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**DERIVING GEOLOGIC INFORMATION FROM SATELLITE REMOTE SENSING
FOR MINERAL EXPLORATION IN A SEMI-ARID ENVIRONMENT:
THE TROODOS MASSIF, CYPRUS**

**by
David Edward Davidson**

**A Thesis Submitted to the Faculty of Graduate Studies
in Partial Fulfilment of the Requirements for the
Degree of Master of Arts**

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"DERIVING GEOLOGIC INFORMATION FROM SATELLITE REMOTE SENSING
FOR MINERAL EXPLORATION IN A SEMI-ARID ENVIRONMENT: THE
TROODOS MASSIF, CYPRUS"

submitted by David Davidson, B.Sc.
in partial fulfilment of the requirements for
the degree of Master of Arts

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24 September, 1993

**DERIVING GEOLOGIC INFORMATION FROM SATELLITE
REMOTE SENSING FOR MINERAL EXPLORATION
IN A SEMI-ARID ENVIRONMENT:
THE TROODOS MASSIF, CYPRUS**

ABSTRACT

The mineral exploration industry requires new cost-effective techniques to aid in locating the world's remaining mineral deposits not found by traditional exploration methods. Changing environmental, economic and social realities have altered the resource sector's demands for new technologies and methodologies, and reduced the time allowable to implement scientific innovation into operational practice. This thesis develops a satellite remote sensing information extraction methodology which can address the needs of, and the challenges facing, the mineral exploration industry. An approach based on visual interpretation of digitally enhanced imagery was evaluated within the context of an operational project model and a technology transfer perspective. Such a perspective includes building applications which produce acceptable results that are feasible to implement using available levels of technology as defined by the operational reality of the user. The Troodos Massif in Cyprus, was chosen as the site for this study as it is a classic mineral deposit rich in volcanogenic base metal sulphides in a semi-arid environment, and there was identified industrial interest in adopting remote sensing capabilities to a mineral exploration program in this region. The results demonstrate that, for this specific case studied, remote sensing can successfully (from the operational user's perspective) provide information which improves the traditional mineral emplacement model, and that the transfer of applications development to industry can be facilitated by the adoption of systematic project planning.

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1.0 INTRODUCTION

1.1 Operational Application of Remote Sensing for Mineral Exploration in the Troodos Massif, Cyprus

While satellite remote sensing has been investigated for geologic applications since the late 1960s, it has only been of late that this technology has become a feasible and accessible tool for commercial (operational) geologic exploration. Current economic constraints, diminishing reserves, and increased environmental regulations have forced the mining industry to search for new methods of identifying mineral deposits. Remote sensing and related computer technologies have demonstrated consistent improvement in data capture and processing, and information extraction capabilities which provide potential for integration into operational mineral exploration programs. To meet this challenge, however, models to guide remote sensing applications research are required that are designed from the outset to facilitate the transfer of this technology to operational users. "Technology transfer" is defined in this thesis as an approach which consists of practical applications developed and demonstrated from an operational perspective; a perspective which demands not only an understanding of the needs and operational realities of the user, but also of the historical context of the technology and user.

This thesis reports on the investigation, development, and evaluation of a satellite remote sensing methodology in support of the Canada Centre for Remote Sensing (CCRS) Cyprus Pilot Project, one of a series of technology transfer demonstration studies carried

out by the Technology Transfer, Training and Development Section (TTTDS). The development and demonstration of a remote sensing application is presented, with the intention to illustrate, remote sensing capabilities for mineral exploration and the needs/risks project planning model (Bruce & Davidson 1991) which guided this application to successful technology transfer to industry.

Research was undertaken with the co-operation of GeoQuest International, Toronto-based geological consulting firm, whose exploration program in the Troodos Massif, Cyprus required the delineation of lithology and structures. GeoQuest International did not possess the expertise or resources necessary to undertake, or contract out, the development of an operational methodology for the use of remote sensing in Cyprus. Figure 1.1 shows that island of Cyprus, the specific areas of exploration interest and image coverage. Imagery are of two scales and areas of coverage; overview images (Fig. A2.1-8) and larger scale scenes of the eastern portion of the Troodos Massif (Fig. A2.9-15). The Troodos Massif is a world famous example of a semi-arid Ophiolite Complex rich in volcanogenic base metal sulphides. Large scale ore production lasted from the 1920s to 1980s, until low copper prices and the near-exhaustion of known deposits led to the closing of most of the mines (Jones, 1990).

Figure 1.1 Map of Cyprus showing image coverage and area of exploration interest. 1:1,000,000 scale. From Cyprus Dept. of Lands & Surveys, 1977

Methodology development for GeoQuest International was attractive because:

- remote sensing is particularly effective for geological applications in semi-arid regions, which always has had a high level of interest amongst the exploration community (Lees et al., 1985);
- this region has world-class copper deposits in a semi-arid environment. Little or no use has been made of modern, intensive exploration technology to locate new copper deposits (Jones, 1990). There has been no published consideration of the secondary mineralization normally associated with these types of deposits (Jones 1990). GeoQuest's mineral emplacement model (Jones, 1990) lends credibility to the proposition that many of the largest deposits have yet to be found;
- the geology maps that are available are of questionable thematic and geometric accuracy, and there are well known geo-political concerns that make access to aerial photography and other data difficult or impossible in Cyprus;
- the only other published remote sensing study (Bruce et al. 1986) successfully mapped the main lithologies using MSS data at regional scales. The increased spatial resolution and strategic placement of TM bands suggest this new sensor could provide geologic information of sufficient quality for direct input into a mineral exploration program; and
- ground reconnaissance and image interpretation have been supplied by GeoQuest International. Their extensive knowledge of the Troodos Massif provide an assessment of the methodology that could not have otherwise been achieved.

The Island of Cyprus lies in the eastern end of the Mediterranean Sea. Cyprus has a semi-arid climate with a pronounced dry season (April-Sept.). Summer drought conditions prevail until the end of September, leaving a dry, parched landscape and seasonal vegetation severely retarded (Kendrew 1961). The winter is mild and receives most of the rainfall. The dominant topographic and geologic feature is the Troodos Massif mountain range, which extends for 100 km east-west along the island and is up to 30 km wide from north to south. There have been more than 30 producing copper mines in modern times, virtually all concentrated in the periphery of the Troodos Massif

(Jones 1990). The largest deposit, the Mavrovouni Mine, produced 15 million tons of ore averaging from 3.5% to 4.5% copper and 0.5% zinc (Jones 1990).

The copper mining history of the Troodos Massif is in some ways typical of most of the major known mineral resources in that they were discovered by prospecting with traditional exploration methods beneath or near to very obvious surface indications of mineralization. To find the remaining deep-seated mineral deposits in Cyprus will require the augmentation of traditional exploration strategies with new tools.

Spatially-continuous digital geographic information, provided by remote sensing and manipulated in image analysis systems (IAS), is proving to be one of the needed keys for new mineral exploration (GRSG 1993). Efforts were concentrated on developing and documenting robust enhancement procedures of Landsat Thematic Mapper data to guide the use of image analysis in support of an exploration program for volcanogenic polymetallic sulphide deposits. An operational technology transfer model (Bruce & Davidson 1991) was used to provide the scope and constraints in the selection of a minimum set of required image products and the model emphasized the documentation and explanation of the methodology employed.

It is evident from an assessment of the considerable body of published remote sensing research to date¹ that standard and accepted practices for band selection, image

¹RESORS, the world's largest online remote sensing bibliographic service has over 7,000 articles specific to geological remote sensing.

processing techniques, and output product design are rapidly being defined for a variety of exploration environments (GRSG 1993, Loughlin pers comm 1992). For these data sources and manipulation techniques to become widely adopted, however, they must be demonstrated to the exploration community in a format which facilitates the transfer of this technology to the end user. This is a format which:

- produces robust methodologies that can perform consistently on the similar data types and exploration environments,
- presents end-products that meet the clients real needs (not perceived needs), which can be interpreted with existing skills, and are well documented to provide confidence in the results,
- is reproducible on acceptable, feasible, and available levels of technology or offered affordably by consulting services.

Within the last 6 years the author has witnessed geologic remote sensing research adopt an aggressive technology transfer approach. This change in emphasis from "...technology-led opportunistic studies to need-fulfilling tasks..." (GRSG 1993) has been driven by the new economic climate and management practices, and dwindling mineral reserves (Bruce & Davidson 1991). Remote sensing researchers now find themselves demonstrating their work to a resource community which cannot afford to acquire the knowledge, develop the skills, and exercise the judgement necessary to minimize the risks inherent in the introduction of remote sensing technology (Bruce & Davidson 1991). The set of assumptions and ground rules under which the scientific community and industry have been operating is changing (Bruce 1993, Dobyns & Crawford-Mason 1991, Frohman & Johnson 1993). New structures and models are required for the way in which research is organized, are undertaken, and the results implemented. This thesis reports

the successful development of an application, demonstration of that application in the context of the client, and implementation of the methodology by the client on an operational scale. The strong link between this research and a commercial exploration program has been fundamental to maintaining an operational perspective and will lend credibility with industry to this remote sensing application that was developed in a institutional setting.

1.2 Thesis Objectives

It is the intention of this thesis to clearly investigate and demonstrate: a) the application of satellite remote sensing for input to an operational mineral exploration program in a semi-arid environment, and b) the project planning model that provided a systematic approach to guide the applications' development for transfer to an operational setting. The underlying premises of this research are that the present socio-economic, technological and environmental conditions are such that the potential of remote sensing is both desired and needed by the mining industry, and that for applications-orientated research to be successfully transferred to these users it must be undertaken using an applications-orientated model.

1.3 Outline of Thesis

In this demonstration of remote sensing for operational mineral exploration in a semi-arid environment, some knowledge of the current understanding of how mineral deposits are formed is necessary. This geological background, and a description of the exploration

targets of the Troodos Massif are outlined in Chapter 2. The remote sensing theory which is exploited to assist in the mapping of the exploration targets is described in Chapter 3. It is presented from basic background theory, through a progression of past research to the current state of operations-oriented remote sensing research. The technology transfer model through which this theory was developed into an application methodology is described in Chapter 4. Chapter 5 is a detailed discussion of the methodology developed for mineral exploration in the Troodos Massif. Chapter 6 is a discussion of the results, and conclusions and recommendations are drawn. The references cited in this paper are given in full in Chapter 7, the bibliography. In the appendices copies of selected correspondence between the industrial partner (GeoQuest International) and the author are found as well as example imagery of the Troodos Massif. As single images are referred to in several different sections within this thesis, all imagery has been placed in the appendices for the reader's convenience.

2.0 BACKGROUND GEOLOGY

2.1 Introduction

Remote sensing can be used to provide ancillary information in an effort to decipher regional geology by showing structures, lithology, and geobotanical anomalies. This is towards the eventual goal of targeting areas of likely mineral deposition for additional site-specific interpretation and field investigation. Understanding the genetic history of the regional geology and mineralization is of great importance, both in the selection of exploration targets and in characterising the surficial expression of these targets which may be recognisable by remote sensing. This demands an understanding of the

relationships between rocks, surficial materials, the vegetation they support and their spectral characteristics.

2.2 Mineral Deposits in General

Prospects are mineral occurrences which are sufficiently large and rich enough to have some potential of being, but are not yet proven to be, ore deposits. Lang (1969) defines **ore deposits** as those that can be mined under present conditions, and **mineral deposits** to be a more general term than ore deposits and to include prospects and ore deposits. It is the great value of mineral commodities which creates the conditions where large resources are allocated for exploration well in advance of possible returns, making possible the operational use of a tool like remote sensing.

The most fundamental division of commodities is into metals, nonmetallics, mineral fuels, and structural materials. Metals other than noble metals¹ are called 'base' metals. Because of the importance of iron ores, base metals other than iron, such as lead, copper and zinc, are commonly grouped as 'non-ferrous' metals (Lang 1969).

Mineral deposits have been formed in many ways and at greatly different depths beneath the surface. Genetic history is of great practical importance in the selection of exploration targets, the appraisal of prospects and mines, and in searching for additional ore at

¹Gold, silver, mercury and platinum group metals are called 'noble metals' because they do not oxidize when heated in air or water.

existing mines. Mineral deposits are formed by natural processes selectively concentrating one or more rare earth elements into abundances above background levels that can be commercially extracted. The theory of mineralization and deposit formation is beyond the scope of this study. It suffices, however, to understand that metallic minerals are contained in host rocks, and so ore deposits are formed by the same chemical and mechanical processes as rocks (Table 2.1).

Table 2.1 Origins of mineral deposits (Gilluly et al. 1954)

MANNER OF FORMATION

Magmatic segregation	By settling of early-formed minerals to the floor of a magma chamber during consolidation; by settling of late-crystallizing but dense metalliferous parts of the magma, there to crystallize in the interstices of older silicate minerals; or to be later injected along faults and fissures of the wall rocks. By direct magmatic crystallization.
Contact-metamorphic	By replacement of the wall rocks of an intrusive by minerals whose components were derived from the magma.
Hydrothermal	By in-filling fissures and replacing both wall rocks and the consolidated outer part of a pluton by minerals whose components were derived from a cooling magma. These differ from contact-metamorphic deposits in having fewer silicate minerals and by more obvious fissure control.
Sedimentary deposition	Sedimentary deposits under conditions which lead to beds of relatively pure minerals; or rocks unusually rich in particular elements; or rocks in which the detrital grains of valuable minerals are concentrated because of superior hardness or density.
Residual deposits	By weathering, which causes leaching out of valueless minerals, thereby concentrating valuable materials originally of too low grade into workable deposits.

2.3 Geologic Setting of the Troodos Massif, Cyprus

The Troodos Massif mountain range comprises the Troodos Ophiolite¹ Complex of Cretaceous age and is flanked by overlying sedimentary rocks of Cretaceous and Tertiary age (the PL unit of Fig. 2.1 defines the outer boundary of the Complex).

Figure 2.1 Exploration target lithologies of the Troodos Massif, 1:500,000 scale. The specific area of exploration interest is indicated. Db=Diabase, Bg=Basal Group, and Pl=Pillow Lavas. (Adapted from Geological Survey Dept. map, Cyprus 1982)

¹Ophiolite: Basic igneous rock associated with geosynclinal sediments (American Geological Institute. Dictionary of Geological Terms. New York 1962)

The oldest stratigraphic units are exposed in the central part of an elongate dome, with younger units arranged radially outward. It is now widely accepted that the copper and pyrite orebodies of Cyprus were formed by a volcanic exhalative process occurring at or near a submarine rift (Boyle & Robertson n.d.). Jones (1990) notes that present day analogues used to demonstrate this process are the brine pools of the Red Sea and the "black smokers" of such places as the submarine Juan de Fuca Ridge in the Pacific Ocean. Under this process, the ore deposits of the Troodos Massif would have been created when metal-rich brines were concentrated in veins or in massive disseminated bodies (infilling of dense micro-fissures in fine grained rocks) precipitating minerals such as iron, manganese, copper, lead, cobalt, silver, and gold. In this type of deposit, formed from a spreading ocean-ridge system, structural fractures (of a certain trend) acted as conduits for hydrothermal fluids transporting metals in solution, which when vented at the ocean bottom and mixed with sea water may have formed metal-rich mounds, chimneys or sediments (Boyle & Robertson n.d., Jones 1990).

Many important minerals weather or undergo alteration to form characteristic secondary minerals. In the Troodos Massif, metallic deposits may be indicated by anomalous concentrations of iron oxides in overlying soils, or by clay, limonite and other hydrous minerals¹ produced by the alteration of rocks along the walls of metallic deposits (Jones 1990). Iron-oxides (hematite, jarosite, goethite, and limonite) result from the oxidation

¹Hydrous minerals are those that have water in the form of hydroxyl ion (OH⁻) bound in their mineral structure.

of iron-bearing minerals. Clays can result from the alteration of primary minerals by the action of hydrothermal solutions, or as a result of intense weathering (Buckman & Brady 1969). Generally, where iron-rich materials are being eroded and deposited goethite ($\text{FeO}(\text{OH})$) predominates, and in areas dominated by chemical weathering processes, hematite (Fe_2O_3) is in greater abundance (Fraser 1991). Fraser (1991) outlined a method in which the relative proportions of these two iron oxide species can be mapped using TM. GeoQuest's exploration model required only to delineate concentrations of generalized weathering products (iron oxides and clays) which may act as indicators of buried mineralization.

The rocks of the Ophiolite Complex (Fig. 2.1) can be divided into three groups, from oldest to youngest geologic age:

- 1) the plutonic complex of mainly basic and ultrabasic rocks which forms the core of the Troodos Mountains,
- 2) the sheeted Diabase dykes (Fig. 2.1, unit Db) and the Basal Group complex (Fig. 2.1 unit Bg), and
- 3) the volcanic complex consisting mainly of Lower and Upper Pillow Lavas (Fig. 2.1 unit PL).

Jones (1990) explained that historically the majority of copper deposits have been found in the pillow lavas and upper part of the Basal Group. The Basal Group is a transition zone between the sheeted dyke complex and the pillow lavas, consisting of mixed dykes and lavas. The Pillow Lavas overlie the Basal Group, the Upper Pillow Lavas being similar to the Lower, except that they have been altered by cold circulating sea-water (Boyle & Robertson n.d.). The target of the exploration program is the copper, zinc and

gold mineralization found near the Basal Unit - Upper Pillow Lava contact. The exploration model required a certain scale of information in the mapping of the geology. This performance standard necessitated the delineation at medium scales of this lithologic contact (Bg-Pl on Fig.2.1), and if possible, areas of Basal Unit with a thin cap of Pillow Lavas, and major structural features.

Remote sensing could play a fundamental role in the exploration effort by making it possible to map the within-unit variations, the contacts between the target rock types, and linears cutting these boundaries. The requirements of the exploration model and the ability of image analysis to differentiate the lithologies of the Troodos Massif, naturally simplified the geology into two main categories;

- 1) the volcanic "feeder" material: Diabase and Basal Group, and
- 2) the volcanic "extrusive" material: the Upper and Lower Pillow Lavas.

Jones (1990) reported that from both chemical analysis and physical features the components of each group are too similar to have sufficiently unique surface expressions to allow finer spectral differentiation. These two targets will be referred to as Basal Unit and Pillow Lavas Unit respectively.

3.0 BACKGROUND SATELLITE REMOTE SENSING

3.1 Introduction

An understanding of some remote sensing theory, the operational realities of the geologic exploration community, and the progression of past research was required for the

successful use of remote sensing in the context of this thesis. It was not sufficient just to understand remote sensing tools; knowledge of the context in which they would be employed was necessary to successfully design and demonstrate this operational application. To make the leap from what is captured in the digital number of a pixel to what is observed on the ground and in the substrate requires consideration of the local environment, the spectral response of the surficial materials, and the characteristics of the sensor. To exploit remote sensing successfully in an operational setting requires the user to go beyond a knowledge of the mechanics of the tool to comprehension of the realities of using this technology in practice.

Satellite-borne remote sensing technology is now more than 30 years old, but it has only been relatively recently that sensors, computers, and software have matured to the point to allow the possibility of widespread operational application of remote sensing. Paralleling this technologic development is a restructuring of budgets, environmental priorities and resource requirements that is formulating, and in some ways forcing, changes in the way research is conducted.

Geologists have the abilities necessary to use remote sensing, and they have the capital and need for remote sensing to be available as an operational tool. Previous research in this area has demonstrated that several TM image products have the potential to provide the geologic information required by exploration programs in a variety of environments (Bruce & Hornsby 1989, Chavez 1984, Crosta & McM. Moore 1989a&b, Colwell 1983,

Davis et al. 1987, Drury 1989 & 1990, Drury & Berhe 1991, GRSG 1993, Lees et al. 1985, Kaufmann 1987). The successful integration of remote sensing technology, computers, and applications research, however, requires technology transfer models. Modern project management practices that have evolved out of the new paradigm dictate that technology transfer and applications research are indivisibly linked. The needs/risk model used in this thesis represents a systematic and critical approach to follow during the decision to adopt remote sensing technology, guide research and utilize it in practice. By adopting an appropriate technology transfer model risk is minimized, ensuring the best chances for success.

3.2.0 Remote Sensing Applied to Mineral Exploration in Semi-Arid Environments

Currently the most two widely used satellites for resource applications are the French SPOT (Système Probatoire de l'Observation de la Terre) and NASA's LANDSAT 5 Thematic Mapper (TM). While both deliver a widely useable product for resource applications, TM is the more widely used for geological applications (Bruce pers comm. 1993, GRSG 1993). This is due in large degree to the strategic placement of TM spectral bands (Table 3.1), TM being available first and having a large body of research literature behind it¹, and the cost of TM imagery.

¹Of the greater than 7,000 articles in the RESORS collection on geologic remote sensing, more than 3,000 use Landsat imagery for their investigation while 364 utilize SPOT. (Resors 1993).

Table 3.1. Visible and infrared wavebands (in microns) detected by MSS, TM and SPOT orbital platforms. Resolution (in meters) is given in square brackets.

Landsat MSS	Landsat TM	SPOT
[79]	[30]	[20]
4. 0.5-0.6	1. 0.45-0.52	1. 0.5-0.59
5. 0.6-0.7	2. 0.52-0.60	2. 0.61-0.68
6. 0.7-0.8	3. 0.63-0.69	3. 0.79-0.89
7. 0.8-1.1	4. 0.76-0.90	4. 0.51-0.73[10m]
	5. 1.55-1.75	
	6. 10.4-12.5[120m]	
	7. 2.08-2.35	

Landsat 6 is the latest in the series (to be launched in 1993), extending the availability of TM data which has been gathered continuously since 1984 (Eosat Corp. 1993). The sun-synchronous orbit of this series of Earth Observation Satellites (EOS) was chosen to provide 16 day repeat coverage of all points along the satellite's ground track with local imaging time around 9:30 am (Sabins 1986, USGS 1984). The ground coverage or size of an individual full scene is 185 km². A global network of receiving stations allows acquisition over most of the Earth, with coverage of specific locations generally available for several dates.

It is also possible to acquire imagery from sources other than SPOT and TM, but characteristics of these data make them difficult to use operationally. Declassified spy satellite imagery is now marketed by Sojuzkarta¹, the Russian mapping agency. These

¹45, Volgogradsky Prospekt, Moscow, 109125, Russia. phone: (011-7-095) 177-40-50.

data are only available in hardcopy format as the low orbit-satellites (KFA-1000 & MK-6) drop film canisters (Central Trading Systems 1993). The photo-images can have 5 meter resolution and are available in pan-chromatic and colour infra-red format. While the resolution is attractive, Soviet data will never be widely used as long as it is only available in analogue format, thereby precluding image analysis, and supply cannot be assured. Applications of current Japanese and Indian satellites have not been widely reported as they have capabilities inferior to TM (Drury 1990). The satellites designed for global weather monitoring (eg. NOAA, AVHRR etc.) are of too coarse a spatial resolution to be used for geological applications.

There are also multi-spectral scanning devices and synthetic aperture radars (SAR) mounted on airborne platforms. Scanners (eg. MEIS¹ & ATM²) offer the advantage of selectable spectral (by filters and/or programming) and spatial (by aircraft altitude) resolutions. SAR imagery has great demonstrated potential as a structural mapping tool (Bogart 1986, Dixon 1986, Harris 1984). Data gathered by airborne SAR or multi-spectral scanners are both expensive to obtain and to use. The costs of chartering a specialized aircraft and handling the large volume of data returned are significant. While structured planning is a necessity of any research or application, the approach outlined in this thesis is most relevant to those operating on restricted budgets. Thus the use of airborne data was not considered in this thesis. SAR data captured from a satellite

¹CCRS designed multispectral scanner carried by a Convair 580 aircraft

²NASA's Airborne Thematic Mapper.

platform could be of great potential and comparable in cost to TM. None, however, are currently widely available¹.

3.2.1 Target Reflectance Spectra

The detectors which make up the sensor onboard a satellite record reflectance over a particular area or pixel. This represents the instantaneous field of view (IFOV)² or the spatial resolution of the sensor. The digital number (DN) of a pixel represents the relative average reflectance of the ground targets within its area. This area may contain rock (potentially weathered), bare soil, and vegetation. Usually, the intermingling of surface types is on a small enough scale that the spectral response in these pixels is relatively homogeneous across a rock unit. A neighbouring rock unit may have a different spectral response due to the combined effects of varying topography, weathering surfaces of this new rock type, bare soil derived from the underlying rock and differences in the vegetation community related to the chemistry and moisture content of its substratum (Berhe & Dothery 1986). Distinction between rock types is diminished if weathering of exposed surfaces is uniform on different surfaces, if the soil and alluvium cover are not locally derived, or if the vegetation is not related to the substratum (Berhe & Dothery 1986).

¹Limited coverage is currently available from the experimental European ERS-1. World-wide coverage should be available from the Canadian RADARSAT in 1995.

²IFOV only refers to the size of a pixel when it is distributed as original, raw data. All digital picture elements can be referred to as pixels. By connotation, when *pixel* is used in literature it may be assumed that its resolution has not been altered from the IFOV unless otherwise stated.

In the general case, for a particular rock outcrop to be visually distinguishable on satellite imagery requires an area of several contiguous pixels. So for TM, outcrop of an area measured in hectares is required for discrimination. It is possible for objects smaller than a single pixel to be recognisable if they have particularly high contrast with their background. Conversely, features of any size can be virtually indistinguishable if they have low contrast with their background (CCRS 1992). In many areas of the world, as in much of Canada, overburden and vegetation make it difficult to find sufficient outcrop to allow direct sensing of geology. In these cases, geologic information is obtained indirectly by observing surface materials and vegetation. This demands an understanding of the relationships of rocks, soils, and the plants that they support, and the small-scale textures in the landscape that weathering and erosion produce (Drury 1990).

3.2.2 Geologic Information from Ground Reflectance Spectra

Where outcrop is of sufficient area to be directly imaged by TM, it is important to note that the minerals that contribute most to the reflectance spectrum it records (visible to short wave infrared) are those that are produced by alteration, which dominates the weathered surfaces of outcrop and the composition of soils. The mineral composition of the weathering rind of outcrop is different from that which makes up the bulk of crystalline rocks¹ (Drury 1987). This is a result of the shallow penetration of the part of the spectrum that TM records to no more than a few micrometres into the surface rind of weathered rock materials (Drury 1987).

¹Main rock forming minerals are quartz, feldspar and iron, and magnesium-aluminum rich silicates.

For practical purposes of lithologic mapping, it must be accepted that remote sensing is best suited to mapping alteration products and vegetation, rather than bulk mineralogy and direct soil geochemistry. Changes in surface mineralogy, however, rarely dominate overall scene variability. Topographic effects, vegetation density differences and albedo changes are the most obvious features observed in most image data sets. By comparison, information content due solely to mineralogical variability can be on the scale of TM sensor noise (Fraser 1986). It should be noted, however, that even though the signal-to-noise (S/N) ratio of mineralogic information is low, background noise by definition is randomly distributed and sensor noise is structured and usually quite obvious as striping. As reflectance due to mineralogy forms patterns which can be interpreted as lithologic and structural information, meaningful results can still be derived in spite of poor S/N ratio.

Understanding of the local environment and of image analysis strategies is required to minimize the lack of direct mineralogic information and the confusing effects of albedo and mixed pixels¹. Specific information relating to a target may be recognised in the complex signal returned from ground features within the IFOV of the sensor if the remote sensing properties of targets are understood. Image analysis procedures can be used to isolate the desired target spectra from the overall signal and enhance and display this information.

¹Mixed pixels are those that contain more than one significant ground feature. The resulting pixel value is an average of these features and thus difficult to interpret.

Thus, specific mineralogic information is not immediately apparent in satellite imagery, but is included within information on topography, surficial materials and vegetation. The application methodologies used to extract the desired information are generally influenced by the local environment, which defines the weathering products, overburden and vegetation. Remote sensing strategies for semi-arid regions exploit the fact that the hot, dry conditions inhibit dense vegetation growth and produce a severe weathering environment for rocks and soils. The less than favourable conditions for vegetation growth and soil development results in comparatively large areas of outcrop which have a deep weathering profile.

3.2.3 Using TM to Identify Surface Mineralogy

TM imagery is a particularly appropriate source of lithologic and structural information of exposed and weathered terrains typically found in semi-arid environments. It can be used to assist the mapping of structure and the extent and boundaries of rock types, and to assist in the location of mineral deposits by identifying anomalous concentrations of the products of weathering and alteration: iron-oxides and/or hydroxylated iron-oxides and clay minerals.

The TM sensor has strategically placed image channels in the spectral range of the diagnostic absorption features of exploitable ground targets (Fig. 3.1). Known absorption characteristics of desired ground targets may be used to isolate and identify information

pertaining to those targets in the recorded multispectral reflectance data. The following features are of particular interest in this regard:

- 1) the minerals resulting from weathering and hydrothermal alteration: the ferrous ion (Fe^{2+}) in iron oxides and the hydroxyl ion (OH^-) bound in the structure or present in fluid inclusions of hydrated iron oxides and clays, and
- 2) the pigment chlorophyll found in the cell structure of leafy vegetation. (Drury 1987, Hunt & Salisbury 1970).

Figure 3.1 Diagrammatic spectra, illustrating positions of diagnostic iron, clay, carbonate and chlorophyll absorption bands. Also shown are the bandpasses of the Landsat MSS and TM sensors. (Kaufman 1987)

The determination of which TM bands to select and enhance for semi-arid environments can be based on an evaluation of band quality, correlation between bands, and the exploitation of known vegetation, iron and hydroxyl ion spectral absorption features. Band quality may vary as individual bands may contain sensor noise and striping, and

the visible bands are affected by atmospheric attenuation (inversely proportional to wavelength). Chavez (1984) reported that high correlation exists within the visible and near infra-red (N.IR) bands of TM. Diagnostic spectral features appear either as well defined troughs (absorption zones) or changes in slope of spectral response curves. They are produced as a result of either biochemical reactions (use of sunlight in reactions), electronic processes¹ (transitions in electron energy states) or vibrational processes (bending of atomic bonds), and are found:

- 1) near approximately 0.45 μm and 0.68 μm from the absorption of solar radiation by chlorophyll: covered by TM1 and TM3 (Fig. 3.1 & 3.2)
- 2) between approximately 0.4-0.55 μm , resulting from the charge transfer effects of the migration of electrons from iron to oxygen: covered by TM1 (Fig. 3.1 & 3.3),
- 3) between approximately 0.8-0.95 μm , from Fe^{2+} crystal field effects: covered by TM4, (Fig. 3.3), and
- 4) around 2.2 μm resulting from vibrational transitions associated with the OH^- ion: covered by TM7. (Fig. 3.4) (Drury 1987, Hunt & Salisbury 1970).

Figure 3.2 Diagrammatic spectra, showing diagnostic reflectance features. Note that whereas all four plants have similar properties in the visible spectrum, they are clearly distinguishable in the near infrared. (Drury 1987)

¹A detailed discussion of the atomic-level processes which cause the absorption of sunlight in minerals can be found in Hunt & Salisbury (1970).

Figure 3.3 Diagrammatic spectra of iron oxides and hydroxides displaying absorption features due to crystal field effects (T-shaped symbols). (Drury 1987)

Figure 3.4 Diagrammatic spectra of clay mineral and micas showing distinctive absorption features due to bending of Al-OH and Mg-OH bonds (T-shaped symbols) (Drury 1987)

As noted earlier, image pixels can represent a mixed reflectance signature composed of albedo, topography, plants, soil, and complex rock mineralogies. Therefore, understanding of spectral absorption features is necessary to isolate information attributable to a specific ground target. From the above general rules and observations by Hunt & Salisbury (1970), Drury (1989) and Loughlin (1991), several reasonable generalizations can be made:

- 1) TM5 is the best single band for differentiating between most rock types, as most minerals have a strong reflectance in this portion of the EM spectrum
- 2) in TM1 and TM4 pixels dominated by iron reflectance will be dark from Fe^{2+} absorption features, the digital numbers (DN) of TM1 being lower than TM4,
- 3) $\text{TM3 DN} > \text{TM1 DN}$ for all iron oxides,
- 4) $\text{TM5 DN} > \text{TM4 DN}$ for iron oxides, and these bands are less affected by atmospheric attenuation than the ratio TM3/TM1 , and
- 5) in TM 7 clay pixels will be dark from OH^- absorption features. Heavily weathered and hydrated iron-oxides (limonite $2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$) may also appear as dark pixels.

Image analysis routines, based on known spectral response features, may be employed to draw information out of the overall signal. For example, ratios such as TM 4/3 highlight spectral absorption peak/trough differences. The indicators of potentially important mineralization, the products of weathering and alteration, can be emphasized by the recognition of their spectral contribution to the overall scene, and enhancement of those spectral features to increase their contrast. There are limitations, however, as the current TM sensor does not have sufficient spectral resolution to differentiate between all of the mineral species that form these absorption features. TM band 7 cannot identify

individual phyllosilicate species, but detects the presence of clay in general (Podysoki & Segal 1983), and TM bands 1 and 4 show absorption features of all iron oxides combined (mainly hematite, jarosite and goethite) (Fraser 1986). While it would be advantageous to differentiate between mineral species, this does not preclude the use of TM, and the general lack of vegetation in semi-arid regions provides relatively straightforward conditions for exploiting these light-target interactions.

3.2.4 False Colour Composites

The application of remote sensing data and enhancement techniques to a semi-arid environment depends upon assessment of the interactions between the illuminating energy, the target, and the sensor which records it. Given that individual sensor channels (bands) record a different portion of the reflected EM spectrum of a target, each band may provide unique information about the composition of a scene. Three individual spectral bands can be combined in a RGB colour space to produce a false colour composite (FCC). This allows an interpreter to view three different sets of information over each pixel simultaneously and constructively¹. In this way remote sensing data can be presented in a powerful and familiar format for interpretation that may yield valuable geologic information.

¹The sum being greater than the parts. For an individual TM band, each pixel can have 256 possible grey levels. In a FCC each pixel can have one of 256^3 possible colours.

Creating an image out of three satellite bands is a simple matter with image analysis software. Individual bands are loaded into the red, green, and blue colour-guns of a video monitor, creating a false colour composite. The colour of a pixel is determined by the relative addition of the three brightness values. These values define a RGB colour-space. The brightness of the pixel is directly related to the radiance of the ground target. Raw TM data are generally of low contrast and relatively dim.

The TM sensor was designed to record spectral signals from surfaces illuminated by different sun angles and ranging from relatively non-reflective to highly reflective (forests, ice, oceans, deserts etc.) for a given portion of the electromagnetic spectrum. Enhancement is needed as the average scene brightness normally does span the full dynamic range of the sensor or the hardware used to display the recorded data. The standard 32-bit video monitor of image analysis systems can be used to display 8-bit TM data (256 grey levels) as three 8-bit video planes in red, green and blue. Look-up-tables (LUTs) are used to stretch the input band to make full use of the possible 256 grey levels of the display.

A linear stretch (Figure 3.5c) is the most simple type of contrast enhancement, as it maps the low end of the input band to a digital number (DN) of 0 and the high end to 256. The shape of the input histogram is maintained and over-all contrast improved.

Figure 3.5. Various contrast stretches. The top line represents input image values and the bottom line the transformed display values. (adapted from Lillesand and Kiefer 1987)

A break-point or custom stretch (Figure 3.5e), is a form of linear enhancement where sections of the input histogram are stretched to different degrees. An input histogram can

be studied to determine what areas represent different ground targets and stretched according to a user-defined weighting scheme. It is in effect a simple form of classification or density slicing (Sabins 1986). Desired areas are stretched proportionally greater and other areas subdued, producing an image where contrast and thus interpretability is maximized for the specific application. A histogram equalization enhancement (Figure 3.5d) assigns image pixel values to a new digital value (over a range of 256 levels) on the basis of their frequency of occurrence. This supposes that the area dominating the reflectance of the image is also the most important from an interpreter's perspective.

3.2.5 Geometric Correction

When image data is initially collected by satellite sensors it contains errors in geometry. These spatial errors are manifested as a distorted portrayal of the earth's surface and can arise from;

- earth curvature and rotation,
- the finite scan rate of some sensors,
- the wide field of view of some sensors,
- sensor imperfections,
- variations in satellite altitude, attitude and velocity, and
- panoramic effects related to imaging geometry (Richards 1993)

Some of the systematic errors are corrected at the ground receiving station. However, to use satellite data in conjunction with other spatial data sets it is necessary to correct the remaining geometric errors so any measurements or interpretations made on the images will accurately correspond with other mapped information. Geometric error could be removed by modelling the nature and magnitude of the sources of distortion, or by

the correction of imagery to an "accurate" map base. The second approach is the most commonly used as it is platform-independent and is based on establishing a mathematical relationship between image pixels and corresponding map coordinates (Richards 1993).

Considering the variabilities in the sources of geometric error it is hard to quantify the amount of distortion in imagery prior to physical correction. Images can be purchased from vendors map registered (precision geocoded) or, using image analysis software the user can correct the imagery to their own map base. The spatial accuracy of the correction can will be determined by the order of the polynomial equation, the accuracy of the map base, the location and number of points chosen by the operator to define the image-map relationship, and the method of resampling the original distorted image to the rectified state (Sabins 1986).

3.3.0 History of Remote Sensing for Mineral Exploration in Semi-Arid Environments

Many Earth Observation Satellites (EOS) have been launched since the 1960s. The majority of these missions placed into orbit low-resolution geostationary satellites providing information for gross atmospheric and oceanographic monitoring¹ (Colwell 1983). The Earth Resources Technology Satellite (ERTS) Program, later renamed LANDSAT, was established in 1972 by the National Aeronautics and Space Administration (NASA) as a research and development tool to demonstrate that remote

¹Known as "mesats".

sensing from space is a feasible and practical approach to efficient management of the Earth's resources (Thomas 1987).

The decade witnessed the successful launching of Landsats 1, 2 and 3, all providing synoptic terrestrial monitoring with their primary onboard sensor, the MultiSpectral Scanner (MSS). In 1984, the first satellite of the second generation series (Landsat 4) was placed into orbit. Due to be upgraded in 1996, this series differs from the earlier craft by improved positional stability and a superior sensor, the Thematic Mapper (TM)¹ (table 2) (Colwell 1984, USGS 1984).

Prior to the advent of commercially available orbital imagery, synoptic views of the earth for geological applications were supplied by aerial photography. The introduction of EOS imagery was given a rough reception as it was competing with, and being compared to a successful, established tool. The MSS was designed specifically for global vegetation monitoring, but also collected information on rock and soil, allowing a limited regional lithologic and structural mapping capability (Drury 1990). The second generation TM sensor was a great improvement over MSS both spatially, with its 25 meter instantaneous field of view (IFOV), and spectrally, as short wave infrared bands (SWIR) designed specifically to collect geologic information were included.

¹An MSS was included to provide continuing temporal coverage in this sensor format.

Geologic applications research largely began and has continued to be dominated by application of TM to semi-arid environments. It has only been of late that this research has begun to define and address the requirements in transferring the methodologies developed into operational use. Driven by the new economic climate, dwindling mineral reserves, and new management practices, scientists are having to demonstrate their work to an audience which can no longer afford to acquire the knowledge, develop the skills and exercise the judgement necessary to minimize the risks inherent in the introduction of remote sensing technology and practices into the workplace.

3.3.1 The Acceptance of Remote Sensing in Practice

Bruce (pers. comm. 1989) stated that initially, the geology community was disappointed with remote sensing as MSS generated products did not match expectations. The relatively inexpensive synoptic coverage and new information captured by the sensor's broad spectral channels were considered a real boon for regional scale geologic mapping. The potential benefits, however, were often frustrated by the dramatic loss in spatial resolution and geometric fidelity evident when the primitive output from image analysis systems on line-printers was compared with the fine grain of the familiar aerial photograph. Perceptual barriers against giving up an effective imaging tool (aerial photography) for adopting a new one of lower resolution (MSS), coupled with over-zealous promotion, largely contributed to the fate of MSS in many minds (Bruce, pers. comm. 1989). It must also be remembered that at this time (late-1970s) computing technology was by today's standards in its infancy, and image processing software and

hardware were not widely available or feasible to implement and viewed by many with a techno-phobia. User-friendliness of technology is a relatively recent design philosophy. Even today there exists image analysis software on the market which is, in the author's opinion, user-hostile.

The perceived costs of using satellite imagery in many users' minds were high, and this was exacerbated by a research community that during this time period was not overly concerned with the demonstration of the "real costs". The actual cost of the data did not reflect the true cost of acquisition and remote sensing was a relatively inexpensive means of data collection considering the coverage it afforded, and the true costs/risks of its operational application were difficult to assess as remote sensing was rarely demonstrated from a "real-world" perspective. One consequence of these perceptions was limited operational use of satellite remote sensing in the resource sector.

Based on 20 years of personal experience in remote sensing in Canada, Bruce (pers. comm. 1992) noted that in spite of initial disappointment with MSS data, the *concept* of satellite remote sensing was more enthusiastically, if quietly, received early in its development by the geologic community than most other applications. With a reputation for being conservative, it might be at first surprising that geologists wanted this new tool, albeit with reservation.

3.3.2 The Special Case for Mineral Exploration

It was the traditionally high costs and risks of mineral exploration that provided the capital and encouraged consideration of remote sensing as a new prospecting tool. The barriers to technology transfer were reduced by the similar format of satellite remote sensing to established spatially continuous data gathering techniques (aerial photography, geophysics, and geochemistry).

Geologists have been refining their manual image interpretation skills since the proliferation of aerial photography after the Second World War (Parks Canada n.d.). They are also accustomed to employing spatially continuous data sets with limited point accuracy (e.g. geology maps, geophysical data)¹. Satellite remote sensing was not automatically accepted, but this pre-disposition towards interpretation of spatial observations of limited point accuracy facilitated the adoption of this new technology. However, the state of the art at the time did not meet perceptions of what was needed (Bruce pers comm. 1993). Over time advancements in technology and changes in business climate have all supported broad acceptance of remote sensing into operational practice. The main information goals for remote sensing have always been to provide ancillary information to the effort of deciphering regional geology by facilitating recognition and interpretation of structures, lithology, and geobotanical anomalies (Lees

¹The author has participated in 7 geological field expeditions with the Geological Survey of Canada, CCRS, and private companies.

1985). This information contributes to the process of targeting areas for additional site-specific airphoto interpretation and field investigation (Lees 1985).

3.3.3 Use of MSS, TM and SPOT

By the time that MSS had been technologically surpassed (Landsat TM: 1984), its geological application was limited to large-scale structural mapping (Bruce, pers. comm. 1992, Drury 1989). When it was used successfully, the results were often dramatic, as in satellite imagery's contribution to the modern theory of plate tectonics (Everett et al. 1986). It was the advent of the second generation, higher resolution, "whiskbroom"¹ instrument onboard the American Landsat series 4-6² and the "push-broom"³ scanner carried by SPOT presented the first widely useable product (from a operational perspective).

Apart from offering resolution and geometric fidelity fine enough to meet perceived operational needs, image analysis theory and hard/software design had matured to the point of delivering a relatively feasible, acceptable and available product. Computers of sufficient power to be image analysis platforms (PC-386s to workstations) can be relatively inexpensive and a range of commercially produced image analysis software

¹Uses a rotating mirror to move the field of view of the single detector along the ground track. (USGS 1984)

²The Landsat satellites 4,5,& 6 are collectively referred to as "TM" after the primary on-board sensor, the Thematic Mapper.

³Employs a detector array to image an entire ground track at one time.

exists for all levels users (eg. PC-VGA, Dragon, EarthView, EASI/PACE, and ER-MAPPER). That remote sensing technology has reached a stage where imagery could be thought of as another tool available to operational regional to medium scale¹ geological mapping is reflected by recent comments of the Geological Remote Sensing Group. Representing hundreds of geologists world-wide, this users' group has noted the shift over the last few years towards operational applications in papers presented at ERIM Thematic Conference on Geologic Remote Sensing (1993).

3.4.0 Previous Research

From the beginning of the availability of Landsat data researchers have thoroughly investigated remote sensing of semi-arid environments for geologic information. This is of no surprise as:

- the absence of thick ground cover gives direct sensing of the target (lithology), and importantly several bands on the most widely used satellite-borne sensor (TM) are ideally suited to imaging exposed rocks,
- the obscuring ground cover found in more temperate climates was viewed by many researchers as an insurmountable hurdle (geobotanical relationships have only recently been applied from a remote sensing perspective), and
- many important and well understood mineral deposits are found in the semi-arid environments of the countries that have traditionally supported remote sensing research (USA & Australia) (Bruce pers. comm. 1992).

The author, from 6 years experience in remote sensing research, has found great frustrations in learning this technology when much of the relevant research is well

¹From project experience the author has found that, depending on the contrast variability within a scene, the maximum scale that TM data may be reliably interpreted is approx. 1:20,000 and generally will always be interpretable at scales of 1:50,000 or smaller.

documented, but few sources¹ are explained the underlying theory in a consistent manner and clearly demonstrated how it can be easily reproduced and applied to sites in similar environments. The difficulties experienced in adapting techniques found in the remote sensing literature to operational applications was one of the main motivations for undertaking this thesis.

Convincing demonstrations are of prime importance as the transfer of new technology to resource management problems requires in-depth understanding of the tools being applied. Practical knowledge demonstrated in this fashion builds confidence in a new technology allowing users to assess and meet the risks inherent in application to their own dynamic individual situations. For resource professionals to use remote sensing confidently requires well documented demonstrations of this technology, based on operational project planning models.

3.4.1 Simple False Colour Composites

The creation of simple false colour composites (SFCC) is a standard process in the enhancement of TM imagery for geological applications. The combination of three image bands to produce a false colour image is a powerful technique to display different sources of information coherently. It is not possible to make the best product for interpretation without considering colour psychology.

¹Crosta 1989a & 1991, Drury 1987, Fraser 1986 & 1991, Loughlin 1991, and PCI 1992 are notable exceptions.

Day vision of the human eye has evolved to have its highest sensitivity to the portion of the electromagnetic spectrum corresponding to green light. Aesthetics, however, play a large role in how humans perceive colour and the most subjectively pleasing image is always the most easily interpreted (Drury 1990). Our ability to discriminate difference in colour decreases from blues, through reds to greens (Drury 1990). Therefore, the allocation of image bands to display colour (RGB) should be influenced by the fact that the human visual system is most responsive to change in blue, and less in red and green (Crosta & McM.Moore 1989a). The choice of bands to combine in a composite is based on the advantages of displaying the maximum amount of spectral information (least correlated bands) and a knowledge of exploitable target spectral characteristics.

Six bands of the TM sensor sample reflected energy in three distinct portions of the EM spectrum, visible (1-3), near-IR (4) and short wave IR (5,7) TM band 6 is in the thermal infra-red (emitted) region of the spectrum. TM bands were numbered sequentially with increasing wavelength, except for TM band 7 which was added on at a late stage (Colwell 1983). By far the largest effect on reflectance spectra is the albedo of different surfaces -the ability of a surface to reflect energy across a large range of wavelengths (Drury 1990). As a result, the spectral reflectance of most objects is highly correlated within the regions sampled by TM. For example, over a given area with both light and dark soils, the reflected energy recorded by the different TM bands is usually all higher for a light soil than for a dark one (Drury 1990). Chavez (1984), Davis et al. (1987) and others have reported that for TM data, a three band combination including one of TM

1, 2, or 3 and one of TM 5 or 7 with TM 4, was the combination with the least possible correlation out of all possible combinations of 6 TM bands. Reported use of TM 6 in literature is marginal, and has generally been avoided by researchers because of its poor spatial resolution of 120m.

Starting with this general rule, specific bands were selected which exploit the spectral absorption characteristics of the dominate ground features of the Troodos Massif: vegetation, iron oxides and clays in the scene. From the literature, these SFCC combinations of TM bands are recommended (displayed as red, green and blue respectively):

- 4,5,7 (Davis et al. 1987)
- 3,4,5 (or 7) (Chavez 1984, Bruce & Hornsby 1989)
- 1,3,5 (Crosta & McM. Moore 1989, and Drury & Berhe 1991)
- 7,4,1 (Lees et al. 1985, and Kaufmann 1987)

3.4.2 Complex False Colour Composites

For the purposes of this thesis a complex false colour composite (CFCC) is defined as an image which has been mathematically manipulated beyond contrast enhancement with simple look-up-tables (LUT). A LUT stores the new intensity values of pixels generated by some form of contrast stretch. The final image results from the input values being mapped to new intensities based on the value held in the LUT. Jones (1986) noted that while large and diverse geomorphological features could be seen in SFCCs, the best

results were achieved with CFCCs. Jones did not judge any single technique for creating CFCCs suitable for all land covers or features. However, the best results were always realized when a specific relationship between spectral response and the physical properties of a target were understood and exploited. This point appears well accepted in the practice, as SFCCs are routinely made, but when scene characteristics allow, the most advantageous use of data is made through the creation of CFCCs. The CFCCs considered in this thesis are band ratios and principal component analysis (PCA). Some other CFCC methods are IHS transformation (Kaufmann 1987), Tasseled Cap Transformation (Richards 1993), Martin Taylor enhancement (PCI 1992), Canonical Analysis (Richards 1993), and Decorrelation stretch (Rothery 1992). These procedures were chosen over the many possible routines which can create CFCC as they have proven to be simple to make as standard on all image analysis software, reproducible for similar environments, and can show a wealth of geologic information in an easily interpreted image.

False colour composites produced by combining ratios of TM bands or principal components (PC) are a common and powerful technique for displaying mineralogic information in semi-arid areas. Drury & Berhe (1991), Fraser (1986 & 1988 & 1991), Vincent et al. (1984), and most remote sensing text books recommend procedures for manipulating TM band combinations which will highlight specific ground targets by exploiting their known spectral reflectance characteristics.

The combining of ratios of two bands to form a FCC has been the primary method of generating complex images. The process is well understood and proved itself for its ability to map iron oxides, vegetation and clays (Segal 1983, Sabins 1986, Crosta & McM.Moore 1989b, Drury 1989, Drury & Berhe 1991). Fraser (1988&1991) and Loughlin (1991) found shortcomings to the standard ratio as confusion could arise between the desired ground targets of, iron oxides and clays, with vegetation. PCA is a more complex procedure than band ratios which can be used to compress and correlate multispectral data. While very powerful, PC images are difficult to interpret as the complete restructuring of the data removes the simple link between digital value and the known spectral response of a ground target.

3.4.3 Band ratios

The ratio of two TM bands, and their combination with single bands or other ratios to form CFCCs, is a simple and powerful technique to:

- compress information from more than three bands into a FCC,
- minimize differences in radiance caused by topography, thus reducing the effect of shadows and the dominance of albedo in reflectance signatures, and
- emphasize differences in slope of spectral reflectance curves, thus accentuating reflectance variations (geologic information) and increasing scene contrast. (Sabins 1986)

CFCCs of band ratios have long been recognised as a very useful procedure for highlighting geologic information and many TM band combinations are suggested in the literature: 3/1 and 5/4 highlighting iron oxides, 4/3 producing a very strong response for

those pixels dominated by vegetation, and 5/7 delineating clays by exploiting the absorption features of water bound in their mineral structure (Segal 1983, Sabins 1986, Crosta & McM.Moore 1989a, and Drury 1987 & 1990).

3.4.4 Principal Component Analysis

Principal component analysis (PCA) is a powerful multivariate statistical technique for the decorrelation and compression of data and was originally proposed for use with psychological statistics (Cracknell & Hayes 1991). PCA preserves total variance and generates coefficients with minimum correlation (Singh & Harrison 1985). Also referred to in literature as the Karhunen-Loeve (K-L), Eigenvector and Hotelling transformation, this procedure has successfully been used for the enhancement of multispectral data (Ready & Wintz 1973, Canas & Barnett 1985, Singh & Harrison 1985). The products of the transform are uncorrelated image bands that have not lost any of their contextual information content due to the statistical manipulation; the original reflectance values, however, are changed.

The procedure can be explained for n input channels by imagining an n -dimensional Cartesian co-ordinate system. This hypothetical, multi-dimensional universe is also known as *feature space*. Each pixel from n -bands is a single point mapped out into this feature space. For example, pixel #1 from 3 TM bands would use the DN from each TM band (0-255) as a co-ordinate which could be mapped onto x,y and z axis (3-D universe). The result of transforming all of the pixels from the n -bands into this n -dimensional

space would be a cloud of complex shape and variable density (Canas & Barnett 1985). The shape of this cloud would have overlapping lobes that reflect the high between-band correlation of TM data. The PCA then identifies n new mutually perpendicular directions in feature space, whose axes are chosen to maximize variance of individual pixel points (Canas & Barnett 1985). In a geometric sense, it rotates the highly correlated features (lobes in the clouds of pixel points) in n -dimensions to an orientation in the feature space, each dimension orthogonal to the others, such that the maximum amount of variance is accounted for in decreasing magnitude along the ordered components (Singh & Harrison 1985).

In formal mathematical operations, PCA can be separated into these steps;

- 1) calculation of the variance-covariance matrix for the image data set.
- 2) computation of the eigenvalues and eigenvectors of the variance-covariance matrix. The eigenvectors define the PC directions and the eigenvalues measure the variance of the feature space distribution along these new PC axes.
- 3) implementation of the transform by forming a weighted sum of the raw images using the eigenvector components as the weighting factors.

The transform concentrates information common to all bands into the first PC, usually resulting from albedo. Other information contained in the input bands are collected in the following PCs in order of their contribution to overall scene variance. That is, the number of PCs created equals the number of original input bands, with both common and unique variance maintained. Lees (1989) describes common variance as the correlation between bands and unique variance is the difference between bands. Singh & Harrison (1985) explained the data reduction ability of PCA by stating that the process compressed

(common) information into a smaller number of components from a large number of features by discarding redundant information (unique) into higher-order components. Many researchers abandoned the higher-order PCs because of their poor signal to noise ratio and limited interpretation to the first few PCs.

Interpreting the results of PCA, however, was not straightforward, as the connection between individual PC image contrast and a spectral response phenomenon was lost as the original information content of the input bands had now been altered. It is possible to look for known ground features within the individual PCs. The complexity of the resultant images, however, makes visual interpretation very difficult and thus of limited value as a final product. For this reason Crosta (1989b) considered standard PCA to be of little use for geological applications. A process which could make the information concentrated into the different PCs recognisable would greatly improve the value of performing PCA.

3.4.4.1 Directed Principal Component Analysis

A new technique for generating CFCC is emerging, called Directed Principal Component Analysis (DPCA)¹. It was found that the principal component transform could be directed to isolate desired spectral information by selecting input bands for known spectral characteristics (Crosta & McM.Moore 1989b, Fraser 1991, Loughlin 1991).

¹Crosta & McM.Moore (1989b) referred to this process as Feature Orientated Principal Component Analysis.

Crosta and McM.Moore (1989b) reasoned that if known spectral features could be recognised in the statistical results of the different PCs, the direct links between ground features and brightness values in PC images could be made. The knowledge that is required to apply this process of interpreting PCs includes a general understanding of PCA and the spectral characteristics of ground targets. Loughlin (1991) recommended the technique as it is "fast, robust, and reliable, requires no atmospheric or radiometric correction and can be carried out with standard PCA software". DPCA was adopted for this study as Crosta & McM.Moore's (1989b) and Loughlin's (1991) work demonstrated that it was effective in different semi-arid settings around the globe (western U.S., southern Spain, the Middle East, and South America), and could be carried out using standard image analysis software. DPCA is a major improvement over standard PCA as the tones in the resultant DPCA images are directly interpretable.

Fraser (1986) stated that a fundamental problem in the analysis of multispectral data for mineralogical mapping is that changes in mineralogy rarely dominate the overall scene variability. Topographic effects, vegetation density differences and albedo changes are sources of common variance and are the most obvious features observed in remote sensing data sets. Through DPCA these dominant effects can be stripped away to leave, as residuals, the comparatively weak signal resulting from mineralogical variability. Thus, through an understanding and exploitation of reflectance spectra, DPCA can be used to eliminate the two most serious sources of non-mineralogical variability in data. These are the high between-band correlation, induced by topographic and albedo effects,

and the confusion resulting from mixed pixels (Fraser 1986). The higher-order PCs, where Fraser (1986), Crosta & McM. Moore (1989b), and Loughlin (1991) maintain that mineralogic information resides, have been generally ignored (Townshend 1984, Lees et al 1985, Kaufmann 1987, Jones 1985) because of poor signal to noise ratio.

This thesis adopts the USGS' definition of noise as "any unwanted disturbance affecting a measurement (as of a frequency band), especially that which degrades the information-bearing quality of the data..." (USGS 1984, p.9-8). This background noise may be caused in TM data by the operation of the sensor (power supply, receiver, rotating mirrors etc.) (USGS 1984). In the feature space defined by the transform, noise is assumed to be uncorrelated, has a zero mean, and formed by identically distributed random variables (Ready & Wintz, 1973). Remembering that the transform places the new zero coordinates (O_x , O_y , $O_z...O_n$) in the centre of the data cloud, randomly distributed noise would in the ideal case form a low density spheroid around the centre point. Information would form dense shapes. Lees et al. (1989) proposed that noise is a component of the unique variance as noise vectors in TM data show a random distribution, so they are not variables which contribute to common variance. Ready & Wintz (1973), however, explain the S/N ratio of the higher-order PCs by maintaining that noise, which is evenly distributed (uncorrelated) in the multi-dimensional space, is not considered by the principal component transform. Therefore, noise should be more or less equally distributed in all of the PCs, except that as the new PC co-ordinate axes are mapped, the ratio of information to noise will get progressively smaller.

It is common when performing PCA that the last three PCs contain less than 5% of the total variance. Singh & Harrison (1985) explained the data reduction ability of PCA by stating that the process compressed information into a smaller number of components from a large number of features by discarding redundant information into higher-order components. Many had abandoned the higher-order PCs because of this, but when considered, it can be reasoned that the small contribution from mineralogy to overall reflectance is unique variance. Mineralogic information may be recognisable because it has a spatial component and random noise does not. It is possible that noise due to the sensor (non-random) itself could have a regular pattern and would therefore be considered unique variance (eg. striping). Townshend's (1984) results confirm this when he found that even though PCA data have an overall three-dimensional structure, discriminatory power could be found in the higher-order components, and in particular PC7 (from 7 TM bands) which showed several important ground features but contained less than 1/1000 of the total variance. The higher-order PCs can only be visually interpreted using the contextual and spatial information that comes from a solid understanding of the geology, terrain and environment of an area.

3.4.5 Structural/Lineament Enhancement

Relationships between regional tectonic, local structural features, and certain types of mineral deposits have long been recognised (Lang 1969, Moore & Waltz 1983). Tectonic features of regions and areas may influence the selection of sites for advanced prospecting, while local structural features and structural anomalies may indicate specific

sites for prospecting and help in evaluation and testing of anomalies and mineral discoveries (Lang 1969).

It has been shown in many previous studies (Bogart 1986, Colwell 1983, Moore & Waltz 1983, Dixon 1986, Bruce et al. 1990) that understanding of geologic structure for mineral exploration can be advanced by the regional and local mapping of lineaments on MSS, TM, and SAR imagery. Rock fractures are commonly indicated by lineaments on remotely sensed imagery (Moore & Waltz 1983). The ASPRS Manual For Remote Sensing defines a *lineament* as "a mappable, single or composite linear feature of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differs distinctly from the patterns of adjacent features and presumably reflects a subsurface phenomenon" (Colwell 1983). Cultural features are excluded. Lineaments on the land surface are formed by a variety of landscape elements, including topographic, drainage, vegetation, and soil tonal alignments (Moore & Waltz 1983).

Drury (1987) has suggested that for structural studies black and white images are more effective than colour as the human eye is most responsive to features of higher spatial frequency in monochrome, and topographic expressions of geological structures have relatively high spatial frequencies. Faults, folds, etc. are often marked by vegetation, stream channels or topographic changes (slope and aspect) that have relatively high reflectances or are conspicuous features in pattern recognition. The best single product which aided delineation of structures in this study proved to be a combination of a

filtered and enhanced TM band 5. For most environments, TM band 5 is considered to be the best single band for such geologic information (Crosta & McM. Moore 1989, Drury 1997). On imagery, most linears are formed of discontinuous line segments which are merged together by the human eye. Delineating linears is a highly subjective process in which the interpreter examines an image for closely spaced linear segments that appear to be aligned (Moore & Waltz 1983). A process was adapted from Moore & Waltz (1983) to produce an enhancement which highlights both structure and lithology, and leaves the subjective analysis to the interpreter. In this way, confidence in the results are maintained as the interpreting geologist is presented with a product that enhances the pertinent information, allowing subjective decisions to be made as to what constitutes a linear.

3.4.5.1 Image Filtering

Image filtering is a geometric (spatial) enhancement that alters pixel values on the basis of the grey level values (DNs) of their surrounding neighbours. An image can be considered in terms of its spatial variations (frequency) of pixel DNs (Richards 1993). High frequency information would describe rapid brightness changes from one pixel to the next, as may be found with lithologic contacts, roads, field boundaries etc. Low frequencies describe the gradual change in brightness over large numbers of pixels associated with ground features such as water bodies, bare soil and agricultural crops.

Filters can be designed to act on the portion of the image frequencies considered to be important. The basis for most filters is a matrix of weighting factors which defines a mathematical relationship between a pixel and its surrounding neighbours. A filtered image is generated by moving the matrix over the image row by row and column by column (Richards 1993). The mathematical relationship defines a new DN for the pixel currently at the centre of the matrix. A high-pass or edge-detection filter emphasizes abrupt changes in DNs between pixels. It is possible, by the choice of the weighting values which define the matrix, to preferentially enhance "edges" of specific directions. These are referred to as directional or programmable filters and are commonly used to enhance structural features of a desired trend (Drury 1987, Moore & Waltz 1983). This type of filtering was explored in this research for the delineation of directional lineaments associated with mineralization.

4.0 NEEDS/RISKS OPERATIONAL PROJECT MODEL

4.1. Introduction

This thesis describes and demonstrates a remote sensing application from an *operational* perspective. The underlying presumption is that in order to present a convincing demonstration to be readily transferred to a user community, the methodology used must be developed from the perspective of the identified recipient. This perspective was maintained throughout the applications development in Cyprus by following a operational project model which emphasised the selective and critical adoption of this

technology. By using project models the risks inherent in introducing remote sensing into an existing methodology (in industry) can be recognised and controlled.

A "needs/risk" project model (Bruce and Davidson 1992) was created for the Technology Transfer, Training and Development Section (TTTDS) of the Canada Centre for Remote Sensing (CCRS). All research projects undertaken by the TTTDS employ this model to focus and direct efforts towards technology transfer to an operational setting in the Canadian geomatics industry. It should be noted that many of the operational concerns of small to medium scale projects are similar and applicable to those in planning for application in the developing world. This model has resulted from the codification of project management experience, much in the same way as a "knowledge engineer" builds experience into an expert system.

The model and an operational application of remote sensing which adhered to this model are presented together. For the demonstration purposes of this thesis, the two are inseparable. The operational model is essential to understanding the structured approach to building applications specifically conceived to be transferred to industry. This structure is also now particularly timely and relevant given the revolutionary interest in the time-management/business-excellence titles rapidly appearing on bookshelves (see Section 4.1.1). There is a notable lack of management literature targeted specifically at non-manufacturing sectors, and this is particularly evident in relation to geomatics.

4.1.1.0 Organizational and Operational Models in General

Effective planning of operations-oriented research requires recognition that structure exists at every step in the life of a project and within the group that conducts the research and implements the results. The way in which organizational structure, project design, management-worker relationship, and the perspective of those employees towards their work are all in a state of change (Peters 1987). This is a natural response to the new global economy and state of the environment, and this evolution marks the formation of a new set of ground rules, or paradigm (Bruce 1993). Whereas in the past it could be argued that there was one dominant paradigm (see Section 4.1.2), the future will probably be made of a patch-work of guidelines. All disciplines are facing pressures to change and they are responding by defining new sets of ground rules "on-the-fly". A dominant paradigm may eventually form or a dynamic pattern of temporary rule-sets may prevail. Either way, success in the future will be achieved by those groups who recognize and react today to the circumstances dictated by the new paradigm (Robson 1991). There is a basic lack of literature on these topics specifically written for research environments and the resource sector of industry. Business is now leading the way and the models they develop to organize themselves and their work can be adapted to guide the transfer of technology and methodologies from researchers to clients in the resource sector.

4.1.1.1 Organizational Models

All companies and institutions exhibit structure and organization (Frohman & Johnson 1992). The most common conventional structure is the Command and Control (C&C)

model. This is a hierarchical form in which information flows vertically upwards and decision making occurs at the top. This supports a traditional style of "top-down" management, based on a business/economic/decision-making paradigm dating from the industrial revolution (Frohman & Johnson 1992).

The challenges facing decision makers today require inputs which cut across this rigid structure and front-line decision making by those people facing the problems regardless of their position in the pyramid. In response to the need for dynamic, flexible models, two new flat structures based on equality and team-work are currently popular. A Matrix organization is one that uses functional supervisors as well as project supervisors to manage the same people in response to specific assignments (Baker 1992). A Hybrid organization is similar in that people are grouped into teams, except that there is an overall hierarchical structure to these groups guiding information flow and decision making (Baker 1992). The Technology Transfer, Training and Development Section of the CCRS has modified the Matrix form to suit its own needs. The Section is formed by teams which reflect all of the facets of technology transfer in their context (training, research, and industrial/institutional liaison).

The paradigm, or set of rules, which has defined how business and research has been conducted, is currently undergoing change. Structures were formed around the reaction to a problem or need. A common maxim of this time was "if it isn't broken don't fix it". The organizations that were particularly successful were those that responded quickly.

As groups grew so did the C&C structure. This was a product of the relative luxury that existed in the economic and resource characteristics of the old paradigm. Information was distilled upwards through every level of an organization to be finally reacted upon by a select few with decision making authority. These conditions have been changing since the Second World War but the old set of ground rules has endured because of sheer momentum and natural resistance to change.

In the new paradigm, successful decision-makers will be those who solve problems through foresight, that is, anticipating future conditions, and, on the basis of this anticipation, identifying opportunities to avoid problems (Bruce 1993). Organizational structure must change to empower decision-makers. However, if these structures begin to change then it logically follows that there must also be a re-evaluation of the way projects are initiated, planned and implemented. As the new paradigm unfolds, those adhering to the old structures and following out-moded project design will not be able to compete successfully.

4.1.1.2 Operational Models

Monitoring and exploration in the resource sector and research activities are based on the execution of projects. Baker (1992) define a project as a unique venture with a beginning and an end, undertaken by people to meet established goals with defined constraints of time, resources and quality. There are common characteristics to all projects and these can form the basis for project planning models. These models recognize the new

paradigm and are designed to guide projects from this perspective. All projects go through phases of conceptualization, planning, implementation and termination (Baker 1992). The needs/risk model employed in this thesis incorporates all of these facets to guide applications research towards operational use under "real-world" conditions. The formulation of methodologies which are, by design, ready-to-use for a specific target audience are generally classified under the catch-all title of "technology transfer".

It would be naive to suggest that the current level of interest of the scientific community in technology transfer was driven solely by the desire of a new generation of scientists to formulate a paradigm to meet the challenges of conducting and applying research in this and future decades. It is probably closer to the truth to say that the rapid changes in the need to improve resource management and that generations of technology which are now measured in months not years, have forced many to redefine the focus, methodologies, and technologies employed in their research. In shaping the new methods required, solutions are sought which are *perceived* to be new.

It is, in fact, the *perspective* that is new, while the approach to methodology development and technology application that define technology transfer can be encapsulated in what is most often simply common sense. The technology transfer model used to guide this research was essential to its success, that success being defined as a holistic application of a methodology. For the given example in Cyprus, it is a considerable step beyond simply developing a process for the delineation of lithology which for reasons that can

lie beyond science (availability, feasibility, acceptability) may never be employed in practice. Perceptually, a process to facilitate the migration of this research into application might be better received if it could be presented as a "magic bullet": a flashy solution with a real sense of discovery and new learning. In reality, it may be somewhat of an over-generalization, but essentially accurate to state that success in technology transfer can be sought in solutions that are simple (not simplistic), inexpensive and robust.

While straightforward, to the point of being obvious, if these principles were widely adhered to the history of remote sensing applications and technology transfer would have been marketed with considerably more success. The power of the model employed in this thesis is that it codifies common sense. It presents a path for conscious, systematic decision making from a technology transfer perspective throughout the planning and execution of a remote sensing application. This critical approach to the adoption of technology can be considered a success if after a structured evaluation of the needs and risks of an application, a user/client can proceed with confidence.

We are presently in the transition phase between two paradigms. This evolutionary period is marked by instability and insecurity in how we organize ourselves and our tasks in response to our changing environment. Evidence lies in the ever increasing number of organizations that are adopting TQM and operational project planning models, and that technology transfer has become one of the catch-words of the 1990s. It will be a slow

process as it is difficult to define a new paradigm while existing in the middle of another.

4.1.2 Operational and Institutional Research

For many disciplines, the majority of the experience gained to date in the development and application of remote sensing has been under research and development conditions for archival, regulatory or administrative purposes of institutional users. While potentials offered by remote sensing for operational resource applications have been suggested and in certain cases demonstrated, relatively little attention has been devoted to the special problems, risks and needs faced by those attempting to adopt this technology under operational constraints. The model outlined here helps ensure a realistic perspective on technology transfer by addressing the process in terms of needs and risks.

Operational environments, as opposed to institutional environments, in general require the timely creation of databases to support the decision-making process. When remote sensing is used as an information source, its full potential is only realised when imagery enhances the ability to reach a decision (stage) quickly. Afterwards, the value of the database stabilizes as it evolves into an archival function. This implies that the most important feature of operational remote sensing is throughput¹, necessitating uncomplicated image analysis systems whose strengths reside in fast, flexible input/output

¹throughput: how fast information can be propelled through a network or structure. Used in both computing and management.

used in an environment of frontline decision making more consistent with the modern, flat management structures¹ (Froham & Johnson 1992).

In the research/planning setting (institutional environment), the value of remote sensing as an information source is perceived through a strategic (long-term) role, where the value of information is realized over a longer time frame. This prioritization necessitates and allows for the use of robust, high capacity systems, where user-friendliness can be sacrificed for analytical power and peripherals, to be used in a more traditional pyramidal decision making structure.

The widely different conditions under which the use of remote sensing can be appropriate are reflected similarly in the technologies wide ranges of cost, functionality and perceived value. It is evident that in the short period since this technology has become available to operational users, the remote sensing research community has not had sufficient time to develop a full understanding of the problems, priorities, and risks encountered by the potentially vast community who could benefit from this technology.

4.1.3 Operational Methodologies Demonstrated

The consequence of the relative scarcity of research planned and executed directly for the operational environment is that potential users must, for the most part, be prepared

¹Modern management practices are moving away from the traditional pyramidal authority structures to disseminated decision making, often referred to as flat management structures.

themselves to acquire the knowledge, develop the skills and exercise the judgement necessary to minimize the risks inherent in the introduction of remote sensing technology into the workplace. Comparatively little support is available from the more traditional sectors of the remote sensing community. The norm of research practice stresses technology specific considerations relating to the accurate and reliable capture, integration and manipulation of remotely sensed data. More effort, however, must be devoted to demonstrating the fundamental tasks of developing, testing and applying the models required for careful, systematic and cost-effective remote sensing assessment and implementation. Success in these efforts is becoming increasingly recognised as the real pre-requisite for successful exploitation of remote sensing in any setting, but particularly so in the operational sector.

This thesis reports on the satellite remote sensing methodology development in support of the CCRS Cyprus Pilot Project. Research was carried out with the co-operation of GeoQuest International, a small Toronto-based geological consulting firm with exploration interests in Cyprus. While Dennis Jones, president of GeoQuest Int., was interested in using remote sensing, he lacked the capability to perform a needs'/risk assessment of this technology and to undertake methodology development. GeoQuest Int. was prepared to commercialize this application if the potential for remote sensing suggested in the literature could be demonstrated in a simple methodology. The TTTDS has been interested in supporting this kind of effort as a follow-on to earlier research in

Cyprus (Bruce et al. 1986), and the generic nature of the local environment would allow the methodology to be applied to many other semi-arid environments world-wide.

The objective of pilot projects such as that undertaken in Cyprus is to develop operational techniques for which there is an identified client, and to assist that client to refine and apply the resultant methodology commercially. The network diagram (Fig. 4.1) illustrates the process which was followed to ensure that the resultant methods were technically appropriate, that commercial services are available for operational application, and that the results can be presented in a way which is acceptable to the client.

The initial Phase I of methodology development is defined by the dominant contribution of the research team which naturally concludes with commercialization. This period is marked by close liaison with the targeted end-user and their service company which will eventually apply the methodology on an operational scale. This thesis reports on aspects of the Site Specific R&D and Methodology Development and Demonstration steps of Phase I. Phase II describes the decreased level of involvement of the research team during commercialization.

Phase II - Commercialization

Figure 4.1. Critical Path Diagram of Geomatics Commercialization Model (Davidson et al. 1993)

This process involves establishing partnerships both with the end user, in this case GeoQuest International, and with the consulting or "value-added" firm whose services they employ. The user or client must be involved in the process of applications development at as early a stage as practical so that the focus on actual user needs is always kept. This builds confidence in the methods and the research and development team. This process involves close liaison with the research team, sensitization to the technology and training in operational methods for the client. It is not intended that the end user necessarily be prepared to carry out all aspects of the work without additional outside support. It is, however, necessary that the client understand all of the steps and operations involved in developing and applying the methodology. In parallel with the research and development and client development efforts it is necessary to ensure that the methods developed are well documented and that one or more potential value added companies are made familiar with the general client need and the methodology developed to carry out the work commercially on an operational scale.

4.2.0 Key Stages in Operational Project Development

The planning process begins with development of a clear definition of the problem to be addressed. This will then naturally focus attention on practical needs to reach problem resolution rather than technologic capabilities (which should be a later concern). A structural needs assessment will lead to an evaluation of the existing problem-related database. Specifying the resulting information/performance gap will then encourage consideration of technologic potential and assessment of risks of incorporating remote

sensing, determined by factors of technologic feasibility, availability and acceptability. This approach can serve as a guide for project development through the stages of: methodology development, operational testing, and implementation, focusing on technologic innovation guided by problem determined information needs rather than technological 'push'.

4.2.1 Problem Definition

Researchers in resource management commonly risk devoting insufficient deliberate effort to defining the problem being investigated and the appropriate technology required to solve it. This may result from technological push (unneeded upgrading), not enough (or even too much) problem-specific experience, work load, or any number of other practical considerations. A degree of resistance to change is natural and stems from confidence in approaches which have 'stood the test of time' but which may not encourage conscious review of the problem as it has evolved over time or the technologies which have been developed to address it.

In this problem assessment effort, consideration of the following simplified checklist could make the difference between success and failure. This is particularly true when incorporating new technology such as remote sensing as one of the secondary objectives or as an essential element of methodology.

Whose problem is it?

What is the problem and what is the scale?

Why is there a problem?

Where is the site of the problem and of the technology?

When is a solution needed and at what performance standard?

After reviewing this list it can be seen that experience may equip us to define some of these elements much more effectively than others. In particular, the intangible elements involving human perception can be the most challenging to qualify and quantify for conscious planning and assessment.

► The Model Applied to Troodos Massif Exploration: Problem Definition

The goal of the exploration efforts of GeoQuest Int. is to identify near surface sulphide deposits. The key to success will be the development of a methodology for the quick identification of drill sites for probable ore deposits. The underlying problems are the lack of accurate geological information and the prohibitive costs of mounting a traditional mapping program to collect this information. It has not been possible to date to secure funding to map this impressive, 100 km by 40 km mountain range using conventional methods, and had this been possible, new sources of mineralization would likely go undetected. GeoQuest Int.'s mineral emplacement model suggests that they are buried under a veneer of overlying rocks. An examination of these problems led GeoQuest Int. to conclude that topographic and geologic information at small to medium scales must be collected. Previous remote sensing experience (Bruce 1985) indicated that satellites could provide the information required for exploration in the Troodos Massif.

4.2.2 Information Needs Assessment

Often new technology can dominate the focus of a research activity. This blurring of perspective can lead to the medium dominating the methodology, i.e., the development of technology-driven methodologies. A commonly observed effect of this on remote sensing applications is the adoption of a noncritical approach to data capture. The natural tendency to gather and compile large databases as a preliminary implementation step does not translate well into an operational remote sensing setting.

A single 7 band TM quadrant (180 km²) requires 88 MB of disk space. A working-database containing two styles of contrast enhancements, edge detection filters (for lineaments) and some scratch space would be more than four times this size. It can be seen that hardware capabilities can be rapidly out-stripped if a continual conscious effort is not made towards data reduction. The added constraints imposed on operations-oriented activities, where time and resource limits can be severe, are a source of major risk and challenge. A noncritical approach to data capture could easily cause a project to stray over the line between practical feasibility and infeasibility.

► The Model Applied to Troodos Massif Exploration: Information Needs Assessment

This initial research into remote sensing lithological mapping of the Troodos Massif demonstrated that MSS could be successfully used to update existing 1:250,000 geology maps and provide information on regional scale structures (Bruce et al., 1986). With improvements in the Landsat series of satellites, it was felt that a systematic approach,

utilizing certain aspects of geophysics, geology and TM imagery, could respond to the performance gap¹ and provide the necessary information for selecting specific drill targets (Jones 1990).

A strategically sound approach was adopted to introduce remote sensing into existing exploration methodologies, while acknowledging and accommodating the strengths, and addressing the weaknesses of remote sensing technology. Efforts focused on enhancing the value of traditional data sets and practices to resolve problems by developing a common frame of reference and improving overall standards of performance. In this way, if there is an absolute performance gap with respect to current problem solving capabilities, then 'new' information sources and related technologies could be evaluated aggressively against original problem requirements, their benefits more easily demonstrated and their perceived threat minimized.

Effective transferring of remote sensing technology and practice is best supported by recognising and acknowledging the existing skills and biases of the recipient. Considering that interpretation of aerial photography and of field maps have long been the stock-in-trade of the exploration geologist, the barriers to acceptance of satellite imagery would be minimized by presentation in a similar format, that is, imagery printed at near photographic quality and sharing typical topographic map attributes. Images of the Troodos Massif were geometrically corrected, and printed with a UTM grid, borders and

¹Defined during the database and information needs assessments.

scale. Once laminated, they could be carried in the field, drawn upon, and serve as a base for interpretation.

TM hardcopy plots would enhance the existing insufficient map base. The plots provide a backdrop for geophysical and geological information which is spatially/geographically correct, and shows lithologic/structural geologic information that cannot be found on existing maps. In Cyprus, it was found that the 30 meter ground resolution of TM could produce interpretable images at scales as large as 1:25,000. Thus, if higher resolution image data were available, it would not have been, from the model's perspective, appropriate to conduct research with it, as an operational client would not likely be able to implement the results in practice. The information was then integrated following a strategy based on the mineral emplacement model developed by GeoQuest International. Promising areas would then be further explored by diamond drilling.

4.2.3 Database Assessment

Having defined the problem and completed an inventory and evaluation of information needs, specific characteristics of the available data which will have an effect on their integration and on methodology design should be considered realistically. A conscious effort is required prior to data integration, since much of the basis for intuitive evaluation of data comparability (required resolution) is lost. Once image analysis begins, the date of acquisition and the resolutions at which the imagery can be reliably used are easily

forgotten. Digitized data can lose important legend and historical information. The ease with which digital data can be manipulated demands that the important attributes of the original data be considered in the integration process.

It should be noted that, at this stage, operational constraints and maximum efficiency usually require data reduction. This can be accomplished by recognition of minimum resolution requirements and sub-area selection. The decisions must, of course, be compatible with information needs and required performance standards. Without this step, data loading can rapidly exhaust storage and reduce throughput, without significant improvements in information quality or availability. Indiscriminate data capture also has the effect of diminishing the perceived value of the entire database.

As remote sensing data characteristics vary widely, it is necessary to evaluate each data source (sensor) in terms of its capability, likely availability, and its compatibility with other data sets in the database and with the desired performance standards. A deliberate and structured approach of assessment is required to ensure that both familiar and new sources of data are evaluated in a consistent way. The basic criteria which could be used for evaluating history, reliability, and compatibility are format, scale and resolution, and accuracy and precision.

4.2.3.1 Format

Synoptic images of the landscape are collected by film cameras and digital sensors. Most satellite and airborne remote sensing data available today are collected, archived and supplied in digital form on a commercial basis. By strict definition, "remote sensing" could include aerial photography. However, common understanding is that low to medium altitude aerial photography is precluded. It is usually possible to purchase enhanced hardcopy products directly from the commercial or institutional operators of the satellite ground receiving stations. The acquisition and integration of digital data (from remote sensing and other sources) may not be practical, desirable or possible. It is thus necessary to identify information requirements prior to data acquisition.

Depending on the required information value of the data set, and the capability of manipulating digital data, decisions must be made on whether to stay with analogue information, develop an in-house capability to analyze digital data, or to utilize the services of a value-added commercial service. Difficulties inherent in integrating remote sensing data (digital or analogue) with conventional databases must also be considered as there may be incompatibilities arising from conflicting formats, co-ordinate systems, and scales.

► The Model Applied to Troodos Massif Exploration: Format

Digital data processing was needed to produce satellite images of Cyprus which would meet the information performance standards of the exploration model. GeoQuest Int.

required lithologic and structural information at scales as large as 1:25,000. Off-the-shelf hardcopy satellite images can be purchased as simple 3 band false colour composites enhanced with standard look-up-tables (LUTs), with the statistics for the contrast stretch being derived from the entire scene. Crosta & McM. Moore (1989), Drury (1990) and Loughlin (1992) all stress the need to draw the image statistics from which the LUTs are derived over the target areas, and in semi-arid environments, excluding areas of vegetation. The strong reflectance of vegetation will dominate certain contrast enhancements at the expense of subtle mineralogic information contained in the scene. Custom enhancement can maximize the contrast over the reflectance range of mineralogic information, thus improving interpretability of desired ground targets. Research was required to identify the minimum suite of enhancements from the wide range of promoted products. The selected enhancement process also must support the level of documentation needed to facilitate repetition on an operational scale by value-added service companies.

Previous remote sensing research (Bruce et al. 1986) successfully mapped the major lithologic units in Cyprus using Landsat MSS. The improved spatial and spectral resolution of TM imagery strongly suggests that significant results could be achieved with this sensor. The digital format of this data source also reduces the initial technology requirements as desired integration with geophysical and map data could occur entirely within an image analysis system. To reduce the volume of information handled, initial research took place on subareas and at overview scales. The entire Troodos Massif is

contained within a single TM quadrant¹. This was further subdivided into a subscene image of 3000 pixels by 1800 lines which would cover the entire target area, reducing the data volume to a relatively small amount².

4.2.3.2 Scale and Resolution

Probably the most common error made in selecting, comparing and merging data sets is failure to determine adequately the scale within which the data were collected and within which they can be used reliably. For example, a classified satellite image consists of polygons representing different classes. It could be enlarged to almost any scale and appear "accurate" as the continuous tones would not look blurred to the eye as an unclassified image does when over-magnified.

A second error is failure to consider fully the scale of observation required for analysis of the problem. Prior to the availability of TM data the mining community had been using MSS imagery. It is entirely possible that some regional structural studies carried out today with TM could successfully use MSS at great savings in time and costs. These two common oversights in considering the scales at which data are captured and required, are encountered during the planning stage of a project and can be avoided by consideration of the scales of area, time, and process appropriate to the problem.

¹A full TM scene covers 185 km X 185 km, a quadrant of 100 square km can be purchased, around a user defined centre point.

²A 3000 column by 1800 line image of TM bands 1,2,3,4,5,7 would require 32.4 Megabytes of disk space.

*** Scale of area:** the required scale of spatial operations that is dictated by the problem should be compared to the available spatial resolution of each data set (i.e., the original scale of observation of data used to produce a final product), and to operational constraints.

*** Scale of time:** the time required for acquisition, transformation, integration, analysis, application, and reporting should be considered in the context of problem-imposed deadlines, as well as the time sensitivity of the application (i.e. time dependent environmental phenomenon).

*** Scale of process:** consideration of the physical processes involved can help determine the appropriate scale of observation, exploitable features within a data set, and the time window/frequency of observation. This assessment can aid greatly in the rationalization of employing remote sensing for data capture.

► The Model Applied to Troodos Massif Exploration: Scale and Resolution

In Cyprus, the currently available source of geologic information are a map of regional scale (1:250,000). TM data represent the highest resolution data available, and experience shows that TM imagery is interpretable at a scale of 1:50,000, and given sufficient scene contrast, an interpretable product is possible at 1:25,000. Successful interpretation of the mineral emplacement model for identification of sites for more

detailed investigation requires regional structural information and identification of lithology and surface mineral alteration at these medium scales.

Cyprus' harsh semi-arid environment has left large areas of outcrop exposed for direct imaging by TM. For the most part, geobotanical relationships do not have to be relied upon as the major exploration targets lie in the areas of least vegetation on the Troodos Massif. The image was captured in August, towards the end of the dry season, when vegetation that might exist has died back from the drought conditions. The general rule in remote sensing, dependent on application, is to obtain the most recent scene, or one that was taken close to date of the database to which it will be compared. Considering the age of geological features, and that there have not been any great, recent cultural events that would obscure the surface, timeliness of data capture is not an issue.

In terms of scale of processes, the macro-scale of geologic structure is ideally suited to the synoptic view of remote sensing. TM provides the functionality to map structure at regional scales and lithologic boundaries at medium scales. The spectral resolution of TM allows the identification of the groups of minerals resulting from the weathering of iron oxides and the products of hydro-thermal alteration. While it would be useful to be able to identify individual mineral species in these groups, TM can provide the ability to recognize anomalous concentrations of these minerals which are important to an exploration model.

4.2.3.3 Accuracy and Precision

Conventional data sets have usually been built up from point observations with efforts concentrated on precision of measurement and sampling strategies. The inherent problem is that the spatial accuracies are limited by the degree to which the point sampling represents the behaviour of the phenomenon which the data hoped to model, both functionally and spatially. For many resource management problems, spatial accuracy can be more critical than point precision, although achieving spatial accuracy may be more difficult to realize in practice, often because of the cost and difficulty of obtaining sufficient sample density.

► The Model Applied to Troodos Massif Exploration: Accuracy and Precision

Geological maps are good examples of spatially continuous representations of observations. The spatial continuity is normally based on interpolation from precise point sampling. If lithologies have sufficient contrast to be discriminated on imagery then relatively accurate interpretations may be made of unit boundaries. From the familiarity with spatially inaccurate geological maps and geophysical data, it is not required for geologists to make a huge leap in faith to adopt remotely sensed imagery. The accuracy of the interpolation from the point observation of ground mapping, when it is even possible, to mapping the extent of a lithology can vary greatly. In fact the 30 m sampling of TM data could not realistically be achieved in Cyprus by ground reconnaissance.

Remote sensing presents a unique opportunity to continuously (spatially) sample large areas at relatively low cost. Integrated with point-derived data sets through image analysis software or GIS, it is possible to derive a mutual advantage from spatially accurate and continuous remote sensing data sources and the precision of traditional point sample data. Accuracy and precision do not have to be considered antagonistic concepts. Their relative advantages can be retained through careful data selection and integration. While remote sensing data may be characterised by lower spatial precision than some conventional point sample data sets, there is compensation in the inherently superior ability to define and model phenomena which have important spatial, spectral and temporal elements to their characteristics, behaviour and interactions. The attributes associated with point sample data can be modelled spatially and the results compared analytically with directly observed spatial distributions provided by remotely sensed image data.

4.2.4 Risk Assessment

Following the TTTDS project model, the operational user will have preceded development of a remote sensing based project plan by assessing the problem and determining if there is a performance gap in the existing methodologies or data sources. At this stage an informed decision will be possible regarding the need to incorporate remote sensing technologies by developing an inhouse capability or by contracting outside services, and regarding the nature of the anticipated benefits.

Prior to the adoption of this technology option, a risk analysis is needed to identify and structure the sources of risk. The structure is formed by prioritizing the identified needs and risks and determining the links between the different elements. It will also assist the operational user in evaluating the risks vis-a-vis practical constraints on available human, budgetary and infrastructure resources. Risk assessment is seldom acknowledged as an important step in project planning as it is often seen as an intuitive exercise, especially when a 'Tried and True' approach is available. When a less familiar technological mix is used, risk analysis should be conscious and systematic as experience can be relied on less as a guide. Any proposed methodology approach must be considered in terms of its compatibility with existing performance standards, assessment procedures, and cost/time/human resource constraints. It is at this stage that some of the most challenging sources of risk to innovation are encountered. The sources of risk associated with new technologies can be attributed to one of three sources:

- **Feasibility:** If preliminary investigation reveals a need for new technology, the first step in managing risk is to determine the technical feasibility of the required application. This is generally a well known process normally beginning with literature research. The process could, however, involve in-house technology transfer testing if the target conditions differ significantly from the test conditions. Where basic research is indicated, operational users must often seek outside support and assistance, accepting longer-term return on investment.
- **Availability:** The technology used in a pilot project resulting from a feasibility test may not always match that which will be used, or should be used in actual working

conditions. It is therefore important to confirm that the levels of technology required to meet the identified need are available in practice and once in place the technology can be maintained in operation. In more familiar terms, this element is really an assessment of the appropriateness and sustainability of the technology required under the conditions (environmental, socio-economic, political, etc.) in which it must be implemented and maintained. If the required technology is not available or appropriate (because of cost, geographic isolation, lack of infrastructure or inadequate human resources), assurances must be obtained that this technology could be put into place and maintained under operational conditions and constraints as a result of specified realistic remedial actions.

-Acceptability: Defining the technology-dependent contribution and determining its appropriateness and sustainability is still insufficient to ensure controlled-risk technology transfer. The missing element of risk assessment is often determination of what barriers must be overcome to support acceptance of the proposed application. Promises of performance must be critically considered. This element of risk commonly receives the least prior consideration as it is highly dependent on human subjectivity.

► **The Model Applied to Troodos Massif Exploration: Risk Assessment**

GeoQuest International approached the TTTDS as they determined the risks in developing the in-house remote sensing capability necessary to undertake the methodology development were not acceptable, and that resources were not available at the beginning of the exploration program to contract-out the research. The final commercialization was made feasible by providing guidance to the consulting firm applying the methodology on

an operational scale. The acceptability of the results was maintained by the involvement of GeoQuest Int. throughout the methodology design. In this way "perceived" needs and "actual" requirements could be judged and met with confidence in the process.

4.2.5 Project development

If, as a result of problem definition, needs assessment and risk analysis, a decision is made to proceed with a project design involving the adoption of appropriate levels of remote sensing technology, project development could now advance with greater confidence. Project development can be considered to consist of three phases: methodology development, operational testing, and implementation. The specific route to be followed through this process is highly dependent on the problems/needs/risk conditions which will have been determined at the earlier stages of the planning process. Some general considerations are still, however, possible.

4.2.5.1 Methodology development This stage in project development involves the coordination and sequencing of steps in computation, transformation or other data processing. The objective is to achieve a logical and efficient progression towards the output products while recognising the unique character of each data set, any hardware/software or logical constraint on the sequence of processing, and the abilities of the people involved.

4.2.5.2 Operational testing Having developed a methodology which meets all the predetermined technical requirements within the known or estimated constraints, a final decision on implementation must be made. In order to reduce further the risks of this decision, the proposed methodology should undergo testing under the 'real world' conditions likely to be encountered in practice.

A 'Benchmark Study' of the methodology should be carried out under conditions which simulate the operational setting as closely as possible. This would consider constraints of technology, resources (human, budgetary, and organizational) and operational deadlines. Ideally, the only difference between the test and reality is in terms of scale of activity. Thus, all major sources of risk can be simulated while the implications of failure are kept to a minimum.

4.2.5.3 Implementation is the objective of this process. It is not, however, a simple step in itself. Not only does it involve activity at a larger scale from preliminary planning, it may also involve individuals outside the evaluation team, and is thus a process of technology transfer in itself. During the planning process certain of the basic elements of successful technology transfer will have been addressed. Such elements include the securing of a mandate, and the infrastructure and support necessary for implementation. Since it is often difficult to implement a training plan prior to the decision to go ahead with the project, the implementation plan must include clear and realistic provision for the training of personnel at all levels from management to technical.

► **The Model Applied to Troodos Massif Exploration: Project Development**

It was beyond the scope of this project to develop an actual project. The goal was to create a methodology which *could be* applied to an actual project. Because the methodology adhered to an operational model it was designed to be transferred, and through the demonstration it could be enacted with confidence in Cyprus or similar environments. In this case, the methodology has in fact been used in an actual project which will be discussed in Chapter 6.0: Discussion and Conclusions.

5.0 OPERATIONAL METHODOLOGY FOR REMOTE SENSING MINERAL EXPLORATION IN THE TROODOS MASSIF, CYPRUS

5.1 Image Analysis

The objectives for using remote sensing in this exploration program were to provide a source of information to GeoQuest Int. to assist in the decision making process of committing resources to costly site-specific field investigations. This process was realised by producing images that could be interpreted by GeoQuest Int. to:

- 1) assist in improving existing lithology maps by delineating rock types based on their tone, texture, landform patterns and alteration characteristics;
- 2) enhance structural information (faults, folds, fractures etc.) as such features will have formed the conduits for the hydrothermal solutions;
- 3) provide corroborating geological evidence for the proposed mineralization emplacement model; and

A resolution test chart featuring several groups of horizontal and vertical lines of varying thicknesses. Each group is accompanied by a numerical value indicating the resolution. The values include 1.0, 1.1, 1.25, 1.4, 1.6, 1.8, 2.0, 2.2, 2.5, 2.8, 3.2, 3.6, 4.0, 4.5, 5.0, 5.6, 6.3, 7.1, 8.0, 9.0, 10, 11.2, 12.5, 14, 16, 18, 20, 22.4, 25, 28, 32, 36, 40, 45, 50, 56, 63, 71, 80, 90, 100, 112, 125, 140, 160, 180, 200, 224, 250, 280, 320, 360, 400, 450, 500, 560, 630, 710, 800, 900, 1000, 1120, 1250, 1400, 1600, 1800, 2000, 2240, 2500, 2800, 3200, 3600, 4000, 4500, 5000, 5600, 6300, 7100, 8000, 9000, 10000.

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

- 4) look for correlations of interpreted structures and lithology with field observations, airborne geophysics, and geochemistry.

These information objectives of the exploration program were met by the production of enhanced images to provide geologic information on the Troodos Massif. The image products were interpreted by a geologist with extensive knowledge of the area as an input to a mineral emplacement model. This model, based on observation on geological observation, explains the presence of existing deposits and provides indications of where undiscovered deposits are expected. The image analysis stage proceeded in four parts,

- 1) Data Preparation - data acquisition, image geocorrection, band selection;
- 2) Image Processing - enhancement: false colour composites and filtering;
- 3) Image Display - generation of hardcopy output; and
- 4) Image Analysis - interpretation.

While not attempting a review of all possible image enhancements for semi-arid regions, several popular false colour composites (FCC), new principal component techniques, and lineament analysis were investigated following the structure outlined by our operations-orientated model (Chapter 4). That is, to identify simple, robust, and reproducible techniques for producing images which can satisfy the information requirements of the stated image analysis objectives. To complete the research these techniques must be clearly documented and demonstrated.

Even modest image analysis systems provide a wide range of routines which may be applied to the data. Efficient use of resources demands that consideration be given to the optimum range of products that are required and what is operationally feasible. The nature of this study was defined by constraints on available resources to carry out the study, the need for results to be operationally implemented, and the need for a specific level of detail of information. Adherence to an operational project model facilitated the recognition of and adherence to boundaries on research necessary to produce a methodology which would be transferable to industry.

The previously stated goals for using remote sensing were derived from the need to supply medium scale lithologic and structural information in a form which could be easily interpreted by a geologist with knowledge of the geology of the Troodos Massif. An added qualification was that the methodology and derived products had to be designed from the beginning to facilitate technology transfer. These goals and operational constraints naturally dictated that the objectives could only be met through simple, yet robust image products. A literature research (Section 3.4) suggested several previously successful band combinations and analysis procedures to produce simple false colour composites (SFCC) and complex false colour composites (CFCC). An effort was made to select the fewest possible products which could address the above mentioned information goals.

Unsupervised and supervised classification were considered and deemed inappropriate for this phase of exploration. In an unsupervised classification the image analysis software examines pixels of n input bands and divides them into a number of clusters based on natural groupings in image data. The basic premise is that values within a given cover type should be close together in spectral space, whereas pixel values of different classes should be comparatively well separated. Supervised classification differs in that pixels are classified through comparison with spectral statistics from user-specified training areas. This generally requires a priori detailed knowledge of ground features in the image area. Both procedures are solely spectral based and very time consuming in that the quality of the results can be highly dependent on trial-and-error analyst intervention to produce suitable thematic maps. Manual interpretation is powerful in that the human brain considers tone, size, shape, associations, and texture when classifying objects. Machine classification can often produce speckled results that look poor, and tend to be viewed with the scepticism that surround black box approaches. Initial images given to GeoQuest Int. indicated that the lithologies of the Troodos Massif could be successfully mapped with SFCC and CFCC, so that the added effort to produce either classification could not be justified. The author's experience suggests that in this case at least, SFCC and CFCC are more readily reproduced and give consistent and acceptable results. Also, a supervised classification could not have been built from the present database. At a stage when the field database is adequate to define training sites, the value of a classification could be re-evaluated against desired performance standards (information needs).

From a full TM scene, a working sub-image was chosen to cover the Troodos Massif mountains (Fig. A1.1), and was geocorrected to a topographic map base. Geographic masks were used in all enhancement operations to restrict statistical data sampling to areas of interest to maximize the potential of enhancement algorithms. SFCCs were produced first, being the most straightforward, and then band ratios and finally a PCA were used to generate CFCCs. To create an image showing primarily structural information, a procedure was established for the generation of an enhancement that combined a black and white TM band 5 image with a directional filter to highlight lineaments (faults, fractures, folds etc.). Hardcopy output of the selected enhancements were printed as "image maps". The images resemble maps in that they are high quality pictures printed in a size similar to topographic map sheets, with a UTM grid and border.

5.1.1 The Data Set

The remote sensing data source for this investigation was a full Landsat Thematic Mapper scene (path 176, row 36) acquired on 3, August 1984. This image was selected from several TM scenes available as there was no cloud cover, the data quality was high, and a scene captured towards the end of the dry season in a semi-arid climate would have the least possible influence from vegetation. The year of the image was not considered crucial as there has not been any recent major geologic or cultural events that have drastically altered the landscape. It is conceivable, however, that an image in a given

season would be required for a particular application. In these cases, if appropriate archive data are not available, it is possible to order a TM mission.

The TM image was purchased from EOSAT Corp¹. on 9-track computer compatible tapes in LGSWG format. The data were analyzed using PCI's EASI/PACE image analysis software based on a PC-386 with a 21 inch RGB monitor (32-bit display). The data volume was reduced through the selection of study areas and production of images at scales of:

- 1:250,000 of the entire Troodos Massif,
- 1:100,000 over the eastern half of the mountains, the main area of interest indicated by GeoQuest Int. (Fig. 1.1, A2.9), and
- 1:50,000 over specific areas of mineral potential indicated by GeoQuest Int. after interpretation of the 1:100,000 images (these sites are confidential).

These scales were determined by the size of the study area, system operational capabilities, and the ability of these scales to meet the desired performance standards of different stages of the interpretation as determined in consultation with the client. This also minimized the computing and output resources required. Physically the Troodos Massif is a large mountain range (100 km by 40 km). By starting with small scale imagery, the entire area was captured on a single image, the interpreter could become accustomed to the imagery and ask for modifications to suit their own interpretation preferences. The image processing was carried out on a PC-386. If judicious sub-area

¹Eosat Corp., Langham, Maryland. Info: 1-800-344-9933.

selection was not exercised the workstation's capabilities would have been rapidly overwhelmed. Further site-specific images of scales of 1:50,000 and 1:25,000 were left to GeoQuest Int. to create commercially. GeoQuest Int. confidently judged the methodology and images created acceptable from the smaller scale images. Also, it was mutually agreed between GeoQuest Int. and the author that this work was intended to be a demonstration of remote sensing capability to provide justification for commercialization of the methodology.

Topographic maps at 1:50,000 were available to geometrically correct the TM data. There is one small scale (1:250,000) geology map available from the Cypriot government. This provides, however, insufficient detail to be of significant use for exploration. A larger scale (1:20,000) geology field map over the Mathiati mining region (eastern Troodos Massif), created by an earlier UN project, was used along with field experience by GeoQuest Int. to evaluate the enhancements.

The strong relief of the Troodos Massif and paucity of cultural features made locating ground control points for the geometric correction challenging. It is thus conceivable that in areas of very steep terrain the positional error could be greater than the overall average of plus-or-minus one pixel. This is of little consequence for this study as the target lithology is on the periphery of the mountain range. This also removes the concern of data loss due to shadows. Had the areas of high relief been important for the interpretation a digital terrain model could have been used to improve the accuracy of

the geometric correction. It could also be argued that in such cases this step is unnecessary as strong shadowing can make interpretation pointless, the macro-scale and point-imprecision of geological boundaries may not require a highly accurate geocorrection, and the resources required to create a DTM are great.

5.1.2 Simple False Colour Composites

There are several simple false colour composites (SFCC) for semi-arid environments that repeat frequently throughout remote sensing literature (TM 4,5,7, TM 3,4,5 (or 7), TM 1,3,5, and TM 7,4,1). (see Section 3.4.1). As references are made to single images of Cyprus at several places in the body of the text all imagery has been placed in Appendix 2.

Table 5.1. Simple false colour composite band combinations

<u>Band Combination</u>	<u>Potential Lithologic Applications</u>
(4,5,7)	should highlight vegetation as red, and show lithology, favouring iron oxide bearing rocks in hues of blue-cyan-green.
(3,4,5 (or 7))	good overall vegetation/lithology enhancement for showing geobotanical relationships.
(1,3,5)	good lithology enhancement showing hydroxyl bearing rocks as bright greens-magenta, and iron oxides in blues. (Fig. A2.1)
(7,4,1)	hydroxyls will be blue-cyan, vegetation green, and iron oxides red. (Fig. A2.2)

A sampling mask was used to restrict generation of LUT statistics to areas on the SFCC that on visual inspection obviously represented target lithologies. All four SFCC combinations were tried with linear, histogram equalization, and breakpoint contrast enhancements. The PCI software allowed the exponent of the linear stretch to be varied so as to be logarithmic (0.5) or linear (1.0). Tails of the histograms could also be trimmed to remove outliers which would reduce the overall range of the stretch. Tail trimming of 2% on both ends of the histogram was used. The decision of the amount of data to trim is a qualitative judgement of the image analyst. If this number was increased overall scene contrast would have improved, but possibly the expense of losing important, subtle image detail. Areas could also be masked on the display to limit the sampling of statistics for the enhancement to maximize contrast over some known ground features.

5.1.3.0 Complex False Colour Composites

CFCC were made from combining ratios of TM bands and principal components (PC) from directed principal component analysis (DPCA). Two DPCA images were produced, one of TM (5/4, 4/3, 5/7) (Fig. A2.3) and a Crosta Composite (Fig. A2.8) (named after the scientist who developed the procedure). Both of these procedures go beyond simple contrast stretching to isolating and displaying specific portions of the reflectance spectrum which theoretically correspond to ground targets. Ratios were created through band division (band a/band b) and rescaling the results to positive real numbers (0-255).

DPCA was generated using a standard PCA algorithm. The reporting feature listed eigenvalue and eigenvector statistics which could be evaluated.

5.1.3.1 Band Ratios

In the reflectance spectra of iron oxides (Fig. 5.1) it can be seen that both the ratios 5/4 and 3/1 would be useful for highlighting a pixel dominated by iron oxide reflectance (High iron reflectance/iron absorption). Drury (1987) recommends the use of 5/4 as the difference in the reflectance curve is greater than for 3/1, and this portion of the spectrum (N.IR) is less affected by haze.

Figure 5.1. Diagrammatic reflectance spectra of hematite, goethite, green grass and dry grass (Fraser 1991).

A combination of (5/4, 4/3, 5/7) was used to produce an image which highlighted iron oxides, vegetation, and clays respectively (Fig. A2.3 & 12). The assignment of bands to colours is a subjective process and there are no hard and fast rules. The colours assigned to this ratio CFCC were chosen to match the colour associated with the ground target the ratio is intended to highlight.

The 5/4 ratio (iron oxides) is displayed as red, 4/3 (vegetation) as green, and 5/7 (water bound in clays: OH-) as blue. The colour assignment was used to increase the interpretability of the image by forming natural associations between image colours and actual ground targets. The result is automatically rescaled by the algorithm. A histogram equalization enhancement was used to increase tonal contrast.

The consequence of insufficient rainfall over the eastern Troodos Massif is sparse vegetation cover (Critchfield 1974) and large areas of outcrop (Jones, pers comm. 1992). In the eastern end of the Troodos Massif, where exploration efforts are concentrated there is little vegetation cover (Jones, pers. comm. 1992). In the central and western reaches of the mountain range there are large areas of trees and grasses (in valleys and due to rain-shadow effect of the mountains). In areas of vegetation, as Fraser (1986 & 1991) found in N.W. Australia, changes in the amount of both dry and green grasses from pixel to pixel can cause enough variability to completely mask mineralogic changes. The 3/1 ratio that is used to map iron oxides is sensitive to dry vegetation and the 5/7 ratio for clays may capture both green and dry grasses. While ratios are a powerful

technique, it would be advantageous to use DPCA to further refine the process by removing any doubt that an anomalous area is caused by mineral alteration and not vegetation.

5.1.3.2 DPCA of a TM Ratio Image

The CFCC of the band ratios (5/4, 4/3, 5/7) produced an image where differences in iron oxides, vegetation and clays could be clearly seen. However, some correlation between the ratio bands used to make the FCC still exists and can be seen in Fig. A2.3 & 12 by the mixed cyan tones (mixed pixels of 4/3 and 5/7). The south-west side of the Troodos, which is of no exploration interest, is relatively heavily vegetated and appears as cyan and magenta tones on the image. This correlation can be expected from similarities in TM 7 reflectance of clays and vegetation, and from widespread iron staining in the deeply weathered soils of the Troodos Massif. DPCA was used to maximize the variance between these ratios and isolate reflectance from vegetation (4/3), iron oxides (5/4), and clays (5/7) (see Section 3.2.2). The results of the transform can be controlled by selectively choosing the input information. Then, by examination of the magnitude and sign of the eigenvector loadings, an indication is given of which spectral properties of vegetation, rocks, and soils are responsible for the statistical variance mapped into each PC (Table 5.2).

Table 5.2. Principal component analysis of 3 TM ratios, Troodos Massif subscene.
Values referred to in the text are bolded.

<u>TM Bands</u>	<u>Mean</u>	<u>S.Deviation</u>	
5/4	31.17	6.60	
4/3	57.71	17.16	
5/7	49.88	6.24	

<u>Eigenchannel</u>	<u>Eigenvalue</u>	<u>S.Deviation</u>	<u>%Variance</u>
1	352.38	18.77	93.44
2	14.82	3.85	3.93
3	9.91	3.15	2.63

Eigenvectors of the Covariance Matrix

<u>TM bands</u>	5/4	4/3	5/7	
<u>PCs</u>				
PC1	-.29	.91	.28	(vegetation)
PC2	-.88	-.38	.30	(iron oxides)
PC3	.38	-.17	.91	(clays)

Eigenvectors of the Covariance Matrix
(eigenvector loadings expressed as percentages of original bands)

<u>TM bands</u>	5/4	4/3	5/7	
<u>PCs</u>				
PC1	-20	61	19	(vegetation)
PC2	-56	-24	19	(iron oxides)
PC3	26	-11	62	(clays)

The eigenvectors have also been listed as percentage loadings of original values. The importance of the sign (+/-) is that it indicates whether the contribution is either bright or dark. For instance, it can be seen that PC1 is dominated by vegetation (in **bold**), PC2 by iron oxides, and PC3 by hydroxyls. PC2 was negated with a linear look up table (slope=-1), as iron-dominated pixels originally appeared dark. It is the absolute value of the eigenvector which is an indicator of magnitude. A positive or negative sign indicates to which side of the central point that the contribution resides (negative=dark, positive=light).

As indicated earlier, a geographic mask was used to base the PC transform on a specific area of the image. In this way the procedure could be specifically targeted at maximizing the decorrelation of certain ground targets. On the west half of the Troodos is a large area of healthy vegetation, likely due to a combination of aspect, preferential winds, and lower temperatures from altitude. This area was included to provide a strong signature for vegetation. On the east half of the Troodos, where the main exploration targets reside, there are some small areas of vegetation and some dry grasses could be expected. DPCA performed with the large areas of vegetation masked-out did not highlight the limited vegetation on the eastern ranges as well as when the entire Troodos was sampled.

Thus, the PC transform was directed by inputting information that contained three specific sets of information (iron oxides, vegetation and clays). The PCs into which each set was concentrated could be recognised by looking at the magnitude and sign of the

resulting eigenvectors. This technique was used to decorrelate the data to improve the interpretability of the ratio image and thus maximize its information value.

5.1.3.3 DPCA of 6 TM Bands

As stated earlier (Section 3.4.4.1) PCA has been traditionally applied to 6 TM bands (TM 1-5, & 7). This produces an image which is difficult to interpret and thus of limited use (Crosta 1989b). Crosta and McM.Moore (1989a&b) developed a method for interpreting the results of a 6 TM band PCA. Relating the resultant eigenvectors back to theoretical spectral signatures of specific targets, they could determine what information had been concentrated into the successive PCs. As expected, mineralogic information was concentrated into the higher-order PCs, albeit with a very poor S/N. This PCA was not used in the interpretation but is included here for illustrative purposes. Crosta began by using 6 TM bands but further refined the technique which has since become popularly known as a Crosta Composite. While it is not necessary to undertake a 6 band PCA prior to making a Crosta Composite, understanding the process and the method of interpreting the results are essential as the Crosta process is built on the same principles.

Table 5.3 is a listing of the results generated from a PCA of the TM bands 1,2,3,4,5, and 7 of the Troodos Massif. The transformation was carried out on raw data. Loughlin (1991) experimented with using raw, stretched and normalized data and found that consistent results could be obtained by using raw data.

Table 5.3 Principal component analysis of 6 TM bands, Troodos Massif subscene.
PC loadings referred to in the text are in bold.

<u>TM Bands</u>	<u>Mean</u>	<u>Deviation</u>
1	104.2	21.6
2	46.5	13.6
3	60.8	23.0
4	70.5	16.9
5	107.5	33.6
7	51.7	19.9

<u>Eigenchannel</u>	<u>Eigenvalue</u>	<u>Deviation</u>	<u>%Variance</u>
1	2716.3	52.1	90.91
2	134.9	11.6	4.52
3	113.6	10.7	3.80
4	13.9	3.7	0.46
5	8.0	2.8	0.27
6	1.1	1.1	0.04

Eigenvectors of covariance matrix (arranged by rows):

<u>PC</u>	<u>TM</u>	-1-	-2-	-3-	-4-	-5-	-7-
1.		0.39	0.25	0.43	0.26	0.63	0.37
2.		0.57	0.28	0.38	-0.42	-0.52	-0.06
3.		0.16	0.12	0.07	0.84	-0.33	-0.34
4.		-0.63	0.03	0.76	-0.01	-0.11	-0.04
5.		-0.12	0.05	-0.12	0.19	-0.44	0.85
6.		0.27	-0.91	0.26	0.07	-0.07	0.08

Eigenvectors of covariance matrix (arranged by rows):
(eigenvector loadings expressed as % of totals)

<u>PC</u>	<u>TM</u>	-1-	-2-	-3-	-4-	-5-	-7-
1.		16.70	10.70	18.40	11.70	28.30	16.60
2.		25.60	12.60	17.00	-18.8	-23.3	-2.70
3.		8.60	5.40	3.10	37.70	-14.8	-15.20
4.		-39.9	1.90	48.00	-0.60	-7.00	-2.50
5.		-6.8	2.80	-6.80	10.7	-24.9	48.00
6.		16.3	54.80	15.70	4.20	-4.20	4.80

It can be seen that PC1 is composed of a positive weighting from all input bands. Overall scene brightness (reflectance) is responsible for the strong correlation between all bands (90% of the variance) and as expected is mapped into the first PC. The remaining components should therefore account for decreasing variance caused by differences between spectral regions and between individual bands. The spectral differences between the visible (TM 1, 2, and 3) and IR bands (TM 5 and 7) are found in PC2 as the loadings for these two regions are opposite in sign.

Materials which have the highest reflectance in the visible region will appear on PC2 as the brightest pixels (positive eigenvector loadings) and those with the highest IR reflectance will appear as darkest pixels (negative eigenvector loadings). The high positive contribution from TM4 to PC3 indicates that it is dominated by vegetation, and the strongly vegetated pixels will appear bright. "Limonitic" iron oxides (including jarosite and goethite) have a higher reflectance in TM 3 than in TM 1 (Loughlin 1991). This can be seen in PC4 (Fig. A2.5), and the strong and opposite signs of these contributions indicate that iron oxide dominated pixels will be bright in this image. In PC5 (Fig. A2.6) there is a moderate negative loading from TM 5 and a strong positive loading from TM 7. This is the inverse of the expected response from clay dominated pixels (5/7 ratio), so hydroxyl pixels in this case will be dark. Hematite is characterized by greater reflectance in TM3 than in TM2, evident in PC6 (Fig. A2.7). It is evident that mineralogic information are being concentrated in the higher-order PCs. The results, however, are both noisy and low in contrast.

Loughlin (1991) advanced this technique by reducing the number of input channels to avoid particular spectral information and improve the chances of defining a unique PC for a specific mineral class. By selectively choosing the input bands for PCA, the transform could be forced to map desired information content of the input bands into single PCs. Loughlin's work is a refinement of previous research by Alvaro Crosta (1989a&b), after whom the image and methodology are named. The Crosta Composite has been used extensively by Loughlin in semi-arid terrains in the US, Spain, eastern Mediterranean, Middle East and South America (Loughlin 1991).

5.1.3.4 Crosta Composite

A Crosta Composite was created by combining the results from two separate DPCAs. The first was a DPCA of TM (1,4,5,7) to isolate and map hydroxyls (Crosta "H" image) and the second was a DPCA of TM (1,3,4,5) to map iron-oxides (Crosta "F" image). The bands are chosen to force the scene variance to be divided into main groups from which the new PC axes will be defined. Thus, the results of the two DPCAs can be interpreted in a consistent manner; it can be generally expected that the first PC will map albedo, the second visible vs. IR (infra-red) wavelengths, the third vegetation and the fourth mineralogic information. It is possible that the order will vary somewhat, but the individual PC contributions can be interpreted using the same rules demonstrated on a PCA of 6 TM bands. The final result was formed by combining the "H", "H+F", and "F" images as RGB respectively (Fig. A2.8 & 14). The three images can be combined in any combination to suit the interpreter. Based on empirical evidence, Loughlin

(1991), judged that (H, H+F, F) was the most suitable for photogeological interpretation.

The Crosta "H" image was created by a PCA of TM 1,4,5, and 7. Bands 2 and 3 were deliberately omitted to avoid mapping iron oxides. The statistical results of the transform are presented in table 5.4.

**Table 5.4. Principal component analysis of TM 1,4,5,7
for hydroxyl mapping, Troodos Massif subscene.**

Input Bands	TM1	TM4	TM5	TM7	
Band Means	104	70	107	51	
SD of Bands	21.5	16.9	33.6	19.8	
	Eigenvector Matrix				% Variance
PC1	0.44	0.30	0.73	0.43	90.46%
PC2	-.19	0.93	-.09	-.30	5.09%
PC3	-.86	-.09	0.48	0.85	4.09%
PC4	-.18	0.19	-.46	0.85	0.35%
(eigenvectors expressed as percentages original bands)					
	Eigenvector Matrix				% Variance
PC1	23.2	15.8	38.4	22.6	90.46%
PC2	-12.6	61.6	-6.0	-19.9	5.09%
PC3	-37.7	-8.3	21.1	37.3	4.09%
PC4	-10.7	11.3	-27.4	50.6	0.35%

From the eigenvector matrix it can be seen that PC1 is an albedo image, PC2 is dominated by vegetation, PC3 shows the spectral difference between visible and IR, and PC4 highlights hydroxyl-bearing rocks as dark pixels. This "H" image is identified by the strong contributions from TM5 and TM7 which are opposite in sign. The value for

TM7 should be negative and TM5 positive to match the 5/7 ratio and have hydroxyl-dominated pixels as bright zones. Thus, PC4 was negated with a linear LUT (slope=-1). It should be noted that now the contribution from TM4 (vegetation) is negative and therefore dark. This compensates for the similarity in spectral response (Fraser 1986) for some kinds of vegetation and clays in TM7.

Table 5.5 lists the PCA statistics from input of TM 1,3,4, and 5. This DPCA was used to generate the Crosta "F" image for iron-oxides. Loughlin (1991) found that TM7 or TM5 could be substituted with little effect on the results. One SWIR band is omitted to deliberately avoid mapping hydroxyls. TM5 was used in this case as its iron oxide response should be higher than in TM7.

**Table 5.5. Principal component analysis of TM 1,3,4,5
for iron oxide mapping, Troodos Massif subscene**

Input Bands	TM1	TM3	TM4	TM5	
Band Means	104	60	70	107	
SD of Bands	21.5	22.9	16.8	33.6	
	Eigenvector Matrix				% Variance
PC1	0.44	0.47	0.29	0.70	90.23%
PC2	-.58	-.41	0.58	0.39	5.18%
PC3	0.28	0.12	0.76	-.57	4.01%
PC4	-.62	0.76	0.01	-.14	0.57%
(eigenvectors expressed as percentages original bands)					
	Eigenvector Matrix				% Variance
PC1	23.2	24.7	15.3	36.8	90.23%
PC2	-29.6	-20.9	29.6	19.9	5.18%
PC3	16.2	6.9	43.9	-32.9	4.01%
PC4	-40.5	49.7	0.70	-9.2	0.57%

The reasoning for interpreting the PC loadings for iron-oxide mapping is similar to that for hydroxyls. PC1 is an albedo image, PC2 shows visible vs. SWIR reflectance, PC3 maps vegetation and PC4 is the "F" image (bright pixels). The eigenvector loadings for iron-oxides can be identified by strong, inversely correlated contributions from TM1 and TM3. To enhance iron-oxide as bright pixels, the high contribution from TM3 should be positive and that from TM1 negative.

The monochrome "H" and "F" images are straightforward to interpret in that anomalous areas are bright. These images can be combined in a CFCC to show areas of iron-oxide, iron-oxide and hydroxyls, and hydroxyls. This "Crosta Composite" is created by displaying H, H+F, and F as RGB. The H and F images can be combined by simple addition and rescaling to 256. Loughlin (pers. comm. 1993) noted that the final image is usually bluish in colour as old, weathered terrains will have a general distribution of iron oxides in soils. The Crosta Composite (Fig. A2.8 & 14) can be interpreted as follows:

- alteration zones are unusually bright;
- white pixels contained within alteration zones are potentially the most prospective in that they are both iron-stained and argillized; and
- bright reddish to orange zones are more argillized than iron-stained, and bright cyan to bluish zones are more iron-stained than argillized (Loughlin 1991).

5.1.4 Structural/Lineament Enhancement Procedure

The creation of a lineament-enhanced image is a standard practice for geologic interpretation of satellite data. As the interpretation of linears is a highly subjective process the best possible image for this purpose is one which "looks good" from the geologist's perspective. Such an image would show both lithology and structure and have high contrast on landscape features which are interpreted as lineaments. A process was developed (Fig. 5.2) to combine a directional enhancement of linears and a B&W TM band 5 image (Fig. A2.15). It was the intention of demonstrating the potential of this process. For operational use, this image would have to be made with the active participation of the interpreting geologist. As geologists becomes "trained" or more familiar with interpreting imagery, the author has found from experience that they will want to further customize enhancements.

Figure 5.2. Sequence of steps for structural enhancement

A low pass image was created by using a 3*3 averaging filter. By removing some of the high frequency signal, the resulting line segments are fewer, thicker, and longer. The longer lineaments are more likely to indicate important structures. Moore & Waltz (1983) tested filters of varying size and found 3*3 optimal. Directional filters (also known as high-pass) were then applied to increase the contrast of edge and line segments that have trends identified as significant by the mineral emplacement model. Lists of filters can be found in Drury (1987) and Moore & Waltz (1983).

The resultant linears in the image have high contrast with the background. Moore & Waltz (1983) noted that virtually all of the directional information is contained near the tails of a histogram of the image. If a portion of the image was displayed from the centre of the histogram, the linears appeared shorter and of irregular orientation. Considering that lineaments are formed visually by adjacent lineations of bright and dark pixels, important structural elements could then be highlighted by thresholding the directionally filtered images. Moore & Waltz's (1983) process consisted of linearly stretching the lower range (<15%) of the histogram to 0, the middle of the histogram to a medium grey range (128) and the top of histogram (>85%) to a very bright value (200+). This was a subjective process that proceeded by trial and error.

With the Cyprus data, a superior image was produced by an alternative technique created by the author (Fig. 5.2). Several commonly used directional filters were tried and visually evaluated for the number, direction and continuity of the linears they highlighted.

The DNs of the brightest linears were queried to find their range. The lower end of this range was stretched to zero and the higher end to 255. Different cut-off points were experimented with by decreasing the break-point until an image remained that showed all of the major linears. This image portrayed the lineaments as bright white lines against a black background. This thresholded image was then added to a linearly enhanced TM 5 image. The result maintained all of the lithological information from band 5, while having the major linear trends highlighted as white lines (Fig. A2.15). An alternative would be to display the filtered linears as vectors on top of an enhanced band 5. This would add to the complexity of processing; the linears, however, could then be displayed in a different colour.

5.2 Hardcopy Output

The final stage of the image analysis portion of this research was the production of hardcopy plots of selected image enhancements. These plots were used for evaluation of the enhancements, for interpretation and to be used during field work. The format of the images was designed for ease of interpretation and to facilitate their use during field research.

GeoQuest International interpreted and assisted in the evaluation of the image products. As the company is based in Toronto, hardcopy imagery were sent to them during the course of the research except for on three occasions when Dennis Jones of GeoQuest Int. visited the CCRS in Ottawa. The author's familiarity with the information requirements

of the exploration model allowed initial evaluation to be performed interactively on the image analysis system video display. Once a final suite of enhancements was selected, it was plotted to facilitate interpretation by a photo-geologist.

Aerial photography has been available as a tool to the exploration geologist for decades. Transfer of remote sensing technology can best be achieved by recognising the existing familiarity of geologists with aerial photography and thematic maps. The hardcopy images of the Troodos Massif were very well received by GeoQuest Int. (details of their evaluation are discussed in the next chapter). The images presented the information sought with photographic quality and in a map-like format. Images were geometrically corrected to a topographic map base and printed on photographic paper by a Kodak XL7700. The image plotting software allowed annotation of a UTM grid, border lines and a scale.

6.0 DISCUSSION AND CONCLUSIONS

6.1.0 Discussion of Results

6.1.1 The Target

The co-operative relationship between GeoQuest Int. (industry) and the author (research) on which this thesis is based, is in many ways an exception rather than the rule. Geologists simply will not discuss the nature of their exploration in any great detail until the mining rights of the property have been acquired. In many cases successful

methodologies are never made public as this could assist competitors. GeoQuest Int. has allowed the publication of the methodology from the beginning of the research with only a few necessary omissions. Due to the proprietary nature of the final image interpretations, they are not be presented in this thesis. This necessary restriction has no implication on the effectiveness of individual enhancements to meet the exploration performance goals. The target of the exploration effort was the copper, zinc and associated mineralization found near the Basal Unit (feeder material) - Upper Pillow Lava (extrusive material) contact. This stage of the exploration program, supported by this research, required delineation at a scale of 1:50,000 of the Basal/Pillow lithologic boundary, major structural features of a particular trend, and if possible, areas of Basal Unit with a thin cap of Pillow Lavas. GeoQuest Int. stated that, based on the operations-oriented methodology presented in this thesis, these information goals could be feasibly achieved using Landsat TM imagery (Jones correspondence 1993, note: for cited correspondence from Jones see Appendix A1).

Jones' (1990) exploration proposal suggested that the Basal/Pillow contact was important from a mineral genesis perspective. This was supported by the location of a number of known mines and prospects existing near this boundary, and by geophysical evidence. Jones (1990) was further convinced from geophysical evidence that certain areas currently mapped as Pillow Lavas were in fact Basal Unit with a thin cap of Pillow Lavas. The true geologic profile of these areas could not have been determined by traditional mapping techniques as the field geologist largely determines lithology based

on exposed rock. Specific faults and their relation to the Basal/Pillow contact, and "hidden" Basal Unit are also important in locating areas of highest mineralization potential. To assist in providing the information necessary to formulate a mineral emplacement model and predict mineral occurrences, several TM image products suggested in the relevant scientific literature were produced by the author and evaluated by Dennis Jones.

6.1.2 Simple False Colour Composites

Four TM simple false colour composites were considered: (4,5,7), (3,4,5), (1,3,5), and (7,4,1). TM 4,5,7 and 3,4,5 proved to be inappropriate for the Troodos Massif. Vegetation would be a large contributor to these band combinations (TM 4 & 5) and these images were immediately discarded. TM 1,3,5 proved to be the best for discriminating the target contact as there was a strong colour and textural contrast between the Basal Unit and Pillow Lavas (Jones correspondence 1993). TM 4 was specifically left out of this FCC to avoid mapping vegetation. Fig. A2.1 shows a 1:375,000 TM 1,3,5 image of the entire Troodos Massif. Fig. A2.10 shows a 1:250,000 TM 1,3,5 image of the eastern edge of the Troodos Massif. These images have been presented in this format due to space limitations.

The steel-blue Basal Unit has a rough texture which would be expected from the tough-weathering ophiolites which comprise this group. This is markedly different from the

yellow Pillow Lavas whose porous surface facilitates weathering and is evident in its smooth texture. These tonal and textural differences made delineation relatively easy.

Table 5.6. Expected image tones for certain ground targets for a TM 1,3,5 FCC, based on Figure 3.1.

	Colour TM	Red 1	Green 3	Blue 5	result
vegetation		low	low	med.	dark blue
hydroxyl		high	high	high	pale white
FeOxide		low	med.	high	blue to blue-green

In Figures 3.1, spectral responses of pure target material under laboratory conditions are given. Table 5.6 lists expected image tones based on these responses for a TM 1,3,5 FCC. The iron-rich, hard rocks of the Basal Group do not weather easily. This has resulted in a rugged topography with poor soil creation. Their tone on the image is dark as their rough terrain has deep shadows and as ultra-mafic rocks they are dark in colour in TM 1 and 3. Their steel-blue colour results largely from a strong reflectance in TM 5. The pillow lavas are physically porous rocks which weather easily to form gentle topography with good soil development. Jones (pers. comm. 1992) remarked that the pillow lavas have developed soils and a sparse vegetation cover. The yellow colour of the pillow volcanics on the TM 1,3,5 image may result from the dry, dead grass cover lowering the TM 5 reflectance.

Jones (correspondence 1991 & 1993) judged the interpretations of the imagery to adequately meet the information requirements of the exploration model, based on

personal geologic knowledge combined with geophysical evidence. The textural component of the visual interpretation was very important, particularly in the areas suspected to be shallowly buried Basal Unit. This aspect of the interpretation placed particular emphasis on the experience of the interpreter.

Both linear and histogram equalization contrast enhancement of the selected false colour composites proved useful. Jones (correspondence 1992a) observed that it took some time to become accustomed to interpreting satellite imagery. This should be expected as the colour associations and perspective of satellite imagery differ from normal visual colour perception and perspective. The histogram equalization stretch produced a better overall picture in that both with-in unit variations and between-unit variations had high contrast. This overall enhancement was judged the best preliminary product for the interpreter to build a familiarity with the image. For the same reason, Jones (correspondence 1992a) also preferred working with the same image in stages, each successive image having a finer scale. Histogram equalization images were provided at 1:250,000, 1:100,000 and linearly stretched images of 1:50,000. The image analysis software allowed the use of masks to limit the gathering of statistics for LUT generation. The sampling mask was drawn over areas of both Basal Unit and Pillow Lavas. After training with the histogram stretched images, Jones (correspondence 1992a) moved to the linearly enhanced TM 1,3,5. This image had less overall tonal contrast, but the finer within-unit subtleties were maintained. These subtle features could not be interpreted on the histogram equalization

images as the small digital range of these surface variations were given a small weighting by the enhancement algorithm.

TM 7,4,1 produced the next best image. As can be seen in Fig. A2.2 & 11, the iron-oxide stained Basal Unit shows up as reddish hues and the Pillow Lavas as mauve. The largest contribution to the colour of the Pillow Lavas is the presence of clays, and to a lesser extent some iron-staining which is to be expected in a terrain as old as Cyprus (Table 5.7). This image is valuable in that areas where vegetation may obscure outcrop can be assessed. Vegetation is displayed in green hues. Differentiation is possible between the Basal Unit and Pillow Lavas, and some areas show within unit variations well. In the TM combinations 3,4,5 and 4,5,7 contrast between these target lithologies was poor.

Table 5.7. Expected image tones for certain ground targets for a TM 7,4,1 FCC, based on Figure 2.

	Colour TM	Red 7	Green 4	Blue 1	result
vegetation		low	high	low	green
hydroxyl		med.	high	high	cyan (pale)
FeOxide		high	med.	low	reddish-brown

6.1.3 Complex False Colour Composites

The complex false colour composites that were made for interpretation consisted of a PCA of TM 5/4, 4/3, 5/7 (Fig. A2.4 & 13), and a Crosta Composite (Fig. A2.8 & 14). The plain ratio image of 5/4, 4/3, 5/7 (Fig. A2.2 & 12) and the individual PCs of PCA

of 6 TM bands (A2.5-7) were included for illustrative purposes. They are important in that they represent conceptual and physical steps in producing final images. Jones (correspondence 1992a & 1993) found value in both of these products, and considered the PCA ratio image the best overall product. The PCA ratio image mapped the Basal/Pillow contact well and the Crosta image showed many "anomalous" areas; those that were both iron-stained and argillized¹.

In the PCA ratio image it is possible to delineate the target lithologies, evaluate extent of vegetation cover and the relative distributions of iron oxides and clays, including anomalously high areas. Unlike this image, the true potential of Crosta Composite will only be known after some initial field investigation. The differentiation between target lithologies varied between areas from weak to good. The real value of this image is that areas which have both a high iron-oxide and clay content are highlighted in a manner more obvious than on any other of the FCC. From the colour assignment (RGB) of the Crosta PCs these areas would show up as white areas on the image. Jones (correspondence 1993) noted that this image appears promising in that white areas correspond with some mines, prospects, and suspected mineralization. This complex image was valuable in helping to identify and evaluate areas that should be investigated in the field. Once the relation between image colour and ground features is understood from field work, the degree of importance to be given to the interpretation of the Crosta image can be determined.

¹High clay content resulting from hydrothermal alteration.

6.1.4 Structural Enhancement

The custom enhanced, black and white TM 5 image (Fig. A2.15) proved to be a useful product for lineament/structural interpretation. Programmable filters were used to edge-enhance linear features trending in two compass directions. This was then added back into the TM band 5 to produce a monochrome image that had both linears and general lithology highlighted. Jones (pers. com. 1993) found that this was the best product to start with for a structural interpretation, and features found on the TM 5 image could then be looked for on the simple and complex false colour composites, and visa versa. The relationship between lithology and structural features was important, and Jones (correspondence 1993) reported that the final structural interpretation weighed significantly in the corroboration of the exploration model.

6.1.5 Hardcopy Output

While it is true that remotely sensed imagery was successfully interpreted in the 1970s plotted out on daisy-wheel line printers, and in the 1980s on ink-jet plotters, the acceptance of this technology in practice will be greatly enhanced by the new printing technologies of the 1990s.

Image interpretation is greatly facilitated by high quality display. Before this decade, this was only available by interpretation from a video monitor. This caused eye strain, the curved screen was difficult to place an overlay on, interpretation was tied to access to an image analysis system with a high quality monitor, and a limited portion of a scene

could be viewed at any one time at a specific scale. The printer used for this research was a Kodak XL7700. It allowed high-definition printing on photographic paper. The software could generate output images annotated with titles, a grid, and scale bar. They were considered very impressive by Dennis Jones and by many people when presented at the 1993 ERIM Thematic Symposium on Geologic Remote Sensing. It is the author's opinion that output technology has now caught up to the visual potential of remotely sensed imagery. This can only help to reduce the barriers to technology transfer and facilitate the use of imagery in practice as has been witnessed by this research.

6.2 CONCLUSIONS

The decade of the 90's will present to the Canadian geological industry grave economic and environmental challenges. It will be only through new technological innovation, professional practices, and attitudes that we can hope to secure continued supply and management of vital resources. Remote sensing technology is an evolving new tool that couples spatially continuous and timely geographic information and the power of computers. Successful exploitation of remote sensing in practice will greatly affect our ability to meet these challenges. Remote sensing research and methodologies developed from within an institutional paradigm must now evolve to meet the needs of a wider segment of the potential community of users. The resource sector demands specific functionality in a methodology to allow the information value of the data gathered to be realised quickly and efficiently under operational constraints; as a key input into the decision making process, and as a contribution to longer term resource monitoring and

management in an archival role. Changing economic, social and scientific paradigms are driving efforts to address these needs from a technology transfer perspective. To this end, the author stresses the need for, as outlined in this thesis, developing operational methodologies from the perspective (historical and present) of the identified users.

Building applications for operational use from within the current scientific paradigm is challenging. The goals and definitions of success in problem resolution have traditionally been different in research environments and industry. A scientific approach would fully investigate all possible methodologies, or create new strategies, that optimally (from the researcher perspective) solve a problem. From a technology transfer perspective the goal would be to identify existing, or create new methodologies, that can successfully solve a problem from a client's perspective. The solution may not necessarily be optimal, but it performs an application to the desired performance standards, with the levels of technology of the user, at an affordable cost in resources. The gap between these two approaches is narrowing as a result of the changing ground rules in which we work. Success in technology transfer is achieved by bridging this gap through planning. A structured approach which requires an understanding of the science a methodology is based on, the technology that will be used, the user's perceived and actual needs, and the realities of their paradigm.

This research has demonstrated that the risks associated with incorporating remote sensing, and for that matter, any new technology, can be understood and controlled

through systematic project planning which places problem solving above technology. In the case reported here, the work has passed from the research and development stage successfully to the commercialization stage. The target lithologies were confidently mapped to provide the information required by the mineral emplacement model which ultimately identified areas of likely mineralization. The commercial application of the methods developed in this thesis have resulted in demonstrated support of the exploration model proposed by GeoQuest International (Jones, correspondence 1992b, 1993). In turn, these results have been sufficiently encouraging to enable GeoQuest Int. and its partners to secure funding for an exploration program. The demonstrated success and the generic nature of this remote sensing application for semi-arid environments was recognised by an award of Best of Session when it was presented at the 1993 ERIM Thematic Conference on Geologic Remote Sensing, the selection of an image of Cyprus for the front cover of both the CCRS and Surveys and Mapping Sector annual reviews, and aspects of this methodology are currently being investigated by exploration firms for application in Australia, Costa Rica and California with the assistance of the author.

The technology transfer model used in this thesis will continue to be refined after each application to a project, such as this co-operative effort with GeoQuest International. The remote sensing methodology developed could possibly be further evaluated and improved through application at different sites and the addition of new image analysis techniques as they arise. This may happen if the other geological firms currently applying aspects of this methodology were to publish the results, however, the author does not hold much

hope of this happening in the highly secretive exploration industry. Advancements to the methodology may be investigated by GeoQuest Int. if initial field exploration is successful as more monies would likely be made available.

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**APPENDIX
A1
Correspondence**

GEOQUEST

INTERNATIONAL

August 2, 1991

Mr. David Davidson
Canada Centre for Remote Sensing
Technology Transfer Section
2464 Sheffield Rd.
Ottawa, Ontario
K1A 0Y7

Dear David,

I am returning these three overlays of the interpreted faults and structures as plotted by Norm Paterson. The reference points which are marked on them are the same as Christine used for the colour-shaded, filtered aeromagnetic maps.

There are three classes of faults and one type of magnetic structure interpreted. The regional faults probably have the greatest significance from a genetic point of view because they might reflect the deep-seated fractures which acted as conduits for the hydrothermal fluids and hence for the mineralization. However, the intermediate and shallow faults sometimes have an influence on exactly where the mineralization is localized and therefore they cannot be discounted.

I find Norm's interpretation of the magnetic structures interesting because several of the mines or known mineral showings fall within these structures. The interpretation of these structures came about almost by accident. Norm decided to produce a map of the residual component of the total magnetic field, not really thinking it would show anything interesting. However, the magnetic structures seem to correlate quite well with exposed blocks of Basal Group and they may help us identify buried but uplifted Basal Group blocks. This would be significant because our model suggests ~~that the magnetic structures are related to the Basal Group~~ and mineral deposits in Cyprus.

Good luck with your processing and best regards,

Pennis

Pennis Jones

Cardinal Newman International #178066-1, 1997-1998, 1999-2000, 2001-2002, 2003-2004, 2005-2006, 2007-2008, 2009-2010, 2011-2012, 2013-2014, 2015-2016, 2017-2018, 2019-2020, 2021-2022, 2023-2024, 2025-2026, 2027-2028, 2029-2030, 2031-2032, 2033-2034, 2035-2036, 2037-2038, 2039-2040, 2041-2042, 2043-2044, 2045-2046, 2047-2048, 2049-2050, 2051-2052, 2053-2054, 2055-2056, 2057-2058, 2059-2060, 2061-2062, 2063-2064, 2065-2066, 2067-2068, 2069-2070, 2071-2072, 2073-2074, 2075-2076, 2077-2078, 2079-2080, 2081-2082, 2083-2084, 2085-2086, 2087-2088, 2089-2090, 2091-2092, 2093-2094, 2095-2096, 2097-2098, 2099-2100, 2101-2102, 2103-2104, 2105-2106, 2107-2108, 2109-2110, 2111-2112, 2113-2114, 2115-2116, 2117-2118, 2119-2120, 2121-2122, 2123-2124, 2125-2126, 2127-2128, 2129-2130, 2131-2132, 2133-2134, 2135-2136, 2137-2138, 2139-2140, 2141-2142, 2143-2144, 2145-2146, 2147-2148, 2149-2150, 2151-2152, 2153-2154, 2155-2156, 2157-2158, 2159-2160, 2161-2162, 2163-2164, 2165-2166, 2167-2168, 2169-2170, 2171-2172, 2173-2174, 2175-2176, 2177-2178, 2179-2180, 2181-2182, 2183-2184, 2185-2186, 2187-2188, 2189-2190, 2191-2192, 2193-2194, 2195-2196, 2197-2198, 2199-2200, 2201-2202, 2203-2204, 2205-2206, 2207-2208, 2209-2210, 2211-2212, 2213-2214, 2215-2216, 2217-2218, 2219-2220, 2221-2222, 2223-2224, 2225-2226, 2227-2228, 2229-2230, 2231-2232, 2233-2234, 2235-2236, 2237-2238, 2239-2240, 2241-2242, 2243-2244, 2245-2246, 2247-2248, 2249-2250, 2251-2252, 2253-2254, 2255-2256, 2257-2258, 2259-2260, 2261-2262, 2263-2264, 2265-2266, 2267-2268, 2269-2270, 2271-2272, 2273-2274, 2275-2276, 2277-2278, 2279-2280, 2281-2282, 2283-2284, 2285-2286, 2287-2288, 2289-2290, 2291-2292, 2293-2294, 2295-2296, 2297-2298, 2299-2300, 2301-2302, 2303-2304, 2305-2306, 2307-2308, 2309-2310, 2311-2312, 2313-2314, 2315-2316, 2317-2318, 2319-2320, 2321-2322, 2323-2324, 2325-2326, 2327-2328, 2329-2330, 2331-2332, 2333-2334, 2335-2336, 2337-2338, 2339-2340, 2341-2342, 2343-2344, 2345-2346, 2347-2348, 2349-2350, 2351-2352, 2353-2354, 2355-2356, 2357-2358, 2359-2360, 2361-2362, 2363-2364, 2365-2366, 2367-2368, 2369-2370, 2371-2372, 2373-2374, 2375-2376, 2377-2378, 2379-2380, 2381-2382, 2383-2384, 2385-2386, 2387-2388, 2389-2390, 2391-2392, 2393-2394, 2395-2396, 2397-2398, 2399-2400, 2401-2402, 2403-2404, 2405-2406, 2407-2408, 2409-2410, 2411-2412, 2413-2414, 2415-2416, 2417-2418, 2419-2420, 2421-2422, 2423-2424, 2425-2426, 2427-2428, 2429-2430, 2431-2432, 2433-2434, 2435-2436, 2437-2438, 2439-2440, 2441-2442, 2443-2444, 2445-2446, 2447-2448, 2449-2450, 2451-2452, 2453-2454, 2455-2456, 2457-2458, 2459-2460, 2461-2462, 2463-2464, 2465-2466, 2467-2468, 2469-2470, 2471-2472, 2473-2474, 2475-2476, 2477-2478, 2479-2480, 2481-2482, 2483-2484, 2485-2486, 2487-2488, 2489-2490, 2491-2492, 2493-2494, 2495-2496, 2497-2498, 2499-2500, 2501-2502, 2503-2504, 2505-2506, 2507-2508, 2509-2510, 2511-2512, 2513-2514, 2515-2516, 2517-2518, 2519-2520, 2521-2522, 2523-2524, 2525-2526, 2527-2528, 2529-2530, 2531-2532, 2533-2534, 2535-2536, 2537-2538, 2539-2540, 2541-2542, 2543-2544, 2545-2546, 2547-2548, 2549-2550, 2551-2552, 2553-2554, 2555-2556, 2557-2558, 2559-2560, 2561-2562, 2563-2564, 2565-2566, 2567-2568, 2569-2570, 2571-2572, 2573-2574, 2575-2576, 2577-2578, 2579-2580, 2581-2582, 2583-2584, 2585-2586, 2587-2588, 2589-2590, 2591-2592, 2593-2594, 2595-2596, 2597-2598, 2599-2600, 2601-2602, 2603-2604, 2605-2606, 2607-2608, 2609-2610, 2611-2612, 2613-2614, 2615-2616, 2617-2618, 2619-2620, 2621-2622, 2623-2624, 2625-2626, 2627-2628, 2629-2630, 2631-2632, 2633-2634, 2635-2636, 2637-2638, 2639-2640, 2641-2642, 2643-2644, 2645-2646, 2647-2648, 2649-2650, 2651-2652, 2653-2654, 2655-2656, 2657-2658, 2659-2660, 2661-2662, 2663-2664, 2665-2666, 2667-2668, 2669-2670, 2671-2672, 2673-2674, 2675-2676, 2677-2678, 2679-2680, 2681-2682, 2683-2684, 2685-2686, 2687-2688, 2689-2690, 2691-2692, 2693-2694, 2695-2696, 2697-2698, 2699-2700, 2701-2702, 2703-2704, 2705-2706, 2707-2708, 2709-2710, 2711-2712, 2713-2714, 2715-2716, 2717-2718, 2719-2720, 2721-2722, 2723-2724, 2725-2726, 2727-2728, 2729-2730, 2731-2732, 2733-2734, 2735-2736, 2737

lavas but that the upper lavas have been altered somewhat by the effects of cold seawater percolation.

Geomatics have produced 1:250,000 black and white images of TM 3,4 and 5 with ENE and NNW structure filters. These were useful for plotting of lineaments, although as with almost all the images I found it was necessary to study them for quite some time before my eye became accustomed to what I was seeing. Several of the mines and known prospects (Geomatics has the updated file on these locations if you want them) lie close to either or trending faults. These may be equivalent to the and faults that seem to control some of the massive sulphide deposits that are presently forming on the Pacific Ocean floor.

As for the 1:100,000 scale images, I liked them all but my favourite ones to work with were the TM 1,3,5 and the PCA of TM 5/4,4/3,5/7. These were great for picking out the Basal Group.

Crater
I have two 1:50,000 scale images of the Mathiati area but so far I have not made much use of them. Soon I hope to relate the mines and prospects to individual pixels of these images and see if there is anything of significance.

One thing that I have noticed time and again is that you cannot depend on any one single image, no matter how good. It is essential to look at a number of different images in order to bring out all the details.

Well, I hope the above comments are of some help. If you have any questions, I shall be back in Toronto on October 9th. Have a good holiday.

Yours truly,

Dennis Jones

GEOQUEST

INTERNATIONAL

21 August 1993

Mr. David Davidson
Canadian Centre for Remote Sensing
588 Booth St.
Ottawa, Ont.
K1A 0Y7

Dear David:

This may be an appropriate time to review the work we did together on remote sensing data from Cyprus. Firstly, let me say that the contribution made by you and the Canada Centre for Remote Sensing was crucial to the overall success of the project. As a small consulting company, GeoQuest has neither the hardware nor software to competently handle the sophisticated enhancements which you carried out on the T.M. satellite data. These services could, of course, have been contracted out to a consulting company but as you know some of the work we were doing involved developing new techniques with no guarantee of success and with no client funding the initial stages of the work the costs of contracting out the project would have been prohibitively expensive.

There were two principle objectives of the T.M. studies:- structural interpretation and identification of lithologies, particularly the critical division between the copper-bearing pillow lavas and the basal group. The T.M. images were very useful for delineating linear structures which, in some cases were interpreted as marking faults either parallel or transverse to the original mid-ocean spreading centres which produced the pillow lavas and their associated mineral deposits. Several of the mines and known prospects lie close to either northeast or northwest trending faults. These may be equivalent to the axial and transverse faults that seem to control some of the massive sulphide deposits that are presently forming on the Pacific Ocean floor in a geological environment considered to be similar to the one which gave rise to the Cyprus deposits.

The photographic products of the T.M. images were superb. I liked the Crosta H, P.F. F image at a scale of 1:250,000. It gave a good outline of the lava/sediment contact, including some of the umberiferous (Fe and Mn rich) sediments in the north. The latter may be closely spatially related to copper mineralization.

The generally iron-stained Basal Group which occurs within the lavas shows up well as brownish polygons, particularly in the Mathiati area. The altered material in the Amiandos asbestos mine, the Mavrovouni tailings site and the Skouriotissa mine dumps also show up well.

As for the 1:100,000 scale images, I liked them all but my favourite ones to work with were the TM 1,3,5 and the PCA of TM 5/4,4/3,5/7. These were great for picking out the Basal Group.

In short, we more than met our objectives and the results were of such a high standard that it proved not to be difficult to find a client to fund further development of the ideas and concepts we had been working on. Thus, we were able to move from an experimental to a fully operational stage in a relatively short time. In this latter phase of the project, it was possible to develop a new and innovative technique of combining lithological and structural data from the T.M. with enhanced aeromagnetic data. With my extensive ground knowledge of Cyprus geology and with a comprehensive geological model for the emplacement of copper deposits in this environment it was possible to construct a Target Prioritization Map. This map will be used for the selection of Prospecting Permits, over which ground follow-up work will be carried out. In this way, we can save a lengthy and costly ground reconnaissance program to identify our target areas.

In summary, the early development work we did together on the methodology adopted in the Cyprus project was instrumental in leading to a funded exploration project which might otherwise not have been possible. Furthermore, some of the techniques developed are likely to have applications in other exploration programs.

Once again, thank you for all your assistance, ideas and encouragement in this project.

Yours truly,

Dennis Jones

GEOQUEST

INTERNATIONAL

15 December 1992

Mr. J.C. Henein
Director of Applications Division
Canada Centre for Remote Sensing
588 Booth St
Ottawa, Ont.
K1A 0Y7

Dear Mr. Henein:

I am writing to thank you for the cooperation that has been extended to me by CCRS.

Some time ago during a conversation with Bill Bruce of the Technology Transfer Training and Development Section, we realized that we shared an interest in the satellite imagery of Cyprus. Bill had already done some studies on this and I had worked on a mineral exploration project for the United Nations in Cyprus.

Late in 1990, Bill and I realized that there might be an opportunity for cooperation to advance the remote sensing studies of Cyprus. This led to working closely with Bill and David Davidson in investigating the possibility of integrating aspects of satellite imagery, existing airborne geophysical data and mapped ground features such as mines, prospects, gossans etc.

This work indicated the potential for this approach and it ultimately led to the start-up of a commercial exploration venture using the services of my company, GeoQuest International, and other Canadian consulting groups.

I feel this has been an excellent example of creative cooperation between government and business and I would like to see more of it. The work has helped us to understand and develop a technology which, although being used abroad in this case, has potential for use in geologically similar terrains in Newfoundland, and it has acted as a catalyst for generating consulting work for Canadian companies.

Yours truly,

Dennis Jones

**APPENDIX
A2
Cyprus Imagery**

CYPRUS TM 1(r), 3(g), 5(b)

1:375,000

Scale 1:375,000
 1:375,000
 1:375,000

Figure A2-2

CYPRUS TM 7(r), 4(g), 1(b)

1:375,000

Kilometers 0 10 20
Miles 0 10 20

CYPRUS PCA OF TM 1,2,3,4,5,7
PC6 Hemalite, 1:375,000

Kilometers 0 10 20
Miles 0 10 20

Figure A2-9

GEOLOGICAL MAP OF CYPRUS**SCALE 1:250,000**

Source: Geological Survey Dept.
Ministry of Agriculture and Natural
Resources, Gov't. of Cyprus.

CYPRUS TM 1(r), 3(g), 5(b)

CCRS - Tech. Transfer, Training & Development Sect.

1:250 000 Scale

10

11

12

13

140000m E.

CYPRUS TM 7, 4, 1

histogram equalization enhancement

1:250 000 Scale

Figure A2-12

CYPRUS TM 5/7 (r), 4/3 (g), 5/4 (b)

CCRS - Tech. Transfer, Training & Development Sect.

1:250 000 Scale

Figure A2-13

CYPRUS PCA of TM 5/4, 4/3, 5/7

FeOxides=red, Vegetation=green, Hydroxyls=blue

1:250 000 Scale

Kilometers 10 0 10
Miles 10 0 10

CYPRUS TM ENHANCEMENT

(R) Hydroxyl, (G) Hydroxyl+FeOxides, (B) FeOxides

1:250 000 Scale

CYPRUS TM 5 Structural Enhancement

NESW & NWSE linears enhanced

1:250 000 Scale

END

1 9-07-94

FIN