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TECHNICAL REPORT WC/95/71
Overseas Geology Series

UNCONSOLIDATED SEDIMENTARY AQUIFERS : REVIEW NO 7 - REMOTE SENSING METHODS

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Unconsolidated Sedimentary Aquifers

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UNCONSOLIDATED SEDIMENTARY AQUIFERS (UNSAs)

PREFACE

This Review is one of a set of reports prepared as part of a project entitled 'Groundwater Development in Alluvial Aquifers', Project No R5561 (BGS 93/2), under the ODA/BGS Technology Development and Research Programme of aid to the developing countries. The project addresses all unconsolidated sedimentary aquifers (UNSAs), not only those in alluvium.

This particular report provides a review of the application of remote sensing methods to the exploration and understanding of UNSAs. The sources and availability of various types of remotely sensed data are described, their responses to surface materials discussed, and the costs indicated. Details are given of the types of geoscientific information that can be extracted from the different data types related to composition, grain size, moisture, vegetation support and so forth.

The report is illustrated by examples of remotely sensed data for many of the major geological settings in which UNSAs occur. Method Summary Sheets are included describing the logical application of each major type of data to the investigation of UNSAs.

The review is a compilation of existing knowledge. It is intended to be updated, as appropriate, following the results of research which will be carried out during the lifetime of the project, which is scheduled to run until 1996.

The project is funded by ODA as part of their research and development programme designed to improve living standards and conditions in the world's developing countries.

Project Manager:	Dr R Herbert Hydrogeological Adviser to ODA British Geological Survey

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A Guide to the sedimentology of unconsolidated sedimentary aquifers (UNSAs)

INTRODUCTION

WHAT ARE UNSAs AND WHY IS IT IMPORTANT TO UNDERSTAND THEM?

UNSAs are unconsolidated sedimentary aquifers. These are the water-bearing strata within the swathes of unconsolidated sediment that mantle much of the earth's surface. There is no clear dividing line between UNSAs and aquifers in consolidated rocks, as lithification is a gradational process: deposits a hundred years old can be lithified, while some deposits 500 million years old are still essentially unlithified. However, for most purposes, UNSAs can be understood as deposits which have accumulated over the past few million years, that is during Quaternary and Neogene (late Tertiary) time. They are important sources of water in many parts of the world, and in particular constitute the only major sources of groundwater for vast areas throughout the developing world. In the influential text-book *Hydrogeology* by Davies and De Weist it says:

> "The search for ground water most commonly starts with an investigation of nonindurated sediments. There are sound reasons for this preference. First, the deposits are easy to drill or dig so that exploration is rapid and inexpensive. Second, the deposits are most likely to be found in valleys where ground-water levels are close to the surface and where, as a consequence, pumping lifts are small. Third, the deposits are commonly in a favourable location with respect to recharge from lakes and rivers. Fourth, nonindurated sediments have generally higher specific yields than other material. Fifth, and perhaps most important, permeabilities are much higher than other natural materials with the exception of some recent volcanic rocks and cavernous limestones."

To date, though, few attempts have been made to understand the detailed internal structure of unconsolidated aquifers even though such knowledge may be crucial to the long term success of any water development project. This shortcoming is probably the reason why the operational lives of many water boreholes are frequently much shorter than expected.

Understanding of the internal structure or "architecture" of many types of sedimentary deposit has, however, advanced greatly over the past couple of decades. Part of this research has been academic, but much has been sponsored by the oil industry, so as to better predict the possible location of oil within sedimentary traps. Oil, like water, is most profitably located within bodies of relatively coarse-grained and porous sediment. Thus, there is obvious scope for applying this recently gained understanding to hydrogeological problems. Advances have also been made in the understanding of the geometry of complex "soft-rock" deposits by the application of appropriate combinations of investigative techniques, including remote sending, rapid geophysical methods and new drilling techniques. The combination of these bodies of knowledge can provide a framework for locating and assessing UNSAs.

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MAJOR AREAS OF UNCONSOLIDATED SEDIMENTARY AQUIFERS WORLDWIDE

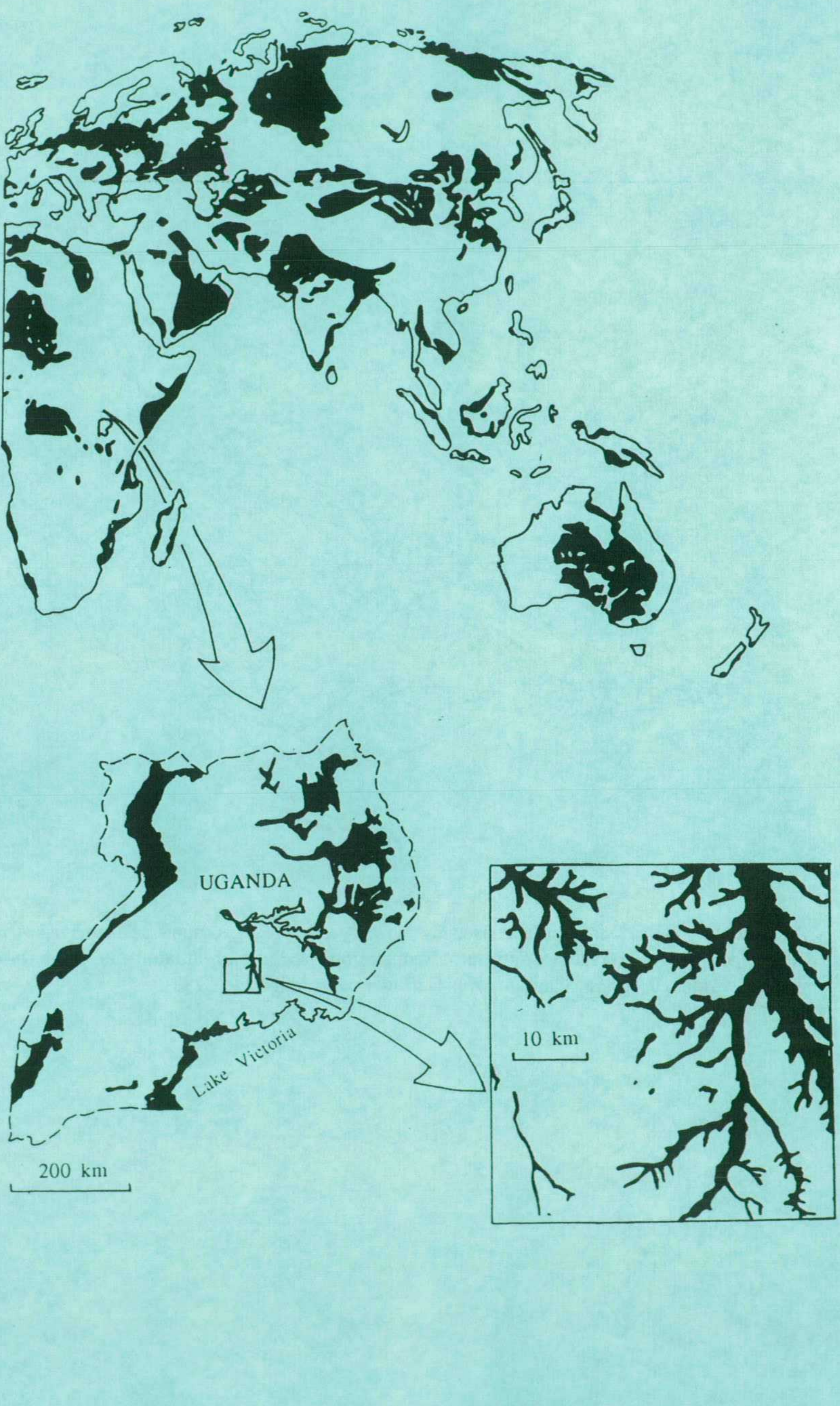
- The map shows the distribution of the thickest and most extensive Quaternary deposits in the world. The great majority of these are unconsolidated, and many include water-bearing deposits (UNSAs).

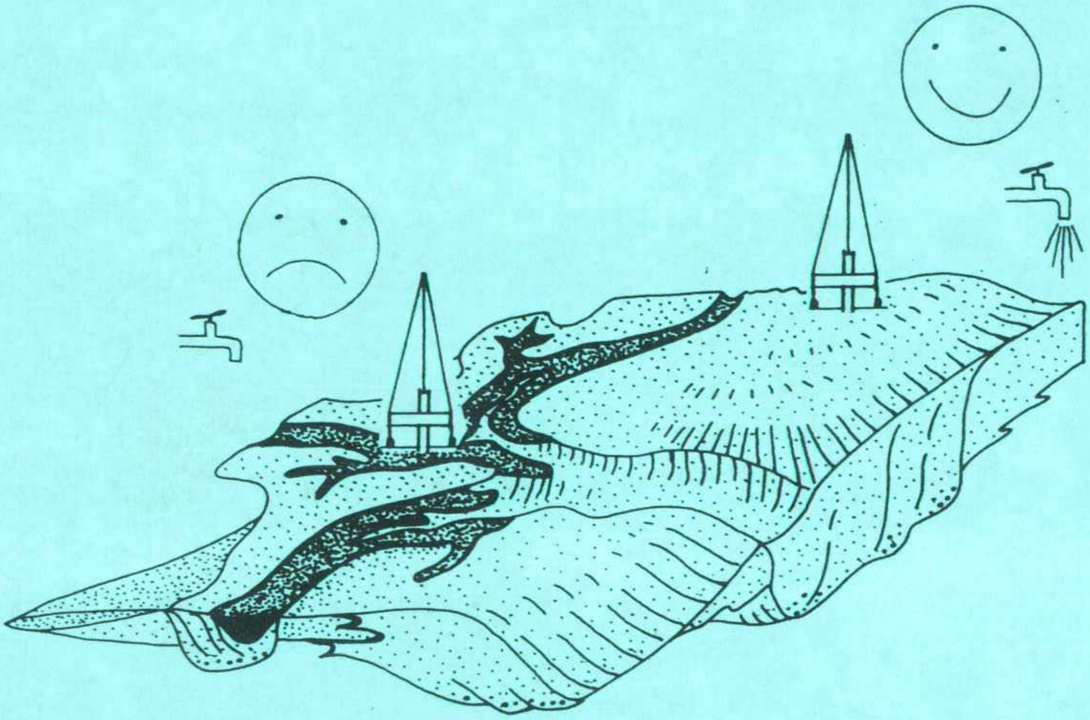
- A generalised world map such as this, though, severely under-estimates the true extent of UNSAs worldwide. This is because:

  - unconsolidated pre-Quaternary deposits are omitted; these too have a wide distribution, though are difficult to delineate (as they grade into consolidated deposits); they too can include significant UNSAs.

  - the simplification of linework necessary at this scale means that a large proportion of unconsolidated deposits have had to be omitted. The inset map shows the example of Uganda, which seems to have no unconsolidated sediments at the global scale, while significant and extensive deposits 'appear' once the country is looked at more closely. At a yet larger scale the unconsolidated sediments appear yet more widespread. The message is clear. *Unconsolidated sediments, and therefore UNSAs, are ubiquitous.*

Diagram data modified from various sources.


UGANDA
Lake Victoria
200 km
10 km



Sedimentary bodies are characterised by variably complex geometry and internal structure. These properties exert a strong internal control on the location, quantity and quality of groundwater. Diagram adapted from Galloway and Hobday (1983).

CONTENTS

1. BACKGROUND AND AIMS

This review is one in a series concerned with different aspects of the exploration, development, and maintenance of ***unconsolidated sedimentary aquifers*** (UNSAs). It describes the potential application of remote sensing methods, both in the exploration for UNSAs and the subsequent development of models which increase our understanding of these important aquifers. The remote sensing sensors include: (1) aerial cameras and (2) optical, thermal and radar electronic sensors. Platforms include both aircraft and spacecraft. The review aims to:

- describe the various remotely sensed data available, and provide information on data acquisition, costs, and the characteristics of each data type;
- describe the types of information that may be derived from each data source and indicate their relevance to environments in which UNSAs occur; and
- provide Method Summary Sheets for each data type for use by hydrogeologists and others working on UNSA development.

2. DATA TYPES AND CHARACTERISTICS

Remotely sensed data may be acquired from two types of platform, aircraft and spacecraft. Four main types of data are generally available: (1) aerial/space photography; (2) optical scanner imagery; (3) thermal imagery and (4) imaging radar data. Drury (1987) provides a good general summary of the geological applications of each of these data types.

2.1 Platforms

Airborne platforms provide flexibility in the timing and conditions of data acquisition. Thus, data can be acquired to take advantage of favourable weather conditions, time of day, or season when the phenomenon under investigation is best observed. Cloudy conditions can be avoided, the ground resolution can be varied by changing the flying height or lens, and the type of sensor can be chosen to respond to particular features of the terrain or target.

The main disadvantage of aircraft data is the geometric distortion present in the data. Aircraft scanner imagery, for example, is subject to two main types of distortion. First, the large viewing-angle necessary to capture a reasonable swath width from low altitude means that a predictable off-nadir distortion is produced. Second, aircraft are unstable in all but the most perfect weather conditions; because scanner images are built up a line at a time as the aircraft passes over the ground, erratic distortions in the image are produced due to yaw, pitch and roll of the aircraft. It is possible to remove these distortions in several ways. Aerial photography suffers from a different type of distortion, mainly due to relief variations. (These, however, provide the basis for the very useful property of stereoscopic viewing).

Satellite images have significantly better geometric fidelity than aircraft data. These data are acquired from very high altitude so that a small viewing angle can be used to image a large area. Also, because the satellite orbits the earth above the main weather systems of the atmosphere, the platform is very stable. These two factors greatly reduce the distortions in the imagery. Consequently, even uncorrected satellite imagery is relatively distortion-free, and it can be fully rectified to a map projection such as UTM through image processing. The disadvantage of satellite data is that the configuration of the sensor, the ground resolution and the acquisition dates/times are all pre-determined or only variable within certain limits. If there is cloud at the time of overpass, an optical or thermal image may well be unusable. In most cases, the spatial resolution is much less than that obtained from aerial platforms making the data more suited to regional than to detailed investigations.

2.2 Aerial and space photography

Conventional aerial photography can be flown at a range of scales depending on flying height and camera focal length. The most common scales of aerial photographs are between 1:10 000 and 1:50 000. Black-and-white, colour and colour-infrared photography all have uses in earth science. In general, the human visual system is able to distinguish more variations in colour than in grey tone, so that colour photographs allow better discrimination of soil and rock types, and are preferred by geologists. Infrared photography is less affected by atmospheric haze than natural colour and achieves clearer discrimination of different vegetation types and soil moisture variations. Photographs are commonly supplied as paper prints, but can be obtained as transparent diapositives, or they can be scanned to provide digital images for enhancement on an image analysis system.

Aerial photograph interpretations may be undertaken at the regional or local scale. Interpretation maps may show geomorphology and drainage, solid and superficial geology, soils, engineering geological features such as landslips and hydrogeological phenomena such as spring lines (Lillesand and Kiefer, 1994). Digital photogrammetrical workstations, such as the Intergraph ImageStation operated by the British Geological Survey, can be used to process aerial photographs in digital form to produce a digital terrain model (DTM). Given photography of a suitable scale and adequate ground survey control (e.g. by levelling or from GPS), this can have a vertical accuracy better than 1 m.

Aerial photography for a given area may already exist; if not, it can be commissioned from one of the many aerial survey companies worldwide. Some of the main suppliers in the UK are: Hunting Aerofilms Ltd, the National Remote Sensing Centre Limited (NRSC), ADAS, the Ordnance Survey, Engineering Surveys Ltd, Cartographical Surveys and the Royal Commission on the Historic Monuments of England (archive of historical photography only). The information required to contact these and other suppliers can be found in the comprehensive NAPLIB

'Directory of Aerial Photographic Collections in the United Kingdom' (1993). For overseas coverage, it is usually necessary to contact the relevant national authority or survey company within the country.

Costs and availability of aerial photography vary widely depending on such factors as: the country in question; the supplying agency; whether archive or new coverage; the number of photographs ordered; the scale of the photography; the medium (print or diapositive); and any copyright involved in reproduction. Some overseas countries actively encourage the sale of aerial photographs, which are thus readily available and at low cost (e.g. Zimbabwe; Namibia). In other countries, however, aerial photographs may be subject to strict security control and difficult to obtain. In some parts of the world, coverage is poor and there may be no recent acquisitions at an appropriate scale. There is no worldwide catalogue of aerial photography.

There are two principal sources of space photography: the USA Space Shuttle and the Russian satellite missions photography.

Throughout the various missions of the US Space Shuttle, the crews have taken *ad hoc* hand-held photographs of sites and views of interest. The photographs are mostly non-vertical shots covering large regions. It is sometimes possible to achieve stereo coverage, and a small percentage of the photographs are available in digital format. The data are catalogued in a series of volumes and maps produced by NASA who supply photographic prints at the cost of reproduction (currently around $9 per print).

Russian satellite photography has been acquired from several camera systems since about 1974. This photography can be obtained as photographic prints but is now also widely available in the form of digitised images. These data are described in Section 2.3.4 below.

2.3 Optical sensor imagery

The most widely available and used optical imagery are satellite data from the US Landsat Thematic Mapper (TM) and the French SPOT system. Data from these two sensors can be purchased in the UK via the NRSC Ltd; they are described below. Besides the Russian imagery mentioned above, the Japanese satellite JERS-1 acquired some useful data in its short, fully-operational, life of 18 months during 1992-93. For some geological projects, airborne thematic mapper (ATM) scanner data may provide more information than satellite imagery; however, there is no systematic coverage available, most of the data having been acquired either over mineral exploration targets for mining companies or by scientific research agencies.

2.3.1 Landsat TM imagery

The US Landsat series of satellites, the first of which was launched in 1972, carried two main instruments, the Multispectral Scanner (MSS) and the Thematic Mapper (the TM on board Landsat 5 continues to acquire data). The earlier MSS had coarse spatial resolution (79 m) and limited spectral range; this consisted of two spectral bands corresponding to green and red visible light, and another two bands in the near infrared. Archive data are still available, but the limited spatial resolution of this sensor compared to TM makes it unsuitable except in small scale regional studies. Its major advantage over TM is cost, since a full MSS scene in digital format can be obtained for as little as $250[1] (data more than 2 years old).

The TM instrument records reflected radiation in six optical wavelength bands, three in the visible, one in the near infrared, and two in the shortwave infrared; all have 30 m ground resolution. A seventh channel records emitted radiation in the thermal infrared at a coarser ground resolution of 120 m. Computer processed TM data can be interpreted in a similar way to aerial photographs but better spectral information from the three infrared bands in particular allows a wider range of natural surfaces to be discriminated, including different soils and rocks. The 30 m ground resolution makes the data useful at scales of up to 1:50 000. Each image covers an area on the ground 185 x 170 km. The satellite overpass return time is 16 days. The main constraint on using this TM data is cloud cover; in some parts of the world it can be several years before a target can be successfully imaged. In digital form, all 7 bands of a full TM scene currently costs $4400. Depending on the area and date of the imagery, quarter scenes, sub-scenes (100 x 100 km) and map sheets (½° x 1°) are available. Special offers, including heavily discounted older scenes, are often available, and photographic prints can be bought for a few hundred pounds, depending on area and scale required. The MSS and TM sensors are fully described in USGS (1984). For the future (Landsat 7, due for launch in 1998), there is a US Government commitment to lower the cost of data to the actual cost of processing an order. This might bring the price down to around $500.

2.3.2 SPOT

The High Resolution Visible (HRV) sensors aboard the French satellite SPOT provide better ground resolution than Landsat TM and a capability for sideways-looking stereo, but have fewer spectral channels (SPOT, 1988). The panchromatic sensor (PAN) has 10 m ground resolution in a single band in the visible wavelengths, and can be used at scales up to about 1:15 000. A full scene costs approximately $3,000 and a stereo pair $4,500. The multispectral sensor (XS) has 20 m ground resolution in three spectral bands, two in the visible and one in the near infrared wavelength region. A full scene costs approximately $2,400 and a stereo pair $3,700. Both data types cover an area of 60 x 60 km (approximately one-ninth that of a Landsat scene, so that the data cost per unit area is significantly higher). Standard processed prints are available for a few hundred pounds. As an additional service, the satellite can be programmed to acquire a specific image or stereo pair. Additional charges for this service are in the range $200 to $2,000 with the possibility of further charges for failed (cloud covered) attempts. The stereo

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[1] All prices are given in mid-1995 US dollars and are approximate

capability allows the production of DTMs with an accuracy of, at best, approximately 10 m.

2.3.3 IRS imagery

Imagery is available from India's satellites, IRS-1B and IRS-P2 which acquire scanner data in 4 spectral bands very similar to Landsat TM bands 1 to 4. The LISS II sensor has a resolution of 36.5 m, slightly less than TM. A full scene (145 x 161 km) costs $3700. The data are distributed by EOSAT but coverage is currently limited to the USA and India. A further satellite (IRS-1C) is due for launch in 1995 and data should be available early in 1996. This will provide multispectral imagery with 23.5 m resolution for a 141 x 141 km scene and panchromatic imagery at 10 m resolution for a 70 x 70 km scene, plus a wide-field sensor.

2.3.4 Russian and Japanese satellite data

Several types of Russian satellite photography are now available in a digital format, all of which are derived by scanning of the original visible to near infrared space photographs. Coverage is worldwide though incomplete. The data are produced by a consortium called Resours-F Worldmap, and distributed in the UK through various companies including the NRSC Ltd (address in reference section). Several different satellite/camera systems are operated from which the scanned digital products are produced. Ground cell resolutions range from 2-3 m to about 20 m. The high spatial resolution sensors only have a single spectral band and the lower resolution sensors have two bands in the visible and a single band in the near infrared wavelength region. Prices vary according to imagery type, number of bands, and number of scenes purchased.

The specifications and approximate current costs of digital products are summarised in Table 1.

Table 1: Digital products from Resours-F Worldmap Russian satellite photography

Camera	Average resolution (m)	Size (km)	Spectral range (nm)	Stereo overlap	Cost (US$)
KFA-1000	5	80x80	570-810	60%	3,000
KFA-3000	2-3	21x21	510-760	30%	4,000
MK-4	7.5	117x117 to 173x173	515-565 (580-800) 635-690 810-900	60%	9,500
KATE-200	15-20	216x216 to 243x243	480-600 600-700 700-850	60%	2,400

The Japanese sensor JERS-1 has 8 bands comprising equivalents of Landsat TM2, TM3, TM4 (2 bands to give stereo), TM5, plus 3 bands covering the geologically important wavelength range of TM7. This increased resolution in the shortwave infrared wavelength region, where clay, sulphate and carbonate minerals have their main diagnostic features, offers significant potential for increased discrimination between rock types. Unfortunately, the sensor was affected by 'noise' problems and is no longer fully operational. Despite this, data already acquired can be processed to yield images of a comparable quality to Landsat TM data and, for research purposes, may be available free or at a nominal charge from The Remote Sensing Technology Center of Japan (RESTEC) (address in reference section).

2.3.5 Airborne scanner data

Data from two instruments are available in the UK, the Daedalus 1268 Airborne Thematic Mapper (ATM) and the Compact Airborne Spectrographic Imager (CASI), both of which are owned and operated by the Natural Environment Research Council (address in reference section). The ATM is an 11-channel scanner covering a similar overall spectral range to Landsat TM. It can be used to acquire data at various ground resolutions down to about 1 m depending on the flying height of the aircraft. The CASI covers the visible and near infrared wavelengths and operates in two alternative modes; the *spatial mode*, whereby 19 spectral bands are collected across the full scene, and the *spectral mode*, in which a single band is acquired over the full scene plus 288-band spectra for several narrow strips within the main image.

Similar instruments are operated in other parts of the world, in most cases on a commercial basis, and higher resolution imaging spectrometers are increasingly becoming available. AVIRIS, for example, is a research system operated by NASA; this measures 224-band spectra for every pixel across a full scene. The GER64 scanner developed by the Geophysical and Environmental Research Corporation, is a commercially available imaging spectrometer. In all cases, the flying height controls the resulting ground resolution and the ground swath covered by each flight line. Costs for commercial surveys vary depending on sensor, area, scale and logistics.

2.4 Thermal data

As yet, no satellite system provides satisfactory thermal data. The thermal channel on the Landsat TM (TM6) has too coarse a resolution for most purposes (120 m) and is acquired at the wrong time of day (during the mid morning rather than pre-dawn) to be of real use to earth scientists. The useful systems are currently all airborne. Future satellite systems, such as the United States/Japanese sensor, ASTER, scheduled for launch in 1998, will include a multiband thermal sensor, and will allow such data to be widely available for the first time.

One airborne instrument is available in the UK, the Daedalus 1230 Thermal Linescanner (TLS), owned and operated by Engineering Surveys Ltd (NAPLIB, 1993). This instrument measures emitted radiation in a single broad band in the thermal infrared wavelength region. It can be used, for example, to map variations in soil moisture related to springs, landfills, buried sources, and changes in soil composition. Once again, ground resolution and swath width depend on flying height. Approximate costs for a 40 km x 40 km area in the UK are $15 to $50 per square kilometre. Similar instruments are available in other countries, and thermal sensors with several bands have been developed, such as NASA's Thermal Infrared Multispectral Scanner (TIMS). The Daedalus ATM (see above) also has a broadband thermal channel and can be used to acquire similar data to the Daedalus 1230.

2.5 Radar data

Two satellite-based synthetic aperture radar (SAR) systems are currently operational: the European ERS-1 and -2 satellites and the Japanese JERS-1. A Canadian radar satellite, RADARSAT, is scheduled for launch in autumn 1995.

Imaging radar differs from other types of remote sensing data in that the system does not rely on the sun's energy. Instead, it uses microwave energy (radio waves) to `illuminate' the ground surface and records the strength and time delay in the backscattered signal. Radar responses vary according to the composition of the surface, its electrical properties, moisture content, surface micro-roughness, and topography. The advantage that radar has over optical and thermal data is that, being an `active system', its acquisition is unaffected by weather conditions (cloud is transparent to most radars). SAR data also have the potential to provide accurate digital terrain models through a new technique called SAR interferometry.

Current SAR systems are almost all single frequency, and the main differences between them are the frequency of the microwave energy and the geometry of the system design. Radar systems are necessarily `sideways-looking'; a small incidence angle may be appropriate in low relief terrain where radar can be expected to respond to variations in sediment grain size, micro-topography, and moisture content. Such a configuration is useful for mapping differences in coastal sediments or volcanic deposits. One disadvantage of all radar imagery is that the oblique geometry causes significant distortion and long shadows. Larger incidence angles can be used to reduce layover effects in mountainous terrain. Topographic information extracted from radar-generated DTMs can be used in geomorphological analyses.

Radar surveys may also carried out using aircraft. One of the main commercial systems is operated by Intera who have built up a database of acquisitions for commercial clients and governments in several countries. High resolution (6 m) Intera radar data are particularly useful for detailed studies in humid regions such as the tropics where persistent cloud cover hinders the acquisition of optical/infrared imagery or photography. Stereo radar cover is usually routinely acquired. The data is generally also available as high quality, planometrically accurate imagery which has been rectified using a DTM. However, despite its advantages, aircraft radar data of this type is expensive and its availability may be restricted (commercially or militarily) in some countries. The commissioning of a special survey is very costly.

2.5.1 ERS-1 and -2

The European experimental satellites acquire SAR data which has a ground resolution of approximately 30 m. Coverage is worldwide. Each image covers an area of 100 x 100 km (ESA, 1992). The incidence angle of the SAR instrument is 23° and the spatial resolution about 30 m; this gives rise to significant layover effects in mountainous terrain, but is ideal for lowland terrain and coastal areas in which many UNSAs are located. Data prices vary according to the level of correction. A full scene costs approximately $750 for raw data through NRSC Ltd. Reductions may be available where the data is for research use.

2.5.2 JERS-1

The Japanese satellite JERS-1 also carries a SAR sensor, the main advantage of which compared to ERS-1 is an incidence angle of 35° which reduces layover effects. As in the case of the optical JERS-1 data discussed earlier, the radar data are affected by noise problems, but computer processing can produce useful images. The data may be available free, or at the cost of reproduction for research applications, from RESTEC in Japan.

2.5.3 RADARSAT

Canada's RADARSAT is due for launch in autumn 1995. An important feature of RADARSAT is the capability to vary the incidence angle of the SAR sensor. This will allow data to be optimised to a particular geological environment, terrain or problem. Another useful feature of this new satellite is the ability to acquire within-orbit stereo image pairs. Prices for these new data are not yet established, but indications are that they will be closer to Landsat TM than ERS-1/2 (i.e around $3-4,000 per scene).

3. APPLICATION OF DIFFERENT DATA TYPES TO THE INVESTIGATION OF UNSAS

The nature and scale of the study, the climatic conditions, and the type and size of features to be mapped, will all influence the choice between satellite and airborne data.

Satellite data are appropriate when some or all of the following criteria apply: (1) the study is at regional scale; (2) time and other resources are limited and there is no access to pre-existing airborne data; (3) map data of the highest geometric quality are required; and (4) the logistics of operating in the country in question prevent the acquisition of aerial data.

Airborne surveys are useful where: (1) detailed information at the site-specific level is required; (2) persistent cloud cover limits data acquisition opportunities; (3) the study will benefit from the use of a data type not available from satellite (e.g. thermal imagery or imaging spectrometry data); (4) the optimum time for data acquisition does not correspond to the time of the satellite overpass; and/or (5) several data types need to be acquired at the same time.

Remotely sensed data can provide various types of information of value to earth science projects. Optical sensors and aerial photography are most useful in arid, semi-arid and temperate regions where there is a good chance of cloud-free conditions. Their spectral responses can be used to produce lithological and soil interpretation maps, whilst their spatial information content can be used to construct structural and geomorphological maps. If stereo data are available, there is the possibility of generating a DTM, provided the necessary specialist computing software is available. In geological studies, optical data provide the maximum information where the lithologies of interest are well exposed at the surface. In wetter regions, vegetation, cultural patterns and transported soils often mask the lithological signal. In these circumstances, geology may still be interpreted from the geomorphological information and from geobotanical anomalies apparent in suitably processed data. Even in arid areas the data may still be useful for the investigation of UNSAs; for example, the pattern and density of vegetation may help indicate the presence or otherwise of shallow groundwater aquifers.

Thermal data have enormous potential for identifying surface features which may be invisible to the human eye. Thermal infrared imagery is useful for detecting groundwater springs and soil drainage patterns, discriminating lithologies where they are exposed, and for mapping soil types. It also has many environmental applications. Unfortunately, apart from simple one-channel linescanners, such data are not yet widely available. However, the commissioning of aerial thermal infrared surveys is relatively inexpensive and can provide very useful results. Ideally, flights should be carried out just pre-dawn, under cold air temperatures, and at a time when rain has not occurred for several days.

Although radar data are less well-understood and thus more difficult to interpret than optical imagery, they can be of use in several situations. Where the ground is well exposed, for example, the ability of radar data to respond to subtle changes in the moisture content of soils may be exploited to map units of different composition. If sedimentary units of contrasting grain size are exposed, radar may provide discrimination by responding to surface micro-roughness, or to sedimentary structures where they are responsible for small-scale variations in surface topography. In tropical environments, persistent cloud cover commonly precludes the acquisition of all data types other than radar. Moreover, where forest cover occurs, radar may be the only sensor capable of providing useful information; although it cannot penetrate the tree cover, it will respond to subtleties in the mature tree canopy which commonly mimic small variations in the ground surface related to geological structure. Radar interferometry is a new technique that can in principle be used to construct an accurate DTM for geomorphological mapping. The usefulness of radar is, however, restricted in areas of high relief due to distortion and intense shadowing.

It should be stressed that in the majority of cases remote sensing by itself will not provide a complete nor an unambiguous solution. Imagery can yield important information but must be supported by 'ground truth' via comparison against existing data sources or through fieldwork. In such a context, however, remote sensing can provide a cost- and time-effective means of understanding overall controls operating in an area and provide a basis for a directed field investigation.

4. EXAMPLES OF REMOTELY SENSED DATA IN DIFFERENT UNSA ENVIRONMENTS

4.1 Alluvial and deltaic environments

Alluvial systems are the gravity-driven paths followed by water from upland areas to a base-level formed by lake or sea (or occasionally an inland swamp). Along this path, UNSAs may occur in: *alluvial fans*, where a stream emerges from an upland area into a basin; *braided; meandering* and *anastomosing rivers*; and *deltas* or *fan-deltas*, where the river meets a body of standing water.

Figure 1 is a panchromatic aerial photograph showing variations in sediment pattern and river morphology for part of the Okavango River flood plain along the Namibia/Angola border, a meandering fluvial system. The accompanying interpretation (Figure 2) illustrates the amount of detailed sedimentalogical information that can be derived from such data. Air photo interpretation is usually carried out in stereo using a mirror stereoscope, a technique which provides considerable detail and understanding of surface variations. In this instance, the interpretation was helped by digitally combining the spectral information from Landsat TM data with spatial detail from the aerial photography (Figure 3).

Optical data can be useful for mapping UNSAs even in wetter, vegetated environments especially where transport of sediment is so rapid that it remains exposed. This is illustrated in the Landsat TM image from Papua New Guinea shown in Figure 4. In this example, an alluvial fan system, here derived from a major upstream landslide, is seen entering the Markham Valley. Figure 5, from the Gulf of Suez in Egypt, is an example of a large fan-delta, formed where high ground and a body of `standing' water (the Red Sea) are juxtaposed, in this case by tectonic uplift either side of a rift valley. This TM image has been produced by combining three separate band ratios designed to maximise the discrimination between surface materials.

Figure 6 is an aerial photograph from Furnace Creek fan in Death Valley, USA. By comparison, Figure 7 is an X-band SLAR image of the same fan. Note how textural differences, largely related to surface variations in grain size and micro-roughness, are picked out; `smooth' areas appear dark and `rough' area bright. Honey mesquite stands, which require fresh groundwater, appear as bright stringers (e.g. radiating outwards in the lower part of the fan). Figure 8 is a similar X-band SLAR image of another location in Death Valley which similarly provides detailed information on the fan structure.

Thermal infrared imagery can be used to map unconsolidated fluviatile deposits as a result of variations in moisture content, in turn related to sediment composition and grain size. Figure 9 is a nighttime (pre-dawn) thermal linescanner image of part of the River Trent valley in the UK. The main river (bottom of image) appears bright because it retains heat relative to the land. Darker (colder) areas tend to be those

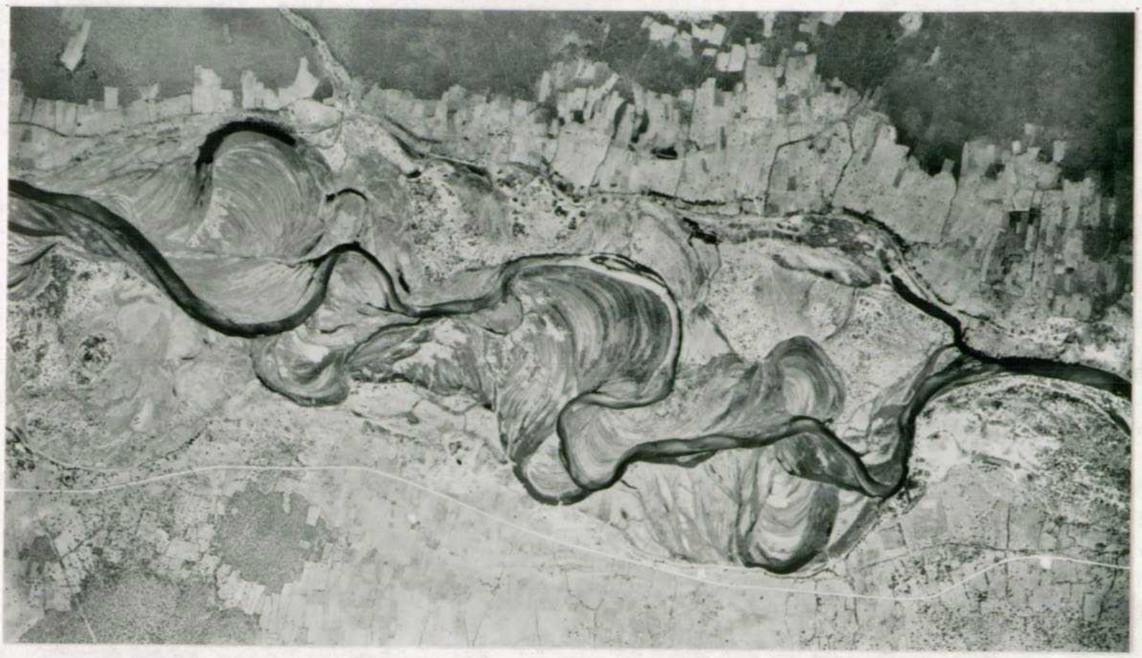

Figure 1: Panchromatic aerial photograph of the Okavango River braided channel and flood plain along the Namibia/Angola border. Approximate scale 1:80 000.

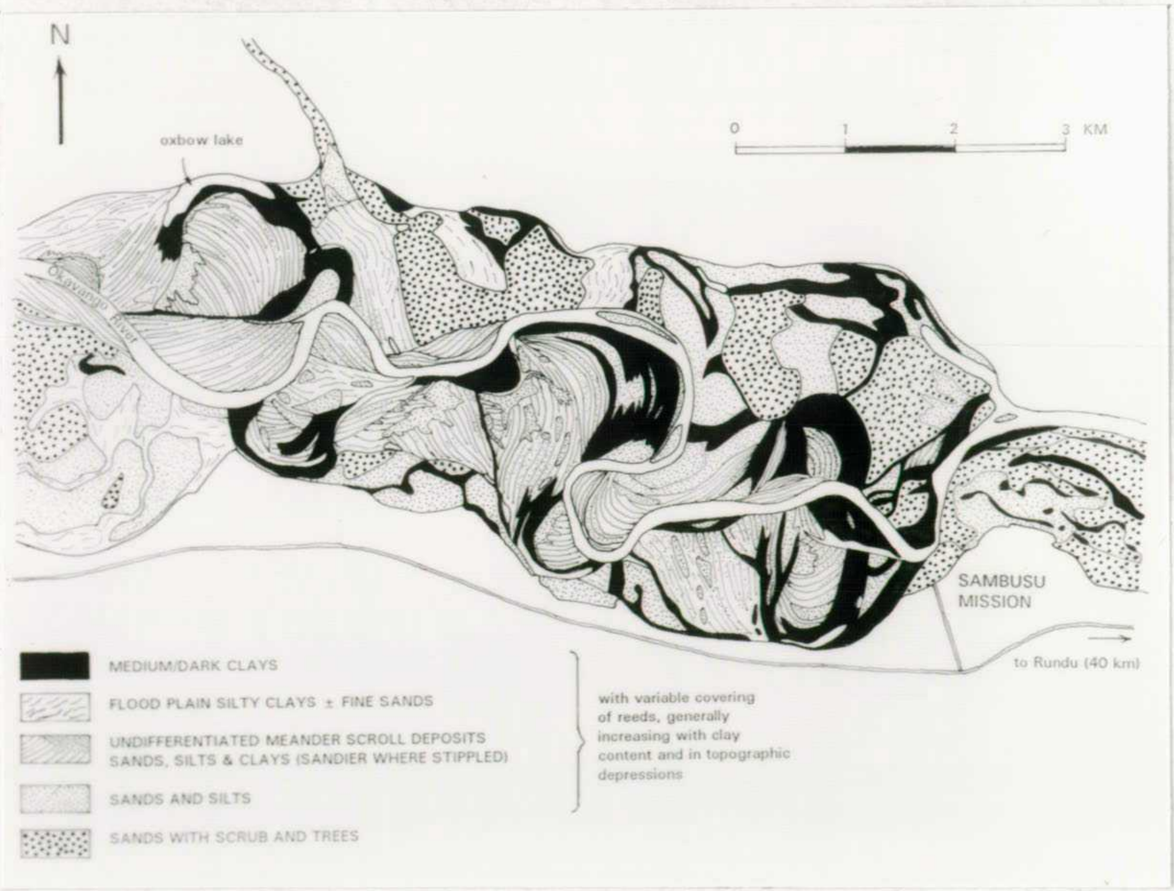

Figure 2: Geological interpretation of the aerial photograph shown in Figure 1, aided by information extracted from Figure 3.

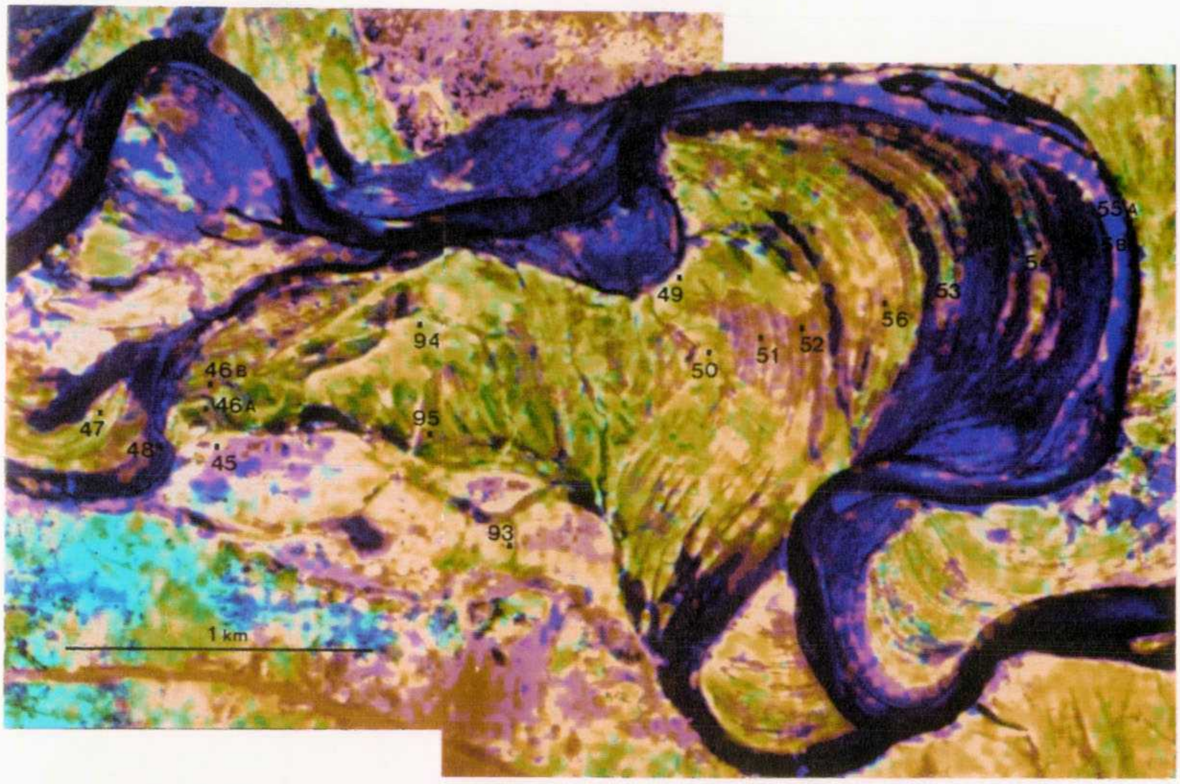

Figure 3: Digital merge of the aerial photograph in Figure 1 (spatial detail) and a Landsat TM image (spectral variation). Approximate scale 1:25 000. (Marked locations are sample collections sites).

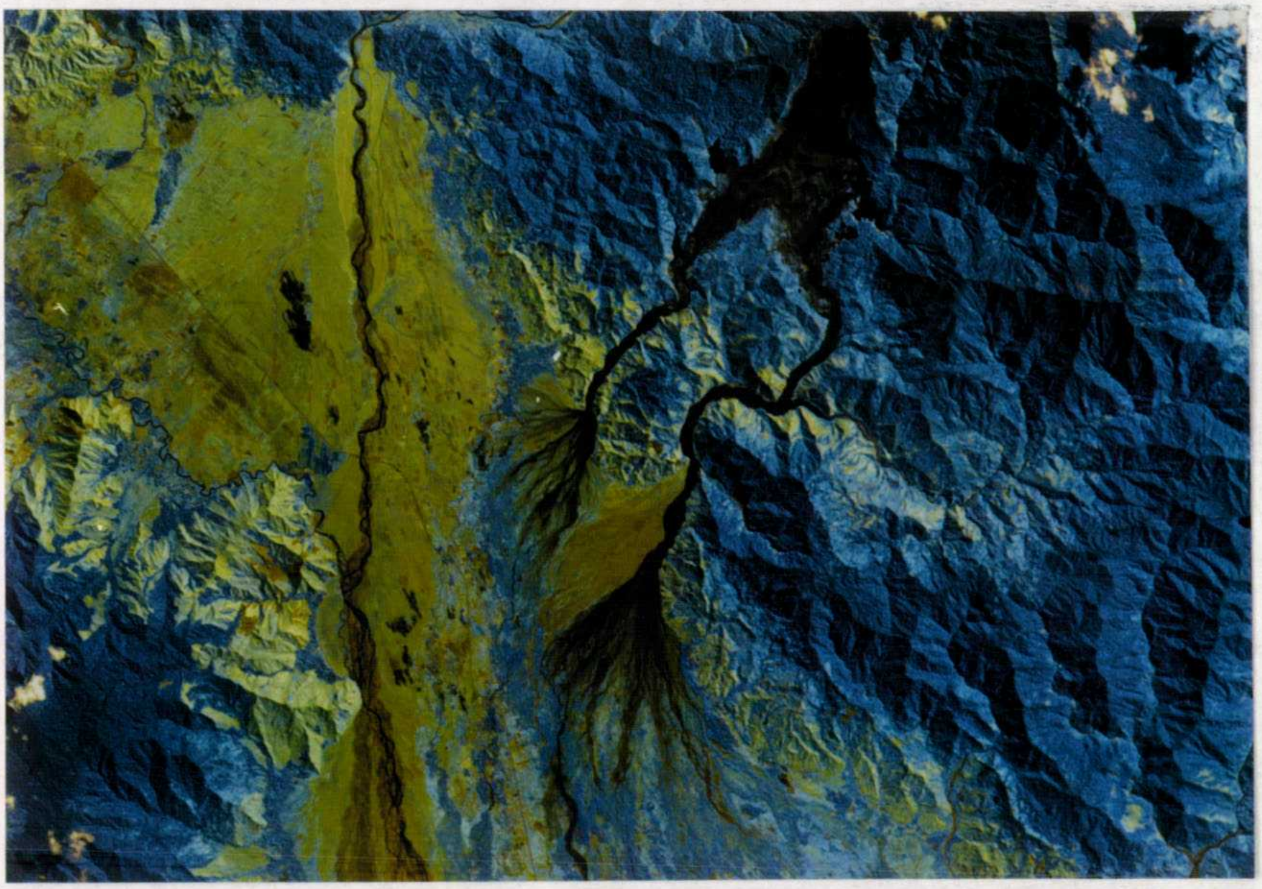

Figure 4: Alluvial fan system discharging from the mountainous interior into the Markham Valley (Papua New Guinea). Approximate scale 1:200 000.

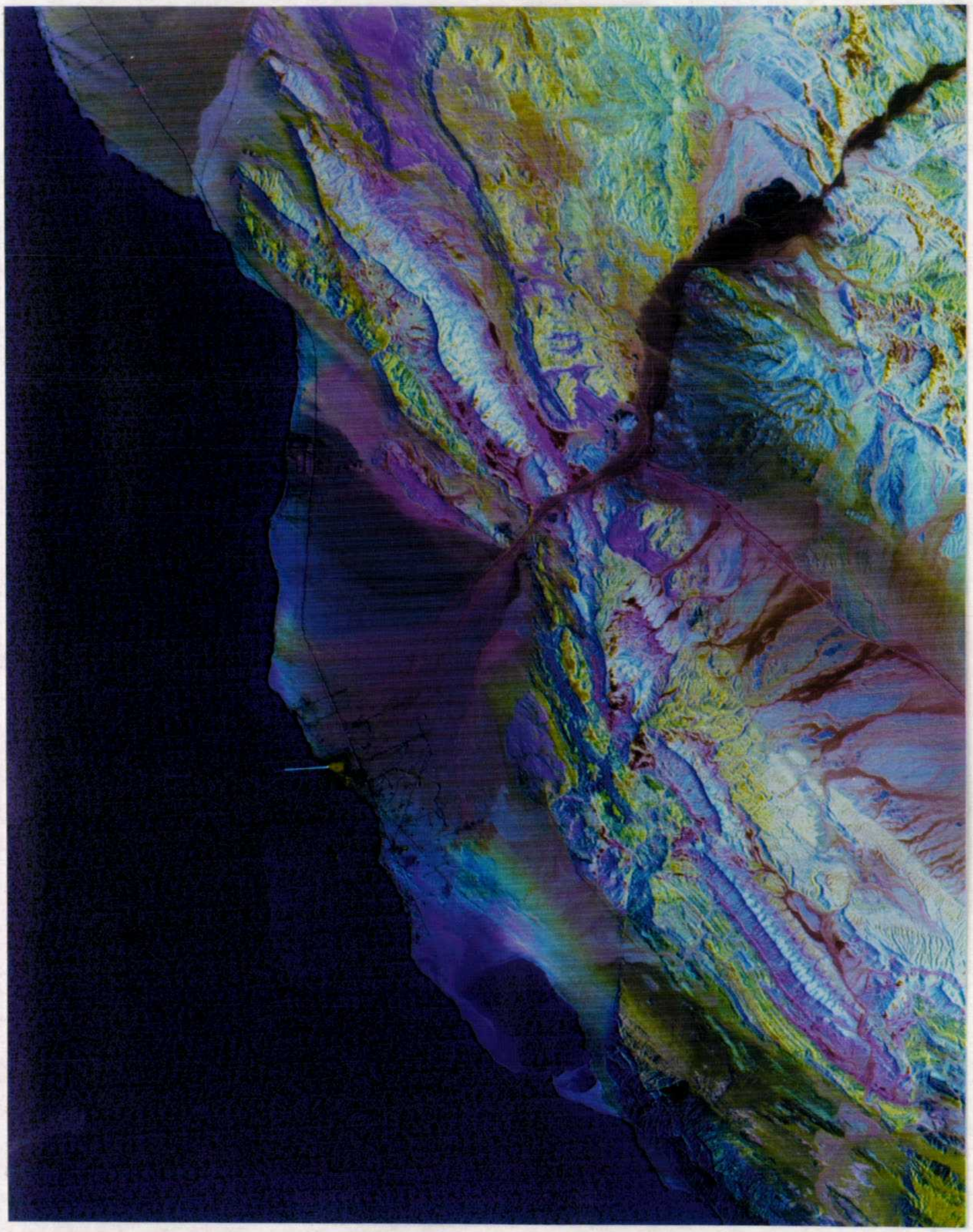

Figure 5: Fan delta formed as a result of sediment discharge from the mountainous interior of western Sinai, Egypt into a body of relatively still water (the Red Sea). Approximate scale 1:220 000.

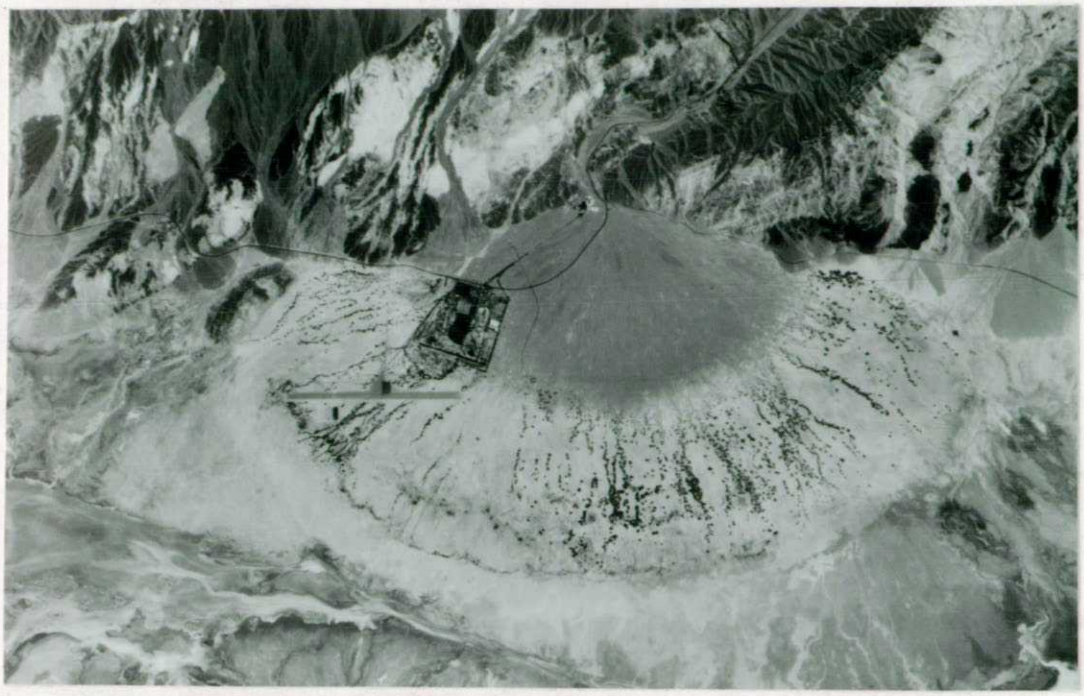

Figure 6: Aerial photograph showing Furnace Creek alluvial fan in Death Valley, USA. Approximate scale 1:75 000.

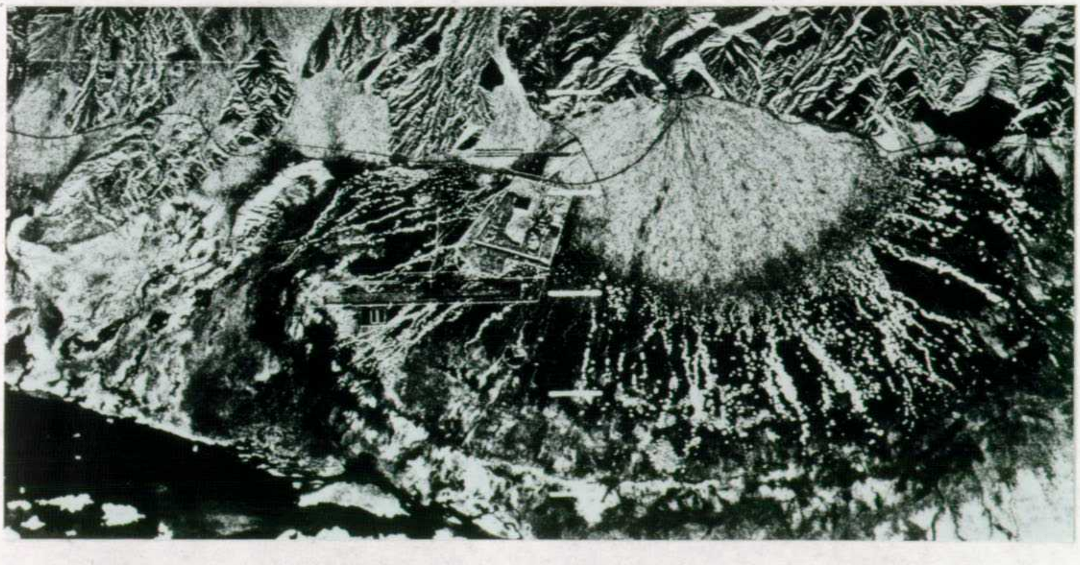

Figure 7: X-band SLAR image of the same fan shown in Figure 6. Note discrimination of textural variations. Approximate scale 1:75 000

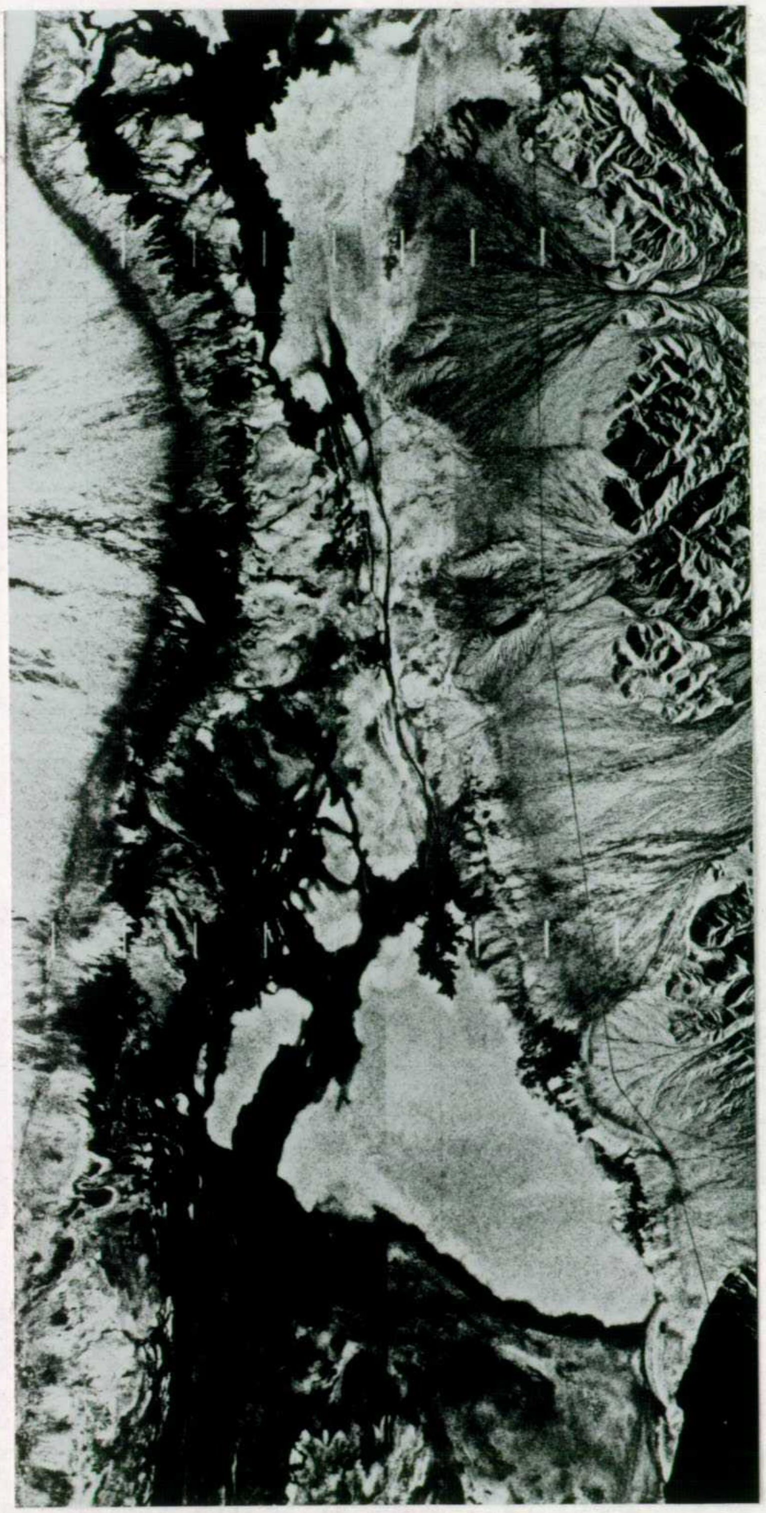

Figure 8: Another example of fan system in Death Valley, USA, imaged using X-band SLAR radar. Approximate scale 1:100 000.

Figure 9: Nighttime thermal infrared linescanner image of the River Trent, Nottingham alluvial flood plain. Bright areas are relatively warm and dark areas cold. Approximate scale 1:8 000.

with a higher moisture content. An abandoned meander, now gravel-filled, is seen as a mid-grey curved feature across the top half of the image. In this instance, the network of dark lines in central field is thought to be a series of infilled, probably iron-age, ditches. Essentially then, such imagery can provide a valuable means of distinguishing clay from sand/gravel. Although not shown, aerial photography of the same area acquired within a few days of the thermal survey showed only the barest indications of these features.

4.2 Coastlines

The geomorphology of coastal sedimentary units is largely governed by the interaction of two energy forms, waves and tides. Where waves dominate, elongate beaches and barrier islands form parallel to the coastline. As tides become a factor, the beaches and barrier island begin to break up. When tides dominate, the shore becomes fringed by tidal flats, and the barrier islands are transformed into tidal sand ridges perpendicular to the coastline. Such coastlines may form from either siliclastic or bioclastic carbonate material, and have very good aquifer potential. Carbonate reef and lagoon geometries are often unsuitable locations for freshwater aquifers, but where well-sorted bioclastic carbonate accumulates, UNSAs may form. Evaporite deposits are deleterious to groundwater accumulation and quality.

Coastal deposits may be well exposed whatever the climatic zone, so that optical data will nearly always be informative. Figure 10 shows a part of the coastline of Albania here depicted by a principal components enhancement of Landsat TM data. The spectral combination in this image discriminates accretionary units along the coastal margin while at the same time enhancing offshore patterns related to water depth and transportation of suspended sediment. In general, the visible wavelengths show greater penetration of the water column, typically down to a depth of about 10 m under clear water conditions. Figure 11 is another TM image, this time of part of Sabah Island, East Malaysia. Here, the visible bands (TM3-2-1) have been used for the offshore area and a combination of the visible and reflected infrared bands (TM4-5-3) for the land. Wind/wave directions from the north east have produced a high-energy, wave-dominated linear northern shoreline with a protected, tidal-dominated area of mudflats in the south.

In coastal areas it is often the grain size which varies more than sediment composition so that radar, which responds to small-scale surface roughness, becomes important. Figure 12 shows a SLAR image of the lower reaches of the Rio Coco along the Nicaragua/Guatemala border. Here, the form of the wave-dominated delta is clearly seen as is the structure of the sediments. This is entirely composed of sub-parallel beach ridges produced by wave reworking of the fluviatile sediment supply. Variations in surface roughness including grain size and micro-relief, together with related vegetational contrasts, are shown by differences in brightness in the radar backscatter.

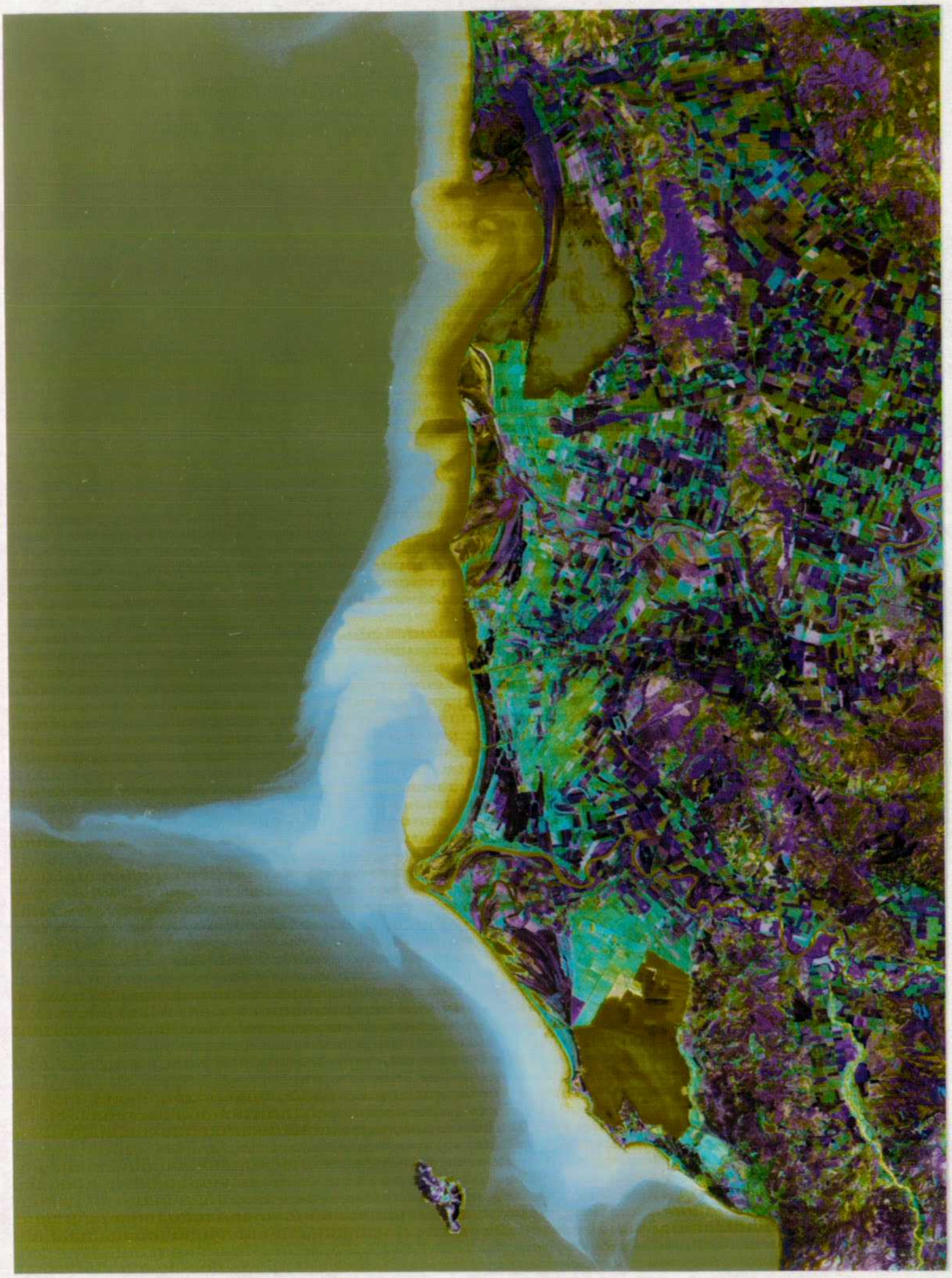

Figure 10: Landsat TM image of part of the Albanian coast. The imagery has been processed using a principal components transform to enhance information relating to both coastal accretionary structures and offshore patterns of sediment transportation. Approximate scale 1:350 000

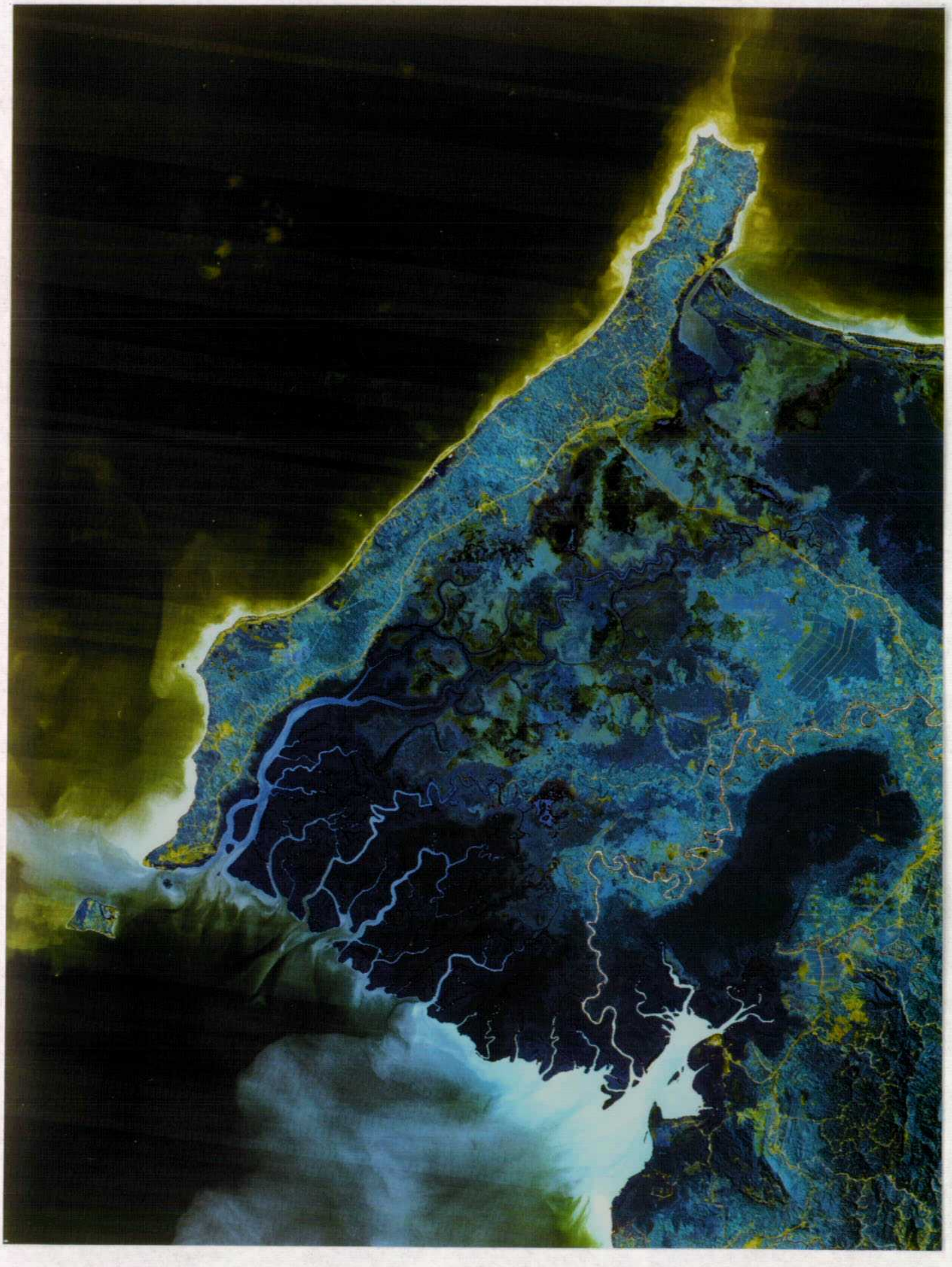

Figure 11: Landsat TM image of part of Sabah Island, East Malaysia (orientated north upwards). Here, the visible bands (TM3-2-1) have been used for the offshore area and a combination of the visible and reflected infrared bands (TM4-5-3) for the land. Approximate scale 1:300 000.

Figure 12: SLAR image of the lower reaches of the Rio Coco delta along the Nicaragua/Guatemala border. Variations in surface roughness due to grain size and micro-relief, together with related vegetational contrasts, are shown by differences in brightness in the radar backscatter. Approximate scale 1:130 000.

4.3 Lacustrine environments

In most lake basins, there is a marked zonation of facies with the fine grained sediment occurring in the centre of the lake and the potential aquifers restricted to the basin edge where coarser sediments accumulate. Fan-deltas entering the lake are likely to contain the most permeable sediments within the basin.

4.4 Volcanic environments

Volcanoes produce two main types of lithological material: lava flows and pyroclastic deposits. Lava flows are usually solidified as rock but may be blocky and can form aquifers where brecciated, such as along their basal and top margins. Pyroclastic deposits have highly variable grain size ranging from blocks to ash and may be welded or unwelded. Such variations lead to very complex patterns of groundwater storage and movement.

Young volcanic terrains provide an opportunity to exploit features of all three types of remotely sensed data. Optical data are effective because, even in moderately vegetated terrains, volcanic deposits are often fresh and still exposed. The types of material also strongly affect the type and density of vegetation cover. Spectral variations between different flows can be used to produce reliable maps which separate not only lithologies but also deposits of different age. Figure 13A & B show an example of Landsat TM data from the Kenya Rift Valley and illustrate how different band combination and processing can improve discrimination of volcanic rocks of very similar chemical composition. The choice of enhancement will depend on the particular objectives of the study. Whereas the retention of topographic shadowing in the band composite (Figure 13A) is better for detecting structures, such as the north-south normal faulting, the ratio composite image (Figure 13B) provides a more vivid discrimination of lithological units and individual eruptions.

The variation in surface roughness which occurs over volcanic deposits means that radar data can also be highly discriminating in this geologic environment. Figure 14 shows part of an aerial photograph of a late Pleistocene volcano in Arizona while Figure 15 is the same volcano imaged using K-band (0.86 cm) radar. The two types of data display different, and largely complementary information, radar responding primarily to physical differences of the surface such as texture (e.g. lava blockiness) and grain size. In such young volcanic terrains vegetation tends to be highly adapted and may serve to enhance radar features that enable sub-units to be discriminated.

Since silica content strongly influences the thermal emission spectra of most rocks, thermal data can potentially be used to differentiate between flows of different ages and to separate units with different silicate minerals. However, at present multispectral thermal data is not widely available and most imagery is single frequency. Figure 16 is a broadband thermal infrared image (8-14 microns) of part of the same lava flow illustrated previously (Figures 14 and 15). This daytime linescanner image shows differences related largely to the thermal inertia (heat capacity) of different materials composing the flow (e.g. lava, cinder and alluvium).

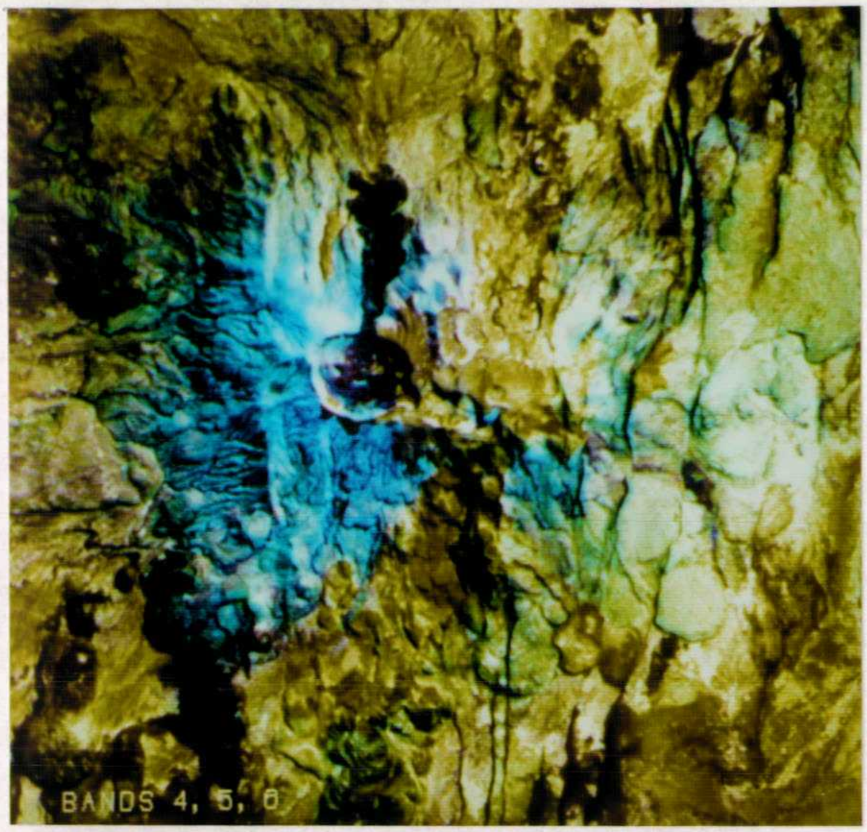

Figure 13A: Landsat TM image of part of the northern Rift Valley, Kenya. In this combination of bands 4, 5 and 6, the volcanic units are moderately discriminated and structures, such as north-south normal faults well displayed. Approximate scale 1:60 000.

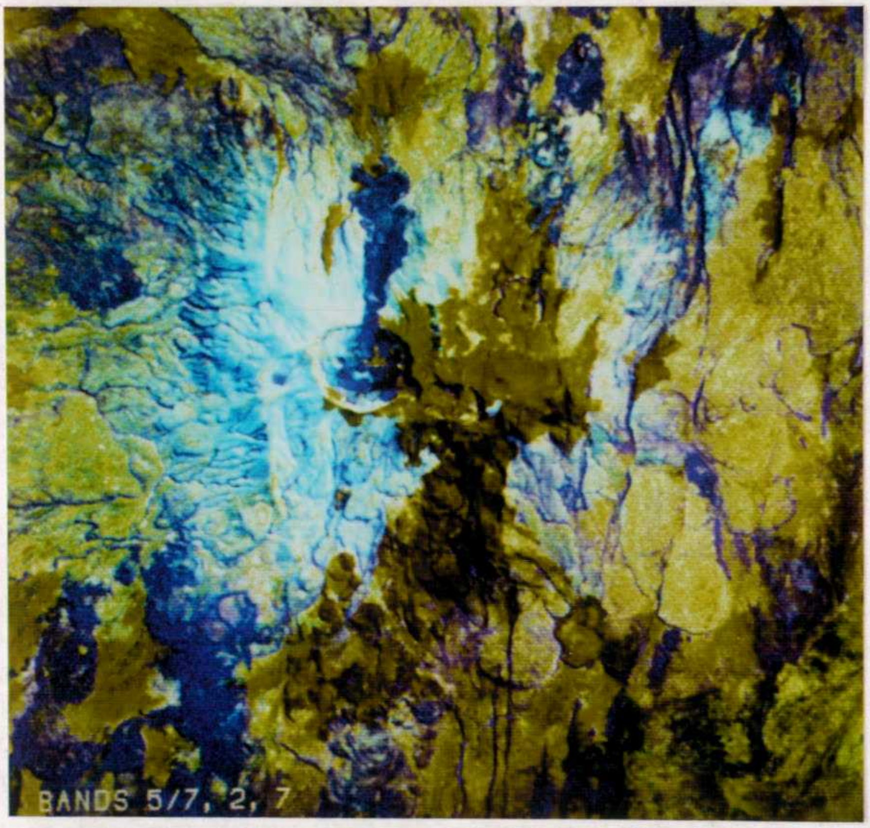

Figure 13B: The same Landsat TM image shown in Figure 13A here processed as a mixed ratio and band composite. This combination maximises the discrimination of eruptive units having closely similar composition. Approximate scale 1:60 000.

Figure 14: Aerial photograph showing part of a young volcanic cone and lava flow in northern Arizona. Approximate scale 1:60 000.

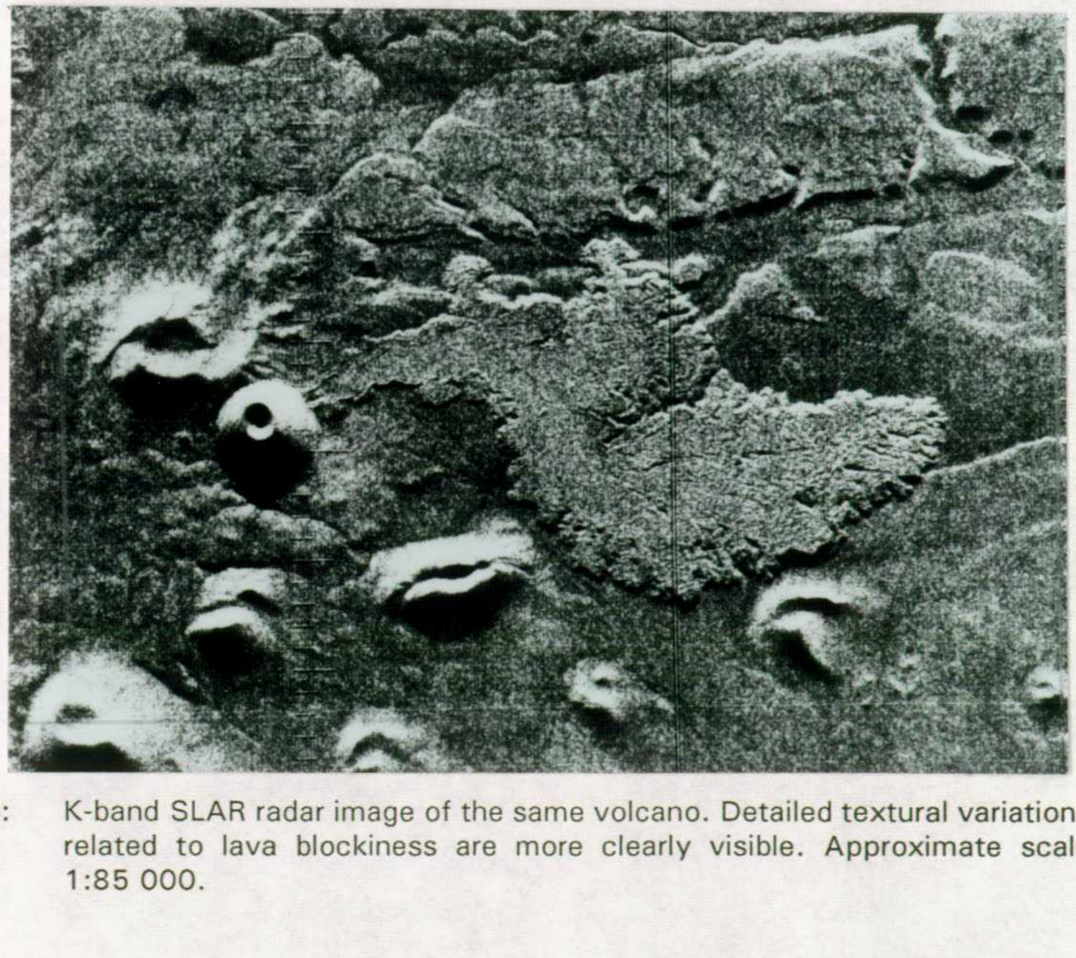

Figure 15: K-band SLAR radar image of the same volcano. Detailed textural variations related to lava blockiness are more clearly visible. Approximate scale 1:85 000.

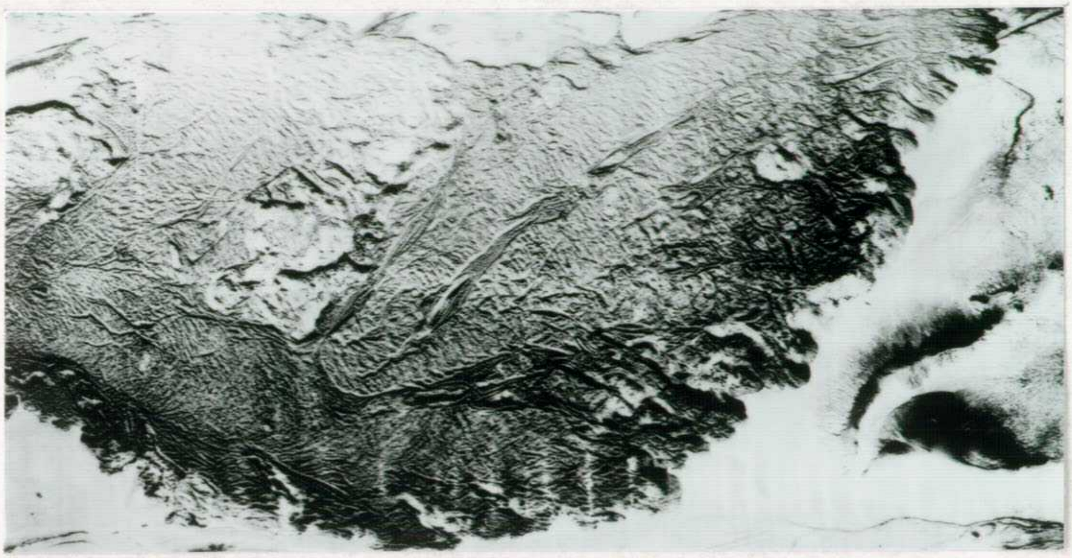

Figure 16: Daytime thermal infrared image of part of the same lava flow shown in figures 14 and 15. Discrimination is here related to the heat capacity of lava, cinder and alluvium. Approximate scale 1:30 000.

4.5 Glacial Environments

Glacial sediments are generally of two kinds: ice-transported tills and water-sorted sediments laid down by glacial meltwater. The former commonly have low permeabilities and are unlikely to form aquifers. The latter include moraines, eskers, in-filled glacial channels, fans and fan-deltas; where these contain sands and gravels significant groundwater resources can occur.

The most important information that remote sensing can provide relates to the geomorphology of the glacial deposits. The Landsat TM image in Figure 17 depicts a major esker system in the Inverness area of Scotland. The low sun-angle in this winter scene picks out the subtle topographic features associated with this deposit. A similar scene from Northern Ireland (Figure 18) provides an example of data that can be used to map a range of glacial outwash deposits. For mapping such subtle geomorphological features, it is important to select imagery with low sun angle.

4.6 Aeolian environments

Aeolian deposits are characteristic of arid climatic regions where transport and deposition of sediment by wind dominates, resulting in efficiently sorted deposits. Gravel forms a lag deposit, sand travels as bedload and accumulates in sand seas and finer material travels long distances in suspension before being deposited as loess. The sand which accumulates is well rounded, well sorted, and has the potential to form an excellent aquifer although groundwater availability can be extremely varied in arid climates. Sand accumulations take the form of dune fields and the dunes may have a variety of internal bedforms, but in terms of their hydrogeology they are essentially homogeneous. The height of the dunes can, however, be related to the overall thickness of accumulated sand. The analysis of dune geometry using topographic information from remotely sensed data may thus offer a means of predicting the overall geometry of the deposit.

Analysis of remote sensing can help understand the overall geometry of aeolian deposits. Figure 19 is part of a Landsat TM image of the southern central Kalahari Desert in Botswana. The central area which appears in shades of blue corresponds to a thinner covering of Kalahari Sands overlying extensive calcrete deposits. Calcrete can form a barrier to groundwater movement and may result in perched aquifers. In central parts of this area an intersecting network of fine lines is evident in the imagery. These correspond to low calcrete ridges which other evidence suggests may have some relationship to the circulation of groundwater and are potential borehole sites. Several pans are visible which, although they are themselves dry or saline, are nevertheless locations around which successful dug wells are common.

5. LOGISTICS

Many of the areas in which groundwater investigations are carried out either have no base maps, or these are inaccurate, or out of date. An incidental, though not

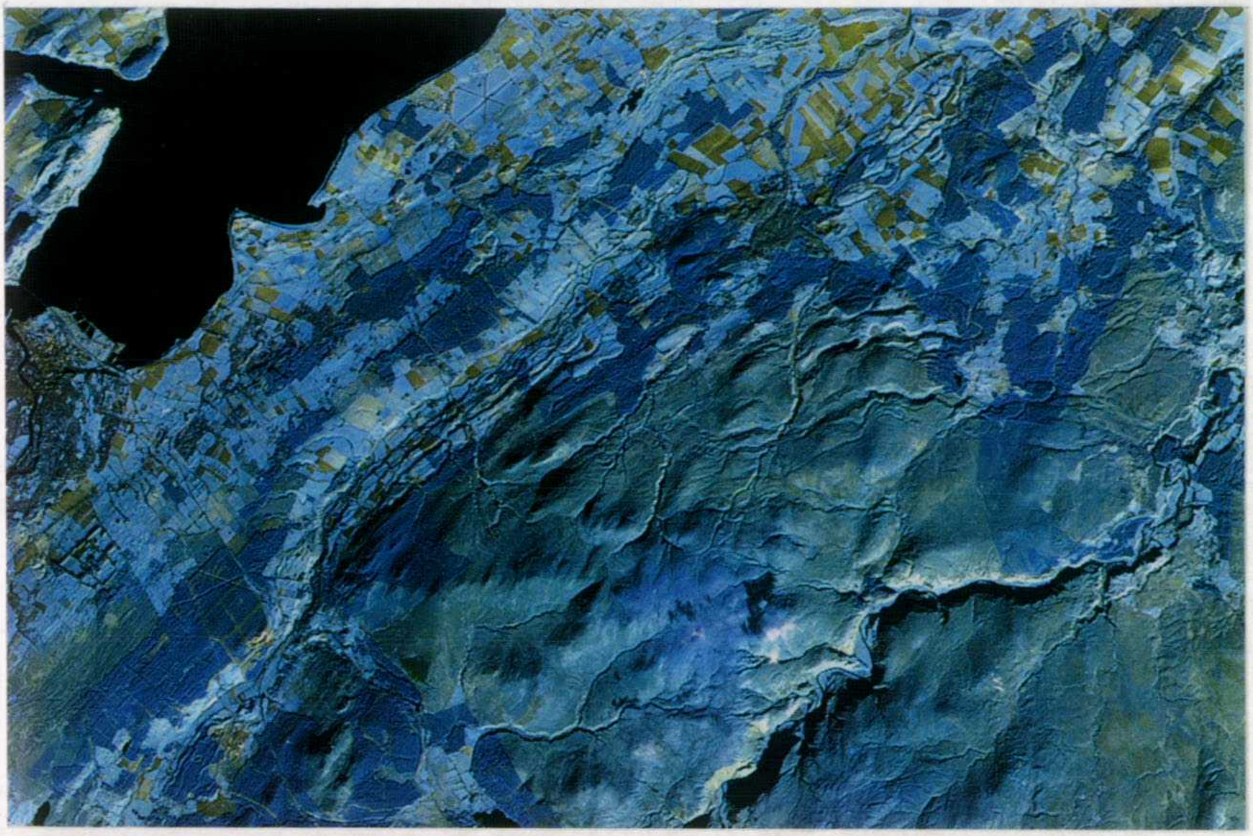

Figure 17: Winter Landsat TM image (bands 4-5-7) of the Inverness area, Scotland, showing a major esker system. Approximate scale 1:220 000.

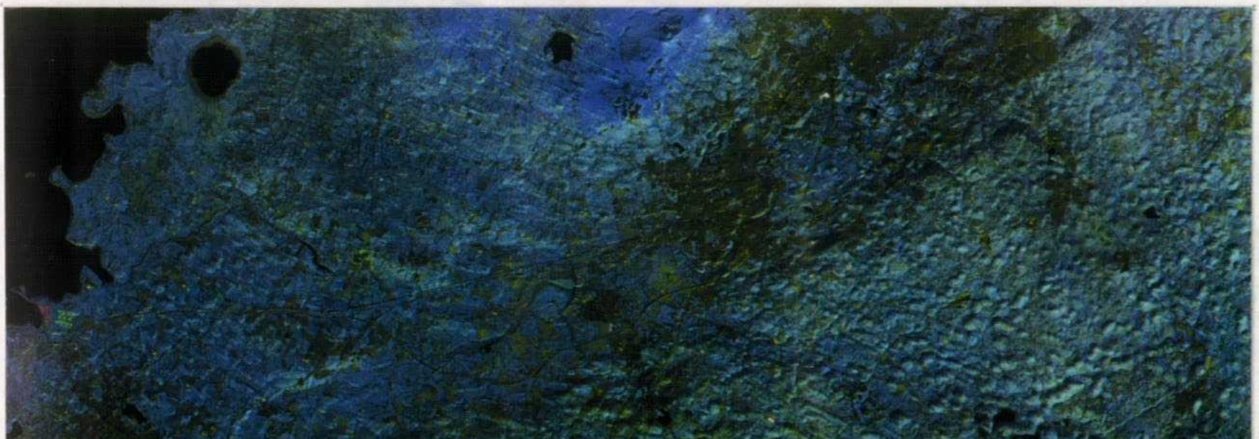

Figure 18: Winter Landsat TM image (bands 4-5-7) of part of Northern Ireland (Belfast in top centre right). A range of glacial outwash deposits can be mapped. Approximate scale 1:200 000.

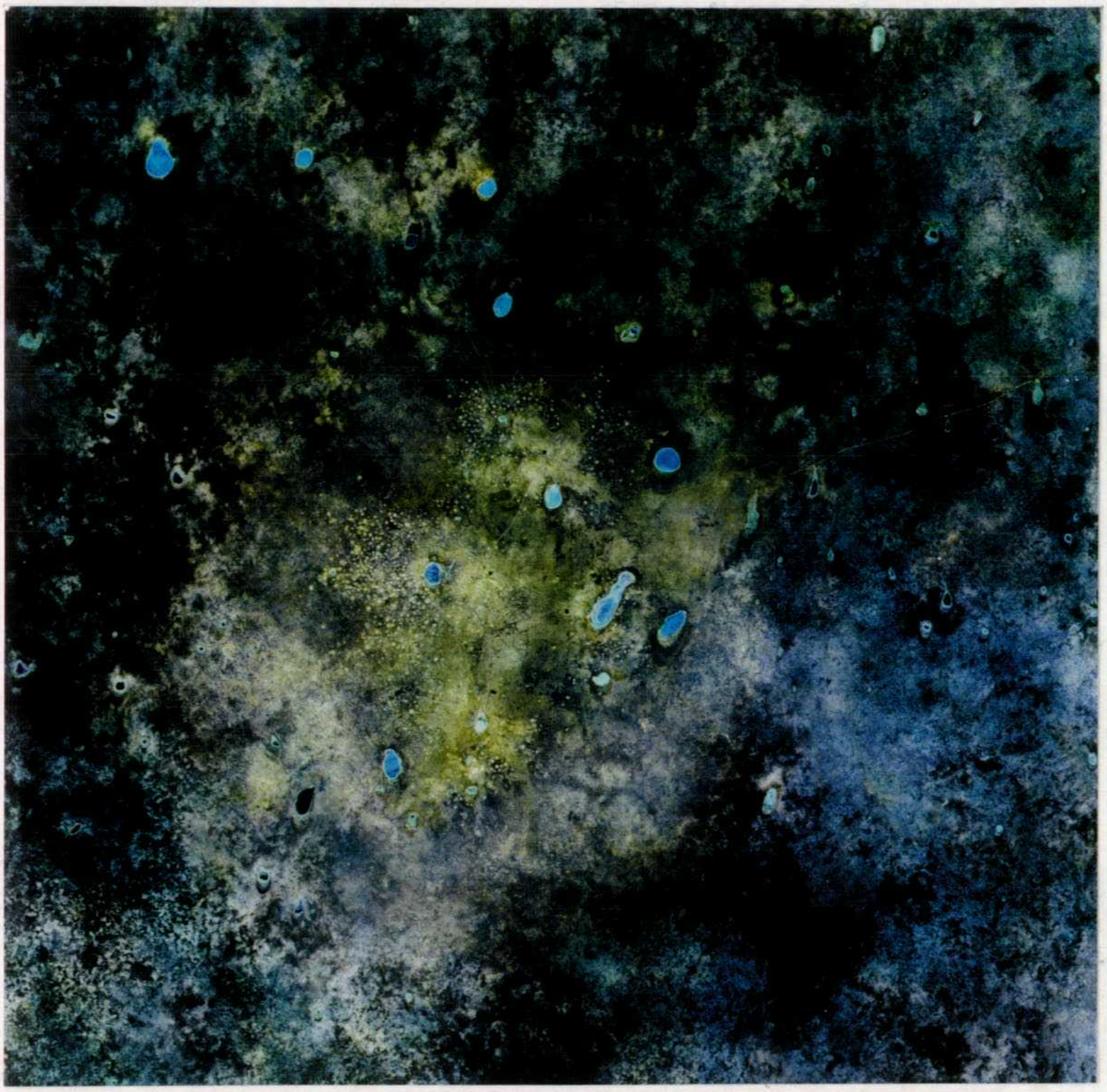

Figure 19: Dry season Landsat TM mosaic (bands 4-5-7) of part of the southern central Kalahari Desert, Botswana. The pale blue colour in central parts corresponds to calcrete at shallow depth, and similarly a pattern of very fine lines to calcrete ridges. The pans appear in various colours according to their composition. Approximate scale 1:600 000.

insignificant, advantage of using satellite optical imagery is that it provides a detailed and, for most purposes, accurate base map which can be used to plan the logistics of an exploration or development programme. Landsat TM imagery, for example, enlarged to scales of between 1:250 000 and 1:50 000 provides detailed information on access and infrastructure, as well as the location of the geological features of interest. The usefulness and cost savings of this information alone may more than justify the use of remote sensing.

6. SUMMARY AND CONCLUSIONS

Remotely sensed data offers the potential to map the surface distribution of a variety of sedimentary deposits which may form UNSAs. Satellite data are most suited to regional studies and initial exploration whereas aerial photography can be used to provide site-specific detailed interpretations. Different types of data are appropriate in different environments and for mapping different types of surface feature.

Optical data can provide information on the distribution of lithologies and the geomorphology of sedimentary systems. They are most effective in arid, unvegetated terrains and temperate areas with less cloud-cover. Where cloud is a persistent problem, radar data may be the only viable option. Radar can provide information on surface roughness, moisture content and topography, all of which can assist in the mapping of sediments. Both radar and optical data can be used to produce DTMs. Thermal imagery is an under-exploited remote sensing data type, due mainly to the fact that no satellite system is yet in place. Thermal data are available from airborne surveys and can be used to map lithologies and detect hidden features such as spring lines of interest to hydrogeologists.

Remote sensing methods should be applied at an early stage in a groundwater project. The data can be used to explore for potential aquifers, delineate the surface extent of particular sedimentary units and help plan more detailed surveys employing expensive, ground-based techniques. Given careful selection of the most appropriate data type for a particular environment, remote sensing provides a cost-effective tool for investigating an area before valuable resources are committed to the implementation of other surveying methods. The use of satellite imagery has the additional advantage of providing a detailed and up to date base map.

7. REFERENCES

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National Remote Sensing Centre Ltd. (NRSC) - all enquiries for satellite and aerial data should be made to: Data Sales Manager, NRSC, Arthur Street, Barwell, Leicestershire, LE9 8GZ. Telephone: 01455 844513. Fax: 01455 841785.

Natural Environment Research Council (NERC) - enquiries about airborne data to: Manager, NERC Airborne Remote Sensing Facility, NERC Scientific Services, Polaris House, North Star Avenue, Swindon, SN2 1EU. Telephone 01793 411500. Fax: 01793 411610

RESTEC - enquiries for JERS-1 data should be made to the User Service Department, Uni-Roppongi Building, 7-15-17, Roppongi, Minato-ku, Tokyo 106, Japan. Fax: 81 3 5561 9541.

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METHOD SUMMARY SHEET RS1

TITLE: **Aerial photography**

Scope and use of method

Stereo aerial photography should be acquired early in a project and used both prior to, and during, the field component. In general, aerial photography is useful where the scale of investigation is 1:50 000 or larger, or where site-specific studies are required.

An aerial photograph interpretation can provide:

- a map showing access, infrastructure and drainage to help plan field studies;
- a map showing geomorphology and geological structure;
- evidence of the health of the vegetation (which may be related to groundwater);
- discrimination of different soils and lithologies; and
- a digital terrain model and accurate contour information if stereo data are available.

Method

The following checklist provides a general guide.

1. Decide the scale of photography appropriate to the features to be mapped.

2. Check availability of the existing coverage (for UK consult NAPLIB, 1993). If necessary, ask survey companies to quote for new acquisitions.

3. Purchase and interpret the photography early in the project.

4. Interpretation should be an iterative process; interpret, verify and then finalise interpretation as field information becomes available.

Lillesand and Kiefer (1994) provide descriptions of different photographic systems and the principals behind photogrammetry and aerial photograph interpretation.

Key References

Lillesand T M, & Kiefer R W, (1994). *Remote sensing and image interpretation (3rd edition).* John Wiley and Sons, New York, 750 pp.

NAPLIB, (1993). *The NAPLIB Directory of Aerial Photographic Collections in the UK.* Published by the Association for Information Management, Information House, 20-24 Old Street, London, EC1V 9AP.

METHOD SUMMARY SHEET RS2

TITLE: **Optical sensors**

Scope and use of method

Satellite data are used in regional studies where the scale is smaller than 1:20 000, where the acquisition timing is not critical, and where a sensor with a suitable configuration is in orbit. Airborne data are useful in regional or local studies at scales of 1:50 000 or greater, where data must be acquired at a certain time/season, or when particular sensors are required.

Interpretation of optical scanner data can provide:

- a map of access, infrastructure and drainage to help plan field studies;
- an interpretation of regional geomorphology and hence geological structure;
- improved discrimination of vegetation types and indications of health;
- improved discrimination of soils and lithologies due to increased spectral resolution; and
- a regional digital terrain model and contour information;

Method

The following checklist provides a general guide.

1. Decide the scale, spectral resolution and need for stereo by considering the features to be mapped. Assess whether the requirement is for satellite or airborne data.

2. Check suppliers to determine the existing coverage (e.g. NRSC, NAPLIB). If necessary, ask suppliers to quote for new acquisitions.

3. Acquire, computer enhance, and interpret the data early in the project.

4. Interpretation should be an iterative process; interpret, verify and then finalise interpretation as field information is increasingly available.

Drury (1987) provides descriptions of different optical sensors and the principles behind digital image processing and photogeological interpretation.

Key References

Drury S A, (1987). *Image interpretation in geology.* Allen and Unwin, London, 243pp.

National Remote Sensing Centre Ltd. (NRSC) - all enquiries for satellite and aerial data should be made to: Data Sales Manager, NRSC Ltd, Arthur Street, Barwell, Leicestershire, LE9 8GZ. Telephone: 01455 844513. Fax: 01455 841785.

METHOD SUMMARY SHEET RS3

TITLE: **Thermal sensors**

Scope and use of method

Usable thermal data are at present only acquired by aircraft sensors. They are generally used in local studies at large scales where they can address a specific problem.

Thermal data respond to variations in heat capacity and moisture content. They can be used to map:

- the position of natural spring lines;
- seepage from landfill sites;
- changes in soil composition;
- geomorphology and hence geological structure; and
- different soils and lithologies.

Method

The following checklist provides a general guide.

1. Determine the optimum acquisition time: pre-dawn, the ground's temperature is governed by its composition and moisture content; post-dawn, differential heating effects mean topography controls the thermal response; and combined night and midday acquisitions can be used to calculate thermal inertia, again related to composition and moisture content.

2. Check suppliers for existing coverage. Ask specialist suppliers to quote for new acquisitions if required.

3. Acquire, computer enhance, and interpret the data early in the project.

4. Interpretation should be an iterative process; interpret, verify and then finalise interpretation as field information is increasingly available.

Drury (1987) describes the acquisition, processing and interpretation of thermal data.

Key References

Drury S A, (1987). *Image interpretation in geology.* Allen and Unwin, London, 243pp.

NAPLIB, (1993). *The NAPLIB Directory of Aerial Photographic Collections in the UK.* Published by the Association for Information Management, Information House, 20-24 Old Street, London, EC1V 9AP.

METHOD SUMMARY SHEET RS4

TITLE: **Radar data**

Scope and use of method

Satellite radar data are used in regional studies where the scale is smaller than 1:50 000 and acquisition timing is not critical. Airborne radar data can be used in regional or local studies at scales of 1:50 000 or larger and where data must be acquired at a certain time or season. Radar has the advantage over optical and thermal data that its acquisition is unaffected by weather, so that radar data are frequently the only practical data type in the tropics.

Radar data can be used to measure:

- moisture content, useful in hydrogeology and soils mapping;
- surface roughness and microtopography, useful in mapping soils and lithologies; and
- geomorphology, useful in structural mapping.

SAR interferometry can also be used to derive an accurate digital terrain model.

Method

The following checklist provides a general guide.

1. Decide an appropriate scale and look angle: a small incidence angle for low relief terrain in which radar responds to variations in sediment grain size, micro-topography, and moisture content; and a larger look angle to reduce distorting layover effects in mountainous terrain. Assess whether the requirement is for satellite or airborne data.

2. Check suppliers to determine the existing coverage (e.g. NRSC, NAPLIB). Ask suppliers to quote for new acquisitions if required.

3. Acquire, computer process, and interpret the data early in the project.

4. Interpretation should be an iterative process; interpret, verify and then finalise interpretation as field information is increasingly available.

Drury (1987) provides descriptions of radar sensors and the principals behind digital image processing and radar interpretation.

Key References

Drury S A, (1987). *Image interpretation in geology.* Allen and Unwin, London, 243pp.

National Remote Sensing Centre Ltd. (NRSC) - all enquiries for satellite and aerial data should be made to: Data Sales Manager, NRSC Ltd, Arthur Street, Barwell, Leicestershire, LE9 8GZ. Telephone: 01455 844513. Fax: 01455 841785.