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THE APPLICATION OF GEOCHEMICAL, BOTANICAL, GEOPHYSICAL, AND REMOTE SENSING MINERAL PROSPECTING TECHNIQUES TO TROPICAL AREAS--STATE OF THE ART AND NEEDED RESEARCH

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ABSTRACT

A disproportionate percentage of the world's known sulfide orebodies are found in the temperate and arid regions of the world. There is no geological reason why such orebodies should not be present in the tropical regions of the world in the same relative abundance as elsewhere; evidently the classical prospecting techniques that have proved effective in other climatic zones are not effective in the tropics. In recent years new and sophisticated prospecting techniques have been evolved in the more developed countries; their application and the research needed to make them fully effective in the tropical environment is the theme of this paper.

Geochemical, botanical, geophysical, and remote sensing techniques of prospecting are in widely differing stages of maturity. Problems of applying these techniques in the tropical environment affect the use of the methods to varying degrees, those caused by the arid tropics the least, those caused by the humid tropics the most. Logistical problems in the rainforest environment cause notable difficulty for all methods; therefore airborne reconnaissance methods have great advantages, although the high cost of precise location is a handicap for even these methods. Research to develop cheaper modes of precise location, both airborne and ground, is needed.

Many geophysical prospecting methods developed in temperate climates are directly applicable in most tropic environments with little change. Highly conductive surficial zones in the humid tropics, particularly over lateritic soils and laterites, complicate some electrical methods and further research in this field would bring improved efficiency of interpretation. Geophysical prospecting is the most mature of the techniques cited.

Geochemical prospecting is one of the more promising methods in tropical environments, although the technique is still immature. The deep weathering, thorough leaching of the soils, and the formation of laterite may hide and modify anomalous concentrations of sought-for elements and greatly increase the importance of "pathfinder" elements. Much research is needed not only on the mobility and fixation of elements but also in acquiring basic data as to sampling media, still in a rather primitive state in the humid tropics. Analytical and data-processing methods have been developed to a high state in the temperate zones, and the techniques can be applied directly to the tropics with little or no modification once the basic problems of sampling media and elemental mobility and fixation have been solved.

Geobotanical prospecting is also in an immature stage in the tropics and perhaps may be more effective in arid and semi-arid climates than in the humid tropics. Little work has been done in this field in the humid tropics; conceivably research might make the tool more effective.

Remote sensing is the newest and, except for photogeologic interpretation, least developed of the prospecting techniques as applied to tropic zones. It has great potential. Radar mapping in the humid tropics has proved the best way to acquire much basic information rapidly in areas of constant cloud cover; it reveals large-scale features of geology and structure that can be secured in no other way. The use of multiband spectral imagery and multiband photography holds great promise but is still in a rather rudimentary state; much research is needed and some is being carried on. Photogeologic interpretation is now a highly developed and standard technique where aerial photographs can be secured; it is of course at its best when used in arid regions.

Most modern prospecting techniques have lowered the cost of prospecting per unit area, but the capital cost of installing the needed equipment is substantial and highly trained personnel are needed. A vast amount of data is necessary to pinpoint the relatively few small areas worthy of detailed physical exploration. In a balanced, integrated survey, several methods should be used in conjunction with each other.

Much of the research hitherto accomplished in tropical areas has been done by private companies and is considered proprietary, or by the United Nations, which publishes a very small fraction of its results. The less developed countries do not have access to the information. Thus capital costs, lack of trained scientists and technicians, and lack of managerial skills inhibit the direct application of these techniques by the developing countries. Basic research by governmental agencies which publish results would have beneficial effects for the developing countries as well as for the rest of the world. Undoubtedly notable mineral deposits are hidden beneath the jungles, under the deep soils, and under the sands of the humid and arid tropics; their development would not only aid the developing countries by building the infrastructure, providing training for indigenous personnel in the industrial arts, and by improving the financial position of the countries, but would also benefit the rest of the world by increasing the raw material supplies on which the world civilization depends.

INTRODUCTION

The U. S. Geological Survey was requested on September 24, 1971, by the Office of Science and Technology, Agency for International Development (PASA TA(IC)9-72), to prepare this position paper on the development of geophysical, geochemical, and geobotanical mineral prospecting techniques for application in tropical areas, both humid and arid. Prospecting for hydrocarbons is excluded from consideration.

The authors of this report wish to gratefully acknowledge very substantial contributions to its substance by the following scientists of the Geological Survey. Without their generously extended and knowledgeable help, the paper would have been impossible to produce. Almost all of these men have tropical scientific experience.

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With many local exceptions, notably North Africa and Western Asia, the tropical zone may be roughly considered as the area between the tropics of Cancer and Capricorn. Within this zone, comprising nearly half of the earth's land area, lie most of the developing countries. Also within this zone lie many areas of extreme climatic conditions, ranging from the snowfields of the Andes to vast tropical rainforests, from the rainless deserts of Africa and Peru to some of the highest rainfall areas of the world. No generalization can be made as to geological conditions; rocks range in age from those now being formed in the coastal swamps of Gambia and the Central American volcanic zone to some of the oldest in the earth's crust.

Ore deposits and deposits of useful minerals and rocks of all types are known and worked in the tropical zone; mineral raw materials are one of the principal inputs to the world economy from this zone. Most of the ore deposits now being worked in the humid tropics are those surficial concentrations of useful minerals that typically form as weathering products in such an environment (bauxite, certain types of iron, manganese, and nickel ore, cassiterite or diamond placers, etc.) that can easily be found by conventional methods.

Because of the existence of great areas that have ample rainfall and high mean annual temperature, with resultant deep soils, deep weathering of the rocks, and formation of wide areas of laterite and other mantling weathering products which effectively hide underlying rocks, the geology of much of the humid tropical zone is known only in gross outline. Difficulty of access makes conventional prospecting relatively slow and expensive. Furthermore, many deposits of useful metals are in the form of sulfides, minerals subject to particularly rapid attack and leaching by surface and near-surface waters in the humid tropics. Although there is no geologic reason why such base-metal deposits should not occur at depth in tropical rainforest areas in the same quantities as elsewhere, deposits in arid, semiarid, and temperate zones are far more easily located; most of the world's production of the nonferrous metals, in fact, comes from such areas. Therefore it is reasonable to conclude that the conventional prospecting techniques used for many centuries in temperate zones are relatively unsuccessful in the humid tropics.

Similarly, such materials as potassium salts, salt, dolomite, limestone, and gypsum, which are of immense industrial importance and some of which have particular agricultural significance in the acid humid tropical soils, are also relatively soluble and are most difficult to locate in high-rainfall areas. Local sources of adequate construction materials other than wood are also hard to find in many areas.

Prospecting for useful minerals has three intergradational phases. The first is the elimination of those large areas which give little chance of success in searching for mineral targets. For this phase the most useful tools are a good geologic map and a sound geologic hypothesis. Where such maps do not exist, as in most of the humid tropics, large areas can be rapidly examined in reconnaissance style by use of photographs in black and white or color, geochemical and aerogeophysical surveys, side-look radar, and other remote sensing means. Interpretation of these data may reveal some anomalous or favorable physical, chemical, topographic, or structural condition conceivably due to or indicative of possible concentrations of useful materials. Good reconnaissance under favorable conditions can in many cases eliminate 90 percent or more of a given large area from further consideration.

The second phase of prospecting is the detailed study of the anomalous or favorable area to resolve the problem of what causes the geochemical or geophysical anomaly or to further investigate the promising structural, lithologic, or topographic target. Various methods are available for this, ranging from detailed geologic mapping through the various geochemical and geophysical techniques discussed below. Commonly more than one method will be used before the third phase, physical exploration by drilling or by test pitting, starts. The engineering and interpretative procedures used in the third phase are essentially the same as those employed in temperate regions and seem to require little or no modification for the tropics.

The humid tropics pose many still poorly understood problems to the geoscientist. The geophysical and geochemical techniques now used were, for the most part, developed and tested in temperate zones where regional geology, rock types, geomorphic history, soil, geophysical and geochemical backgrounds, and water conditions are now fairly well known. Different physical and chemical parameters are met in the humid tropics and the basic data affecting the exploration techniques must be defined. Commonly, little general geologic and geomorphologic information is available, and some existing information may be antiquated, suspect, or incomplete. Thus, the adaptation of the techniques to mineral exploration under tropical conditions requires considerable research, much in conventional geologic fields.

Notable complications in geochemical prospecting techniques are caused by shifting climatic zones because progressive aridity is accompanied by a change from acid to alkaline soil and groundwater environments. For example, relatively little is known of the climatic variation in north-central Africa except that it has been important even in historic times. Laterite is found today in some places where it could not form under present climatic conditions. When and of what duration were the humid cycles that formed this laterite; how did they affect the leaching of possible sulfide ore bodies, the distribution of trace amounts of metals in soil, the possible formation of nickeliferous residual ores over ultramafic rocks? To illustrate the importance of knowledge of climatic shifts, the very active bauxite exploration in the Amazon valley resulted from the discovery by a Dutch geologist that only one of several erosion cycles in that area produced bauxite. With the target so limited by geomorphic studies, rapid discoveries followed and very large reserves are now being developed. The unique erosion cycle possibly marks a climatic shift. Much basic knowledge must be acquired over large areas of the world to use most effectively the prospecting techniques now existent and to be developed.

The arid tropics present problems not radically different from those in arid regions in the temperate zones of the world; here too underground water, the occurrence of which is strictly controlled by geologic factors, is often a target. In the arid parts of Africa, the Arabian Peninsula, and western South America large areas are covered by windblown sand that effectively limits prospecting by many present geochemical and geophysical techniques. Research on the movement of surface material by wind or water under present and past climatic conditions would increase the effectiveness of geochemical techniques. Maximum effectiveness of such research can only be achieved by interdisciplinary projects that locally may include an archeological input.

Although for convenience of exposition, geochemical, botanical, geophysical, and remote sensing techniques of prospecting are treated separately in this paper, it cannot be emphasized too strongly that, particularly in the humid tropics, an integrated, multidisciplinary approach to ore-finding will be the most successful. Moreover, in areas of nearly ubiquitous soil cover, the application of all these methods may be the only way in which the regional and local distribution of rock units and structural features can be defined. Because the distribution of rock units and structure in most cases control the distribution and localization of ore deposits, such information is of prime importance to any prospecting campaign.

For completeness it should be stated clearly that many international mining companies and semipublic organizations are doing and have done much geochemical and geophysical prospecting. Thus, in the year June 1, 1970 to May 30, 1971, more than 900,000 geochemical samples were analyzed in Australia and more than 800,000 in Canada. A single commercial laboratory in the United States analyzed more than 100,000 samples. Some prospecting companies have excellent research facilities, others contract with private companies specializing in scientific instrumentation and research. The United Nations Development Programme (UNDP) has for some years been engaged in prospecting programs throughout the world, using geochemical and geophysical techniques. The Royal School of Mines in England has pioneered in geochemical prospecting applications. The problem is that both company work and most UNDP work are focused on ore finding and on volume production of analyses, not on fundamental problem-solving. Much valuable research has been and will be done in the course of these activities. However, most of this basic information is considered proprietary and does not reach the scientific public here or abroad or, in the case of UNDP, is not published because of restrictive contracts. The data and the methods rarely become part of the scientific heritage on which progress is built; limitations and possibilities of the instrumentation so developed are not fully defined.

The purpose of the fundamental research proposed in the following pages is not necessarily to find ore bodies directly, but to so improve our knowledge of geochemical and geophysical prospecting techniques and parameters that ore finding by specialized agencies and companies will be made more effective and, hopefully, less expensive. Many of the techniques to be discussed in the following pages were pioneered and refined by the Geological Survey, which has proven capability in the types of research needed, as well as friendly professional contacts with many geological agencies of countries in the tropic zones throughout the world.

In the following discussion, it must be borne in mind that geophysical, botanical, geochemical, and remote sensing prospecting techniques are in widely different stages of maturity. Although each technique except remote sensing can trace its beginning to remote antiquity, none was widely used until about four decades ago, when geophysical applications began in earnest. Adequate chemical methods of trace element analysis for exploitation of geochemical and botanical techniques first became available some three decades ago, and since then the development of more effective analytical procedures and instrumentation has continued at a rapid pace. Although the use of photography for prospecting was introduced six decades ago in Alaska by the USGS, the subtler forms of remote sensing were developed less than a decade ago and the techniques are still rapidly evolving. Remote sensing techniques of prospecting are still unproven but during the next decade appreciable development may be confidently expected. In the same period solid but perhaps less dramatic progress can be expected in the field of geochemical and botanical prospecting, especially in the area of interpretation of data. Development of classical geophysical techniques will probably be confined to refinement of present instruments, methods, and principles.

GEOCHEMICAL PROSPECTING

Geochemical prospecting as discussed in this paper is intended to define patterns of distribution of elements or combinations of elements, largely in surficial materials but also in rocks, water, and air, the presence or absence of which may indicate associated economic concentrations of useful minerals. Three equally important functions are involved: a) selection of sample media adapted to the local environment and targets (the orientation survey) and sample collection (the geochemical survey), b) sample analysis, in which a balance must be struck between speed, sensitivity, and precision; between a broad spectrum of elements sought and cost in time and money, and c) analysis of data and correlation with local geological, geophysical, and climatic factors; in short, interpretation of the data collected. Function c) is the most difficult and **important**.

State of the art

The conceptual basis for geochemical prospecting is that during the emplacement and the later weathering and erosion of concentrations of useful metals, a dispersal pattern will be created that contains anomalous quantities, either more or less than background quantities, of the elements sought or of elements commonly associated with them in ore bodies, the "pathfinder elements". The dispersal pattern will usually be far larger areally than the sought-for ore body and thus easier to locate.

The anomalies sought are of the order of a few parts to a few thousand parts per million, depending on the element involved. Thus, by sampling stream sediments or soils, the prospector can investigate drainage basins of varying size and can localize the sources of anomalous concentrations of metals. The presence of a geochemical anomaly does not guarantee the presence of an economic ore deposit. The method is simply a much refined version of that used in the old days to locate gold deposits by panning upstream.

The state of the art in the three functions of geochemical prospecting is not uniform. Enormous strides have been made in recent years in developing instrumentation and methods for the inexpensive, rapid, and sensitive analysis of a variety of geological materials for a broad spectrum of elements. Thirty elements are routinely sought and determined in the USGS Denver laboratories, for some elements to parts per billion, in most cases to within 10 parts per million. This is done on a large scale, with more than 1,400,000 determinations routinely performed in fiscal year 1971.

The great mass of raw data is stored in computers, together with the location of the samples and significant geologic parameters. The computers can produce maps showing distribution of particular elements, combinations of elements, or ratios of elements in a district, mine, or other specified area. This of course greatly facilitates the manipulation of the raw data to reveal gross and subtle relationships in element distribution and the relation between that distribution and geologic parameters, space, and rock types. Thus techniques of chemical analysis and analysis of the information produced have achieved considerable maturity.

However, in the application of exploration geochemistry to specific environments, inadequate attention has been paid to the selection of the type of material to be sampled. Frequently, the results of orientation studies in one area are used, without critical appraisal, in other areas that are not necessarily comparable, with consequent loss or distortion of information. Although much geochemical work has been done in recent years in tropical areas, basic research on sampling media and modes of sampling has not been systematically carried out. Research by the U. S. Geological Survey and other entities in the arid tropical and temperate zones indicates some of the pitfalls and complications, but does not resolve many of the problems to be met in the humid tropics.

Despite these problems, the method is particularly useful in deeply weathered areas where surface expression of ore deposits has been hidden from the unaided eye. The more we can understand these limiting parameters, the more useful the technique will become.

Two types of geochemical research, regional and local, may be undertaken. Clearly, if the regional work has been done, the local work can be planned more closely and accurately. In regional studies 5 to 60 samples are commonly taken in each 100 square kilometers of area. In a regional study of the Arabian Peninsula by the U. S. Geological Survey, about 20,000 samples were collected, and determinations made for 27 elements in each sample. In a local survey for a specific target, anywhere from 100 to more than 10,000 samples may be collected and analyzed for 1 to 32 elements, depending on the area studied and the targets sought.

In geochemical prospecting, samples of soil, stream sediment, rock, or, less commonly, caliche, iron or manganese oxides or hydroxides, heavy minerals, forest litter, air, or water are taken according to a sampling plan established after an orientation survey. In the broadest regional geochemical prospecting, the samples can be taken on widely spaced intervals chosen to establish regional variations, provincial distributions, metallogenic provinces, etc. More commonly, sampling is for identifying specific targets in detailed investigations; such samples may be taken in individual drainage basins or according to a plan devised to get at least one sample in a dispersal pattern of the size expected or believed to be significant from an economic viewpoint. Choice of the medium to be sampled and of the types of targets sought is critical to the success of the program.

Samples taken during geochemical prospecting are generally analyzed, after partial or complete dissolution, by simple colorimetric or atomic absorption methods or by optical emission spectrography and x-ray fluorescence spectrography. Emission spectrography is particularly useful during reconnaissance surveys because many elements can be determined simultaneously in small samples and at low cost. This procedure of course requires a moderately costly instrument and a dependable supply of electricity and photographic film or plates. In surveys of areas in which a small number of metals is sought, wet analytical methods may be more satisfactory. Atomic absorption analysis is very rapid and has minimal manpower requirements but demands an expensive instrument and, like the emission spectrograph, a reliable electric power supply. Colorimetric analytical methods are especially popular in remote or primitive areas with lower labor costs, because they require simple, cheap, and readily portable equipment and are rapid, but these methods require more man-minutes per sample than atomic absorption methods. Unfortunately the organic reagents required are sometimes difficult to obtain and may be unstable (heat- or light-sensitive), leading to unreliable results. It should perhaps be emphasized that careful maintenance and air conditioned housing of the delicate instruments involved in most analytical methods is critical to their successful operation, particularly in tropical zones, and that competent, conscientious, and well-trained personnel are essential to successful operation of a geochemical laboratory.

Data from the analytical work may be processed by manual means if the program is relatively small and uncomplicated and indigenous personnel and equipment can be profitably used in point plotting, contouring, and map work. However, full use of the data collected in more sophisticated and broader-spectrum work involving numerous elements and many samples can be facilitated by computerization. Needless to say, the data must be interpreted, whether it is computerized or manually processed. The interpretation of the data is the key to the success of the whole operation, and the more complex the environment of the sampling, the more difficult and critical the interpretative process becomes.

Regional heavy-mineral reconnaissance is a method of geochemical exploration in which the identity, abundance and/or composition of detrital heavy minerals are determined over areas of thousands of square kilometers to define districts favorable for detailed search for ore deposits. The method is complementary to conventional regional geological and geophysical surveys. The conceptual basis of the technique is that certain heavy accessory minerals in rocks, veins, and ore deposits, as well as certain ore minerals, are not destroyed by weathering and accumulate in residual soils or colluvial and alluvial material. Owing to their high specific gravity, these minerals can be recovered quite simply by panning from stream sediments or other material. The panned concentrate can be studied mineralogically or chemically and the results of the analyses related to the geology and ore deposits of the drainage basins.

For some inert mineral raw materials, and especially for nonmetallic minerals, the method is more suitable than conventional geochemical or geophysical methods. Simple, even primitive field procedures are suited to heavy-mineral reconnaissance; thus, low-salaried local mineral collectors can be used. However, when the concentrates reach the laboratory, a staff of mineralogists, or mineralogically trained subprofessional persons, are needed to perform the mineralogical analyses.

To make an effective, modern technique of the method, the laboratory procedure should be brought as nearly as possible to an automated procedure. A scheme of automated mineral identification needs to be evolved, possibly using X-ray diffraction with read-out to tapes that can be processed statistically by computer to give a best-fit, semiquantitative estimate of the mineral species in the concentrate and plot these results on maps of the region surveyed. Laboratory treatment of the concentrates would need to be done outside most developing countries to take advantage of the automated mineralogical analyses.

Geochemical prospecting has been successful in finding "exotic" mineral deposits. Such deposits are concentrations of useful metals or materials either in unusual mineral species normally overlooked by most prospectors and geologists during field examinations, or in geological environments outside the normally expected association, or in combinations of these two "unusual" habitats. Thus beryllium commonly occurs as the mineral beryl, easily identified and almost always in pegmatite bodies. A few years ago a very large commercial deposit of the beryllium-containing mineral bertrandite, theretofore known only as specimens, was discovered in an environment which a knowledgeable beryl prospector would never think of as a profitable place to look. Other examples could be cited and undoubtedly a number of major "exotic" deposits of useful metals remain to be discovered in unsuspected places and minerals. The search for a broad spectrum of elements, particularly in orientation surveys, will help locate such deposits. It is in such work that the emission spectrograph is particularly valuable.

Hitherto most prospecting has been guided by the principle of analogy, for example, copper deposits will be found in environments similar to those in which copper deposits have been found before. One great advantage that broad-spectrum geochemical prospecting confers is that the occurrence and behavior of each element can be determined independently of the operator's hypotheses. Thus, well-executed geochemical surveys have occasionally revealed deposits of kinds other than those originally anticipated.

Instrument and survey costs

Some data on cost of instruments for analytical support of geochemical exploration projects are given below. Such support can range from the older colorimetric methods of analysis for about 20 elements, to the modern atomic absorption methods for about the same elements, to the optical emission spectrographic methods for some 30 or more elements useful primarily in reconnaissance sampling.

The cost of a simple spectrophotometer to use in conjunction with the colorimetric methods is given, but the spectrophotometer and associated voltage regulator are not absolutely essential. A skilled analyst can make visual comparisons of unknowns with knowns and thus produce analytical data to meet the needs of exploration geochemists. These methods were designed for "cookbook" application, and, except for the particular color-forming reagents needed and some skill in distinguishing colors, do not require unusual or expensive laboratory facilities or personnel. Moreover, they have been used extensively in remote areas of Africa, India, Indonesia, South America, etc. Equipment needed is as follows:

Spectrophotometer	$1,000 to $1,600
Accessories such as cuvettes, voltage regulators	1,000
Reagents and miscellaneous apparatus	1,000

In many geochemical exploration laboratories, atomic absorption analytical methods have displaced the colorimetric methods referred to above. The atomic absorption methods are fast and reasonably good for many chemical elements such as copper, zinc, and manganese, but not wholly satisfactory for elements such as arsenic, antimony, molybdenum, and tungsten. They require specific instrumentation listed below, and fuels such as acetylene, and in certain applications oxidizers such as nitrous oxide. The atomic absorption instruments require a hollow cathode lamp for each element determined, and the hollow cathode lamps have limited usefulness and shelf life. Instrumentation needed is as follows:

Atomic absorption instrument	$12,000
Accessories including nitrous oxide burner head, air compressor, and gas regulators, standards, etc. . . .	800
Hollow cathode lamps, 15 for several different elements, e.g., Cu, Pb, Zn, Co, Ni, Cd, etc.	1,800

Many geochemical exploration laboratories also have optical emission spectrographs that provide analytical data on single samples for about 30 elements including copper, lead, nickel, cobalt, and others, using the so-called 3-step or 6-step semiquantitative methods. In addition to the specific instrumentation listed below, the analyst has to have unique skills which are needed in order to guarantee reliable data from this instrumentation. Specific instrumentation is as follows:

1.5 meter spectrograph including lens, filters, arc-stand	$7,500.00
Comparator	6,000.00
Power supply --- d.c. arc only	1,500.00
Electrodes, each sample	.30

Although these costs do not appear large for a spectrographic laboratory, most spectrographers will agree that a fully equipped spectrographic laboratory might easily cost $20,000 or more.

The above costs for the three kinds of chemical support laboratories would have to be increased by 25 percent or more for overseas delivery.

A detailed analysis of costs for a simple colorimetric geochemical prospecting campaign carried on in cooperation with the United Nations Development Programme is given in Exploration for disseminated copper deposits in humid, mountainous tropical terrain, Sto. Nino, Mountain Province, Philippines; W. W. Brown et al; Report of Investigation No. 66, Republic of the Philippines, Department of Agricultural and Natural Resources, Bureau of Mines, Manila, 1968.

Costs of geochemical prospecting campaigns obviously will vary widely, depending on the degree of complexity of the analytical work, the number of elements sought, the density of sampling, the sample medium, the area covered, the nature of the area covered, and the location of the area covered. For example, one company, in carrying out a widespread and successful geochemical sampling campaign in certain far eastern islands, is said to have equipped a ship with complete laboratories, housing, hospital, and recreational facilities for personnel, and landing and maintenance facilities for the helicopters which carried skilled personnel to sampling sites.

The other end of the scale is the type of work carried on in the Philippines cited above, which was successful in locating both the known orebodies and previously unknown anomalies. After the initial capital investment in equipment, the principal costs in geochemical prospecting are in securing meaningful samples, an operation which demands experience, skill, and, in many cases, complex logistic support.

Regional heavy-mineral reconnaissance, discussed on page 16, is an underused technique that is well adapted to the purposes and capabilities of many of the developing countries, because sample collection can be done by relatively untrained and low-cost personnel; mineral identification can be taught to subprofessionals who would be willing to do the very dull and routine mineral identification on a production basis; and relatively few highly skilled professionals would be needed for analytical work and interpretation. If research succeeded in automating mineral identification as suggested, the method would be even more widely applicable.

Current research

Current research in geochemical prospecting techniques may conveniently be divided into the three basic functions of the method: 1) investigations of sampling media, spacing, and techniques; 2) improvement and development of new analytical techniques; and 3) analysis, manipulation, and interpretation of data.

With respect to the last, current research as known to us is centering on the use of more sophisticated and efficient means of storing, retrieving, and manipulating the great mass of data now becoming available so that regional and local data will be of deeper and wider use, and also on the production of interpretative aids by computer methods. Several countries have installed or are installing data banks. Although electronic and other devices aid substantially in presenting data in useful forms, the final step, interpretation of the data, is the most demanding and important and requires experienced and imaginative professionals to relate the often subtle geochemical variations to the geology and geomorphology and climatic regimen of the area prospected. No "black box" can substitute for the human mind.

With respect to research on analytical methods and instrumentation, many governmental and private organizations are continuing the never-ending search for more efficient, cheaper, more portable, more accurate instrumentation and methodology to lower costs and increase efficiency and flexibility. An example is the mercury detector, now able to detect mercury in a few parts per trillion in the air (certain types of ore deposits emit low concentrations of mercury vapor); this instrument is being adapted for use in slow-flying aircraft.

The standard techniques and instrumentation, however, which are quite adequate for most work, are available to all who need them and have the funds to buy or contract for them. The capital costs of a fully equipped laboratory are relatively high and key personnel must be highly trained, although much routine work can be done by intelligent subprofessionals. Skilled management of fully equipped laboratories is of major importance, for a large throughput is essential to justify the capital cost.

A major problem still remaining is the development of criteria for selection of sampling media, spacing, and techniques suited to the great variations that occur in nature and to the variation in targets. Because of this variation, many modes must be studied and evaluated to aid the essential orientation surveys and the interpretation of results. Most research to date has been in temperate climates and semiarid to arid regions. The Royal School of Mines in England has done excellent and valuable work in East Africa on this and related problems. Monsoonal climates present problems that should not be too difficult to solve except in areas of very steep relief. The collection of meaningful samples in the humid tropics has not yet been fully investigated. Much meaningful data has been acquired as a result of UNDP or company prospecting programs in the humid tropics, but the results of most of this work are unpublished and unavailable to both developed and developing countries. Some recent results of research were discussed in papers for the 50th Anniversary Conference of the Uganda Geological Survey and Mines Department in July 1969 at Entebbe, and a UNESCO sponsored seminar on geochemical exploration in the tropic environment held in September 1970 in Ceylon.

Research gaps and priorities

Because, in the humid tropics, anomalies caused by the solution, transportation, and redeposition of key elements (secondary anomalies) are generally the target, much new knowledge of the geochemistry of the elements in this environment is needed. As an example, much of the copper in secondary anomalies is sorbed by clay minerals or trapped with iron or manganese hydroxides deposited in favorable environments. However, the complexities involved in these studies is illustrated by recent work in Puerto Rico, showing that gold anomalies were a better indicator of leached copper deposits than copper itself, owing to the fugitive nature of the latter element in this climate. Although an adjacent unleached copper body was found by standard geochemical field techniques, a richer leached body was missed, illustrating the need for wide-band rather than narrow-band geochemical prospecting techniques.

Soil formation and soil horizons in the humid tropics differ markedly from those in semiarid or temperate zones and much research is needed to definitely establish preferred sampling sites. Geomorphic history of the areas being sampled is often obscure in the humid tropics but is as important as everywhere else. Which elements can be used as pathfinder elements in geochemical prospecting in the humid tropics is still, in many areas, to be determined, although some work has been done on this by the Geological Surveys of Guyana, Japan, and India.

Confining the discussion to geochemical prospecting in tropical regions, it would seem that research should be concentrated on the problems of the monsoonal and humid tropics, because techniques developed elsewhere may be applied with modifications to the arid and semiarid tropics. Patterns of agriculture unusual elsewhere, such as paddy-rice cultivation over large areas in the Far East, introduce major problems. Analytical methods must be improved, particularly for determining contents of important metals in high aluminum, manganese and iron samples. Many procedures developed elsewhere will be directly applicable to tropical areas. Data storage, retrieval, and manipulation research elsewhere will also spin off information of direct use in tropical areas.

Thus, the highest priority research in the monsoonal and humid tropics would be targeted on:

1) Increased understanding of movement and fixation of elements in tropical and monsoonal soils and sediments, and the size and nature of dispersion patterns created by ore deposits in this region.

2) Detailed evaluation of sample media of modern and fossil soil horizons, stream sediments, and water, optimum grain size of samples collected, and heavy-mineral concentration, both magnetic and nonmagnetic, in various types of environment in the humid tropical and monsoonal zones.

3) Detailed studies of laterites, which cover enormous tropical areas, to establish whether or not some trace elements may be indicators of underlying mineralized zones.

4) Large areas of the Far East, particularly in stream and river valleys, are under paddy cultivation. Paddy cultivation creates a highly organic soil quite different geochemically from normal soil and much soil has been carried from hillside to fields. Stream valleys are preferred sites for geochemical sampling, but at present, paddy soils are essentially removed from possible sampling because significance of results cannot be interpreted. A specialized attack on this problem might lead to useful results, opening large areas to geochemical prospecting.

5) In recent years, much progress has been made in defining metallogenic provinces in the world, and much effort is being expended by public agencies and private companies in this fundamental research because it helps to define broad exploration targets. For example, it was possible for a geologist in Washington to advise a UNDP party chief in Madagascar, on the basis of his knowledge of variation in the thorium content in monazite on that island, that tin deposits should occur in the southern part of that island. Rechecking of samples revealed cassiterite, and a tin deposit was eventually located. Broad-scale, multi-element regional

geochemical surveys will greatly assist in defining different metallogenic provinces; indeed, in the tropical rainforest environment, this is the most practical approach, for metallogenic provinces are defined by distinctive trace-element assemblages. Such regional surveys depend on rather widely spaced samples and demand analyses for a wide range of elements. Their objective is not the location of mineral deposits per se, but to show what types of mineral deposits might be looked for in a given large region.

In the large virtually unexplored rainforest areas of the humid tropics, regional geochemical surveys would be most useful in guiding later prospecting efforts aimed at specific targets and should receive a fairly high research priority if adequate regional analytical laboratories can be established.

6) Research on analytical methods is needed to establish more efficient procedures suited to iron and aluminum-rich sample media, common in the humid tropics but not usually encountered in temperate or arid zones.

The discussion on geochemical prospecting is largely based on experience and research objectives in the United States, with very little input from other countries active in the field. This apparently provincial approach is forced by the lack, until recently, of a centralized scientific society dedicated to geochemical exploration. Such an international organization, The Association of Exploration Geochemists, was formed in Toronto, Canada, in 1970 and plans for a quarterly scientific publication are well advanced. The 300 members are drawn from all continents; European, Canadian, Australian, and American contingents are particularly strong. Within a few years it may be expected that a large input to the science on a world-wide basis will result, and new information derived from research activities such as those discussed here can be widely and rapidly disseminated, benefiting all the developing countries.

BOTANICAL METHODS OF PROSPECTING

Botanical methods of prospecting have been recognized and, to some extent utilized for many years; the first reference to these methods is in De Re Metallica, written by Agricola in 1556. However, these methods have never been as widely used as other methods, probably because of their limited applicability if only simple techniques are used, because of inadequate basic research on principles, and because other methods of prospecting commonly are more direct and simpler to perform and interpret. Furthermore, few geologists or prospectors are competent to use botanical methods to their full potential. Some of the techniques, however, are so simple they can be used by any careful observer.

Two distinct botanical methods, botanical and biogeochemical, are used in prospecting for mineral deposits. Because the two methods are based on different principles, their applicability, the expertise required, and the instrumentation necessary are different. These methods are treated separately in the discussion that follows.

State of the art

Botanical prospecting

This method utilizes the principle of selective adaptation, or lack thereof, by plant species to anomalous concentrations of certain metals in their substrates. In using this method, the trained observer can determine the presence or absence of certain species, gradients in abundance or vigor of species around a dispersion halo, relative abundances of different species as a reflection of their requirements for (or resistance to) concentrations of metals in the substrate, conspicuous morphological modifications, and the general vigor of vegetation at the site. These observations are made by on-site visual inspection or, in suitable environments, by the examination of aerial photographs or other remote-sensing techniques. The plant species employed need not necessarily be deep-rooted trees or shrubs; small herbaceous species, and even mosses and lichens, have been used with success. This method does not require the collection of samples and chemical analyses, and, therefore, may be especially applicable to exploration in tropical areas where access is difficult or where complex instrumentation is not available. A review of botanical methods was given recently by Cannon (1971).

As practiced, botanical techniques may be as simple as merely observing, from the ground or from the air, the areal distribution of a conspicuous species that grows only where a metal in the soil is highly concentrated. This technique was used to detect uranium deposits on the Colorado Plateau by observing the species that grew preferentially in anomalous concentrations of selenium, an element that is associated with uranium deposits (Cannon, 1960, p. 21-28). This technique was also highly successful in the Katanga region of Africa, where an herb with conspicuous flowers grows on soils that have a copper concentration higher than can be tolerated by other plants (Duvigneaud, 1958). Such a plant is called an "indicator species". The use of indicator species, however, is thought to be of limited applicability, because so far as is presently known, few species have such absolute dependence on metallic anomalies in the soil as does this copper indicator in Katanga.

In some areas certain plants occur only over specific geologic formations, or other geologic features, either because of the favorable supply of essential elements or the abundance of water that is provided. The distribution of these plants may then be used in geologic mapping and, therefore, contribute indirectly to mineral prospecting. In heavily-forested areas of North Borneo, for example, Meijer (1960, p. 16) reported (translated) "The structure of the vegetation on ultrabasic formations makes it possible for the geologist to map these formations by the use of aerial photographs". There is no doubt that this technique, which has had extensive use in temperate zones, could be used in many other heavily forested tropical areas.

Physiological stress produced in plants that grow over areas of metallic deposits, as indicated by changes in proportion of the chlorophyl or other pigments in the leaves, may indicate the location and extent of the deposits, and may be observed both on the ground and by use of remote sensing techniques. This method has proved effective in certain types of temperate-zone vegetation growing over copper deposits, and work is under way to test its applicability in tropical regions. Physiological stress may also produce morphological changes, such as teratological developments, gigantism, albinism, and others, that are easily recognizable by observations at the site (Malyuga, 1964, p. 10-12).

Genetic stress, produced by mutagenic low-level radiation from underlying radioactive minerals, may produce morphological changes that are conspicuous from the ground and, conceivably, could be observed by remote sensing techniques. The use of this method has been demonstrated in exploration for uranium on the Colorado Plateau (Cannon, 1960, p. 22-23) and in north temperate areas where pitchblende deposits occur (Shacklette, 1962, 1964). Instances of the application of this technique in tropical areas are not known.

More sophisticated techniques of botanical prospecting include the detailed mapping on the ground (or conceivably, from remote sensing) of the frequency distribution of various plant species around suspected geochemical halos. Theoretically, it is unlikely that two species of plants have exactly the same degree of tolerance to concentrations of toxic metals in the soil; therefore, as the center of a dispersion halo is approached, the species composition of the vegetation at successive points on a traverse should change as a reflection of relative tolerances among species. This technique has been used extensively in temperate zones (Cannon, 1960, 1964), and has been successfully used in delineating deeply buried mineral deposits in tropical regions of Africa and Australia where dispersion halos are so weak that they cannot be detected by soil analyses. However, a high level of botanical training and experience is required for the successful use of this technique, and it may be of limited application where such expertise is not available.

A unique application of botanical methods is provided by a technique wherein certain mosses and liverworts that require high concentrations of copper or other metals in the substrate (see Morton and Gams, 1925; Persson, 1948, 1956; Shacklette, 1961, 1965, 1967; and Gams, 1966) are used to locate sites having anomalous concentrations of metals. These plants, designated "copper mosses", are widespread in both temperate and tropical regions, and many specimens already are on file in major museums.

The locations where copper mosses have been found in Scandinavia, as shown by museum specimens, were investigated by other geochemical techniques, and the presence of a previously unknown copper deposit was confirmed (Persson, 1956, p. 5). Copper moss specimens from the Azores Islands, Ecuador, Costa Rica, Bolivia (34 species!), and doubtless from many other tropical countries, are on file in various botanical museums throughout the world. Insofar as is known, the exact sites where these specimens grew have not been examined for geochemical anomalies. Professional bryologists would be required to search the museums for these species; follow-up studies of the original locations of the specimens would be made by geologically oriented geochemists.

Biogeochemical prospecting

This method is based on the fact that certain metals, or characteristic suites of metals, that occur in the soil or other substrate are concentrated in the tissues of some plants. This concentrating ability is controlled by two factors -- the inherent characteristics of the species, and the concentrations of the metals in the substrate. Some species, designated "accumulators", are able to preferentially concentrate certain metals to high levels.

The use of this exploration method requires the collection of plant samples, chemical analysis of the samples, and, commonly, statistical analysis of the data. This method has the advantage of being potentially applicable to most regions of interest in exploration, in contrast to the botanical method which relies entirely on the fortuitous occurrence of suitable species. It has the disadvantages of requiring highly trained personnel, sophisticated and expensive equipment and supplies, and access to the sites under investigation. In their present states of development, remote sensing techniques are not applicable to this method.

The basis for biogeochemical prospecting was first formally suggested by Goldschmidt (1937). Reports of the application of this method were given by Warren and Delavault (1949), Cannon (1960), Hawkes and Webb (1963), Malyuga (1964), and many others. The rationale for the use of this method in mineral exploration, commonly in conjunction with other geochemical methods, lies in the following properties of plants:

1. The ability of many species to concentrate elements to detectable levels in their tissues from undetectably low concentrations in the soil or rocks on which they grow. This ability is related in some manner to the large quantities of dilute soil solutions that are absorbed by roots, transported to other organs where certain elements in these solutions are chemically bound; other elements remain as deposits in the leaves when the water is lost from the plant through transpiration.
2. The great depth and lateral extents to which roots grow. By virtue of this feature, mineral deposits that are covered by deep layers of surface deposits such as till, alluvium, and laterite can, in some cases, be detected by analyses of deep-rooted trees and shrubs, even though the dispersion halo in the surficial deposits is absent or too weak to detect. The lateral extent of tree roots tends, in effect, to sample the elements in a large volume of soil, whereas a single soil sample represents only a "point" in this volume. In general, roots are thought to extend to greater depths in arid than in

humid regions, although reliable data on root systems are scarce. The presumed shallow root penetration in wet tropical regions may reduce the effectiveness of tree analysis in detecting deeply-buried geochemical anomalies in these regions.

3. The presence of vegetation may retard the removal of metals from surficial deposits by erosion and leaching. When the tissues of plants that have absorbed metals from the substrate die and decompose, the metals are released in a mobile form and are, to a great extent, reabsorbed by other plants, rather than removed by erosion and leaching. Thus the plants tend to annually absorb small amounts of metals from depths as great as their root penetration, and to transport the metals to the biosphere, where an abbreviated geochemical cycle holds and continually concentrates them. This process is known as the Goldschmidt enrichment principle (Rankama and Sahama, 1955, p. 333-334), and results in a concentration of metals in the plant litter (A_{OO} soil horizon) greater than that in other horizons of the soil. It has been shown that analyses of this forest litter (mull or mor humus) may indicate deeply buried anomalies in metal concentrations where typical soil samples do not (Curtin and others, 1968). This enrichment principle may be an important attribute of vegetation in geochemical prospecting in wet tropical regions where erosion and leaching are intense.

Instrument and survey costs

Too few data are available to permit an estimate of survey costs for the various botanical and biogeochemical modes of prospecting. Instrumentation for biogeochemical prospecting is the same as that used in soil analyses for geochemical sampling, and instrumentation and analytical costs would be quite similar. Sample collection costs would be very similar to those for geochemical sampling and would largely depend on the nature of the terrain being sampled and the logistical problems encountered.

Current research

Research in both geobotanical and biogeochemical methods is being conducted throughout the world, perhaps more in other countries than in the United States. Some results of research on techniques are proprietary in nature, others are unpublished, and full accounts of these results, of course, cannot be given here.

One of the most significant fields of research is in sampling design, because not only are costs of exploration directly related to the efficiency of the design, but the ability to establish the validity of conclusions is also dependent upon the use of an appropriate design. Current research by the U. S. Geological Survey is resulting in techniques of sampling design that could be of highly practical significance in geochemical exploration by the developing countries.

A difficult problem in the interpretation of most biogeochemical data is the definition of concentrations of metals in plants that may be considered anomalous, and, therefore, indicative of mineral deposits. This is due, in part, to the largely undefined inherent differences in metal accumulation of the many species that may be sampled, and in part to the unknown taxonomic level at which species can be grouped according to tendencies in accumulation of metals of interest in exploration. The U. S. Geological Survey has studies under way to help elucidate these problems in relation to the use of plant analyses both in exploration for minerals and for evaluation of the ecological impact of environmental pollution.

Experiments are currently being conducted that are designed to clarify the means by which certain metals can pass from the lithosphere to the biosphere where analyses of plant tissues can detect their presence. Native gold, for example, was shown to be solubilized by hydrogen cyanide derived from plant secretions, and, as gold cyanide, was then absorbed in measurable amounts by other plants (Shacklette and others, 1970).

Proprietary results of a novel sampling technique for large-scale geochemical reconnaissance can be only briefly reported. One exploration company sampled a large tract of forested mountainous terrain that was difficult of access by sampling the tops of certain trees, on a grid pattern, from a helicopter. Informal reports indicated that the method was effective in locating anomalous target areas that were followed up by encouraging results from soil sampling. A very large area was sampled in a short period of time and at small expense compared to some conventional sampling methods, but the hazards to personnel (a man was lowered on a cable from the helicopter) were reported to be significant.

Current research in refinements of analytical techniques have been significant, both in cost reduction, in precision of results, and in the increase in number of elements that can be detected by practical methods. This research, however, applies in general to all geochemical exploration methods, and will not be discussed here.

For obtaining the greatest amount of information from biogeochemical data, the use of special statistical techniques generally are necessary. The U. S. Geological Survey has investigated the use of several kinds of formal sampling designs in geochemical surveys of large regions. The designs are based on statistical models such as those described by Miesch (1967), and are intended to assess and overcome the effects of sampling and analytical errors (Miesch, 1964) to insure the reproducibility of the geochemical maps. A great variety of designs that are of potential use in exploration, biogeochemical exploration in particular, remain to be studied.

Reliable estimates of characteristic concentrations of metals in samples of many different biogeochemical materials, as well as in other media sampled in exploration for minerals, require large amounts of data. In order to make best use of these data, computer-based storage and retrieval systems must be utilized for effective data management, and where possible, should provide automatic entry of the data into data-processing systems for statistical reduction and graphic presentation (including the plotting of geochemical maps). Moreover, a broad range of multivariate statistical methods needs to be investigated for applicability to the problem of detecting subtle biogeochemical anomalies. The multivariate methods may serve to identify anomalies that cannot be identified by examination of one element at a time. Most such methods require computer facilities.

Research gaps and priorities

Research gaps in botanical and biogeochemical methods as applied to tropical regions are indicated by the following suggestions for research emphasis:

1. Studies to determine root penetration in laterite.
2. Confirm the Goldschmidt enrichment principle, as applied to wet and dry tropical regions (the principle was developed from research in temperate zones).
3. Test the application of remote sensing techniques over known metal deposits in the wet tropics.
4. Develop simple, precise, and rapid methods of plant analysis that employ truly portable equipment. Methods of this type have been developed for soil analysis.
5. Study, by ground and aerial observation, known near-surface deposits of radioactive minerals in tropical regions, and search for indicator species.
6. Develop efficient and safe methods for tree sampling from aircraft. A simple device, lowered on a safety release cable,

would seem to be ideal.

7. Develop a central repository for information regarding botanical techniques that are particularly well adapted to geochemical exploration in tropical regions.

GEOPHYSICAL PROSPECTING

Geophysics here is restricted to what is conventionally thought of as exploration geophysics, including radiometric techniques which overlap into the geochemical area. Remote sensing, using the term in a limited sense for electromagnetic sensors operating in the radar to ultraviolet range, will be considered in a separate section.

Geophysical prospecting is used as part of many minerals exploration programs, and proper integration of the several exploration techniques within the overall exploration program is essential. In general, one of the more important advantages of geophysical techniques is that they give information in three dimensions. With some exceptions, the tropics present no unique problems to the application of conventional exploration techniques. The two principal problems encountered in the tropical environment are (1) the local presence of highly conductive surficial material limiting the depth of penetration of the various electrical methods, and (2) accessibility. As in the case of geochemical analysis, maintenance of delicate equipment may become a serious problem in the humid tropics.

In geophysical exploration for minerals, two somewhat distinct types of operations are used. These are regional programs focussed on obtaining an understanding of the broad geologic setting of a region, and, secondly, target-oriented detailed exploration programs. Regional programs are often conducted by governmental organizations because they are not principally target-oriented and the information is of value to a variety of users. Such regional programs utilize aeromagnetic techniques, often supplemented with either airborne electromagnetic or radiometric measurements. An example of such a program is the recent combined airborne magnetic/radiometric survey of Liberia made cooperatively by the governments of Liberia and the United States at a cost of about $600,000 for data acquisition and reduction to map form. This resulted in the discovery of an offshore sedimentary basin now being explored for oil.

Target-oriented programs will utilize a variety of airborne and land techniques, depending on the particular type of mineral being sought and the geological environment. This type of exploration is generally done by private mining companies and involves large expenditures. It has recently been estimated that exploration costs to find and bring to development a major nickel deposit in Australia were approximately 10 million dollars, of which about 25 percent was spent on geophysical prospecting. A number of references in the bibliography contain case histories illustrating the use of target-oriented programs in both tropical and temperate zones. Of particular interest is the paper by Gay (1966) on the Marcona district, Peru, which not only illustrates a typical geophysical program, but also briefly discusses problems encountered due to planning in terms of temperate zone experience.

On the other hand, much temperate or arctic zone experience can be adapted with little change to exploration in the tropics. An excellent example would be the highly successful Russian program for diamond-bearing kimberlite pipes. Their program has used a combination of magnetic, radiometric, and gravimetric techniques (Brodovoy, 1967) integrated with other disciplines. This program has changed Russia from an importer of diamonds to the world's second larger producer (Liddicoat, 1970). The Russian techniques could be easily adopted in both South America and Africa.

The first step in a broad minerals-exploration program in areas without adequate geologic maps is to secure regional geophysical data, particularly airborne magnetics. This data must be integrated with the other mapping techniques such as photointerpretation and remote sensing, so that priority exploration areas can be selected. In the case of the tropics little, if any preliminary research is needed to conduct such regional geophysical programs. The principal purpose is to provide a means of obtaining the necessary regional information on which a rational detailed minerals-exploration program can be based. Because of serious accessibility problems on land in most tropical areas, the primary emphasis of regional work should be airborne magnetic surveys with combined geophysical sensors used whenever possible. Within limits, the larger the area flown, the lower the unit cost. Follow-up programs then would be based primarily on the type of mineralization target sought for.

State of the art

One method of assessing the state of the art is to analyze the statistics on the application of the various techniques and their cost. This is now being done by the Committee on Geophysical Activity of the Society of Exploration Geophysicisits, Allen (1971). Table 1 compiled from Allen's data was prepared to show the importance in terms of dollars spent on the various geophysical methods.

This table, which covers all expenditures in geophysical prospecting from regional reconnaissance to development work on a located deposit, provides a basis from which priorities assigned by industry and government to each of the techniques may be judged. It should be remembered that only the western and non-aligned nations are represented in this survey. Relevant statistical information is not available for the communist nations, although a wealth of highly relevant work is being done, particularly in the USSR.

Table 1.--Comparison of dollars spent on major mining geophysical techniques by agencies in the free world (in thousands of dollars), 1969

Land methods	Expenditure
Induced polarization	$7168
Drill hole logging	2518
Combined EM/Mag	1378
Electromagnetic	1369
Gravity	835
Other	748
Magnetic	642
Seismic	246
Resistivity	242
Radiometric	241
Geothermal	118
Self potential	26
Earth current	4
Airborne methods	
Magnetic	558
Combined EM/Mag	526
Radiometric	203
Electromagnetic	28
AF Mag	2

Besides the gross dollar figures, expenditure trends are important as indicators of exploration priorities. Figure 1, adapted from Hood and Kellogg (1969), shows the principal changes occurring in ground and airborne applications during the 1960's. The abrupt increase in airborne radiometric work since 1967 is due to the renewed interest in uranium exploration.

Pertinent to the subject of this paper is the distribution of this exploration and research money within various countries. Figure 2, in a broad manner, shows the distribution of geophysical dollars on a global basis for 1968, again excluding the communist nations. The relative percentages are believed to be reasonably valid today, although expenditures within individual developing countries have changed considerably. It is interesting to note that Latin America shows the least expenditure, although many geologists consider its mineral potential to be vast. It can be expected that expanded geophysical work in Latin America would yield a significant return.

Each of the individual methods is briefly described below and its principal application in minerals exploration indicated. More detailed and particularly good explanations of current methods are available in the Society of Exploration Geophysicists "Mining Geophysics" and "Mining and Groundwater Geophysics/1967", L. W. Morley, editor.

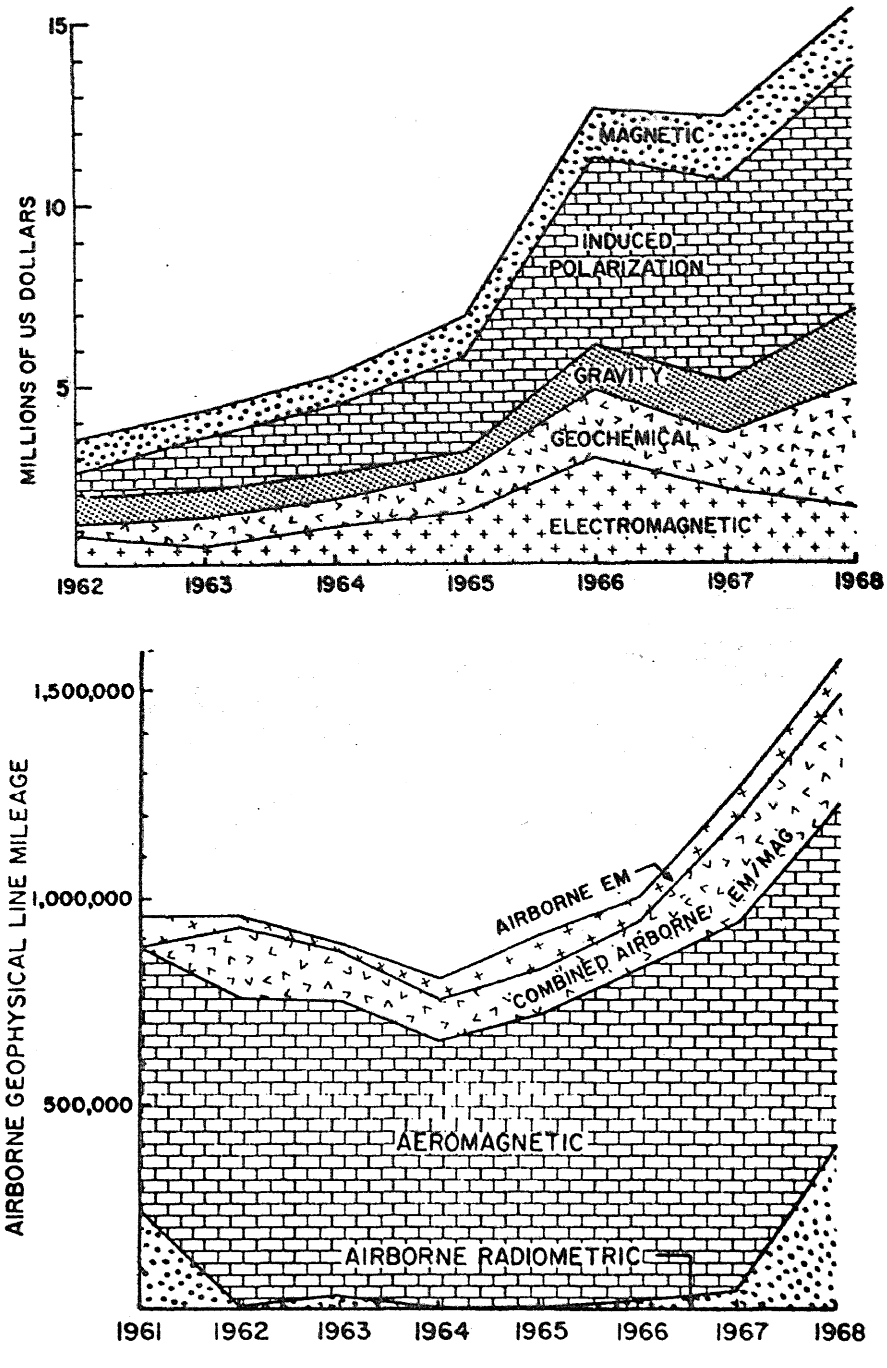

Figure 1.--Variation in airborne and ground geophysical activity from 1961 to 1968, adapted from Hood and Kellogg (1969).

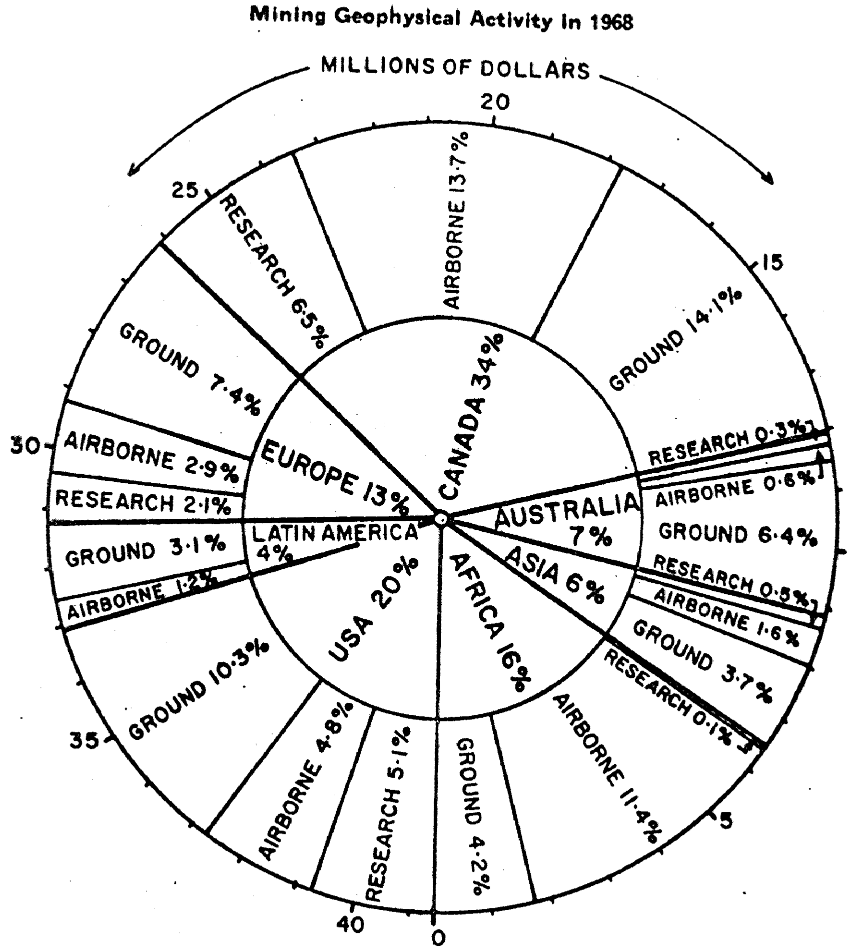

Figure 2.--Free world distribution of mining geophysical activity in 1968, from Hood and Kellogg (1969)

Induced polarization (IP)

IP is basically an electrical resistivity technique in which variations in apparent resistivity in the ground are measured as a function of frequency. The field measurements are made by either pulsed or constant-frequency current sources in the range of 0.05 to 10 Hz (cycles per second). IP anomalies are caused by electrochemical action at the interfaces of ionic and electronic (metallic type) conductors within the earth and by membrane polarization principally due to clay minerals. Because the principal electronic conductors in nature are the base-metal sulfides, this method has become the major geophysical tool for direct mineral exploration. It has found wide application in the exploration for disseminated sulfides in which other geophysical methods have been of marginal utility. Because resistivity data is also obtained in any IP survey, this may be considered a combination survey. Self-potential information may also be obtained easily during an IP survey but requires slightly more time.

Principal problems in the interpretation of IP surveys are caused by difficulty in distinguishing between the conductive sulfide minerals and the clay minerals, which also give rise to polarization effects. Deep weathering in the tropics forms abundant clay minerals and leaches sulfides. Interpretive methods which provide information on shape, size, and depth as well as estimates of percentage sulfides from field anomalies are still poorly developed. Private mining companies probably have much proprietary information on these matters which is not available to the public.

The principal problem for IP exploration in tropical areas is the widespread presence of highly conductive surficial deposits, although this is not unique to tropical areas. Because some geophysical equipment is heavy and because electrical cables must be stretched along the ground, accessibility and transportation can be a major problem and expense in tropical areas.

Computer application in IP investigations has generally been limited to the construction of theoretical anomalies over bodies of simple geometry.

A. A. Brant (1966) gives examples of the use of IP techniques in the Cuajone area, Peru, where porphyry copper was found, and also for the Nobabeep Flat mine, O'okiep, South Africa, where massive and vein sulfides were discovered.

Gravimetry

Gravimetric techniques measure differences in the distribution of mass in the subsurface. This is accomplished by determining the difference in weight of a standard mass to an accuracy of one part in one billion. These methods are generally used by the public sector in regional surveys to aid in the interpretation of gross geologic structures in a region. They have received limited application in the direct phase of minerals exploration, although work has been reported on massive sulfides, salt domes, chromite, and diamond-bearing kimberlites. Gravimetry has also been successfully applied in the estimation of ore reserves in advance of major drilling campaigns.

Recent development work has centered on fixed-wing and helicopter-borne systems, but lack of sensitivity has limited the use of these airborne systems.

No unique problems exist for gravimetric exploration in the tropics. However, in gravimetric work, elevation precision between stations should, in general, be on the order of 30 cm to 3 meters for regional surveys to as little as 3 cm in detailed mining surveys. In hilly or mountainous regions it is often necessary to make terrain corrections which require accurate topographic maps. Adequate maps are lacking in many tropical areas.

The computer is used in gravity data reduction where sufficient data and maps are available to make practical digitization of the topographic and gravity data. The derivation of other maps from the simple or complete Bouguer map, such as second derivative or residual, is often handled by large computers. These derived maps are used as interpretational aids.

An excellent case history of gravimetric exploration for chromite in Cuba is given by Davis and others (1957) and also by Bhattacharya and Mallick (1969) covering work in India.

Magnetics

Magnetic exploration is a well established technique in both ground and airborne work. Recent development work has produced light-weight, easily-read instruments for land use, facilitating data acquisition anywhere a man can go. Land instruments in use today are mostly of the total-field type (proton precession) or the flux-gate variety normally measuring the vertical component of the earth's field. No problems are encountered near the magnetic equator in the use of the vertical field magnetometers because even there, vertical field anomalies can be large. Hood (1969) gives the characteristics of all commercially available ground and airborne magnetometers.

Besides the exploration for magnetic iron ores, ground magnetic surveys have found application in tracing of old stream channels, in chromite exploration, and in mapping such geologic units as mafic dikes, serpentinites, etc.

The greatest use of airborne magnetic data is as an aid to geologic mapping and interpretation on a regional or semiregional scale. This assists in the elimination of large areas of low priority for prospecting. Combined with EM techniques, it has also found application in the exploration for base metals. At the present time, the single most important need for geophysics in the tropics is the acquisition of aeromagnetic data rather than any further research. Such data have a long technologically useful life and can be reinterpreted as scientific progress and more accurate geologic knowledge accumulate over the years.

Recently developed airborne instrumentation makes possible high-precision surveys, less than 1 gamma, the use of which should be considered in some areas of the tropics. In regions of deep sedimentary or metasedimentary cover where the magnetic field would be expected to be fairly uniform, high-precision surveys could reveal subtle magnetic patterns associated with mineralization. An example would be the Rio São Francisco region in Brazil in which local lead-zinc mineralization exists in the Eocambrian (?) Bambui Limestone.

Most of the airborne data acquisition is done by governmental or service organizations and many systems have gone to digital data acquisition with data reduction and compilation performed almost entirely by computer. As in gravimetry, many computer-aided interpretational techniques are available.

Many references in the bibliography illustrate the use of magnetic surveys in minerals-exploration programs in all areas of the world.

Electromagnetics (EM)

Electromagnetic techniques offer a wide variety of both ground and airborne types, many of which will be seriously compromised in areas of deep conductive soils. The most promising of these are the airborne systems recently developed such as Input, Turam, and AFMAG. Input is the trade name for a pulse transient technique in which electromagnetic source and receiver are both used on a single aircraft. Turair (airborne turam) employs an alternating current source on the ground and airborne electromagnetic receiver. AFMAG (audio frequency magnetics) employs an airborne electromagnetic receiver that senses variations in natural electromagnetic fields generated by distant lightening storms. Little information is available in the literature on the use of these systems in tropical areas. Sufficient depth of penetration is the principal problem in application of these techniques in tropical areas where weathering normally removes the conductive sulfide minerals from near the surface.

In the humid tropics where the height of vegetation is extreme and weathering depth also great, many airborne EM systems are severely compromised because they cannot approach near enough to the desired targets. Ward (1969) discusses the depth of exploration of most commercial systems. These usually do not exceed 100 meters. The three mentioned above offer the best in terms of depth of penetration.

Recently developed very low frequency systems (VLF) offers promise in the mapping of conductivity variations in surficial materials. This may prove of use in exploration for such commodities as bauxite or gravel deposits. The method uses signals from powerful low frequency radio transmitters in the range of 15 to 25 kilohertz.

Data acquisition and reduction is highly variable, depending on the particular type of system employed. The trend is toward digital data acquisition in airborne work, although this has not become universal. Computer-aided data compilation and analysis are not well advanced.

Seismic

Seismic techniques in minerals exploration are generally of the refraction type. Little use is being made of the reflection techniques developed to such a high degree of sophistication by the petroleum industry because targets are different in nature and geometry. The principal application is in determining the thickness of unconsolidated surficial deposits, such as in mapping abandoned river channels, both on land and offshore. The method thus assists in exploration for placer deposits of such minerals as gold, diamonds, and cassiterite, and for gravel deposits to be used in road fill, aggregate, etc. Bacon (1966) reviews the application of these techniques in mining exploration and engineering.

The techniques employed in data acquisition, reduction, and interpretation are straightforward for most of these applications, and little use of the digital computer is generally made. No particular problems exist for the application of these methods in the tropics.

Resistivity

Resistivity methods have found principal application in the search for base metals, placers, and ground water. This method is by far the most important geophysical technique in ground-water investigations.

Data acquisition and reduction are straightforward. The tropics present the problem of highly conductive surficial deposits in some areas, which limits the depth of penetration and target discrimination. In heavily wooded tropical areas laying electrical cables also becomes a problem.

Data is collected by profiling, i.e., moving the four electrodes used along the ground with a uniform spacing, or by sounding. In sounding the four electrodes are moved apart in a particular manner so as to give an interpretation of the variation in rock conductivity as a function of depth. Sounding interpretation assumes horizontal layering so lateral facies changes impose severe restrictions on accuracy.

Many examples of the use of these techniques are included in the references listed.

For most minerals exploration problems only minor use would be made of the computer as an interpretational aid.

Radiometric

Radiometric methods consist of total-count gamma or gamma-ray spectrometric measurements that give qualitative values of potassium, uranium, and thorium in various rock units. The principal application of these techniques has been in the search for uranium mineralization, although recent research is looking at the method as an aid in regional geologic mapping. In common with many geochemical problems, the vertical and lateral transport of the radioactive elements in deeply weathered rocks and soils is not well understood. Since radiometric information comes from the upper meter of soil and rock, its use is restricted to areas of residual soils and rock outcrops.

Airborne spectrometric systems are now well developed, the trend being toward large crystal detector volume for increased sensitivity.

One contractor specializes in data acquisition in digital form with highly sophisticated computer-aided data compilation and analysis.

Recently, portable gamma-ray spectrometers have been developed for land investigations. Their applicability has yet to be established for minerals exploration, but for some applications they offer promise.

Other methods

Drill-hole logging employs many of the techniques already mentioned, adapted to the environment of the small diameter drill hole. Radiometric, electrical, and sonic measurements are most often used. The principal applications are in providing supplementary information to core analysis, control data for corresponding surface measurements, and engineering data for mine development.

Various other applications make use of the basic techniques already described. As an example geothermal exploration employs resistivity and heat-flow measurements, sometimes combined with gravity and magnetics. In table 1 these disciplines have not been completely separated.

Instrument and survey costs

Table 2 presents a summary of the description of the techniques described and approximate guides on instrument and contract survey costs. The costs should be considered approximate only, because special local requirements such as import laws, taxes, security laws, etc. can significantly affect costs. In some areas of the tropics accessibility will be a major factor in determining survey costs. This is particularly true of ground geophysical surveys, but may influence pricing of airborne surveys if no airfields are near by, particularly if helicopter operations are desired. Table 2 also contains average costs for the various techniques.

Table 2.--Summary of geophysical techniques and costs

Techniques	Application	Type of field data obtained	Type of compilation	Instrument and cost	Survey cost and production rate
Induced polarization	Base-metal exploration, limited use in ground water and geothermal exploration	Frequency domain--difference in apparent resistivity at 2 or more frequencies Time domain--one or more characteristics of the electrical decay transient	Generally as artificial cross sections, at times as contour maps or profiles	Usually separate receiver and transmitter. Transmitter power from a few watts to 30 kilowatts and 100 to 1,000 volts output. Receiver is a specialized electronic voltmeter or specialized device. Common price range $3,000 to $10,000	$200 to $600 per line-kilometer, 6 to 30 line-kilometers per man-month
Magnetics					
Airborne	Regional mapping, ferrous metals exploration, defining sedimentary basins, location of intrusive stocks	Variations in total intensity of earth's magnetic field	Commonly as contoured total intensity maps. Derived maps often also prepared. Seldom as profiles	Flux-gate magnetometer, proton-precession and optical absorption types. Cost $5,000 to $15,000	$6 to $12 per line-kilometer, 300 to 700 line-kilometers per day of flying
Ground	Ferrous metals, alluvial channels base metals, mafic rocks	Variations in total intensity or vertical component of total intensity, rarely the horizontal component	As contoured maps and as profiles	Flux-gate magnetometer, and proton-precession type $2,000 to $4,500. Small less sensitive devices are available at lower cost	$10 to $90 per line-kilometer, 50 to 200 line-kilometers per man-month, up to 400 stations per day
Gravity	Regional mapping, ore reserve estimates, base- and heavy-metal exploration, salt domes	Variation in the earth's attraction	As contoured maps and derived maps as in magnetics	Worden or Lacoste-Romberg type, $8,000 to $12,000	$50 to $300 per line-kilometer, 5 to 50 stations per day
Electromagnetic					
Airborne	Base-metal exploration, limited application in geological mapping and ground water investigations	Changes in the EM field due to the presence of conductors. The nature of anomalies highly dependent upon the particular instrument	Contour maps, nested profiles, vector maps	A wide variety trade-marked systems available, a great many of Canadian manufacture Cost $50,000 to $100,000	$12 to $25 per line-kilometer, 200 to 700 line-kilometers per day of flying
Ground	--------Do-------------	---------do------------	---------do----------	-----------do----------- Cost $2,000 to $6,000	$40 to $500 per line-kilometer. 50 to 75 line-kilometers per man-month.

Table 2.--Summary of geophysical techniques and costs--continued

Techniques	Application	Type of field data obtained	Type of compilation	Instrument and cost	Survey cost and production rate
Radiometric					
Airborne	Uranium and thorium exploration, rare earths, geological mapping	Total-count gamma radiation and/or equivalent activity of uranium, thorium, and potassium	Contour maps, nested profiles, ratio maps and profiles	From simple scintillometer to multichannel equipment for spectrometer application, $1,000 to $40,000	$6 to $20 per line-kilometer, 200 to 700 line kilometers per day of flying
Ground	---------Do---------	---------do------------	---------do-----------	-----------do------------ Cost for more portable ground equipment $500 to $5,000	$10 to $50 per line-kilometer, 50 to 200 line-kilometers per man-month
Resistivity	Ground water, base metals, alluvial deposits	Apparent resistivity along profile or as function of electrode spacing	Contour maps, profiles, or sounding curves	Transmitter and receiver similar to that used in frequency domain IP equipment. Cost $500 to $5,000	$100 to $500 per line-kilometer, 10 to 50 line kilometers per man-month, $30 to $200 per sounding, 3 to 8 soundings per day
Seismic refraction	Alluvial deposits	Sonic travel time as a function of distance to one or more detectors	Travel time sections or interpreted depth sections	Single to multichannel (up to 24) recording systems using oscillograph, oscilloscope or other display systems. Energy source, weight drop, or explosive type. Cost $2,000 to $10,000	$150 to $800 per line-kilometer, 8 to 20 line-kilometers per man-month
Drill hole logging	Control data for surface surveys and core analysis, mine development	Refer to particular technique	Generally as nested profiles showing quantities measured versus depth	Cable and reel assembly recording device and sensing tool. Cost $10,000 to $15,000, each tool in range of $2,000 to $4,000	$0.10 to $0.25 per foot per tool, logging rate average 30 ft. per minute

In few cases would it be practical for a developing country to attempt to form its own airborne geophysical capability. A number of international geophysical companies are now providing contract airborne service throughout the world at competitive costs. It would be difficult for a small nation with limited capital and human resources to operate at a reasonable cost level. Reford and Sumner (1964) give an excellent summary of what is involved in an airborne magnetics survey. It is not a simple operation. Costs in table 2 for the airborne operations reflect only cost for the particular instrument in question, not all the peripheral equipment required such as doppler radar, flight camera, etc., nor for staging and logistics.

Regarding ground geophysical operations, the single most important source for developing countries will be the development of experienced geophysicists and equipment maintenance specialists. In particular, experienced professionals who can go into the field in difficult conditions and run an efficient operation are essential to successful operations.

Of the ground geophysical activities, self potential (SP) and resistivity methods could be most easily and inexpensively initiated by developing countries. In many cases the equipment could be manufactured within the country also. Next in complexity for developing nations would probably be shallow seismic, gravity, and magnetics surveys. These could be contracted for or developed internally if trained professionals are available. Induced polarization, drill-hole logging, and the various electromagnetic techniques would probably best be contracted for until a fair degree of sophistication had been developed within the country.

Research gaps and priorities

In geophysics there appear to be a few areas unique to the tropics in which research could facilitate prospecting. There are three fields in which significant improvements might be made.

1. A definite need exists for relatively inexpensive airborne navigational systems with performance superior to the commonly used Doppler radar systems. Inertial or Decca type systems are available which are capable of giving accurate position information in remote regions, but they are extremely expensive. Reduction in the cost of such systems would be of major help in all airborne operations in remote tropical regions.

2. Studies of the physical and electrical properties of lateritic soils and laterite would be very important in determining the applicability of the various geophysical methods. The principal properties to be investigated from a geophysical viewpoint would be electrical conductivity and magnetic susceptibility. Both laboratory and _in situ_ studies should be carried out. The latter studies would be particularly important because the electrical properties are strongly controlled by soil porosity and the quantity and quality of the contained water. These studies should be carried on in close cooperation with a soils expert and also in conjunction with the research proposed above for geochemical and geobotanical prospecting.

3. In conjunction with these soils studies, field evaluation of various EM systems should be undertaken in tropical areas having conductive soils in order to evaluate which system is best adapted to the variable environment. Airborne AFMAG, Turair, and Input systems should all be evaluated. This is particularly important in view of the limited depth

of exploration of most EM systems. It would be interesting to evaluate these techniques along with a VLF airborne system which is more responsive to near-surface conductors. A combination of these techniques will probably prove to be most effective. All flying should be combined with airborne magnetics surveys in the tropics.

Geophysics and geochemistry overlap in two areas which have great promise for future application. Experimental systems are available but much more instrument development and applications research is needed.

The first is the detection of trace gasses in the atmosphere on a continuous or quasi-continuous basis. In minerals exploration most research has been centered on mercury, and several types of systems have been developed for airborne application. The correlation spectrometer appears to be the most promising at present and is a continuous-reading device. Research needs to be directed toward the application of these devices in the tropics and also to employing other gasses that may have geological significance, such as I, SO_2, and H_2S. Hydrogen sulfide and sulfur dioxide may be very useful in the tropics where pollution problems are not as severe as in more industrialized areas of the world.

The second area is the use of radiometric techniques employing an active source such as neutron activation and X-ray fluorescent methods. Again some instrument systems are available, but additional work is needed. These methods hold great promise for rapid elemental analysis in the field and would be valuable tools in many exploration programs, as well as for more general geological mapping.

Another area of potential promise would be the development of a practical airborne gravimetric system. Present experimental systems appear to be close to meeting many requirements for a minerals-exploration program. Development money might well be spent in this area.

Because of the importance of induced polarization in minerals exploration, additional research into interpretive techniques is needed. Because IP techniques have been developed mainly by private interests, there is much proprietary information which is not easily available to the science in the developing countries. Research into interpretive techniques which could be made available to the public is needed. The most promising lines would appear to be in computer-aided interpretation of field data and in research toward extracting more information from the time-domain data.

REMOTE SENSING

Remote sensing is a rapidly developing branch of science which has a short but honorable past and a promising future. It may be said to have started with the development of aerial photography, the precursor of photogeology. Although used for many years before World War II, for example in the regional development associated with activities of the Tennessee Valley Authority, photogeologic interpretation received a great impulse during World War II and has been increasingly applied and refined since then. The development of color photography added a new dimension and the later development of films, filters, and other devices by which the visible and invisible electromagnetic spectrum could be subdivided into narrow bands and recorded opened even greater fields of application. Much development has been spurred and financed by military and space applications, but these relatively specialized applications are being modified to make them useful to the everyday needs of our civilization, not only in geology and the search for minerals and water, but also in control of pollution, in agriculture and forestry, in mapping, and a host of other applications. For the geologist, as for many other scientists, unpredictable new horizons are opened by the development of this tool. As with other branches of science, many simple and complex devices have been and will be developed to aid interpretation and to automate the great mass of data secured.

Remote sensing as discussed here encompasses observations made from aircraft or spacecraft covering wavelength regions of the electromagnetic spectrum from ultraviolet to microwave (0.3µm - 30 cm). These observations are limited to the surface or to very shallow penetration, but provide a basis for discriminating natural materials because of differences in reflection or emission of electromagnetic energy in a wide spectral range.

Because the survey methods involved offer great flexibility of coverage and ground resolution, objectives attained may range from rapid reconnaissance of larger unknown areas to very detailed examination of specific mineral areas. Although conventional photography is an important part of remote sensing, it is commonly true that photos and images taken for parts of the spectrum beyond man's normal vision are of even more importance in showing variations of many types of surface materials. From such data it may be possible to obtain unique information on the distribution of geologic units and structural framework of an area. The specific capability in this regard of each major technique is discussed in following sections.

Because the observations made by remote sensing techniques are of surface properties of materials, areas of excellent rock exposure such as deserts are ideal for remote sensing geological surveys. Except for radar and some types of photography, in the humid tropics such surveys for geologic purposes generally would be limited to unforested areas, thus restricting their utility.

For developing countries which may not have highly specialized professionals available, it is worth emphasizing that remote-sensing data in photo or image form can be analyzed by conventional photogeologic techniques for a first level of discrimination of geologic units and structure. Only relatively brief training of local geologists should suffice to make them aware of the different kinds of information seen in remote-sensor images. Moreover, if local analysts are not available, interpretation of data can easily be done by expert consultants. Because much remote-sensing data contains a second level of information, concerning such things as rock composition and ground moisture content, and because data may be complicated by terrain or climatic factors, the use of consultants generally will be desirable at some interpretive stage.

Low-resolution coverage of much of the tropical region of the world can be obtained at very low cost from such satellites as Nimbus and ERTS, and it will be inexpensive to perform sufficient analysis of the satellite data to discover new information on broad-scale geologic or structural relationships in relatively unexplored regions. ERTS-A (Earth Resources Technology Satellite) will be limited to reflectance data at a resolution of 80 meters in the visible and near infrared, but this should permit excellent remote geologic reconnaissance in areas without constant cloud cover. ERTS-B will add a thermal-infrared channel at 220-meter resolution. Nimbus V will provide daily coverage of the earth at resolution of 700 meters in several visible and infrared channels. All such data should add significantly to geologic information presently available on those parts of the world which have not been mapped in detail.

State of the art and current research

Techniques can be divided conveniently according to the spectral region involved and are discussed here as visible and near-infrared, thermal-infrared, and microwave surveys. Current research gives a fairly good measure of what can be done with readily available sensors as well as indications of what future extensions of effort may prove fruitful.

Visible and near infrared

Reflection differences have long been used to discriminate surface materials on conventional photographs. Color and color-infrared photographs add to such capability of discrimination because the eye can distinguish color differences about 100 times better than shades of gray. In broad band visible-region photos, however, it still commonly is difficult to distinguish different geologic units. In many areas, narrow-band photos singly or in combination show reflection contrasts better, and much research is now directed toward use of photos taken simultaneously at more than one band.

Common and inexpensive photographic systems available (bands of 4 to 6 Hasselblads; 4-band I^2S camera[1/]) use various filters to obtain fairly broad-band data across the visible and near-infrared regions of the

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[1/] A camera designed and sold by International Imaging Systems, Inc. containing four lens systems, that photographs a scene simultaneously through filters at different wavelengths.

spectrum. Data from the various bands may be used simply as black-and-white or color pictures which may show differences in surface materials from one band to another owing to differences in spectral reflectivity. Or the data may be combined in special viewing instruments to produce color, color-infrared, or false-color images as desired for enhancement of specific contrasts or features. Photogeologic analysis of the data can produce outcrop maps and achieve discrimination of units based on color, spectral reflectivity, or textural differences. Color-infrared is particularly useful, even from very high altitudes, because of "haze penetration" capability (the blue wavelength region, where most atmospheric scattering occurs, is filtered out), and because vegetation appears in red tones. This provides very clear pictures in which rocks or soils are in pronounced contrast with vegetation and in which the red tone indicates vegetation vigor as a possible index of ground moisture. In addition, some rocks (e.g., mafic and ultramafic) can be discriminated better in color-infrared pictures because of greater reflectivity contrast in the near-infrared than in the visible region.

Multichannel scanners (a device for optically sensing separately a number of narrow wavelength bands by sweeping laterally in relation to the vehicle's forward motion; the results are recorded on tape or film, from which images, not photographs, are constructed) also are used to gather reflectance data in narrow spectral bands through the visible and near infrared regions. Automated techniques can then be used to examine classes of materials based on the statistical properties of their spectral reflectance. Some success has been achieved in discriminating terrain features and a limited set of rock units. Future success will rest largely on the ability to characterize geologic units uniquely from color, roughness, and textural properties. Such characterization of terrain units such as forest, marsh, outcrop, etc. has been automated with considerable success by use of digital scanner data and ratioing or cluster processing techniques. Research is underway to test the applicability of this to discrimination of geologic units.

A potential application of multispectral data is based on the presence of reflection minima near 0.70 and 1.0μm associated with ferric and ferrous cations, respectively. Images that record reflectivity in these bands show greater contrast between iron-poor and iron-rich rocks than at other wavelengths. Narrow-band data recently obtained by multi-channel scanner showed that basalt and andesite were more iron-rich than dacite porphyry and dacitic alluvium. Thus computer-generated ratios for the two specific channels permit discrimination of flows having different ferric:ferrous proportions. This technique appears to have application in general mapping as well as specific promise in examination of oxidized ground in mineral areas or in search for gossan deposits. In addition, it appears possible that multiband photographs filtered in the desired bands will permit visual discrimination of various iron-bearing rocks.

Research also is under way to determine possible geologic application of a Fraunhofer line discriminator, a device which measures the presence of luminescent materials. With improved techniques, it may be possible to discriminate geologic units containing certain minerals of economic value on the basis of their diagnostic luminescence. Evaporites, various carbonates, and phosphates are likely target materials for this technique.

At present there is widespread interest in developing remote sensing techniques for the detection and mapping of geochemical soil anomalies in heavily forested areas. In considering ways of sensing abnormal chemical conditions in the soil, the use of vegetation is for two reasons a natural avenue to explore. First, as has been indicated elsewhere in this paper, data from many biogeochemical and botanical surveys performed during the past few decades have shown that plants growing in a geochemically anomalous soil generally reflect this in their trace-element content and also may show symptoms of physiological stress (e.g. chlorosis, a diseased condition characterized by absence of or deficiency in green pigment). Second, the forest canopy is easily visible to a sensor in a plane or satellite.

Prospectors and geologists have long known that a chlorotic patch of vegetation may indicate an area of metal-rich soils and, therefore, merits their attention. Actually, mineral-deposit-related chlorosis is rather rare in virgin environments. While different species of plants and trees seem to vary greatly in their ability to tolerate excesses of various elements in their nutrient solutions, the concentrations of most elements required in the supporting soil to produce symptoms visible to the naked eye are often fairly high. Thus, in areas of many geochemical soil anomalies that are genetically related to important mineralization, the vegetative canopy is apparently healthy, no toxic symptoms being visible to the eye. However, experiments by the U. S. Geological Survey during the past several years have shown that abnormal chemical environment can cause subtle - but nevertheless definite - changes in some physical or chemical aspect of one or more plant organs. The detection of changes in reflectance characteristics of vegetation in the visible and near infrared portions of the electromagnetic spectrum that are induced by the abnormal chemical environment of the supporting soil is thought to be the method that offers the greatest hope of success. The U. S. Geological Survey is only one of several organizations engaged in the application of this method over known mineral deposits, and in determining the nature of the induced changes in vegetation that affect their reflectance characteristics. Applications of this technique have great potential, especially in tropical regions where ground access is difficult and where many other problems in conducting a conventional soil-sampling program are usually encountered.

Thermal infrared

Geologic materials differ widely in albedo (reflectivity) and thermal inertia (the square root of the product of thermal conductivity, density, and specific heat). These are the most important factors governing surface-temperature variations as materials heat and cool in a diurnal cycle. Aerial surveys made with infrared scanners have shown that temperature contrasts commonly are sufficient to discriminate well-exposed rock and soil units of many kinds which do not have reflection contrasts in normal photographs. Thermal contrasts also permit detection of ground moisture along faults or in soils units as an important way of defining structure that may not be visible at the surface. Moreover, because the thermal properties are linked to composition of the materials, temperature measurements made in the infrared provide information that may help to identify the materials.

A modeling technique has been developed to determine the diurnal temperature cycle for different values of albedo and thermal inertia at any geographic location. This can be used to determine in advance if any unit will contrast thermally with adjacent units, as well as to define the optimum time of day or night to make surveys to record such contrasts.

Specific demonstrated examples of the utility of thermal-infrared data include the discrimination of limestone from dolomite and sand from gravel, definition of folds and faults in areas of poor outcrop and units of low visual contrast, and location of water-rich zones of potential hazard to engineering prospects or of interest in groundwater prospecting.

In desert areas where different rocks may look dark because of thin coatings of desert varnish, thermal-infrared data provide a means of discrimination of whole rock masses below the surface coating on the basis of temperature differences related to heating and cooling.

Infrared scanners in general use today have spatial resolution of one milliradian (one meter from altitude of one kilometer), and thermal resolution of $0.25^{\circ}K$. They record data on film or magnetic tape in one or more channels, generally the 3-5µm and 8-14 µm windows of the Earth's atmosphere.

An important recent advance depends upon using a multichannel scanner to record thermal emission for discrimination of siliceous rocks from nonsiliceous rocks, or for mapping broad compositional variations in silicate rocks. This technique is based on the fact that silicate minerals have emissivity minima (reststrahlen bands) in the 8-12µm region, which shift to longer wavelengths in a general fashion as SiO_2 content decreases. Radiances can be recorded for two channels within that spectral region, and their ratio used to measure the shift in the emissivity minimum. This ratio can be processed as a photofacsimile image to show SiO_2 variations. With addition of a third channel outside the reststrahlen region to correct for temperature variations among surface materials, SiO_2 variations of about 14 percent can be discriminated. This permits discrimination of siliceous from nonsiliceous rocks, and gross subdivision of igneous silicate rocks into felsic, intermediate, or mafic categories, and possible discrimination of silicified zones in mineral areas. The method recently was used successfully to discriminate dacite (intermediate) from basalt (mafic) at Pisgah Crater, California. Further refinement of the technique seems theoretically likely to permit mapping of 10 percent variations in SiO_2 content.

Another recent effort has demonstrated considerable geologic utility of Nimbus satellite data at 8-km resolution. In a test study of Oman, individual maps of nighttime and daytime ground temperature and of reflectivity were constructed from digital data. As was known from previous studies, these maps were not very useful in discriminating geologic units. However, by using thermal models to relate reflectivity and daily temperature change to thermal inertia, a map was made to show thermal inertia variations of the surface materials. Even from 8-km resolution data, this map showed the regional distribution of, and thermal distinctions among, chert, limestone, dolomite, ultramafic rocks, gravel, and sand. Discrepancies between the thermal-inertia map and an earlier 1:2,000,000-scale reconnaissance geologic map were checked from a later more detailed map and from Gemini space photographs, and the earlier reconnaissance map was found to be in error. To the extent that reflectivity and thermal inertia data are related uniquely to particular rock composition, the combination of such data represents the first step from simple <u>discrimination</u> toward actual <u>identification</u> of geologic units. It should be noted that thermal-inertia maps can be derived from digital thermal and reflectance data obtained in airborne surveys; these would be of particular value in defining geologic or hydrologic units at much larger scales than possible from satellite data.

The Nimbus test study involved an extremely arid area, but it is believed that near-surface moisture variations in semi-arid or temperate areas will be manifest in thermal-inertia differences, so similar studies could be important for hydrologic purposes. The technique in this study can be easily computerized for rapid handling of large volumes of data. This will be extremely important when tremendous amounts of data from Nimbus V (700-meter resolution) and ERTS-B (220-meter resolution) will require an automated version of this technique for detailed reconnaissance geologic mapping of unknown or inaccessible areas of the world. In addition, Nimbus V will have thermal-infrared channels which may prove suitable for automated mapping of silica variations as described above.

Microwave

Techniques in this wavelength region (0.5 - 30 cm) involve either reflected or emitted energy from the ground (radar or radiometry). Radar is certainly the best known of the techniques. The capability of radar to obtain, in a single swath, images of very large areas despite cloud cover is well known. In addition, side-looking radar provides an oblique look at terrain in which subtle topography may be enhanced because of illumination/shadow effects. Both of these aspects can be of special importance in studies of heavily forested or jungle areas of persistent cloud cover where the topography of a tree canopy surface may reflect ground topography. This in turn may be enough to reveal geologic structure; the highly publicized radar images of Panama are an excellent example. In truly inaccessible areas, properly rectified radar mosaics may provide an excellent and otherwise unobtainable planimetric base showing fine details of drainage systems, vegetation development, and geologic features. Even in arid areas, radar can reveal geologic structure by enhancement of extremely subtle topography; this effect can be essentially duplicated (though not in a single image) by aerial photographs taken at low angles of sun illumination.

Radar, however, provides more than low-sun photographic effects. The signal reflected from the ground is, in a complex fashion, related to the scale and configuration of roughness and the dielectric properties of the reflecting surface. Thus, it should be possible to discriminate many geologic materials on the basis of radar return as an indication of surface roughness (e.g., blocky vs ropy lavas, gravel vs sand, jointed carbonate rock vs shale and massive or friable sandstone). For such purposes, and possibly for differentiating vegetation types, it would be advantageous to employ a range of radar wavelengths to examine the relationship between scale of surface roughness and radar wavelength. Most surveys are made with 1-cm radar, but systems have been flown to span the range to 25 cm.

At similar wavelengths it is possible to use microwave radiometers for emission measurements. Such observations are particularly sensitive to moisture content in the top few centimeters of the ground. Soil moisture variations and water-rich fracture zones thus might be fairly readily discriminated, and it may be possible to explore for sand, gravel, and clay deposits. Microwave radiometers typically provide single-scan data, so that only a profile of microwave emission is obtained. However, airborne microwave imaging systems are now being used on a research basis and soon may be available for wider use; these provide film data on which gray tones are related to surface temperatures, comparable to infrared-scanner images.

Immediate high return from use of the remote-sensing techniques described may include:

1. Rapid discrimination of geologic units, structure, and ground moisture over large areas. Could include construction of geologic maps with relatively small amounts of field checking, suitable for pinpointing possible target areas for more detailed surveys. Selection of technique(s) will depend on type of terrain, vegetation cover, and general nature of geologic materials to be surveyed.
2. Detailed surveys using visible and near-infrared reflectance data in arid zones where information on surface state of iron may define mineralized zones.
3. Radar image mosaics (as planimetric, geologic structure "maps") of areas either inaccessible or unphotographed because of cloud cover.
4. Location, by thermal infrared techniques, of outflows of fresh water along coastlines where fresh water emerges in the sea as submarine springs.

Instrument and survey costs

The cost of instruments depends on exact specifications; only broadly representative examples are given here:

Multiband camera systems	$ 6000 to $10,000
Multiband film color-combination viewers	7500 to 9,000
Infrared scanners (several models available; principal choice is film vs tape recording)	30,000 to 90,000
Multichannel scanners (achieve prime utility when meshed with computer processing capability)	up to 500,000

Scanners with multiband cameras or infrared scanners are simply extensions of normal aerial photographic surveys. Once an aircraft is in the area, costs may run on the order of $3 to $8 per line kilometer flown, depending on type of film and processing. Most of the techniques described here are suitable from moderate to very high altitudes (depending on the problem and desired result).so that broad areas can be covered at relatively low costs. Multichannel-scanner missions and associated computer processing for data handling are considerably more expensive. As one example, data gathered in 17 channels for 222 line kilometers and processed to produce images for each channel, digital and analog maps for two channels, and analog ratio maps showing silica variations for three sets of two bands each has been estimated at $34,000. A computer-generated map of surface materials for the imaged 222 kilometers would cost an additional $11,000. Radar surveys delivering seimcontrolled mosaics are generally done on contract because of the expense of the equipment; they may cost on the order of $5.00 per square kilometer (plus aircraft mobilization costs), depending on size of area surveyed.

Research gaps and priorities

Research in the near future should be concentrated in several areas:

1. Pursuit of computer techniques for handling satellite data to derive reflectivity, temperature, and thermal inertia maps. This is of special importance now if such techniques are to be available when the flood of relatively high-resolution data from Nimbus V and ERTS-B arrives.
2. Development beyond research stage of iron-band ratio processing. Copper and chromium also appear to have spectral structures

appropriate for similar use of multispectral data and research may develop a new tool for prospecting these metals.

3. Refinement of ratioing technique for mapping silica-content variations.

4. Detailed investigation of the potential of microwave for discrimination of soils and soil moisture in various climatic vegetation zones.

5. Thorough examination of the potential of thermal-infrared and microwave in prospecting for and defining geothermal fields.

6. Testing of active (laser) sources to measure the characteristic backscatter from different terrain from 1/2 μm to 20μm. This would include application to visible, near infrared, and thermal spectral features.

7. Investigation of foliage reflectance or temperature as possible indicators of geochemically stressed vegetation marking mineralized ground.

ANALYSIS OF CAPABILITY OF DEVELOPING COUNTRIES TO USE RESULTS OF SUCCESSFUL RESEARCH AND LIKELY ECONOMIC PAYOFF

The last decade has witnessed the discovery of enormous deposits of bauxite in Brazil, Australia, and Africa, of great new deposits of iron and manganese in South America, Africa, and Australia, of nickel in South America, the Far Eastern islands, and Australia, of large copper deposits in Indonesia and elsewhere in the Middle and Far East and in South America and Africa, and of industrial minerals in the whole tropic zone. There is every reason to believe that many more deposits of useful metals and industrial minerals will be found in the tropic zone as prospecting methods continue to improve and as research defines ever more closely the chemical and physical properties and behavior of the sought-for materials and the effects on the environment of such materials so that improved modes of sensing them and more sophisticated geological interpretation can discover their location. The potential effect on the developing countries of the wise use of these raw materials can be great, for it could provide the capital for infrastructure development, the industrial know-how to make use of modern technology in many fields, and the more productive use of human energy in agriculture, manufacturing, transportation, and commerce.

Developing countries can either attempt to discover these hidden mineral deposits themselves with their own personnel, can allow the skilled prospecting and mining companies that operate on an international basis with adequate capital and with experts drawn from the whole world to search for their deposits under concession arrangements, can contract at their own expense companies specializing in the newer techniques to prospect their countries for them, or can request international help such as that furnished on a bilateral basis by several developed countries or on a multinational basis by regional and United Nations agencies. The choice is both financial and political and will be made by the individual countries.

However, no matter which mode or modes may be chosen, it is extremely important for each country to develop enough indigenous expertise in the field of minerals prospecting to be able to judge the proper tools and the use that should be made of them and, even more important, to be able to judge the calibre of work being done, for not all foreign or international companies and agencies or all indigenous personnel or agencies are capable of doing complete and thorough and fully adequate work. Indigenous knowledge will bring understanding of the problems involved in prospecting; understanding will banish the suspicion that often accompanies relations between developing countries and outside public or private agencies in the minerals field, making possible more rational relations and more efficient operations.

The foregoing pages make clear that application of these modern modes of prospecting demand a high degree of scientific, technical, and managerial competence. Although costs per unit area prospected have been decreased and chances of success increased by modern scientific and technological developments, the capital investment needed to achieve these reduced areal costs has vastly multiplied.

Characteristics shared by most developing countries are the relative scarcity of a) managerial competence, b) funds for large-scale capital investment, c) scientific and technical competence, and d) inadequate facilities and skills for maintenance of complex equipment. Furthermore, many of the newly created countries are too small ever to be able to support on their own account the level of capital investment in scientific and technical capacity and instrumentation needed in modern prospecting techniques.

For such small countries, the obvious but, for political reasons, not the simplest, solution is the regional approach: the pooling of scarce managerial capacity, capital investment, and scientific skills on a regional basis. For mineral prospecting and research, relatively small groupings of contiguous countries with reasonably homogenous climatic and geologic environments would be the most effective. To such groups, effective broad-spectrum assistance could be rendered by developed countries, whereas bilateral assistance to smaller countries is often too fractionated to be effective except with specific and limited attainable objectives. In such cases a small investment may bring a large return, as was the case in U. S. Geological Survey assistance in geochemical prospecting to Guyana.

The foregoing pages also emphasize the enormous volume of raw data resulting from a modern regional geochemical or geophysical exploration campaign. Except for rather limited objectives and for some techniques, computerization of the data is desirable; the data can be manipulated and maps produced by computer in a small fraction of the time needed for manual work. The large investment needed for reduction of raw data to usable form is another and powerful argument for regional groupings of developing countries for mineral exploration and definition of promising targets within their borders. The interpretation of the maps and data, however, are the domain of the trained and experienced human mind.

Thus, in response to the AID question concerning the capability of developing countries to use the results of successful research, one must state that without some pooling of human and material resources by the smaller countries, it is unlikely that such countries will be able to enter as individual prospectors into a game with such a large ante.

The more advanced and richer countries, such as Brazil and Venezuela, are already using both conventional (such as aerogeophysical surveys) and advanced techniques (such as side-look radar and infrared imagery); they are purchasing the data-collection technique and either purchasing or doing the interpretation themselves after personnel have been trained in the United States. Such countries can almost certainly within a few years, with additional managerial experience and scientific expertise, make very effective use of results of research aimed at adapting and developing geochemical and geophysical prospecting techniques to their geologic and climatic environments.

As for likely economic payoff, classic prospecting methods are relatively unsuccessful for many types of mineral deposits in the humid tropical environment. The new methods are powerful and have proved productive in other environments, with limited but significant successes in humid tropic environments. Some of the problems to be solved are refractory and complex, but there is no reason to believe they are insoluble. The payoff would be notable, both in terms of bringing the pioneer mining industry into undeveloped areas, with its ancillary benefits of creation of broad infrastructures in transportation, education, and agriculture, and, not less important in the worldwide view, of opening large new sources of raw materials on which our civilization is based.

Because the developed countries with major research capabilities in these fields lie in the temperate zone, research specifically aimed at developing prospecting capability in the humid and monsoonal tropics has lagged. To apply the new avenues of ore-finding specifically to tropical areas, a conscious effort must be mounted to provide facilities for such research in these zones <u>in cooperation with</u> countries which lie in those zones. This would not only help to develop methodology, but, perhaps more important, would also help create a cadre of scientists and technicians in those countries capable of themselves carrying on and extending the work in their own environments.

It should be emphasized that, in order to achieve maximum benefit to the developing countries and to the rest of the world as well, publication of the results of both scientific research and routine prospecting work in geochemistry, geophysics, geobotany, and remote sensing carried on by government and international agencies is essential. Scientific and technological progress depends on the interaction of many minds; what may not seem important to one may open new avenues of investigation to another. Enough raw data is now hidden in files and classified reports to solve many of our problems; "the wheel must be reinvented" because of the public unavailability of these data.

International bodies such as the UN and the UNDP are financed by the public of many nations; for them to write contracts with developing countries resulting in the withholding of knowledge gained at the cost of the world public is to deny full return on investment to those who pay the bills. Furthermore, the professional community is unable to judge the professional adequacy of work done if it is not made public. This can result in some cases in useless repetition of good work or in leaving unprospected areas condemned by poor or incomplete work. The developing countries have little basis for judgment as to whether a good or poor prospecting job has been done. Moreover, the technological life of much geophysical and geochemical data is long; if made public, such data are often profitably reinterpreted in later years as the science progresses.

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