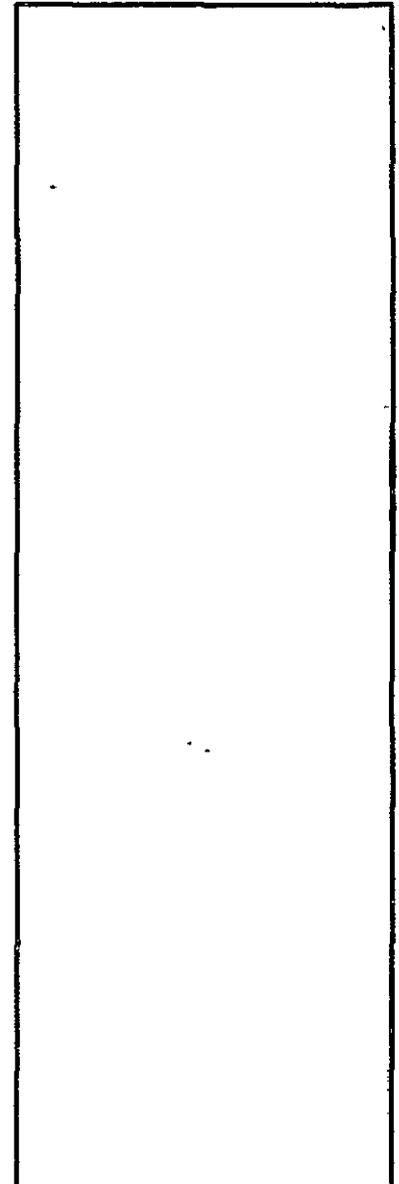
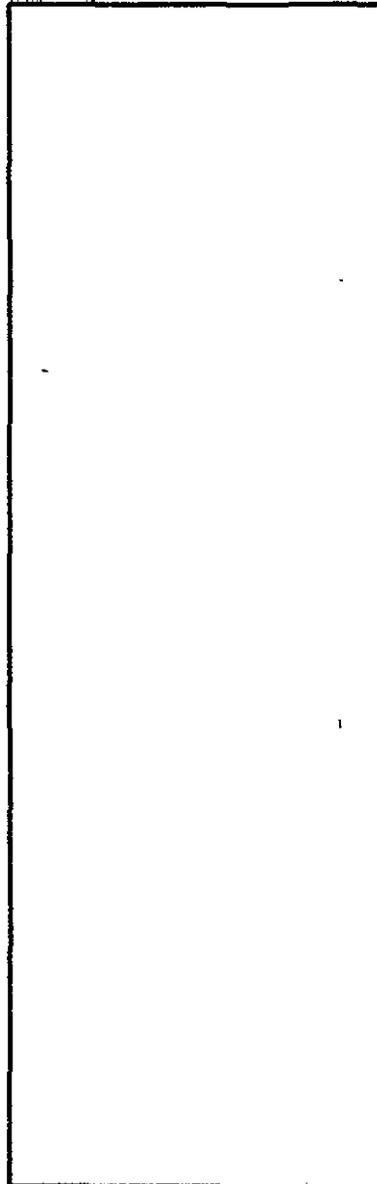


**THE APPLICATION OF GEOCHEMICAL,
BOTANICAL, GEOPHYSICAL, AND REMOTE SENSING
MINERAL PROSPECTING TECHNIQUES TO TROPICAL AREAS
(State of the Art and Research Priorities)**



Office of Science and Technology
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PREFACE

This Report was prepared in connection with the activities of the Planning Group on Science, Technology, and Development established by the Organization for Economic Cooperation and Development. It is intended to serve as a basis for evaluating the current state of the art and research priorities with respect to prospecting for mineral deposits in tropical regions. This activity area was selected for analysis due to (1) its importance in the development context; (2) the relative neglect of research in the area by donor countries and international agencies; and (3) the likelihood that additional research will make major contributions to the solution of critical problems.

This Report is based largely on a preliminary analysis prepared by the U.S. Geological Survey for the Agency for International Development^{1/} and comments subsequently received from numerous reviewers in U.S. Government agencies and universities, other donor countries, and international development institutions. Special appreciation for assistance in reviewing drafts of the Report is extended to the College of Mines, University of Arizona; Geological Survey of Alabama; Agriculture Research Service, U.S. Department of Agriculture; Engineer Agency for Resources Inventories, U.S. Department of the Army; Smithsonian Institution; Institute of Geological Sciences, United Kingdom; Resources and Transport Division, United Nations; and the International Bank for Reconstruction and Development.

Both conventional and emerging new technologies for mineral prospecting are treated in this paper under the following major topical headings: Geochemical Prospecting, Botanical Prospecting, Geophysical Prospecting, and Remote Sensing. In addition to providing brief descriptions of various instruments and survey methodologies and their principal applications, approximate costs for basic instrumentation as well as for particular types of surveys have

1/ The Application of Geochemical, Botanical, Geophysical, and Remote Sensing Mineral Prospecting Techniques to Tropical Areas -- State of the Art and Needed Research; Dorr, J. Van H.; Hoover, D. B.; Offield, T. N.; Shacklette, H. T.; U.S. Geological Survey (Open File Report), December 1971.

been estimated. Each section concludes with an identification of on-going research activities, research gaps, and priorities with respect to future research. The closing chapter of the Report provides a general discussion of the current capacity and requirements of developing countries for undertaking mineral prospecting programs.

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ABSTRACT

A disproportionate percentage of the world's known ore bodies are found in the temperate and adjacent arid regions of the world. However, there is no geological reason why economic mineral deposits should not be present in the tropical regions of the world in the same relative abundance as elsewhere. The anomalous situation appears to be largely the result of economic and political considerations which have thus far impeded mineral development in the tropics. Another factor is that many of the classical prospecting techniques have not proved to be nearly as effective in non-temperate regions. In recent years a variety of promising new mineral prospecting techniques have been developed in the more technologically advanced countries; their potential application in the tropical environment, including the research needed to make them fully applicable, is the theme of this Report.

Geochemical, botanical, geophysical, and remote sensing techniques of prospecting are in widely differing stages of maturity. Further, marked geophysical differences within the tropical environment impose constraints on various possible applications. As a rule of thumb, the humid tropics present somewhat greater difficulties than the arid tropics, a case in point being the problem of logistics in the rainforest environment which severely limit ground-based prospecting. Consequently, several airborne reconnaissance methods have great advantages in these situations although the high cost of precise location then becomes a handicap. As a result, research to develop cheaper modes of precise location in support of both airborne and ground-based prospecting is needed.

Geochemical prospecting is one of the most 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 increase the importance of "pathfinder" elements. Research is needed not only on the mobility and fixation of elements but also on sampling instrumentation and techniques, 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 in tropical areas is also in an immature stage. Although indications are that this technique may be effective in arid and semi-arid climates, little work has been done in the humid tropics. It is likely

that research could make the tool more effective.

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.

Remote sensing is the newest and, except for photo-geologic interpretation, least developed of the techniques which may facilitate mineral prospecting in tropical regions. 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 exposed 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. Photo-geologic 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 sometimes 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 is permitted by host countries to publish only a small fraction of its results. The developing countries themselves apply modern exploration techniques to some extent.

Basic research by the concerned governmental agencies and rapid publication of 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 lands 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 supplies of raw materials.

INTRODUCTION

The tropical zone comprises the area between the Tropics of Cancer and Capricorn, and in addition is usually considered to include those adjacent regions of like climate as far north and south as 25 to 30 degrees latitude. Within this extended zone, which contains nearly half of the earth's land area, lie most of the developing countries and also most of the world's population. Although the zone is characterized generally by warm climate, within it are areas of extreme climatic conditions. These range from the snowfields of the Andes to vast tropical forests of the Amazon Basin, and from the dry deserts of Mali, Pakistan, and Peru to regions of greatest rainfall in the world in Zaire and Venezuela. 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 found in the South American and African shields. Ore deposits and deposits of useful minerals and rocks of all types are known and worked in the tropical zone; its mineral raw materials are one of the principal inputs to the world economy. 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, tin or diamond placers, etc.) that can easily be found by conventional methods.

At present, the geology of much of the humid tropical zone is known only in gross outline. This is the result of the existence of great areas within which ample rainfall and high mean annual temperature favor rapid weathering and the subsequent formation of thick lateritic soils and other mantling weathering products which effectively hide the underlying rocks. In addition, difficulty of access makes conventional prospecting relatively slow and expensive. Furthermore, many deposits of useful metals are often subject to rapid attack and leaching by surface and near-surface waters in the humid tropics. This is especially true of sulfide minerals, although rapid erosion in areas of dissected topography often expose unoxidized sulfide deposits at the surface, particularly along stream channels. While 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. Conventional prospecting techniques used for many centuries in temperate zones have been less extensively utilized and less successful in the humid tropics.

Similarly, materials such as dolomite, limestone, gypsum, and salts of potassium and sodium, which are of immense industrial importance and which frequently 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. Hydrocarbons, although obviously very important, are excluded from consideration in this Report.

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 existing metallogenic literature, geologic maps, and a sound geologic hypothesis. Where adequate maps do not exist, as in most areas of the tropics, examination of large areas in reconnaissance style is advisable, through 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 anomalous or favorable physical, chemical, topographic, or structural conditions conceivably due to or indicative of possible concentrations of useful materials. Good reconnaissance under favorable conditions can in many cases rapidly 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 potentially favorable area to resolve the problem of what causes the geochemical or geophysical anomaly or to further investigate the promising structural, lithologic, or topographic conditions. 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 initiation of the third phase, physical exploration by drilling or by test pitting. 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 application in the tropics.

The tropics pose many very 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 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. It is of utmost importance to gather available geologic information -- no matter how scant -- on the immediate setting. Such information is a major determinant of how much value can be derived from the data provided by the methods discussed in this Report.

Notable complications in geochemical prospecting techniques are caused by shifting climatic zones since progressive aridity is accompanied by changes in the acidity of soils and groundwater. For example, relatively little is known of the climatic variation in northcentral 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?; and 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 the several erosion cycles (associated with climatic changes) in that area produced bauxite. With the target thus limited by geomorphic studies, rapid discoveries followed and very large reserves are now being developed. This example also illustrates the point that much basic knowledge of climates, soils, rock types and other environmental factors must be acquired over large areas of the world to utilize effectively prospecting techniques now available and to be developed.

The arid tropics present problems not radically different from those in arid regions in the temperate zones of the world. In both instances, the occurrence of water, the economic resource of principal interest, is strictly controlled by geologic factors. 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 which 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 can not 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, and 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. For example, in the case of UNDP, much is not published because of provisions in contracts with host governments. Thus, too often, newly acquired data and information on the effectiveness of new methods fail to become part of the scientific heritage on which progress is built; limitations and possibilities of associated instrumentation are also not fully defined.

The purpose of the fundamental research proposed in the following pages is not to directly find ore bodies in the first instance, 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.

It is well to bear 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 almost to 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 by 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 U.S. Geological Survey, 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 with respect to data interpretation. 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 Report is intended to define patterns of distribution of elements or combinations of elements, largely in surficial materials but also in rocks, water, and air, which by their presence or absence may indicate the occurrence of economic mineral deposits. There are three basic aspects to prospecting by this method: (a) selection of sample media adapted to the local environment and targets (the orientation survey) and actual collection of samples (the geochemical survey), (b) sample analysis, in which a balance must be struck among speed, sensitivity, and precision, and between the spectrum of elements sought and the 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 both the most difficult and most 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 of particular elements, either more or less than background quantities (i.e., the baseline average concentration for a certain locality). The quantities observed may be the elements sought or elements commonly associated with them in or near ore bodies. These are the "pathfinder elements." The dispersal pattern will usually be far larger areally than the sought-for ore body and thus easier to locate. Indicative anomalies are usually of the order of a few parts to a few thousand parts per million, depending on the element involved. Thus, the prospector can sample stream sediments, soils, or sometimes water in basins of varying size and can systematically localize the sources of anomalous concentrations of metals. Of course, the presence of a geochemical anomaly does not guarantee the presence of an economic ore deposit just as a petroleum seep does not necessarily indicate that one will strike oil if he drills at that spot. Nonetheless, important mineral finds have been based on locating such anomalies.

The state of the art with respect to the aforementioned three components 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 geo-

logical materials for a broad spectrum of elements. Thirty elements are routinely sought and measured in the U.S. Geological Survey's laboratories in Denver, Colorado. In most cases concentrations are measured within 10 parts per million, in others, to several parts per billion. 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 data processing 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. The result is a considerable 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 surveys, regional (reconnaissance) and local (detail), 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 100 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, any-

where 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 surveys, samples can be taken on widely spaced intervals chosen to establish regional variations, provincial distributions, metallogenic provinces, etc. More commonly, detailed sampling over smaller areas is undertaken to investigate specific targets; 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 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.

Generally, samples taken during geochemical prospecting first undergo partial or complete dissolution and then analysis by simple colorimetric or atomic absorption methods or by optical emission spectrography and x-ray fluorescence spectrography. Emission spectrography is particularly useful for reconnaissance purposes because many elements can be determined simultaneously in small samples and at low cost. This technique, however, requires a moderately costly instrument and a dependable supply of electricity and photographic film or plates. In surveys for 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, like the emission spectrograph, requires a moderately expensive instrument and a reliable electric power supply. Colorimetric methods require more man-minutes per sample than atomic absorption techniques but are popular in remote or primitive areas with low labor costs because they require simple, cheap, and readily portable equipment and are rapid. 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.

During 1971, forty-three laboratories in North America analyzed some one million geochemical samples. According to the Association of Exploration Geochemists (as reported by Harold Bloom, Geotimes, January 1972), the analytical methods used were distributed as follows:

<u>Method</u>	<u>Percent</u>
Atomic absorption	72
Colorimetry	15
Emission spectroscopy	9
Cold extraction colorimetry	4
X-ray spectrometry	4
Selective-ion electrodes	0.7
Other	4.5
<hr/>	
Total	109.2

(note: Total exceeds 100 because some samples were tested by two or more methods.)

Data from the analytical work may be processed by manual means if the program is relatively small and uncomplicated, and if indigenous personnel and equipment can be profitably used in point plotting, contouring, and map work. However, full use of the data collected in a 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 subprofessionals, are needed to perform the analyses.

Maximum information from application of this technique can be expected if the laboratory analysis phase is brought as nearly as possible to an automated procedure. A scheme of automated mineral identification needs to be evolved, possibly based on 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 then automatically plotted 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 valuable metals or materials which occur either in unusual mineral species normally overlooked by most prospectors and geologists during field examinations, in geological environments outside the normally-expected association, or in combinations of these two "unusual" habitats. Thus, while beryllium commonly occurs as the mineral beryl, easily identified and almost always in pegmatite bodies, a very large commercial deposit of the beryllium-bearing mineral bertrandite, heretofore known only as specimens, was discovered a few years ago in an environment which a beryllium prospector would commonly bypass. Other examples could be cited and undoubtedly a number of major "exotic" deposits of useful metals remain to be discovered in unsuspected sites. 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.

Heretofore, 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

Selected data on costs 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 which are used primarily in reconnaissance sampling.

The cost of a simple spectrophotometer for 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. Such visual 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 costs are 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 laboratories, atomic absorption analytical methods have displaced the colorimetric methods referred to above. Atomic absorption techniques are fast and reasonably accurate for some important chemical elements such as copper, zinc, and manganese, but not wholly satisfactory for others such as arsenic, antimony, molybdenum, and tungsten. They require specific instrumentation listed below, and fuels such as acetylene, and, for certain applications, oxidizers such as nitrous oxide. Atomic absorption instruments require a hollow cathode lamp for each element sought, and these have only a limited shelf life. Instrumentation needs are as follows:

Atomic absorption instrument	\$4,000 to \$14,000
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 laboratories also have optical emission spectrographs that provide analytical data on single samples for about 30 elements including copper, lead, nickel, and cobalt, using so-called 3-step or 6-step semiquantitative methods. In addition to the specific instrumentation listed below, the analyst must have unique interpretive skills in

order to guarantee reliable data. 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 sample30

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 prospecting survey carried on in cooperation with the United Nations Development Program 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. The operations were conducted in 1965 and at very low cost, viz., \$0.45 per square kilometer, for stream sediment sampling on a reconnaissance scale. More typically, later UNDP work in Guatemala in 1968 cost \$12 per square kilometer and \$8 per square kilometer in Panama in 1970..

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, and the size, location, and physical characteristics 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, and recreational facilities, a hospital, and landing and maintenance facilities for the helicopters which carried 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 earlier, 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 on geochemical prospecting techniques may be conveniently 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 third function, current research 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. It requires experienced and imaginative professionals to relate the often subtle geochemical variations to the geology and geomorphology and climatic regimen of the survey area. No "black box" can as yet 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 techniques 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; this instrument is being adapted for use in slow-flying aircraft since certain types of ore deposits emit low concentrations of mercury vapor.

Standard techniques and instrumentation, however, are quite adequate for most work and 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 chemistry, geology, and topography of the target areas. Because of these variations, many combinations of instruments and methodologies must be studied and evaluated to determine the proper specifications for the 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 important data have been acquired as a result of UNDP or private 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 research results 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 absorbed by clay minerals or trapped with iron or manganese hydroxides deposited in favorable environments. The complexities involved in these studies are 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 tropical areas 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. Still to be determined are the elements which can be used as pathfinder elements in geochemical prospecting in the humid tropics, although some of this work has been done by the Geological Surveys of Guyana, Japan, and India.

It would seem that the major research effort 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. Unfamiliar patterns of agriculture and other cultural practices, 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 associated with samples high in aluminum, manganese and iron. 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 include:

- 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 humid tropical environments.

- 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. In addition, much of the 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 require analyses for a wide range of elements. The objective of such surveys 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.

In addition, research on geochemical dispersion in the arid tropics also requires special studies. Handicaps to prospecting in that environment include absence of drainage patterns, lack of soil, and windblown sand cover. It would be worthwhile to examine the effect on exploration techniques of the briny ground water at shallow depth under large arid areas.

BOTANICAL 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 prospecting methods, probably because of their limited applicability if only simple techniques are available, 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, they differ markedly in applicability, the expertise required, and the requisite instrumentation. 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. The trained practitioner of this technique can determine the presence or absence of certain plant 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, pp. 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 chlorophylls 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; pp. 10-12).

Genetic stress, produced by mutagenic low-level radiation from underlying radioactive minerals, may result in 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, pp. 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 by 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. Locations in which 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 then be made by 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 concentrate preferentially 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 on-site access to the areas 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 technique were given by Warren and Delavault (1949), Cannon (1960), Hawkes and Webb (1963), Malyuga (1964), and many others. The rationale for the use of biogeochemical 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 undetectable 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 and 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 absorb annually 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, pp. 333-334), and results in a concentration of metals in the plant litter greater than that in other horizons of the soil. It has been shown that analyses of this forest litter may indicate deeply buried anomalies in metal concentrations where typical soil sampling 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 depend largely on the nature of the terrain being sampled and the logistical problems encountered.

Current research

Research on both geobotanical and biogeochemical methods is being conducted throughout the world. 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 in the United States and elsewhere is producing 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. Studies are under way in the United States 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 pass from the lithosphere to the biosphere as a basis for designing analytical techniques which can detect and interpret the presence of these metals in plant tissues. 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 subsequently followed up by soil sampling with encouraging results. 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 on refinements of analytical techniques has had significant payoffs, both in reducing costs, in increasing the precision of the data, and in expanding the 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 further discussed here.

In general, to obtain the greatest amount of information from biogeochemical data, the use of special statistical techniques are necessary. There has been some investigation of the use of several kinds of formal sampling designs for 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 activities - 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 sampled media, require large amounts of data. In order to make best use of these data, computer-based storage and retrieval systems can be utilized for effective data management. Where possible, automatic entry of the data into data-processing systems should be possible to facilitate 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 methods of this type 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. Attempt 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

For purposes of this discussion, "geophysics" is restricted to what is conventionally thought of as exploration geophysics, including radiometric techniques which overlap the geochemical area. Airborne remote sensing, by means of electromagnetic sensors operating in the radar to ultraviolet range, will be considered in a separate section.

Geophysical prospecting is a major component of many minerals exploration programs, and proper selection and integration of the various alternative geophysical exploration techniques in 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 geophysical techniques. Two principal problems encountered in the tropical environment are (1) accessibility and (2) the local presence of highly conductive surficial material limiting the depth of penetration of the various electrical methods. Such conductive overburden is a nearly universal problem in arid regions and also in certain volcanic and clay soils of the rain forest. As in the case of geochemical analysis, maintenance of delicate equipment may become a serious problem in the humid tropics.

Geophysical exploration for minerals involves two somewhat distinct types of operations. These are regional programs focussed on obtaining an understanding of the broad geologic setting of a region, and, secondly, target-oriented detailed exploration programs. Since regional programs do not usually pin-point the location of economic ore deposits, their financial support and implementation normally resides with governmental organizations. However, the information obtained is of value for a variety of uses and users, within and outside the minerals field. Such regional programs often utilize aeromagnetic techniques, supplemented with either airborne electromagnetic or radiometric measurements. An example of such a program is the recent combined airborne magnetic/radiometric survey of Liberia carried out 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 which appears to be favorable for the occurrence of petroleum. The Government of Liberia subsequently sold leases for exploration which is now underway.

Detailed, target-oriented survey 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 develop a major nickel deposit in Australia were approximately 10 million dollars; of the total, 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 on the basis 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 Soviet program for diamond-bearing kimberlite pipes. That program has used a combination of magnetic, radio-metric, and gravimetric techniques (Brodovoy, 1967) integrated with other disciplines. Its value is evident from the fact that the USSR has now evolved from an importer of diamonds to the world's second largest producer (Liddicoat, 1970). The Soviet 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 that obtained from other, follow-on 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 programs. Because of serious accessibility problems in most tropical areas, the primary emphasis of regional work should be on airborne magnetic surveys with combinations of 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 interpretation of the regional data and the type of mineralization target sought.

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 Geophysicists (Allen, 1971). Table 1 compiled from

Allen's data shows the dollars spent by free-market nations in 1969 on various types of geophysical surveys. The table includes all expenditures in geophysical prospecting, from regional reconnaissance to development work on a located deposit, and thereby provides a basis for assessing the priorities assigned by industry and government to each of the techniques. Relevant statistical information is not available for the socialist nations, although a wealth of highly productive geophysical exploration is being carried out, particularly by the USSR.

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

<u>Land methods</u>	<u>Expenditure</u>
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
 <u>Airborne methods</u>	
Magnetic	558
Combined EM/Mag	526
Radiometric	203
Electromagnetic	28
AF Mag	2

Trends in expenditures are useful indicators of changing 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 radio-metric work since 1967 is due to the renewed interest in uranium exploration. Also of interest is the distribution by country of money spent on geophysical exploration and research. Figure 2 shows the distribution of expenditures for these purposes on a global basis for 1968, again excluding the socialist 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

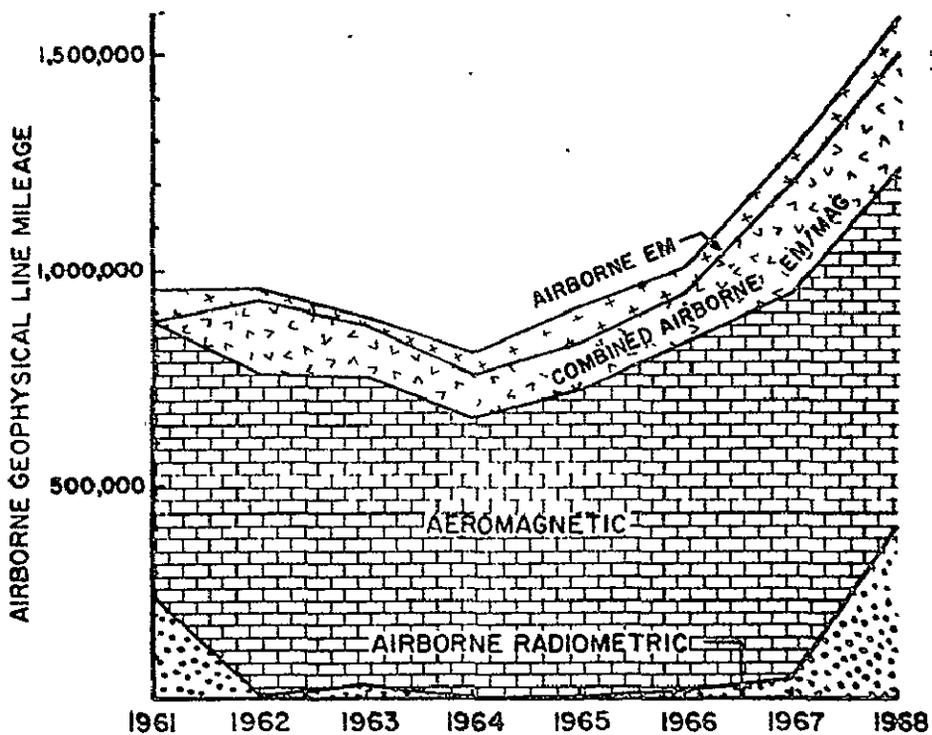
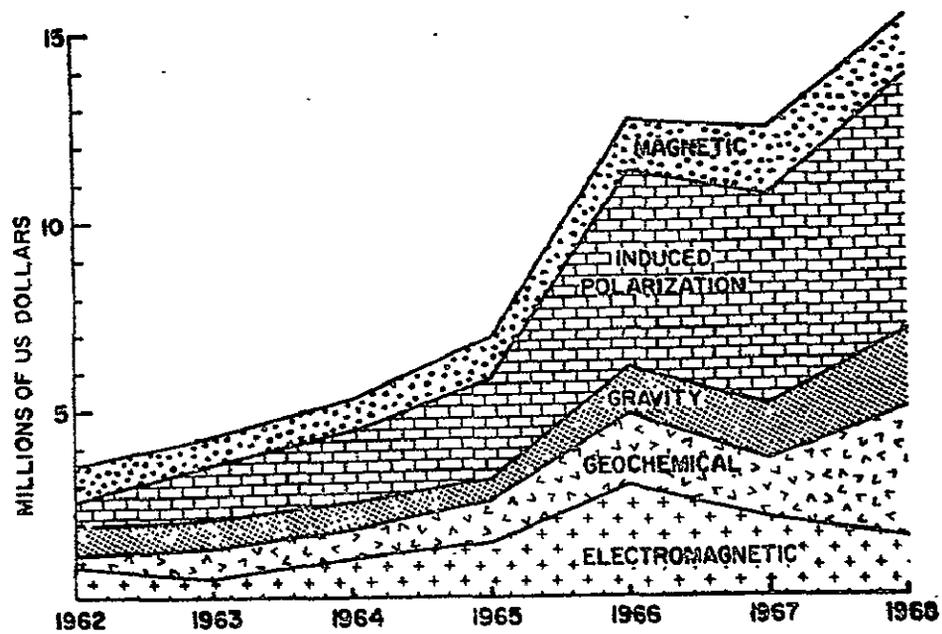


Figure 1.--Variation in airborne and ground geophysical activity from 1961 to 1968, adapted from Hood and Kellogg (1969).

Mining Geophysical Activity in 1968

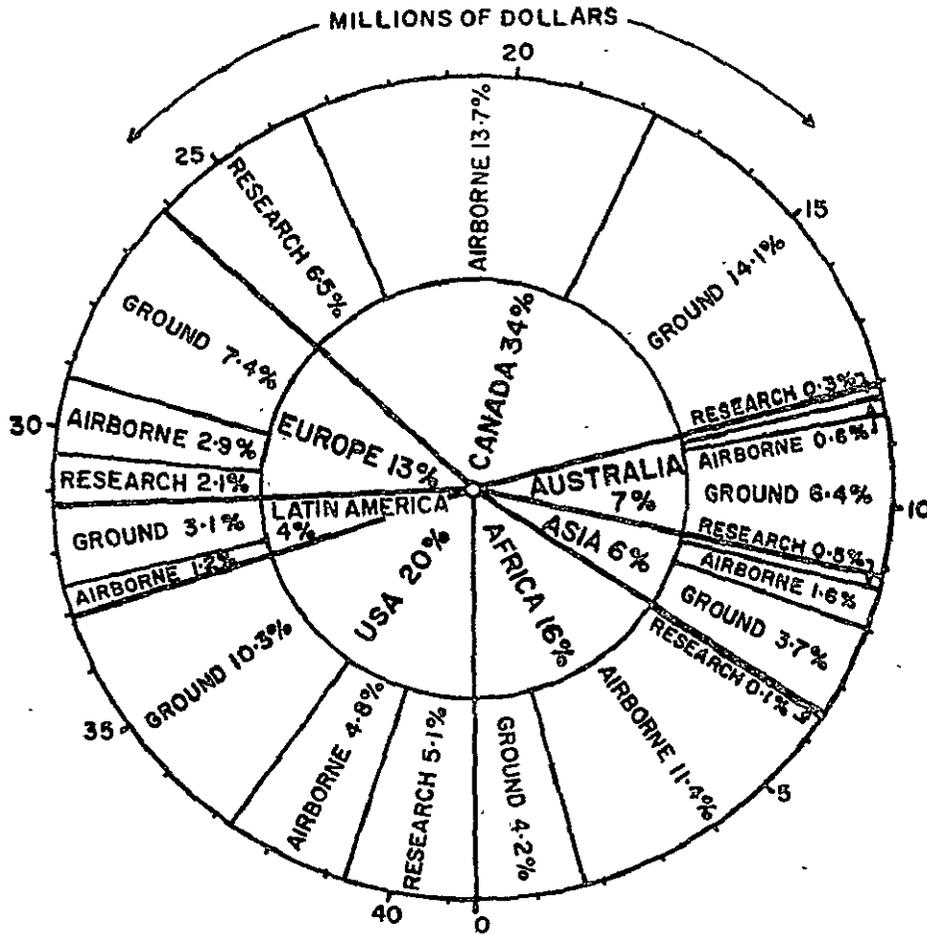


Figure 2.--Free-market nation distribution of mining geophysical activity in 1968, from Hood and Kellogg (1969)

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 principal geophysical exploration methods is briefly described below, including its major applications to minerals exploration. Excellent, detailed discussions of current methods appear in the Society of Exploration Geophysicists' "Mining Geophysics" and "Mining and Groundwater Geophysics/1967." L. W. Morley, editor.

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-coated 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. Self-potential information may also be obtained easily during an IP survey but requires slightly more time.

The interpretation of IP surveys is often impaired due to difficulty in distinguishing between the conductive sulfide minerals and the clay-coated minerals, both of which 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 problems 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 deposits, 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 the digitization of the topographic and gravity data. The derivation of other maps from the simple or complete Bouguer (gravity anomaly) map is often handled by large computers. Such 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

Geomagnetic techniques are well established for both ground and airborne surveys. Recent development work has

produced light-weight, easily-read instruments which greatly facilitate ground-based data acquisition. Land instruments in use today are mostly of the total-field type (proton precession) or the flux-gate variety which normally measure 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.

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

The greatest use of airborne magnetic data is as an aid to geologic mapping and interpretation on a regional or semi-regional scale. This assists in the elimination of large areas of low priority for prospecting. Combined with electromagnetic 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 with an accuracy of less than one gamma, the use of which should be considered in tropical areas. 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 Sao Francisco region in Brazil in which local lead-zinc mineralization exists in the Eocambrian Bambui Limestone.

Most airborne magnetic data acquisition is done by governmental or service organizations which employ systems based on digital data acquisition with data reduction and compilation performed almost entirely by computer. As in gravimetry, many computer-aided interpretational techniques are available.

A number of references in the bibliography illustrate the use of magnetic surveys in mineral exploration programs in all areas of the world.

Electromagnetics (EM)

Electromagnetic techniques are utilized in a wide variety of both ground and airborne-based systems. The most promising of the alternatives are the recently-developed airborne systems 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 an airborne electromagnetic receiver. "AFMAG" (audio frequency magnetics) employs an airborne electromagnetic receiver that senses variations in natural electromagnetic fields generated by distant lightning 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. Also, many possible applications are seriously compromised in areas of deep conductive soils.

In the humid tropics, where the height of vegetation is extreme and weathering depth also great, many airborne EM systems have severe limitations 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) offer promise in the mapping of conductivity variations in surficial materials. These may prove of use in exploration for such commodities as bauxite and gravel deposits. The method uses signals from powerful low frequency radio transmitters in the range of 15 to 25 kilohertz.

Data acquisition and reduction techniques are highly variable, depending on the particular type of system employed. The trend is toward digital data acquisition in airborne work, although this is not universally practiced. 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 hard minerals targets are different in nature and geometry. The principal application of seismic refraction is in determining the thickness of unconsolidated surficial deposits,

which is a valuable aid 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; as a general rule, little use is made of the digital computer. 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 either by profiling (i.e., moving the four electrodes used along the ground with a uniform spacing) or by sounding. Sounding is carried out through the use of four electrodes which 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 are based on 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 ongoing research is investigating the application of 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 techniques previously described and approximate guides on average instrument and contract survey costs. The costs should be considered approximate only, because special local factors such as import laws, taxes, and security laws etc. can affect significantly total requirements. In some areas of the tropics, accessibility will be a major factor in determining survey costs. This is particularly true of ground-based geophysical surveys, but may influence pricing of airborne surveys if no airfields are nearby, particularly if helicopter operations are desired.

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 services 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. It should be borne in mind that the cost data presented in Table 2 for the airborne

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	<u>Frequency domain</u> -- difference in apparent resistivity at 2 or more frequencies <u>Time domain</u> --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 \$10,000 to \$20,000	\$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.

operations reflect only the costs of the particular instrument in question, not all the peripheral equipment required such as Doppler radar, flight camera, etc., nor the staging and logistical requirements.

With respect to ground geophysical operations, developing countries should seek to build indigenous capabilities. The single most important requirement will be the training of geophysicists and equipment maintenance specialists, who will be able to go into the field in difficult conditions and carry out their operations and programs efficiently.

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

Research gaps and priorities

There appear to be several areas unique to the tropics in which research could facilitate geophysical prospecting. The following 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 could 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 valuable to evaluate these techniques along with a very-low-frequency airborne system which is more responsive to near-surface conductors. A combination of these techniques probably will 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 additional instrument development and applications research is needed.

The first is the detection of trace gases in the atmosphere on a continuous or quasi-continuous basis. Most research of this type in the minerals field has been centered on mercury, and several types of systems have been developed for airborne application. The correlation spectrometer, a continuous-reading device, appears to be the most promising at present. Research needs to be directed toward the application of these devices in the tropics and also to employing other gases that may have geological significance, such as I, SO₂, and H₂S. Hydrogen sulfide and sulfur dioxide determinations may be very useful in the tropics where natural concentrations are not affected by the addition of similar gases from industrial effluents.

The second area for additional R & D is in the use of radiometric techniques such as neutron activation and x-ray fluorescent methods. Again some systems are available but refinement and adaptation are needed. These methods hold great promise for rapid chemical analysis in the field, as well as for general geological mapping purposes.

Another area of potential promise is 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 effort might well produce significant results in this area.

Because of the importance of induced polarization in minerals exploration, additional research on interpretive techniques is needed. Since IP techniques have been developed and applied mainly by private interests, there is much proprietary information not easily available on experience and potential applications in the developing countries. Consequently, research on 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 designed to optimize the extraction of 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 U. S. Tennessee Valley Authority, photogeologic interpretation received a great impulse during World War II and has been increasingly applied and refined since then. 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 and recorded as narrow bands opened many new fields of application and opportunity. Much development has been spurred and financed by military and space requirements, 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 the detection and monitoring 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 being opened by the rapid evolution of the state-of-the-art of remote sensing by both aircraft and satellites. 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 (0.3 μ m - 30 cm). These observations are limited to the surface or to very shallow penetration, but provide a basis for discriminating among 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 mineralized 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. Specific capabilities and applications of various remote sensing techniques are discussed in the next sections.

Because remote sensing observations principally record the surface properties of materials, they are ideal for geo-

logical surveys in areas of excellent rock exposure, such as in many arid regions. Except for radar and some highly specialized types of photography, remote sensing surveys for geologic purposes in humid regions generally would be limited to unforested areas, thus greatly 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. Short-term training of local geologists should suffice to make them aware of the different kinds of information presented in remote-sensor images, and how to interpret it. 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 on important parameters such 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 stage in the interpretation process.

Low-resolution coverage of much of the tropical region of the world can be obtained at very low cost from satellites such as the Nimbus weather satellite and the Earth Resources Technology Satellite (ERTS). This should enable inexpensive but sufficient analyses of satellite imagery to be performed aimed at discovering new information on broad-scale geologic or structural relationships in relatively unexplored regions. The first of the ERTS satellites, scheduled for launching in July 1972, will be limited to collecting reflectance data at a resolution of 80 meters in the visible and near infrared. However, 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 for 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 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 various shades of gray. Even with broad-band color photos, however, it is often difficult to distinguish different geologic units. Since some narrow-band photos, viewed singly or in combination, enhance reflection contrasts, much research is now directed toward use of photos taken simultaneously at more than one band.

Common and inexpensive photographic systems currently available (from aggregates of 4 to 6 Hasselblads to the single 4-band I²S camera 1/) use various filters to obtain fairly broad-band data across the visible and near-infrared regions of the spectrum. Data from various bands used simply as black-and-white or as color pictures may reveal 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

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.

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 between a limited number of rock units. Future success will rest largely on the ability to characterize unique geologic units on the basis of color, roughness, and textural properties. Characterization of terrain units such as forest, marsh, outcrops, 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 these methods for the discrimination of geologic units.

A potential application of multispectral data is based on the presence of reflection minima near 0.70 and 1.0 μm 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 prophyry and dacitic alluvium. Thus computer-generated ratios for the two specific channels permit discrimination of volcanic flows having different ferric:ferrous proportions. This technique appears to have application for general mapping purposes as well as for the examination of oxidized overburden in mineralized areas, and in the search for gossan deposits. In addition, it appears possible that multiband photographs which are 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 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 anomaly in their trace-element content, sometimes even by exhibiting 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 attention. Actually, mineral-deposit-related chlorosis is rather rare. 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 soil concentrations of most elements required to produce symptoms visible to the naked eye are often fairly high. Thus, in most areas of geochemical soil anomalies that are genetically related to important mineralization, the vegetative canopy is apparently healthy and no toxic symptoms are visible to the eye. However, experiments by the U. S. Geological Survey during the past several years have shown that abnormal chemical environments can cause subtle - but nevertheless definite - changes in some physical or chemical aspect of one or more plant organs. Thus, 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. 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 structures not 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 distinguishing 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 resolutions of one milliradian (one meter from altitude of one kilometer), and thermal resolutions of 0.25°K . They record data on film or magnetic tape in one or more channels, generally the 3-5 μm and 8-14 μm windows of the Earth's atmosphere.

A recent and important advance in the application of thermal infrared imagery depends upon the use of a multi-channel scanner to record thermal emissions for purposes of discriminating between siliceous and nonsiliceous rocks, and 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 8-12 μm 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 the 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. It was known from previous studies that 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 depicting 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 discrimination toward actual identification 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.

It has also been demonstrated that through the use of two radar antennae mounted on a single aircraft, a single image can be produced which consists of bands of light and dark areas. These result from the alternate reinforcement and destructive interference of radar waves from the two antennae as affected by their reflection off the ground at different angles. By knowing the position of the aircraft with respect to the ground, it is possible to relate various light and dark bands to angles of reflection, and to derive relative elevations. If the absolute elevation of one point on the image is known, then a rough topographic contour map can be produced from a single radar image.

The use of microwave radiometers for emission measurements also may have broad application to geologic surveys. 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 just described may include:

1. Rapid discrimination of geologic units, structures, and ground moisture over large areas. This could facilitate construction of geologic maps with relatively small amounts of field checking, which are 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 the 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 <u>vs</u> tape recording)	30,000 to 90,000
Multichannel scanners (achieve prime utility when meshed with computer processing capability)	up to 500,000

Surveys 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 collection 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, have 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 semi-controlled mosaics are generally done on contract because of the expense of the equipment. Such surveys 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. Development of computer techniques for processing 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 the research stage of iron-band processing. Copper and chromium also appear to have spectral structures appropriate for similar use of multispectral imaging, and research may develop a new tool for locating these metals.
3. Refinement of ratioing techniques for mapping silica-content variations.
4. Detailed investigation of the potential of microwave for discrimination of soils and soil moisture in various climatic and vegetative 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 $1/2 \mu\text{m}$ to $20 \mu\text{m}$. 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 associated with mineralized ground.

CAPACITY OF DEVELOPING COUNTRIES TO USE THE RESULTS OF SUCCESSFUL RESEARCH

It is obvious that developing countries differ markedly in their capacities to utilize the results of new research, principally by virtue of the great differences that exist in the quantity and quality of available financial, human, and institutional resources. A number of them -- those more richly endowed, relatively speaking, with respect to investment capital and a growing cadre of trained experts (e.g., Brazil, Venezuela, Thailand, the Philippines) -- will be able to absorb and utilize many of the more sophisticated new instruments and techniques.

This does not mean, however, that these or other developing nations will be able to, or should seek to, be entirely self-sufficient in the application of the new prospecting tools. Satellite-based remote sensing will clearly be out of reach for the immediate future, as will the procurement and operation of large, expensive analytical instruments and advanced data processing equipment that is at the forefront of the state-of-the-art. However, lack of a self-contained indigenous capability to acquire and use new research results does not foreclose its application. The major objectives of the developing countries generally should be to gain an understanding of all options, old and new, open to them and to develop a capability to gain access to and apply the most relevant and profitable of the alternatives. This translates first into having a nucleus of trained professionals who can keep up with the evolution of the state-of-the-art, and assist decision-makers with increasingly difficult choices of how, when, and where to invest scarce resources in the minerals exploration area. A country must have the capability 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. In addition, although costs per unit area prospected have been decreased and the chances of success increased by modern scientific and technological developments, the capital investment needed to achieve these reduced areal costs has vastly multiplied. Wise investment requires wise people. Many developing countries are currently availing themselves of new training opportunities in the more advanced countries in an attempt to build a solid nucleus of trained professionals, particularly in the remote sensing field.

With respect to actually acquiring and applying the new tools, several paths are open. If a country cannot launch its own resources satellite, it can cooperate with others that do. Expensive surveying instruments, such as radar scanners, can be essentially "rented" under contracts with private firms which obviates a much larger capital investment for outright procurement. If complex data processing is required, often the requisite computer programs can be purchased from computer "software" firms for operation on computers already available in the developing country. Indeed, if complex computer banks and advanced data interpretation techniques are required, most developing countries will probably choose not to build a total in-country capability, but will instead seek to have the surveys and analyses carried out under contract. The critical factor is the availability of experts in the country who are aware of what the new research breakthroughs are, how they can be applied, and what their costs and potential benefits are, and who can thereby provide intelligent guidance on which of the available tools and techniques will contribute the most in the country-specific situation.

The previous discussion has assumed continuation of the status quo with respect to the products of successful research in the minerals exploration field; namely that the products will be techniques and equipment which are more diagnostic, more exact...and more sophisticated, complex, sensitive, and costly. It is a principal intent of this report, however, to articulate the need for new research designed for new needs, specifically, the desire of developing countries to conduct their own mineral exploration surveys, with their own experts and own equipment. The research challenge then is to develop techniques and instruments which are adapted to the special requirements of developing countries in tropical areas. With respect to instruments, for example, such requirements may include low cost; simplicity of design, maintenance and repair; easy recalibration and data reproducibility; lightweight; and heat and moisture resistance.

As evidenced by the recent developing country endorsement of a new United Nations Revolving Fund for mineral surveys, radar mapping programs in Brazil and Venezuela, and the nature of the international participation in the forthcoming U. S. Earth Resources Technology Satellite Program, developing countries are vitally interested in -- and are investing in -- intensified mineral exploration. However, at the same time they are assigning this activity a high priority within their development planning, they are calling attention to (recently in the U.N. Committee on Natural Resources) the unique constraints they face, not only as a result of lack of financial resources, but also due to the

absence of adequate capabilities to cope with the peculiar characteristics of the tropical environment -- inaccessibility of vast areas of their countries, thick jungle canopy and soil mantles, and extremes of heat and moisture which quickly ruin much of the sensitive instrumentation available today. Removal of these constraints will require an infusion of new research funds, as well as imaginative scientists who will address not only the problem of how to design a prospecting tool for application in tropical areas, but also the problem of designing it for use by developing country specialists in the developing country.

Because the developed countries with major research capabilities in the mineral exploration field lie in the temperate zone, research specifically aimed at improving prospecting capabilities 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 to be carried out in cooperation with the countries involved. 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.

At the same time, it would be useful to encourage more extensive publication of existing knowledge on research and experience with various prospecting techniques. Naturally, there are occasions when private firms and individual nations consider it advisable to withhold exploration findings, at least for a limited time. However, generally all would benefit from wider publication of the results of both scientific research and routine prospecting work in geochemistry, geophysics, geobotany, and remote sensing carried on by government, international agencies, and private organizations. 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. Raw data is now hidden in files and classified reports which would undoubtedly solve many of our problems; sometimes "the wheel must be reinvented" because of the public unavailability of these data.

Furthermore, the professional community is unable to judge the adequacy of existing knowledge, the value and potential applications of new instruments and methodologies, or the requirement for additional research, if information on the nature and results of research and survey operations are 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 often have insufficient basis for judgment as to whether a good or poor prospecting job has been done. More-

over, 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.

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 tropics as prospecting methods continue to improve and as research defines ever more closely: (1) the chemical and physical properties and behavior of the sought-for materials; and (2) the effects on the environment of such materials so that improved modes of sensing and interpreting them can be designed. The potential effect on the developing countries of the location and development of these raw materials can be great, for they can provide the capital to support infrastructure development, the expansion of industrial know-how needed 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 in some areas might find advantages in regional approaches to mineral exploration that more than offset the political and institutional problems which will be encountered. This would be especially true for groups of contiguous countries with reasonably homogenous climatic and geologic environments and faced with a 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. Sharing of exploration, data-processing, and map-making equipment and facilities appear to be areas in which cooperative activities would be feasible and effective.

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