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TECHNOLOGY UTILIZATION

APPLICATION OF BIOGEOCHEMISTRY TO MINERAL PROSPECTING

A SURVEY

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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A SURVEY

Written under contract for NASA by
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FOREWORD

The relationships of plants to the minerals in their growing medium is at least partially recognized and appreciated by anyone who has tried to make a flower bed healthy or get the lawn to look respectable. Few of us appreciate the converse idea that the response of plants to minerals in the soil makes at least some plants useful in pointing out excessive or deficient amounts of such minerals. The development of this idea into a prospecting tool has been investigated for centuries by various individuals concerned with the location of mineral resources. Recent and current development of a variety of sophisticated instruments for the surveying of the earth and its cover from various altitudes has resulted in new techniques of resource monitoring, such as forest reserve inventory, grazing land evaluation, and even the location of areas apparently having characteristics of mineral-rich lands.

This monograph was undertaken to bring together the growing technology of remote sensing of environment with the advancing techniques of biogeochemistry: the study of the relationship of minerals to the biological species which reside in their vicinity. This survey is neither intended to be a textbook on prospecting nor an exhaustive treatise on geology or botany. It represents an effort to bring into focus the possibilities that exist in combining the techniques of botany, geology, and reconnaissance into one of the several tools for more efficiently locating natural resources, whether they be mineral, forest, or water. The survey on biogeochemical prospecting is not exhaustive, but is intended to establish the state of the art of biogeochemistry and techniques useful in that science.

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CONTENTS

ABSTRACT

The application of a combination of disciplines into the hybrid science termed biogeochemistry has gained momentum in recent decades, bringing the benefit of research into the overlapping areas of geology, biology, and chemistry. This report coalesces these technologies in a coherent interrelationship for application to mineral prospecting. This particular prospecting method is still undergoing the slow refinement process any new science must; however, it has been demonstrated to be a valuable addition to prospecting technology. Theoretical concepts are presented herein, including the geochemical cycle through which chemical elements pass in the process of becoming plant nutrients, the physiological requirements necessary for plant growth, and the interrelationship of these two bodies of knowledge which are directly applicable to the solution of the problem of prospecting.

The location of certain minerals has been accomplished in various parts of the world using this biogeochemical knowledge. Modernization of prospecting techniques is possible and in progress, using the techniques of remote sensing at various altitudes. The direct applicability of remote sensing has been shown by recent NASA work. The means of applying aerial observation to prospecting and, further, to integrating biogeochemistry as a general tool for aiding mankind, are becoming available. This collection of the essentials of the sciences amalgamated into biogeochemistry, together with recent developments in remote sensing of environment, delineate the possibilities which exist for general application.

ILLUSTRATIONS

TABLES

INTRODUCTION

The rapidly expanding population of the world, with its accompanying technological advances, is consuming natural resources at nearly unbelievable rates. It has been estimated that the consumption of supplies since the first of the century has already exceeded the total use of raw materials in all the previous years of man's existence put together (W. A. Fischer, 1967). This is a sobering thought to those concerned with the irreversible disappearance of natural resources. It also poses new problems in the locations of yet undiscovered supplies.

In pre-20th century America, ore bodies of valuable materials were found exposed at the surface of the earth as outcrops, in relatively accessible position. Today, these more convenient sources are gone, long since manufactured into cars, wires, and myriad other products. Hidden sources of raw materials are being sought, under whatever rock, sand, or soil cover they may lie (H. L. Cannon, 1960).

Prospecting in the recent and far past has been largely a process of more or less random selection of an area for surveillance, trekking across it by foot, burro, or jeep, and periodically taking any unusual rock or soil sample for closer examination or analysis by some assayer. This process, with the aid of luck, intuition, sometimes know-how, and patience, at times rewarded the lone prospector or team of mining company geologists with a find of precious or lucrative materials. Once an area bearing riches was located, other lodes were sought in the immediate vicinity, so that from a "pinpoint" source some relatively large mining districts have been found. This concept of working outward from a point source, as it were, may never become completely obsolete as a prospecting method.

However, the technology of the space age is casting a new shadow of possibilities for locating and inventorying natural resources across this old technique. A new concept of moving from a wide surveillance of the earth's surface to the pinpointing of mineral-rich areas is now becoming possible, using the tools of orbiting satellites and multispectral imagery to identify likely areas in which to apply the less exotic ones of soil sampling and chemical analysis. The viewing of large areas of the earth to select portions for closer examination of that area most likely to be fruitful has been shown technically feasible by high-altitude work and by the photographic feats of the Gemini crews. The idea of inventorying resources, unencumbered by the myopia attendant to being too close to the subject, is becoming a comfortable one to many experienced groups of workers in the fields of forestry and land management. Such a new wide view of the earth cannot help but appear attractive as a means of locating mineral resources, as well as geologic mapping.

Geologic observation on this grand, world-wide scale does have some problems. Over two thirds of the earth's land surface is covered with vegetation, of which some 42 percent is forest, 24 percent grasslands, and 21 percent desert shrubs and grass (Draeger, 1967). This vegetative covering prevents direct viewing of most of the underlying soil and rocks for even casual estimation of their identity and economic value. The presence of that vegetation itself can, with the supplement of geological, botanical, and biogeochemical knowledge and experience, facilitate and accelerate the location of some mineral resources. The technique of aerial observation, combined with sampling and analysis of plants growing in suspected mineralized areas, comprise the technology of biogeochemical prospecting.

The study of plants as a guide to mineral deposits has been done for centuries of recorded prospecting, and probably many more of unrecorded searching. Alum deposits were discovered near Rome in the 1400's by prospectors who noted that a type of holly plant growing in the area was also profuse above alum mines in Syria (Sanders, 1967, p. 42A). Other medieval miners used vegetation to locate other ores, such as "pyrite plants" for copper in Scandinavian areas, zinc flora in Belgium and the Rhine. M. V. Lomonosov, in 1763, wrote: "in mountains, in which ores or other minerals are present, growing trees usually are not healthy, that is, their leaves are pale and the trees themselves are low, bent, distorted, gnarled, and rotten, before reaching old age." Collection of geochemical relationships of plants in a systematic manner began in the last half of the 19th century, and was reviewed in 1929 by O. V. Linstow (D. P. Malyuga, 1963).

Broad, in-depth research in biogeochemical prospecting began about 1945 in Russia on a fairly large scale, and in Canada and the United States in a more limited range. Since 1945 in the USSR, a geobotanist has been included on all major geological expeditions; in 1955, the Russian Ministry of Geology and Conservation made biogeochemical work a mandatory part of all geological exploration (Cannon, 1960). Today, geological study of areas in the USSR includes preparation of geobotanical maps, as a result of plant analysis and identification. Information of the same type of some areas in the United States and Canada is now available.

The usefulness of plants in prospecting arises from these facts: (1) plant roots can, in an oversimplified sense, act as conduit systems for carrying metals in solution up into the plant body, where, by one of several mechanisms, the metals become incorporated into the plant's physiology; (2) the incorporation of the metals into the plant system may cause physical changes in the plant which are more or less readily discernable, visually, or by means of one or a combination of photographic techniques.

The first phenomenon makes the plant a storehouse for some metals that have come to the plant from the soil some distance around the plant, and from depths dependent upon the ground water situation and the root depth. Subsequent chemical analysis of the plant which has concentrated metals in some part of its anatomy is then used to monitor the soil for metals. In practice, the chemical behavior of the metals, the pH of the soil and of waters present in them, the nutritional needs and metabolism of individual plants, are all important in establishing what actually occurs in any given situation or locality. However, the ability of plants to "sample" the soil around them, and the advantages for field purposes offered by the comparatively lighter-weight plant samples and accessibility of plants in dense underbrush or forest areas make this technique sufficiently attractive to merit consideration in a wide variety of sampling situations. The advantage in sampling plants is clear in situations in which prospectors must battle rain-forest-dense growth and carry out samples on foot. In this case, plant samples, being lighter in weight and more representative of a larger area than a moist soil sample, can save a tremendous amount of effort (Brooks and Lyon, 1966).

The second phenomenon, in which morphological changes are produced in plants by abnormal amounts of metal ions in their systems, offers a technique for seeking out mineral ore bodies by optical methods to prospectors prepared to equip themselves with a minimum of background knowledge and understanding of the interplay between plants, topography, and chemistry of the region. Cyclic changes in plant appearance and health, with respect to time and extremes in weather, may complicate the application of this technique; but the rewards to be reaped in simplicity and speed may be well worth the effort spent in evaluating the applicability of this phenomenon to a given locale. As more research is done into the effects of abnormal mineral concentrations on the absorption and reflectance of radiation in the near infrared, far infrared, visible, and radar regions of the spectrum, the possibilities for prospecting expand. With development, microwaves will be a useful range. Ultraviolet reflectance and absorption study is not of general value in high-altitude observations because of atmospheric attenuation. Techniques for examining vegetation from orbital altitudes, while perhaps orginally conceived for purposes of surveying extraterrestrial bodies, may prove convenient means of inventorying the vegetative and geologic natural resources of the earth.

Because of the infinite variation in topography, climate, and geology in the earth's surface, the problems involved in carrying out meaningful investigations using biogeochemical principles seem formidable, if not impossibly complicated. However, the workers who have conducted such studies

(Warren et al, 1952) have concluded that the details involved in biogeochemistry are of the same complexity as in geophysical methods. Accordingly, this discussion will include geochemical, botanical, and chemical considerations deemed essential in the application of biogeochemical techniques to prospecting, according to workers actively engaged in this endeavor.

The manuscript is organized into three major topics: (1) Theoretical, which provides background and presents technical details of (a) geology and chemistry, (b) botany, and the interrelationships of the three to (c) biogeochemical prospecting; (2) Biogeochemical Prospecting, which describes the application of the three scientific disciplines to prospecting (literature survey); and (3) Remote Sensing Techniques, which presents the aerial observation technology with which biogeochemical prospecting can be conducted on a grand, overall-view scale, to seek out promising areas for closer scrutiny.

THEORETICAL

GEOCHEMICAL ASPECTS

Most discourses on the subject of geochemistry as applied to mineralization and its effects on plants begins with a discussion of the geochemical cycle. This concept is a "Theoretical Model Created to Summarize the Behaviour of Particular Chemical Elements in Nature." It provides a useful over-all picture of the dynamic geology of the earth, and interactions of various domains (J. A. C. Fortescue, 1967). This model usually involves (1) a major cycle, consisting of broad processes, occurring in the upper lithosphere, of igneous differentiation and metamorphism, and (2) a minor cycle, embracing the secondary weathering processes. The latter includes the dispersion of the elemental components to different parts of the earth's crust, and their reassembly into secondary rocks. Extreme changes, resulting from burial of the secondary rocks, may return them to magmas, hence to the major cycle. The major cycle is a geological phenomenon occurring at depth below the surface of the earth. The minor cycle, surface-associated by definition, is directly related to processes critical to the concept of biogeochemical prospecting. Some understanding of these processes is essential to the prospector to evaluate a given situation quickly in terms of the applicability of any of the various prospecting methods, biogeochemical in particular.

In the discussion of geochemical processes, terminology found in the literature is fairly consistent with respect to descriptions of the interacting regions and the processes. For example, <u>dispersion</u> in the geochemical cycle refers to the pattern of metal content distribution of soil, rock, water, or vegetation. <u>Primary</u> dispersion is that original distribution of materials which occurred when the molten magma reached the surface of the earth and separation of materials resulted from cooling and crystallization processes. <u>Secondary</u> disperions are re-distributions of this original array of materials, by interaction of minerals with other minerals, water, air, or living organisms. Juvenile material is that coming to the surface for the first time. It is applied chiefly to gases and waters.

Processes involved in geochemical changes, represented as the geochemical cycles, include diagenesis, metamorphism, metasomatism, magmatism, and weathering. Diagenesis refers to processes involving physical and chemical changes in sediment after deposition which converts it to consolidated rock. These changes include compaction, cementation, recrystallization, and exchange of chemical species. Metamorphism is the alteration in composition, texture, or chemical structure by interaction with new chemical substances, pressure, and heat. Metasomatism is a replacement process, involving practically simultaneous capillary solution and deposition of chemical species, resulting in alteration of portions of one mineral into a whole new one. Magmatism refers to the development and movement of naturally occurring mobile (more or less liquid) rock material within the earth. Weathering includes the processes of chemical action (air, rain, plants, and bacteria), and mechanical action (temperature and abrasion), which causes surface rocks to crumble eventually into soil through stages of alteration and decay. (Reference: Dictionary of Geological Terms, Dolphin Books, Garden City, New York, 1962 Ed.)

The domains which are discussed in geochemical cycles are the lithosphere, atmosphere, hydrosphere, and biosphere. The lithosphere is the solid portion of the earth's crust; the atmosphere is the gaseous envelope surrounding the earth; the hydrosphere is usually taken as the water portion of the earth's crust, including water vapor in the atmosphere, the sea, rivers, and ground waters. The biosphere refers to the zone at and adjacent to the surface of the earth where life exists, and to all living organisms of the earth.

Two examples of the many ways in which the geochemical cycle can be graphically shown are given as Fig. 1 and 2. H. E. Hawkes (1957) outlines simply the geochemical path available to materials brought to the surface of the earth by movement of magma or by general uplift of land. The vastly different environments at depth and on the surface are responsible for the gross differences between deep and surface rocks: at depth, low amounts of oxygen, and high temperatures and pressures result in "Plutonic rocks" of several types. At the surface, the environment which is encountered by emerging magmas is one of abundant oxygen, lower, fairly uniform pressure, and mild temperature. This particular model does not specifically include the participation of the biosphere in the weathering processes acting upon rocks at the surface of the earth.

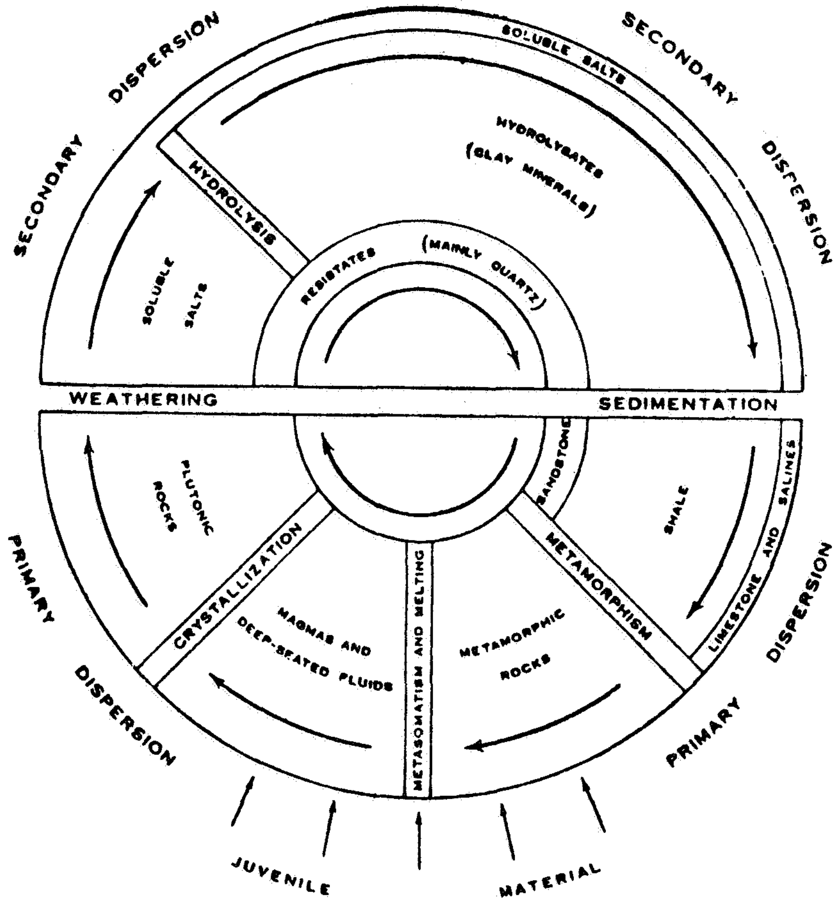

Figure 1. The Geochemical Cycle

Figure 2, from J. A. C. Fortescue (1967), employs different nomenclature and accents the role of biological activity in the alteration of surface rocks. In this model, introduction of the weathered rocks into the biosphere is shown as proceeding from the lithosphere/hydrosphere interface; this detail, and the return of the materials from the biosphere to biogenetic deposits are the processes pertinent to biogeochemical prospecting.

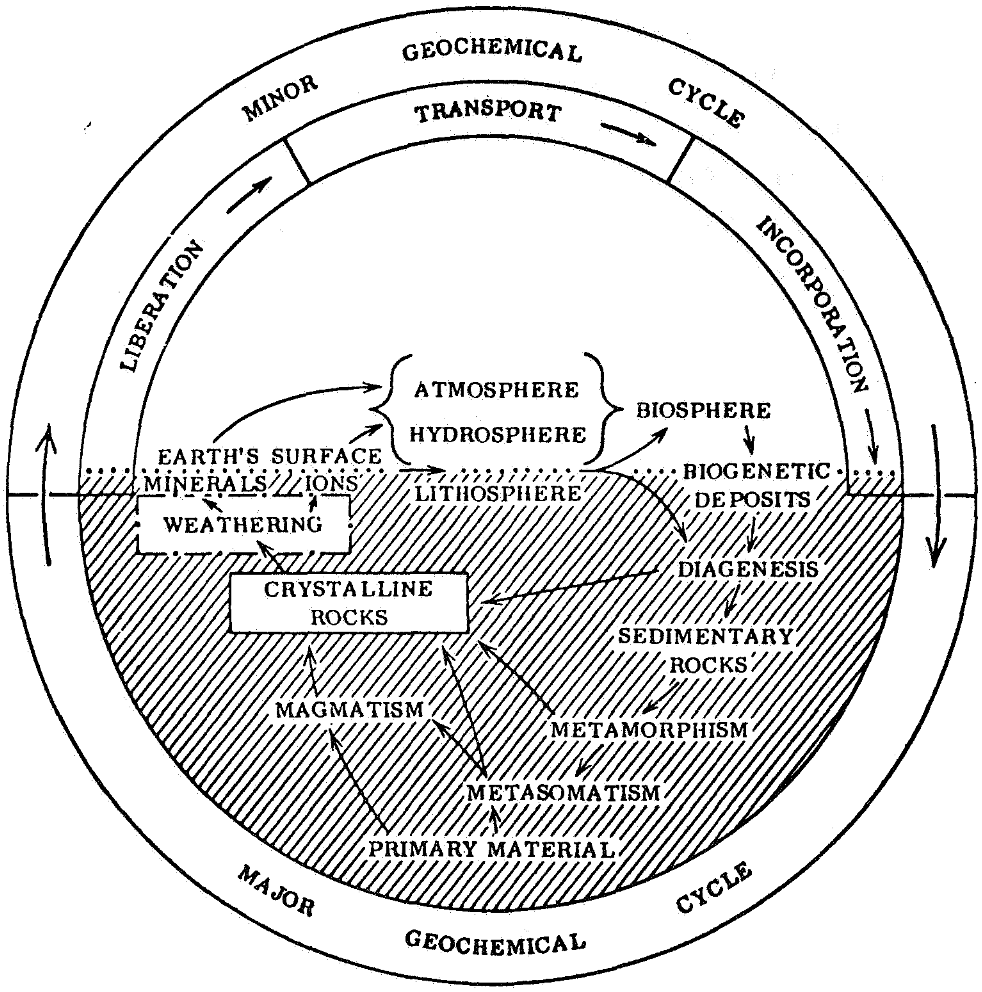

Figure 2. The Geochemical Cycle (Modified Slightly After Mason, 1958)

An exhaustive discourse on the subject of weathering, and the chemistry involved, is beyond the scope of this work, since it encompasses the entire science of geochemistry. A short discussion will be undertaken, however, to introduce some concepts necessary to the topic of biogeochemistry, and to emphasize general types of chemical phenomena which change rocks into materials that the biosphere can and/or must incorporate into itself.

The bulk of the relatively thin crust of the earth's land portions, which are more or less accessible to us, consists of silicate rocks or their derivatives. The rocks are mineral aggregates formed by different and varying processes, and are of three types: igneous, metamorphic, and sedimentary. The bulk of igneous rocks, which have originated from a magma source, consists of relatively few minerals, mostly silicates and oxides. The major types are quartz, feldspar, pyroxene, amphibole, micas (muscovite and biotite), olivine, garnet, magnetite, ilmenite, and apatite. Table 1 shows the gross compositions of these types of minerals.

Metamorphic rocks are rocks formed by alteration of pre-existing rocks as a result of changes in equilibrium conditions, such as pressure and temperature. The crystalline schists, which are metamorphic rocks, contain such minerals as secondary garnet, staurolite, kyanite, andelusite, cordierite, chlorite, and cericite. Table 2 indicates the gross compositions of these typical metamorphic minerals.

Sedimentary rocks are formed by action of water, wind, or living organisms to decompose older rocks. Accumulations of the sediments include fragments or particles of many sizes of rocks, organic residues, and chemical species deposited from the waters in which the sediments aggregate. The sedimentary rocks may contain, besides fragments of the igneous and metamorphic minerals mentioned above, considerable calcite, dolomite, and differentiated sedimentary products such as salts, gypsum, iron ores, sandstone and shale, as shown in Table 3.

Ores are rocks and minerals which can be recovered profitably. Technically, ore is a term referring only to metals or metal-rich minerals, but has, by common usage, come to include a few nonmetallic materials, such as sulfur and fluorite. Building stone and industrial materials, called economic minerals, include abrasives, clays, refractories, salts, etc., and are not properly called ores (C. F. Park and R. A. MacDiarmid, 1964). The definition of an ore as a material concentrated in economically valuable amounts and from which some metal or nonmetallic element can be recovered profitably is a very useful one. Modern technologists continually improve recovery methods and discover new uses for materials, so that the economic value of a given

TABLE 1

COMMON MINERALS OF IGNEOUS ROCKS

Rock	Description	Typical Chemical Composition
Quartz	Silica, one of the most common minerals in the earth's crust; crystals are found in many colors	SiO_2
Feldspar	A group of aluminum silicates, with varying amounts of calcium, potassium, sodium, etc. Most common of all minerals, in pastel colors with pearly or glossy luster	$KAlSi_3O_8$
Amphibole	A group of complex silicate minerals, hydrous, with calcium, magnesium, iron	
Pyroxene	Group of complex silicate minerals of widely varying composition, often fibrous or needle-like	$MgSiO_3$ (Instantite) $NaAl(SiO_3)_2$ (Jadeite)
Mica	A family of silicate minerals noted for cleavability into thin, flexible sheets. All mica contains aluminum, with other elements, and water.	
Muscovite Mica	A pale, almost colorless mica, of variable compositions	$H_2KAl_3(SiO_4)_3$
Biotite Mica	Dark-colored mica of variable composition	$H_2K(Mg, Fe)_3(Al, Fe)(SiO_4)_3$
Olivine (also called peridot or chrysolite)	Magnesium-iron silicate found in various shades of green, sometimes transparent	$2(Mg, Fe)O \cdot SiO_2$
Garnet	A group of silicate minerals, usually with combinations of calcium, magnesium, iron, and aluminum	$Fe_3Al_2(SiO_4)_3$
Magnetite	Iron oxide, the only black ore easily picked up by a magnet	Fe_3O_4
Ilmenite	Iron titanate, has metallic black color	$FeTiO_3$
Apatite	Calcium phosphate, named from the Greek "to deceive" because of varied forms and colors. May be white, green, yellow, violet, to brown; transparent to opaque	$Ca_5(PO_4)_3(F, Cl, OH)$

TABLE 2

COMMON MINERALS OF METAMORPHIC ROCKS

Mineral	Description	Composition
Crystalline schists (rock)	Close, separable layers that break into a wavy, uneven surface	Quartz, mica, garnet are common
Garnet (secondary)	Formed in essentially solid state from constituents released from breakdown of other minerals (See also Table 1)	
Staurolite	Iron-aluminum silicate, brown to black. Almost always crystals, commonly twined into crosses	$Fe(OH)Al_4(AlSi_2)O_{12}$
Kyanite (cyanite)	Aluminum silicate, occurring white to blue-gray or black blade-like crystals	Al_2SiO_5
Andalusite	Aluminum silicate with square cleavage, often showing mica-like scales. Brown or gray colored	Al_2SiO_5
Cordierite	Magnesium aluminum silicate, usually some shade of blue; resembles quartz	$Mg_2Al_4Si_5O_{18}$
Chlorite	A mixture of magnesium and iron-aluminum silicates, green, yellow, pink, red, or brown, with a layered structure resembling mica	$Mg_6Si_8O_{20}(OH)_4$ + $Mg_6(OH)_{12}$ (hypothetical clusters of layers)

TABLE 3

COMPOSITION OF MAJOR TYPES OF SEDIMENTARY ROCKS

Rock or Mineral	Description	Composition
Calcite	Calcium carbonate occurring in over 300 forms, always fracturing in rhombs. Calcite is the major constituent of limestone rock.	$CaCO_3$
Dolomite	Calcium magnesium carbonate is white or varicolored masses, or crystals with curved faces; pearly luster.	$MgCa(CO_3)_2$
Gypsum	Colorless or white hydrated calcium sulfate which occurs as clear crystals ("selenite"), compact masses ("alabaster") and in curved fibrous forms	$CaSO_4 \cdot 2H_2O$
Iron ores	Hematite is an example, which may be black shiny crystals or reddish brown lumps or masses.	Fe_2O_3
Sandstone	Layers of coarse-grained sand, more or less cemented together, in various colors	
Shale	Fine-grained mud, silt, and clay, hardened in thin layers which can be split along the layers	

ore may change from "worthless" a few years ago, to "profitable" now or in the near future. This implication not only makes valuable known deposits of low grade, but changes the task of the prospector from hunting only relatively concentrated materials to seeking even fairly low enrichments of minerals. These may include highly weathered dispersions of materials.

Igneous rocks, by the nature of the processes of separation of materials in the molten magma, are often the sources of larger concentrations of the elements of economic interest. It is obviously of commerical advantage to have the elements being sought located in relatively small, unscattered areas. The weathering of these relatively concentrated bodies of mineral scatters the components. The process also renders the components available to plants, the subject under study here. Accordingly, igneous rock weathering into secondary materials (metamorphic and sedimentary rocks) deserves a closer look.

The weathering of rocks and of ore elements involves abrasion of large masses into successively smaller ones, together with chemical modifications affected by water, heat or cold, and atmospheric gases, such as oxygen and carbon dioxide. The particular environmental conditions under which these destructive processes occur determine the products, which will be the stable forms of the material combinations in the prevailing thermodynamics of the system. The abrasion mechanically results in a tremendous increase in the surfaces of the particles; the surfaces may be chemically active, as in the case of certain clays. Simultaneous chemical reactions, such as the oxidation of sulfide ores, may generate considerable heat, increased by solar exposure.

V. M. Goldschmidt (1945) presented a classification of sediments formed during weathering and subsequent transportation and sedimentation. Patterned after this classification, Rankama and Sahama (Geochemistry, 1950) modified the original concept into several classes of sediments:

1. Resistates
2. Hydrolyzates

3. Oxidates

4. Reductates

5. Precipitates

6. Evaporates

7. Bioliths

Resistates are the chemically undecomposed residues, which mechanically are broken into the quartz and other sands, gravels, sandstones, arkoses (feldspar-rich sands), conglomerates, etc. Gold, platinum, magnetite, zirconia are found in sediments of this group.

Hydrolyzates include bauxites, clays, shales, and slates, which are combinations of finely powdered, chemically resistant rocks, and of weathering products of less inert rocks. In this class may be found enrichments of vanadium, uranium, arsenic, antimony, molybdenum, copper, nickel, cadmium, gold, silver, platinum, titanium, and beryllium.

Oxidates include iron and manganese ores formed by precipitation of iron and manganese as hydroxides, after oxidation of the metals (from Fe^{+2}, Mn^{+2}) in waters bearing oxygen. Other materials in the class are carbonates of calcium, lead, and strontium. These may be enriched in lithium, tungsten, barium, boron, titanium, cobalt, nickel, copper, and other heavy metals.

Reductates, formed in chemically strong reducing atmospheres, are such groups as the sulfides of metals in the lower chemical oxidation states.

Precipitates are compounds deposited from solution when chemical changes cause decomposition (e.g., bicarbonate decomposing to carbonate, causing precipitation of calcium carbonate), or when temperature or concentration changes in solution initiate deposition (e.g., solubility product of compound is exceeded).

Evaporates are salts deposited from waters which are totally evaporated, such as the sodium, lithium, potassium, calcium, and magnesium chlorides, borates, nitrates, etc., found in dry lake beds.

Bioliths are sediments, organic in origin, such as the chalk cliffs of Dover, England, and coral reefs. These materials contain calcium, magnesium, fluorine, silicon, and phosphorus, from the structures of shells and skeletons of myriad organisms.

A graphic representation of the weathering of some of the most common primary minerals is illustrated in Fig. 3. The essential factors of the behavior of minerals to weathering processes are (1) the chemical and mineralogical nature of the mineral; (2) composition and nature of country rock, state of fissuring, and permeability; (3) the climate; (4) ground water level and rainfall; (5) topography; and (6) geological age and history of the deposit or rocks of interest. Weathered minerals may support characteristic vegetation types.

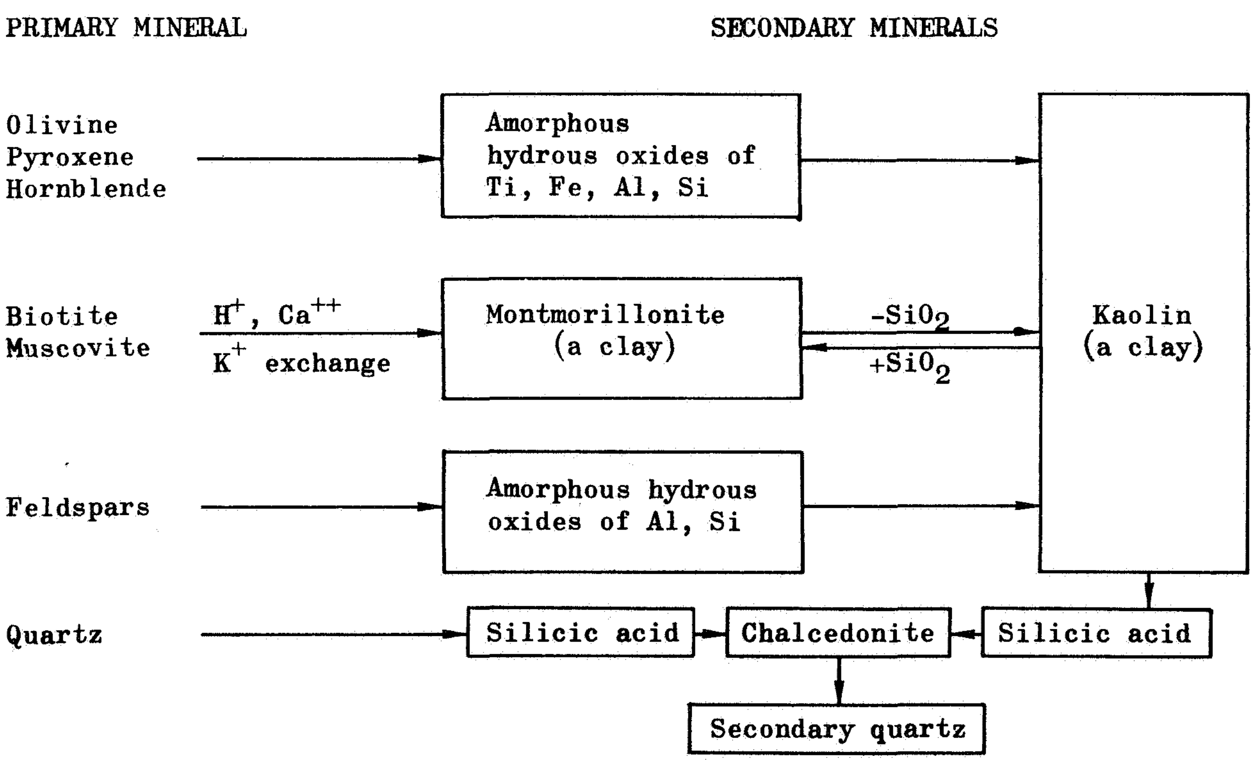

Figure 3. Weathering of Primary Rock-Forming Minerals (After Fieldes and Swindale, New Zealand J. Sci. Tech. 36B, 140 (1954).)

In areas of moderate rainfall, the groundwater level is usually less than 30 meters below the surface, while in dry areas the groundwater level may be 100 meters below the surface. In general, the depth of groundwater corresponds to the depth at which active oxidation occurs, at rates related to ambient temperatures. On the other hand, rainwaters made acidic by dissolved carbon dioxide and which percolate through the zone of oxidation will dissolve many oxidized materials rapidly. These factors indicate that in warm, dry climates oxidation will characteristically occur at fairly large depths, but oxidation products will not quickly be carried away by groundwaters. Even deeply buried deposits of some minerals may be weathered into compounds mobile enough to reach plant roots, but only slowly dispersed in the earth's crust. In tropical zones, in which leaching is especially effective due to large annual rains, oxidized, soluble compounds dissolve with comparative rapidity, and all but insoluble oxides like iron and aluminum are carried off.

Figure 4 shows relative depths of actively leached and decomposed weathered crust as related to annual precipitation and climate. The diagram shows two climatic conditions favorable to weathering: the first corresponds to the taiga podzol zone (damp, forested region, temperate latitudes), where the weathered crust is about 2 meters thick; the second occurs in the moist tropics, where the weathered crust may be several hundred meters thick. The leached, decomposed crust does not develop pronouncedly in the tundra, desert, and semidesert climatic zones, although oxidation occurs to considerable depths. The availability of weathered, water-soluble nutrients at depth grossly determines the types of plants, with given root depths and particular nutrient requirements, which will be able to grow in a given climatically governed soil zone.

The newly formed materials in the soil and the weathered crust are more or less characteristic of the climate in which they were formed. The Russian taiga podzol is a highly leached soil, low in iron and lime, which forms under moist, cool conditions. In the warm, wet climate of the tropics, silica leached soils are formed, rich in aluminum and iron hydroxides. Desert weathering processes result in sulfate and carbonate salt-rich crusts (Malyuga, 1963).

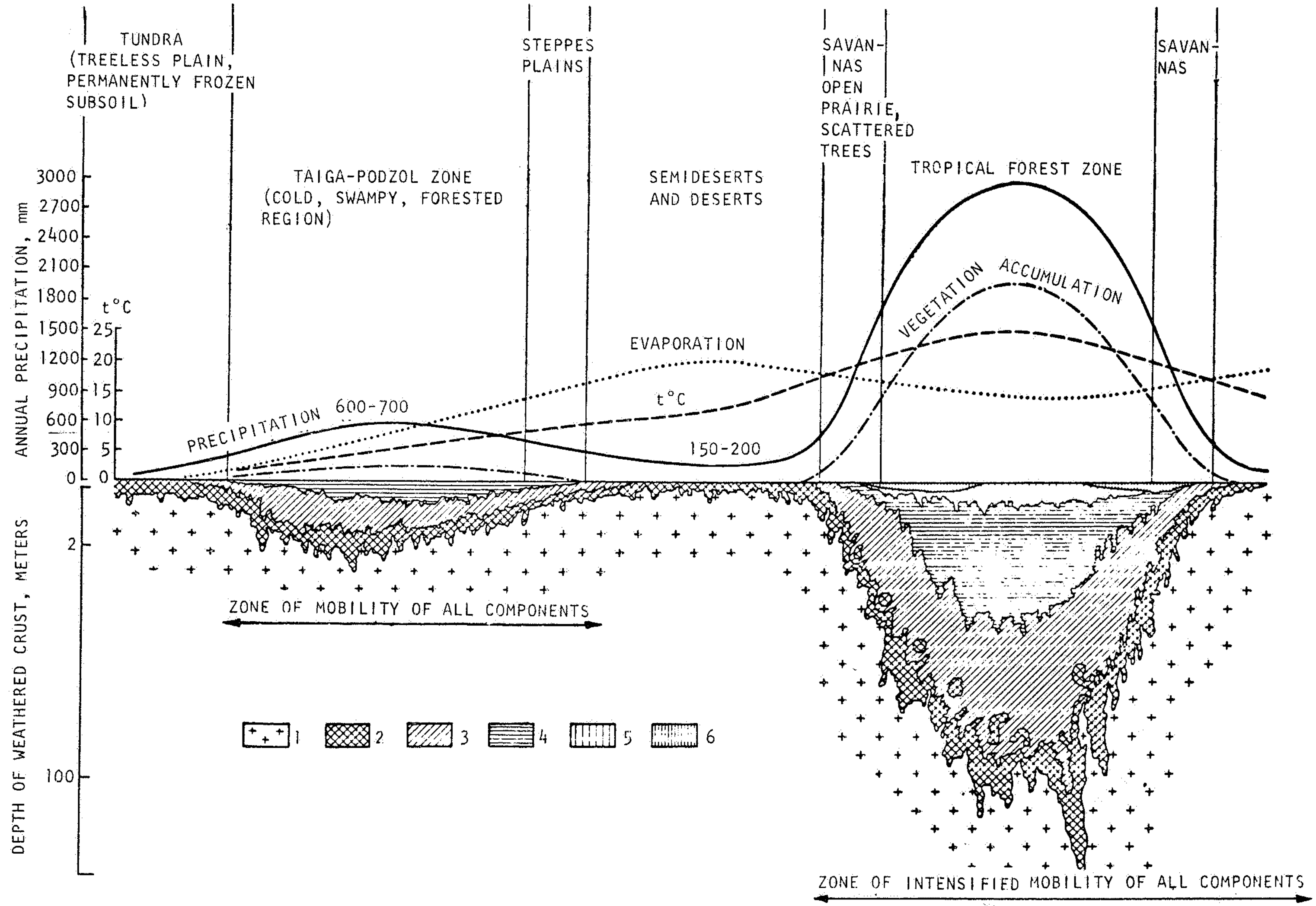

Figure 4. Formation of Leached and Decomposed Weathered Crust in Tectonically Inactive Areas. (1) New Crust; (2) grus zone, chemically little modified; (3) hydromica-montmorillonite-beidellite zone; (4) kaolinite zone; (5) ochers, Al_2O_3; (6) hard layer $Fe_2O_3 + Al_2O_3$ (according to Strakhov, 1960).*

*Reference: Malyuga, Biogeochemical Methods of Prospecting, p. 32, 1964).

Transport of the weathered components of a given mineral into the area surrounding the original concentrated deposit causes the formation of dispersion haloes. This phenomenon is the enrichment of the area surrounding the mineral deposit in the mobile components, so that the concentration of the mineral elements is, in that area, lower than in the original deposit, but higher than in the original country rock. Such zones of relatively high concentrations of metals over or around ore deposits are often termed geochemical anomalies. Dispersion haloes are localized in rocks of the weathered crust (alluvial and residual material), and are disseminated in soil, ground water, and in plants. Since the location of a dispersion halo may indicate a valuable mineral deposit, techniques facilitating such location become important. Biogeochemical exploration has as its objective the location of such dispersion haloes. Processes which occur as ore bodies weather are therefore important in consideration of the technique of biogeochemical prospecting, since the availability of specific nutrients as a result of such weathering governs the survival of plants.

The zone in the crust in which oxidation occurs characterizes the migration of the elements in an ore under the prevailing climatic and chemical conditions in the area of the ore body. In the case of sulfide ores, oxidation produces iron sulfite and sulfuric acid, which can enter the soil and ground water to migrate away from the ore body, producing changes in the surrounding country rock in the process. The oxidation process is: $FeS_2 + 3O_2 + H_2O = FeSO_3 + H_2SO_4$. The oxidation can occur by air and water interactions with the mineral, or by action of bacteria. The sulfuric acid becomes diluted by leaching into ground waters, and is slowly neutralized by reaction with bases present in the soil. Table 4 illustrates behavior of some ore minerals during oxidation. The topography, character of the country rock, acidity, and amount of water available from any source, will all influence the direction, extent, and nature of the geochemical dispersion halo. Temperature also has an effect on the mobility of materials leached away from an ore body.

Topographical influence on the direction of movement of materials away from an ore body must be considered when relating a dispersion halo to an ore-body

TABLE 4

BEHAVIOR OF SOME ORE MINERALS DURING OXIDATION

Element	Primary Minerals	Oxidized/Secondary Minerals	Mobility (Relative Rate of Dispersion)
Fe	Siderite, silicates Hematite, magnetite Pyrite Pyrrhotite	Limonite Limonite Limonite Hydrated Ferric Silicate	Moderate Slow Fast action of $Fe_2(SO_4)_3$ as oxidizing agent Fast
Cu	Many Sulfides	Sulfates	One of the most readily transported, migrates, forms supergene sulfide zone/ upper oxidized zone
Zn	Sphalerite (oxides, sulfides)	Smithsonite Calamine	Sulfates and chloride very soluble. Carbonate, silicate difficult. Zinc is generally mobile, easily oxidized in presence of pyrite which is common. Migrates, forms supergene deposits.
Pb	Galena and other mixed sulfides	Cerussite Anglesite	Slight mobility in oxidized zones (somewhat mobile in presence of ferric sulfate and chlorides)
Au	Gold Amalgam Tellurides		Slight mobility in form of chloride, precipitates fast in reducing conditions
Ag	Argentite Native silver Telluride Minor in other sulfides/ sulfosalts	Cerargyrite	Mobile in presence of $Fe_2(SO_4)_3$ Less than Cu, Zn, more than gold
Pt Pd	Platinum Sperrylite (Pt, As)		Highly resistant to oxidation Highly resistant to oxidation
Hg	Cinnabar	Calomel Hg_2Cl_2 Oxychlorides	Not easily attacked, not very mobile in H_2SO_4 acid, chlorides, or alkaline sulfides
Cd	Sphaterite Greenockite	Greenockite	As mobile as zinc
Ni/Co	Sulfides Arsenides	Arsenates	Very mobile in sulfate solutions
Cr	Chromite	Chromates	Very insoluble
Mn	Manganosiderite (Mn, Fe) CO_3 Oxides, sulfides	Pyrolusite (MnO_2) Hydrated oxides and silicates	More soluble than Fe; less easily precipitated. Easily transported as sulfate or bicarbonate
Sn	Cassiterite		Very resistant, immobile
W	Scheelite (Ca WO_4) Wolframite (Fe, Mn) WO_4		Very resistant, highly immobile
V		Vanadinite and other vanadates	Complex oxysalts mobile in ground water
U	Uraninite Complex oxides	Hydrated oxides and many salts	Very mobile, easily oxidized Immobile
Mo	Molybdenite	Molybdite Molybdic ocher Wulfenite	Not very mobile in solution. Limited transport and enrichment by colloidal processes
Bi	Bismuthinite (Bi_2S_3) Native Bi Pb-Br sulfites	Bismite Bi_2O_3: $3H_2O$ Bismuthite (Bi_2O_3. CO_2.H_2O)	Like lead, is difficult to dissolve, no great mobility
As	Arsenopyrite (Fe As S)/and other arsenides	Arsenolite As_2O_3 Hydrated arsenates	Mobile in presence of Na, K salts. Arsenic is fairly mobile (more than antimony)
Sb	Stibnite Antimonides	Cervantite (Sb_2O_4) Other hydrated oxides	Considerably less mobile than arsenic

location. Gravity will tend to pull water downhill, carrying small particles of minerals and dissolved materials along. Opposed to this, tiny fractures in rocks, acting like capillaries, and large surface area of very finely divided particles will tend to hold mineral solutions in place, or even to move them uphill against gravity. The texture of the soil will, therefore, affect the movement of the material from ores and determine in part the extent and profile of a dispersion halo. The profile of the dispersion halo, in turn, may directly determine the profile of the vegetation growing over it.

The character of the country rock as an efficient dam or relatively porous medium for the flow of dissolved or suspended minerals from a buried deposit directly affects formation of dispersion haloes. The chemical nature of the country rock is also important, since alkaline soils would neutralize acids formed by oxidation of some minerals. This interaction of soils or rock with waters could either hasten movement of the dissolved minerals by keeping them in solution, or cause them to precipitate as solids and stop the movement through the soil. The amount of water passing through soils in any given time governs the rates of solution and redeposition of minerals, rate of mechanical movement of small particles, and the amount of vegetation supportable by the soil. The presence of vegetation will also markedly influence dispersion. According to Malyuga (loc cit, p. 50), "surface vegetation mobilizes mineral nutrients from a stratum of considerable thickness, attaining 22m (black haloxylon) and on the average (for all surface vegetation) is equal to 3-5m." In general, the organisms populating the soil move ore elements to the surface; the formation of the humus layer favors the accumulation and retention of many metals, and in moist forest zones, woody and shrubby vegetation actively extract ore elements. This activity results in haloes in the humus with a high metal content. The direct effects on vegetation of mineral enrichments in the supporting soil and ground waters vary with different types of vegetation. A discussion of general kinds of mineral-plant interactions is, therefore, in order to orient the kinds of plants one finds associated with specific elements with respect to geologic availability of those elements.

BOTANICAL THEORY

The processes of identification of plants and their chemical analysis to locate mineral resources are the activities called, by most workers in this field, biogeochemical prospecting. Geobotany is a related operation (if not a subdivision) by which mineralogical "anomalies," or abnormally high metal concentrations, can be detected in plant species and related ecological complexes by observation methods alone. These distinctions in methods, after I. I. Ginzburg (1960), are usually adopted in the literature on the subject, but some confusion may arise from the interchanging of terms. In this survey, the definitions given above have been used, but geobotany has been treated as a special type of biogeochemical prospecting. This is deemed logical because the application of geobotany rests, in general, upon a background of information gained by the more rigorous biogeochemical operation. A brief discussion of mineral uptake by plants and morphological changes produced in some species as a result of abnormal mineral concentrations is considered useful here, as an introduction to the survey of information available on the subject.

V. M. Goldschmidt (1937), in a discussion of the geochemical nature of the earth, grouped the chemical elements according to their behavior with respect to low oxygen and sulfur affinity ("siderophiles"), high sulfur affinity ("chalcophiles"), and enrichment in the silicate crust of the earth ("lithophiles"). Rankama and Sahama (1950, p. 88) further group the elements to indicate those which occur in the atmosphere and the biosphere. A modified form of the "Biophilic" array is shown as Fig. 5. Figure 6 presents the typical elements found in the lithosphere, and Fig. 7 shows those elements with relatively low sulfur and oxygen affinities (siderophiles) which are enriched in the nickel-iron core. Figure 8 indicates the chalcophilic elements which have a strong affinity for sulfur, while Fig. 9 shows elements which typically are found as atmospheric gases.

The distribution of the chemical elements into these groups is of interest from a biogeochemical prospecting standpoint, in that (1) the natural occurrence of elements of interest as metals (e.g., gold) or in combinations such as

Periodic Table of the Elements

Group	I	II				Transition	Elements			III	IV	V	VI	VII	0
Period						Mn	Fe	Co	Cu						
1	H 1*														
2										B 5	C 6*	N 7*	O 8*	F 9	
3	Na 11	Mg 12									Si 14	P 15*	S 16	Cl 17	
4	K 19	Ca 20				Mn 25	Fe 26	Co 27	Cu 29						
5														I 53	

*Indicates pronounced behavioral preference; unstarred elements are members of another group but show less pronounced affinity for the biosphere

Figure 5. Biophilic Elements

Group	I	II					Transition Elements					III	IV	V	VI	VII	0
Period																	
1	H 1																
2	Li 3	Be 4										B 5	C 6		O 8	F 9	
3	Na 11	Mg 12										Al 13	Si 14	P 15	S 16	Cl 17	
4	K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	
5	Rb 37	Sr 38	Y 39	Zr 40	Nb 41						Cd 48	In 49	Sn 50			I 53	
6	Cs 55	Ba 56	(a) 57-71	Hf 72	Ta 73	W 74						Tl 81	Pb 82				
7	Fr 87	Ra 88	(b) 89-														

a	La 57	Ce 58	Pr 59	Nd 60		Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
b	Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96							

Figure 6. Lithophilic Elements[1]

[1] These elements have a strong affinity for oxygen and are enriched in the lithosphere or silicate crust of the earth.

Group / Period	I	II	Transition elements						III	IV	V	VI	VII	0
1														
2										C 6				
3											P 15			
4					Fe 26	Co 27	Ni 28			Ge 32	As 33			
5			Mo 42		Ru 44	Rh 45	Pd 46			Sn 50				
6			W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79		Pb 82				

Figure 7. Siderophilic Elements[1]

Group / Period	I	II	Transition Elements						III	IV	V	VI	VII	0
1														
2														
3												S 16*		
4				Fe 26*	Co 27	Ni 28	Cu 29*	Zn 30*	Ga 31*	Ge 32	As 33*	Se 34*		
5			Mo 42	Ru 44		Pd 46	Ag 47*	Cd 48*	In 49*	Sn 50	Sb 51*	Te 52*		
6						Pt 78		Hg 80*	Tl 81*	Pb 82*	Bi 83*			

*Indicates pronounced behavioral preference; unstarred elements are members of another group but show less pronounced affinity for sulfur.

Figure 8. Chalcophilic Elements[2]

[1]These elements are particularly enriched in the nickel-iron core of the earth, and exhibit relatively weak affinity for oxygen and sulfur.
[2]These elements, with strong sulfur affinity, are enriched in the "chalcopheric," or sulfide-oxide shell.

Periodic Table of the Elements

Group	I	II			III	IV	V	VI	VII	0
Period										
1	H 1									He 2
2						C 6	N 7	O 8		Ne 10
3										Ar 18
			Transition Elements							
4										Kr 36
5									I 53	Xe 54
6				Hg 80						Rn 86

Figure 9. Atmophilic Elements*

sulfide ores (e.g., copper) affects the weathering properties, which in turn affects soils and plant growth, and (2) the absolute requirement by plants of some elements and rejection of others affects the survival of plants in the presence of the various groups of elements. The fact that many elements are more likely to be found in, for example, the iron-nickel core of the earth (siderophiles) than as surface weatherable ores (chalcophiles) leads to some distinction in the prospecting tools one would reasonable apply in searching for the elements of each group. The elements likely to have an effect on plants are logically those whose ores weather to form and change soils, and those essential to plant growth.

The inorganic mineral constituents of plants have been noted since antiquity, although quantitative investigation was first recorded in 1684 (J. F. Sutcliffe, 1962). In a study of total nutrient weight change in willow growth, Van Helmont

*These are elements which are enriched in the atmospheric envelope surrounding the earth.

noted a small change in soil weight, even though he did not pursue or elaborate on the finding. The work was reported by his son 40 years after the death of the investigator. The German chemist, Justus von Liebig, in 1840 published Die Chemie in ihrer Anwendung auf Agricultur und Physiologie, an important work in which strong arguments for the role of inorganic constituents in vegetation growth were presented. The experimental evidence with which he followed up his theory was largely instrumental in the general acceptance of the idea that plants use inorganic materials (Sutcliffe, loc cit, p. 2).

The continued study of the problem of plant nutrition has resulted in the evolution of a list of "essential" elements, without which plant growth cannot occur. The list given by Sutcliffe (p. 6) is shown in Table 5. In this list, macro-nutrients shown are those needed in fairly gross amounts, while micro-nutrients are needed only in trace quantities. Absence of sufficient quantities of any of these elements in a form usable by plants will result in visible symptoms of malnutrition. Symptoms may vary from yellow spots on leaves (chlorosis), to abnormal growth or total growth inhibition. Such deficiency disease indications are correctable in most cases by supplying the deficient nutrient. A discussion of nutrition and mechanisms is given in Mineral Nutrition of Plants, Emil Truog, Ed., University of Wisconsin Press (1961).

In addition to these generally essential nutrients, there are other elements which are beneficial to many plants and essential to specific plants. Notable among these are cobalt, silicon, sodium, vanadium, and selenium.

Inconclusive evidence has been offered as to the substitution of some of these for "essential" elements in plant growth. The presence of a particular element in plant (or animal) tissue does not necessarily indicate that a useful function is performed by that element.

For optimum plant growth, the essential elements must be available to the plants in a form soluble in water and in concentrations in rather definite ranges. Excessive amounts of an element--particularly of one of the micronutrients other than chlorine--results in symptoms of toxicity. The levels

TABLE 5

ESSENTIAL ELEMENTS OF PLANTS, AND MAJOR FORMS IN WHICH THEY ARE ABSORBED*

Macro-nutrients		Micro-nutrients	
Element	Form Absorbed	Element	Form Absorbed
Carbon	Carbon dioxide Bicarbonate	Boron Chlorine	Borates Chorides
Hydrogen	Water Various anions	Copper Iron Manganese	Cations Cations Cations Manganates
Oxygen	Water, gaseous oxygen Various anions	Molybdenum Zinc	Molybdates Cations
Nitrogen	Nitrate, ammonium		
Phosphorous	Phosphates		
Sulfur	Sulfates		
Potassium	Cations		
Calcium	Cations		
Magnesium	Cations		

*From Sutcliffe, Mineral Salts Absorption in Plants, Pergamon, N.Y. (1960)

of toxic concentrations vary with the elements and with the plants. The essential elements are, of course, used for protein protoplasm and other cell constituents, enzyme, and other regulatory structures. Magnesium has been found to be the only metallic constituent of chlorophylls, and is also important in enzymatic functions. Micro-nutrients are thought to be direct enzyme constituents or activation agents for enzymatic processes. Only the role of boron in plant growth has not been discovered. Interestingly, the minima and maxima of boron requirements for given plants are narrow and may overlap so that boron concentration for maximum plant growth may cause (simultaneously) boron toxicity symptoms to appear (Meyer and Anderson, 1952). A simplified picture of the absorption and movement of mineral salts by plants is shown in Fig. 10. This diagram grossly shows probable routes taken by nutrients, but necessarily ignores the complex and poorly understood mechanisms involved. Purely physical transport and purely chemical involvements have been postulated as mechanisms; the truth is undoubtedly a complicated combination of ion exchange, solvent exchange, cell membrane osmosis, diffusion, adsorption, and complexation processes, many occurring under far-from-equilibrium conditions. Since every organ of a plant is a complex system of cells, the mechanism of nutrient assimilation is a maze of processes which have been studied in many different systems from single organs to whole plants.

Since prospecting by definition is the seeking of amounts of elements greater than those generally found in the "average" location on the earth, the effects on plants of abnormally high nutrient concentrations is of particular interest.

The concentration of some elements by plants to levels significantly higher than the surrounding environments has been known since early workers used plants as potassium sources--hence, the name "pot-ash" given to some plant ashes. Plants which take up a particular element in quantities considerably greater than that in "normal" plants are called "<u>accumulator plants</u>." For example, iodine is accumulated by seaweed (laminaria digitata) to about 3000 parts iodine per million parts water from waters only about 1 part per million

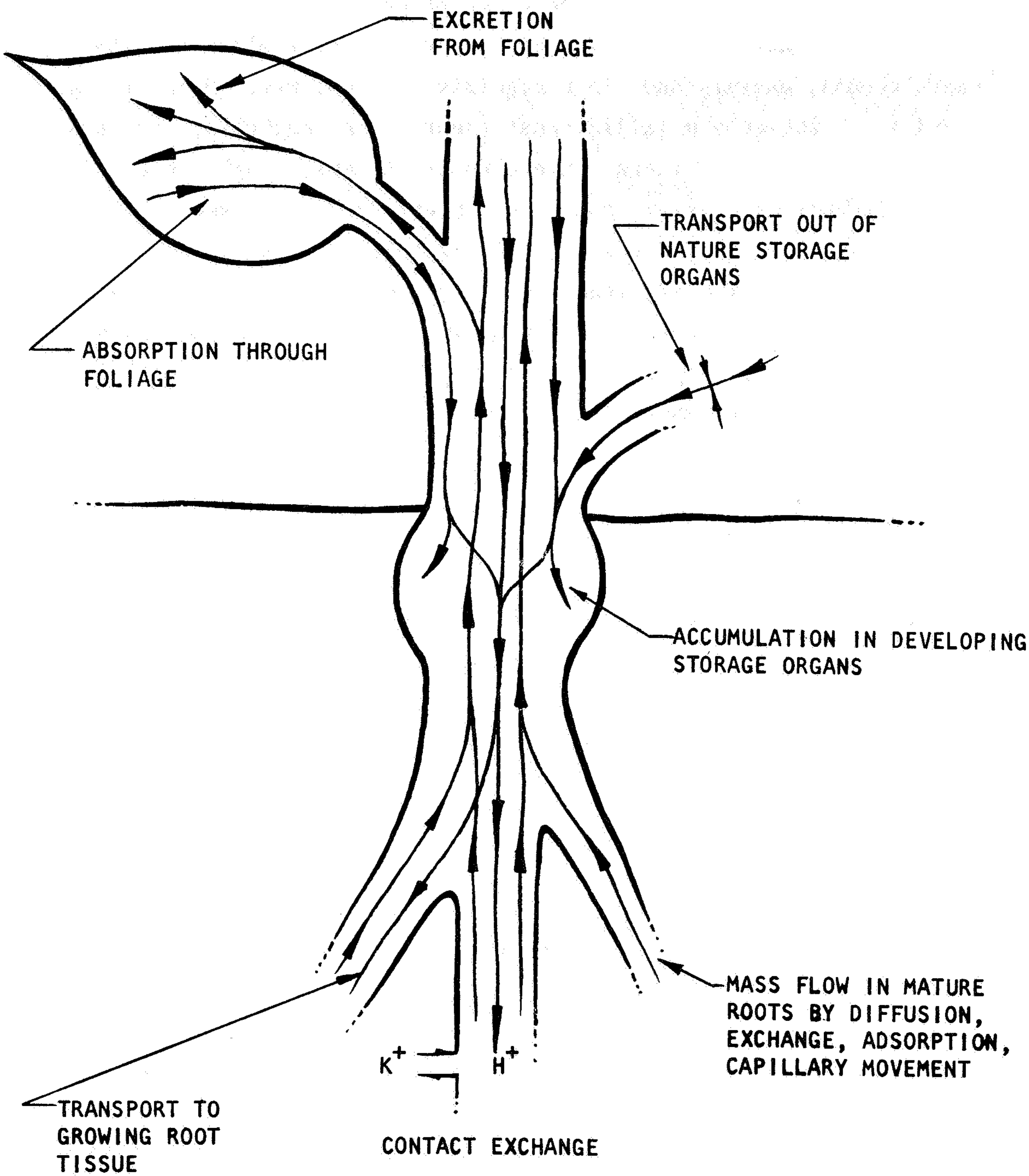

Figure 10. Mineral Salt Absorption in Vegetation*

*After Sutcliffe, p. 9 (1960).

iodine. The kelp source of iodine was noted in 1812 by Courtois (Sutcliffe, p. 6). The enrichment by plants of some mineral constituents was further demonstrated by Goldschmidt when certain coal ashes were found to have notable concentrations of germanium and, later, other elements, relative to average concentrations in the earth's crust (V. M. Goldschmidt, 1930, p. 398).

Physiological effects on plants of nutrient concentrations greater than can be used or tolerated by the plant have been studied and described by a rather large number of workers. W. Stiles (1961) discusses concentrations of elements singularly, and of pairs of elements whose relative concentrations were varied. Meyer and Anderson (1952) presented a concise discussion of nutritional roles of the essential elements in plant metabolism, along with symptoms arising from deficiencies and toxic excesses. Physiological effects of toxic mineral excesses on plants may appear as relatively transient, reversible changes in color or size or health, or as subtle or drastic mutations in form which are irreversible and pass to progeny.

Examination of the nutrient-flow diagram (Fig. 10) leads to several conclusions with respect to prospecting.

1. Availability of nutrients to rootlets in water soluble form is essential. Soils which are excessively acidic or basic (caustic) may cause formation of insoluble precipitates, such as hydroxides or anions of some metals (like zinc or molybdenum). Such precipitates render the metals insoluble in water, and may mechanically block the rootlets from all nutrient intake. In either case, retarded and/or abnormal growth may result.
2. Movement of nutrients tends toward actively growing cells, such as seeds, growing tips, new foliage, etc. Excessive quantities of nutrients above the optimum range for the specific plant involved also tend to be carried toward these areas. Such toxic levels may interfere chemically or physically with the metabolic processes essential to plant growth. Whatever the mechanism, the abnormalities may appear as altered, chlorotic leaves; stunted organs; abnormally sized or colored blossoms, and fruits or seeds.

In cases in which the plant's transport system has been unable to remove toxic amounts of nutrients, the extremities of leaves, blossoms, or fruits may carry away part of the excess when they depart from the plant. This phenomenon has several interesting results: the debris from such nutrient-loaded members will enrich the humus layer below and around the plant with the already excessive nutrient; any animal ingesting such plant members may suffer toxic symptoms from such nutrients. A classical example of the latter phenomenon is the appearance of selenium syndrome or "alkali disease" in cattle grazing in selenium-enriched areas of the Middle Western United States. This phenomenon, blamed originally on alkali in waters drunk by grazing animals, manifested itself in a variety of symptoms. These ranged from loss of hair and development of abnormal hooves, to emaciation, listlessness, and death. Internal organs such as heart, liver, and kidney were found to carry lesions. Poultry which were feeding on toxic plants laid eggs which failed to hatch. Study of this problem revealed that several classes of plants found only on seleniferous soils concentrated selenium in extraordinary amounts; <u>Astragalus bisulcatus</u>, <u>A. racemosus</u>, <u>A. pectinatus</u>, <u>Stanleya pinnata</u>, <u>S. bipinnata</u>, <u>Appolpappus fremonti</u>, and <u>Xylorrhiza parryi</u>. Plants found to absorb selenium, but also to occur without selenium, were common cereals, wheat, rye, barley, and corn, and several types of flowers. Accumulation of vanadium by plants which are later eaten by people is of health interest. Vanadium has been found to decrease dental caries in children, and to inhibit the biosynthesis of cholesterol in man (Cannon, 1963). These dramatic findings , while rather extreme, are not unique and illustrate the possible results of peculiarities in metabolic habits of certain plants (W. Stiles, 1961). The extraordinary effects of toxic food plants on animals which ingested them demonstrate the inseparable interrelationship between diverse members of the biosphere and the constituents of its environment.

The physiological characteristics of individual plants are of utmost importance in the overall biogeochemical scheme. Depth of root, and plant growth rate and habit determine the usefulness of the plant for prospecting. An example of the importance of root structure is given in Fig. 11, which shows the relationship between root habits of several types of plants

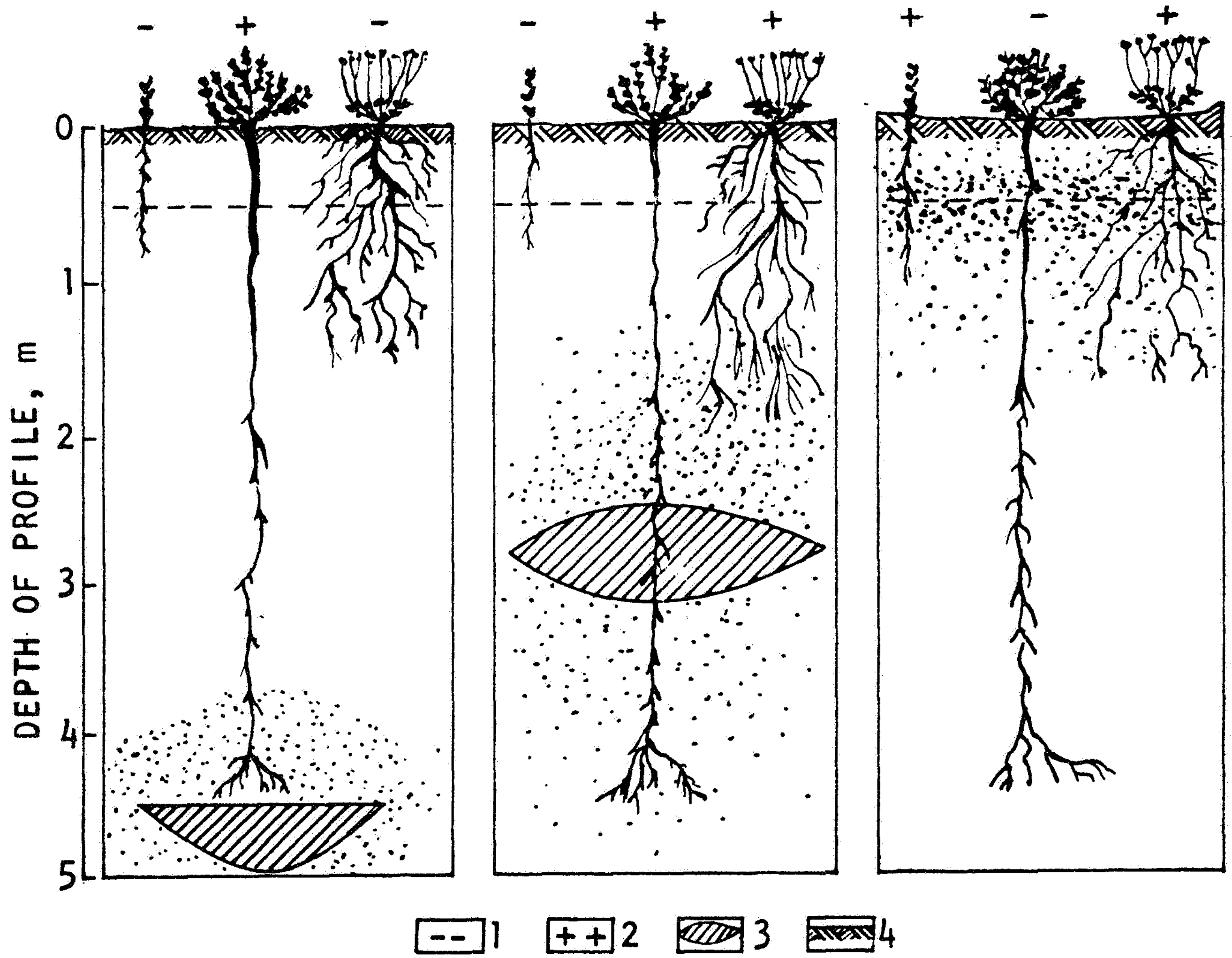

Figure 11. Diagram of Plant Indication of Boron, Dependent on the Structure of Root Systems (1) background content of boron in plant; (2) high boron content in plant; (3) horizons enriched with boron; (4) soil.

*Reference: Malyuga, Biogeochemical Methods of Prospecting, Consultants Bureau, p. 24, (1963).

and a boron enrichment in the soil. By knowing the depth of root systems, it is possible to locate and outline the size and even depth of the ore body which contributes metals to plants growing above it. The principle applies to other metals, as well as to boron.

BIOGEOCHEMICAL THEORY

As defined previously, biogeochemical prospecting includes the identification and chemical analysis of vegetation species. The related technique of using the physical appearance or conspicuous presence or absence of plants is geobotanical prospecting. These two techniques and the pertinent literature will be discussed separately in this survey. There may be overlap in the discussions because plant sampling teams may have specifically noted geobotanical details in the process of taking samples, and geobotanical details in many cases may have been shown to be valid prospecting tools by plant analyses. The geobotanical information is of particular interest in making aerial observation techniques applicable to locating new promising prospecting areas. Plant sampling and analysis techniques are discussed in detail in the literature survey section below.

The theoretical basis for prospecting methods involving plants was outlined in flow-sheet form by Fortescue and Hornbrook (Fig. 12). In the flow sheet, the terminology and pertinent relationships are clearly evident and self-explanatory. Specific examples of the types of toxic effects arising from mineralization of soils are of interest, however. The toxic effects vary from morphological changes in the plant to complete debilitation resulting in bare soil areas devoid of vegetation. Sparseness or total lack of vegetation has been successfully used as a geobotanical prospecting tool in locating soils containing toxic amounts of metals. This "negative indication" was used, for example, in the location of soils in the Congo containing 8 to 14 percent copper in shrub-and-grass covered glades within generally tree-forested areas (Helen L. Cannon, 1960).

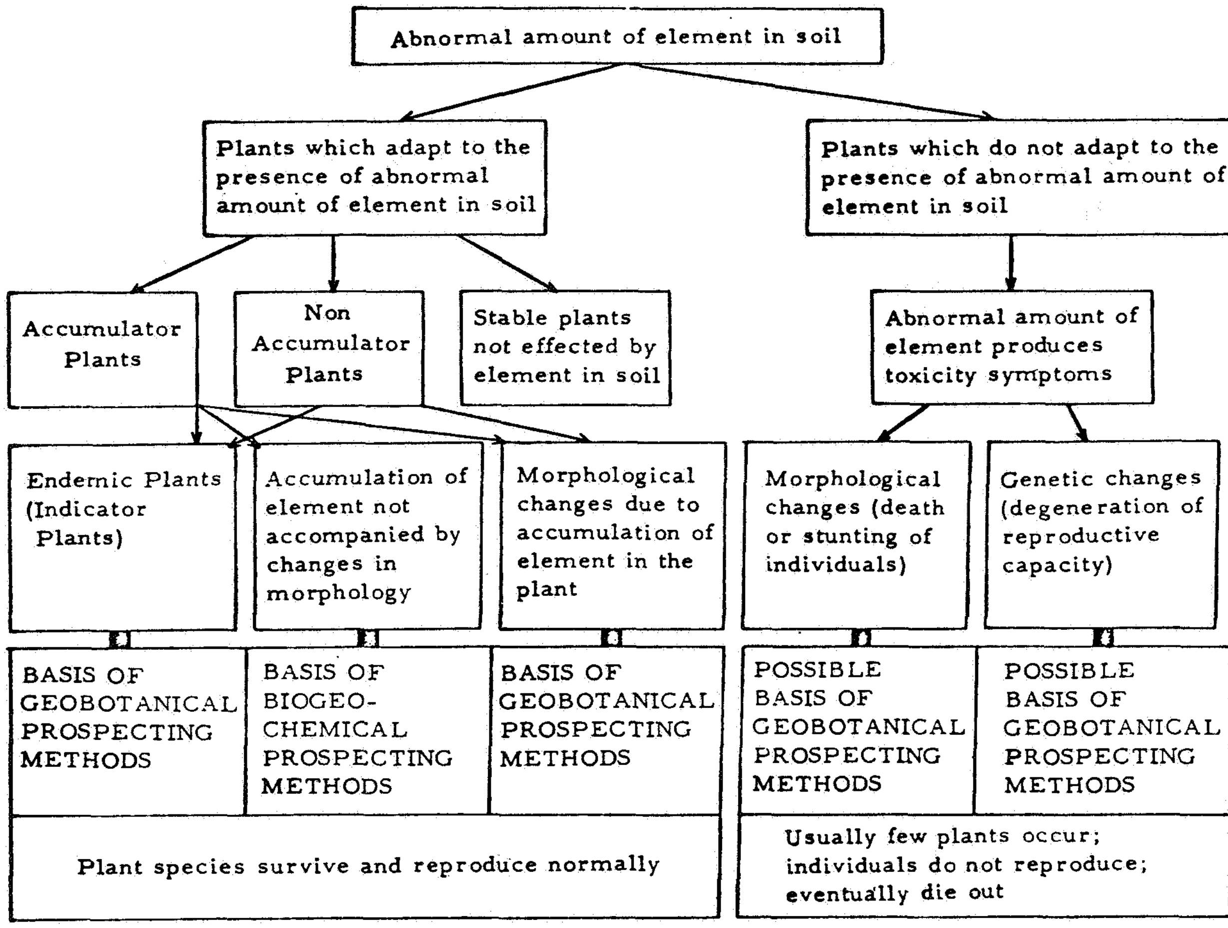

Figure 12. Flow Sheet Showing the Possible Effect of Abnormally High Amounts of an Element in Soil on Individuals of Species of a Plant Community (After Korvalsky and Petrunina, 1965).*

"Indicator plants" are those whose distribution is related to the chemical components of a mineral enrichment. "Universal" indicators always indicate the presence of a specific element, while "local" indicators only act as mineral signals in a particular district. Aside from specific-element indicators, there are some plants which are able to survive in high concentrations of various minerals under conditions too toxic for most other species. These plants are also useful in prospecting even though they are not specific. Universal indicators are plants whose metabolism requires the specific element or combination of elements to which it is related.

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*Reference: Fortescue, J. A. C. and E. H. W. Hornbrook, Geological Survey of Canada, paper 67-73, Progress Report on Biogeochemical Research at the Geological Survey of Canada 1963-1966 (1967).

Morphological changes and indications of physiological disorders have been studied as prospecting tools, notably by Cannon and others in the United States, teams of workers in the USSR (Malyuga, Chikishev, and others), and Warren, Delavault, Fortescue, Hornbrook and others in Canada. The symptoms exhibited by plants as a result of mineralization include (1) dwarfing; (2) gigantism; (3) variations in development cycle completion, growth, and flowering cycles; and (4) changes in form, sterility, and coloration (mutation).

1. The dwarfing of plants, while often due to deficiencies, may occur when toxic amounts of some metals are present. Since growth of vegetation is regulated by plant auxins (plant hormones), the mechanism of interference by metals with plant growth is probably one of interference with specific enzymes necessary in the sequences of auxin synthesis in the plant. Auxins are both synthesized and inactivated in plant cells, so that any agent which could bind or destroy auxin molecules could cause dwarfing or even death of plants. Similarly, since temperature is an important factor in auxin formation, abnormal amounts of metal ions in cell fluids might cause changes in the characteristic heat absorption properties of the plant, hence alterations in patterns of auxin formation.

2. Gigantism, or abnormally large, lush growth relative to surrounding "normal" plants, may reflect a more favorable chemical nutrient balance than that available to neighboring plants (which may have deficiencies). It also may reflect abnormal enzymatic activation by metals absorbed, resulting in plant auxin abnormalities. Since plant auxins, and the enzymes essential to their formation, are important in all phases of growth such as fruiting, flowering, etc., any chemical alteration of auxin formation rates may affect any or all development stages of plants. The super-colossal growths of plants described in science fiction writings for years have been attributed to climatic or peculiar chemical causes essential to the plot of the fiction. Such fictions are only exaggerations of actual, recorded effects of climate and mineral environments on plant growths.

3. Variations in development cycles of plants as a result of mineralization of the soil is perhaps best seen in areas in which both "normal" and mineral-affected plants are growing. Growth acceleration and early fruiting of herbaceous plants have been described as a result of toxic amounts of uranium and vanadium being supplied to plants near uranium-vanadium deposits. Molybdenum or selenium may also produce such results (Cannon, 1960).

In a private communication, Mrs. Cannon mentioned her observation that aspen leaves in the areas adjacent to the mines in the Central City district of Colorado seem to turn color in the fall before those farther removed from the mines. As she points out in her reports on work in the Colorado Plateau, altitude and latitude also affect bloom times and dormant times of vegetation, so that use of variations in development cycles for prospecting is valid only for relatively small areas.

4. Mutation and specific morphological alterations of plants as a result of inorganic salt absorption include the changes shown in Table 6. Aside from abnormal size, physiological features such as foliage color, blossom color, shape of plant or plant members, and fruit shape are the types of alterations noted. Other effects have been noted on plants from radioactive uranium-vanadium deposits on the Colorado Plateau besides stunted growth and fruiting habits: chlorosis, "thin and fragmented roots, which contain a yellow deposit;" and abnormal flowers without stamens and petals on portions of flower spikes (Cannon, loc cit).

Mutation of plants as a result of inorganic salt absorption has been attributed to chromosome breaks and rearrangements in the cells. It has been postulated that genetic effects of inorganic salts are due to the creation of abnormal cellular conditions favorable to chromosome breaks, rather than a direct reaction with deoxyribonucleic acid, commonly called DNA (Aerbach, 1967). Any of the cellular life processes (repair mechanisms, propagation, growth) may be altered by incorporation of metallic constituents abnormal in character or concentration with respect to cellular structure.

TABLE 6

PHYSIOLOGICAL AND MORPHOLOGICAL CHANGES IN PLANTS DUE TO METAL TOXICITIES*

Element	Effect
Aluminum	Stubby roots, leaf scorch, mottling
Boron	Dark follage; marginal scorch of older leaves of high concentrations; stunted, deformed, shortened internodes; creeping forms; heavy pubesence; increased gall production
Chromium	Yellow leaves with green veins
Cobalt	White dead patches on leaves
Copper	Dead patches on lower leaves from tips; purple stems, chlorotic leaves with green veins, stunted roots, creeping sterile forms in some species
Iron	Stunted tops, thickened roots; cell division disturbed in algae, resulting cells greatly enlarged
Manganese	Chlorotic leaves, stem and petiole lesions, curling and dead areas on leaf margins, distortion of laminae
Molybdenum	Stunting, yellow-orange coloration
Nickel	White dead patches on leaves, apetalous sterile forms
Uranium	Abnormal number of chromosomes in nuclei; unusually shaped fruits; sterile apetalous forms, stalked leaf rosette
Zinc	Chlorotic leaves with green veins, white dwarfed forms; dead areas on leaf tips; roots stunted

The alteration of flowers, in color or habit, has been found to be directly related to mineral anomalies. Such relationships as prospecting tools are discussed below in surveying the subject. It is noteworthy here to mention some of the variety of changes which occur. The color of hydrangea blooms (Hydrangea macrophylla)

*From H. L. Cannon, (1960)

has been found to be related to the aluminum content of the floral tissue; blue flowers always contain more aluminum than pink flowers. The color shift from pink to blue can be induced by treatment of plants with soluble aluminum compounds (Allen, 1943).

Changes in blossom habits are mentioned by Malyuga (loc cit p. 11) in poppy plants subjected to molybdenum-copper and other enrichments. Such blossom alterations are, of course, only evident during the flowering season.

Abnormal concentrations of metals such as nickel, copper, cobalt, chromium, zinc, and manganese may interfere with the assimilation or utilization of essential nutrients by plants. Yellowing of leaves or spotting with dead tissue is evidence of such interference. Copper has caused the development of a creeping sterile form of a plant (Protea goetzeana) in Katanga. Use of morphological or physiological changes for prospecting may require the "ability to distinguish genetic changes in otherwise normal species or merely to recognize variations in color, size, or shape" (Cannon, 1960).

Specific examples of accumulator plants, their analysis, indicator plants, and mineral-related morphological changes are given in the following survey of the literature on biogeochemical prospecting. The survey is intended to include some examples of each of the relationships discussed above.

SURVEY OF BIOGEOCHEMICAL PROSPECTING LITERATURE

Information about efforts in the field of biogeochemical prospecting (including geobotany) was gleaned from many sources. Those cited in the following discussion are among the most prominent found in the search of the literature. Although some of more recent prominence may have been overlooked, most of the major efforts appearing in print have been examined and are mentioned here.

The literature survey has been divided rather arbitrarily into the areas of geobotany and biogeochemistry, mostly because of convenience in presenting the data. For the most part, U.S. Geological Survey Abstracts, NASA, Department of Defense, chemical, and geological literature served as sources, supplemented by personal communications with prominent workers in the various related fields.

The problem of selecting a field method for mineral searching may determine the success or failure of the investigation (Warren et al, 1952). The methods selected as most practical for a particular exploration program are determined by the landscape conditions and the type of deposit sought. It should be noted that biogeochemical techniques in general may have an optimum field season for application, depending upon the climate of the area of interest. In practice, the application of biogeochemical techniques, although it may sound involved and fraught with conditions and reservations, is probably no more complicated than the selection of a conventional geophysical technique (Warren et al, loc cit). Figure 13 shows an expanded diagram illustrating the components of a landscape system that may be examined during a methods research for prospecting. The landscape components which can be selected for examination by various available prospecting methods are given to show the range of possible choices. Specialized exploration methods currently used for prospecting in Canada are also shown. The particular landscape investigated, its topography, and the climate, should all be evaluated for judicious selection of the prospecting approach to be applied.

GEOPHYSICAL METHODS OF EXPLORATION

AIRBORNE METHODS

REMOTE SENSING

PHOTOGRAPHY

MAGNETICS

ELECTROMAGNETICS

RADIOACTIVITY

GROUND METHODS

MAGNETICS

ELECTROMAGNETICS

INDUCED POLARIZATION

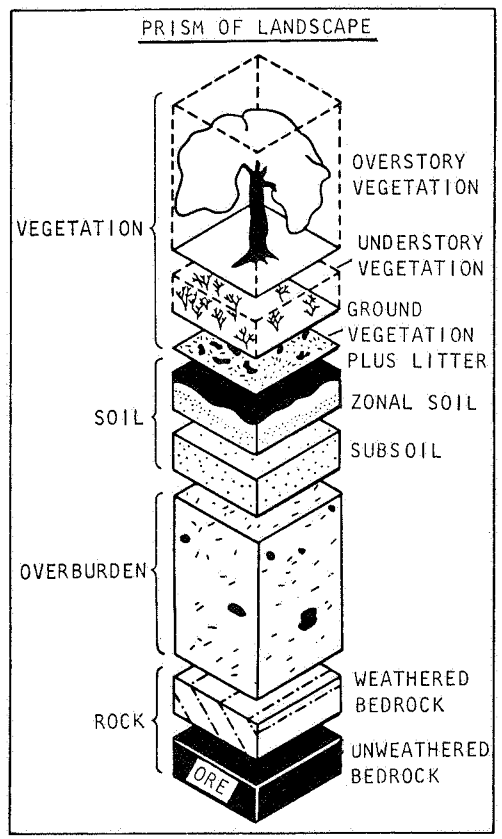
SELF POTENTIAL

GRAVITY

RESISTIVITY

SEISMIC

RADIOACTIVITY



GEOCHEMICAL METHODS OF EXPLORATION: GEOCHEMISTRY OF :

PLANT

SOIL

BOG

WATER

STREAM SEDIMENT

OVERBURDEN

ROCK

SPECIALIZED GEOLOGICAL METHODS OF EXPLORATION

HEAVY MINERAL ANALYSIS

BOULDER TRACING

DIAMOND-DRILLING

TRENCHING

EXPLORATORY MINING

Figure 13. Diagram of Generalized Prospecting Prism Showing Different Components of Landscape System Involved in Prospecting Methods Research; and Specialized Geological, Geophysical, and Geochemical Methods Currently Used for Prospecting in Canada.*

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*Fortescue, J. A. C. and E. H. W. Hornbrook, Geological Survey of Canada, Paper 67-23 Part I Progress Report on Biogeochemical Research at The Geological Survey of Canada, 1963-1966.

Geologists skilled in the recognition of rock types generally associated with ore deposits approach the problem through identification of rock types, age, weathering, etc. But since the geological features are often obscured by vegetation, the use of plants--consciously or intuitively--to delineate geological structures has long been practiced as an extremely useful aid. Although few geologists are botanically knowledgeable, simple observations may suffice. The distribution of vegetation gives clues as to the chemistry of the rocks, because extraordinary chemical assemblages in rocks very likely will have unusual vegetation associated with them or none at all. The association of plant species with particular rock or soil types is used in mapping rock outcrops. This is particularly useful in arid regions of alkaline soil in which little or no chemical weathering occurs to cause differentiation between soils and the rocks from which they were derived. In cases in which outlines of geologic formations are shown by plant species variations, the delineation may be visible in aerial photographs.

The aerial surveillance tools becoming available, such as orbital observation techniques and highly sophisticated lower-altitude photography, can be expected to make easier the logical selection of prospecting techniques to be applied to various areas (H. Cannon, unpublished communication).

The following survey of the biogeochemical prospecting technique includes as specific topics: (1) Plant Sampling and Analysis, and (2) Geobotany.

PLANT SAMPLING AND ANALYSIS

Prospecting based on the analysis of plants for metal content has been used more widely than other techniques involving plants (Cannon, 1960). United States Patent No. 2,158,980 was issued in May, 1939, to Brundin of Romford, England, for a "Method of Locating Metals and Minerals in the Ground." The method described involves the taking of vegetation of the same species at regular intervals along lines distributed over the area under investigation. The patent also mentioned that samples from the humus layer may be taken in addition to or instead of plant samples. The samples are ashed and the ashes analyzed spectrographically. The analytical results are plotted in a map of the sampled area to delineate regions in which the metal is in greatest concentration. The rudiments of this procedure have been elaborated by many practitioners since the late 1930's, to improve the techniques of sampling and clarify results with respect to meaningful metal concentrations in plants.

Absorption by plants of metals in some water-soluble form from the soil has been discussed briefly above, and others have reviewed and discussed the subject. The metals absorbed may be those which are necessary or useful, or may be of no discernable benefit to the plant. In some cases, amounts of metal in a plant may be much larger than those ordinarily found in that plant or in other species, and this may be related to extraordinarily high concentrations of metal in the soil from which the plant derives nutrients. As stated above, plants taking up quantities of metals much larger than "normal" plants are called "accumulators."

For prospecting purposes, however, extraordinary accumulation is not as critical as was once regarded, because increasingly sensitive analytical techniques are becoming available. Such accumulation may not be even useful, since relative abundance of elements in the soil may not be accurately reflected by accumulation in plants. This circumstance can arise if an element is actively accumulated by plants from soils which may have even less than "average" abundance of that element. Zinc, for example, has been commonly found in dwarf birch (growing over unmineralized soil) to be 1 percent of twig ash, while normal soils contain about 100 parts per million zinc (Hawkes, 1957). The response of plants to variations in zinc contents of soils may be confused by factors such as sunlight and drainage, which are unrelated to mineralization. A comparison is shown in Table 7 of plant analyses collected by Cannon (1960) from the literature of U.S. Geological Survey data, with concentrations of some of the same elements in specific types of vegetation.

TABLE 7

AVERAGE METAL CONTENT IN ASH OF VEGETATION GROWING

IN UNMINERALIZED GROUND*

Element	Metal Content, ppm			Deciduous		
	Average of More Than 100 Species of Plants	Grasses (Above Ground)	Herbs (Above Ground)	Shrubs (Leaves)	Trees (Leaves)	Conifers (Needles)
Al	8610					
Fe	6740					
Mn	4815					
Zn	1400	850	666	1585	2303	1127
B	700					
Cu	183	119	118	223	249	133
Pb	70	33	44	85	54	75
Ni	65	54	33	91	87	57
V	22	25	23	25	16	21
Mo	13	34	19	15	7	5
Cr	9	19	10	14	5	8
Co	9	10	11	10	5	7
Sn	5					
Be	2					
Ag	1					
U	0.6					
Au	0.007					

*Data from H. L. Cannon, Science 132 (1960).

Another interesting comparison is that of metals content of plants with those of soils and of the lithosphere as shown in Table 8. This list presents a larger proportion of the elements found in the earth, expressed in percent because of the wide diversities in the orders of magnitude of the concentrations. The data for plant metal contents in Tables 7 and 8, while not identical, show that averages taken from a variety of sources are reasonably comparable.

Species of plants which are generally most meaningful for sampling for prospecting have these properties: deep root systems; general, common occurrence; and fairly constant correlation between composition of plant and soil. Absolute values of metal content in a plant are not, in general, as useful for showing mineral enrichment in the supporting medium as the accumulation ratio.

$$\text{Accumulation ratio} = \frac{\text{metal content of plant growing over ore}}{\text{metal content of same plant over nonmineralized ground}}$$

The structure and acidity of the soil, the ion-exchange properties of the soil, and the metabolic characteristics of the plant affect the accumulation ratio. The properties of the element being sought, plant distributions, and root characteristics must be considered in selecting a plant for prospect sampling. The data in Table 7, showing variations in metallic constituents of plants growing over unmineralized ground, points up the value of the accumulation ratio concept.

Variations in plants due to soil acidity, drainage, and sunlight from one area to another may be minimized by determining, and mapping on the sampling map, the ratio of two different elements in a given plant species. The ratio of copper to zinc is cited as an example by H. W. Hawkes (1957) to show the application of this technique to these elements of which the ratio in plants is fairly constant despite variations of absolute quantities. A copper mineralization in the supporting medium would be indicated by a high copper-to-zinc ratio, while an unusually low ratio would indicate zinc mineralization (Cannon, 1960).

TABLE 8

MEAN CONTENT OF CHEMICAL ELEMENTS IN ROCKS, SOILS, AND SURFACE PLANTS (IN PERCENT)*

Element	Lithosphere	Soil	Plant (In Ash)	Element	Lithosphere	Soil	Plant (In Ash)
Li	6.5×10^{-3}	3×10^{-3}	1.1×10^{-3}	Zn	5×10^{-3}	5×10^{-3}	9×10^{-2}
Be	6×10^{-4}	6×10^{-4}	2×10^{-4}	As	5×10^{-4}	5×10^{-4}	3×10^{-3}
B	6×10^{-4}	1×10^{-3}	4×10^{-2}	Se	6×10^{-3}	1×10^{-6}	--
F	2.7×10^{-2}	2×10^{-2}	1×10^{-3}	Br	1.6×10^{-4}	5×10^{-4}	1.5×10^{-2}
Na	2.64	0.63	2	Rb	3.1×10^{-2}	6×10^{-3}	1×10^{-2}
Mg	2.10	0.63	7	Sr	4×10^{-2}	3×10^{-2}	3×10^{-2}
Al	8.80	7.13	1.40	Zr	2×10^{-2}	3×10^{-2}	--
Si	27.60	33	15	Mo	3×10^{-4}	2×10^{-4}	2×10^{-3}
P	8×10^{-2}	8×10^{-2}	7	Ag	1×10^{-3}	$\eta \times 10^{-5}$	1×10^{-4}
S	9×10^{-2}	8.5×10^{-2}	5	Cd	5×10^{-5}	5×10^{-5}	1×10^{-6}
Cl	4.5×10^{-2}	1×10^{-2}	$\eta \times 10^{-2}$	Sn	4×10^{-3}	1×10^{-3}	5×10^{-4}
K	2.60	1.36	3	I	3×10^{-5}	5×10^{-4}	5×10^{-3}
Ca	3.60	1.37	3	Cs	7×10^{-4}	5×10^{-4}	$\eta \times 10^{-4}$
Ti	6×10^{-1}	4.60×10^{-1}	1×10^{-1}	Ba	5×10^{-2}	5×10^{-2}	$\eta \times 10^{-2}$
V	1.5×10^{-2}	1×10^{-2}	6.1×10^{-3}	Au	5×10^{-7}	--	1×10^{-4}
Cr	2×10^{-2}	2×10^{-2}	2.5×10^{-2}	Hg	7×10^{-6}	1×10^{-6}	1×10^{-7}
Mn	9×10^{-2}	8.5×10^{-2}	7.5×10^{-1}	Pb	1.6×10^{-3}	1×10^{-3}	1.10×10^{-3}
Fe	5	3.80	1	Ra	1×10^{-10}	8×10^{-11}	2×10^{-11}
Co	1×10^{-3}	1×10^{-3}	1.5×10^{-3}	Th	8×10^{-4}	6×10^{-4}	--
Ni	6×10^{-3}	4×10^{-3}	5×10^{-3}	U	3×10^{-4}	1×10^{-4}	5×10^{-5}
Cu	1×10^{-2}	2×10^{-3}	2×10^{-2}				

*After Vinogradov, A. P.: Geochemistry of Rare and Dispersed Chemical Elements in Soils, Moscoe, Izd-vo Akad. Nauk SSSR (1950).

The problem of sparity of available plants for uniform sampling frequency of a given species has been circumvented by still another "ratio" technique. The sampling of two species in one area to avoid sampling gaps was applied successfully by E. E. Roberts (1949). In a search for barite deposits, soil and/or plant analyses were performed in five areas. Two plant species were sampled and analyzed because of irregular plant distribution over the area of interest. The plant analysis data obtained for both plants growing close together was scrutinized, and a conversion factor was derived for relating the metal content of one plant to that of the other. In this manner, the barium content of the two species was plotted as if only one species had been sampled. In the study cited, live oak and whiteleaf manzanita were sampled at one known barite deposit, and Douglas fir and whiteleaf manzanita at another deposit. By expressing the barium analyses of the oak and fir samples in terms of the manzanita, the results could be simplified and plotted as if only manzanita had been sampled. Variation in the barium contents of the plants analyzed did correlate with barium levels in the soil samples.

Plants which have been used successfully in biogeochemical studies, or which look promising from agricultural data, are presented in Table 9. A few indicator plants are included with these accumulator plants. It will be noted that the list includes primarily trees. The data was compiled from various published and unpublished sources, and presented by D. Carlisle and G. B. Cleveland (1958).

Preliminary sampling and analysis of an area should precede any extensive sampling program to minimize the effort necessary to acquire meaningful data. This preliminary screening should enable the investigator to select the one or several species of plants most useful in the particular area under study.

Sampling

The selection of plant samples for prospecting involves several significant variables besides that of the species having most useful root depth, etc.

TABLE 9

SAMPLER PLANTS FOR BIOGEOCHEMICAL PROSPECTING

Plant Name		Metal Detected																					
Common	Scientific	Cu	Zn	Al	Se	Hg	Ge	Fe	Au	B	U	Mn	Ni	Mo	Ag	Sn	W	V	Sr	Co	Mg	Ba	Pb	RE*
Green alder................	Alnus sinuata................	X	X					X				X												
Willow.....................	Salix sp.	X	X							X		X												
Scrub oak..................	Quercus tubinella............	X																						
Emery oak..................	Quercus emoryi...............	X																						
Mountain mahogany..........	Cercocarpus ledifolius.......		X																					
Mountain hemlock...........	Tsuga mertensiana............	X	X																					
Balsam fir.................	Abies amabilis...............	X	X																					
Giant cedar................	Thuya plicata................		X																					
Lodgepole pine.............	Piaus contorta...............	X	X					X	X	X		X			X									
Black cottonwood...........	Populus trichocarpa..........	X	X					X		X		X												
Larch......................	Larix occidentalis...........	X	X							X		X												
Aspen......................	Populus tremuloides..........	X	X					X	X	X		X			X									
Soolpolallie...............	Shepherdia canadensis........		X							X		X												
Douglas fir................	Pseudotsuga taxifolia........	X	X					X	X			X			X									
Western red cedar..........	Thuja plicata................	X	X					X				X												
Western hemlock............	Tsuga heterophylla...........	X	X					X				X												
Rocky mountain juniper.....	Juniperus scopularum.........	X	X																					
Juniper....................	Juniperus sp.							X			X	X												
Pinyon pine................	Pinus monophylla.............										X													
Ponderosa pine.............	Pinus ponderosa..............	X	X					X				X			X									
White bark pine............	Pinus albicaulis.............	X	X																					
Englemann spruce...........	Picea engelmanni.............	X	X					X				X												
Sitka spruce...............	Picea sitchensis.............	X	X																					
White spruce...............	Picea glacua.................	X	X					X				X												
Dwarf juniper..............	Juniperus communis...........	X	X						X						X									
Rocky mountain fir.........	Abies lasiocarpa.............	X	X						X						X									
Scrub birch................	Betula glandulosa............	X	X																					
Mountain birch.............	Betula occidentalis..........	X	X																					
Silver birch...............	Betula popyrifera............	X	X																					
Syringa orange.............	Philadelphus lewisii.........	X	X																					
Mountain maple.............	Acer glabrum.................	X	X					X				X												
Apple......................	....		X																					
Poplar.....................	Populus grandidintata........		X																					
Western red birch..........	Betula fontinalis............							X				X												
Grand fir..................	Abies grandis................							X				X												
Willow.....................	Salix scouleriana............							X				X												
Red alder..................	Alnus rubra..................							X				X												
Broad leaf maple...........	Acer macrophyllum............							X				X												
Vine maple.................	Acer circinatum..............							X				X												
Citrus.....................	....							X													X			
Choke cherry...............	Prunus demissa...............	X	X																					
Flowering dogwood..........	Cornus nuttallii.............							X				X												
Sumac......................	Rhus typhina.................		X																					
	Sassafras variifolium........		X																					
Soft maple.................	Acer saccharinum.............		X																					
Pignut.....................	Carya cordiformis............		X																					
	Carya ovalis obvalis.........		X																					
Hickory....................	Carya ovata..................		X																					
Flowering dogwood..........	Cornus florida...............		X																					
Black walnut...............	Juglans nigra................		X																					
Red cedar..................	Juniperus virginiana.........		X																					
Osage orange...............	Maclura pomifera.............		X																					
Sycamore...................	Platanus occidentalis........		X																					
Black cherry...............	Prunus serotina..............		X																					
White oak..................	Quercus alba.................		X																					
Red oak....................	Quercus borealis maximus.....		X																					
Bur oak....................	Quercus macrocarpa...........		X																					
Blackjack oak..............	Quercus marilandica..........		X																					
	Quercus muhlenbergii.........		X																					
Pin oak....................	Quercus palustris............		X																					
Post oak...................	Quercus stellata.............		X																					
Black oak..................	Quercus velutina.............		X																					
Sumac......................	Rhus copallina...............		X																					
Black locust...............	Robinia pseudoacacia.........		X																					
Nees.......................	Sassafras albidum............		X																					
Winged elm.................	Ulmus alata..................		X																					
American elm...............	Ulmus americana..............		X																					
Slippery elm...............	Ulmus fulva..................		X																					
Pine.......................	....																	X						
Hickory....................	....							X				X									X			X
Sugar maple................	Acer saccharum...............																						X	
Princess pine.......... ....| Lycopodium fabelliforme......			X																				
Pecan......................	....																							X
Brazil nut.................	....																					X		
Chestnut...................	....																							X
Oak........................	Quercus wislizeni............													X								X		
	Pseudotsuga douglasii........																					X		
	Afzelia africana.............		X												X								X	
	Rubiacaea sp.		X												X								X	
	Bahia nitida.................		X												X								X	
	Parinari curatellifolia......		X												X								X	
	Albizzia zygia...............		X												X								X	
	Lophira alata................		X												X								X	
	Vitex cuneata................		X												X								X	
	Parkia oliveri...............		X												X								X	
	Millettia sp.		X												X								X	
	Newbouldia lavis.............		X												X								X	
	Trichilia prievriana.........		X												X								X	
	Anacardiaceae sp.		X												X								X	
	Sp. indet....................		X												X								X	

*RE = rare earth.

TABLE 9

(Continued)

Plant Name		Metal Detected																						
Common	Scientific	Cu	Zn	Al	Se	Hg	Ge	Fe	Au	B	U	Mn	Ni	Mo	Ag	Sn	W	V	Sr	Co	Mg	Ba	Pb	RE*
Blue oak..................	Quercus douglasii...........													X										
Sagebrush.................	Artemisia tridentata........							X				X												
Salal.....................	Gaultheria shallon..........							X				X												
Red huckleberry...........	Vaccinium parvifolium.......							X				X												
Kinnikinnick..............	Arctostaphylos uva-ursa......							X				X												
False box.................	Pachystima myrsinites.......							X				X												
Hazel.....................	Corylus californica..........							X				X												
Blueberry.................	Vaccinium sp.	X	X																					
Devil's club..............	Echinopanax horridus........	X	X																					
Bracken...................	Pteridium aquilinum.........	X	X																					
Ocean spray...............	Holodiscus discolor.........	X	X																					
Mesquite..................	Prosopis juliflora...........	X																						
Milkvetch.................	Astragalus sp.				X																			
Indian ricegrass..........	Oryzopsis hymenoides.........				X																			
Shadscale.................	Atriplex confertifolia.......				X																			
	Vaccinium vitis idaea.......	X	X										X											
	Ledum palustre..............	X	X										X											
Horsetails................	Equisetum sp.								X						X									
	Vaccinium ovalifolium.......	X	X																					
Wax berry.................	Symphoricarpos racemosus.....	X	X																					
Sagebrush...	Artemisia trifida............	X	X																					
Violet....................	Viola calaminaria**..........		X																					
	Thlaspi calaminaria**........		X																					
	Amorphia canascens**........																						X	
Violet....................	Viola tricolor**............		X																					
	Thlaspi alpestre**..........		X																					
	Asparagus officinalis........		X																					
Butter and eggs...........	Linaria vulgaris............		X																					
Red clover................	....		X																					
Corn......................	Zea mays....................		X																					
	Euphorbia masculata.........		X																					
Golden rod................	Solidago sp.		X																					
Horsetail.................	Equisetum arvense...........		X																					
	Lobelia inflata.............		X																					
	Lobelia syphillitica........		X																					
Plantain..................	Plantago lanciolata..........		X																					
	Pycnanthemum flexuosa..		X																					
Ragweed...................	Ambrosia artemisiifolia......		X																					
Shad bush.................	Amelanchier canadensia......		X																					
Solomon seal..............	Smilacina racemosa..........		X																					
	Tomanthera auriculata........		X																					
Violet....................	Viola sagittata.............		X																					
Wild carrot...............	Daucus carota...............		X																					
Yarrow....................	Achillea millefolium.........		X																					
Ground cherry.............	Physalis sp.		X																					
Hackberry.................	Celtis occidentalis....... ..		X																					
Smart weed................	Persicaria hydropiper........		X																					
Ragweed...................	Ambrosia coronopifolia.......		X																					
Ragweed...................	Ambrosia elatior............		X																					
Giant ragweed.............	Ambrosia trifida............		X																					
Big bluestem..............	Andropogon furcatus..........		X																					
Little bluestem...........	Andropogon scoparius........		X																					
Dogbane...................	Apocynum sibiricum..........		X																					
Cudweed.	Gnaphalium obtusifolium		X																					
Sunflower.................	Helianthus mollis...........		X																					
	Liatrus aspera..............		X																					
	Desmodium sessilifolium......		X																					
Pokeweed..................	Phytolacca decandra..........		X																					
	Salvia pitcheri.............		X																					
Indian grass..............	Sorghastrum nutans...........		X																					
Buckbush..................	Symphoricarpos orbiculatus...		X																					
	Tridens flavis..............		X																					
Ironweed..................	Vernonia interior............		X																					
Saskatoon.................	Amelanchier alnifolia........	X	X																					
Clover....................	....																	X						
Beets.....................	....																	X						
Beans.....................	....																	X						
	Calluna rulgaris.............															X								
Sweet leaf................	....			X																				
Club moss.................	....			X																				
Meadow beauty.............	....			X																				
Shortia...................	....			X																				
Galax.....................	....			X																				
White clover..............	....																			X				
Sweet clover..............	....									X														
	Polycarpia spirostyles.......	X																						
	Thymus serpyllum............	X																						
Violet....................	Viola hirto.................	X																						
Tobacco...................	....											X												
Woody aster...............	....													X										
Devil's paint brush.......	....													X										
Chick pea.................	....													X										
	Astragalus racemosus.........				X																			
	Oonopsis condensata..........				X																			
Two grooved poisonvetch ...	Astragalus bisulcatus........				X																			
	Xylorhiza parri..............				X																			
	Astragalus pectinatus........				X																			
	Astragalus grayii............				X																			
	Aplopappus fromantii.........				X																			

*RE = rare earth.
**Denotes plants also used as indicators.

TABLE 9

(Concluded)

Plant Name		Metal Detected																						
Common	Scientific	Cu	Zn	Al	Se	Hg	Ge	Fe	Au	B	U	Mn	Ni	Mo	Ag	Sn	W	V	Sr	Co	Mg	Ba	Pb	RE*
	Stanleya pinnata.............				X																			
	Gutierrezia sarothrae........				X																			
Dandelion..................	....	X																						
	Arctostaphylos viscida.......																					X		
	Adenostoma fasciculatum......																					X		
	Vivia americana..............													X										
	Medicagohispida..............													X										
	Lotus corniculatus...........													X										
	Trifolium repens.............													X										
	Trifolium fragiferum.........													X										
	Trifolium subterraneum.......													X										
	Melilotus alba...............													X										
	Melilotus indica.............													X										
	Melilotus sativa.............													X										
	Triticum vulgare.............													X										
	Avena sativa.................													X										
	Hordeum vulgare..............													X										
	Chloris gayana...............													X										
	Lolium perenne...............													X										
Rothrock gramma grass......	Bautiloua rothrockii**.......	X																						
California poppy...........	Eschscholtzia mexicana**.....	X																						
	Holostium umbellatum.........					X																		
	Viscaria alpina**............	X																						
	Melandrium dioecum**.........	X																						
Carnation..................	Polycarpaie spirostylus**....	X																						
Wild rose..................	Rosa woodsi**................	X																						
Horsetail..................	Equisetum variegatum**.......	X							X															
Bush cinquefoil............	Dasiphara fruticosa**........	X																						
	Cneoridium dumosum...........													X										

*RE = rare earth.
**Denotes plants also used as indicators.

Compiled from various published and unpublished sources.
Compiled from D. Carlisle and G. B. Cleveland, Plants as a Guide to Mineralization, State of California, Department of Natural Resources, Division of Mines, San Francisco (1958).

These variables include plant part to be sampled, season optimum for sampling, and sampling pattern.

The portions of plants to be sampled have been viewed by some workers as critical to the success of the prospecting effort. After a considerable effort aimed at clarifying this problem, Warren, Delavault, and Irish (loc cit) resolved it into three parameters: (1) which plant organ can be most readily collected, (2) which can be most easily analyzed, and (3) which organ responds most readily to geological anomalies. The results of their investigations, while not final, are enlightening.

1. Plant organ most readily collected. The analysis of parts of various trees for copper and zinc showed that wood and bark yielded erratic results. Leaves have been used successfully, but suffer in that their metal content and their accessibility are seasonal. Needles are troublesome to collect, but available

all seasons. Drying before removal from stems renders the collection of needles somewhat easier. Young buds and branch tips of evergreens are easy to collect, after the early part of the growing season. Stems of one full season's growth were judged most satisfactory because they are easily collected, are seldom contaminated with dirt, ash easily, may be taken from deciduous trees in winter (while leaves cannot), are easily denuded of leaves or needles, are readily prepared for shipping, and do not mold (Warren and Delavault, 1948, 1949; and Reichen and Lakin, 1949).

2. Plant organ most easily analyzed. Stems of one full season's growth were found most convenient for analysis, based upon analytical results of a variety of plants, the relatively high metal content, the low ash content, and ease of ashing. Second-year twigs, on the other hand, may give more reproducible results. Other plant organs, such as leaves, have been used almost exclusively by some workers, and in some cases analytical methods have been evolved for the circumvention of specific problems (Reichen and Lakin, 1949; Rankama, 1940; Reichen and Ward, 1951).

3. Plant organ most responsive to geologic anomalies. Because of variations in metabolic processes, and in the functions of different plant organs, the metal content of different organs of the same plant may be dramatically different, as may the same organs of different plants. Absorbed materials move from the roots to various structural parts of the plant, generally the younger parts which are more actively growing. On the contrary, heavy metals which are incompatible with most plants tend to accumulate in the roots. Such diverse results as 2200 parts per million vanadium in deep roots vs 78 parts per million in a surface root and 55 parts in tree branch tips were found by Cannon (1964). Mrs. Cannon points out that the usefulness of roots in prospecting has often been overlooked because of the necessity for extensive digging, the difficulty of identifying the tree to which a given root belongs, and the interference of soil contamination. Redistribution of nutrients within the plant

as metabolic requirements change, perhaps with season of climatic conditions, has an adverse effect in the problem of organ sampling. Carlisle and Cleveland (1958) present data, shown in Table 10, based on nine biogeochemical investigations, involving metals in 75 tree samples and 13 smaller plants. The organs are listed in order of decreasing metal concentration. It is noted that in the tree samples, leaves showed the highest metal concentration in 49 percent of analyses, while in 28 percent of the samples twigs were highest. In the smaller plants, the leaves had highest metal concentration in 77 percent of the samples.

TABLE 10

ORGANS WITH THE HIGHEST METAL CONCENTRATION, IN ORDER OF DECREASING CONCENTRATION

Trees	Smaller Plants
1. Leaves	1. Leaves
2. Twigs	2. Roots
3. Cones	3. Stems
4. Wood	
5. Roots	
6. Bark	

Uptake of material from the soil levels off to a constant value after a plant reaches a certain minimum age, characteristic for each type of plant. This is true for the plant as a whole, but the effect of seasonal growth, as previously mentioned, is probably the cause for the erratic results of analyses of young plant organs. The sunlight and water available, temperature, flowering, and fruiting cycles may cause fluctuations in the metal content of plant organs.

In general, all these variables may be considered in the sampling operation, but variations which may confuse the study will be minimized if comparison of metal content is made only between the same plant parts of the same age, of the same species, and from the same height on the plant. Samples should be taken from all sides of a tree, since the branches of one side of the tree are fed from the roots on that side of the tree. The entire area to be sampled should be, as far as possible,

TABLE 11

EFFECT OF SEASON ON MOLYBDENUM CONTENT OF PLANTS

Plant	Location	Molybdenum in Leaves, ppm		
		Spring April-May	Summer June-July	Fall September-October
Alfalfa	Coloma	16.0	20.0	28.4
Alfalfa	Buttonwillow	.9.2	11.3	18.0
Mehlotus alba	Pond	--	32.0	77.5
Mehlotus alba	Greenfields	18.1	44.8	--
Lotus corniculatus	Greenfields	30.0	43.6	92.2
Lotus corniculatus	Wasco	20.6	31.0	72.0
Rhodes grass	Buttonwillow	8.1	14.0	25.0
Rye grass	Greenfields	2.5	4.3	6.5
Rye grass	Shafter	4.3	7.5	10.0
Orchard grass	Pond	1.7	5.0	--
Orchard grass	Shafter	3.6	4.9	9.8
Water grass	Buttonwillow	3.9	--	8.2
Bermuda grass	Greenfields	4.0	--	7.6

covered at about the same time. An interesting comparison of molybdenum analyses of plants sampled in various locations in Kern County, California, is given in Table 11, after Barshad (1951).

Warren, Delavault and Irish (ibid.) found no substantial differences between high and low branches, or variations in samples taken at different times of the day. Brundin, in his patent (1939), recommended that sampled trees be of the same size so that their roots extend downwards to approximately the same depth.

Sampling Pattern. Formal methods of vegetation study have been described by Phillips and others (E. A. Phillips, 1959). In general, however, the pattern of sampling in a given area depends upon the size and shape of the area. In areas where the suspected ore-bearing terrain is level and with a uniform cover, systematic sampling on a grid pattern is a technique often employed (Ward et al, USGS Bulletin 1152). The distance between tree samples may be large (100 to 200 feet) initially, decreasing to 50 feet or less in areas showing anomalies. In areas in which there is a sloping rock-debris cover (talus), such as at the foot of hills or cliffs, much smaller distances, such as 15 feet or so, are to be recommended.

Care in sampling procedures must be taken to avoid or remove contamination, or all the care in selecting samples will be negated. Contamination in the field arises from two particular sources: windblown matter from dumps, smokestacks, etc.; and soil contamination by physical contact or rain-spatters. Twigs should be sampled in preference to leaves in areas of likely contamination, since the total area of potential contamination is smaller compared to the total volume of the organ.

Contamination can be removed by washing the sample carefully in dilute hydrochloric acid, or by peeling away bark from roots or twigs. Distilled water, or some detergent wash followed by distilled water, may be sufficient to remove dust. The necessity for removal of contamination cannot be over-emphasized, since many analytical methods for materials of economic importance are extremely sensitive. For example, the determination of copper by dithizone is sufficient to detect the small amount of metal picked up by a hand during the turning of a brass doorknob. The possibilities of contaminating (by dust) sample containers in the field must not be overlooked (Carlisle and Cleveland, loc cit).

Analysis

A complete discussion of analytical methods useful in determination of metals in plants for the delineation of geologic anomalies is beyond the scope of this work. A brief description of methods available, and of analytical problems peculiar to the analysis of plants will be undertaken, however.

Preparation of Samples. One of the aspects of biogeochemical prospecting techniques which is often cited as a disadvantage is that plant analyses require careful preparation of samples prior to chemical analysis for the analytical results to be reliable for geological interpretation. This sample preparation involves several steps, and the selection of the preparation procedure may depend upon the elements sought.

Metal analyses are often related to the "dry weight" of the plant material, in which case the first step is the drying of the plant sample in the sun or in an oven, to remove water but leave the woody matter. The samples are sometimes weighed before and after drying to allow the monitoring of gross water content. The dried material is weighed, then is usually ashed to remove the remainder of the organic, woody matter and to convert the inorganic portion to a form suitable for analysis. The procedure for ashing the sample is important, since some elements are easily lost by improper handling at this step. "Dry ashing" and "wet ashing" are the alternative methods applicable.

"Dry ashing" is a technique in which the samples are ignited to a temperature sufficient to burn away the organic material and leave the inorganic ash as residue. The ignition may be by carefully controlled electric furnace, or by a simple burner or brazier for field ashing. Ignition in the laboratory, using a furnace, entails placing the dry sample in a dish or crucible and positioning the dish in a cold furnace. The temperature of the furnace is increased slowly, usually to 500 to 600 C (932 to 1112 F), and held at the temperature for at least several hours. The furnace is then cooled and the ashes are weighed. This procedure is convenient in the lab, but field ashing may require more manipulation.

The U.S. Geological Survey has described the use of a charcoal brazier for field tests, which has been found satisfactory for uranium and probably is useful for many heavy elements. The procedure involves covering the bottom of a brazier with aluminum foil and a 1- to 4-inch layer of coarse gravel. Each sample is placed in an aluminum can and covered with a lid bearing a 1/2-inch hole. A wire sleeve supports the can above the charcoal used to ignite the samples. Such a simple procedure is obviously useful, but is neither as complete nor reproducible as laboratory procedures (Ward, Lakin, Canney, et al, U.S. Geological Bulletin 1152, 1963).

The ash procured by the ignition method is subsequently analyzed by a process suitable for the element of interest, some of which are discussed below. If chemical analysis requiring a solution is to be carried out, such as colorimetric methods, the ash must be dissolved, usually in hydrochloric acid. The usual procedure involves the transfer of the ash to a beaker, where the ash is moistened with a few drops of water then a few drops of concentrated hydrochloric acid. This solution is evaporated to dryness, slowly, to avoid spattering. The beaker is cooled somewhat, followed by the addition of a few milliliters of hydrochloric acid then a few of water. This acid treatment usually dissolves most materials, but more refractory samples may require fusion of the ash with sodium carbonate or potassium bisulfate before the materials can be dissolved in water or dilute acid.

Elements such as mercury, arsenic, antimony, and selenium may form volatile compounds under the conditions of dry ashing by any method, which precludes the application of this technique to samples in which such elements are of interest. The "wet ashing" procedure must be used for these and other elements which may be at least partially vaporized by ignition with carbonaceous matter.

"Wet ashing" involves the destruction of organic matter with chemicals. The dried sample is weighed, placed in an Erlenmeyer flask (usually fitted with an air condenser), and digested in a mixture of sulfuric and nitric acids. Small portions of concentrated nitric acid are added to the boiling mixture at short intervals until the liquid becomes straw-colored or pale yellow. At this stage, a few milliliters of hydrogen peroxide added to the solution to hasten the removal of the last traces of organic matter and to destroy oxides of nitrogen which may interfere with subsequent analyses. The resultant colorless solution is diluted with distilled water, usually to a known volume, so that portions may be analyzed for one or more metals (Ward et al, loc cit).

The U.S. Geological Survey Bulletin cited describes the compressing of plant sample material into pellets before ashing by ignition or chemical methods. The pelletizing reduces the volume of samples, so that more samples may be fitted into a furnace or other ignition device; this was found to save time by permitting more samples to be ignited at once, in smaller containers, and also to result in more uniform ash. The procedure consists of pulverizing the dried vegetation in a blender or other pulverizer, then compressing a weighed portion in a hydraulic press.

Elemental Analysis. The method by which a plant ash is to be analyzed depends upon the element to be analyzed, the sensitivity necessary to monitor the element of interest, and the speed with which results must be obtained. The requirement of rapidity in a method is usually governed by the accuracy necessary to give useful results, so that a compromise is usually required, the method selected being the most rapid without sacrificing minimum accuracy essential for the study. Methods used currently are primarily colorimetric or spectrographic, most of which are rapid, sensitive, and sufficiently accurate to yield data of the required quality with the required rapidity for prospecting on a fairly broad scale.

Workers in the U.S. Geological Survey laboratories have devised a fluorimetric method of analysis for uranium in plant ash. The method involves the mixing of the plant ash with a fluoride-carbonate flux, and the measurement photometrically by a transmission fluorimeter of the fluorescence of the resulting flux button. Manganese and some other elements interfere with the measurement by quenching the fluorescence, hence must be separated chemically from the uranium before formation of the flux button. Uranium ores have also been monitored for radioactivity as an analytical method; but alpha-particle counting may be masked by potassium, which is often a major constituent of plant ash (Grimaldi, May, and Fletcher, 1952).

Colorimetric methods are those which depend upon the formation of some specific colored compound when proper chemical reagents are mixed with the metal-bearing sample solution to be analyzed. The U.S. Geological Survey Bulletin on Analytical Methods (cited above) describes relatively simple methods for 24 elements, which are useful by workers having little technical training in field analyses as well as laboratory work. Many of the procedures described are colorimetric methods.

Three types of colorimetric methods are presented:

1. Solution extraction, in which the desired metal is removed from the aqueous solution (resulting from ashing treatment) into another solvent not miscible with water, which carries a reagent forming some colored compound (usually a complex) with the desired metal. The shade or intensity of the color formed is related to the quantity of the element present, and may be estimated by comparison with prepared standard solutions.

2. Paper chromatography, which is based upon the separation on a paper strip of the desired metal from other constituents of the sample. This is followed by the treatment of the paper with a reagent, usually sprayed on, which causes the formation of a colored compound of the desired metal. The width of the colored area and/or its intensity is related to the quantity of the element present, again estimated by comparison with standards.

3. Confined-spot tests, in which the sample is introduced into or forced to pass through a confined area of a paper (or other material) which carries a reagent. The metal of interest reacts with the reagent to form a colored compound, which is compared with standards, as discussed above.

Colorimetric methods of all of these types are usually very useful for field work, as described by the workers at the U.S. Geological Survey, and in more general laboratory texts on analytical chemistry. The reagents and apparatus required are ordinarily simple and readily acquired from chemical suppliers.

Spectrographic methods depend, briefly, upon the excitation of light from the metals to be detected by means of an electrical discharge. The light from this excitation, the wavelengths of which are characteristic of the element excited, is recorded on a photographic film. The intensity of the light is related to the amount of the element present in the sample, which may be used to estimate the quantity by comparison with standards. The equipment required is obviously not simple. The United States, Canada, and the Soviet Union have each procured mobile spectrographic units for use in the field (Canney et al, 1957). Fortescue and Hornbrook (1967) describe the Canadian spectrographic equipment and their procedure for analysis of samples. Their brief procedural outline is shown in Fig. 14 as an example of the analytical steps required in this method (from p. 77 of the cited report).

Stage I	Sample batch of oven dry material ashed overnight in muffle furnace.
Stage II	Ash cooled, weighed and mixed.
Stage III	A 10 mg portion of ash of each sample placed on platrode after mixing with a known volume of sugar solution containing indium as an internal standard.
Stage IV	Each suspension of a subsample in sugar solution dried under a heat lamp. Samples prepared in batches of 15, plus a reference standard.
Stage V	Batch of prepared platrodes excited while rotating in spark discharge. Light emitted is passed through the spectrograph and recorded on photographic film.
Stage VI	The film is developed and fixed. After washing it is allowed to dry.
Stage VII	Film with 16 spectra is matched visually with a master film made by exactly the same technique as that described above, except that synthetic plant ash base standards are substituted for unknowns.
Stage VIII	The results obtained from the unknown samples and the standard spectrum are recorded element by element on specially designed computer input sheets.

Figure 14. Flow Sheet Showing the Sequence of Operations Involved in the Analysis of a Batch of Samples of Plant Material by a Field Spectrochemical Method. From: Fortescue and Hornbrook, 1967.

For specific analytical methods for individual elements, the reader is referred to U.S. Geological Survey Bulletin 1152, cited above, and to the analytical chemical and geochemical literature.

The results of plant analyses, once procured by an appropriate procedure, are processed to relate the metal content of plants to the area from which the samples were taken. This may be done by plotting directly the concentrations of metal on a map to allow the location of areas of highest concentrations. Alternatively, the results of the analyses may be compared to results obtained from the samples taken from mineral-barren areas, and the accumulation ratio plotted.

$$\text{Accumulation ratio} = \frac{\text{Content over ore}}{\text{Content over unmineralized area}}$$

The ratios of one metal (such as copper) to that of another (such as zinc) may be determined and plotted on the map. In any of these cases, it sometimes is useful to set a value of the ratio or the concentration of the metal as a "threshold," or minimum value, below which the area is to be regarded as mineralogically not promising, and above which more investigation or serious effort should be expended for ore recovery. Since the concentration of the metal found in a particular plant species depends upon the chemical character of metal, the plant, the acidity of the soil, the exchange capacity, and the topography of the soil, the ratio method might be the most reliable guide in most investigations.

GEOBOTANY

As discussed above under theoretical considerations, the geobotanical method of prospecting rests upon the facts that plants may indicate mineralized areas by their conspicuous presence or absence in the area, or by morphological changes produced in the plants by the presence of the minerals. Secondary effects produced in animals which eat mineral-affected or enriched plants may also be used as clues to the location of ore-bearing areas. The use of physical changes, in population or physical condition, of a plant population to indicate the presence of a mineral enrichment has the obvious advantage that time, effort, and money may be saved if costly chemical studies may be circumvented or reduced in locating even the general area of an ore. Workers in the Soviet Union have investigated this technique seriously for some time, probably because of the vastness of the territory in which economically valuable materials may be sought in that country. Workers in Canada and the United States also have expended effort in the development of the botanical technique. Reexamination of Fig. 12, from Fortescue and Hornbrook (1967) is useful, noting the effects on plants of minerals in the supporting medium which will give rise to details useful in botanical prospecting. The following discussion of the technique as applied by workers in the field is arranged so that plants whose presence is indicative of certain metals ("indicators"), those plants whose physical appearance may reflect abnormal mineralization, and the mineral conditions which may debilitate all plant growth are considered separately.

Sparseness of Vegetation

The thinning or total debilitation of vegetation in an area may be the result of deficiency of a necessary nutrient, excess quantities of a toxic or even an essential metal, adverse acidity conditions of the soil, or artificial denudation of the area by human activity. Even with all of these contributing factors, the phenomenon of dramatic decrease or absence of vegetation in an otherwise plant-covered area may be a good indication that an ore body may be present, and further investigation might prove profitable. This shred of information is as much or more than that offered by many other methods of exploration employed in the search for natural resources. The knowledgeable prospector need not waste time blindly exploring every thinning of vegetation, however, if other information about the area is available. For example, in the Mojave Desert area of California, where boron is economically recovered, a conspicuous debilitation of vegetation cover might lead an observant prospector to suspect. logically, a boron enrichment, allowing field tests for boron to be applied before more expensive complete analyses were requested on samples. Similarly, toxic amounts of copper might be first sought by field methods in Arizona's well-known copper areas before exhaustive laboratory analyses were procured. While observations of this type may lead to discovery of economically unimportant causes for the vegetation spareness, contrarily, they may lead to rapid and relatively inexpensive discovery of valuable materials. Since many metals may be toxic to plants in concentrations much above the physiological requirements of the plants, specific consideration of toxic elements appears to be superfluous in this discussion. It must be noted, however, that the amount of an element which can produce toxic symptoms in species of plants depends upon the plant, the element, and the characteristics of the soil. The technique of using conspicuous plant sparseness as an indication of mineralization is useful as a screening tool, if not a specific or quantitative clue to mineralization.

A stark example of the effect of mineralization in killing vegetation is the modern tree stump-killing chemicals to be found in nurseries. Many of these contain copper salts, which are applied to eliminate the small shoots which persist around tree stumps until the roots are killed. Arsenic ant poisons liberally applied around any garden will debilitate or kill the plants in the immediate vicinity. Arsenic is a common component in weed killers by tobacco growers to air their crops. A drive along roads below mines from which arsenic-laden or otherwise mineralized waters are pumped yields evidence of the efficiency of plant-killing by such metals.

Examples of the use of this phenomenon in prospecting were cited by Helen Cannon in her 1960 article. They include: (1) copper-poisoned areas in Armenia, Rhodesia, and the Congo, in which the lack of vegetation, or its sparseness, in otherwise forested districts, were prospected successfully; (2) barren areas near pyrite deposits in Italy; (3) platinum in the Urals; (4) zinc deposits in New York State; and (5) strontium sulfate mines in Arkansas. also located in this manner.

Indicator Plants

The general population of plants growing in any given geological situation is a balance between the requirements of the plants with respect to nutrients, sunlight, soil consistency, moisture, acidity, and many other factors. Since the different species of plants have particular requirements, some thrive in acidity and mineral conditions that kill others. Some plants do not grow in areas deficient in a metal required for the metabolism of that plant and not for that of most other plants, yet will thrive in areas in which that metal occurs in concentrations toxic to most other plants. While the presence of such metal-dependent plants always indicates mineralization, their absence does not necessarily exclude the presence of ore, since all of the nutritional and environmental requirements of a plant must be met if it is to survive. These plants whose presence indicates the availability of a minimum amount of a particular metal to the roots are called universal indicators.

Local indicator plants are those which have been demonstrated to indicate mineralization only in specific ecological or geographic locations. These plants accumulate or tolerate fairly high concentrations of minerals, but do not require the metallic constituents of the mineral for growth. In a mineralized area in which they do occur, their population density is often greatly above that in unmineralized areas. This may be due to lack of competition for water and nutrients by mineral-intolerant plants. Local indicators are often classed as primary or secondary: primary indicators react to the metal of interest, while secondary indicators respond to some condition associated with the ore. Mention of local indicators in the literature often omits the distinction between these classes, which may lessen their usefulness to prospectors. An example of an unusual aggregation of California poppies, a local copper indicator, is shown in Fig. 15.

The use of plants as indicators for mineralization involves preliminary efforts to identify and test the validity of plant-ore relations. Which

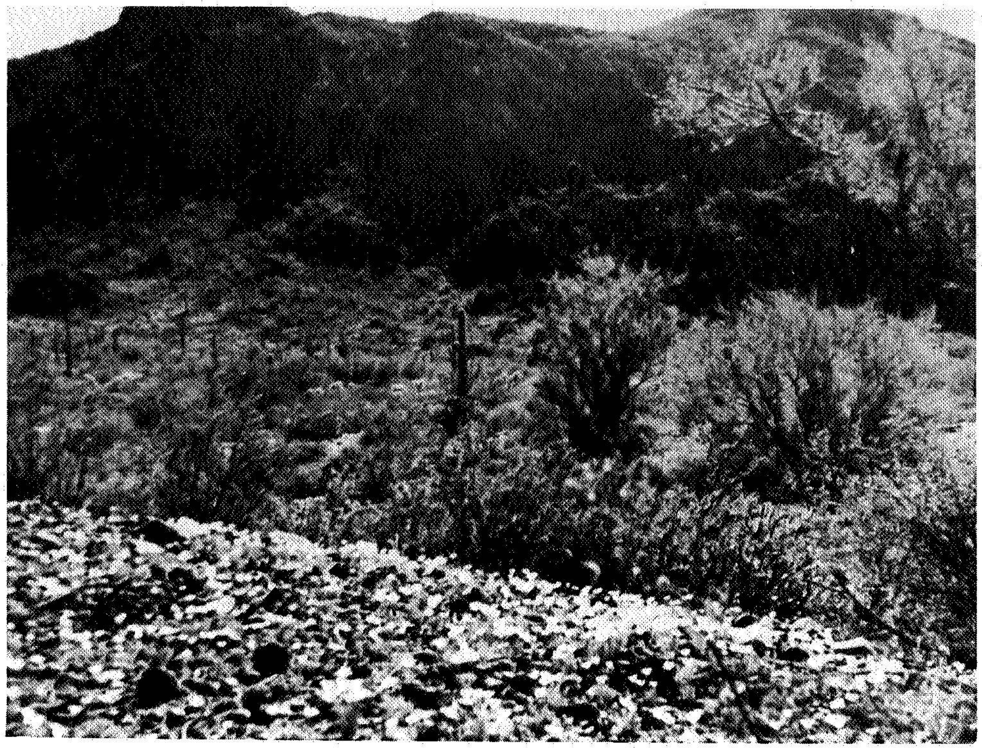


Figure 15. California Poppies (Eschscholtzia mexicana), Indicating Copper Mineralization Bounded by A Fault, in San Manuel, Arizona (From H. L. Cannon, 1960)

species of plant is useful as an indicator will, of course, depend upon the chemical nature of the ore body and the position of ground waters. The steps usually required in a systematic search for indicators are:

1. Discovery of indicators. This may be approached by examination of the vegetation growing in soil known to be mineralized, and preparation of lists of all the species present. Tolerant plants and indicators are identified from this activity. Any plant may be used as a prospecting indicator if its distribution is directly controlled by <u>any</u> factor related to the overall chemistry of a deposit.

2. Evaluation of indicators. Presence of any of these listed plants in a new area is noted and study of such distribution proceeds to determine usefulness in prospecting. This evaluation ideally

includes the study of the biology and ecology of the indicators and their relationship with the mineral with which they are associated. Mapping of indicator associations to outline mineralization of the new area would logically be followed up by further (probably chemical) investigation of the area.

After evaluation of the identified indicators, similar plant associations during reconnaissance may be identified and pursued. Of course, not all mineralizations located in this manner may be of economic value, but the same is true of most exploration techniques.

Universal indicators have been applied successfully to prospecting in widely divergent conditions. For example, Shacklette (1965) studied bryophytes (mosses and liverworts) in Alaska, and tabulated species which grow commonly or exclusively on or near ores of copper, lead, zinc, mercury, antimony, arsenic, and other elements. Cannon (1956, 1957, 1960, and 1964) studied various areas in the Western United States.

The number of identified universal indicator plants is limited to very few. Plants known to indicate specifically the presence of copper, cobalt, selenium, uranium, vanadium, and zinc have been reported and summarized by Helen Cannon (1960 and 1964) and by D. P. Malyuga (1963). Table 12 presents data on universal indicators derived from the summaries of these two workers, who in turn gleaned it from the literature. Table 13 lists data presented by Cannon (1960) on local indicator plants used in prospecting. Reference books and other compilations of plant indicators are mentioned in literature cited by Chikishev (1965). The availability of some of the compilations is probably limited; however, a list of such works is given in Table 14.

The information given in reference books, such as those mentioned, varies from author to author, but generally includes information about the indicator plant's appearance, flowers, locale or occurrence, districts in which it has been found useful, and often pictures and/or drawings of the plant, with or without bloom. Geological features of the soil and terrain, typical landscape, and special features, such as plant odor, may be included.

TABLE 12

UNIVERSAL PLANT INDICATORS*

Botanical Name		Common Name	Metal(s) Indicated	Area Noted
Family	Genus and Species			
Pink	Gypsophila patrini	Karum	Copper	USSR
Mint	Acrocephalus roberti		Copper	Katanga
Mint	Ocimum homblei	Basil	Copper	Rhodesia
Moss	Merceya latifolia	Copper Moss	Copper	Sweden and Montana
Legume	Astragalus bisulcatus	Poisonvetch	Selenium	Western U.S.
Legume	Astragalus racemosus	Poisonvetch	Selenium	Western U.S.
Legume	Astragalus pectinatus	Poisonvetch	Selenium	Western U.S.
Legume	Astragalus confertiflorus	Blue poisonvetch	Selenium	Western U.S.
Legume	Astragalus preussi	Preuss poisonvetch	Selenium	Western U.S.
Sunflower	Oanopsis spp.	Goldenweed	Selenium	Western U.S.
Sunflower	Aster venustus	Woody aster	Selenium	Western U.S.
Mustard	Stanleya spp.	Princeplume	Selenium	Western U.S.
	Xylorrhiza		Selenium	Western U.S.
Composite	Townsendia incana		Selenium	Western U.S.
Legume	Astragalus pattersoni	Poisonvetch	Selenium, Uranium	Western U.S.
Violet	Viola calamineria (lutea)	Zinc violet	Zinc	Belgium and Germany
Violet	Viscaria alpina	German catchfly	Copper	Norway
	Crotalaria colbalticola	Rattlebox	Cobalt	Katanga
	Silene colbalticola	Catchfly	Cobalt	Katanga

*From data collected from various sources in the literature

TABLE 13

PLANTS USED AS LOCAL INDICATORS IN PROSPECTING

Family	Genus and Species	Common Name	Metal Indicated	Locality
Goosefoot	Anabasis salsa		Bitumen	Caspian Sea
Goosefoot	Salsola spp.	Saltwort	Bitumen	Caspian Sea
Lily	Allium sp.	Onion	Bitumen	California
Goosefoot	Salsola nitraria	Saltwort	Boron	USSR
Goosefoot	Eurotia ceratoides	Winter Fat	Boron	USSR
Plumbago	Limonium suffruticosum	Statice	Boron	USSR
Pink	Polycarpea spirostylis	Pink	Copper	Australia
Mint	Elsholtzia haichowensis	Elsholtzia	Copper	China
Poppy	Eschscholtzia mexicana	California Poppy	Copper	Arizona
Plumbago	Armeria maritima	Thrift	Copper	Scotland
Buckwheat	Criogonum inflatum	Desert Trumpet	Gypsum	Western U.S.
Loasa	Mintzelia spp.	Blazing Star	Gypsum	Western U.S.
Burch	Betula sp.	Birch	Iron	Germany
Guttiferae	Clusia rosea	Copey Clusia	Iron	Venezuela
Grass	Erianthus giganteus	Beardgrass	Lead	Tennessee
Morning Glory	Convolvulus althaeoides	Bindweed	Phosphorus	Spain
Legume	Astragalus preussi	Poisonvetch	Selenium, Uranium	Western U.S.
Legume	Astragalus sp.	Garbancillo	Selenium, Uranium	Andes
Buckwheat	Eriogonum ovalifolium	Eriogonum	Silver	Montana
Saxifrage	Philadelphus sp.	Mock Orange	Zinc	Washington

TABLE 14

INDICATOR PLANT REFERENCE WORKS

Helen L. Cannon	Description of Indicator Plants and Methods of Botanical Prospecting for Uranium Deposits on the Colorado Plateau, Geological Survey Bulletin 1030-M, Government Printing Office, Washington, DC (1957).
I. V. Larin	Determination of Soils and Agricultural Lands from the Vegetation Cover, Moscow, Sel'khozgiz (1953).
A. Krudener A. Becker W. Escher R. Mussgang I. Zacharias	Atlas Standortkennzeichender Pflanzen (Atlas of Plant Indicators of Habitat Conditions), Berlin (1941).
E. A. Vostokova A. V. Shavyrina N. N. Preobrazhenskaya L. N. Tagunova	Reference Book on Plant Indicators of Groundwaters and Terrains in the Southern Deserts of the USSR. (Mentioned in A. G. Chikishev, below)
A. G. Chikishev	Plant Indicators of Soils, Rocks and Subsurface Waters, Consultants Bureau, New York (1965)
D. P. Malyuga	Biogeochemical Methods of Prospecting, Consultants Bureau, New York (1964).

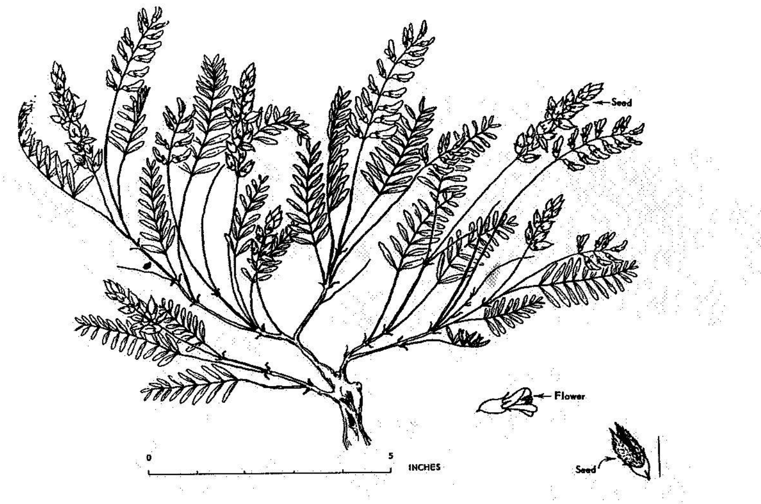
Figures 16, 17, 18, and 19 from the H. L. Cannon reference cited illustrate several of the selenium-indicating plants found useful for uranium prospecting on the Colorado Plateau. Figure 16 shows the artists drawing of Astragalus confertiflorus (blue poisonvetch), with description of the plant's dimensions, habit, and other useful details. Figure 17 is a photograph of the actual plant, with a small penknife alongside for dimensional reference. Note that the artist's drawing points out particularly distinguishable features of the plant easily seen in the actual photograph.

Figure 18 is a photograph of Astragalus bisculcatus, the two-grooved poisonvetch found in another area noted in the description.

The distinctive appearance of some indicator plants in winter, which renders them useful even when they are dead and dry, is illustrated in Fig. 19 which depicts the dead plants of Astragalus pattersoni (Patterson poisonvetch). This plant is the one noted as most useful in the uranium districts of the Colorado Plateau because of distinct requirement for selenium and concentration of selenium and molybdenum. The cited report includes discussion of plant associations, the soil and ground-water conditions, and prospecting procedures, along with descriptions and illustrations of 50 plants indicative or tolerant of mineralization related to uranium deposits.

Morphological Effects

Changes wrought in plants by abnormal quantities of metals in the nutrient supply may be subtle or dramatic variations in vitality, completeness of the development cycle, growth and flowering cycles, growth abnormalities, changes of physical form, and sexual sterility. The phenomena might be illustrated by the citation of specific examples given by various observers. Table 6, presented earlier, summarizes physiological and morphological changes which have been found in plants as a result of toxic quantities of metals.



Family:	Pea, Leguminosae
Subgenus:	Cnemidophacos
Flowers:	Cream-colored, irregular flowers in dense inflorescence; blooms in May
Fruit:	Erect one-celled pod from stalk, not inflated, and with no individual stem; woody
Leaves:	Pinnate, with 11 to 15 linear leaflets; silvery hairs
Plant:	Perennial; about 8 inches; has erect stems and bluish foilage
Altitude:	5000 to 6000 feet
Occurrence:	Restricted to seleniferous clay which commonly underlies ore deposits
Districts noted:	Thompson, Henry Mountains, Monticello, and Uinta Basin, Utah, Grants, New Mexico

Figure 16. Astragalus confertiflorus (A. Gray)*

Figure 17. Blue Poisonvetch

*From: Cannon, H. L., Description of Indicator Plants and Methods of Prospecting for Uranium Deposits on the Colorado Plateau, Geological Survey Bulletin 1030-M, p. 420 (1957).

Family:	Pea, Leguminosae
Subgenus:	Diholcos
Flowers:	Deep purple, irregular flowers in dense elongated spikelike inflorescence which extends above the foliage; blooms in June and July
Leaves:	Smooth pinnate with oval or oblong leaflets
Fruit:	Linear one-celled pod with two deep grooves on the upper side; pod with stem extends from calyx
Plant:	Stout, erect; perennial
Altitude:	3500 to 8000 feet
Occurrence:	Dry meadows and sandy soil. This species absorbs large amounts of selenium and molybdenum and is very poisonous to stock.
Districts noted:	Powder River Basin, Wyo.; Huerfano, Colo.

Figure 18. Astragalus bisulcatus, Hook, (Two-grooved poisonvetch), A. Gray*

*Reference: Cannon, H. L. (loc cit p. 423).

Family: Pea, Leguminosae
Subgenus: Jonesiella
Flowers: Cream-colored irregular flowers with purple dot on keel, growing in tall clusters which extend beyond the foliage; blooms in April and May
Leaves: Pinnate with numerous oval leaflets
Fruit: Fat pods mounted on short stem. Seeds rattle in pod when dry (then called rattleweed).
Root: Very long taproot, commonly 30 feet or more in length
Plant: Perennial, 1 to 4 feet high. Garlic-like odor common to foliage owing to presence of selenium.
Altitude: 4500 to 7500 feet.
Occurrence: Best selenium-indicator plant in uranium districts of the Colorado Plateau because requirements and absorption of selenium are very high. Commonly absorbs several thousand parts per million of selenium and several hundred parts per million of molybdenum from ore bodies. Plot experiments suggest growth stimulated in vicinity of carnotite deposits by increased solubility of selenium and molybdenum but inhibited by excesses of calcium sulfate.
Districts noted: San Rafael, Thompson, Green River, Monticello and Circle Cliffs, Utah; Ship Rock, in Arizona; Slick Rock and Gypsum Valley, Colo.; Grants and Pojoaque, N. Mex.

Figure 19. Dead Plants of Astragalus pattersoni Useful in Fall and Winter in Deciding Where to Drill*

*Reference: Cannon, H. L. (loc cit p. 409).

1. Gigantism. On boron-rich soil, many plants may become twice or thrice their normal size and develop larger, greener leaves than normal. Some species may develop abnormal creeping habit. These characteristics can be used as a guide in prospecting for new boron deposits (N. I. Buyalov and A. M. Shvyryayeva, 1955). Bituminous materials in soils were found by Bostokova et al (1955) to cause gigantism in 29 species of plants growing over oil deposits. Abnormal flowering habit and growth of shoots was also noted.

2. Dwarfing. The toxicity of copper concentrations produced stunting of the growth of Protea goetzeana in Katanga. The relative effect varied with the copper concentration, extreme toxicity causing the development of a creeping, sterile form (Duvigneaud, 1958).

3. Chlorosis. The yellowing of leaves has been noted in areas containing excess quantities of nickel, copper, cobalt, chromium, zinc, and manganese. These elements apparently interfere with the assimilation of iron which is required for the production of chlorophyll, even though iron is absent from the chlorophyll molecule. Cannon (1955) observes that chlorotic crops due to zinc excesses from zinc-bearing dolomites were used to follow the dolomites for 20 miles in New York State. Other chlorotic effects are the zinc-caused yellowing of trees in New England and in Missouri (H. L. Cannon, 1960). Figure 20 shows a chlorotic leaf from a maple tree growing in copper rich-soil.

4. Flowering and fruiting changes. Malyuga et al (1959) report a marked alteration in the development of the black areas on petals of the poppy Papaver commutatum, as a result of copper- and molybdenum-enriched areas. Abnormal metal concentrations caused the usual lilac-red petals to change from having one small black spot at the base to a form in which the black spots elongated to reach the edge of the petal forming the image of a black cross. Figure 21 illustrates this change to the mutation.

Figure 20. Chlorotic Leaf Pattern Developed in a Maple Tree Growing in Copper-Rich Soil in Ely, Vermont[1]

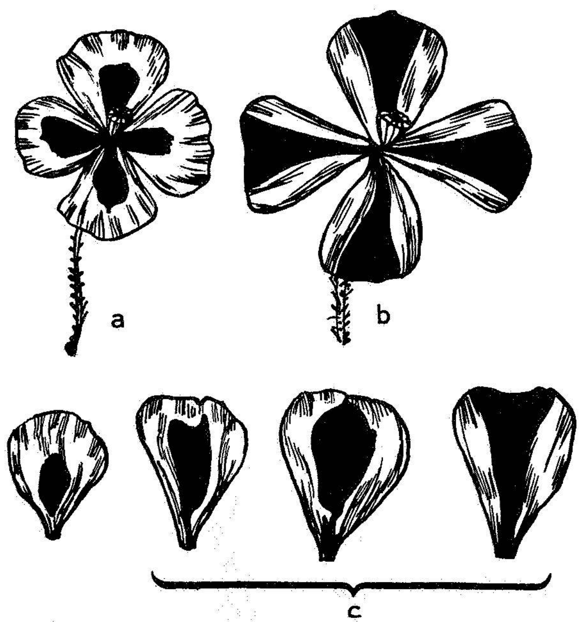


Figure 21. Change in Petal Color of the Flower of the Poppy *Papaver commutatum* F. et M. (1) Normal flower; (2) modified flower; (3) degree of mutability of petals of the corolla.[2]

[1]From H. L. Cannon (1960).
[2]From Malyuga (1963).

Variations in the color of flowers of fireweed, Epilobium angustifolium L. was studied by H. T. Shacklette (1964). He noted that the blossoms of this plant are ordinarily magenta throughout the wide range in which it grows, yet occasional pale pink or white blossoms appeared. Investigation revealed that the variations were environmental, and perhaps due to the long exposure of the plant to radiation from materials in the supporting medium.

The color of blossoms of Pulsatilla patens, an anemone, and Linosyris villosa, a composite, have been found to become abnormally white in the presence of nickel-cobalt deposits in the Ural Mountains of Russia (Vinogradov, 1954).

The form of the blossom of Papaver macrostonum, a poppy, was found to change from a single-petaled form to double petals, when the plant grew in soil bearing high zinc and lead concentrations. The mutation has the appearance of having more than the usual four petals in the flower. The petals of Pulsatilla patens were found to change in size, even to disappear, when the plant was found growing on a nickel silicate deposit in Russia. Figure 22 shows the normal and modified forms of this anemone (Malyuga, 1963, p. 12).

Figure 22. Mutability of the Flower of the Anemone Pulsatilla patens Mill. (a) Normal form; (b) Modified specimens

Wide variations in the fruits of the Dwarf Blueberry, Vaccinium uliginosum, were found in an area less than 400 square meters by Shacklette (1962). Although some variation in the shape of fruits is normal, the dramatic number of changes noted in this instance were extraordinary, varying from pear-shaped to elongated cylinders. The area lies directly over a deposit of pitchblend, leading to the speculation that genetic changes of the species have been caused by radiation from the uranium.

The use of changes in form or habit of plants growing in mineralized soils for prospecting does not appear to require particular knowledge of botany, although such knowledge would be of great help. The prospector must be able, however, to recognize changes in a species from its formal form to some abnormal one. This may require only the capability for noting variations in color, size, or shape (Cannon. 1960).

Other Effects

Aside from indicator plants and morphological changes as clues to mineralization, the relative abundance of species of some trees has been used to prospect. Kleinhampl and Koteff (1960) found that the ratio of the numbers of pinyon and juniper trees on a sandstone formation in the Circle Cliffs area, Garfield County, Utah, were related to the thickness of the sandstone. The occurrence of uranium deposits was also related to the sandstone thickness in some sections, leading to the application of a tree-ratio method to uranium prospecting in that area.

The practice of biogeochemical prospecting techniques by prospecting teams in various parts of the world is, of course, far more detailed than the short summary presented above would indicate. The subject has been reviewed from time to time by various authors, whose efforts are recommended for precise and complete details and descriptions. Table 15 presents a list of surveys of biogeochemical prospecting, which is representative, if not exhaustive.

In general, the morphological effects discussed herein have been used for prospecting only during ground studies, since most of them are too subtle to be observed from distances larger than a few feet. Efforts funded by the National Aeronautics and Space Administration and some other agencies are being directed towards technique development which, though presently aimed at agricultural and geological uses, shows promise in detecting gross geobotanical effects with the aid of special optical and photographic equipment. Such efforts should be directly applicable to prospecting from various altitudes, including orbital altitude. Accordingly, the advances being made in reconnaisance of geological and agricultural details by aerial observation will be discussed in the following portion of this survey.

TABLE 15

SURVEYS OF BIOGEOCHEMICAL PROSPECTING

1. Buck, L. J., "Association of Plants and Minerals," J. N.Y. Bot. Garden, 50, 265-269 (1949).

2. Dorn, Paul, "Pflanzen als Anzeichen Für Erzlangerstätten" (Plants as indicators of ore deposits): Der Biologe, 6, 11-13, Munich (1937).

3. Hawkes, H. E., "Geochemical Prospecting for Ores: A Progress Report," Econ. Geology, 44, 706-712 (1949).

4. Hawkes, H. E., "Geochemical Prospecting for Ores, in Applied Sedimentation, a Symposium," edited by P. D. Trask, I. Wiley, p. 537-555 (1950).

5. Malyuga, D. P., On Soils and Plants as Prospecting Indicators for Metals (In Russian), Izv. Akad, Nauk, SSSR, Ser. Geol. No. 3, p. 135-138 (1947).

6. California Division of Mines, "Geochemical Prospecting," California Division of Mines Information Service, 6 (1953).

7. Davidson, C. F. and S. H. U. Bowie, "Methods of Prospecting for Uranium and Thorium," in United Nations, Geology of Uranium and Thorium: International Conference Peaceful Uses of Atomic Energy, Geneva. Proc., 6, 659-662 (1955).

8. Nesvetazlova, N. G., "Geobotanisheskiye issledovaniya pri poiskakh rudnykh mestotozhenity" (Geobotanical Investigations for Prospecting for Ore Deposits), Geobotanical Methods for Geologic Investigations (a symposium), Vses. Aerogeol. Trest, Trudy, 1, 118-134 (1955).

9. Viktorov, S. V., "A Brief Outline of the History and Present Status of the Geobotanical Method in Geology," Geobotanical Methods of Geological Investigations (sbornik statey), Vses. Aerogeol. Trest. Trudy 1, p. 5-10, (1955).

10. Viktorov, S. V., Utilization of Geobotanical Methods of Geologic and Hydrogeologic Studies, Akad. Nauk SSR Inst. Geoy. Trudy, p. 199 (1955).

TABLE 15

(Concluded)

11. Vinogradov, A. P., Search for Ore Deposits by Means of Plants and Soils Akad. Kauk SSSR Biogeokhim Lab. Trudy 10, p. 3-27 (1954).

12. Vinogradov, A. P. and D. P. Malyuga, The Biogeochemical Method for Ore Search and Prospecting, 1956 abs., International Geological Congress, 20th, Mexico City (summaries of the papers presented), p. 378-379, (1956).

13. Plant Indicators of Soils, Rocks, and Subsurface Waters, edited by A. G. Chikishev, Consultants Bureau, New York (1965).

14. Malyuga, D. P., Biogeochemical Methods of Prospecting, Consultants Bureau, New York (1964).

INTRODUCTION

The advantages of having the ability to perform reconnaissance from a distance has long been known to anyone who has stood on a hilltop or tall building and gazed across the landscape. Treetops and towers as vantage points were improved upon when the balloon was developed as a vehicle, for great altitudes were made possible from which vast areas were visible. Technically, this reconnaissance is "remote sensing of the environment," which has been improved by the development of tools such as photography, radar, and other technological means for recording and interpreting the terrain. Aerial photographs, whether procured from balloon, large or small aircraft, or orbiting space vehicles, provide information not obtainable by direct ground observation of an area or by visual study from altitude.

Early aerial photographers were able to use only visible light to obtain images for study; the development of the science of photography has led to improvements in the film which recorded all colors as variations in shade from black to white (panchromatic film). New techniques arose, including the simultaneous photographing of the same terrain using selected energies of the light spectrum from ultraviolet through the visible colors to the infrared and microwave regions. The application of sensing devices which use such a wide variety of energies of the light spectrum is known as <u>multispectral imagery</u>, or multispectral remote sensing.

Since the discussion of remote sensing by multispectral imagery involves the nature of light, a brief resumé of the basic features of light will be undertaken. The concepts essential to the technical development of imagery depend upon the properties of light which are analogous to waves. Using the ocean wave as a model, one describes the waves as having <u>wavelength</u>, which is the distance from the crest of one wave to the crest of another; wave <u>frequency</u>, which is the number of crests which pass a given point in some specified period of time; and velocity, the speed at which a wave crest advances. The aggregate of waves of all different lengths is called a spectrum. These properties of waves are related to each other, such that wave frequency is directly proportional to velocity and inversely proportional to wavelength. A chart of the electromagnetic spectrum is shown in Fig. 23. The types of information shown are related to properties of materials which may be interpreted from photography or other sensing of reflectance, or absorbance by the materials of the energies of the various spectrum regions. The approximate wavelengths of the regions shown are given in millimicrons, the unit most workers in the fields of optical instrument design use. (One micron is a millionth of a meter; one millimicron is 10^{-3} microns.)

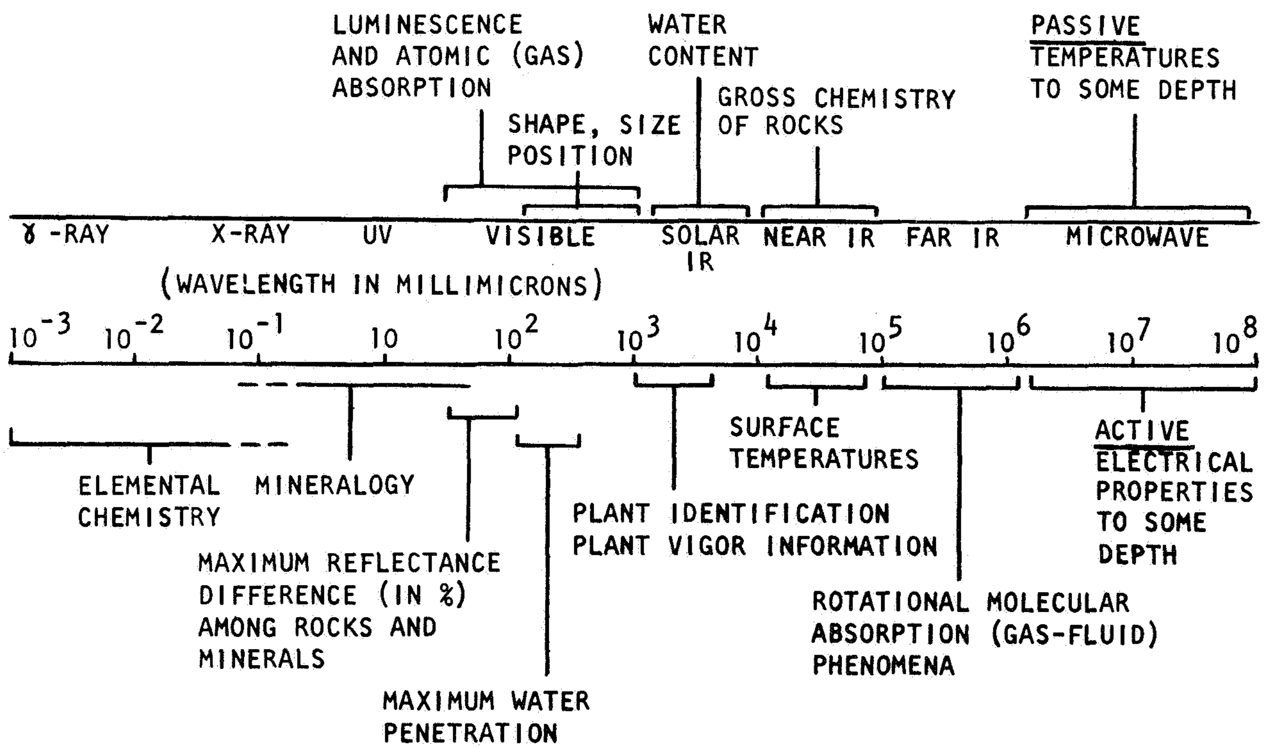


Figure 23. Types of Information and/or Properties of Material That may be Procured From Observations of Various Parts of Electromagnetic Spectrum

Electromagnetic waves are all the same in character, but differ only in wavelength, frequency, and energy. Since energies differ, the interaction of the waves with matter which they contact differs; absorption reflectance, scattering, or transmission of the light by the matter upon which it strikes is characteristic of the light and of the matter. This phenomenon allows the observation of such interactions to be used for such practical applications as the identification of vegetation types, and recognition of features related to the health and nutritional state of plants.

Avid proponents of the art of multispectral imagery have been enthusiastic in their estimate of the information which may be derived from the technique, and the ease with which it is procured. Such enthusiasm about any technology almost invariably is offset by pessimistic counterclaims regarding failures of the method to produce useful data. The state of the art probably lies somewhere between the extremes of these views: much information is to be gained by the application of remote environmental sensing, but it is far from being a ready-to-plug-in panacea for the needs of prospecting teams presently confronted with the task of locating valuable, critically needed natural resources. The discussion of the art which follows is undertaken in the effort to acquaint the reader with some of the technical details in aerial photography which must be considered in selection of instrumentation and technique to solve a particular problem in biogeochemical prospecting.

AERIAL PHOTOGRAPHY

In this discussion, the term aerial observation includes both aircraft and orbiting space vehicles serving as observation platforms. The space vehicle offers a view of an extremely large area of the surface of the earth at one time, so that geological and geobotanical features can be properly understood and interpreted in the context of their surroundings. Some geological features are so large that they cannot be seen in their entirety except from orbital altitudes. The aircraft, on the other hand, offers the opportunity of flying over a selected region at various altitudes. The aircraft can carry much heavier instruments and provide more power to operate them than present space vehicles.

For biogeochemical prospecting purposes, the airborne prospecting crew can accomplish the data collection that would take a ground crew months to perform. It also can do the job more thoroughly, and with much less cost and trouble. This is of particular value now that most prospecting for minerals is being carried out in remote regions relatively inaccessible to ground crews. The vantage point afforded by aircraft or satellite has proved invaluable in observing the crowns of tall trees, which reflect the health of the tree fairly well and which are not accessible to ground crews. The vantage point of altitude also permits the use of instruments for measuring and analyzing the light emitted and reflected by plants, soil, rocks, and bodies of water. Most of these instruments are impractical for ground-level operation. The reader desiring more detailed information on the techniques or instruments mentioned in this brief survey should consult the references cited.

The discussion herein on the art of remote sensing of the environment is an effort to acquaint the reader with the present techniques, point out current directions of development in techniques and instruments, and outline fundamental limitations imposed by the laws of nature and practical considerations. It is hoped that the discussion of projected developments will point up the need for and encourage the rapid development of new techniques.

The comment by Ray (1960) in Professional Paper 373, "Aerial Photographs In Geologic Interpretation And Mapping," prepared for the U.S. Geological Survey, is of interest as an introduction to the subject. "Vegetation as an element of the soil pattern has been considered one of the most difficult to interpret. It is known, for example, that certain trees, such as aspen, are tolerant of many different soils and soil conditions, but some types of vegetation are strongly influenced by soil type.....Nevertheless, vegetation may reveal significant information in engineering studies provided valid interpretations are made with regard to how vegetation is associated with soil textures, soil-moisture content, and topography;

thus a knowledge of plant ecology is necessary if maximum information on soil conditions is to be obtained from aerial photographs." This observation must be kept in mind, lest it be forgotten that the most wonderful photos in the world will not provide any information without careful and skilled interpretation based on general biogeochemical knowledge, regardless of the sophistication of the instrumentation with which the photos were made.

An early application of remote sensing to successful prospecting was the discovery of the copper deposits in central Africa, cited earlier. These deposits were indicated by open spots in the brush cover where the high concentration of copper in the soil caused changes in the type of vegetation from that prevailing in surrounding areas where the copper concentration was lower (Walker, 1929). A similar phenomenon was observed in Arizona, where, as shown in Fig. 15, the California poppy acts as an indicator of copper in the soil (Cannon, 1960).

The use of aerial photos to deduce the identity of surface features requires skill and experience in interpretation of such photos. The less ground data is available regarding the area of interest, the more training and experience is required for accurate interpretation. Problems attendant to this task were painfully apparent during World War II, during which photographic interpreters were called upon to prepare terrain intelligence reports from aerial photographs accompanied by little or no other information. Since the military personnel were a cross section of citizens of diverse backgrounds and not trained in the arts of interpretation, they sought aid from geologists. Eventually, handbooks and guide materials were prepared to assist interpreters to increase the accuracy and rapidity of their work. These aids were prepared by the Naval Photographic Interpretation Center, Anacostia, Washington, D. C., and by other government agencies in the United States, and were the basis for subsequent research (Truesdell, 1950).

Armed with some experience, some photos of areas for which ground truth has been established, and reliable keys and guides, an interpreter can provide fairly correct information, even when faced with the handicap of photos of totally unknown terrain. He may also jump to totally wrong conclusions, if the photos are poor or bear misleading features, or his own background is too shallow. This pitfall must be recognized as a problem, but not an insurmountable one, in the application of such photo-interpretation to prospecting, since many of the primitive areas in which valuable resources are being sought have no other available data.

Specifically, the interpretation of vegetation involves the judgment of correlation between vegetation patterns and soil, topography, bedrock, and recent history of the land surface. Variations in climate, human intervention, and interactions of plants with the supporting medium affect the patterns which one must identify on aerial photographs (Sigafoos, 1950). For identification of patterns on photos, criteria must be defined for each different scale, describing textures, configuration, shade, and other pattern details. This requires correlation with actual ground details, often laboriously collected. The value of aerial photographs makes such effort well worthwhile.

Interpretation of ground details is constantly undergoing evolution as new technical aids are developed. Instrumentation is now available for increasing the sensitivity possible in discriminating colors beyond the capabilities of the human eye, and for recording the absorbance or reflectance of radiations from plants and other surfaces in regions of the electromagnetic spectrum previously not usable. Infrared, microwave, and radar (centimeter wave) spectra have been or are being studied and used in interpretation, with or without data from the visible region of wavelengths in various combinations. Such "multispectral imagery" techniques expand the accuracy and usefulness of vegetation observations, as well as geologic studies. Stereoscopic viewing of black and white films has become important in geologic interpretation (Ray, 1960). Electronic scanning and computational treatment of small changes in the details of photographic negatives or positives has been described by Vinogradov (1963) in vegetation studies.

The application of the useful regions of the spectrum for prospecting is outlined in Table 16. This data illustrates the specific information obtainable by the listed photographic techniques.

The usual technique applied to making aerial photographs is the mounting of the scanning equipment in the carrying craft so that it is aimed vertically downward. Photographs are taken of the terrain at specific intervals during the flight to ensure some overlap between pictures. The overlapping photos are later compiled into a mosaic picture of the entire area photographed. This technique suffers from frequent variation in tone and texture of the film, which may mask details essential to the reconnaissance. Photographs taken from orbital altitudes, such as the dramatic pictures returned by NASA's Gemini mission crews, circumvent this problem by allowing much larger areas to be photographed on one single piece of film. An alternate approach to the still photograph is the exposure of a thin strip of film through a slit. As the film is moved past the slit at a speed related properly to the ground speed of the vehicle, a relatively undistorted picture of the terrain is achieved.

VISIBLE-RANGE PHOTOGRAPHY

Observations of the reflected radiation in the visible and infrared wavelengths have been shown to be useful in discriminating between different species of plants and between healthy and diseased plants of the same species. Photos recording reflectance in the range of 0.32 to 5.5 microns have been used to discriminate among soybeans, corn, wheat, and oats, and have been proposed as a means of conducting agricultural surveys. Moreover, in many cases the earliest symptom of disease or insect infestation is a loss of reflection in the near infrared, just beyond the range of human vision. This phenomenon is

TABLE 16

POTENTIAL VALUE AND USE OF REMOTE SENSORY SYSTEM FOR GEOLOGIC AND GEOBOTANICAL STUDY*

Panchromatic Photography	Panchromatic photography is the most widely used remote-sensing technique because of its availability and relatively low cost. Interpretive techniques are well developed and formal training in its use is available.
Multispectral Photography	Multispectral photography interpretation requires a background of spectral-signature studies of terrain and vegetation. Data returns from multispectral systems may be so voluminous that they cannot be readily interpreted. Some work has been done on interpretation for geologic-lithologic purposes. Little work in vegetation has been accomplished.
Infrared Photography (Black and White)	Infrared photography is of value in mapping drainage features and shorelines. The water is always black in a positive print. Some vegetation characteristics are discernible. Its most valuable use is as an adjunct to, but not a replacement for, standard aerial photography. Some contrast between rock formation is attained; haze is penetrated.
Color Photography	Color photography promises to be a major tool of the geologist/geobotanist and, in many special fields, provides geologic information not only through normal stereoscopic viewing but also through certain color measurement techniques. Narrow-band filters when used for printing in spectral ranges of maximum contrast enhance subtle differences. Electronic enhancement techniques are very promising.
Infrared-Color Photography and Camouflage-Detection Film (Visible, near-infrared 400 to 880 miles)	Infrared-color photography may be superior to standard color photography in some respects. It shows significant differences in vegetation; allows recognition of species, diseases, morphological abnormalities; and shows minimum variation in color and tone of individual species of vegetation throughout the photograph. Less useful for lithologic characteristics, but useful for variation in moisture content.
Infrared Imagery	Useful in locating patterns of ground water movements, moisture content, and areas and lines of thermal abnormalities. Some lithologic interpretation is possible through variations in surface temperature and cooling rates.
Infrared Radiometry	Infrared radiometry is very useful for sequential measurements of changes in land and water surface temperatures because it is a simple measurement technique and data reduction is easier than for infrared imagery. More work is necessary for interpretation of vegetative distribution and physiological abnormalities.
Radar Imagery	Radar imagery is an excellent tool for all-weather coverage of large areas. It is of moderate use in mapping structural features and of some use in differentiating some rock types. It is quite valuable for small-scale planimetric mapping where no better maps are available.

*C. J. Robinove: Paper P/708, International Conference on Water for Peace, Washington (May 23-31, 1967).

being studied as a forestry tool, allowing diseases in forests to be more quickly located (Colwell and Shay, 1965). The identification of the plant disease as insect infestation or as a mineralogical effect on plant nutrition may be possible as study of the technique progresses.

Photographic recording of images has two limiting factors inherent in the process: spatial resolution and intensity resolution. Spatial resolution is the ability to distinguish small, closely-spaced objects, usually expressed as the reciprocal distance between fine lines in the image that can be recognized as distinctly separated. Typical values for this parameter range between 40 and 120 lines per millimeter, although special films are available with finer resolution (Kodak, 1967). Intensity resolution is that between images of slightly different intensity, i.e., differences in the darkening of the photographic image. In black and white photographs, the terms texture and tone are applied in an effort to recognize these parameters.

Spatial resolution, or discrimination based on texture, is limited by film characteristics, the aberrations in the optical system of the camera, vibration of the camera during exposure, the distance moved by the aircraft while the camera is open (ground speed), the resolution available in the viewing equipment, and the like.

Movement of the camera with respect to ground, while the camera shutter is open, causes stretching of points in the image into short lines. The length of such a line is equal to the ground speed times the length of exposure times the scale of the photograph. Suppose the photographing aircraft is traveling at a speed of 250 feet per second at an altitude of 5000 feet above the terrain. The camera has (for example) a focal length of 6 inches. The scale is 1:10,000. Suppose also the shutter exposes the film for 1/500 second. The length of the blur lines on the photograph is 1/500 x (250) x 1/10,000 = 0.00005 foot. Since 1 foot = 304.8 millimeters, the length is 0.01524 millimeter. To distinguish such a blur line from a point, the resolution of the films must exceed (1/0.01524) or 66 lines/millimeter. Values for resolutions for several commercial films are shown in Table 17.

Aberration of the lens system of the camera produces several types of distortion. Straight lines in the object may be curved in the image, particularly if they fall near the edge of the photograph. A point in the object becomes a small spot in the image. The image may not be in focus everywhere on the photographic plate.

TABLE 17

COMMERCIAL FILM RESOLUTION POWER

Film Type	Aerial Exposure Index	Resolving Power of Intensities, Ratio of	
		1000:1	1.6:1
Kodak Plus-X Aerographic, 5401 (D-19 developer, 20 minutes)	80	115	40
Kodak Super XX Aerographic, 5425 (D-19 developer, 20 minutes)	100	75	30
Kodak Tri-X Aerecon, 8403 (D-19 developer, 20 minutes)	200	71	22
Anscopan Aerial Film (Developer No. 1, 16 minutes)	80	125	---
Kodak High-Definition Aerial Film, 3404 (D-19 developer, 20 minutes)	1.6	475	200

The task of designing a lens for an aerial camera is simpler than in the case of a camera for closer work. The aerial camera is always focused at (or near) infinity so that the lens designer does not have to work out a satisfactory compromise between good image quality for an object at infinity and for an object close to the camera lens.

However, even the best possible lens produces some aberration due to the diffraction of light. To illustrate the effect of diffraction, consider this example.

The lens of the camera has a focal length (F) and a diameter (D). The diameter of the spot on the film corresponding to a point on the object is about $2.44\ \lambda\ F/D$, where λ is the wavelength of light. The average value of the wavelengths for visible light is about 0.5 micron. Hence, the spot has a diameter of 0.00122 (F/D) millimeter. The quantity F/D is the F-stop setting of the lens. Thus, for an F/4 lens, the diameter of the spot is about 0.0049 millimeter. Two such spots separated by half a diameter can just be resolved. For this example, the film resolution would have to exceed 410 lines per millimeter in order that diffraction should be the limitation on spatial resolutions.

It is usually stated that the effects of other aberrations are greater than those of diffraction for most optical systems. The case of diffraction-limited optics is thus the ideal case, in which the barrier to further improvement is imposed by a natural law.

Film parameters which determine the usefulness of a given type of black and white film in aerial photography are film speed, resolving power, spectral response, latitude, and contrast.

Film speed is the reciprocal of the exposure time required to produce a negative of optimum contrast when exposed to the terrain under standard daylight at a standard F-stop. A numerical value of the film speed is called the aerial exposure index. The aerial exposure index is defined for an F-stop of 17.9. Thus, films having an index of 80 should be exposed for 1/80 second at F/17.9, 1/100 second at F/16, 1/1000 second at F/5.1, etc., when photographing terrain with normal daylight.

Resolving power is defined in terms of the spacing of lines on a test pattern formed on the film. To determine the resolving power, a standard test pattern is photographed at several magnifications. The finest spacing of lines that can be resolved, expressed as lines per millimeter, is the resolving power. Resolving power depends on the contrast in the image, or ratio of maximum-to-minimum light intensity. The resolving power at a contrast ratio of 1000:1 is about twice as great as at a contrast ratio of 1.6:1. Resolving power and film speed are both related to the nature of the film emulsion and have an inverse relation to each other. Fast film has a lower resolving power than slow film, as can be seen from the values presented in Table 18. Typical values for resolving power range between 40 and 120 lines per millimeter.

The importance of the resolving power of the system, which is the combined effect of shutter speed, aircraft ground speed, lens aberrations, film resolving power, and scale factor, is that it limits the ability of the system to detect small objects on the ground. The relationship is given simply by the ratio of resolving power to scale factor. Suppose, for example, aerial photographs are taken at a scale of 1:20,000, and the resolving power is such that 20 lines per millimeter can be resolved. The dimensions of the smallest object on the ground that can be resolved is given by:

$$\text{Ground Resolution} = \frac{\text{Resolving Power}}{\text{Scale Factor}}$$

for example,

$$\frac{(1/20)\ \text{millimeter}}{(1/20{,}000)} = 1000\ \text{millimeter} = 1.0\ \text{meter}$$

Thus, lines on the ground spaced 1 meter apart can be resolved with this system. Table 18 shows estimates of instrumental resolution needed to ensure meaningful data applicable to geological studies, including biogeochemical efforts.

TABLE 18

ESTIMATES OF INSTRUMENT RESOLUTION NEEDED TO ENSURE MEANINGFUL CONTRIBUTION TO SOME GEOLOGIC APPLICATION AREAS OR PROBLEMS*

Specific Application (or Geoscience Problem), Parameters to be Measured, and Sample of Interpretive Features to be Studied	Most Important Applicable Sensing Instrument	Resolution		Wavelength
		Meters	Temperature by Infrared, C	
STRUCTURAL CONDITIONS				
Delineation of small folds (200 inches from trough) Observations of attitudes of rock beds, distribution of rock units, from analysis of drainage patterns, from study of soil moisture distribution	Photography Radar Infrared Imagery Ultraviolet Imagery	1.5 20 300 60	 0.1 	~100mμ
Delineation of large folds (from 200 inches to several miles) Observations of attitudes of beds, distribution of rock units, from analysis of drainage patterns, from study of soil moisture distribution	Photography Ultraviolet Imagery Radar Infrared Imagery, Ultraviolet, and Infrared Spectroscopy	6 150 300 600	 0.1	~100mμ
Delineation of linear elements (e.g., faults) Observation of alignments of features—commonly topographic features or abnormalities in soil moisture content expressed directly by contrasting vigor of vegetation, or by variations in surface near-surface temperature	Photography Infrared Passive Microwave Radar	6 300 900 30	 0.1 0.05 	~300mμ
STRATIGRAPHIC				
Assumes low dip and major interest in units 20 inches or more in thickness Differentiation of like and unlike rock units analysis of their spatial distribution and, if possible, identification of rock types Comparison of absorption emission characteristics, of vegetation and of rocks	Ultraviolet Radar Infrared Imagery Ultraviolet Spectroscopy Photography	3 6 300 30 1.5		 50A ~100mμ
PETROGRAPHY				
Deduced from landform, and color of rocks and residual soils, or determined from spectroscopic observations in ultraviolet and infrared parts of the spectrum	Photography Infrared Spectroscopy Ultraviolet Spectroscopy Radar	6 300 30 		100mμ 0.5μ 50A
ENGINEERING PROPERTIES				
Compaction (deduced indirectly)	Infrared Imagery Photography	300 30		
Slope stability Observe landslides, slope distributions, abnormal moisture distributions	Photography Infrared Imagery	30 3000		
"Fine-scale" roughness Variations in goniometric distribution of reflected/emitted radiation and analysis of absorption/emission coefficients	Photography Infrared Imagery Infrared Radiometry Passive Microwave Radiometry Radar	30 300 300 1500 30		
Permeability Analysis of drainage, soil moisture distributions	Photography Infrared Imagery	1.5 300	 0.5	
GEOTHERMAL STUDIES				
Gross geothermal gradients Observations of radiant temperature distributions	Infrared Imagery Passive Microwave Radiometry Infrared Radiometry Photography	900 3000 300 60	0.05 0.01 0.05 	
Local geothermal anomalies Observations of radiant temperature distributions	Photography Infrared Imagery Passive Microwave Radiometry Infrared Radiometry	6 900 1500 300	 0.05 0.01 0.05	
Volcanoes *Observations of seismic activity tumescence and* radiant temperature distributions, and intensities Telemetering links from seismometer and tilt meters	Infrared Passive Microwave Photography	300 150 15	1.0 1.0 	
GEOMORPHIC STUDIES				
Source-deposit relationships of sediments Analysis of spacial relationships of source area and transport mechanisms—measurements of volumes of deposits	Photography Radar	30 		
Mountain building and denudation Observations of altitudes and changes of altitudes with respect to the center of the sphere	Photography Laser Altimetry Radar	15 1 		
GLACIOLOGICAL STUDIES				
Inventory of ice features Observation and measurement of ice features, e.g., bergs, glaciers	Radar Infrared Imagery Photography	30 150 15	 1.0 	
PREPARATION OF BASE MAP FOR PRESENTATION OF RESULTS (1:250,000 scale)				

*Reference: U S. Geologic Survey, "Detailed Plan and Status Report of Unclassified United States Geological Survey Research in Remote Sensing Under the Natural Resources Space Applications Program" (NASA-CR-75565).

Spectral response is defined as the amount of darkening produced by a standard exposure of the film to light of a given wavelength. For aerial photography, a high response to the longer wavelengths (green, yellow, and red) is more useful than a high response to shorter wavelengths (blue, violet, and near ultraviolet), since the latter are easily absorbed and scattered by haze. For this reason, the camera lens or the films must be equipped with a filter that removes the shorter wavelengths (blue and violet) to achieve a clear image.

Film latitude denotes the range of light intensities that can be recorded on the film. Contrast denotes the change in darkening or density per unit fractional change in exposure or light intensity. Inasmuch as the useful range of density is limited, these two quantities are related. The greater the contrast of a film, the less the latitude.

PHOTOGRAPHY IN THE NEAR INFRARED

Near infrared is the region of the electromagnetic spectrum denoted for most photographic purposes as that extending from 0.7 to about 1.0 micron. The shorter wavelength (0.7 micron) is the long-wavelength limit of the visible spectrum. The longer wavelength (1.0 micron) is approximately the upper limit recorded by infrared film.

The equipment used for near infrared aerial photography is identical or similar to conventional photographic equipment, except for the films. Two types of infrared films are commercially available. One type forms a black and white (monochrome) negative. The film itself is sensitive to radiation over a broad band of wavelengths, extending from some point in the visible spectrum (0.4 to 0.7 micron) out to about 1 micron. To use this film exclusively in the infrared region, the camera must be equipped with a filter that rejects radiation of wavelengths shorter than 0.7 micron. The other type of commercial infrared films has three sensitized layers which are sensitive to green, red, and infrared. Because the three dyes are by necessity optically visible colors, the film is a false color film. Although originally developed to detect camouflaged objects, this film now is widely used in forest survey work.

MEDIUM AND FAR INFRARED IMAGING

The medium and far infrared regions include wavelengths of about 1 to 50 microns. The medium region is arbitrarily defined as that from 1 to 15 microns, in which solid-state detectors of the photovoltaic or photo-resistive type are used. In the longer wavelength, far infrared region, temperature sensors are the only available detectors. These sensors, which respond to the heating effect of the radiation, are either thermo-couples or resistance thermometers. In the medium infrared range, refraction optics can be used, while reflection optics are required in the far infrared range. In practice, the optics of infrared imaging devices are designed usually for a variety of detectors, so that reflection-type optics are included in nearly all equipment. The images displayed by one of these infrared devices are equivalent to temperature distribution maps of the object or surface observed.

Figures 24 and 25 illustrate the infrared technique by recording thermal radiation of different targets at different times during the day. These photos were taken with the camera looking downward from an elevated platform, the water tower on the Davis campus of the University of California (Colwell, 1967). They illustrate fluctuations of emitted radiation of the targets, which have different heat capacities due to moisture contents, reflectance, surface, radiation, transpiration, convection, absorbance, etc. The target materials, identified in Fig. 24, were selected for the purposes of "calibrating" the interpretation of thermograms of abstract materials, the properties of which were somewhat familiar to the investigators, and materials which were expected to be found in the field area to be studied later. The study of the target array included the monitoring of surface temperature of each component of the array at the same time as the thermogram was recorded, which allowed correlation of the image obtained with actual temperatures. Thermograms were taken at various times of the day, as various target components were heated by the sun. The objective of the experiments was to ascertain the usefulness of thermal infrared sensing devices as one component of a multispectral reconnaissance

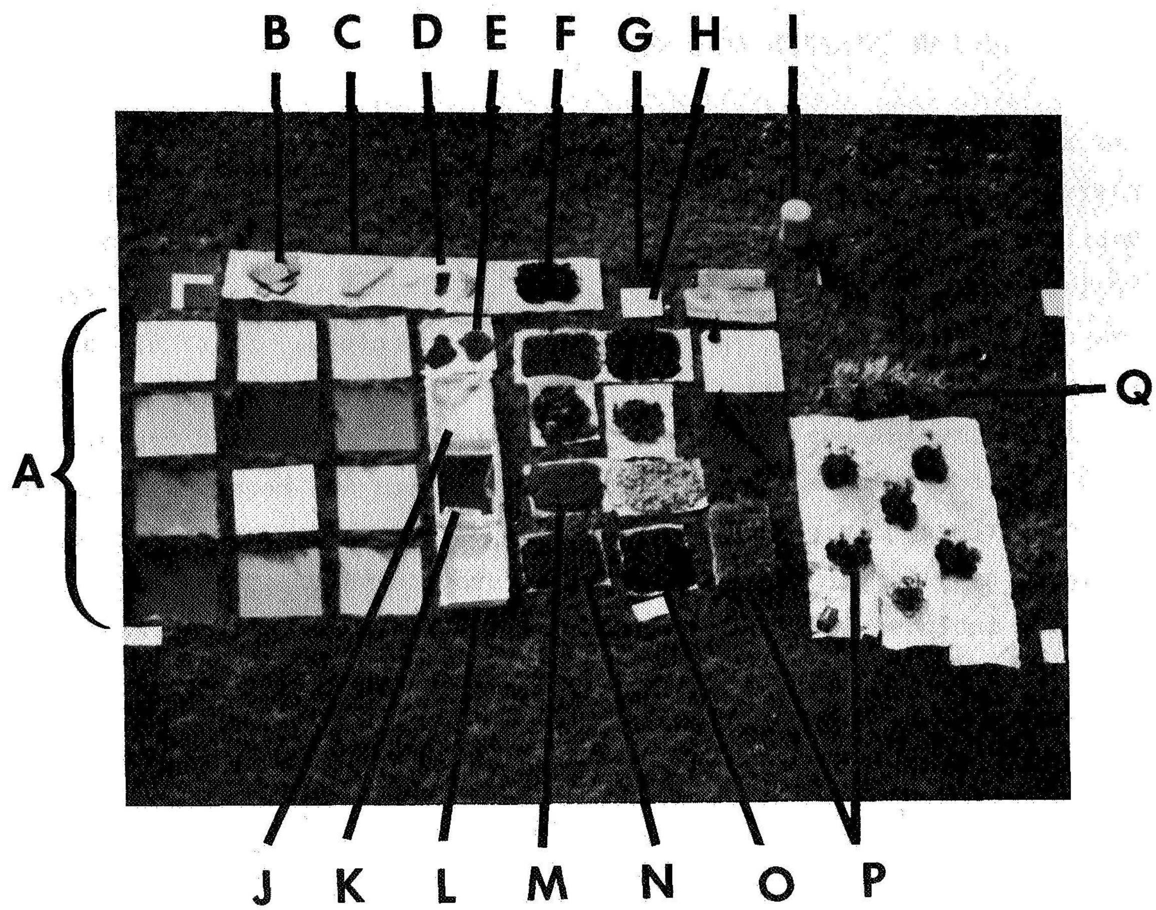


Figure 24. Simulated Aerial Photo Taken with Panchromatic Film and a Wratten 12 Filter From the Camera Station

A. Masonite Panels
B. Asphalt
C. Concrete
D. Granite
E. Lava
F. Charcoal
G. Black Painted Aluminum
H. Shiny Unpainted Aluminum
I. Garbage Can Half Filled with Water
J. Foamy Water (Detergent Added)
K. Muddy Water
L. Clear Water
M. Dry Dubakella Soil (Red)
N. Moist Dubakella Soil (Red)
O. Wet Dubakella Soil (Red)
P. Healthy Pine Seedlings
Q. Dead Christmas Tree

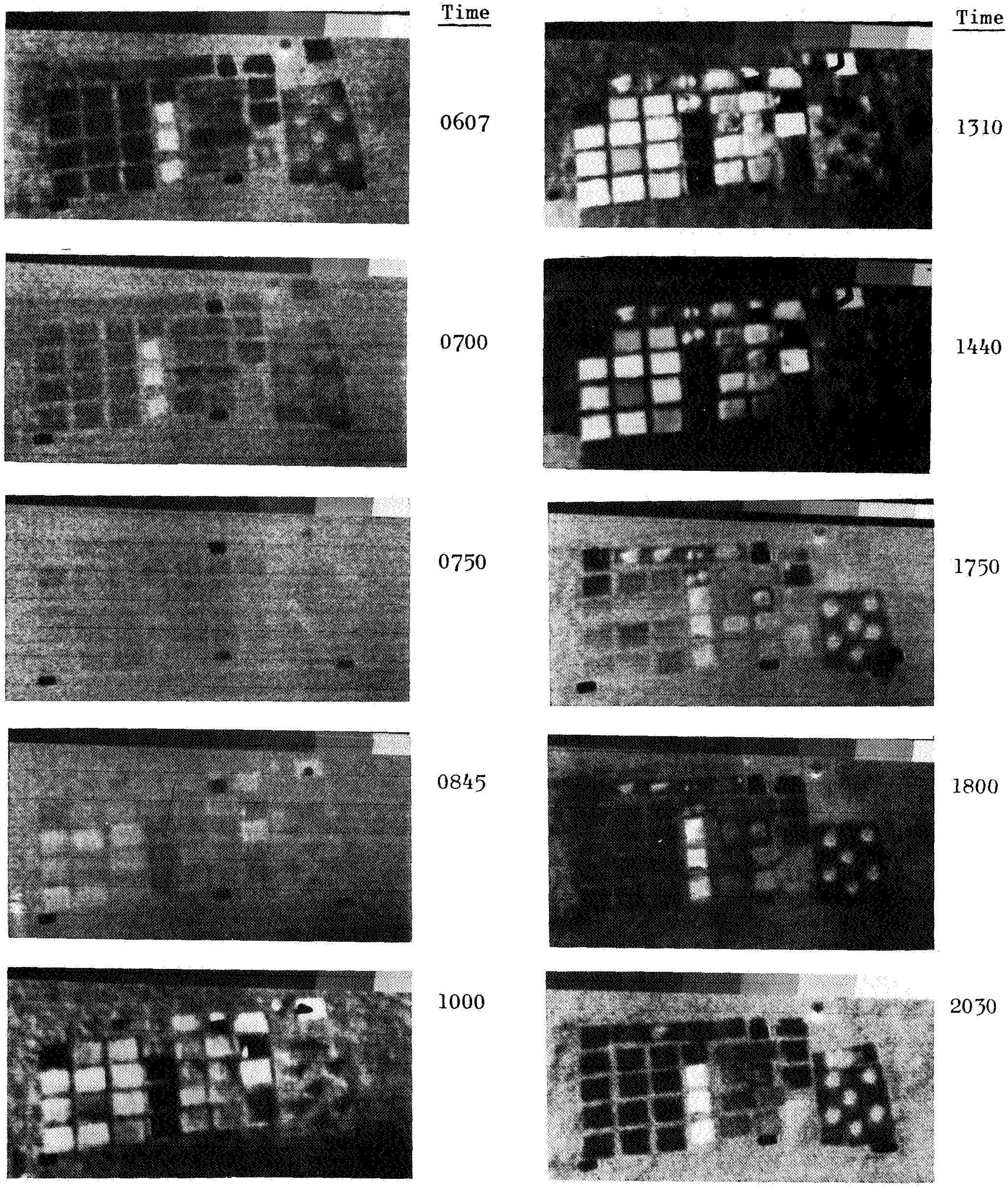


Figure 25. Thermograms of the Davis Target Array Illustrating Diurnal Fluctuations of Emitted Radiation

system intended to identify various features present on agricultural and forested lands. The equipment used for the study included a Barnes Infrared Camera, having a wavelength sensitivity in the 8- to 14-micron infrared band.

After completion of the tests of the target array, the equipment and part of the array were transported to Yosemite National Park. The camera was positioned at Glacier Point, about 3200 feet above the floor of Yosemite Valley where the target was assembled. Figure 26 shows thermograms of the valley, which illustrate diurnal fluctuations of the radiation emitted from various terrain features found there. Figure 27 is a panchromatic photo, and Fig. 28 is an Infrared 89B photo of the valley. They are included to permit comparison of familiar panchromatic photography with an infrared image of the same area.

The study performed by Colwell indicated that, while single thermograms might not yield useful information about terrain features, thermal infrared images obtained at different times during the diurnal cycle of temperature fluctuations do provide a fairly uncomplicated tool for terrain study. The approach taken by Colwell to gain "calibration" and field data appears to be the most useful for relating ground truth to multispectral data, then correlating this with an unfamiliar area.

A basic limitation of all successful infrared imaging devices developed so far is the time required to form an image. Each of these instruments employs a single detector. A pair of oscillating or rotating mirrors in the optical system is used to expose the detector sequentially to different areas of the image. The electrical output of the detector is combined with electrical outputs from position indicators attached to the two moving mirrors to generate a visible representation of the image. The visible representation may be formed on photosensitive paper or on a cathode-ray tube.

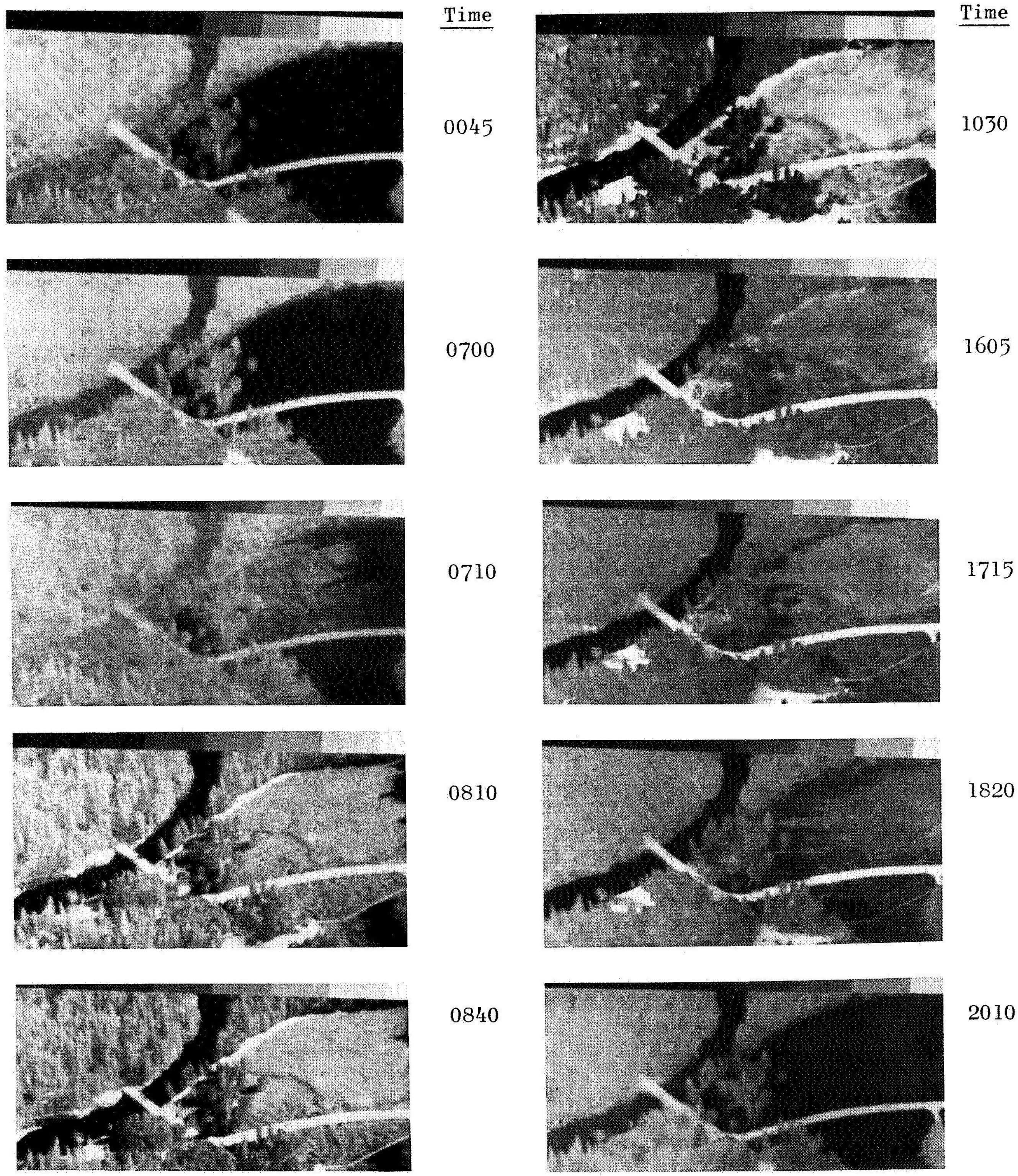


Figure 26. Thermograms of Yosemite Test Site No. 1 Illustrating Diurnal Fluctuations of Emitted Radiation From Various Terrain Features

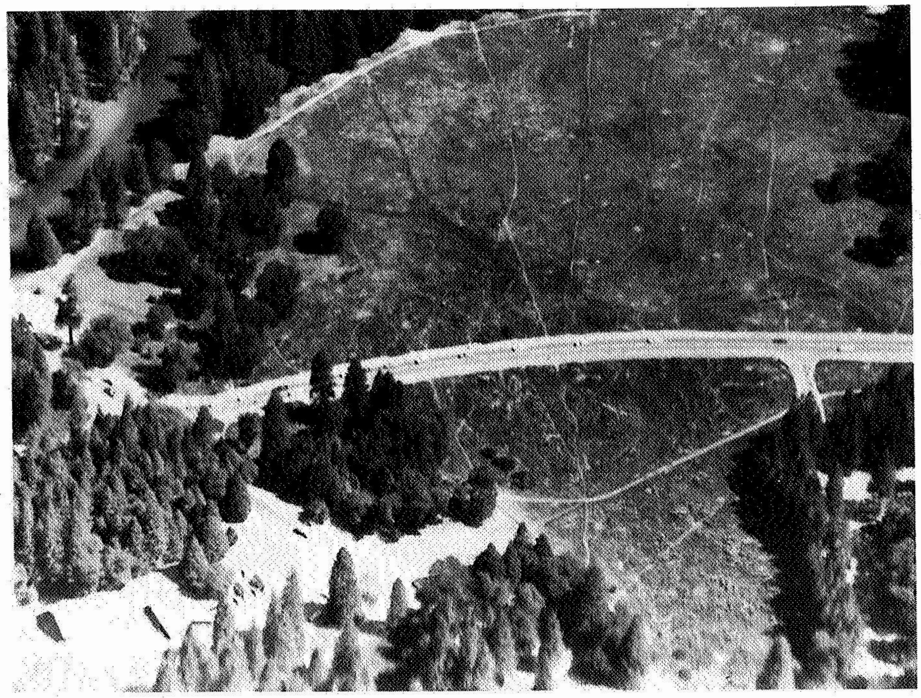


Figure 27. Yosemite Test Site No. 1 (Panchromatic Film)

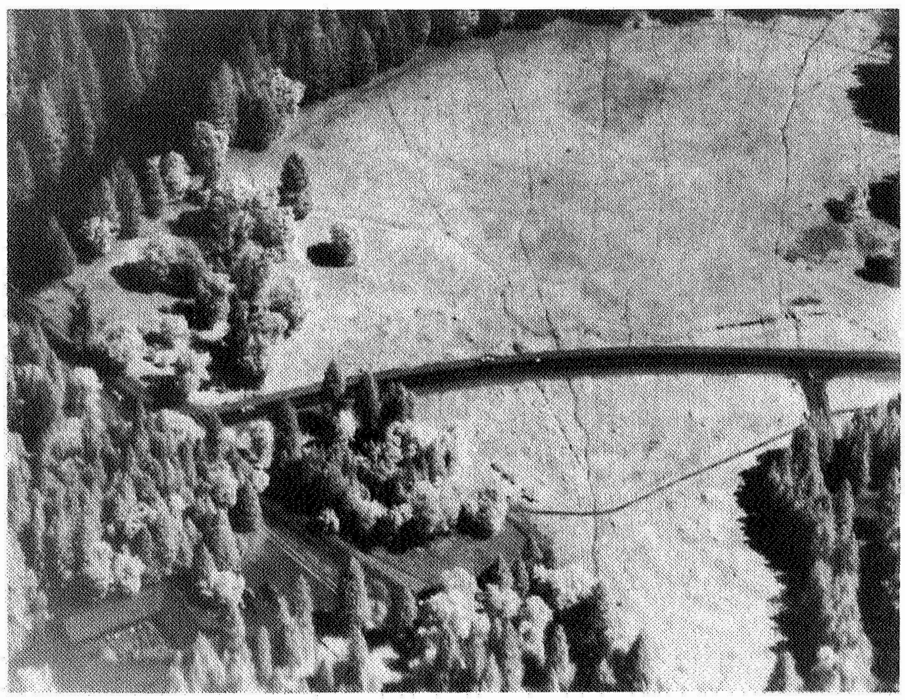


Figure 28. Yosemite Test Site No. 1 (Infrared 89B Film)

The time required to complete a scan cycle and form a complete picture of the image is determined by the time response of the detector and the desired resolutions of the finished picture. The semiconductor detectors used in the medium infrared range respond directly to the radiation by processes that are analogous to the photoelectric effect. These detectors have short response times, generally less than a microsecond.

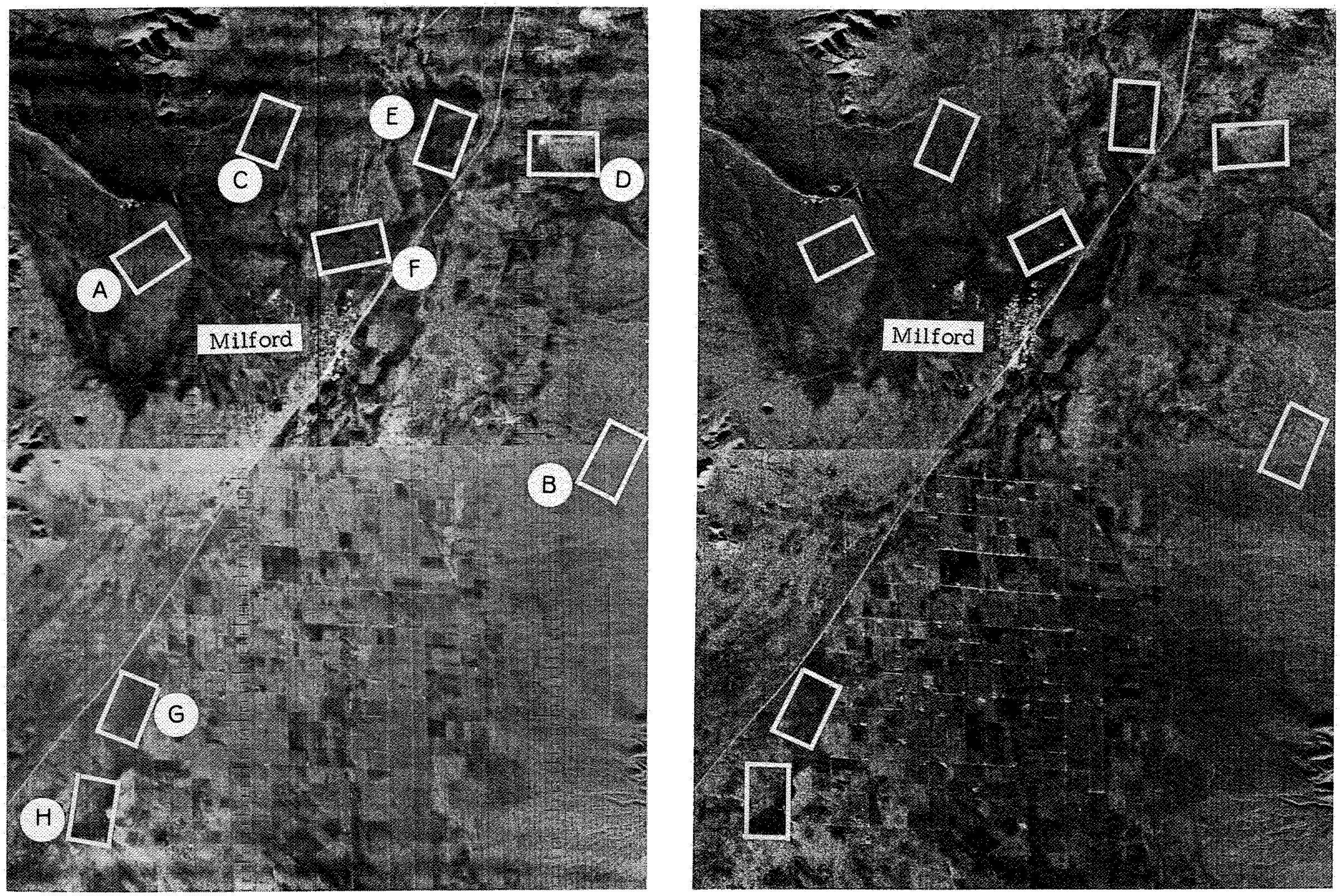
The thermocouple or resistance-type detectors, which are used at the longer wavelengths, do not respond directly to the radiation, but rather to the heating effect produced by it. These detectors have relatively long response times; on the order of a millisecond or longer.

RADAR AND MICROWAVE IMAGERY

In contrast to infrared imaging devices, where airborne instruments are not generally available, radar technology has included reliable airborne equipment for many years. Although techniques for analyzing plant life for prospecting purposes have not been developed, the radar region of the spectrum (relative long wavelengths, 1 to 10 centimeters) should be most useful in ascertaining gross physical shapes of vegetation. Microwaves (0.1 to 1.0 centimeter) have not been used under airborne conditions, but have been widely used for communication.

Radar is an active system, comprising both a source of radiation and a detector. The other techniques discussed above rely solely on natural sources of radiation, such as reflected sunlight and thermal radiation from the earth. The radar source is accurately controlled with respect to frequency, pulse duration, and phase of polarization. Changes in frequency and phase of polarization of the reflected signal can be detected readily and used as additional aids in identifying or characterizing the terrain. Travel time between the radar set and the object can be accurately measured, hence distances to various objects on the ground and features of the terrain can be determined without the use of stereoscopic pictures. Because of the long wavelengths of radar waves, the radiation will penetrate to some depth below the surface of dry soil. (Radar returns have been obtained from rock layers many feet below the soil surface.) Most radar equipment operates at wavelengths that are transmitted without appreciable attenuation by the atmosphere, making a radar set an all-weather observation instrument.

To date many of the advantages of radar in aerial observation have not been exploited. Some work has been done in relating the polarizations of the echo to the plant life and other details of the terrain (Morain and Simonett, 1966). Even so, some rather interesting pictures have been obtained with radar, two of which are shown in Fig. 29a and 29b.



(a) HH Polarization (b) HV Polarization

Figure 29. K-Band Radar Positive Imagery of a Portion of Escalante Valley, Utah (From Morain and Simonett, 1966).

Figure 29 shows two radar images of the region around Milford, in the Escalante Valley, Utah. The left image was formed with the horizontally polarized component of the received signal or echo, while the right image was formed with the vertically polarized component. In both cases, the transmitted signal or source was horizontally polarized, so that the notation is designated by HH and HV, respectively, indicating the polarization of the signal and the echo. The fact that the right image could be formed is due to the depolarizing effect of the terrain.

The radar return patterns in these images correspond primarily with vegetation patterns, and also to the roughness of surface material where the shrubs are widely spaced. Sharp boundaries in the film density are judged to be due to vegetation changes, since the surface material undergoes only a gradual change in particle size. The absence of distinct variations in image texture makes separation of vegetation zones difficult, so that film density patterns were used for visual interpretation of the images. The areas marked A through H were studied later on the ground to provide verification of the interpretation. In general, vegetation types are related to conditions of soil texture, salinity, and depth, which allows recognition of distinct elevational zones. Species are segregated into zones, but height and geometry are quite uniform. Shrubs are small, intricately branched, irregularly deciduous, and widely spaced. Dead bushes are plentiful and often remain intact.

Probability density curves were prepared to relate density of the image to vegetation types on the basis of the field investigation (Fig. 30). The interpretation is of interest even with only visual examination of the images: Areas A, B, and C are populated with sagebrush (Artemisia tridentata), with almost no grass understory, on a pebble surface. Area D has bare land with several pockets of sagebrush. Sites E, F, and G contain largely shadscale (Artiplex confertifolia), over fine-textured soils. Area E, however, contains a tight mosiac of other shurb species, such as greasewood (Sarcobatus vermiculatus) and little rabbit brush (Crysothamnus lanata), and G contains patches of saltgrass. Interpretation from area H was not clear. An aerial photomosaic of the same region is shown

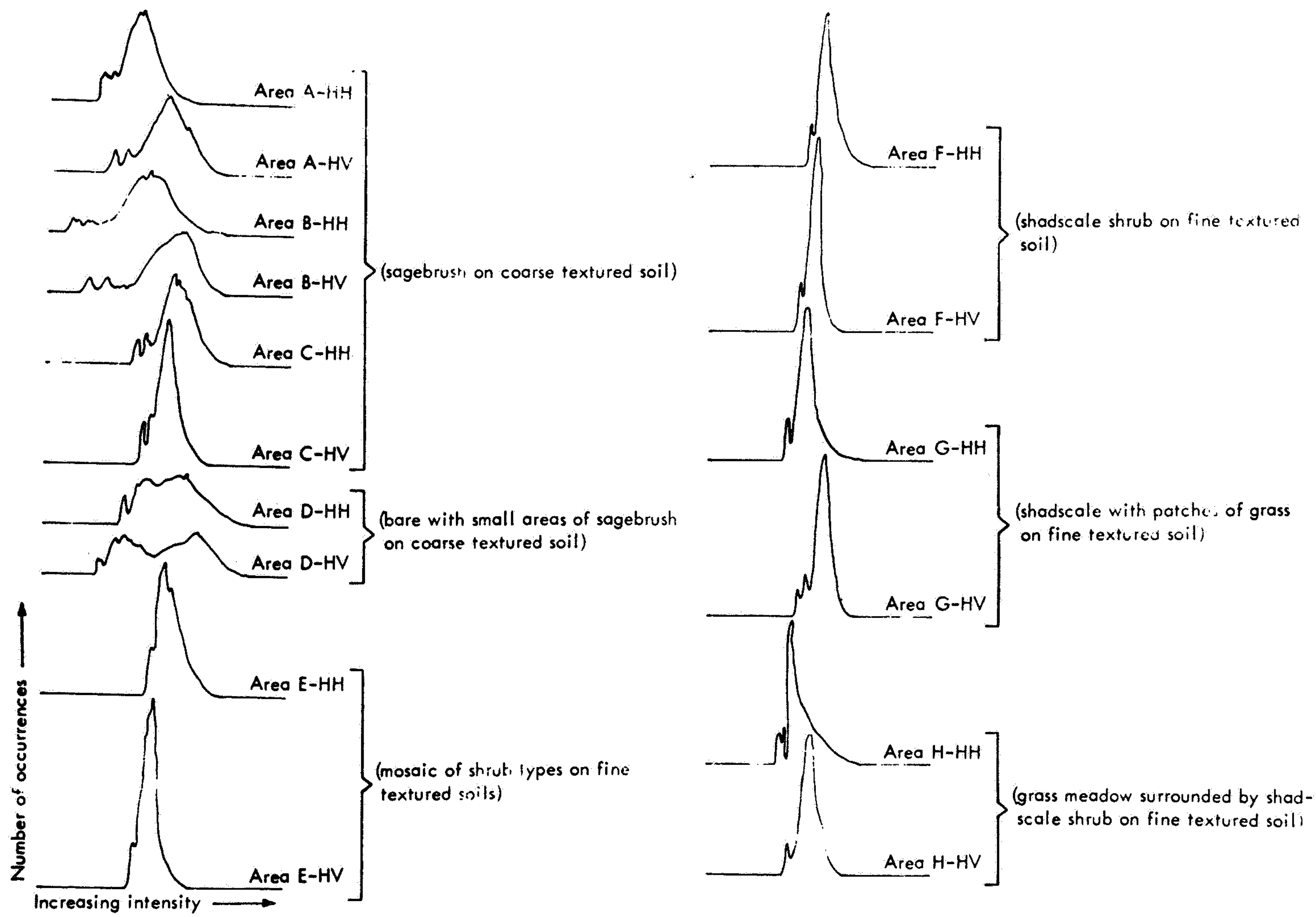


Figure 30. Probability Density Curves for Representative Vegetation Types (Film Densities) in Escalante Valley, Utah.

in Fig. 31. Morain and Simonett conclude from this study that a combination of radar imagery and analytical interpretation techniques would be useful in mapping vegetation zones in the semiarid part of the United States.

Figure 32 shows a similar pair (HH and HV polarizations) of radar images of the region near Horsefly Mountain in south-central Oregon, also studied by Morain and Simonett. This region is covered with a coarse mosaic of pine forest and low-lying shrub and grass. The areas marked are those studies by means of the probability density curve technique applied by the investigators. The curves are shown in Fig. 33. Area A is marsh, B is dry prairie, and C is grass-shrub transition. Area D is a forested section, and E represents forest-shrub transition. (A complete discussion of the interpretation may be found in the reference cited.) Note the gross similarity between the curves for the different vegetations studied in Utah and in Oregon; as the authors point out, secondary peaks and minor variations in the shapes of the prepared curves are important diagnostic differences to be noted in vegetation analysis by this technique.

Radar has been proposed as a general-purpose instrument in orbiting observational satellites, particularly for studying weather, by using a wavelength that is reflected by clouds and water vapor (Rause, Waite, and Walters, 1965; Moore and Simonett, 1967). To date, however, the power requirements of such a radar system (about a kilowatt) have been too high for use in a satellite powered by solar cells.

Table 19 presents a summary of the parameters of various types of remote sensors built or designed for geologic experiments to be conducted from orbital altitudes as of March 1966. The data was compiled by the U.S. Geological Survey for presentation in "Detailed Plan and Status Report of Unclassified United States Geological Survey Research in Remote Sensing under the Natural Resources Space Applications Program" (NASA-CR-75565). Some parameters not discussed above are included, but whose dimensions appear self-explanatory.

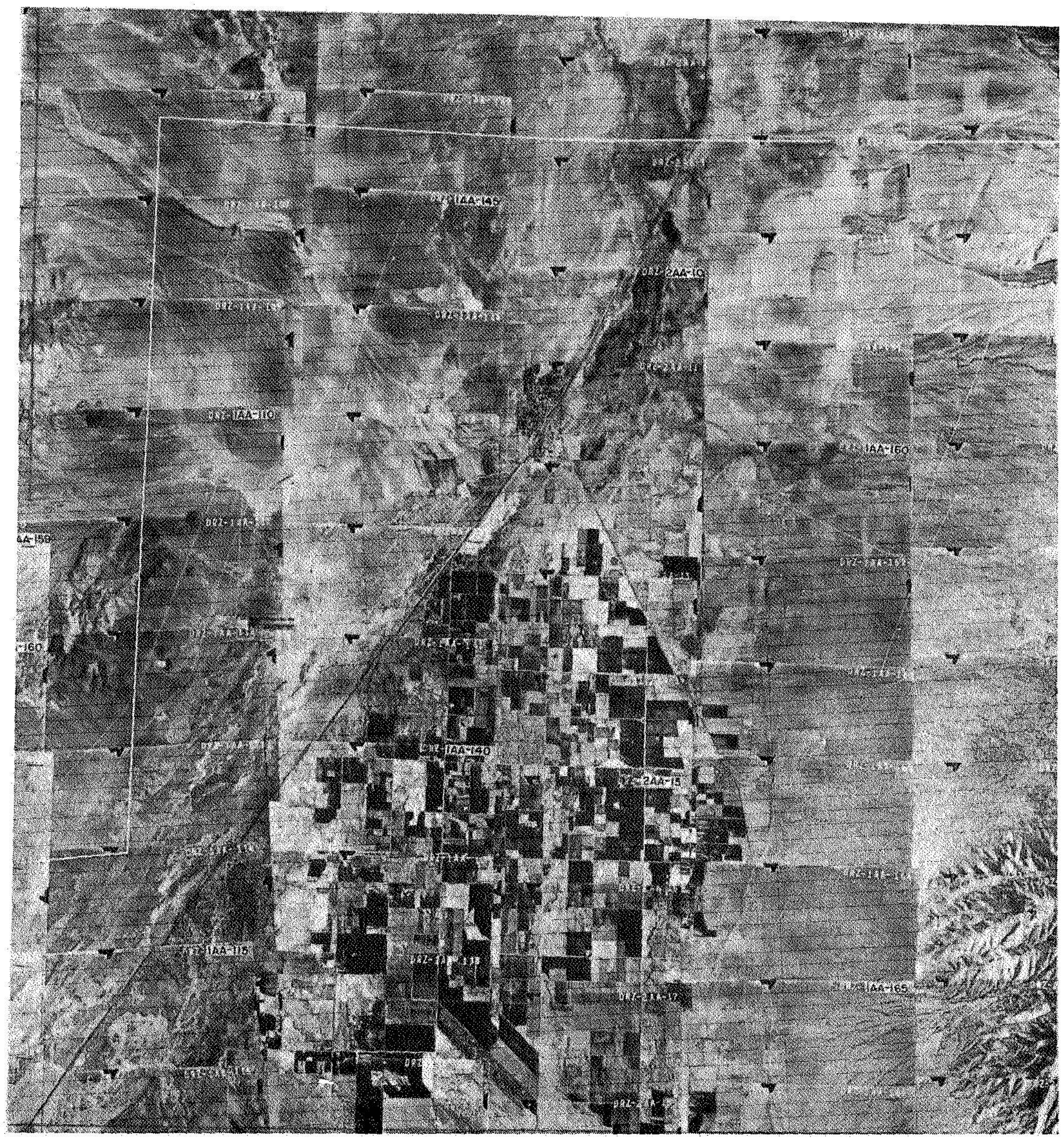
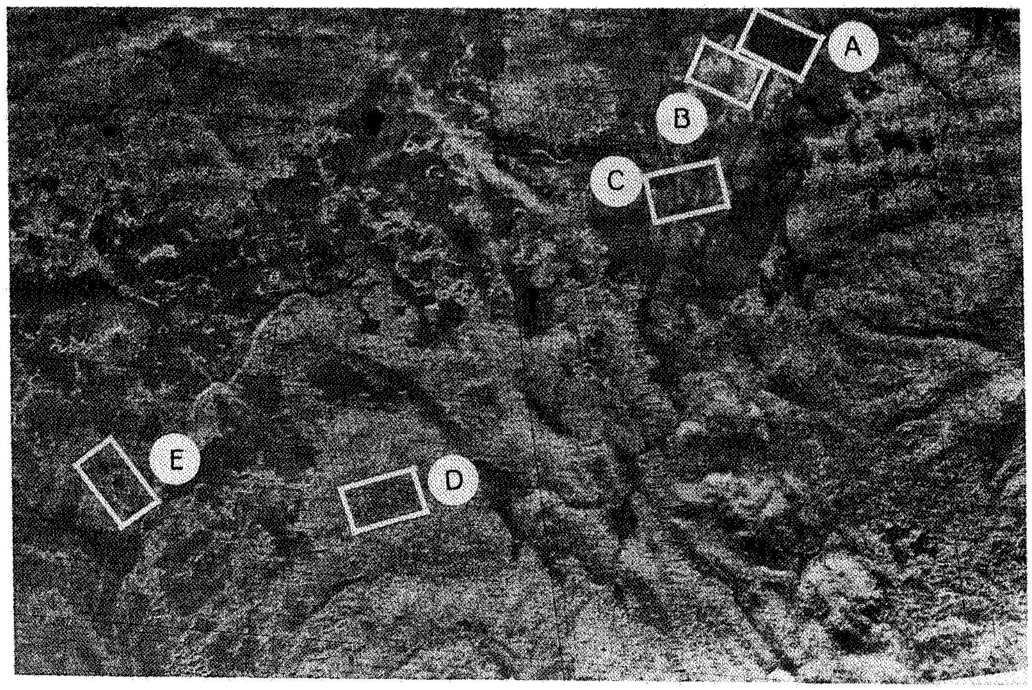
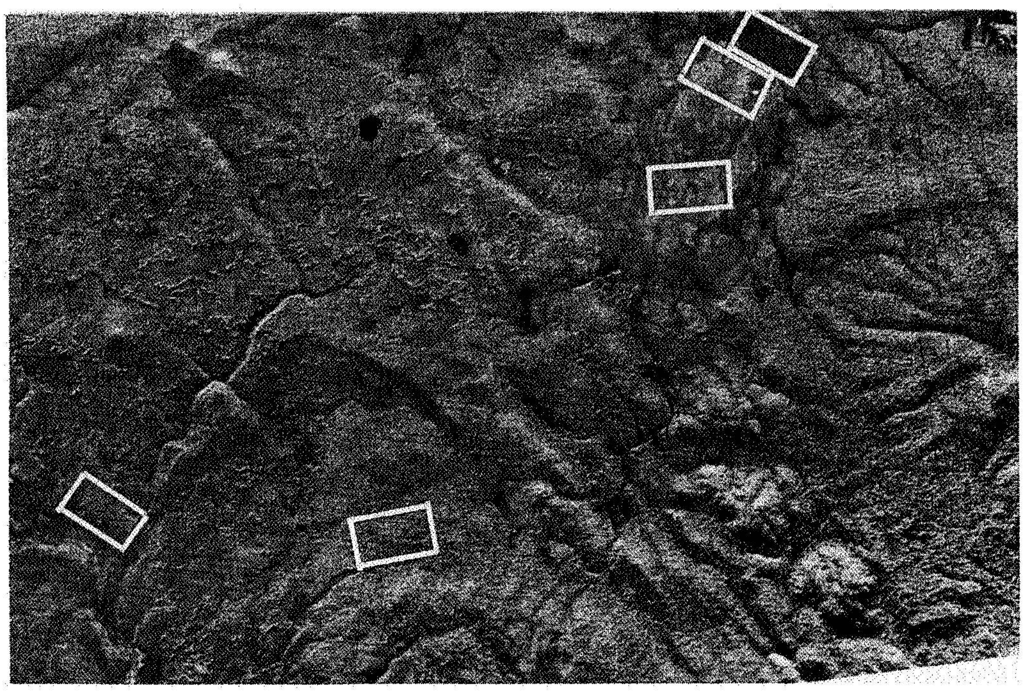


Figure 31. Airphoto Mosaic of Portion of Escalante Valley, Utah, Reduced to Scale of Radar Imagery (Morain and Simonett, loc cit).



(a) HH Polarization



(b) HV Polarization

Figure 32. K-Band Radar Positive Imagery for the Vicinity of Horsefly Mountain, South-Central Oregon (Areas A through E represent the major film density and image texture classes which were utilized in preparing a tentative vegetation map for this area).

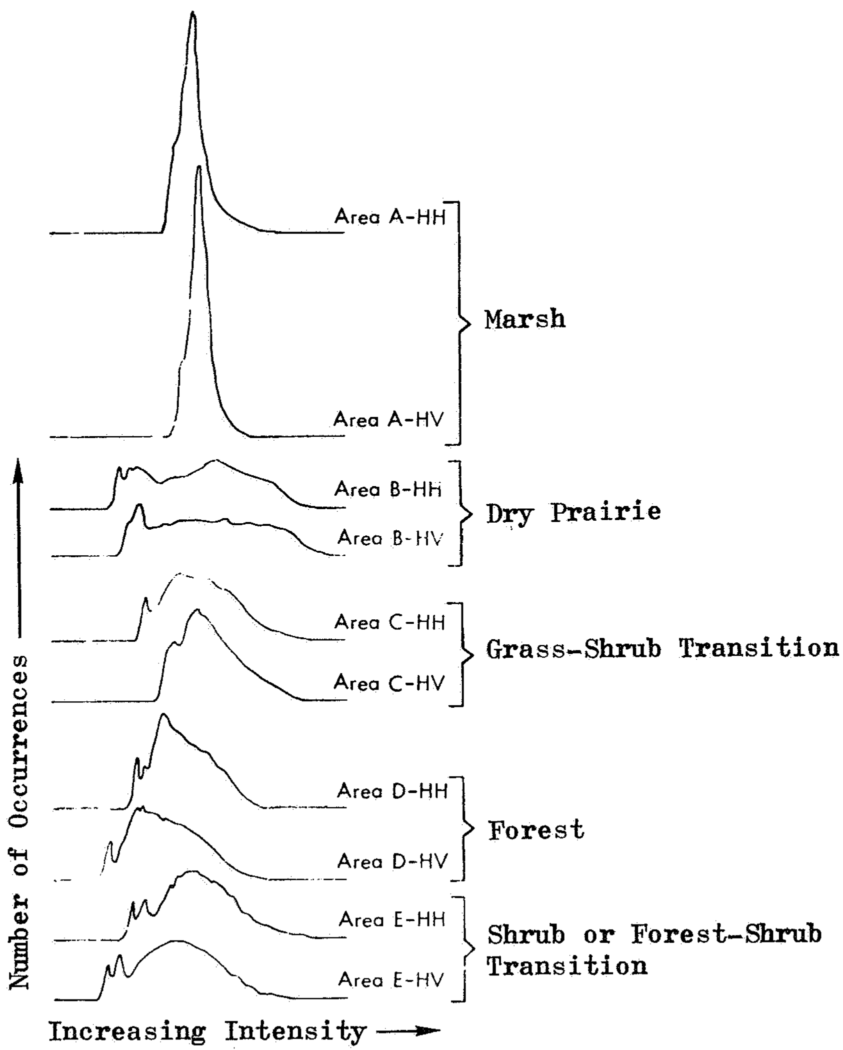


Figure 33. Probability Density Curves for Representative Vegetation Types (Film Densities) in South-Central Oregon

TABLE 19

PARAMETERS OF REMOTE SENSOR INSTRUMENTS DESIGNED FOR SPACEFLIGHT GEOLOGIC EXPERIMENTS USING THE ELECTROMAGNETIC SPECTRUM

Experiment or Equipment	Operating Spectral Range	Estimated Total Weight, pounds	Estimated Total Power, watts	Estimated Dimensions, ft^3	Resolution (from 125 Nautical miles), meters	Instrument Description	Estimated Data Rate	Windows Required	Pointing Accuracy Required
Metric cameras	Visual 0.3 to 1.0 μ	1000	100	50	<12	Two 12-inch frame cameras	16 lbs. film per day depending on coverage	Open port for vertical viewing	±0.5° 0.05°/sec
High-resolution panoramic cameras	Visual and near infrared	1400	200	50 to 100	<4	Two 24-inch panoramic convergent cameras	1.0 lb film per 100 nautical miles ground track	Open port 1 by 1.5 feet	±0.5° 0.05°/sec
Ultrahigh-resolution camera (telescope)	Visual and infrared	900	900	50 to 100	<2	One tracking telescope and one 70 mm frame camera	2 lb/orbit film (land coverage)	Open window or viewport 2 by 3 feet	A few seconds of arc
Synoptic multiband cameras	Visual and near infrared 0.35 to 1.5 μ	900	200	50	<30	Four 6-inch frame cameras	1.5 lb/orbit film (land coverage)	Access to telescope mount	0.1° to 0.5° with image motion compensation
High-resolution radar imager (coherent)	8.0 gc	210 (radar with antenna and recorder)	550	13	15 by 15 (independent of altitude)	Synthetic-aperture antenna, imaging radar	~ 5 lb/orbit film (100X land coverage)	None (antenna external)	0.05° yaw, 1° pitch and roll
Ultraviolet spectrometer imager	0.39 to 0.49 μ 0.58 to 0.68 μ (luminescence) ~0.35 to 0.4 μ imagery	125	100	2	20	Spectrometer, for optics, recorder, and imaging system	103 K bits/sec (film, tape, or transmission)	Open port or viewport (high silica glass)	0.5 sec/sec
Altimeter scatterometer	0.4 and 8 gc	50 (radar and recorder)	220	18 (antenna length 27 feet)	13,500 (0.4 gc) 1700 (8 gc)	Pulsed altimeter scatterometer	4.4×10^8 bits per orbit	None (antenna external)	±3° in all arcs
Infrared imaging	0.5 to 16 μ (three or more bands)	80	13	2.5	1	Infrared detector array, optical mechanical scanner	40-Kc rate stored on film	Open hatch	0.02 to 0.5 deg/sec
Infrared spectral emission	7 to 30 μ	60 (without tape recorder)	55	3.9 (without tape recorder)	2500 (0.5 km with 16-inch telescope)	Infrared spectrometer 0.1 μ resolution	100 to 300 bits/sec	1 Ge or Si window: larger than collecting optics	Observed area variation less than 10% over 0.5 to 2 sec of time
Passive microwave imaging (steroscopic)	9 gc center Δ F-1 gc	150 (without film)	100 (avg) 150 (peak)	Antenna (3 by 5 feet) internal (2 by 2 by 2 feet)	3000	Dual-beam electronic scan, microwave images	70 mm kalvar film (600 feet: 30-day mission)	None (antenna external) viewfinder	±0.25° (known to ±0.1°)
Passive microwave spectrum emission	0.4 to 21 cm (six bands)	100 (excludes power and recording)	50 (standby) 200 (avg) 250 (peak)	Antenna (6-foot diameter by 1 foot)	3000 to 7000	Six-channel microwave radiometer	720 bits/sec on magnetic tape	None (antenna external) viewfinder	±0.25° (known to ±0.1°)

Figure 34 visually represents the collection of spectral data by satellite. The vehicle depicted is the Apollo Lunar Command Module, but the system of data collection is generally applicable. The same system undoubtedly applies to data collection from any surface from orbital altitude, using the electromagnetic spectrum.

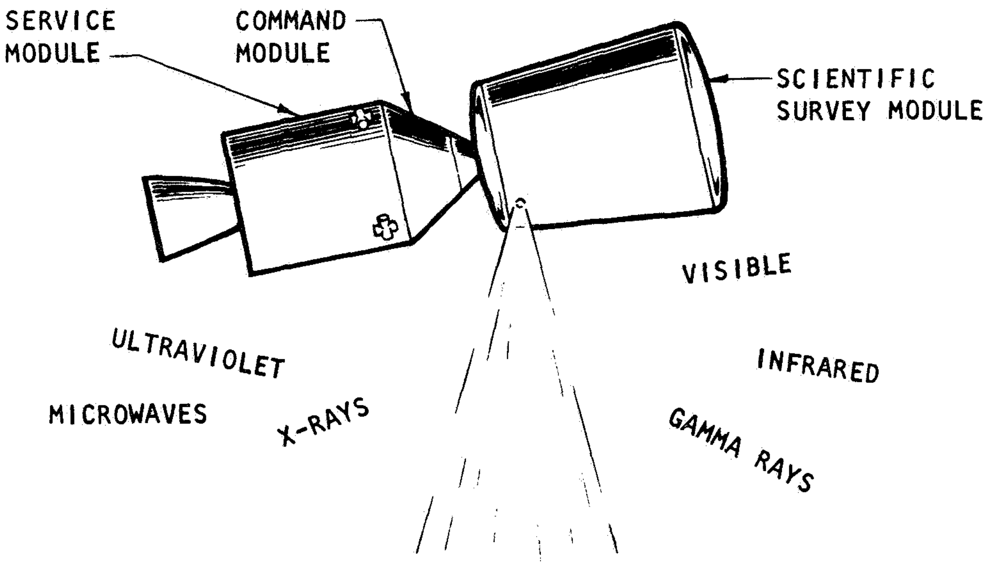


Figure 34. Pictorial Representation of Data Collected From Lunar Surface by Satellite.*

*Reference: Peter C. Badgley, NASA, Proceedings of the Third Symposium on Remote Sensing of Environment, The University of Michigan, Ann Arbor, Michigan, p. 14 (1964).

CALIBRATION OR ESTABLISHMENT OF GROUND TRUTH

In nearly all aerial surveying techniques, it is necessary to make careful observations of a selected area on the ground to provide a reference or calibration point for the survey map. The technical term for this calibration is called "ground truth." The reason for establishing this point of reference is that all of the imaging techniques discussed provide maps in which the relative darkening of any given incremented area provides only a relative measure of the intensity of the reflected or radiated electromagnetic radiation from the corresponding area on the ground. In the discussion of the Colwell work above, the project was outlined by which the average temperatures of a portion of the terrain were measured. At the same time, a thermogram of the terrain was made.

The establishment of points of reference would also be performed, for example, after a preliminary multisensor survey of an area in which it is suspected that there are deposits of some valuable mineral, such as copper. The resulting vegetation map may show several areas in which the vegetation appears different from that in the rest of the region. This difference may be due to the presence of copper, or to a deficiency of some other mineral or nutrient, such as phosphorus, nitrate, or water. It may even be due to disease or insect infestation. Only by careful observations and comparisons on the ground of selected sites in the copper-poisoned and otherwise denuded areas can one determine whether or not the suspected areas really contain copper. Figure 35 presents a summary of data-gathering systems and anticipated applications to biogeochemical prospecting. Table 20 lists the general geologically oriented activities in which the National Aeronautics and Space Administration is engaged as part of the current Apollo Applications Program.

In summary of the application of remote sensing of the environment to prospecting by biogeochemical techniques, the following example is cited. Diamond deposits were discovered in the Yakutiya area of the USSR. Aerial methods were applied to locate other original sources in the Daldyn region,

	Agricultural						Geographic						Geologic					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Metric Mapping Camera	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X
Panoramic Camera	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X
Tracking Telescope	X	X	X	X	X		X	X	X	X		X	X	X	X	X	X	X
Multiband Synoptic Cameras	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X
Radar Imager	X	X		X	X	X	X	X		X	?	X	X	X	X	X	X	
Radar Scatterometer/Altimeter							?	?								X	X	
Infrared Imager							X	X					X	X	X	X	X	X
Infrared Radiometer/Spectrometer	X		X	X		X	X	X					X		X	X	X	X
Optical Mechanical Scanner*	X	X	X	X	X	X												
Microwave Imager				X	X			X	?				X	X	X			X
Microwave Radiometer				X	X	X	?	?					X					X
Laser Altimeter/Scatterometer														X	X	X	X	X
Absorption Spectroscopy													X				X	
Viewfinder						X		X		X	X			X	X			X
Ultraviolet System													X	X	X	X		
Thermometer and Hydrometer				X														

1. Vegetation Density
2. Grass-Brush-Timberland Interfaces
3. Plant Species and Vigor
4. Soil Series, Temperature, and Moisture
5. Irrigation Water
6. Fire Detection
7. Land Use
8. Transportation and Linkages
9. Settle and Population Movements
10. Resources Utilization
11. Climatic Conditions
12. Geomorphology
13. Composition
14. Structure
15. Stratigraphy--Sedimentation
16. Mineral Deposits
17. Engineering
18. Crustal-Mantle Studies

Figure 35. Summary of Data-Gathering Systems Having Anticipated Applications to Biogeochemical Prospecting.[1]

TABLE 20

CURRENT AND FUTURE EXPERIMENTS FOR TERRESTRIAL AND LUNAR APPLICATIONS RELATING CURRENT MANNED SPACE RESEARCH AND TECHNOLOGY MISSIONS AND FUTURE APOLLO APPLICATIONS PROGRAM[2] EFFORTS[3]

To 1968	Remote sensor geologic mapping capability: Aerial overflight of terrestrial and oceanic sites to determine scientific significance of multispectral responses plus associated ground truth calibration in laboratory and field.
1968-69	Earth orbital overflight of same geologic test sites: Overflight will permit additional calibration of sensors from orbital altitudes.
1968-70	Manned lunar orbital scientific survey carrying many of same sensors used in earth orbit. Apollo Applications Program ground traverses provide additional ground truth calibration.

[1] From data prepared by the U.S. Geological Survey, presented by P. C. Badgley and The Proceedings of the Fourth Symposium on Remote Sensing of Environment, Michigan University, p. 557 (1966).
[2] Apollo Applications Program was formerly termed Apollo Extension Systems.
[3] Reference: Peter C. Badgley, Proceedings of the Third Symposium on Remote Sensing of Environment (1964).

after some exploratory experiments. The area suspected of containing some diamond-bearing pipes because of noted similarities to known deposits was photographed at a scale of 1:15,000, using panchromatic, infrachromatic, and spectrazonal films. The photos were made into an interpreted photomap.

Aeromagnetic surveys were performed in synchronization with a short-focus camera so that the magnetic data could be easily related to the photomap of the same area. The data were checked by a field team, consisting of a geologist, a geobotanist, and a geophysicist, who applied the magnetic data thus eliminating a great deal of field work. The key for the kimberlite identification found was the characteristic image pattern of associated vegetation. (Kimberlite weathering forms a rich soil which supports a dense forest of alder and larch, dramatically contrasting with the sparse taiga growth of the region.) Three new pipes were discovered in this study, which illustrates the advantage of combining several techniques to the solution to a prospecting problem (Kobets and Komarov, 1959).

PROJECTED FUTURE DEVELOPMENTS IN AERIAL OBSERVATION TECHNIQUES

The great advantage of aerial observation is that a large amount of information can be collected and recorded in a short time and at a negligible cost in comparison to ground observation. To exploit this advantage properly, it will be necessary to develop techniques for rapid, accurate, instrumental analysis of the data.

Some interesting work along this line has already been reported by Vinogradov (1963). In this work, a microphotometer was used to scan the varying densities on aerial photographs. A plot or recording was made of the photometer output vs position along the scan line, then a statistical analysis was applied to the plot and a correlation was obtained with the size and average spacing of trees and shrubs on the ground. Several statistical parameters were computed and compared for areas on the photographs where ground truths were known to consist of pure stands of tamarisk or of sand acacia. The parameters corresponding to these two types of vegetation were sufficiently different to permit them to be easily distinguished.

This Russian work represents a first step in the development of a computerized technique for aerial surveying. The next development would be to record the electrical signal directly by equipping the aircraft with an optical scanning device and a photocell. The electrical signal would be recorded on magnetic tape and subsequently analyzed with a computer.

A more sophisticated approach involves the use of a multichannel optical-mechanical scanner, as described by Tundgreke and Phillips (1967). In this concept, a slit image is scanned by a rotating or oscillating mirror. The beam is resolved according to wavelength by a prism or grating spectrometer, and applied to several detectors. Each detector thus responds to a narrow-wavelength band in the 0.4- to 1.0-micron range. The detector outputs are recorded on a multichannel tape recorder. A particular species of vegetation, such as an agricultural crop, will have a characteristic, unique signature consisting of a particular spectrum of reflected radiation. In the subsequent analysis, a computer can be programmed to recognize these signatures and print out a plot of the land areas carried by each of the species in question.

Although the primary application of this concept has been the efficient execution of agricultural surveys, it seems clear that it could be applied profitably to biogeochemical surveying and prospecting, provided that further investigation reveals the existence of multiband signatures of indicator or accumulator plants which indicate the presence of minerals.

The approach of Vinogradov (1963), in which a detailed analysis is made of the texture of the strip of image, and the approach described by Tandgreke and Phillips (1967), in which a spectrum analysis is carried out for each incremental area of the image, could conceivably be combined and automated for analysis by an airborne computer. The overflight and the analysis of the data would be simultaneous. A special-purpose computer would occupy less space, weigh less, require less power, and be more reliable and trouble-free than a multichannel tape recorder.

A television camera equipped with a vidicon or image orthocon tube is a feasible prospecting tool. This appraoch is used in satellites and space probes for converting an image to an electrical signal, which is recorded and subsequently telemetered to a terrestrial receiving station. This camera's mode of operation is analogous to a conventional photographic camera. The sensitive surface of the vidicon or orthocon is exposed briefly to the image to be recorded. The surface, which now stores the latent image, is scanned by sweeping it with an electron beam. The electrical output corresponds to the intensity of the illumination of the image at the point touched by the electron beam. After the image has been read out in this way, the sensitive surface is again ready to store another latent image.

The television camera is ideally suited for an electrical readout of the image, either into a tape recorder or directly into a computer. In commercial television in the United States, the scanning rate and picture repetition rate is 30 times per second. For aerial observation and prospecting work, a much slower repetition rate would be used. As indicated previously, the image repetition rate would be dictated by the field of view, the speed of the aircraft or satellite, and the amount of overlap desired between pictures. Typical repetition rates would be in the range of 0.5 to 1 image per second.

The present status of radar and microwave equipment for utilization in aerial observation, discussed previously, can be extended. Present limitations on the use of radar are the unsolved (as yet) problems of interpretation and, to a smaller degree, the expense, weight, and power requirements. Because of the required power, no unclassified observational satellites used by the United States carry radar equipment. However, radar systems have been proposed for satellite use that have very modest power requirements (Moore and Simonett, 1967), and computer analysis of the data would facilitate and improve the concept.

A detailed discussion of the possible future improvements in radar has been given by Rouse, Waite, and Walters (1965).

PHYSICAL AND BIOLOGICAL LIMITATIONS

Certain limitations on what can be ultimately done by aerial observations are imposed by the known laws of nature. The more important of these limitations and their probable implications are stated briefly below.

The attenuation of electromagnetic radiation of some wavelengths of light by the atmosphere is a serious handicap. The most important band <u>not</u> attenuated is the one including visible and near-infrared light, and extends from about 0.4 to about 1.0 micron. Below 0.4 micron, the attenuation rises rapidly, a phenomenon that rules out ultraviolet or X-radiation as a possible means of observation. In the infrared regions, there are several "windows" separated by absorption band due to water vapor, carbon dioxide, molecular oxygen, and molecular nitrogen. There are absorption bands in the microwave and radar regions as well. The various bands of radar equipment now in use have been chosen to operate in the atmospheric windows between the absorption bands. However, radar equipment used to observe clouds, rainstorms, and tornadoes is designed to exploit the attenuation and scattering of water vapor and clouds.

Diffraction effects, due to the finite wavelength of the radiation, represent an ultimate limit on resolution. At present, resolution is limited by other considerations in each of the instruments discussed.

According to present knowledge, the usefulness of plants as mineral indicators is limited by the subtlety of responses of plants to changes in environment. The uptake of minerals in the foliage may produce attenuation or reflection spectra characteristic of the minerals, but these effects have not been studied. In general, the plant is either healthy or sick, and presence of mineral deposit cannot be deduced only from an observed abnormality in the plant cover. Clues that minerals may be present are of value, however. Plant symptoms must be studied in detail to ascertain whether a more direct relationship between mineralization and optical effects of plants does exist.

CONCLUSION

There is considerable prospecting advantage to be gained by the judicious application of biogeochemical techniques to the problems of locating mineral enrichments. The over-view advantage of locating areas from altitude, which are promising for prospecting on a more intense basis, calls for the combination of geobotanical knowledge and remote sensing skills, with other techniques such as geophysical measurements. Such combined techniques can be invaluable in eliminating many huge undeveloped areas as mineralogically unpromising and, better, in pointing out specific locales as worthy of ground exploration. Intensive, ground-based prospecting can be greatly facilitated by the use of accumulator plants to "sample" soils, so that chemical analysis of the plants gives a better chemical picture of the area sampled. Indicator plants and the geobotanical technique can be applied by knowledgeable practitioners to delineate ore bodies much more quickly and easily than other conventional methods. Biogeochemical prospecting, like other types, is not the substitute for hard work in the field; it can greatly reduce the intensity and quantity of the work in areas to which it is applicable.

APPLICATIONS AND RECOMMENDATIONS

Modern prospectors face problems not encountered by earlier seekers of valuable mineral materials, because most of the easily located and recovered minerals have already been found and exploited. On the other hand, modern prospectors have at their disposal tools for facilitating the location of hidden minerals which were undreamed of by earlier prospectors, and which are the products of modern technology. The application of a combination of disciplines into the hybrid science termed biogeochemistry has gained momentum in recent decades, bringing the benefit of research into the overlapping areas of geology, biology, and chemistry. Some practitioners of this hybrid science have begun to crystallize the bits and pieces of information regarding the interaction of environment and living organisms into a prospecting tool. While this particular prospecting method is still undergoing the slow refinement process any new system must, it has been demonstrated to be a most useful addition to prospecting methods.

Like any tool, biogeochemical prospecting is at optimum efficiency in the hands of skilled personnel who possess at least a rudimentary knowledge of the advantages and limitations of the method, so that effort will not be wasted in applying the technique where another method would be more valuable. Since the major portion of the earth's available land surface is covered with some sort of vegetation, and since vegetation depends upon the soils supporting it for nutrients, the chemical or morphological aberrations caused by abnormal nutrient supplies to vegetation in specific regions are an obvious means of monitoring soils. The pitfalls in this observation arise in the necessity to sort out aberrations due to topography, altitude, latitude, and other variables not related to geological anomalies. This necessity is the factor which requires that practical, economical biogeochemical prospecting, like any other kind, be conducted by prospectors with the realization that biogeochemistry is an adjunct to, not a substitute for, other prospecting methods.

Perhaps the most spectacular new developments in the modernization of the prospecting art into a science have come in the areas of remote sensing. These new developments are in interpretation, in the devices used for recording data for evaluation of the earth for promising prospecting areas, and in the means of transporting the devices to a vantage point above the earth from which data may be collected. Most of this effort has been supported by the National Aeronautics and Space Administration. The advantage of observing huge areas of the earth at one time from orbital altitude has led to a whole new concept in geological mapping, and in the application of biogeochemical knowledge to aid the geologists in interpreting data from vegetation-covered areas. The ultimate application of aerial observation to prospecting will be the ability to relate data from the entire multispectral arsenal of instruments to the rock → soil → plant cycle, so that deductions about rocks (and minerals) can be made from data on plants. This takes broad knowledge of the rock-soil-plant interrelationship.

A summary of the biogeochemical contribution to an overall technique for prospecting may be of value to facilitate the formation of guidelines for advancing the art and incorporating it into an overall technology. The advantages and disadvantages, and a few pitfalls, are summarized in Table 21.

There appears to be no organized effort in the United States at the present time aimed at creating a usable technology for prospecting from the separate advances being made in the areas of biogeochemistry, chemical analysis in the field, geobotany, and remote-sensing techniques. Efforts in each of these individual techniques apparently are not suffering, however, since advances are being made in general, if not specifically, for prospecting. Examples of this progress may be found in the emphasis on analytical methods useful in the field for chemical analysis of fuels, soils, pollutants, and other materials of modern importance, and techniques for mapping. Using photographs taken from NASA's Gemini 9 spacecraft, a

TABLE 21

SUMMARY OF THE BIOGEOCHEMICAL TECHNIQUE

Plant Analysis (Plants analyzed and results mapped)	Geobotanical Mapping (Plants identified, and their presence and density mapped)
Advantages	**Advantages**
1. Vegetation samples are much lighter in weight than soil samples of comparable representation.	1. Absolute knowledge of identity of plants need not be known if mineralization causes differences over a small area in the same plant.
2. Plants can reflect mineralization in a larger area than a soil sample.	2. The relationships between types of vegetation, if known, can delineate types of geological formations to locate mineral-likely rock areas.
3. Deep roots of plants can sample ore dispersion halos not accessible by surface-soil sampling.	3. Aerial use of remote-sensing techniques can drastically cut time and effort needed to locate suspected mineralized areas.
4. In densely overgrown areas, biogeochemical techniques may be very much faster, both for procuring and transporting samples, than other methods.	4. Specific indicator plants can quickly pinpoint ore-body locations.
5. Analysis of plant ash has fewer interferences than soil samples.	5. Multispectral techniques are rapidly becoming sophisticated.
Disadvantages	**Disadvantages**
1. For best interpretation, plants which are analyzed should be identified and something known of their root habits. Few geologists are botanically knowledgeable.	1. Specific and general botanical knowledge is required for optimum application of geobotany.
2. Variables, such as soil acidity and the general chemistry of the elements sought, have marked effects on uptake of minerals by plants.	2. Little is known about plant-soil-mineral relationships in general.
3. Knowledge of useful plants is limited.	3. Remote sensing data on plant-soil-ore fingerprints is scant. Knowledge lags behind the instrumentation technology.

1:1,000,000-scale photomap of Peru, Bolivia, and Chile was prepared, from which some terrain structures were discovered for the first time. This and other exercises performed on data from Gemini and Mercury missions have led the National Aeronautics and Space Administration and the Department of Agriculture to collaborate on deriving a set of specifications for an initial earth resources satellite which will provide data useful in earth exploration (Fischer, 1967).

Already, a large quantity of advanced technology is available which can be applied to biogeochemical prospecting. Canadian and Russian exploration teams, for example, are applying some of this technology to evolve coherent prospecting efforts involving amalgamation of all of the scientific disciplines that can contribute to the solution of immediate problems.

The effort to evolve a coherent biogeochemical science is to be recommended. Development of such an advanced prospecting technology will require the acquisition of data relating general properties of plant types to general mineral properties, of acidity, etc., and the correlation of this relationship to parameters measurable by remote sensing. An organized, coordinated effort to procure this data would greatly accelerate the useful application of biogeochemistry to prospecting. Acquisition of specific "fingerprints" of vegetation, with and without associated mineralization, would seem to be a logical area of attention.

During preparation of this survey, biogeochemistry applications other than to prospecting were discovered or deduced. The mapping of human and animal disease as related to the biogeochemistry of staple food plants, and of water supplies used to nurture them, may be of utmost urgency in all the countries of the earth, particularly the over-populated, underfed ones. The importance of trace elements in food as a general and specific aid to health is acknowledged on every food label giving "minimum" daily requirements" of minerals and vitamins. The fact that the selenium-concentrating Astragalus plants are the locoweed, known to kill stock, is harsh evidence for the importance of awareness of the chemistry of farm soils and food plants, for humans or for grazing stock. Biogeochemistry may help identify new food crops, or places to grow known ones.

Additional applications await exploration, such as the use of biogeochemical techniques in the tracing and even in the reduction of pollutants in our national waters and on land, if not in the atmosphere. The physical control of mine wastes, sewage discharges, and arid sand-covered land may be a dividend from concentrated study. Other returns from a pursuit of biogeochemistry will undoubtedly become evident as the technology develops.

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APPENDIX A

INTERNATIONAL ATOMIC WEIGHTS

Element	Symbol	Atomic Number	Atomic Weight	Element	Symbol	Atomic Number	Atomic Weight
Actinium	Ac	89	227	Mendelevium	Md	101	(256)
Aluminum	Al	13	26.98	Mercury	Hg	80	200.61
Americium	Am	95	(243)*	Molybdenum	Mo	42	95.95
Antimony	Sb	51	121.76	Neodymium	Nd	60	144.27
Argon	Ar	18	39.944	Neon	Ne	10	20.183
Arsenic	As	33	74.91	Neptunium	Np	93	(237)
Astatine	At	85	(210)	Nickel	Ni	28	58.71
Barium	Ba	56	137.36	Niobium (Columbium)	Nb	41	92.91
Berkelium	Bk	97	(249)	Nitrogen	N	7	14.008
Beryllium	Be	4	9.013	Osmium	Os	76	190.2
Bismuth	Bi	83	209.00	Oxygen	O	8	16
Boron	B	5	10.82	Palladium	Pd	46	106.4
Bromine	Br	35	79.916	Phosphorus	P	15	30.975
Cadmium	Cd	48	112.41	Platinum	Pt	78	195.09
Calcium	Ca	20	40.08	Plutonium	Pu	94	(242)
Californium	Cf	98	(251)	Polonium	Po	84	210
Carbon	C	6	12.011	Potassium	K	19	39.100
Cerium	Ce	58	140.13	Praseodymium	Pr	59	140.92
Cesium	Cs	55	132.91	Promethium	Pm	61	(145)
Chlorine	Cl	17	35.457	Protactinium	Pa	91	231
Chromium	Cr	24	52.01	Radium	Ra	88	226.05
Cobalt	Co	27	58.94	Radon	Rn	86	222
Columbium (see Niobium)				Rhenium	Re	75	186.22
Copper	Cu	29	63.54	Rhodium	Rh	45	102.91
Curium	Cm	96	(247)	Rubidium	Rb	37	85.48
Dysprosium	Dy	66	162.51	Ruthenium	Ru	44	101.1
Einsteinium	Es	99	(254)	Samarium	Sm	62	150.35
Erbium	Er	68	167.27	Scandium	Sc	21	44.96
Europium	Eu	63	152.0	Selenium	Se	34	78.96
Fermium	Fm	100	(253)	Silicon	Si	14	28.09
Fluorine	F	9	19.00	Silver	Ag	47	107.880
Francium	Fr	87	(223)	Sodium	Na	11	22.991
Gadolinium	Gd	64	157.26	Strontium	Sr	38	87.63
Gallium	Ga	31	69.72	Sulfur	S	16	32.066
Germanium	Ge	32	72.60	Tantalum	Ta	73	180.95
Gold	Au	79	197.0	Technetium	Tc	43	(99)
Hafnium	Hf	72	178.50	Tellurium	Te	52	127.61
Helium	He	2	4.003	Terbium	Tb	65	158.93
Holmium	Ho	67	164.94	Thallium	Tl	81	204.39
Hydrogen	H	1	1.0080	Thorium	Th	90	232.05
Indium	In	49	114.82	Thulium	Tm	69	168.94
Iodine	I	53	126.91	Tin	Sn	50	118.70
Iridium	Ir	77	192.2	Titanium	Ti	22	47.90
Iron	Fe	26	55.85	Tungsten	W	74	183.86
Krypton	Kr	36	83.80	Uranium	U	92	238.07
Lanthanum	La	57	138.92	Vanadium	V	23	50.95
Lead	Pb	82	207.21	Xenon	Xe	54	131.30
Lithium	Li	3	6.940	Ytterbium	Yb	70	173.04
Lutetium	Lu	71	174.99	Yttrium	Y	39	88.92
Magnesium	Mg	12	24.32	Zinc	Zn	30	65.38
Manganese	Mn	25	54.94	Zirconium	Zr	40	91.22

*Values in parentheses are mass numbers of longest-lived or best-known isotopes

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