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REMOTE SENSING IN THE SEARCH FOR METALLIC ORES: A REVIEW OF CURRENT PRACTICE AND FUTURE POTENTIAL

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Abstract

Remote sensing denotes the aerospace practices of measuring the ultraviolet, visible, infrared and microwave radiations emitted and reflected from the surface of the Earth and from the atmosphere. As defined here, remote sensing excludes the more conventional methods of geophysics and geochemistry.

Aerial photography, side-looking airborne radar and airborne thermal infrared scanning are remote-sensing techniques that can currently provide the mineral industry with high-resolution data to meet specific requirements at acceptable costs. With respect to mineral exploration, other types of airborne remote sensing are largely experimental.

Several systems for remote sensing from satellites can be utilized for mineral exploration. Undoubtedly, the most universally available and most cost-effective type of remote sensing from the prospector's point of view is multispectral scanning by NASA's series of experimental Landsat satellites. Cloud-cover permitting, these satellites provide repetitive data of moderate resolution at low cost for many parts of the world.

Neither airborne nor orbital remote sensing are "stand alone" exploration techniques. Their effectiveness is optimized by integration, in the usual exploration manner, with other sets of data from geological, geophysical and geochemical surveys. While visual interpretation is the most widely used method of analysis, digital processing can provide improved images, enhancements and spectral discriminations that may meet specific exploration needs. However, digital analysis as a general tool for mineral exploration should still be viewed as largely experimental.

While atmospheric attenuation, heavy vegetational cover and "inadequate" spectral and spatial resolutions may cause problems, the major current limitations of remote sensing for mineral exploration are: (1) a lack of significant penetration below the surface of the ground, and (2) an inability to classify rocks and soils except in a generalized way. Despite these limitations, remote sensing, and in particular the complementary tools of Landsat and aerial photography, can provide much useful information at relatively low cost.

The principal contemporary benefits accruing from remote sensing in the search for metallic ores are: rapid regional reconnaissance, access to remote areas, and mapping of geological structures and formational continuity. While discovery of mineralization through both airborne and orbital remote sensing has been reported, such discovery of an economic mineral deposit has not been documented in the literature.

National remote sensing programs, both in Canada and abroad, have generally failed to provide adequate incentives for essential development of practical applications in contradistinction to strong support for development of technology to generate and process data.

In the future, airborne remote sensing will develop as a specialized source of detailed information to meet recognized goals. In particular, aerial thermography will be more widely used in arid terrains. Visual interpretation of Landsat data is already developing into a widely-used exploration tool for regional reconnaissance. Digital analysis of such data will soon achieve practicality for a few specific applications, particularly in arid regions. However, because of the increasing emphasis on subsurface exploration, relevant development of remote sensing should be focused in a co-ordinated program of demonstration projects. Specific objectives for such projects might include: (1) inexpensive interpretive techniques; (2) case histories related to rock alteration, soil contrasts and biophysical anomalies associated with orebodies; (3) classification of linears and their relation to ore; (4) integration of remote sensing with other exploration data, and (5) demonstration of techniques in an exploration mode.

Résumé

On désigne par télédétection les techniques aérospatiales mises en oeuvre pour mesurer les rayonnements ultraviolet, visible, infrarouge et de micro-ondes, émis par la surface de la Terre et réfléchis par elle, ou émis par l'atmosphère. Ainsi définie, la télédétection exclut les méthodes classiques de la géophysique et de la géochimie.

Les techniques de télédétection peuvent fournir à l'industrie minérale des données très fouillées pour répondre à certaines demandes particulières tout en restant à des prix relativement bas; ces techniques sont, la photographie aérienne, le radar à faisceau latéral et le balayage thermique en infrarouge. En ce qui concerne la prospection minérale, les autres techniques de télédétection aéroportée sont encore à l'état expérimental.

Pour la prospection minérale, on peut utiliser plusieurs systèmes de télédétection à partir de satellites. Le plus répandu et le plus rentable du point de vue du prospecteur, est sans conteste le balayage multispectral des satellites expérimentaux Landsat de la NASA. Lorsque la nébulosité est favorable, ces satellites fournissent, à intervalles répétés pour plusieurs régions du globe, des données exploitables, avec une résolution moyenne et pour un coût peu élevé.

Les techniques d'exploration aéroportée et de télédétection orbitale ne sont jamais utilisées seules. Leur efficacité est optimale si on les intègre, comme on fait toujours en prospection, à d'autres données provenant de levés géologiques, géophysiques et géochimiques. L'interprétation visuelle est la méthode d'analyse la plus largement utilisée, mais le traitement des données numérales peut donner de meilleures images plus contrastées, avec une bonne séparation spectrale qui peuvent répondre à certains besoins spécifiques de la prospection. Cependant, l'analyse numérique prise comme une technique générale d'exploration minérale doit être considérée comme une méthode largement expérimentale.

Alors que l'atténuation atmosphérique, la densité de la végétation et l'insuffisance des pouvoirs de résolution spectrale et spatiale peuvent créer des problèmes, les principales limitations de la télédétection pour l'exploration minérale sont: 1) le manque de pénétration dans le sol, 2) l'incapacité de définir de fa on suffisamment spécifique les roches et les sols. Malgré ces limitations, la télédétection, et en particulier les outils complémentaires que sont les satellites Landsat et la photographie aérienne, peuvent donner des renseignements très utiles à des prix relativement bas.

Les principaux avantages actuels de la télédétection dans la recherche des gîtes métallifères sont: reconnaissance régionale rapide, accès aux régions les plus lointaines, possibilité de faire le levé des structures géologiques et de suivre la continuité des formations. On a signalé une découverte de minéralisation par les techniques de télédétection aéroportée et orbitale, mais on n'a pas décrit dans la littérature la découverte d'aucun gisement minéral présentant un intérêt économique.

Les programmes nationaux de télédétection, au Canada et à l'étranger n'ont pas, en général, réussi à encourager la mise au point d'applications pratiques alors qu'ils ont porté, avant tout, sur la mise au point des techniques de production et de traitement des données.

Dans l'avenir, la télédétection deviendra une source spécifique de renseignements détaillés permettant de répondre à des objectifs définis. En particulier, la thermographie aérienne sera plus largement utilisée en terrain aride. L'interprétation visuelle des données Landsat est en voie de devenir une technique d'exploration largement utilisée en reconnaissance régionale. L'analyse numérique des données Landsat deviendra bientôt pratique courante pour certaines applications spécifiques, en particulier dans les régions arides. Cependant, étant donné l'importance croissante que prend la prospection par les méthodes de sub-surface, l'expansion de la télédétection devrait se concentrer sur un programme coordonné d'opérations de démonstration. Les objectifs spécifiques de ces opérations pourraient comprendre: 1) des techniques d'interprétation peu coûteuses, 2) des cas concrets se rapportant à l'altération des roches, aux contrastes des sols et aux anomalies biophysiques associées à des gîtes minéraux; 3) une classification des linéaments et de leur relation avec la présence de minerais; 4) l'intégration de la tétédétection aux autres données d'exploration; 5) la démonstration des techniques dans des conditions de prospection.

INTRODUCTION

In conducting their search for metallic ores, explorationists are faced with a severe problem of selecting and acquiring information that can advance their specific work. A great variety of data, or factual knowledge, may feed into an exploration program. The sources of such data are many, their scale of observation is greatly variable and the potential volume of their details is vast. For example, in addition to personal observation in the field, sources of exploration data may include: thin sections for microscopic analysis; samples of rock, soil and water for chemical analysis; geophysical maps for extrapolating beyond the outcrop; aerial photographs for stratigraphic trends; and radioactive ages for chronological relationships. Recently, these sources have been augmented by spectral surveys from airborne and orbital platforms. Each source of data, in its own way, presents a wealth of detail. No one source can stand alone as the fount of geological information and none can serve as a substitute for another in the sense of completely replacing it.

This paper is concerned primarily with remote sensing and the integration of relevant data into information, or instructional knowledge, which may be used to make appropriate decisions in an exploration program. As is well known, such information includes: (1) peripheral factors e.g. terrain conditions, current weather, environmental changes; (2) broad inferences and conditional analogies that lead to the recognition of exploration targets; (3) specific indicators that suggest the presence of mineralization; and (4) definitive analyses that establish the presence of ore. Remote sensing can, and regularly does, provide some information in each of the first three classes. However, it should be immediately obvious that no type of remote sensing, however defined, can provide the specific information required to establish the presence of ore.

WHAT IS REMOTE SENSING?

In its broadest scope, remote sensing can be defined as: the measurement or acquisition of information about some property of an object or phenomenon by means of a recording device that is not in physical or intimate contact with the feature under study (after Reeves et al., 1975, p. 2102). However, such a definition includes, among others, such exploratory practices as geophysics and geochemistry as well as astronomy and medical diagnosis. For some years, a few practitioners have argued that the concept of remote sensing should be narrowed to represent a practical paradigm i.e. an accepted model or body of knowledge which serves, for a time, to guide the collective research and practice of a specialized community of scientists or technologists (after Kuhn, 1970). Thus, the following practical definition is used herein (c.f. Gregory, 1972; Gregory and Moore, 1975):

> *Remote sensing denotes the aerospace practices of measuring the ultraviolet, visible, infrared and microwave radiations emitted and reflected from the surface of the Earth and from the atmosphere.*

So defined, remote sensing has little capability for measuring below the surface of the ground, except for the limited penetration of low-frequency microwaves. This restricted meaning includes most work reported as remote sensing (c.f. Gregory, 1972; Anon., 1977) but does not satisfy the purists. On the other hand, there are valid reasons for including gamma radiation in the definition although current practice tends to place it in exploration geophysics. The argument, however, is really pedantic because the paradigm of remote sensing will surely expand and ultimately subdivide. Over the years, geophysics has split into exploration geophysics, solid earth geophysics and atmospheric physics and then, subsequently, exploration geophysics has split into magnetics, gravity, electromagnetics and the other practical paradigms that were represented in this symposium.

FUNCTIONS OF A REMOTE SENSING SYSTEM

A restricted definition of remote sensing does not imply that the technology of remote sensing comprises a relatively few tools. Indeed, there is great variety in the choice of possible components for a remote sensing system. However, for the purposes of this review, the components may be grouped together in terms of functions, of which the following four are principal from the applications point-of-view:

1. Sensing: The potential number of sensors required to cover the remote sensing spectrum is vast; some sensors are as old as the camera while others are as new as the Fraunhofer line discriminator;
2. Coverage: The platforms which carry sensors constrain the velocity, altitude and scale, field of view and repetition of the actual sensing as well as the means of transmitting the data for subsequent operations;
3. Preprocessing: Digital and/or photographic processing may be required to present the data set in a format suitable for interpretation;
4. Interpretation: This is the essential function of the remote sensing system in that useful information is derived from the data by mechanized, digital, optical and/or visual techniques, all supported by human judgment.

Sensing

A great array of sensors is available (Reeves et al., 1975, p. 235-537) to measure the intensity of radiation as functions of wavelength, time, geometry, phase change or polarization. No single instrument can do all these things well, or even satisfactorily, because each sensor emphasizes some parameters at the expense of others. Imaging sensors stress spatial resolution. Maximum resolvable detail is attained in the visible band. In the ultraviolet and thermal infrared, resolution is about one order of magnitude less while radar is almost another order of magnitude lower. Non-imaging sensors relate intensity to factors other than scene geometry. Active sensors, such as radar, provide their own illumination while passive sensors measure radiation that originated elsewhere. Each sensing system records some attribute of a cover class (e.g. vegetation, water, soil, buildings, and, here-and-there, rocks) as measured through the atmosphere.

Thus, the sensor is the definitive component of the remote sensing system in that it specifies the range of radiation parameters that can be measured. The more specific the sensor, the more carefully it must be matched to the spectral characteristics of the target. Such matching is one key to practical remote sensing.

Coverage

Sensors and ancillary equipment are carried on platforms that provide access and mobility relative to the target. Many types of platforms are available (Reeves et al., 1975, p. 538-588). Free and tethered balloons, powered aircraft of all sizes, helicopters, drones, dirigibles, sailplanes and manned and unmanned spacecraft all have been used at one time or another because of particular advantages. Depending upon the specific sensing system, data may be returned to base station by telemetry or by physical return of films and magnetic tapes. In many cases, the user's choice of platform is more limited than the preceding list suggests because of restricted availability or high cost for a particular platform. On the other hand, a wide variety of data collected from restricted platforms, especially at high altitudes, may be available if the user contacts the responsible agencies.

Thus, the type of platform may markedly affect scale, spatial resolution, field of view and format of raw data, as well as periodicity for repeated acquisition and temporal analyses. Hence, choice of platform and related coverage are important considerations in planning for remote sensing.

Preprocessing

As used here, preprocessing refers to operations performed on a set of remotely sensed data in order to compile that data in the format most suitable for subsequent interpretation. Preprocessing includes three different types of operations, which are here referred to as: (1) restoration, which removes effects that are inherently extrinsic to the target; (2) modification, which purposely alters the data-set to match standard conditions or to emphasize selected characteristics in the data; (3) correlation, which interrelates and registers several sets of data on a common geometric base. Typical restoration includes correction for geometric and radiometric distortions in the sensing system and clean up of artifacts and noise. Common modifications include reduction to standard conditions for atmospheric transmission and/or illumination; contrast stretching; density slicing; spectral classification; addition, subtraction and ratioing of bands; selective filtering and edge enhancement (c.f. Reeves et al., 1975, p. 688-710). Often such modification may improve the interpretability of the data although it may destroy their original character. Correlation primarily involves manipulation of data sets to register them on a common base e.g. aeromagnetics or radar with Landsat, or change detection using similar data for different dates (c.f. Fischer et al., 1976). It may also include statistical analyses to define the probabilities of relationships between features in the data sets.

The choice of preprocessing needs to be carefully considered because it can significantly affect the quality and, in some cases, the very success of subsequent interpretation. While digital processing may blur the distinction between preprocessing and interpretation, the functions are inherently and distinctly different.

Interpretation

In general, interpretation is the operation that assigns significance to the preprocessed remotely sensed data and, thereby, defines their utility. Spectral data are seldom sufficient, in themselves, to identify an object. With a few notable exceptions, the concept of unique spectral signatures is not generally valid in any field of remote sensing. Shape, texture, pattern and context are important, and usually essential, clues to the identification of geological features (c.f. Grossling and Johnston, 1977, p. 34-37). Unfortunately, detailed geometric and contextual data are not readily incorporated into digital systems.

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While interpretation is not always amenable to rigid statistical expression, it is a probabilistic statement about the target and its environment. The greater the knowledge concerning the capabilities and limitations of the system and its target, the greater will be the probability of correct interpretation. Obviously, if the target is well known, there is little need for interpretation except as calibration or verification of technique. The interpretative process comprises three stages that may appear to be an iterative continuum: (1) analysis, which identifies, selects and calibrates useful observables from the more numerous elements of the data set; (2) synthesis, which puts the selected observables together in the context of the user's need; and (3) explanation, which integrates complementary data and human judgment with remote sensing to derive significant information. Feature extraction, thematic classification, mapping, mensuration and change detection are the principal activities of interpretation. There are many visual, machine-assisted and digital methods for solving the related problems (Reeves et al., 1975, p. 711-787, 869-1076). Automation and digital processing may accelerate these interpretive operations but, as practically foreseen, they will not obviate the need for human judgment especially with respect to geomorphic expression of rocks exposed to different climatic conditions (c.f. Doyle, 1977; Gregory, 1973, p. 89; Grossling and Johnston, 1977, p. 37-39; Reeves et al., 1975, p. 1072).

Experience has shown that not all professional resource scientists are good interpreters (c.f. Reeves et al., 1975, p. 1057). There are striking differences between individual interpreters, especially with respect to consistency, accuracy, colour discrimination and other personal factors. Imagination (which is the synthesis of new concepts), prior experience and accumulated knowledge are also key factors in interpretation. Accordingly, the quality of interpretations, be they digital, machine-assisted or manual, will continue to be influenced by the specific capabilities of the human beings involved in the process.

In the context of mineral exploration, remotely sensed data are surrogates for observables related to geology, among other things, as seen through the atmosphere. Interpretation of remotely sensed data by an experienced geologist is no less factual than the interpretation of visual observations on an outcrop, although the scale of observation and the size and nature of the observable may be different. Few geological observables are seen in their totality on either outcrops or images. Obviously, the closer the geologist is to the rock, the smaller the observable that he can utilize; and, also, the more detail he is exposed to. Hence, he must become more selective. On the other hand, observables of grand scale simply may not be apparent without a broad overview, such as that provided by Landsat. Thus, several sets of remotely sensed data may be required to advance mineral exploration.

In summary, the quality of any interpretation depends greatly on three choices: data, interpretive process and human interpreter. All should be carefully matched to the specific need for information in an exploration program.

Operational Remote Sensing Systems

Over the past few years, numerous potential applications for remote sensing have been suggested. Regardless of how beneficial they may appear, potential applications remain potential until three factors are assessed: the need for the derived information, the timeliness of interpretation and the cost-effectiveness compared to other methods of acquiring comparable information. There is a fundamental difference between operational sensing systems and operational sensing to meet specific exploration objectives. Failure to recognize this difference can cause financial problems for the unwary user. At this relatively early stage in the evolution of remote sensing, many sensors are still being used in experiments to develop practical applications. However, contemporary applications in mineral exploration can be recognized for some sensing and interpretive systems which are operational and which are, or could be, used systematically with reasonable economy.

APPLICATIONS OF REMOTE SENSING IN MINERAL EXPLORATION

General

While complete data do not appear to be available, there is abundant evidence that the mineral industry is a major user, if not the principal user, of remotely sensed data. Of the many sensors available, only aerial photography, side-looking airborne radar, aerial thermography and Landsat have immediate potential for systematic use in mineral exploration. Of these, aerial photography and Landsat are currently receiving the greatest use, presumably because of their relatively low cost (see p. 520). For example, exploration companies and consultants involved in the search for minerals and petroleum are major purchasers of Landsat data in Canada, the United States of America, Australia and, probably, South Africa (Wukelic et al., 1976; Gregory and Morley, 1977; U.K. Remote Sensing Society, 1975; Sabins, 1974). However, the split between use in ore exploration and use in oil exploration is not clear. The latter use may be greater although the former is significant and increasing on a worldwide scale.

Airborne Remote Sensing

Aerial Photography

Undoubtedly, conventional low-altitude aerial photography is the contemporary system of remote sensing that is most widely used in mineral exploration. As is well known, black-and-white photographs with high spatial resolution are systematically acquired and extensively used in the geological mapping of rocks and structures.

Monoscopic and stereoscopic techniques for interpreting black-and-white photographs and their relevant geological applications have been well described elsewhere (Allum, 1966; Miller, 1961; Newton, 1971; Reeves et al., 1975, p. 911-941; Tator, 1960). Accordingly, no attempt is made here to outline either the practice or the benefits for mineral exploration. Instead, attention is directed to a few of the newer techniques that can also be applied to the search for ore.

Colour and colour-infrared (CIR) films have added a new and slightly more costly dimension to aerial photography (Smith and Anson, 1968). While these films have a potential for improving feature identification, it is uncertain whether their capabilities with respect to geology are worth the additional cost unless specific colour contrasts are of principal interest in the target area. Anderson (1963) noted that outcrop areas are more readily discerned on colour photography than on black-and-white at comparable scale. He concluded that colour film would be preferable if the criteria for recognition of rock types were based on colour contrasts that might not be separable on black-and-white films. Gilbertson et al. (1976) reported that both colour and false colour (CIR) were ineffective in identifying rock types (schists and amphibolites) and in distinguishing gossans from soils under arid climatic conditions. On the other hand, Slaney (1975) noted that "many, if not most, gossans known to be present" could be recognized on colour photography for part of the Canadian tundra. In addition, Offield (1976) reported that coloured aerial photographs have long been used in the search for surficial discolorations associated with sedimentary uranium deposits in arid areas.

The practical utility of multiband aerial photography in mineral exploration is equally uncertain. Discrimination between rock types, especially sedimentary rocks, does not appear to be practical (Raines and Lee, 1974). Geobotanical differences, especially in areas of heavy vegetation, are dominant but may sometimes be useful in mapping rocks and structure (Reeves et al., 1975, p. 1231-1238). Gilbertson et al. (1976) were able to enhance differences between outcrop and overburden and to distinguish between gossan and some rock types. They concluded, however, that most differences can also be detected on conventional photography and that, because of the cost, multiband photography would not be an effective exploration tool.

On the other hand, B. Bølviken (Norges Geologiske Undersolkelse, Trondheim, Norway; pers. comm., 1977) reported that multiband photography has detected natural poisoning of birch forests over copper sulphide deposits in Norway. Differences in texture, pattern and tone that are related to severe damage to the vegetation are visible also on black-and-white aerial photographs. However, on such photographs, the area of copper poisoning is difficult to distinguish from common bogs (c.f. Bølviken et al., 1977). The multiband images also defined a surrounding spectral anomaly, possibly stressed vegetation, that appears to coincide with a major geochemical anomaly.

In summary, black-and-white photography continues to be widely used for general exploration. However, colour, colour-infrared and multiband photography can provide more specific data where the metallic mineralization is known to cause geological and/or botanical anomalies that are detectable with specified film/filter combinations.

Side-Looking Airborne Radar (SLAR)

Because of its unique capability for imaging through clouds, haze and darkness, side-looking airborne radar has a contemporary application for obtaining timely and moderately detailed data about the terrain under conditions that are not favourable for photography (Jensen et al., 1977; Reeves et al., 1975, p. 443-475). Resolution, however, is commonly less than for camera systems.

SLAR is an active microwave sensing system that illuminates terrain to the side of the aircraft and records the backscatter or reflected returns on either magnetic tape or photographic film. The SLAR image represents a continuous strip of the terrain but the image is not a "snapshot". It is produced by a line-scanning technique and, hence, may not have fixed two-dimensional geometry. In addition, foreshortening (or layover) may be a problem in areas of high relief.

There are two basic types of SLAR. Real aperture radar (RAR) is less costly but its spatial resolution (30-100 m) varies with depression angle, range, and altitude. Synthetic aperture radar (SAR) is more expensive because it utilizes elaborate signal-processing techniques. However, it provides a finer resolution (10-30 m) that can be invariant with range and also a multispectral capability.

Most SLAR imagery is at small scales (1:150 000 to 1:500 000) but enlargements of up to 5X may be useful. Radiometric calibration is not usually required except for quantitative measurements e.g. spectral discrimination of materials on the ground.

Geometric corrections can be made, which for synthetic aperture radar, result in positional errors of less than 150 m (Peterson, 1976). Landsat can also be used to control the geometry of SLAR mosaics. Further, SLAR can replace one spectral band in a Landsat image to provide a synergistic combination of radiations from two different parts of the spectrum (Harris and Graham, 1976).

The utility of SLAR depends on the physical nature of the terrain and on the orientation of the sensing system relative to topographic features. Depression angles must be matched to the relief of rugged terrain. Shadowing may cause severe loss of detail, especially at low angles of illumination.

Photointerpretive techniques, similar to those used with airphotos but augmented by experience with radar, comprise the basis of practical application (Reeves et al., 1975, p. 982-1057; Parry, 1977). Pseudo-stereoscopic viewing is preferable, provided appropriate images are available.

Surface roughness is the principal determinant of tone on a SLAR image. Specular, or mirror-like, reflection results from smooth surfaces. A diffuse, or scattered, reflection is returned from rough terrain. Intensity, or brightness, varies with angle of incidence and roughness of the surface. Electrical properties of the surface comprise another major determinant of tone. The complex dielectric constant of a material varies directly with contained water. Penetration is greatest and reflection least for low water content.

As might be expected, texture, shape and pattern are the major discriminants used in interpreting SLAR data. Microtexture, or speckle, is an inherent random noise in the system which is commonly expressed as a fine texture in specular reflectances. Mesotexture in the SLAR data represents oriented, small-scale features in plant communities, as well as minor topographical relief. Macrotextures represent the coarser geomorphic elements of the terrain and are the principal features used in geological interpretation. Slope of surface and relative relief can also be estimated (Reeves et al., 1975, p. 1006-1008).

SLAR is most useful for the study of near-surface geological features because current systems have very limited penetration into the ground or overlying vegetation. Geomorphic patterns and textures are well expressed; hence, a knowledge of local geomorphology is important. SLAR images can assist in distinguishing surficial materials, outcrop boundaries, fractures, foliation and other structure (Reeves et al., 1975, p. 1224-1231, 1271-1289; Dellwig and Moore, 1977). Distinctions between rock types may be apparent in lightly vegetated or arid regions, especially if there is associated microrelief of the order of the radar wavelength (ca 3 cm) or greater, as on alluvial fans or volcanic flows. In the presence of abundant vegetation, such distinctions are difficult to make unless different vegetational communities are also associated with the rock types. However, it is worth noting that many of these features are also displayed on airphotos, especially if the photos are acquired at low solar inclinations (c.f. Reeves et al., 1975, p. 1174-1175; Lyon et al., 1970).

Synthetic aperture radar has been flown over large areas of remote tropical rain forest where persistent cloud cover precludes systematic aerial photography. The final maps are mosaics at a scale of 1:250 000. Such maps are available for all of Brazil and parts of Venezuela, Colombia, Peru and Bolivia. Other SLAR coverage is available for smaller areas in Panama, United States and other countries. Such maps provide valuable geographic and geological information for large areas about which little was previously known.

Where SLAR data are widely and inexpensively available (because of government support as in Brazil and USSR), they have been used extensively in mineral exploration. Kirwan (Hood, 1977, p. 9-10) noted that synergistic analysis of SLAR and Landsat has given major impetus to geological mapping and mineral exploration in Brazil.

The major value of current SLAR systems for mineral exploration is related to the acquisition of regional

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information about remote, poorly mapped areas obscured by persistent cloud. SLAR data can be acquired very rapidly, regardless of weather or lighting conditions. The systems can be flown at high altitudes to present relatively detailed, multi-interest images of large areas. Under such conditions, the delineation of drainage and the mapping of structure and other geological features may be well worth the additional cost to exploration, especially if the data can be applied subsequently in other disciplines relevant to natural resources and regional development.

Aerial Thermography

Airborne line scanners are complex optical-mechanical instruments that can make single-band or multispectral measurements in parts of the ultraviolet, visible and infrared regions of the electromagnetic spectrum (Reeves et al., 1975, p. 375-397). Radiation intensity is measured by a sensing system that scans a line perpendicular to the track of the aircraft. Hence, the data do not have fixed geometry and must be corrected for a variety of distortions related to movement of the aircraft (Reeves et al., 1975, p. 953-970). The electrical signal from the detector can be recorded on magnetic tape or on strip film. At present, aerial photography is a less expensive alternative for surveying the reflective radiations. UV scanning has not developed practical applications. Hence, only aerial thermography has the imminent potential of providing new data for mineral exploration.

Most thermal infrared (TIR) systems operate in two atmospheric windows: 3.5 to 5.5 micrometres and 8 to 14 micrometres. In those bands, thermometric temperature and emissivity of the surficial materials are the principal determinants of signal strength. The emissivities of rocks and soils depend largely on the roughness of their surfaces and on their chemical composition, especially the moisture content. The thermometric (or true) temperature depends on the heating or cooling history of the material and on its thermal inertia or rate of heat transfer. Water, for example, has high thermal inertia and thus warms or cools very slowly. Consequently, its diurnal temperature range is small. On the other hand, rock has low thermal inertia and a much larger diurnal temperature range. The combination of different emissivities and different thermometric temperatures in rocks and soils can produce large contrasts in radiometric (or apparent) temperature.

Time of day and season of the year are important parameters affecting both data acquisition and subsequent interpretation. Emission of TIR radiation from the surface of materials varies with time because of differential heating and cooling which in turn are related to intensity and angle of incidence of the solar illumination. Thus, two different materials may have contrasting radiometric temperatures at one time but will not be separable at other times when such temperatures are similar i.e. during diurnal or seasonal crossovers (c.f. Spectral Africa, 1977).

For geological purposes, nighttime imagery is superior to daytime imagery. Predawn appears to be the best time for thermography directed to geological objectives (Reeves et al., 1975, p. 964; Spectral Africa, 1977). The predawn conditions minimize solar contribution and emphasize reradiation of energy and, hence, the physical properties of rocks and soils. Maximum thermal contrast is attained early in the evening but effects of air temperature and shadowing may be significant also. Thus, in order to define specific requirements, an understanding of local diurnal and seasonal conditions should be obtained.

The standard TIR product is a black-and-white image which is a spatial record of radiometric temperatures within the field of view. Usually, cold areas are dark grey to black and warm areas are light grey to white. The image may, or may not, be corrected for geometric distortions. The mapping of TIR contrasts with reasonable resolution requires careful planning to minimize and correct geometric distortions so that a mosaic can be prepared. However, such corrections are not usually adequate for a precise planimetric presentation.

Practical interpretation is based on standard photogeologic principles, augmented by experience with TIR. Radiometric temperature contrasts may be enhanced by density slicing and/or colour coding. Calibrated TIR data may be obtained and contoured maps of temperature can be prepared. However, such data have had limited use in the search for metallic ores. Artifacts, unrelated to geology, may appear in the TIR data as a result of electronic noise, level shifts, wind and weather conditions and blooming or exaggeration of hot spots (Sabins, 1973; Quiel, 1974; Slaney, 1971).

Because of the many variables affecting aerial thermography, extensive field work is required to identify subtle radiometric contrasts. In the past, practical geological applications have been limited to major thermal contrasts such as volcanoes, hot springs and fumaroles and major emissivity/thermal contrasts such as moist soil in and over fault zones or thin, dry soil over bedrock (Fig. 22.1). Extensive tests in arid alluvial terrains, however, have recently shown that remarkable detail concerning bedrock structure and lithology can be obtained by aerial thermography during the dry season (Spectral Africa, 1977). Few comparable details are recognizable on relevant conventional aerial photographs. While there is much promise in the technique of discriminating rock types on the basis of their thermal inertia, it has not yet become an operational technique for mineral exploration (Gillespie and Kahle, 1977).

Orbital Remote Sensing

Meteorological and Manned Spacecraft

Systematic remote sensing from space began in 1958 with the meteorological satellites, particularly the Nimbus and current NOAA systems. From the viewpoint of a photogeologist, meteorological sensing systems have improved in resolution (to about 0.5 km) but they still are useful only for very small-scale studies, repetitive observations of large regional features and, of course, weather factors that determine operational conditions (Reeves et al., 1975, p. 565-577, 583-586, 1244; Gregory and Moore, 1976, p. 155). The geological information that can be derived from these telemetered black-and-white images (both visible and thermal infrared) is simply inadequate for most applications in mineral exploration (c.f. Reeves et al., 1975, p. 972-973).

Manned spacecraft have provided more detailed data in several bands of the electromagnetic spectrum for those regions of the Earth over which the spacecraft have passed. None of these systems was designed specifically for remote sensing, although the Mercury, Gemini, Apollo and Skylab programs all returned useful, and sometimes spectacular, images that can be used in mineral exploration. The resolution (of up to 10 m) is adequate for many geological applications (Maffi and Simpson, 1977; Cassinis et al., 1975; Reeves et al., 1975, p. 577-583, 1244-1247). However, the images are limited in geographic location to the lower latitudes, they are rarely repetitive and they are not current. For these reasons, such data have not received much attention in Canada although they may be very useful where relevant coverage is available (c.f. Fischer et al., 1976).

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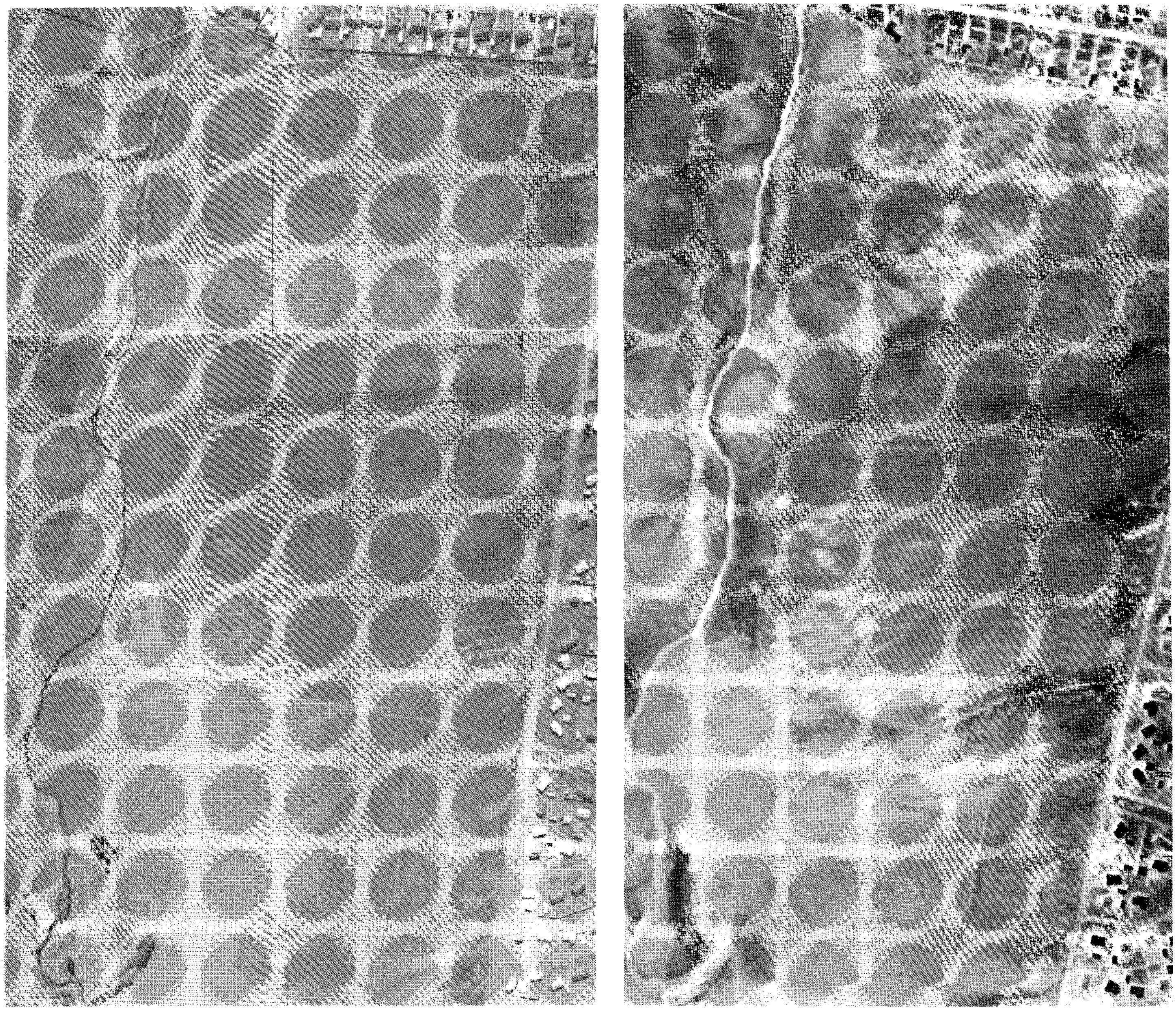

(GSC 203492-F) (GSC 203492-C)

Figure 22.1. *(a) Conventional panchromatic aerial photograph and (b) pre-dawn thermal IR scanner image (8-14 micrometres) acquired within a few weeks of each other, Witpoortjie fault area, West Rand, South Africa. Scale: approximately 1:5000. The fault, which is represented by the abrupt termination of the light grey to white outcrop and sub-outcrop, is one of the most obvious features on the thermal image. Note also the faulted shale horizon (dark grey) in the lower third of the image. For further details, see Spectral Africa, 1977.*

Photograph and image courtesy of Spectral Africa (Pty) Ltd., P.O. Box 976, Randfontein, South Africa.

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Landsat (ERTS)

On July 23, 1972, NASA launched the experimental Earth Resources Technology Satellite (ERTS-1) to begin an era of systematic and relatively detailed exploration of the world's land areas from space. A second, similar satellite was launched January 22, 1975 and both were renamed as Landsat-1 and Landsat-2. These satellites provided data from a 4-band multispectral scanner (MSS) that recorded in two bands of the visible spectrum and two bands of the reflective infrared (Williams and Carter, 1976; Short et al., 1976). Weather permitting, each Landsat collects MSS data every 18 days over preselected areas in its near-polar, sun-synchronous orbit. Coverage of all land masses at least once is a principal goal of the program. Landsat-1, which operated well beyond its designed lifetime, is no longer operational. When both satellites were operating, data were collected every 9 days. A similar satellite, Landsat-3, was launched on March 3, 1978, to record the same 4 bands plus an additional thermal infrared band as well. These satellites also carry a data collection system that relays data by telemetry from remote ground platforms via Landsat to a central readout terminal.

The remotely sensed data provided by the current Landsat system comprise: four black-and-white images in visible green, visible red and two non-thermal infrared bands. Relevant computer compatible tapes (CCTs) are also available. The CCTs provide 64 levels of radiation intensity with an inherent resolution of 80 m, whereas the photographic products have the same resolution and the equivalent of 16 levels of intensity.

False colour composites are usually prepared for any scene with three appropriate bands (c.f. Pl. 3). Digital processing is used to locate ground control, to perform radiometric and geometric corrections and to compile the image. The standard products [1] (false colour and 4 bands) are near-orthographic prints with common, pre-selected scene geometry and a scale of 1:1 million. Each scene represents about 34 000 km^2 (or about 13 000 sq. miles). Ground resolution is of the order of 80 m for many observable geological features but smaller targets with high contrast are often recorded. Other types of data that may be acquired include: transparencies, enlargements, mosaics, digital enhancements, digital transforms and, for Canada only, microfiche for one infrared band (MSS 6).

Most systematic interpretation of Landsat data for mineral exploration is based on the recognition of tonal contrasts, shapes and patterns using standard photogeologic techniques adapted to the selected wavebands (Gregory and Morley, 1977; Wukelic et al., 1976; Gregory and Moore, 1975). While prints are widely used in visual interpretation, transparencies may be usefully projected at various scales onto airphotos and topographic, geological or geophysical maps. Such projections can be used for systematic interpretation with a "zoom" capability for focusing on detail at scales as large as 1:30 000 provided that the targets have dimensions of 100 m or more, depending upon relative contrast.

The most common type of interpretation (i.e. monocular, single band analysis) should take into account the wavelength being interpreted because the black-and-white images are not directly analogous to ordinary aerial photographs [2]. Stereoscopic viewing of Landsat images is feasible but is inherently limited by the geometry of the sensing system. Such stereoscopy is unidirectional along the scan line rather than omnidirectional as in aerial photography. Stereoscopic capability improves with increasing geographic latitude or occasional orbit overlaps. In these cases, the technique can be exploited to study major geological features such as incised river valleys or mountain belts but it is not suitable for most photogrammetric purposes (c.f. Welsh and Lo, 1977). In addition, pseudostereoscopic viewing of the same scene in two bands (i.e. band-lap stereo) or at two times (time-lap stereo) may also provide information useful for mineral exploration.

A colour composite is prepared from 3 bands which may be variously coded by colour. Some composites approximate natural colour but the most common type simulates aerial colour infrared (CIR) film, a product which has been a standard tool of photointerpreters for many years. On the Landsat equivalent of this latter product, healthy vegetation appears red because chlorophyll is one of the best reflectors of the infrared radiation (which is coded red) while clear, deep water is a strong absorber and thus appears black.

A heavy cover of vegetation may obscure bedrock features. However, Kirwan (Hood, 1977, p. 9) noted that controlled colour composites have improved the interpretability of Landsat images, especially for terrains covered by tropical rainforest. Similar improvements can be achieved by digital processing (c.f. Offield et al., 1977) and by selective filtering in projection systems.

Visual thematic classifications have been used to map mine wastes, geological formations, laterites and placers, as well as environmental and vegetational themes. Such classifications, are based on spectral response, texture and context. Digital classifications of spectral data appear to be on the threshold of practicality for a few specific geological applications in arid areas (see page 521) but, in most cases, further research appears warranted to define costs and applicability to mineral exploration. Density slicing and other forms of optical-mechanical analysis have not found major applications in the search for ore.

Unlike most aerial photography Landsat data are not always acquired under optimal conditions. Further, seasonal aspects of climate, weather and illumination provide different views that may preclude, hinder or assist the interpretation of geology. Therefore, it is preferable to visually select data for each interpretation. Such selection of optimal data should consider the following interrelated factors: coverage, scene quality, seasonal aspects, waveband, format and delivery schedule (Gregory and Moore, 1975).

Repetitive Landsat data have proven very useful in mineral exploration, primarily because various seasonal phenomena enhance geological features. Data acquired in appropriate seasons can provide the following enhancements (Gregory and Moore, 1975):

1. Low inclination of the sun, giving a pseudo-radar effect with shadows enhancing even minor topography;

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[1] Standard products and ISISFICHE for Canada may be purchased from: Integrated Satellite Information Services Ltd., P.O. Box 1630, Prince Albert, Sask., S6V 5T2. For other parts of the world, standard products may be purchased from EROS Data Centre, U.S. Geological Survey, Sioux Falls, S.D. 57198, U.S.A., or from relevant national agencies.

[2] Images in MSS 5 (visible red) have tones and contrasts that will be most familiar to the photogeologist as they approximate the common panchromatic photograph, or, more closely, the less common orthochromatic photograph.

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2. Uniform surface of a thin cover of snow or sand obscures terrain noise and serves to emphasize topography and penetrative structures especially in conjunction with low sun;
3. Residual snow and ice remaining in the solar lee of hills and depressions enhances associated linears;
4. Meltwater swells drainage channels and temporarily fills minor drainage features to enhance linears, particularly through low reflectance in the infrared bands;
5. Soil moisture patterns following rainfall in semiarid regions may enhance soil and related bedrock contrasts;
6. Preferential growth of vegetation may enhance associated rocks and soils because of the high infrared reflectance of vegetation; relative vigour of growth is measurable.

The chief value of Landsat data to the search for ore lies in the regional view and the moderate level of detail that is presented in either a single frame or a mosaic. As can be readily seen through comparison of relevant maps and images at the same scale, many Landsat images portray greater detail in topography and geology than do the comparable maps. With experience, Landsat images can be used at scales of 1:50 000 or larger although they lack the detail of photographs at similar scales. However, Landsat does not provide definitive information about rock composition or the third dimension of depth below the surface.

While neglect of spectral content in the four bands is not recommended, photogeological interpretation alone can provide much geological information that is valuable in the search for ore. As such, these simple techniques may be readily adopted by an experienced field geologist. Information interpreted from Landsat can assist mineral exploration with: mapping of major geological units; discrimination of rock classes (such as alluvium, sedimentary rocks, metamorphic rocks, granitic gneisses, intrusions and volcanic cones and flows); mapping of structures[1], including linears; and detection of alteration zones and other broad surface indications of mineralization. Such geological mapping has already effected significant savings in time, by factors of 3 to 10, relative to conventional mapping at similar scales. Many examples of these benefits have been published recently (Palabekiroglu, 1974; Slaney, 1974; Barthelemy and Dempster, 1975; Gregory and Moore, 1975; Viljoen et al., 1975; Short et al., 1976; Williams and Carter, 1976; Iranpaneh, 1977; Shazly et al., 1977; Woll and Fischer, 1977). Alteration zones in arid regions may be visually delineated (c.f. Schmidt, 1973; Smith et al., in press) but digital modification can provide significant improvements (see page 521).

In addition, Landsat images can be used in appropriate enlargements as relatively detailed base maps for reconnaissance, as control for preparing mosaics of aerial photographs and, under favourable conditions, as a base map for compiling airborne geophysical surveys.

Costs of Remote Sensing Applied to the Search for Ore

The costs of acquiring and interpreting remotely sensed data are estimated in Table 22.1. Few definitive costs have been published except for aerial photography. Hence, the tabulation should be construed as a preliminary approximation. It is based on many bits of information including price lists, published papers, personal communications and experience, all of which were updated to 1977 dollars. Even if actual costs vary by a factor of 2 or 3, the trends remain obvious. The current cost of acquiring Landsat data is much less than the cost of interpretation. This is rarely true for other types of remote sensing except under special but analogous circumstances i.e. when the data have been acquired by government for multiple use and are sold across the counter at nominal prices. Otherwise, the cost of new airborne sensing is greater than the cost of interpretation and much greater than the total cost of interpreted Landsat data. While significant savings can be effected for airborne surveys of very large areas, the cost per unit area will still be greater than current Landsat costs. Cost, however, should be balanced against the desired level of detail which is inherently greater for airborne surveys.

Equally noticeable is the fact that the total cost for small scale photography is only about twice the total cost for Landsat if the airborne data are available across the counter at a nominal price. In Canada, the wide availability of black-and-white aerial photography is comparable to that of Landsat. Also, total costs for interpreted information are low for both types of sensing. Undoubtedly, these two factors (i.e. wide availability of data and low cost of visual analysis) are major reasons for the emphasis on those two types of sensing by the exploration industry in Canada (c.f. page 514).

Although they lack the detail of aerial photographs, Landsat data have a number of unique advantages relative to aerial photography, including:

(1) synoptic scale, which makes it possible to view major features in their entirety;

(2) constant raked illumination, which results in uniform presentation of features over a large area;

(3) spectral sensing, which serves to emphasize contrasts in reflectance and may ultimately assist in classifying materials;

(4) repetitive imaging, which provides seasonal enhancements and facilitates monitoring of the terrain;

(5) moderate resolution, useful for identifying many features with dimensions greater than 80 m and smaller features with high contrast; and,

(6) global coverage, for all land masses between latitudes 81°N and 81°S, without interruption at national boundaries.

However, the principal benefit to mineral exploration from any remote sensing lies in the quality of geological information that can be derived from the data. Except for very special conditions, this paper shows that conventional aerial photography and Landsat can provide more useful information per exploration dollar than other types of remote sensing (as defined herein). Landsat has advantages relative to its generality and spectral/temporal content while conventional aerial photography provides detail. The systems, thus, are complementary rather than competitive sources of data.

CHALLENGES TO THE ADVANCE OF REMOTE SENSING IN THE SEARCH FOR ORE

At the present time, the role of remote sensing in mineral exploration is undergoing quiet assessment in Canada and elsewhere in the world. In part, this reflects the current low level of exploration activity in this country. There is little doubt, though, that simple practical applications of remote sensing have been recognized and are being integrated with other exploration tools.

Further advances of remote sensing with specific application to mineral exploration will require that the mining industry face up to several major challenges and decide which challenge, if any, it wishes to accept. There are two interrelated types of challenge: technical and financial.

[1] Note that the restricted range of sun azimuths introduces a bias against structures subparallel to that azimuth.

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Table 22.1

Approximate 1977 costs[1] for acquisition and interpretation of remotely sensed data

Data	Format	Acquisition Cost[2] (per 1000 sq. km) over the counter	Acquisition Cost[2] (per 1000 sq. km) new mobilization[3]	Interpretation Cost[4] (per 1000 sq. km)	Range of Total Costs[5] (per 1000 sq. km)
Landsat	Colour Transparency (1:1 million)	$0.40[6] ($12)	–	$180-$1000 (visual)	$190-$1000
	Colour & 4 bands, transparencies (1:1 million)	$1.30[6] ($44)	–		
	CCT (1 tape)	$4.50[6] ($150)	–	$2000-$9000+ (digital)	$2200-$9000+
Air photos (stereo coverage; 22.8 cm format)	b & w 1:50 000	$42	$1000-$2300	$700-$1500 (visual)	$740-$3800
	b & w 1:20 000	$250	$2400-$4000	$3000-$9000 (visual)	$3300-$13 000
	colour 1:50 000	$100	$1500-$4500	$700-$1500 (visual)	$800-$6000
	colour 1:20 000	$640	$3900-$5000	$3000-$9000 (visual)	$3600-$14 000
Multiband photography	4 bands, 1:20 000	–	$5000-$20 000	$8000-$30 000 (visual)	$13 000-$50 000
SLAR	strips & mosaics (1:250 000)	$4-$8	$8000-$20 000	$1000-$5000 (visual)	$1000-$25 000
Aerial Thermography (IR)	strips & mosaics (1:50 000)	–	$5000-$10 000	$1000-$2500 (visual)	$6000-$13 000

1 Costs were estimated from many sources, inflated to 1977 Canadian dollars and rounded to two significant figures.

2 Single purpose, single coverage.

3 Including a mobilization cost of $1000.

4 Single theme mapping; includes professional salaries and overhead, but wide range reflects amount of detail in image, scale, objectives of project and method of interpretation.

5 Exclusive of field studies.

6 Subject to minimal cost of data for 1 scene as given in brackets.

This section of the paper is concerned primarily with the former although, without doubt, the greatest challenge is financial.

Technical Challenges

A multitude of specific sensing needs that are related to particular systems can be quickly identified by any experienced technologist e.g. improvements in spectral and spatial resolution of a sensor, refinements to corrections for attenuation or development of a new algorithm to enhance contrasts. Geologists and geophysicists can identify needs related to characteristic spectral radiances for rocks or better understanding of the ubiquitous linears which have well publicized, but poorly defined, relationships to ore (c.f. Carter et al., 1977; Gilluly, 1976). All such problems, however, are details – though important details – which do not alter the fact that the current capabilities of remote sensing can now provide significant assistance in the search for ore.

However, there are two broader technical challenges which, if they are approached in orderly way, can be overcome to advance not just remote sensing but also mineral exploration in general.

These challenges, which are related to the practicality of digital preprocessing (see page 513), are not inherently system specific, although current focus is on Landsat. These challenges are:

1. Correlation of multiple data sets, and
2. Digital modifications to assist geological interpretation.

Correlation of Multiple Data Sets

The principles of synergism, or integration of different sets of data to produce more or better information than the sets can separately provide, are receiving much current attention in remote sensing. While he may not recognize the terminology, the experienced explorationist is familiar with the principles and intuitively practices them in his everyday work. He uses converging lines of evidence and optimizes his interpretation by integrating all relevant geological, geophysical, geochemical and topographical data. Commonly, this is done by mental approximations, by overlaying maps at the same scale or by projecting an image of one set of data onto another data base. The limitations for multiple data sets are obvious. Recently, digital techniques have been developed to register Landsat data with other data, including Landsat data for different times as well as SLAR and geophysical data (c.f. Fischer et al., 1976; Harris and Graham, 1976; Anuta, 1977; Reeves et al., 1975, p. 1100). Perhaps the most significant trend with respect to mineral exploration is the ultimate development of precise location of data relative to ground control or other field data (c.f. Raynolds and Lyon, 1976).

With respect to practical application, these developments are still experimental in that their specific advantages and costs for use in mineral exploration have not been established. Their potential for correlation and probability analyses could be of value in mineral exploration if we can decide what data sets should be combined and what goals should focus the synergism.

The visual correlation of Landsat prints and transparencies with other (e.g. geophysical) data is now a practical simple method of synergistic analysis. Further improvements are warranted, including: better image quality, a broader range of photographic enhancements and augmented optical projection systems with magnifications of the order of 30X to 100X. Further research is required to determine the need for cosmetic improvements, contrast stretching, preselection of density levels, band ratios, etc., and, especially, to define the most useful products for specific conditions.

Digital Modification to Assist Geological Interpretation

Background

Optional cosmetic improvements can now be effected on Landsat images, usually at considerable expense. Noise, striping and dropped lines may be removed (Goetz et al., 1975) and definition improved (Longshaw et al., 1976) to obtain a more aesthetically pleasing image. However, the image must still be interpreted to derive geological information. While there appears to be an improvement in interpretability for some images, it has not yet been established that the improvement is generally worth the additional cost. In fact, it now seems likely that cosmetic improvements and reductions to standard conditions (c.f. Ahern et al., 1977) are not essential for geological interpretation. The human interpreter can handle adequately the relatively small interference and bias, except for subtle geological contrasts that require enhancement in any case.

Other modifications, however, have exciting potential. Enhancements can serve to emphasize subtle spectral contrasts that may have lithologic significance (Goetz et al., 1975). Also, spectral classifications and transformations can define areas with similar spectral characteristics and may help to discriminate rock types (Podwysocki et al., 1977). While exciting, these modifications contain a major pitfall: it is too easily – and too commonly – assumed that spectral classes (often called thematic classes by digital analysts) are the same as user-defined thematic classes for rocks and soils on the surface of the ground. Fortunately, the magnitude of this problem is declining with increasing involvement of geologists in digital processing.

The thematic classification of rocks by remote sensing is hindered by many almost overwhelming factors. First of all, the spectral radiance of rocks in situ is rarely characteristic in any available waveband and usually requires textural information for even generalized classification (c.f. Podwysocki et al., 1977; Rowan et al., 1976). Further, outcrops of rock comprise a minor part of many landscapes although massive exposures are not uncommon. Frequently, the outcrops are obscured by weathered surfaces, lichen, moss, dust, rain or snow or an overhanging canopy of vegetation. And as every geologist knows, each rock type is represented by a range of compositions. Because of these factors, the absolute identification of rock types by remote sensing is a highly improbable task. However, spectral discrimination (or separation of spectral units and subtle contrasts) may, under certain conditions, facilitate future mapping of rock units and alterations.

Arid and semiarid areas

Digital processing techniques have been developed to retain textural information in a modified image. Under arid conditions, these images may be useful in discriminating among rock types (Podwysocki et al., 1977; Rowan et al., 1976; Goetz et al., 1975). Spectral classifications, devoid of texture, do not appear to be useful for mapping similar arid areas (Siegal and Abrams, 1976).

Discrimination of altered zones related to ore deposits has received much attention. Current work is based mainly on the enhancement of reflectance minima resulting from absorption bands representing ferric iron (primarily limonite, jarosite, etc.) and hydroxyls in clays (c.f. Pl. 4). Rowan et al. (1976, 1977) used stretched ratio enhancements to discriminate both limonitic and siliceous hydrothermal alterations in a Tertiary volcanic complex in the Nevadan desert. Shales and siltstones, being similar in composition to the altered rocks, were not separable. In Western Australia, Smith et al. (1978) used digital analysis to improve on their visual thematic classification of hydrothermal silicate alteration in flow tops in a Keeweenawan-type volcanic sequence. Current success seems to be dependent on minimal shadowing from flat to slightly undulating terrain, flat formational dips that provide broad targets, and a weathered profile that accentuates the spectral contrast between altered flow tops and less altered basalts. Discriminatory capabilities were similarly assessed for iron oxides associated with uranium deposits in flat lying, pallid sedimentary rocks of Wyoming (Offield, 1976; Vincent, 1977) and iron oxides associated with mercury in the McDermitt caldera of Nevada and Oregon (Raynolds and Lyon, 1976). Similar modifications to Landsat data have delineated anomalies considered to represent sulphates and alteration zones associated with porphyry coppers in Pakistan (Schmidt, 1976; Schmidt and Berstein, 1977). In the latter case, no significant amounts of ferric iron were present in the alteration. Schmidt (1976) also tested his technique in a quasi-exploration context and selected 23 targets for prospecting in areas adjacent to his training site. Seven of these areas contained hydrothermally altered rock, mostly porphyry (Schmidt, pers. comm., 1977).

All of these feasibility studies used data for arid to semiarid sites. In all cases, known alteration zones were delineated although errors were more numerous than desirable. Errors of commission (misidentifications or false alarms) and errors of omission (nonrecognition of known occurrences) were both experienced. On the other hand, it is debatable whether such errors are any more numerous than those experienced with other exploration techniques, especially at a comparable early stage in the development of those techniques.

Moderate vegetational cover

To date, digital modifications of Landsat data seem to work best in areas with little or no vegetation. Grasses and trees can significantly mask and alter the spectral reflectance of the ground as measured by sensors in aircraft or satellites (c.f. Siegal and Goetz, 1977). A cover of about 30 per cent green vegetation may overwhelm the reflectance of underlying rocks and soils. Indeed, if such materials have low albedo, the reflectance may be altered beyond recognition by only 10 per cent green cover. On the other hand, dead or dry vegetation has minimal effect on reflectance from the ground (Levine, 1975).

The staff of Gregory Geoscience Limited have attempted to adapt some of these digital classifications for use on the tundra where there may be abundant grass but no tree canopy. Spectral classifications based on band ratios were not successful in identifying gossans associated with the Muskox intrusion but they partially discriminated between several rock types (H.D. Moore, pers. comm., 1976). Subsequent work followed up on rock discrimination in an area near the Great Bend of the Coppermine River, N.W.T. where the dominant lithologies are flatly dipping basalt, sandstone and dolomite with sandy alluvium. Various ratios of MSS bands and algebraic combinations of ratios were tried but separations were incomplete (P. Chagarlamudi, pers. comm., 1977). An attempt was then made to strip out the vegetational contribution by developing a complex algorithm that minimized the effect of vegetation. On a pixel-by-pixel basis, this classification provided encouraging results but further testing has not been completed.

Spectral geobotanic anomalies

Vegetation covers over two thirds of the land surface of the world and the root systems sample the solutions in underlying soils and bedrock. Geobotanical anomalies are known to be related to metallic mineralization under certain conditions and relevant surveys are used in mineral exploration. It is not surprising, then, that the concept of measuring related spectral anomalies by remote sensing has been investigated for several years.

Except for relatively short transient changes, natural vegetation is always in equilibrium with the soil, moisture and climate. Contemporary research indicates that vegetation with an intake of excess metal ions or complexes will develop stress symptoms. Relative to unstressed vegetation, such symptoms are manifested by both geometric and spectral differences e.g. extinction of some species, unique plant associations, stunting, sparse foliage, wilting or chlorosis, among others. It is possible, then, that plant communities could serve as surrogates for the chemical state of soils and soil solutions and, hence, for mineralization. Related biophysical anomalies could be expected to have dimensions of a kilometre or more.

Aerial multiband photography and modified Landsat data have been used to test the feasibility of mapping biophysical anomalies related to stress. As noted previously, multiband photography has serious limitations as an exploration technique, despite some seeming successes (c.f. Canney, 1975). Evidence from Landsat is equivocal. Anomalies have been delineated and related to copper poisoning in the boreal birch forests of Norway (Bølviken et al., 1977), and to molybdenum poisoning in the pine and juniper forests of Nevada (Lyon, 1977). The specific causes of spectral anomalies in both areas are uncertain. Low ratios for band 7/band 5 (or band 4) may result from spectral contrasts such as chlorosis, from textural contrasts such as sparse foliage or from some combination of the two. At the Norwegian test site, clearings unrelated to copper poisoning have a normal grass cover. Hence, their high 7/5 ratios serve to separate them from the poisoned areas. No similar anomalies were found in tropical rain forest over a porphyry copper deposit (Lyon, ibid.).

Experience has shown that the link between geobotanical anomalies and ore may be tenuous. The link between a remotely sensed anomaly and ore will be even more so, in part because there are other natural causes of stress. Nevertheless, current results should encourage further work if only to define the most favourable environment in which to continue development. It may be, for example, that the best time to detect metal toxicity in vegetation is during the time when the regional plant community is under uniform stress so that metal poisoning is accelerated in plants adjacent to mineralization. Such uniform stress could result from irregular but persistent droughts in temperate climates or from the annual dry season in more arid areas.

Summary

The successful, though limited, detection of Landsat anomalies related to metallic mineralization and geobotanic anomalies points to an obvious extension: a more detailed study with more specific bands in an airborne multispectral scanner. Above all, however, successful discrimination of alteration zones, rocks or geobotanical anomalies by sensors in aircraft or satellites must be shown to be cost-effective in an exploration context. To date, the costs appear to be too high for general use although they may be acceptable for specialized surveys in areas where specific useful contrasts have been identified.

Financial Challenges

Remote sensing is an array of interdisciplinary technologies that depends upon many fields of science. This requirement for broad knowledge, plus specialization, is a strength in that it builds on converging lines of evidence to reach decisions. Unfortunately, it is also a weakness because the scope cuts across accepted boundaries of science, practice and administration. Nothing shows this better than the lack of a co-ordinated program for developing practical applications of remote sensing in Canada. Over the past seven years, the federal government has invested millions of dollars in the technology and methodology of remote sensing (c.f. annual reports of the Canadian Advisory Committee on Remote Sensing). As a consequence, Canadians are in the forefront as far as acquiring data and creating products of high quality. During that seven years, however, neither government nor industry in Canada has invested even a small fraction of those millions in the development of practical applications. This has resulted in a severe gap in credibility with respect to the use of remote sensing -- and not only in the mineral industry.

Five years ago, it seemed obvious (Gregory, 1973, p. 89-91) that the innovators of remote sensing faced the same problems that are experienced by any other innovator of a new product -- the problems of identifying and assessing the market. The principal determinants of successful sales (i.e. use of a product) are two interrelated factors: technical quality of the product and acceptability to the user. Both must be high. The evidence to date shows that current remote sensing products are consistently of high quality. What then can be done for acceptability to the user and, more specifically, the user in mineral exploration?

With respect to mineral exploration in particular, the key requirement still seems to be a need for demonstration projects, both visual and digital, with a practical cost-effective focus. This paper, backed up by relevant detail in the references, shows that certain types of remote sensing can now make significant contributions to practical mineral exploration. It is no criticism of those involved to say that these practices are relatively simple. How can they be otherwise in a time when investment by Canadian industry in research and development is rapidly declining and when the government contribution to the development of practical applications of remote sensing, especially for geology and mineral exploration, is almost negligible?

A co-ordinated program could bring together many ideas about the practical application of remote sensing to the search for ore. Such ideas may be technical and related to making sensors or data more specific to the needs of mineral exploration. They may be geological and related to understanding what we have sensed and what we should sense. As isolated projects, such ideas are difficult to sell to either government or industry. But by combining the splendid capabilities of government agencies with the practical experience of the exploration industry, the ideas could be filtered and developed into practical applications.

Of course, the major challenge is funding in the current economic climate. Perhaps the solution is a shared common fund with interdisciplinary support for the development of practical applications. The annual cost need not be great and initially could be less than the annual cost of a small exploration program. Most of the money would be expended on salaries and office expenses. Hardware and technology, already supported by a co-ordinated program, might continue to be shared. A comparable vehicle to support the development of practical applications should achieve comparable advances. Industry and government can work together towards such an end. It is not the lack of an operational satellite that confounds the development of practical applications of remote sensing, but the lack of a co-operative will to do something practical with the available data – even for mineral exploration.

SUMMARY AND FORECAST

In several large countries around the world, conventional aerial photography and Landsat images comprise complementary data that are widely used in mineral exploration. Conventional photography provides detail while Landsat data have advantages related to their overview and spectral/temporal content. Both tools are relatively simple and inexpensive to apply in the search for ore, although neither is specific with respect to the precise location of ore. The practices of photogeology are well established and can be adapted to Landsat with little difficulty. In general, Landsat images are so inexpensive per unit area and their information content is so comprehensive, that no regional exploration program should proceed without preliminary analysis of carefully selected images. Digital analysis of Landsat data has an encouraging potential that can, in some cases, be exploited. However, in general, further development is required to define limiting conditions and costs as applied to mineral exploration.

Side-looking airborne radal (SLAR) and aerial thermography can meet specific needs in the search for ore. Under certain conditions, one or the other may be the only means of providing essential exploration data. In some countries, SLAR is becoming more widely available through government acquisition. In such countries, SLAR imagery is widely used in geological mapping and mineral exploration. Aerial thermography yields significant amounts of geological information that may not be apparent from conventional aerial photography, especially for arid areas with sparse outcrop.

In the future, airborne remote sensing will develop as a specialized source of detailed information. There will be increased emphasis on multispectral scanners, selection of diagnostic wavelengths and digital processing to meet specific needs. Orbital remote sensing will provide higher resolution, perhaps with a zoom capability, although still retaining synopticity. Increased government participation in the acquisition of regional data seems probable because the high costs for large areas can be shared by several users.

The gap between remotely sensed data and information needed for mineral exploration will decline as government and industry recognize the need for co-ordinated effort in order to develop future reserves of ore. Much of that ore lies buried under soil and vegetation. In learning to deal effectively with those constraints, many new tools will be needed, including remote sensors to map new attributes of geology e.g. alteration patterns in residual soils, ghost linears that reflect buried structures and biophysical anomalies related to geobotanical stresses. To further these ends, a co-ordinated program for developing specific applications of remote sensing should be started now.

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REFERENCES*

Ahern, F.J., Goodenough, D.G., Jain, S.C., Rao, V.R., and Rochon, G.
1977: Atmospheric corrections at CCRS; Proc. 4th Canadian Symposium on Remote Sensing, p. 583-594.

Allum, J.A.E.
1966: Photogeology and regional mapping; Pergamon Press, Oxford, U.K.

Anderson, D.T.
1963: Colour photography as an aid to geological interpretation; in Air Photo Interpretation in the Development of Canada, Part IV, p. 2-9, Dep. Energy, Mines and Resources, Ottawa.

Anonymous
1977: What photogrammetric engineering and remote sensing is; Photogramm. Eng. and Remote Sensing, v. 43 (5), p. 451.

Anuta, P.E.
1977: Computer assisted analysis techniques for remote sensing data interpretation; Geophysics, v. 43 (3), p. 468-481.

Barthelemy, R. and Dempster, A.
1975: Geological interpretation of the ERTS-1 satellite imagery of Lesotho, and possible relations between lineaments and kimberlite pipe emplacement; Proc. 10th Internat. Symposium on Remote Sensing of Environment, v. II, p. 915-924.

*Bølviken, B., Honey, F., Levine, S.R., Lyon, R.J.P., and Prelat, A.
1977: Detection of naturally heavy-metal-poisoned areas by Landsat digital data; J. Geochem. Explor., v. 8, p. 457-471.

Canney, F.C.
1975: Development and application of remote sensing techniques in the search for deposits of copper and other metals in heavily vegetated areas – Status Report June/75; U.S. Geol. Surv. Project Report (IR) NC-48.

* A short list of the more significant references with respect to mineral exploration includes the special issue of Geophysics (v. 43, no. 3, 1977) and the compendia and references marked with an asterisk herein.

Carter, W.D., Lucchitta, B.K., and Schaber, G.G.
1977: Preliminary lineament map of the conterminous United States; Proc. 11th Internat. Symposium on Remote Sensing of Environment, v. II, p. 1543 (summary).

Cassinis, R., Lechi, G.M., and Tonelli, A.M.
1975: Application of Skylab imagery to some geological and environmental problems in Italy; Proc. NASA Earth Resources Survey Program, Houston, p. 851-867.

Dellwig, L.F. and Moore, R.K.
1977: Tradeoff considerations in utilization of SLAR for terrain analysis; in Woll and Fischer, 1977 (which see), p. 293-306.

Doyle, F.J.
1977: Photogrammetry: the next two hundred years; Photogramm. Eng. and Remote Sensing, v. 43 (5), p. 575-577.

El Shazly, W.M., Abdel Hady, M.A., El Ghawaby, M.A., and Khawasik, S.M.
1977: Application of Landsat satellite imagery for iron ore prospecting in the western desert of Egypt; Proc. 11th Internat. Symposium on Remote Sensing of Environment, v. II, p. 1355-1364.

Fischer, W.A., Hemphill, W.R., and Kover, A.
1976: Progress in remote sensing (1972-1976); Photogrammetria, v. 32, p. 33-72.

*Gilbertson, B., Longshaw, T.G., and Viljoen, R.P.
1976: Multispectral aerial photography as exploration tool IV-V; An application in the Khomas Trough Region, South West Africa; and cost effectiveness analysis and conclusions; Remote Sensing of Environment, v. 5, p. 93-107.

Gillespie, A.R. and Kahle, A.B.
1977: Construction and interpretation of a digital thermal inertia image; Photogramm. Eng. and Remote Sensing, v. 43 (8), p. 983-1000.

Gilluly, J.
1976: Lineaments — ineffective guides to ore deposits?; Econ. Geol., v. 71, p. 1507-1514.

Goetz, A.F.H., Billingsley, F.C., Gillespie, A.R., Abrams, M.J., Squires, R.L., Shoemaker, E.M., Lucchitta, I., and Elston, D.P.
1975: Application of ERTS images and image processing to regional geologic problems and geologic mapping in northern Arizona; Tech. Report 32-1597, Jet Prop. Lab., Cal. Inst. Tech., Pasadena, Cal.

Gregory, A.F.
1972: What do we mean by remote sensing?; Proc. First Canadian Symposium on Remote Sensing, p. 33-37, Canada Centre for Remote Sensing, Ottawa.

1973: A possible Canadian role in future global remote sensing; Can. Aero. and Space J., v. 19 (3), p. 85-92.

Gregory, A.F. and Moore, H.D.
1975: The role of remote sensing in mineral exploration with special reference to ERTS-1; Can. Inst. Min. Met. Bull., v. 68 (757), p. 67-72.

1976: Recent advances in geologic applications of remote sensing from space; in Astronautical Research, 1973, p. 1-18, Pergamon Press.

Gregory, A.F. and Morley, L.W.
1977: An overview of Canadian progress in the use of Landsat data in geology; Proc. First Annual W.T. Pecora Memorial Symposium (1975), U.S. Geol. Surv. Prof. Paper 1015, p. 33-42.

Grossling, B.F. and Johnston, J.E.
1977: Gap between raw remote sensor data and resources and environmental information; Remote-Sensing Application for Mineral Exploration, edited by B.L. Smith; Dowden, Hutchison & Ross, Inc., Stroudsburg, Pa.

Harris, G., Jr. and Graham, L.C.
1976: Landsat-radar synergism; paper presented to Commission VII, 13th Congress, International Society of Photogrammetry, Helsinki; available from Goodyear Aerospace Corp.

Hood, P.J.
1977: Mineral exploration trends and developments in 1976; Can. Min. J., v. 98 (1), p. 8-47.

Iranpanah, A.
1977: Geologic applications of Landsat imagery; Photogramm. Eng. and Remote Sensing, v. 43 (8), p. 1037-1040.

Jensen, H., Graham, L.C., Porcello, L.J., and Leith, E.N.
1977: Side-looking airborne radar; Sci. Am., v. 237 (4), p. 84-95.

Kuhn, T.S.
1970: The structure of scientific revolutions; in International Encyclopedia of Unified Science, v. II, no. 2, Univ. Chicago Press.

Levine, S.
1975: Correlation of ERTS spectra with rock/soil types in Californian grassland areas; Proc. 10th International Symposium on Remote Sensing of Environment, v. II, p. 975-980.

Longshaw, T.G.
1976: Application of an analytical approach to field spectroscopy in geological remote sensing; Modern Geology, v. 5, p. 201-210.

Longshaw, T.G., Viljoen, R.P., and Hodson, M.C.
1976: Photographic display of Landsat-1 CCT images for improved geological definition; IEEE Trans. on Geosci. Electr., v. GE-14 (1).

Lyon, R.J.P., Mercado, J., and Campbell, R., Jr.
1970: Pseudo radar; Photogramm. Eng., v. 36, p. 1257-1261.

Lyon, R.J.P.
1977: Mineral exploration applications of digitally processed Landsat imagery; in Woll and Fischer (1977), p. 271-292.

Maffi, C. and Simpson, C.J.
1977: Skylab photography for geological mapping; Aust. Bur. Miner. Resour., Geol. Geophys. J., v. 2, p. 17-19.

Miller, V.C.
1961: Photogeology; McGraw-Hill, New York.

*Newton, A.R.
1971: The uses of photogeology: a review; Trans. Geol. Soc. S. Africa, v. LXXIV, part 3 (Sept./Oct.), p. 149-171.

Offield, T.W.
1976: Remote sensing in uranium exploration; in Exploration for Uranium Ore Deposits, International Atomic Energy Agency, Vienna, p. 731-744.

Vincent, R.K.
1977: Uranium exploration with computer-processed Landsat data; Geophysics, v. 42 (3), p. 536-541.

Welch, R. and Lo, C.P.
1977: Height measurements from satellite images; Photogramm. Eng. and Remote Sensing, v. 43, no. 10, p. 1233-1241.

*Williams, R.S., Jr. and Carter, W.D. (editors)
1976: ERTS-1: a new window on our planet; U.S. Geol. Surv., Prof. Paper 929, 362 p. incl. illust.

*Woll, P.W. and Fischer, W.A. (editors)
1977: Proc. First Annual William T. Pecora Memorial Symposium (1975); U.S. Geol. Surv. Prof. Paper 1015.

Wukelic, G.E., Stephan, J.G., Smail, H.E., Landis, L., and Ebbert, T.F.
1976: Final report on survey of users of earth resources remote sensing data; Battelle Columbus Laboratories, Columbus, Ohio, 43201.

Discussion

V.R. Slaney: In the South African example of aerial thermography used to map faults, was the panchromatic image acquired at the same time as the thermal image?

Reply: The thermography and panchromatic photography were acquired separately but within a few weeks of each other. At scales of about 1:10 000, the 8-14 micrometre band consistently provided more geological detail than either the panchromatic photograph of the second TIR channel (3.5 to 5.5 micrometres). The Witpoortjie fault is a prime example of this discrimination. No seasonal changes have been observed in the area since the imagery was obtained (Viljoen, R.P., pers. comm.).

V.R. Slaney: What remote-sensing techniques would you recommend to: (a) a field geologist mapping a quarter degree sheet in the Northwest Territories; and (b) a mining company operating in northern Ontario or Quebec?

Reply: In both cases, interpretation of LANDSAT colour composites in transparency format for the regional analysis plus interpretation of selected black-and-white aerial photographs for clarification. Recommendations for more detailed analysis would depend on specific terrain conditions and needs for information at the particular location.

K.A. Morgan: Can we anticipate that the resolution of new satellites will be better than the 80 m of the current LANDSAT system?

Reply: The next LANDSAT, to be launched early in 1978, will have one sensor with about twice the current resolution. Higher resolution has been requested for a number of purposes. A major constraint on increased resolution results from the greater volume of data and associated problems of telemetry.

K.A. Morgan: In applying numerical data processing techniques to integrate LANDSAT data with other digital data acquired near surface (e.g. low level gamma ray spectrometry), I anticipate the necessity of degrading the resolution of such near-surface data.

Reply: The high resolution data may not require degradation. We have optically integrated LANDSAT spectral data with aerial photographs and aeromagnetic data to obtain synergistic benefits without degrading any data.

T. Findhammer: Could you tell us something more about research into thermal inertia in Canada?

Reply: To the best of my knowledge, no such work is in progress in this country. The U.S.G.S. in Denver and Jet Propulsion Laboratory in Pasadena both have programs related to thermal inertia.

B. Bølviken: I disagree that multispectral photography has restricted use in exploration. The occurrence of natural poisoning of vegetation is a common feature associated with sulphide deposits. Such occurrences can be detected by multispectral aerial photography which, therefore, is an important tool for prospecting.

Reply: The point of dissension here is one of semantics rather than science. Natural poisoning of vegetation by metallic elements in ore deposits has been demonstrated in some terrains (e.g. your studies in Norway). However, other studies mentioned in my review have not revealed analogous biophysical anomalies in other terrains. Hence, at this point in time, multiband photography should be considered as a specialized technique to be used where the occurrence of detectable poisoning has been established. It is, thus, not yet a tool for general exploration. In essence, further research is required to define the range of applications and costs.