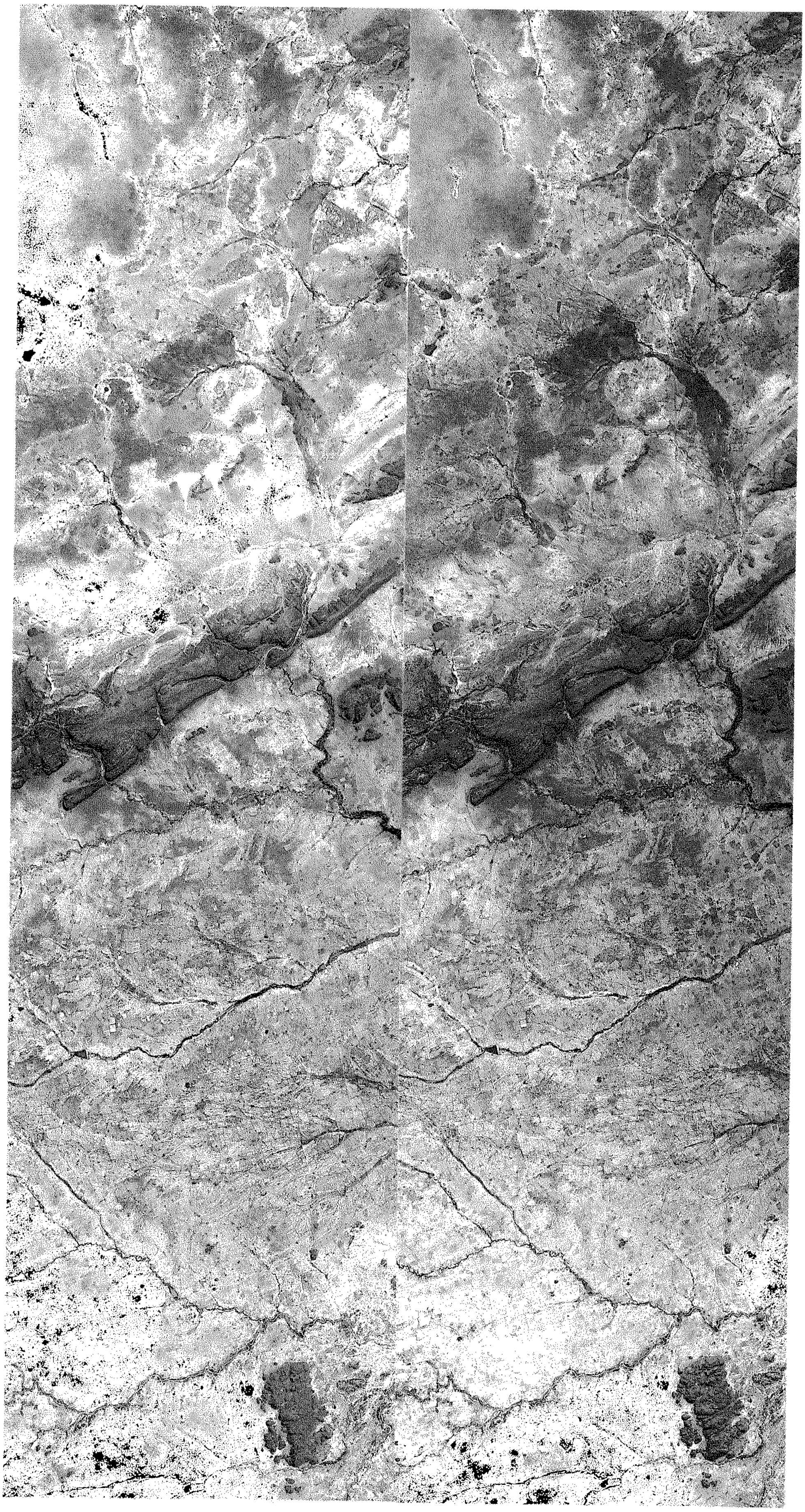


PLATE 5: 1/250,000 GEOLOGICAL MAP OF GABORONE

GEOLOGICAL MAP

From original maps

1/125 000

GABORONE SHEET
MOLEPOLOLE SHEET

LEGEND

K : Karoo : feldspathic grit - sandstone

D : Sill, Dyke, dolerite (diabase)

W : Waterberg undifferentiated

W_4 : shale sandstone

W_3 : feldspathic and quartzitic sandstone

W_2 : shale siltstone sandstone

W_1: red sandstone

T : Transvaal : chert - quartzite

G : Gaborone granite : granite

F : Kanye volcanic : felsite

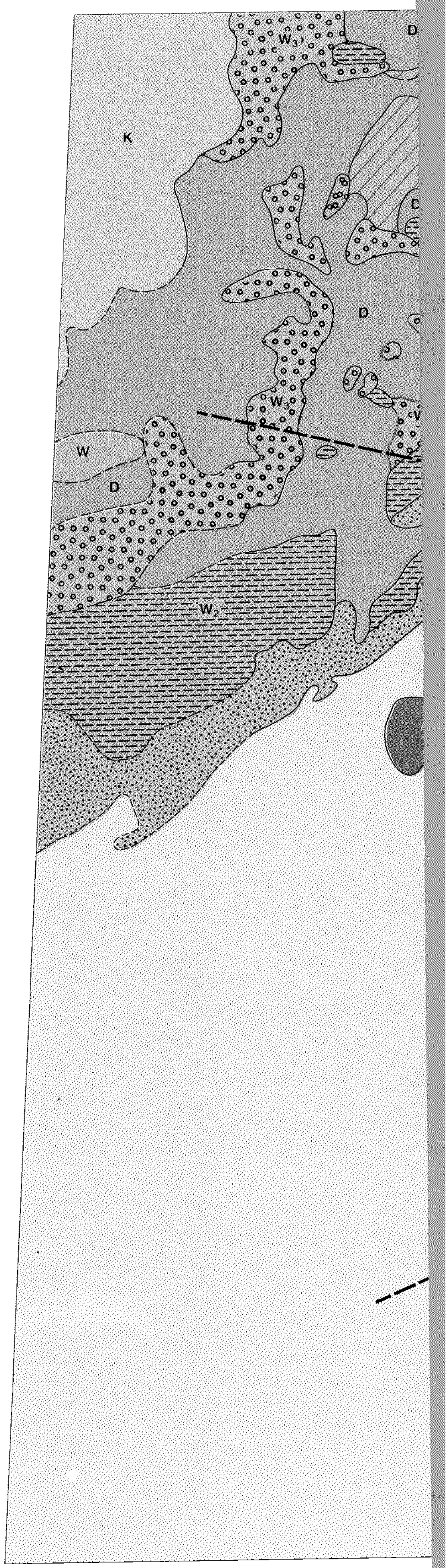
S : syenite

SPOT interpretation :

----- Extrapoled boundaries

——— Improved boundaries

---< Lineament



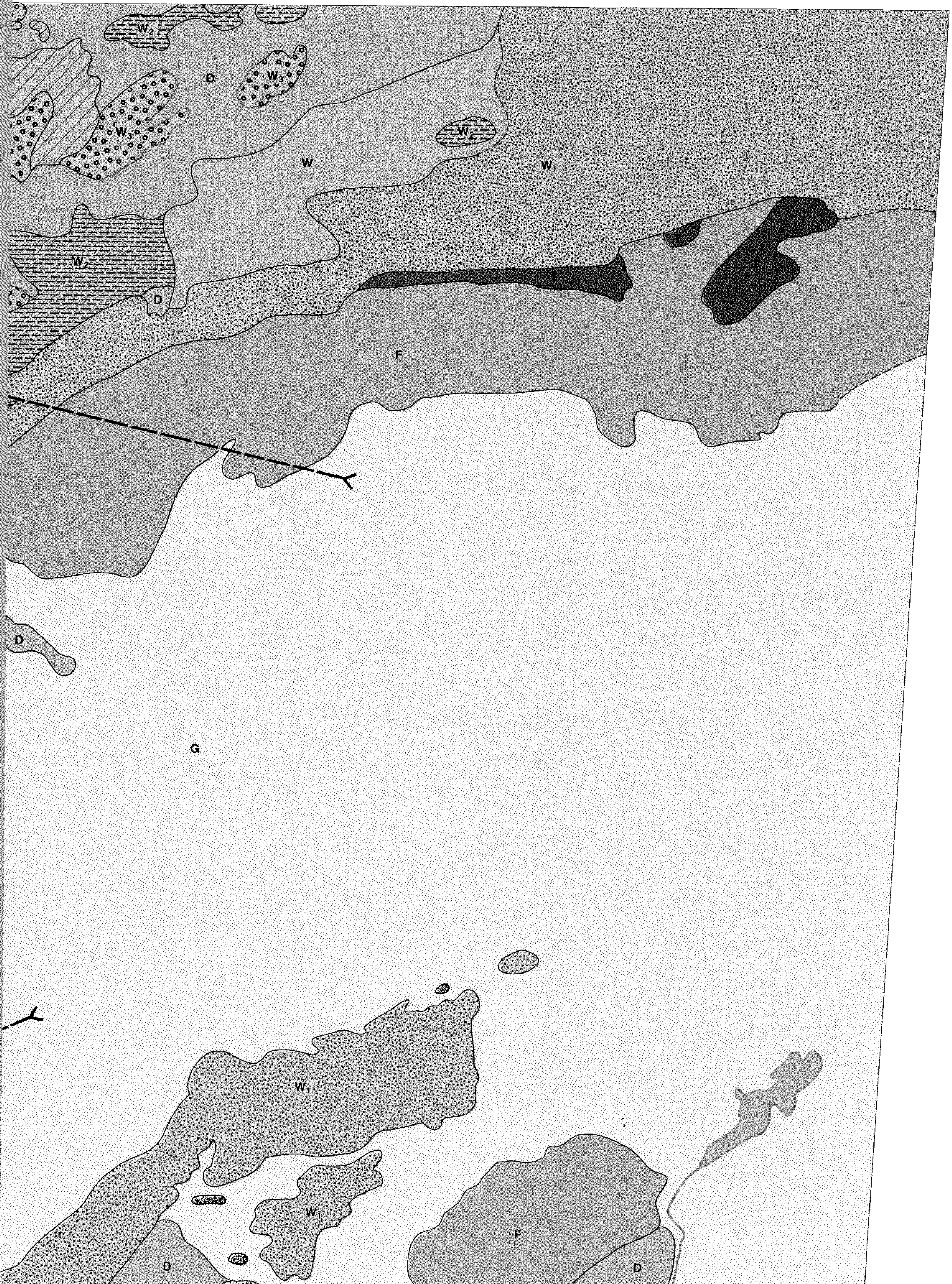


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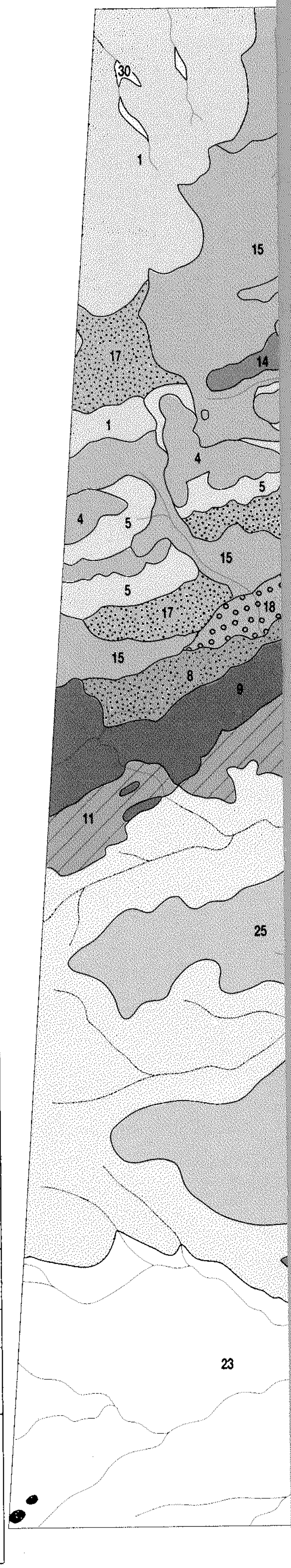
PLATE 6: 1/250,000 MORPHO-PEDOLOGICAL MAP OF GABORONE

Land unit	Geology	Lithology	Landform	Soils (FAO)	
Kalahari plateau	Karoo	feldspathic grit	plateau	cambic arenosols	1
Tabulary or Cuesta	Waterberg	shale	rocky butte	lithosols	2
		sandstone	hollow denudation pediment	chromic luvisols eutric regosols	3
		feldspathic and quartzitic sandstone	convex hill	arenic ferric luvisols	4
			slope pediment	arenic ferric luvisols ferralic arenosols	5
		shale sandstone	convex hill	lithosols and regosols	6
			denudation pediment	ferric luvisols regosols	7
			colluvial pediment	arenic ferric luvisols	8
		red sandstone	structural surface residual hill	lithosols	9
			colluvial pediment	ferralic aerosols lithic	10
		sand deposit from red sandstone	colluvial pediment	arenic ferric luvisols arenic luvic xerosols	11
				ferralic arenosols arenic ferric luvisols	12
Reliefs	Transvaal Ventersdorp	quartzite chert shale siltstone	structural surface	lithosols	13
	sills various age	diabase	rocky hill	lithosols	14
			hollow	chromic luvisols	15
				pellic vertisols	16
		sand deposit on diabase	colluvial pediment	ferralic arenosols	17
				arenic ferric luvisols	18
Metsemothaba	Kanye volcanic	felsite porphyry	convex hill	regosols, lithosols	19
			denudation pediment	regosols	20
	pre Ventersdorp	granite	mixed pediment	dystric regosols	21
			inselberg	lithosols	22
			denudation pediment unstable environment	dystric regosols ferric luvisols petroferric ferric luvisols	23
"Weald"	post Kanye volcanic		denudation pediment stable environment	ferric luvisols petroferric ferric luvisols	24
				ferric luvisols dystric regosols	25
				ferric acrisols ferric luvisols petric	26
			mixed pediment (Dimawe hollow)	ferric luvisols petric ferric luvisols arenic	27
	Gaborone post gaborone granite	syenite	inselberg	lithosols	28
			slope	dystric regosols petric ferric luvisols petric	29
Valleys Inland valleys	quaternary	alluvium colluvium	valley flat	calcaric cambisol chromic luvisols ferric luvisols gleyic luvisols calcic luvisols pellic vertisols	30



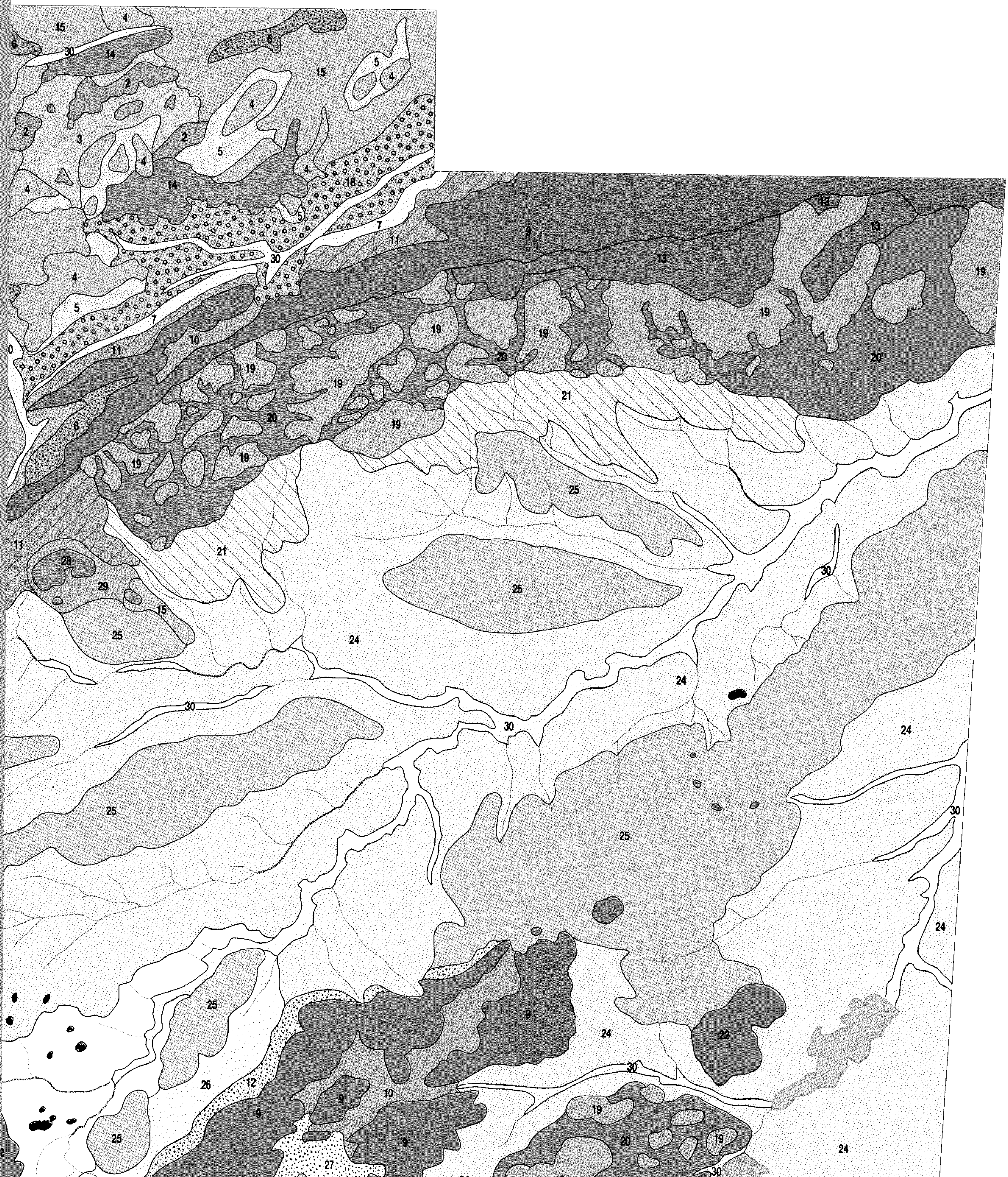


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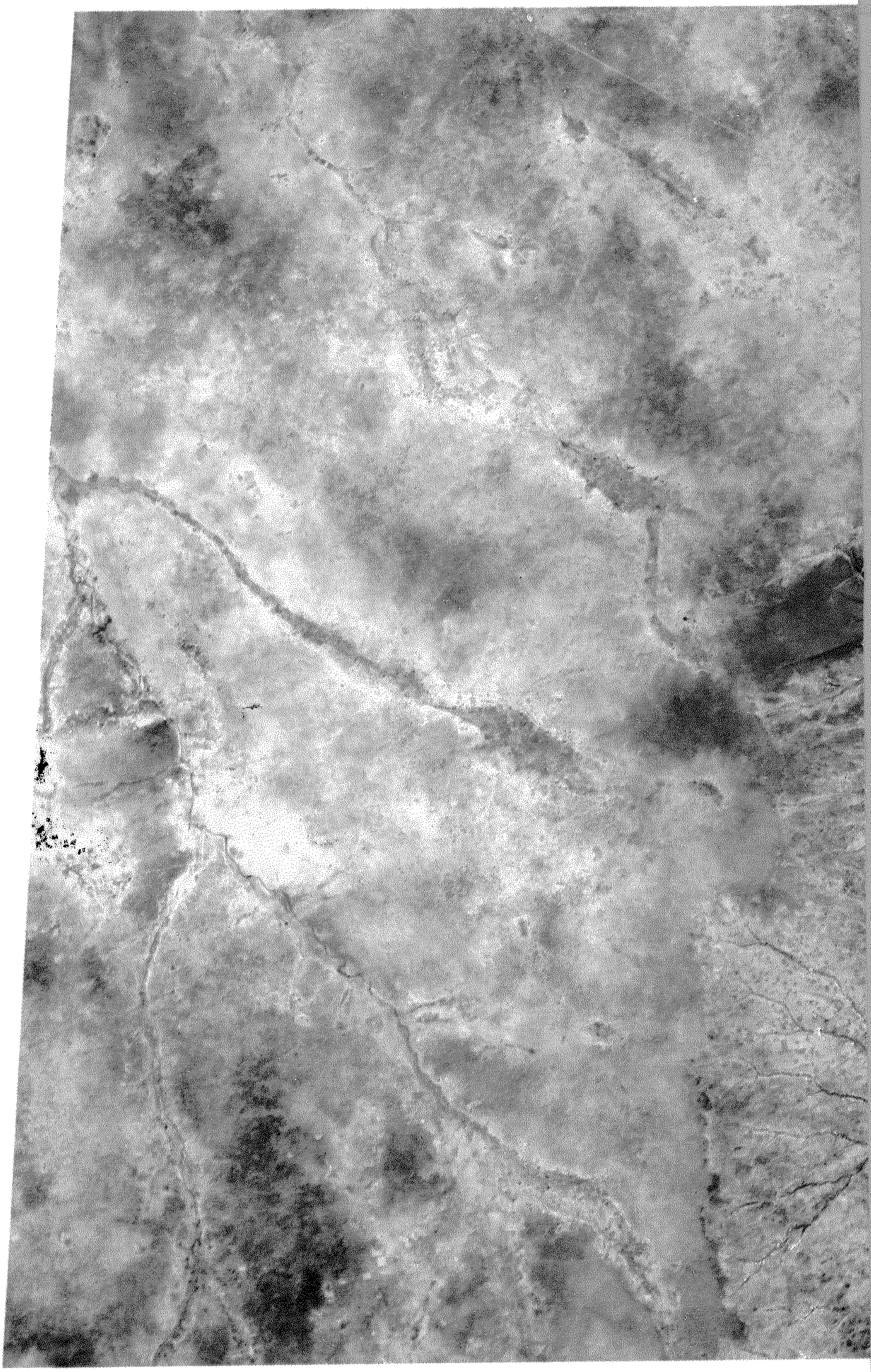
PLATE 7: 1/250,000 STANDARD SPOT XS COLOR COMPOSITE IMAGE OF KANY



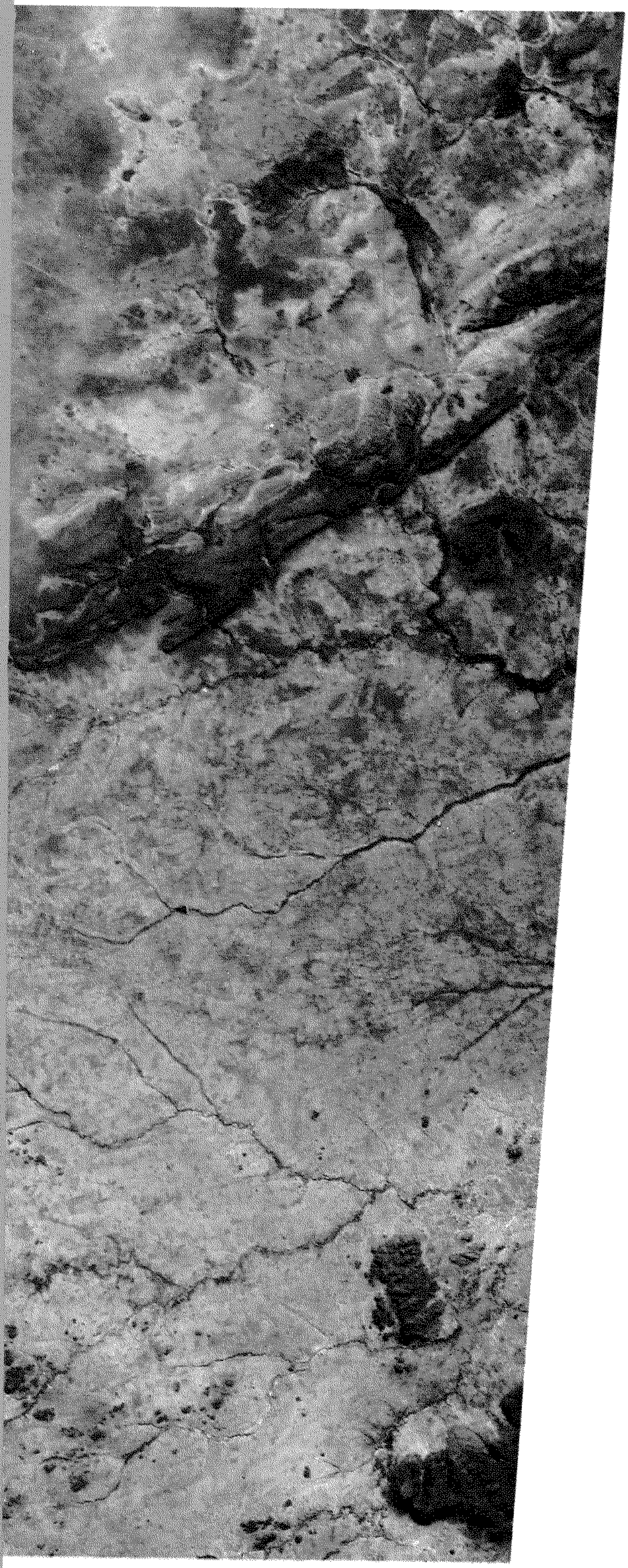
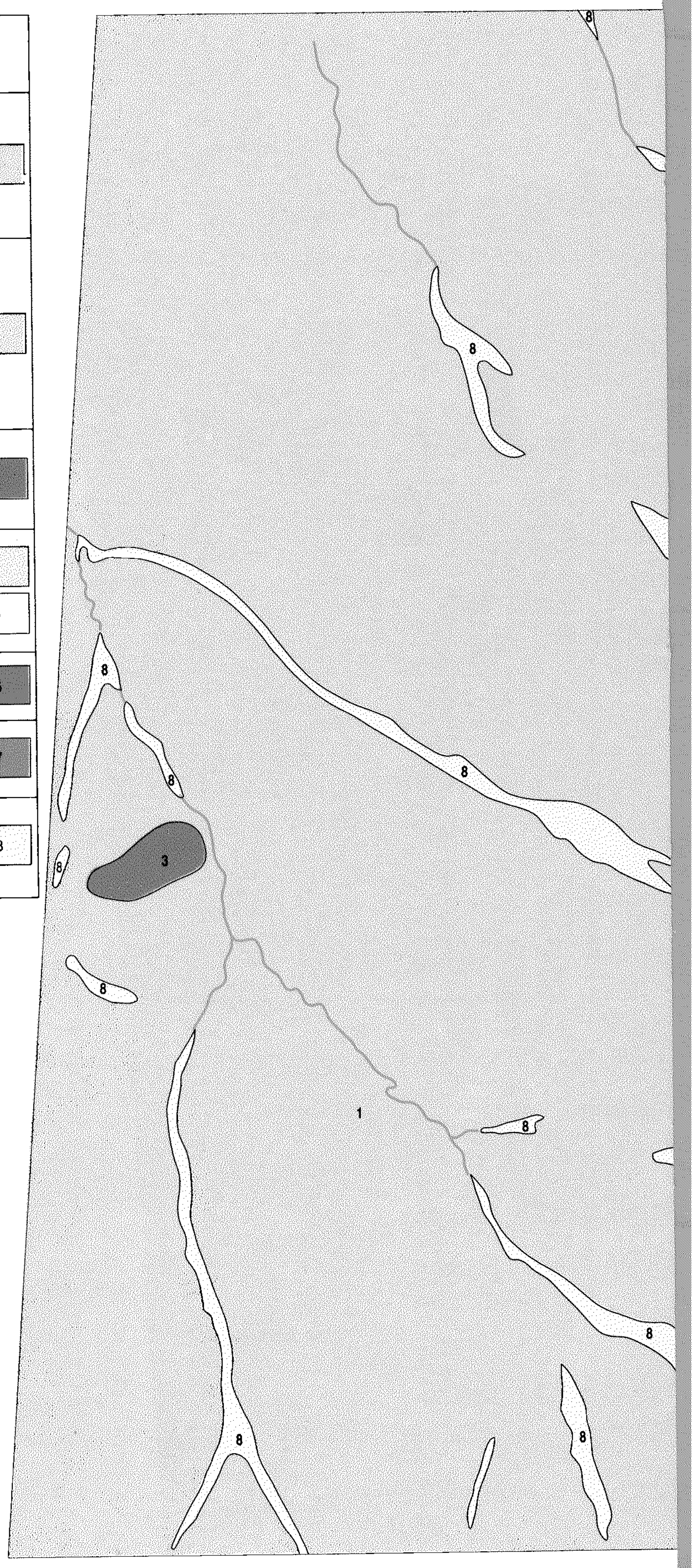


PLATE 8: 1/250,000 MORPHO-PEDOLOGICAL MAP OF KANYE

Land unit	Geology	Lithology	Landform	Soils (FAO)	
Kalahari Plateau	Karoo Kalahari	feldspathic grit sands	hill and plateau	cambic arenosols ferralic arenosols	1
Tabulary or Cuesta Reliefs	Waterberg	sandstone shale diabase	hill cuesta plain	arenic ferric luvisols arenosols chromics luvisols	2
		red sandstone	plateau cuesta	lithosols	3
Metsemothaba "Weald"	pre Ventersdorp	granite	pediment stable	ferric luvisols	4
			unstable	chromic luvisols	5
			inselberg	lithosols	6
		syenite	inselberg	lithosols	7
Inland valleys	quatemary	alluvium colluvium	small valley valley	luvisols	8



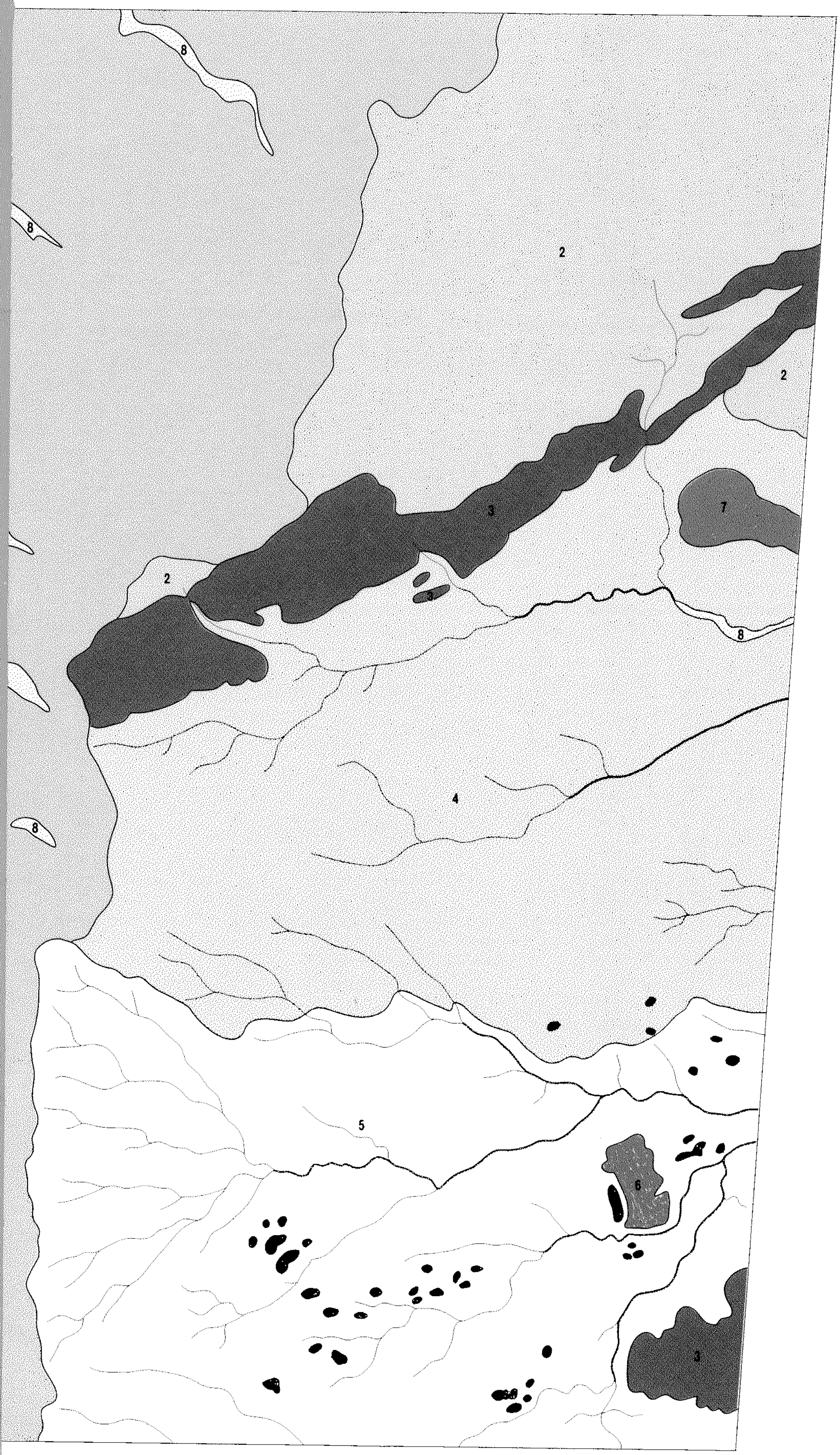
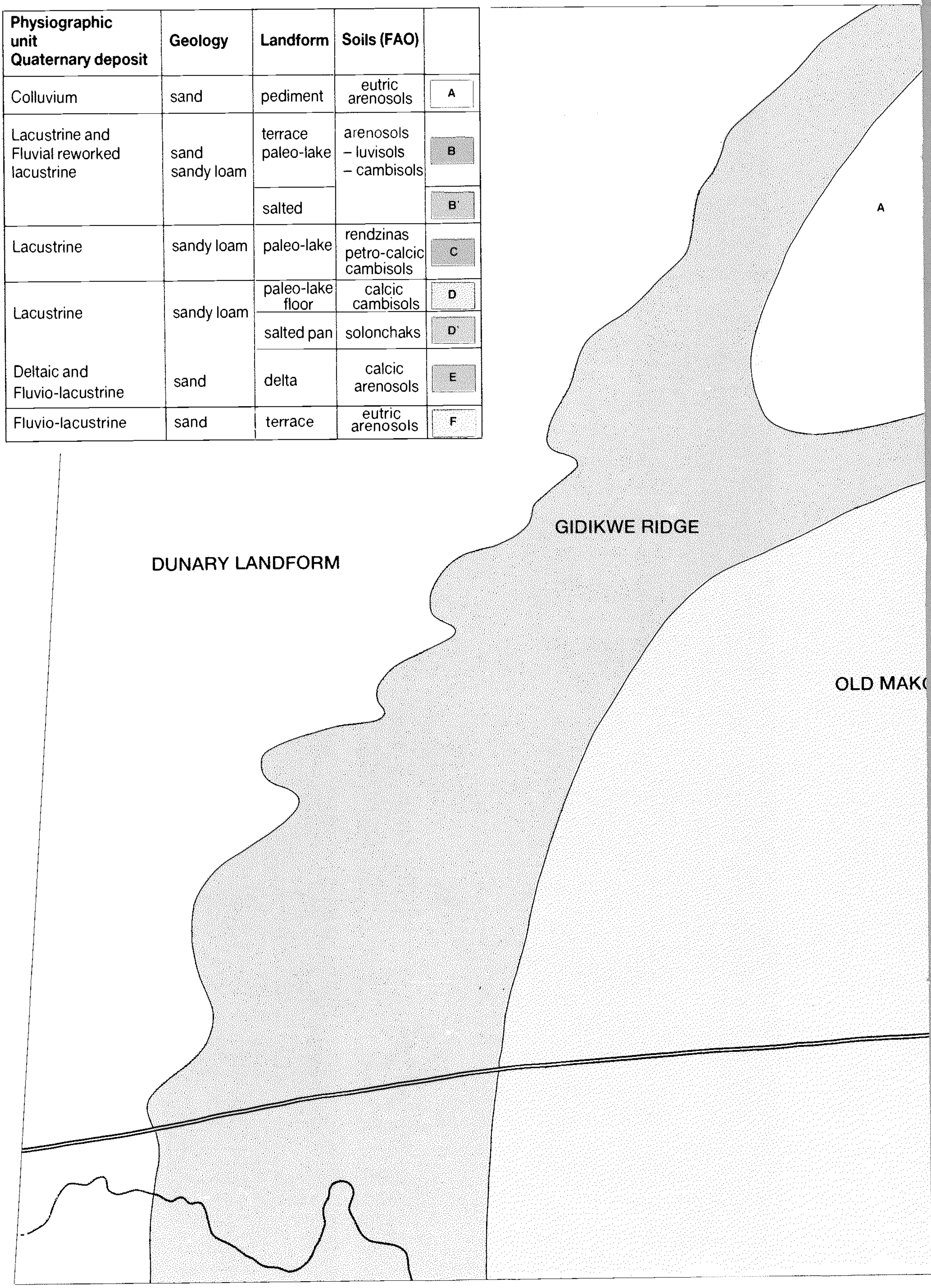

8
8
2
2
3
7
2
3
8
4
5
6
3

PLATE 9: 1/250,000 STANDARD SPOT XS COLOR COMPOSITE IMAGE OF NXAI PAN

PLATE 10: 1/250,000 PHYSIOGRAPHIC MAP OF NXAI PAN

Physiographic unit Quaternary deposit	Geology	Landform	Soils (FAO)	
Colluvium	sand	pediment	eutric arenosols	A
Lacustrine and Fluvial reworked lacustrine	sand sandy loam	terrace paleo-lake	arenosols – luvisols – cambisols	B
		salted		B'
Lacustrine	sandy loam	paleo-lake	rendzinas petro-calcic cambisols	C
Lacustrine	sandy loam	paleo-lake floor	calcic cambisols	D
		salted pan	solonchaks	D'
Deltaic and Fluvio-lacustrine	sand	delta	calcic arenosols	E
Fluvio-lacustrine	sand	terrace	eutric arenosols	F



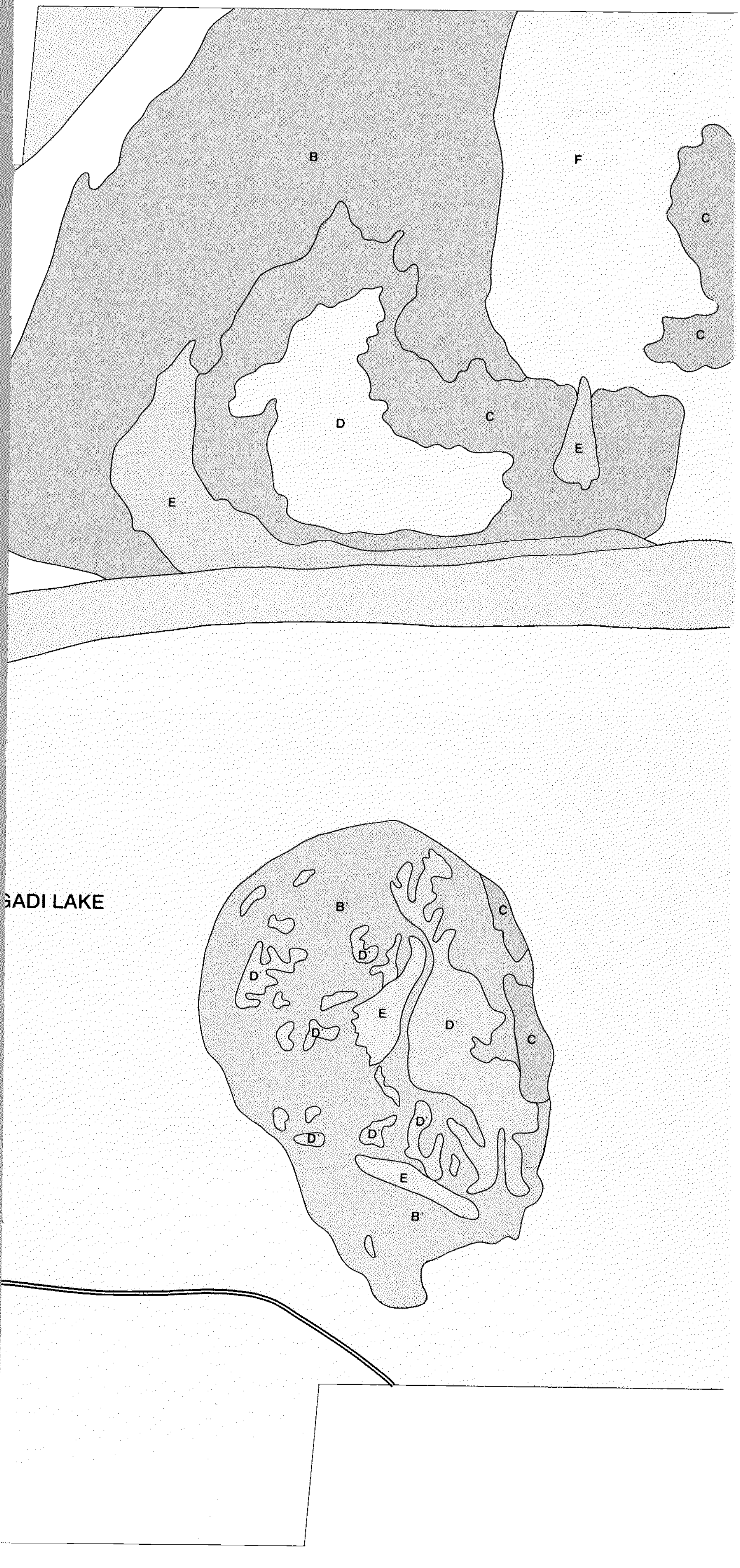

B
F
C
C
D
C
E
E
GADI LAKE
B'
C
D'
D'
E
D'
D'
C
D'
D'
D'
E
B'

PLATE 11: 1/50,000 SPOT XS COLOR COMPOSITE IMAGE OF DIMAWE

PLATE 12: 1/50,000 MORPHO-PEDOLOGICAL MAP OF DIMAWE

Land unit		Geology	Lithology	Landform	Soils (FAO)	Landuse
Tabulary Relief	1a	Waterberg	red sandstone	plateau	lithosols	woodland
	1b			cliff	lithosols	woodland
	1c			hollow	lithosols	woodland
	2		sand	colluvial pediment	arenic eutric regosols	dryland farming
Metsemothoba "Weald"	3	pre Ventersdorp	granite	denudation pediment	ferric luvisols ferric acrisols	dryland farming fallow
Dimawe Hollow	4a	pre Ventersdorp	granite	pediment	ferric luvisols ferric acrisols	dryland farming mixed savanna
	$4b_1$	various age sills	dolerite	denudation pediment	pellic vertisols	dryland farming
	$4b_2$				chromic luvisols	thicket fields
	4c	quaternary	sand deposit	colluvial pediment	arenic eutric regosols ferralic arenosols	dryland farming mixed savanna
Valleys Inland valleys	5	quaternary	colluvium alluvium	small valley flat	luvisols	fallow

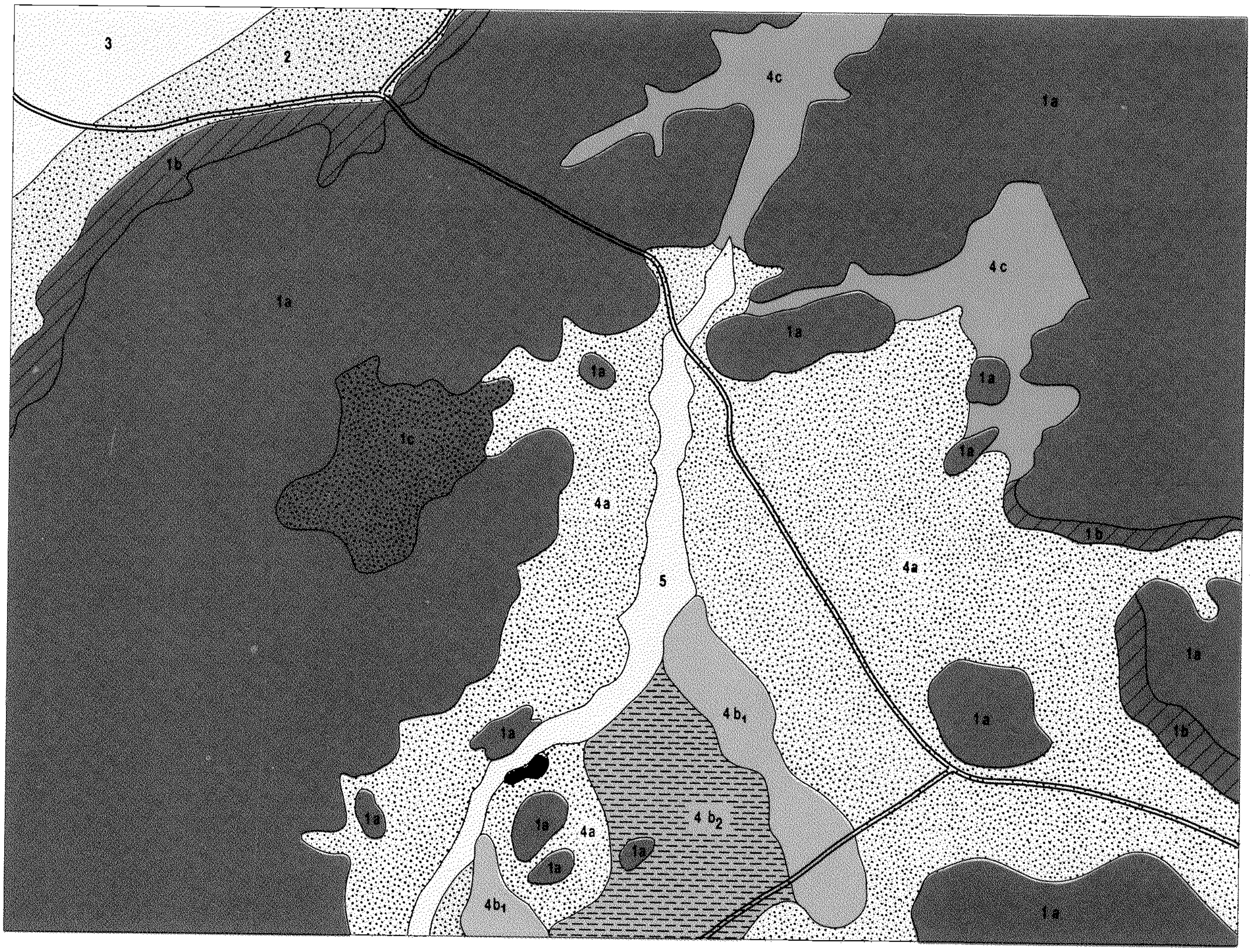


PLATE 13: 1/50,000 SPOT XS COLOR COMPOSITE IMAGE OF MOLEPOLOLE

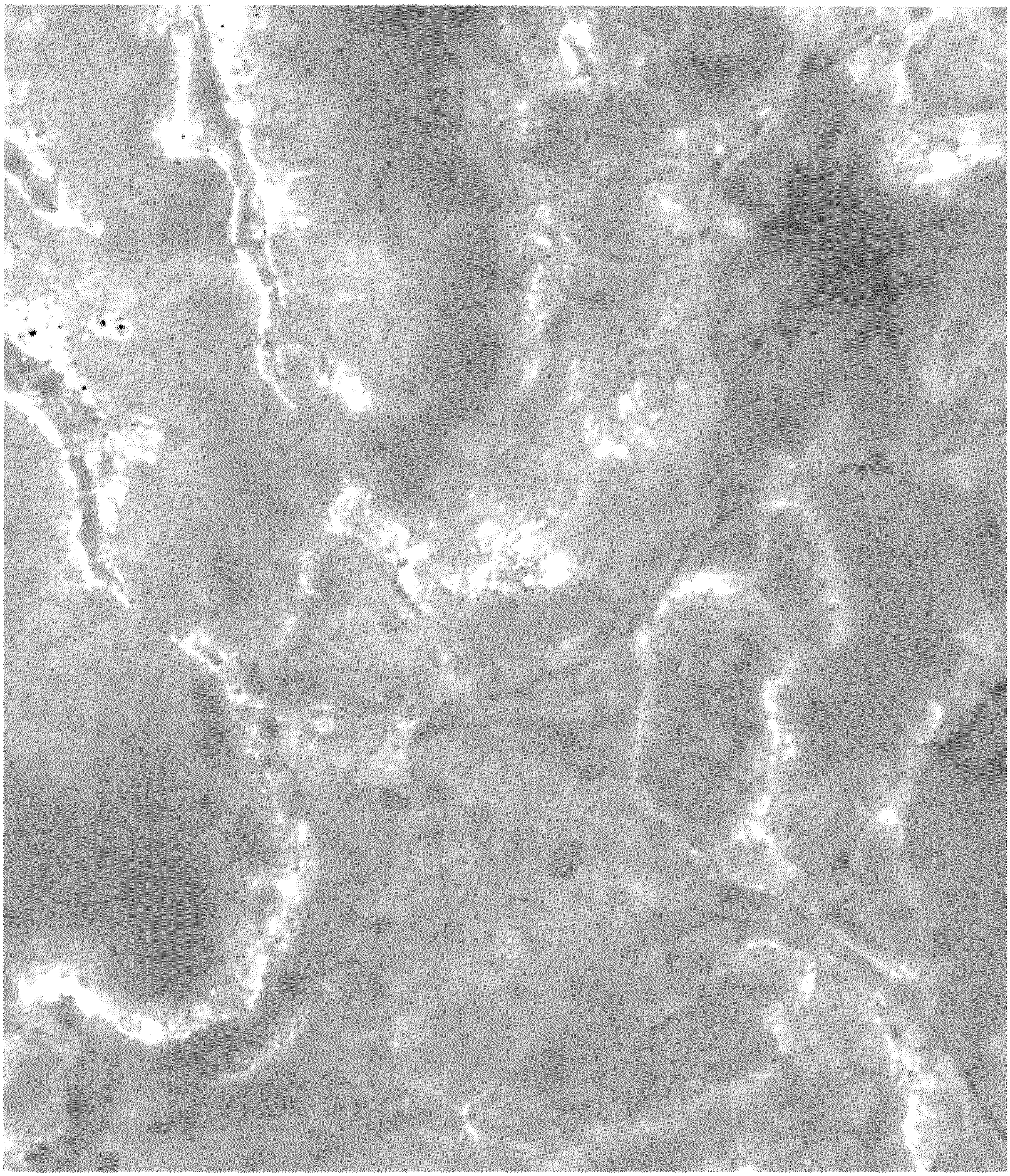
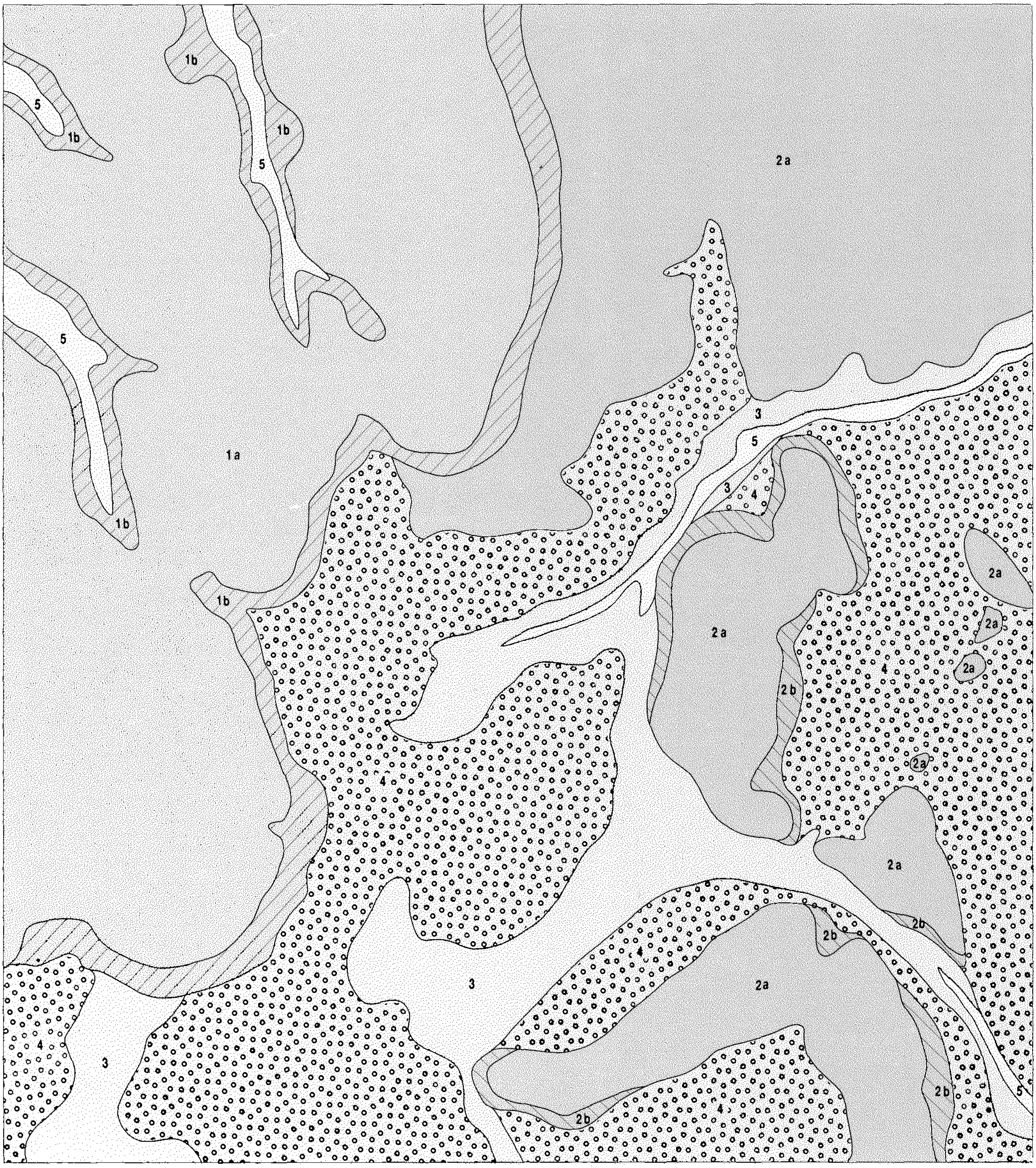


PLATE 14: 1/50,000 MORPHO-PEDOLOGICAL MAP OF MOLEPOLOLE

Land unit		Geology	Lithology	Landform	Soils (FAO)	Landuse
Kalahari	1a	Karoo	feldspathic grit	plateau hill	ferralic arenosols	tree savanna shrub savanna
Plateau	1b		sandstone	escarpment	arenosols	savanna, grassland
Cuesta	2a	Waterberg	feldspathic and quartzitic sandstone	convex hill	arenic ferric luvisols	savanna, fields
	2b			escarpment	arenosols	savanna, fields
Relief	3	various age sills	diabase	hollow	chromic luvisols	dryland farming
	4			plain	chromic luvisols (petric)	fallow
Inland valleys	5	quaternary	alluvium colluvium	small valley	luvisols	fallow



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