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The Use of Multispectral Satellite Imagery in the Exploration for Petroleum and Minerals

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The use of multispectral satellite imagery in the exploration for petroleum and minerals

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[Plate 1]

The paper reviews the application of multispectral satellite imagery to mineral and petroleum exploration, from the stage when satellite imagery first became available, with the launch of ERTS-1 (Landsat) just over 10 years ago, to the present day. The operation of Landsat is briefly described, and it is noted that the continuing success of this system for geological application has been in part due to the development of a world-wide network of receiving stations and the application of sophisticated data-processing techniques. Current research into the measurement of infrared spectra for the discrimination of rocks and minerals is discussed. Interpretation techniques are important but their success depends largely upon the experience of the interpreters as geologists. Examples of the use of Landsat imagery in exploration are given, and interpretational techniques are reviewed. Combining Landsat interpretation with that of regional geophysical surveys can bring important advantage. Finally the new generation of imaging multispectral satellites is described and the implications with regard to petroleum and mineral exploration are discussed.

Introduction

Multispectral remote sensing for mineral and petroleum exploration has become incorporated into everyday practice. It is now standard procedure to examine satellite imagery at the area selection stage and to carry out an interpretation at the inception of field studies for integration with the results of geophysical surveys. Real benefits can be demonstrated by explorationists, who at one time were sceptical about the value of satellite remote sensing. The impact on mineral and petroleum exploration is enormous although not yet everywhere appreciated. It represents the greatest single advance in regional and semi-detailed exploration since aerial photographs were first used for geological purposes.

Since the first orbital pictures were obtained during the Gemini programme there has been an increasing recognition of the importance of the view obtained from the satellite-platform. Fred Hoyle predicted that once a photograph of the Earth was taken from the outside, new ideas as powerful as any in history would be let loose. The past 10 years have seen a vast accumulation of papers and presentations on the application of satellite imagery for civilian scientific purposes, including those geological. Therefore, in order to reduce the subject matter to manageable proportions the title of this paper has been deliberately selected to encompass only the applications summarized below.

At present multispectral satellite imagery is virtually synonymous in the minds of most with the Landsat series of satellites, as it is the imagery from these satellites that is most readily available to exploration geologists. Other passive remote-sensing satellites are not discussed and this review has been restricted to the direct application of Landsat imagery to petroleum and minerals. Landsat has been employed for many geological purposes, including hydrogeology, geothermal exploration, seismic hazard prediction, and engineering studies. Also excluded from this paper are the indirect use of Landsat in exploration as a mapping base, for terrain evaluation and bathymetric mapping in shallow marine environments.

The Landsat system (originally named ERTS (Earth Resources Technology Satellite) was primarily orientated towards land-use purposes but was also designed to test four geological hypotheses (Fischer 1977):

(1) that some dynamic geologic phenomena could be better viewed in a time-lapse mode, e.g. sedimentation and glaciation;

(2) that colour would prove useful in mapping rock types, geochemical anomalies and alteration products;

(3) that some geological and hydrogeological features are only intermittently visible;

(4) that large structures exist on the Earth's surface which because of their size have gone unrecognized by ground or aerial survey.

For exploration the recognition of the features mentioned in (2) and (4) have proved of greatest importance to the search for petroleum and minerals.

At this stage it is timely to review the practical results achieved so far in this field by the Landsat system, as we shall soon be receiving data from the next generation of civilian land remote-sensing satellites.

The Landsat system

Landsat was originally conceived as the Earth Resources Technology Satellite (ERTS), and ERTS-1 was launched in July 1972. The system was renamed Landsat in 1975 after the launch of Landsat-2. So far, four satellites in the series have been launched. This series of experimental satellites was designed to provide multispectral imagery for the study of renewable and non-renewable resources, and the system is about to become operational.

The satellite weighs 850 kg and is launched into a near-polar orbit at an altitude of approximately 900 km. The orbit is Sun-synchronous, with the satellite passing southwards over the Equator at approximately 9.30 a.m. on each pass. This ensures that there are approximately similar illumination conditions on adjacent tracks, which are one day apart. The image swath is 185 km wide and in this orbit, which takes 103 minutes, the entire surface of the Earth (apart from high polar regions) is covered every 18 days. For convenience each swath is divided up into 185 km segments, designated 'scenes'.

The sensor payloads have varied slightly between each of the first three satellites, and Landsat-4 is an entirely new system. The sensors, the multispectral bands and some comments about their performance are given in table 1. In essence the sensors comprise the multispectral scanner (MSS), recording in four bands, and the Return Beam Vidicon camera (RBV), which is panchromatic. Only the application of the generally available MSS imagery is considered here, as RBV is not generally available because of sensor failure or variable quality of the data.

The Landsat multispectral scanner has an instantaneous field of view of 79 m, and with side lap along each scan line each picture element (pixel) represents an area of 56 m × 79 m on the ground. Each scene is made up of approximately 3240 × 2340 pixels.

Initially, imagery in both real-time and from the on-board recorders was received at the two receiving stations in the United States of America. Since the launch of Landsat-1, receiving stations have been built or are planned in Canada, Sweden, Italy (Earthnet), Brazil, Argentina, South Africa, India, Thailand, China, Japan and Australia. Each station is responsible for generating and distributing a range of image products, which usually include both photographic and computer-compatible items.

The convention is to compose false-colour composite images from three of the four bands, assigning red to the infrared band. The range of surface coloration and the convention for false-colour imagery are shown in table 1. Colour composite images can be made photographically, or through a colour television monitor with an image display system.

Table 1. Landsat mss bands

band	wavelength/μm	type of radiation	filter for colour composite
4	0.5–0.6	visible green	blue
5	0.6–0.7	visible red	green
6	0.7–0.8	reflected i.r.	red
7	0.8–1.1	reflected i.r.	
8†	10.4–12.6	thermal i.r.	—

† Landsat-3 only.

Geologists began to use Landsat imagery as soon as it became available in 1972, realizing the importance of the synoptic view, which is of great value in structural geology. The first images used were commonly black and white prints at 1:1 000 000 scale of MSS band 5 or band 7. At that stage there were very few laboratories with the facilities for processing computer-compatible tapes (c.c.ts). The importance of working with multispectral bands and colour composite imagery was progressively appreciated. Also at that time there was some resistance to be overcome, because many explorationists could not appreciate the advantages that might be obtained from using Landsat. This in part was due to the over-optimistic claims that were being made at the time, and laid emphasis on the identification of minerals from space, claims that, apart from a few instances, could not be substantiated.

During the late 1970s two important developments took place that contributed to the more widespread use of Landsat imagery. The first of these was the gradual build up of a worldwide network of receiving stations, which means that a large proportion of the land surface can now be imaged in real-time. At first this may not seem of importance for geological applications, in that geologists only need one 'without-repeats' picture, but experience has shown that this is not always true. It is extremely important to obtain the best image for interpretation with regard to season and Sun elevation. More receiving stations mean that the chance of obtaining a clear cloud-free scene is very much improved. Also, it has been shown that images from different dates can contribute to the geological knowledge of a region. This facility will become of increasing importance once geobotanical changes become better understood. Greater choice of imagery has therefore contributed to the increase in geological application.

The second important advance was the development and general availability of image processing and analysis systems coupled with the appreciation of the advantages of working with Landsat c.c.ts. The application of this technology has contributed to many programmes using the current Landsat imagery, and it will become of increasing importance in the application of future satellite imagery. The advantages that could be obtained from the computer processing of Landsat imagery were demonstrated for the discrimination and detection of hydrothermally altered rocks (Rowan *et al.* 1974) and for general regional applications in

Alaska by Albert & Chavez (1975). The early work in this field, principally by the United States Geological Survey, established the image-processing techniques now being generally applied.

IMAGE PROCESSING

The use of computer-based image processing and analysis systems has gained momentum over the past 5 years, to the situation where nowadays many geologists use computer-compatible data tapes. This groundswell in the use of image-processing systems has resulted from a number of factors that have come together at one time: primarily the development of increasingly powerful mini-computers coupled to image display systems capable of producing results at video rates, and also the development of the software required to produce hardcopy imagery that geologists need, and a desire by exploration geologists to use the best available image to extract the utmost benefit from their interpretations.

The general use of image processing and analysis systems has meant that the full range of data in the Landsat image can be examined to the best effect. The interactive processing of imagery where the results of each stage can be assessed is invaluable, and as a consequence interactive interpretation has been developed as a useful technique. The main functions carried out as part of a programme of geological exploration are image restoration, image enhancement and data extraction.

Apart from replacing lost data, i.e. dropped lines and bad pixels, for purely aesthetic effects, the geologist has been particularly interested in performing geometric corrections. These remove the distortions due to platform movement and correct the data to a cartographic projection by resampling. At the same time the pixel size can be reduced to aid enlargement. Rectification to a cartographic projection is particularly important if the imagery is to be related to the results of geophysical survey techniques where survey stations have been accurately located on the ground. To carry out routine geometric correction of imagery the Canadian Centre for Remote Sensing has built a system dedicated to this task, and the DICS (Digital Image Correction System) was described by Butlin *et al.* (1978). The output from this system is geocoded imagery in the same format as the national topographic maps; these products are required not only for geological use.

In the preparation of enhanced hardcopy the geologists require the best possible display of the data to provide the greatest impact for interpretation. An example is shown in figure 1. This involves the removal of sixth-line banding or striping, which is an inherent defect resulting from drift within the detectors. Also the enhancement will involve a contrast-stretching routine, preferably carried out interactively under the control of the interpreter. Spatial filtering techniques are used to enhance naturally occurring straight-edge features such as fractures. The filters can be omni-directional or if desired can be tuned to a particular direction. The principles for filtering out sixth-line banding and for carrying out edge-sharpening to enhance fracture patterns were described by Chavez *et al.* (1976). These techniques were applied to the interpretation of fracture patterns in southwest Jordan, and several previously unmapped faults were identified.

Information extraction processes are carried out interactively. The processes most favoured by geologists are band ratios, multispectral classification, principal component analysis and colour rotation. These can all be used to enhance specific geological features. Principal component analysis and colour rotation are generally needed to help distinguish lithological

FIGURE 1. An enhanced Landsat image of MSS band 7, Path 163, Row 040, 7 March 1975, showing the fold closure over the Sui gas field in Pakistan (central part of image). The outcrops to the north are folded Mesozoic sedimentary rocks with the irrigated Indus Valley to the south.

(*Facing p.* 246)

differences, whereas ratios are used to suppress illumination differences because regardless of illumination variation a material will exhibit the same ratio value. Ratios are important for the recognition of ferruginous and limonitic cappings, and in addition the drainage pattern tends to be well displayed in band ratios. Supervised and unsupervised MSS classification can prove helpful in exploration, particularly where the target is large or the region is densely vegetated and differences in the vegetation reflect underlying conditions.

The advantages of using a particular method or technique are generally determined by the terrain conditions of the area being explored. These are now better understood by geologists and the programme of image processing is tailored accordingly.

Interpretation

Geologists are principally concerned with subsurface conditions, whereas satellite multispectral imagery provides a measurement of surface reflectance. In the application of multispectral imagery to exploration, the geologist is also interested in the indirect indications that can be interpreted from the spatial relations within the imagery, as well as the direct measurement of the spectral reflectance of geological materials. At present we have a situation where routine geological information is obtained by the interpretation of imagery, whereas research is concentrated in the identification of rocks and minerals by reflectance measurements.

Laboratory experiments to determine the characteristics of spectral infrared emissions from rocks and minerals, and whether this technique could be used as an analytical tool, were carried out by Lyon (1965). The conclusion was that composition could be determined with fair precision and this led to the design of a flight-weight spectrometer for remote measurements. Further laboratory tests were conducted by Hunt (1977) with the publication of the visible and near infrared spectra of a large number of rocks and minerals. Experiments carried out with an airborne scanner flown over the Pisgah Crater test site before the launch of ERTS (Landsat-1) enabled Vincent (1972) to reach the conclusion that by ratioing the MSS bands of ERTS images it would be possible to identify iron-rich rocks and minerals. This would be potentially valuable for mineral exploration in the identification of gossans and ferruginous alteration zones in arid and semi-arid regions. The discrimination is due to the iron absorption bands that occur at 1.0 μm for ferric compounds and 0.70 and 0.87 μm for ferrous compounds. After the launch of ERTS (Landsat-1) the application of this technique was demonstrated by Rowan *et al.* (1974) in south-central Nevada and Blodget *et al.* (1978) in Saudi Arabia.

From the results of further test work with the airborne multi-channel scanner the importance of the 2.25 μm part of the spectrum for lithological discrimination was identified. A band in this part of the spectrum has been included in the Thematic Mapper on Landsat-4, and it will be useful for the identification of clay minerals particularly in alteration zones. The N.A.S.A./Geosat test site programme was carried out before the launch of Landsat-4 to simulate the expected results. The application of the Thematic Mapper bands to exploration for porphyry copper deposits has been reported by Abrams *et al.* (1981), to uranium exploration by Conel & Niesen (1981), and to petroleum exploration by Lang & Baird (1981).

Airborne test work to test narrower and narrower bands is continuing, and Siegrist & Schnetzler (1980) identified the optimum bands for rock discrimination, while some test work is also being carried out with narrow-band spectroradiometers as profiling instruments. Goetz & Rowan (1981) describe the aircraft test work carried out before the SMIRR (Shuttle Multispectral

Infrared Radiometer), and Collins *et al.* (1981) describe the results achieved with a 64-channel profiling radiometer. Although further applications of these instruments are likely to be restricted to small areas and be carried on aircraft rather than satellite platforms, the results will inevitably affect the selection of instrumentation to be used in future satellites.

In the practical field there is one basic feature common to all exploration programmes: the need for a geological map. In the use of satellite imagery the explorationist wants to improve his understanding of the geology of the region involved. Only if the geological mapping of the region can be improved in some way will direct benefits be derived from a study of multispectral satellite imagery. Despite the increasing application of computer-based analytical techniques, most of the exploration work carried out in the geological field has a substantial interpretational content, where the vital information for application to petroleum and mineral exploration is not detected by a unique spectral signature or by the use of a particular processing option, but by means of visual interpretation to coordinate context, texture, colour, and shape. In addition the experienced field geologist can also bring in previous knowledge of similar regions, which is an important contribution to any interpretation.

At present the practical application of satellite imagery to petroleum and mineral exploration involves an important element of interpretation. This is generally improved by providing the interpreter with the best processed imagery available, and including interactive image analysis, which allows the interpreter to identify specific features with a greater degree of confidence. This was recognized by Raines (1981) when he commented that the interpretative approach has been needed to derive the maximum amount of information. He recognized that the practical application called for systematic discrimination, which comprised the following:

(1) a well defined problem;
(2) the spatial or map approach, which emphasizes characteristics and interrelations, not points;
(3) a knowledge of the application of remote-sensing physics and image-display technology;
(4) a geologist with broad experience.

This succinctly outlines the current practical application of Landsat imagery, which is reinforced by Nash *et al.* (1980) in their paper dealing with photogeology and satellite image interpretation. They detail the steps whereby target areas can be identified and the zone of search is substantially reduced progressively, by using satellite imagery followed by photogeological studies. The paper includes a number of examples from Australia, Africa and Arabia, and the essentials of the approach are a study of existing data, and a Landsat interpretation, to select areas for photogeological study so that targets may be located for detailed ground operations. That paper also emphasizes the need to integrate the interpretation of Landsat imagery with other data, particularly the results of geophysical surveys.

When describing the application of Landsat imagery to petroleum exploration in the western United States, Zall *et al.* (1981) also emphasized the importance of interpretation. They describe the interpretation of Landsat imagery of four regions in the western United States, where they claim that the interpretation made an important contribution to petroleum exploration by reducing the field programmes needed to locate the discoveries. They were able to focus on the target area more quickly by undertaking the following steps:

(1) examination of enhanced imagery;
(2) literature search;
(3) formulation of geological models for entrapment of oil and gas;
(4) integration with geophysical interpretation.

This illustrates the way in which Landsat imagery is being applied to both mineral and petroleum exploration, and the approach in each case is the same. The interpretative approach has until now been the only route possible, but this may be modified once Landsat-4 Thematic Mapper data became available. So far Landsat has proved ideal for evaluating the mineral or petroleum prospects of large regions. This applies equally to unexplored and well known parts of the Earth. Often, by re-examining previously explored territory, structures not previously known can be perceived.

Mineral exploration examples

A number of different interpretative techniques have been used in mineral and petroleum exploration, and these generally fall into two categories: (1) thematic classification to identify surface features directly related to the target; and (2) structural interpretation, which may give clues to important subsurface features. So far, most of the thematic classification work has applied to mineral exploration, mainly because petroleum deposits are often deeply buried. The more important techniques are described here, with some illustrations from the public domain. Unfortunately, many good examples of the application of Landsat imagery cannot be published for proprietary reasons. The examples given also include areas where a particular technique has been tested over a known area. In some instances this has resulted in additional discoveries being made in the surrounding region.

Landsat imagery has contributed significantly to the advancement of geological mapping in the well known and the remote regions of the world. Although regional geological mapping is a prerequisite for all exploration programmes it is not within the scope of this paper to cover this field. However, it does deserve a brief mention and an example is the Landsat interpretation of the southern Sudan made by Hunting Geology and Geophysics (1976). Here the first geological maps were made of 300000 km² of territory to identify priority areas for mineral exploration. This involved the interpretation of 39 Landsat scenes by using MSS bands 5 and 7 at 1:500000 scale; an interpretation map was prepared for each scene at this scale. The interpretation was supported by a rapid reconnaissance of the region to verify the main features identified on the imagery. A lithostratigraphic and a structural synthesis of the region was prepared at 1:2000000 scale and this was used to identify the priority zones. This was followed by more detailed photogeological and field studies in two of the areas chosen.

Ferruginous residual deposits overlying mineralized ground (gossans) were first identified as colour anomalies on enhanced colour ratio composites by Rowan *et al.* (1974). Most of the gossans identified in this way could not be seen on the standard imagery. This led to the application of this technique to a test site at Wadi Wassat in Saudi Arabia (Blodget *et al.* 1978). The procedures developed by those authors have now become standard practice for searching for gossan in semi-arid terrain, to the extent that it has been used by the U.S.G.S. in the regional examination of the Walker Lake quadrangle. Here Rowan & Purdy (1981) have used colour ratio composites of enhanced MSS imagery, where the composite is made as follows: 4/5 blue, 4/6 yellow, 6/7 magenta. On these images the limonite zones appear green, and the belts of limonitic alteration can be mapped.

The discovery of using MSS imagery in this way prompted experimentation with additional bands in the infrared portion of the spectrum, particularly to aid the identification of alteration zones due to mineralization. Airborne tests carried out before the launch of Landsat-4 have proved successful, particularly in the mapping of alteration zones to porphyry copper deposits

(Abrams *et al.* 1981), and the delineation of bleached zones in sandstones covering deposits of uranium (Conel & Neisen 1981).

Where mineral deposits or their related alteration zones occur at surface and a known site can be identified on Landsat imagery, and provided that the spectral reflectance of the known site contrasts with its surroundings, it is possible to use multispectral classification techniques to locate sites with a similar spectral response on the image. This technique has proved successful initially at Saindak, Pakistan (Schmidt 1975), where supervised classification based on a 55 km^2 training area located 50 similar sites. Of these 50, 5 proved to be due to copper mineralization, which is an acceptable level for the results of field checking.

Similar studies have been carried out on gold-bearing gossans in Chile (Baker 1980), where supervised multispectral classification was used to locate new deposits. This technique has proved of use in the search for calcrete uranium deposits at Yeelirrie in Western Australia and in the Somali Republic.

By far the most common structures identified on Landsat are faults, fractures, linears and circular features. These can often be found in abundance and, following photogeological practice, statistical analysis of fracture traces can be carried out. This, together with some field information, can provide the means of deducing the stress pattern in the area at different periods of geological time. With structural data we are looking for clues to the location of concealed deposits, and not measuring something directly related to the deposit. There are abundant papers dealing with fractures and linears; some of the most notable are mentioned here.

The distribution of mineralization was found to be related to a major lineament in Saudi Arabia identified on Landsat by Moore (1976). The Al Amar fault was traced for 210 km, and a string of metalliferous and industrial mineral deposits form a belt that coincides with the volcano-sedimentary belt controlled by the fault line.

In the study of the Powder River Basin Uranium Deposits, Wyoming, Raines *et al.* (1978) carried out a statistical fracture analysis based on Landsat imagery. They found that the basin axis is marked by a strong linear feature, which is the boundary between two structural zones. There is evidence that this linear feature has influenced sedimentation in the region and later influenced the flow of groundwater, which controlled the distribution of uranium deposits.

Large circular and curvilinear features and their relation to mineralization have been studied by Norman (1980). It is suggested that these features may be related to meteorite impacts that occurred during the Archaean (more than 2600 Ma B.P.). This type of study has been used to investigate impact tectonics, which had previously been advanced to explain the occurrence of the Sudbury nickel deposits in Canada.

A Landsat study including digital analysis was integrated with a field study programme in Nova Scotia (Bruce & Stevens 1981), and nested circular and elliptical patterns were suggestive of convection cells in batholiths. This was verified by the study of the alignment of feldspar crystals on the ground, which followed the curved trend of an elliptical cell. Tin and uranium deposits were located along the cell margins.

In the Powder River Basin in Wyoming, Raines *et al.* (1978) found the local variation in vegetation density to be due to a facies change in the underlying rocks. Here the occurrence of uranium is restricted to one facies, and they were able to identify the differing vegetation density on Landsat imagery. Instances of vegetation stress have been identified on Landsat imagery and have been shown to be related to lithological or mineralogical changes in the substrata. These changes have in some cases been shown to be due to metal toxicity, and this type of study is referred to as geobotany (or remote geobotany); it is an area where more research is required. An example where this technique led to a discovery is described by Cole (1980). Copper deposits were found in Botswana after the investigation of a botanical anomaly identified on Landsat imagery.

Examples from petroleum exploration

The use of multispectral satellite imagery does not generally involve looking directly for indications of petroleum on the Earth's surface, although these do occur in the form of natural seepages and tar sands. Because there is little chance of detecting petroleum directly at the Earth's surface most applications for petroleum exploration involve geological mapping and structural analysis, i.e. indirect techniques. Structural analysis forms a major part of all petroleum exploration programmes, as it is necessary to locate a 'closed' structure to trap hydrocarbon gases and fluids in the crust before they escape into the biosphere and atmosphere. In this respect Landsat studies have contributed significantly to many exploration programmes, particularly if undertaken during their early stages, because they provide a means of reducing the ground to be covered so that the prospectors can concentrate their more expensive ground surveys to greater advantage.

Like many other disciplines, petroleum exploration has benefited from the use of Landsat interpretation for terrain analysis in remote regions. This is particularly true throughout many regions of Africa and the Middle East, where the best available maps are geometrically corrected Landsat imagery. In addition the imagery is used in shallow marine areas, where the waters are clear, as a means of producing preliminary bathymetric charts for planning inshore seismic surveys. Landsat imagery is also being used to assist the navigation of airborne surveys and for planning and map-base purposes the imagery has made a very useful contribution to many exploration programmes.

For detailed lithological mapping in petroleum exploration Landsat does not have the resolution needed for plotting the stratigraphy in detail, but it is sufficient for mapping major structural features. Apart from locating folds and salt domes Landsat has been much used in the analysis of fractures and linears. One of the main discoveries from the synoptic view offered by Landsat was the recognition of linear alignments of landscape features that often extend for tens of kilometres. Many studies have been made to assess their geological significance in many parts of the world. It is generally believed that these linears represent the surface expression of fundamental changes in the crust. The dimensions are not apparent to the ground observer and in depth a structural discontinuity is not apparent. Nevertheless, studies have shown (Halbouty 1981) that facies changes occur across these linears throughout geological time, and they are generally aligned parallel to an important regional stress direction. From this evidence it is concluded that linears mark the boundaries of basement blocks, the relative movements of which influence sedimentation and therefore influence the accumulation of hydrocarbons. From the examination of imagery from 15 giant oilfields, Halbouty (1980) concluded that Landsat would have been of invaluable assistance in the search for these fields if it had been available at the time.

Of equal importance is the analysis of small fracture traces that can be observed on satellite imagery. Very often these do not have any associated evidence of movement and can be detected through a superficial cover of alluvium, soil, etc. The analysis of fracture patterns of this type can be carried out by visual inspection, or, more often these days, by computer analysis of the fractures annotated by the interpreter. Several attempts have been made to detect fracture patterns automatically without a great deal of success. Together with a study of the geological history of the region and reconnaissance field work to measure joint and fault directions a history of the stress fields pertaining to different periods of geological time can be worked out for the region under analysis. This can be used to assist in the selection of structural targets for petroleum exploration.

Circular and arcuate features of small to medium radius (5–20 km) have also been used for the location of structural targets for petroleum exploration. Small circular structures are often due to salt doming, but of equal importance is the possibility that the large structures are due to basement topography concealed beneath younger sediments. This possibility was recognized by Zall *et al.* (1981), where circular features and fracture trace analysis assisted in the identification of petroleum targets in four regions in the western United States.

Fracture trace analysis has also been used to detect petroleum reservoirs in fractured rocks (i.e. where the permeability has been caused by brittle fractures). Such a study is described by Lang (1982) in the Lost River field of Wyoming. Here Lang used weighted linear density maps to detect the regions where fractures were most prevalent, and related this to the occurrence of petroleum reservoirs in the field.

The combination of satellite and airborne synthetic aperture radar was used for the exploration of fractured petroleum reservoirs in the Arkoma Basin in the United States of America (McDonald *et al.* 1981). In this gas-producing region an attempt was also made to correlate the production and density of gas wells with fracture density. The researchers concluded that MSS band 7, winter, with uniform contrast stretch was best for linear detection, but band 7 combined with SAR (Synthetic Aperture Radar) is significantly better if the radar look direction is orthogonal to the solar illumination. However, they were unable to demonstrate any relation between fracture density and gas production that tapped different formations in different parts of the area.

The importance of combining image interpretation with geophysical potential field techniques has been stressed by many workers. This appraisal of different but related data is important to petroleum exploration. Hunting Geology and Geophysics (Australia) (1982) have undertaken a study of the Eromanga Basin, where the Landsat interpretation has been integrated with gravity and aeromagnetic data, as well as assessing the relation of the movement of groundwater to petroleum. Many studies where the integration of regional survey data has played a significant role in petroleum exploration are known (Hunting Geology and Geophysics Limited, personal communication). In many instances the information obtained from the satellite imagery is of a relatively simple nature, such as being able to map the contact between metamorphic Precambrian rocks and the edge of a sedimentary basin that is concealed beneath superficial deposits and to confirm the existence of basement highs within the basin, or to be able to pick out fault trends that define the development of horsts and grabens within a sedimentary basin.

The possibility that natural oil seeps might be detected in the Santa Barbara Channel, California, from Landsat was investigated by Deutsch & Estes (1980). The fact that slicks caused by oil spillage could be seen on Landsat imagery had already been established (Estes *et al.* 1972; Deutsch *et al.* 1976). In this study, oil from the natural seepages was identified on contrast stretch enhancements of the digital imagery, and the distribution was confirmed by aerial observations made within a few hours of the Landsat pass. The experimenters concluded that this technique might have valuable application for offshore oil exploration.

New satellites

Landsat-4, the first of the new series of land remote-sensing satellites that will provide multispectral imagery, was launched in July 1982. This heralds a new era in the application of satellite remote sensing to resource assessment, as it marks the changeover from an experimental to an operational status. There is also the introduction of a new sensor system with improved spatial resolution, spectral separation, geometric fidelity and radiometric accuracy. This new sensor is designated the Thematic Mapper, and on Landsat-4 it will operate in addition to a multispectral scanner producing imagery at 80 m resolution in the same four bands used on the three previous Landsats.

The Thematic Mapper records in seven spectral bands and these are summarized in table 2. The ground resolution has been improved by reducing the pixel size to 30 m in all but band 6, which has a pixel size of 120 m. As already mentioned, band 7 will be important for geological applications, as it will aid in the discrimination of clays and zones of hydrothermal alteration.

Table 2

band	MSS/μm	thematic mapper/μm	SPOT/μm
1	0.5–0.6	0.45–0.52	0.50–0.59
2	0.6–0.7	0.52–0.60	0.61–0.68
3	0.7–0.8	0.63–0.69	0.79–0.89
4	0.8–1.1	0.76–0.90	—
5	—	1.55–1.75	—
6	—	10.40–12.5	—
7	—	2.08–2.35	—
pixel size/m	80	30 (B6 = 120)	20 or 10 panchromatic

The French Earth observation satellite SPOT (System Probatoire de Observation de la Terre) is due to be launched in 1984, and this system will have two modes of operation: either recording multispectral imagery in three bands with a 20 m pixel size or panchromatic imagery at 10 m pixel size. Furthermore it is designed to obtain stereoscope imagery, as it will be possible to tilt the scan head to repeat coverage of the same area. This will only be possible in areas of stable weather conditions.

Discussion

In this appraisal of the use of multispectral satellite imagery for mineral and petroleum exploration, the objective has been to demonstrate that the practical use of Landsat imagery has become established. The general application of satellite imagery has come about because it has been possible to demonstrate real benefits to prospectors. This is verified by the number of organizations both in the United Kingdom and throughout the world that are offering services in the geological applications of Landsat remote sensing. These groups are now ready to take advantage of new systems and new developments and to undertake the practical application of current research.

In remote sensing the geologist has to make deductions about subsurface conditions on the basis of surface observations, and this means that significant reliance is placed upon interpretative skills. So far with the Landsat system there have been relatively few opportunities to use thematic classification as a means of locating potentially valuable mineral deposits in the Earth's crust. This has been mainly due to the limitations of resolution and recording broad spectral bands. This will be somewhat alleviated once imagery from Landsat-4 is made generally available, as this system will have both greatly improved ground resolution and additional spectral bands specifically requested for geological applications.

In petroleum exploration the emphasis has been on the structural interpretation of imagery, and this will greatly benefit from having stereoscopic data. The proposed launch of the SPOT satellite in 1984 will to a certain degree fulfil this need because it will be possible to acquire stereoscopic images, albeit separated by several days. This will be limited to those regions of the globe where both surface conditions and atmospheric conditions undergo only slow change, as there will be some risk attached to specifying stereoscopic coverage for a specific programme. However, SPOT will also go further towards providing improved resolution, which will be welcomed by the geological remote-sensing community.

Research into the application of narrow band infrared radiometers continues with the SMIRR experiment on the Space Shuttle, and this together with airborne experiments is likely to lead to new discoveries about the geological application of different wavebands. As the application of such imagery becomes understood it is conceivable that the demand will be for specialized satellites; this is not practicable unless the rewards are very great (e.g. the Canadian Radarsat). The need will therefore arise for waveband selection to be under ground control, or by technicians carried on board the Space Shuttle. Other future developments will be the demand for faster access to data, which will be achieved by satellite data links distributing raw data to clients rather than a series of standard products as at present. In the applications field more research is needed in the development of geobotanical techniques, which are equally important in temperate and tropical regions, particularly in understanding the chlorophyll infrared edge shift in chemically stressed vegetation; the importance of the 'red edge' has been emphasized by Horler *et al.* (1981).

One facet of Landsat that should not be overlooked is that within the period of one decade it has contributed greatly to the training of a cadre of applications-oriented remote-sensing scientists. It therefore can be expected that the clever combination of different image data sets will provide considerable application. This will go hand in hand with the increasing use of computers in geology for correlation of exploration data and development of geological models for the occurrence of valuable materials. Work on the digital combination of exploration data with Landsat has been described by Aroidson & Guiness (1981), Missallati *et al.* (1979) and Peters (1980).

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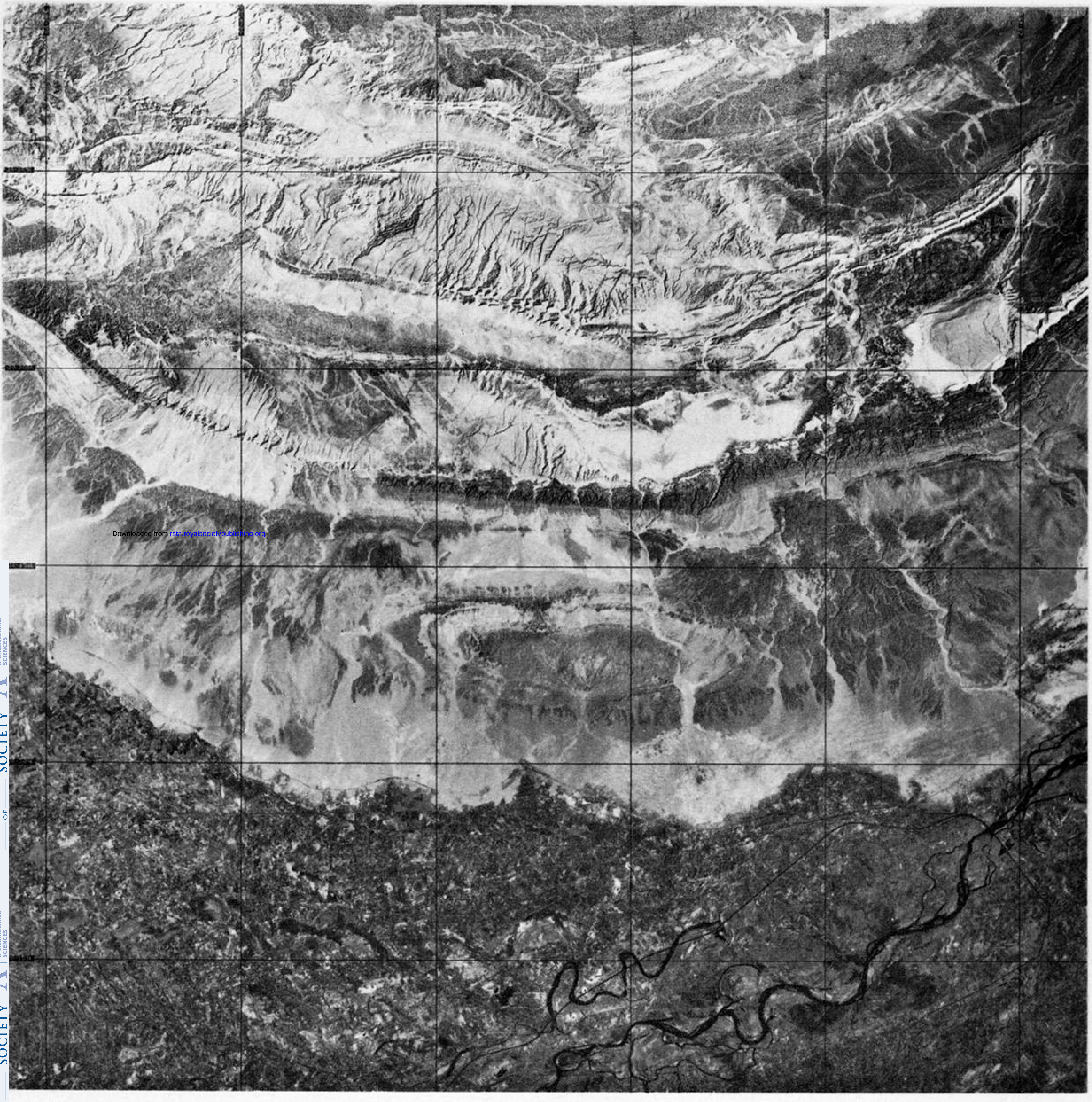

FIGURE 1. An enhanced Landsat image of MSS band 7, Path 163, Row 040, 7 March 1975, showing the fold closure over the Sui gas field in Pakistan (central part of image). The outcrops to the north are folded Mesozoic sedimentary rocks with the irrigated Indus Valley to the south.