18A.

ADVANCES IN BOTANICAL METHODS OF PROSPECTING FOR MINERALS
PART I – ADVANCES IN GEOBOTANICAL METHODS

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Abstract

The presence or absence of particular species or varieties of plants in mineralized areas, and the effects of metals on plant growth have been observed and used in the search for concealed ore bodies since the 8th century. In the last ten years, studies of sparsely vegetated areas in wooded country have led to the discovery of lead in Norway and copper in the United States. Botanists have recently observed the actual evolution under stress conditions of new subspecies in mineralized or metal-contaminated ground, and there is now a growing understanding of metal-tolerance mechanisms in various plants. The development of new, highly tolerant races of plants in metal-poisoned ground is much more rapid than was previously supposed. Plants also may rid themselves of metal by dying to the ground each year or by concentrating metal in root cell walls and subsequently growing new adventitious roots. In widely separated areas of Europe, distinctive plant communities have been found to characterize terrain that has an anomalously high content of specific metals. New nickel accumulators have been identified in many countries, and a study by R.R. Brooks of herbarium specimens of previously reported indicator plants has shown many to be true accumulators of specific metals. These and other advances indicate the continuing usefulness of geobotanical methods of prospecting.

Résumé

Dès le VIII^{e} siècle, on a constaté la présence ou l'absence de certaines espèces ou variétés de plantes dans certaines zones minéralisées, et observé l'effet des éléments métalliques sur la croissance des végétaux, et enfin, utilisé ces observations pour déceler des corps minéralisés enfouis. Au cours des dix dernières années, l'étude de zones de végétation maigre dans une région boisée ont abouti à la découverte de gisements de plomb en Norvège, et de gisements de cuivre aux #tats-Unis. De fait, récemment, des botanistes ont observé, dans un sol minéralisé ou contaminé par des éléments métalliques, l'apparition dans des conditions de stress de nouvelles sous-espèces, et l'on commence à mieux comprendre les mécanismes de tolérance vis-à-vis des métaux. L'apparition de nouvelles races de plantes caractérisées par un niveau élevé de tolérance dans un sol empoisonné par des métaux est beaucoup plus rapide qu'on ne le supposait auparavant. Il peut aussi y avoir élimination progressive du métal, si les plantes meurent chaque année; elles peuvent aussi concentrer les éléments métalliques dans les tissus radiculaires, avant d'acquérir de nouvelles racines adventives. On a constaté, que dans des régions d'Europe très distantes les unes des autres, des communautés végétales distinctives s'étaient établies sur des terrains caractérisés par une teneur anormalement élevée en certains métaux. Dans de nombreux pays, on a identifié de nouvelles plantes concentratrices de nickel, et R.R. Brooks, qui a étudié des spécimens botaniques de plantes indicatrices déjà signalées a démontré que plusieurs d'entre elles concentraient réellement certains métaux. Ces découvertes, parmi d'autres, mettent l'accent sur l'utilité à long terme des méthodes géobotaniques de prospection.

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INTRODUCTION

Geobotanical prospecting has not been popular in the geological world because geologists have the mistaken idea that plant relationships in mineralized areas can be seen only by a botanist and that it is necessary to know the whys and wherefores of the distribution of species to be able to use them. Neither of these assumptions is correct. One need not know the exact name of a plant or why it grows where it grows to be able to use it. It is necessary, however, to be able to recognize the species of plants that appear to be most commonly restricted to metal-rich soils wherever they grow, and to observe in detail their distribution in relation to others of the local plant society in relation to the rocks. A plant's distribution may be useful even though it is controlled by a pathfinder element rather than by the most economically valuable element of the suite. The use of geobotany in prospecting through 1971 has been reviewed by Brooks (1972) and by me through 1965 in a previous paper (Cannon, 1971). In the last ten years new indicator plants have been reported, and new uses have been found for old ones. The association of bare areas with mineralized ground has been used for prospecting for lead in Norway and for copper in the northern United States. During this time, great strides have been made in understanding the factors that affect metal tolerance in various plant groups and the actual evolution, under stress conditions, of new varieties or subspecies in mineralized or metal-contaminated ground. We owe thanks for these studies to botanists such as Wilfried Ernst of Germany, H. Wild, G.H. Wilshire and Clive Howard-Williams of Rhodesia, Paul Duvigneaud of Belgium, T. Jaffré of New Caledonia, and Arthur Kruckeberg of the United States.

HISTORY

A short look at the early history of botanical methods of prospecting may help in setting the stage for a discussion of present research. The Chinese are reported to have observed the association of certain plant species with mineral deposits at least as early as the 8th or 9th century and to have been aware of metal uptake. Agricola in 1556 published observations concerning physiological effects of metals on vegetation (Boyle, 1967). It is reported that Thalius noted the

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association of **Minuartia verna** with metalliferous soils as early as 1588 (Ernst, 1965). The use of plants in prospecting was described in some detail by Barba (1640) in his book on "Methods of Prospecting, Mining and Metallurgy," which was completed in Potosi, Mexico in 1637 and published in Spain in 1640. Barba states, "Certain trees, marsh plants, and herbs are sometimes indicators of veins. Of these are plants of one type, which appear to be planted on a line; they repeat on the surface the course of the underground vein. Plants growing on top of a metallic vein are smaller and do not show their usual lively colors. This is due to the exhalations of the metals. They injure the plants, which seem emaciated." Lomonosov also noticed the depauperating effects of mineralized soils on plants in 1763 (Malyuga, 1964).

In the 19th century, seven indicator plants were reported in the literature. Of these, three have been confirmed as indicators of mineralized ground: **Polycarpea spirostylis**, discovered by Bailey (1889) on copper soils in Australia; **Viola lutea**, reported by Raymond (1887) as an indicator of zinc deposits in Aachen, Germany; and **Eriogonum ovalifolium**, reported as a silver indicator in Montana by Lidgey (1897). Their distribution and accumulative powers are being studied in detail in these areas today. From 1900 through 1965, more than 100 species indicative of one or more of 24 elements were reported, and in many cases, analyses showing them to be accumulators of the element were also given. Since 1965 many new indicator-accumulator plants for nickel have been reported, and a few for other metals. Much research has been reported on the mechanisms of metal tolerance and the evolution of metal tolerant species.

PLANT TOLERANCE FOR METALLIFEROUS SOILS

Many plants are unable to grow in strongly mineralized soils; such soils commonly have a reduced flora or may, in extreme cases, be entirely bare. In these relatively open areas, there may be an abrupt change in the degree of sunlight, soil moisture, soil temperature, or drainage. The lack of competition may permit the continued growth of relict stands of species that formerly had a wider range, or seeds of tolerant species or varieties from elsewhere may be able to germinate and grow in these areas that are so highly toxic to average plants.

Two types of plants have been shown to be tolerant of highly metalliferous soils. The first type, which includes many indicator plants, is capable of accumulating large amounts of metal in the foliage without excessive harm to the plant. These plants, as reported by Wild (1968) in Rhodesia, concentrate the metal in the leaves, but generally have heavy perennial rootstalks, and die to the ground in dry or cold periods of the year, thus sloughing off a considerable portion of the absorbed metal. The second type, represented most commonly by grasses, tolerates mineralized soils by preventing the toxic element from concentrating in the aerial parts of the plant, either by retention of metals in the root or by a true exclusion of metals at the root surface, possibly owing to a low root cation exchange capacity that permits the entry of monovalent cations but rejects divalent cations (Duvigneaud and Denaeyer-De Smet, 1973). The aerial parts of the second type of plants may contain the same amount of the toxic element regardless of whether it is growing on mineralized or barren ground. The number of such plants may be increased in mineralized areas owing to a lack of competition and their high tolerance for metals.

In metalliferous soils there are several factors that affect the absorption and uptake of metals. First, the absorption depends upon the available metal rather than the total metal in the soil. Varying amounts of metal will be water soluble, exchangeable, or organically bound. Factors that control the availability of metals in mineralized soil are largely unknown. David Grimes (pers. comm., 1975) found that certain Montana soils in areas that support restricted and unusual plant communities contain more EDTA-extractable copper (a measure of available copper) than soils with normal vegetation. Second, an increase in the availability of major plant nutrients such as phosphate or calcium in mineralized soils of low pH commonly affects the absorption of metals. Third, ore-associated elements, such as iron, sulphur, arsenic, cadmium, or selenium, may be deterrents or stimulants to plant growth or may interact with the more abundant metals to decrease or increase their toxic effects. Fourth, there are physiologic differences between plant species, races of the species, and perhaps individual plants that affect metal tolerance and uptake. For instance, the chelated form in which a metal is transported is unique to each species. Finally, the characteristic pH and total ion concentration of cell sap may determine whether a plant can live in a given soil environment and how much metal it can absorb. Plants adapted to a soil with a high cation content generally have a higher total cytoplasmic ion concentration than do plants that are intolerant of mineralized soils.

The location of metals in the cell is also closely associated with metal tolerance. The cell sap (vacuole system) of leaves has been shown to contain copper, zinc, iron, nickel, manganese, and a small amount of lead, but no cobalt or chromium. Bradshaw (1970b) has demonstrated that the greater percentages of copper and zinc occur in the cell wall of tolerant and accumulator plants, and in the mitochondrial fraction in nontolerant plants. Ernst (1972) proposed that the cell walls of metal tolerant plants have a high exchange capacity for heavy metals, and that the older

Table 18.1

Species with metal tolerant races
(taken from Antonovics et al., 1971)

Species	Metal(s) tolerated
GRASSES:	
Agrostis tenuis	Cu, Pb, Ni, Zn
Agrostis stolonifera	Pb, Zn
Agrostis canina	Pb, Zn
Anthoxanthum odoratum	Zn
Festuca ovina	Pb, Zn
Festuca rubra	Zn
Holcus lanatus	Zn
FORBS:	
Alsine (Minuartia) verna	Zn
Armeria maritima	Zn
Campanula rotundifolia	Zn
Linum catharticum	Zn
Melandrium silvestre	Cu
Plantago lanceolata	Zn
Rumex acetosa	Cu, Zn
Silene vulgaris (inflata, cucubalus)	Zn
Taraxacum officinale	Cu
Thlaspi alpestre	Zn
Tussilago farfara	Cu
Viola lutea	Zn

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leaves die off as the sites in the cell wall are used up, thus continuously ridding the plant of toxic metals. In the root, most metals are tightly bound in the cortex, but are water soluble in the xylem, where they are available for transport to the upper parts of the plant. Chromium, however, is tightly bound in both the cortex and xylem and remains in the root. Lead is mostly bound in the cortex, but a part is water soluble and available for transport Ernst (1972).

Peterson (1969), using radioactive ^{65}Zn, determined that more than 80 per cent of the Zn absorbed by zinc-tolerant plants of **Agrostis tenuis** separates in the pectate extract. The cation exchange capacity of pectin, a cell wall component, would enable the pectin to remove zinc from the cytoplasm by binding it to the cell wall. Work by Miller et al. (1975) has shown that high lead uptake by soybeans is inversely proportional to the pH and to the soil cation exchange capacity. Timed sequence studies with the electron microscope showed that insoluble amorphous masses of a lead complex are first formed in dictyosome vesicles which then move to and are incorporated in the cell wall of corn roots. Crystals of lead phosphate were also observed to form on the outside of the root (Malone et al., 1974). Normally, if the root becomes clogged with metal the plant dies. However, in monocotyledons, roots are adventitious and can be replaced continuously. This phenomenon probably explains the dominance of grasses and sedges on metalliferous soils. There also is evidence that the growth of tolerant plants is stimulated by small amounts of minor metals; this suggests that the minimum requirements for these elements are greater in tolerant than in nontolerant plants. Antonovics et al. (1971) suggested the alternate possibility that these plants more efficiently inactivate a number of elements and hence have a greater daily requirement for minor metals.

Early work by Bradshaw (1952) showed that metal tolerant populations of **Agrostis tenuis** could grow on mine soils, but that plants transplanted from normal pastures could not survive. Research by Peterson (1969), Bradshaw (1970a), and Smith and Bradshaw (1970) with populations of tolerant species of **Agrostis tenuis, Agrostis stolonifera,** and **Festuca rubra** demonstrated that these plants became established more easily, and produced greater root and shoot growth when they were transplanted to mine waste in Wales than did control plants of **Lolium perenne.** Root growth in solution culture can be studied using a method developed by Wilkins (1957) in which tillers and cuttings are taken from mineralized soils. By this method, the development of tolerant races by a large number of species has been established; these include both grasses and forbs. A few of these reported by Antonovics et al. (1971) are shown in Table 18A.1. The transplantation of plant populations known to have high tolerance for metals would appear to be a powerful tool in stabilizing and reclaiming mine wastes. The rapid natural evolution of populations of high tolerance is accomplished by selection, which is possible through a survival screening process of the few tolerant individuals that normally occur in every generation of an average nontolerant population. There may be only three to four survivor seedlings in many thousand, but these are sufficient to start a new population of highly tolerant plants (Smith and Bradshaw, 1970). The tolerance of evolved races of plants is highly specific for individual heavy metals. Generally, the specialists or indicator plants for one metal are not tolerant of another metal. **Indiofera dyeri** populations, for instance, are 10 times more tolerant of zinc than of copper; **Indiofera setiflora** populations are very tolerant of nickel but of no other metal (Ernst, 1972).

INDICATOR PLANTS

Plant indicators of mineral deposits are species or varieties of plants that give a clue to the chemistry of the rock substrate by their presence or absence on mineralized soils. Most species that have been reported are local indicators. Research during the past 10 years suggests that there are few, if any, universal indicators which do not occur somewhere in the world on nonmetalliferous soils where conditions are particularly favourable for their growth. For this reason, researchers have become more cautious in declaring plants to be indicators, and describe them instead as super tolerant, accumulators, or specialists. In this paper, plants have been given indicator status only where so described by the authors quoted.

Since 1965, relatively few new indicator species have been recognized, but much research has been carried out on the relationships that exist between plant species or varieties and mineralized ground (phytogeoecology). True endemic indicator plant species of any particular metal are rare, and in many cases they survive only in localized refugia because of biotype depletion. That is to say, changing climatic conditions and competition from other closely related species have severely restricted their distribution in general; but, being highly tolerant of metal-rich ground of low pH, they have continued to exist in open, treeless areas of mineralized ground. Given a favourable environment with no competition, they may also be found in isolated areas of unmineralized ground, as on a sunny scree slope.

Recent work by Bradshaw (1959), Duvigneaud and Denaeyer-De Smet (1963), and Denaeyer-De Smet (1970) has shown that physiological ecotypes, which develop in a relatively short time on metalliferous soils, have a much higher tolerance for a particular metal than their counterparts growing on normal soils. These ecotypes may show no unusual morphological differences and can only be identified by root growth studies in solution culture (McNeilly and Bradshaw, 1968; Wilkins, 1957). Although they are true indicators and can grow well only on metaliferous soils, they may be indistinguishable in the field from plants of the same species growing nearby on normal soils.

PLANT COMMUNITIES

In many areas the recognition or delineation of metalliferous soils is aided by observing the patterns of distribution of all species rather than that of a single indicator plant.

The observation of plant communities as an aid in geological mapping was proposed by Karpinsky (1841), and the method has been developed to a fine art in the Soviet Union (Malyuga, 1964). Excellent reviews of this work have been provided by Chikishev (1965) and Viktorov et al. (1964).

"Plant communities" or even the larger unit of "plant associations" may be definitive in outlining particular rock units such as limestone, sandstone, halite, or ultrabasic rocks. Quantitative information concerning the total number of species, their density, and vitality can be obtained on the ground by observations in quadrats or along transects.

The control of plant associations by surface features (physiognomy) and geological substrate was studied by Nicolls et al. (1965) in the Dugald River area of Australia. In areas of base metal mineralization, they found that normal vegetation was absent, and was replaced by specialized plant communities dominated by **Polycarpea glabra** and **Tephrosia** sp. nov. They concluded that geobotany was a useful and inexpensive method that complemented stream-sediment sampling, and that the two methods should be used together when personnel with some botanical training were available.

The tree cover in forested areas or the shrub cover in unforested areas can also be observed and mapped from the air, as is done routinely in Russia, or by remote sensing, as has been used by Cole (1971a, b) in South Africa.

Braun-Blanquet (1951) described the study of plant communities on metal-contaminated soils as a technique necessary to phytosociology, and he devised a system of classifying plant associations and their smaller components. The method provides a means of recording the relative abundance of different but associated species on metalliferous soils. In recent years, the plant communities characteristic of copper, lead, and zinc soils have been examined in Germany by Schwickerath (1931), Ernst (1965, 1968a), and Baumeister (1967); in France by Ernst (1966); and in Great Britain by Shimwell and Laurie (1972) and Ernst (1968b). Ernst found that the associations studied in many of these areas had several species in common – **Viola calaminaria, Thlaspi alpestre, Minuartia verna, Silene vulgaris, Armeria** sp., and **Festuca ovina** – although occasionally one or two were absent owing to climatic differences. He therefore created one phytosociological "order" called **Violetea calaminariae**, which he subdivided into three "families". His work showed that typical communities exist in widely separated mineralized areas, and that their distribution is not controlled solely by habitat, climate, or geography. Such disjunct areas of plants are considered by Stebbins (1942) to contain two types of species: (1) "paleo-endemic" species that formerly had a wide distribution but are now confined to isolated areas and (2) "neo-endemic" species that have developed in response to environmental stress. Such relict communities of formerly widespread species might be caused by glaciation or by widespread volcanic ash fall which has since eroded away. The latter may account for the isolated areas extending from Utah to Texas of **Astragalus pattersoni,** a plant that requires and absorbs large amounts of selenium for survival and at the same time only occurs in areas of measurable radioactivity (Cannon, 1962).

ANOMALOUS GROWTH CHARACTERISTICS

Visible effects of high concentrations of metal on plant growth habits can be observed by on-the-ground studies. The surface area of highest metal content may appear as a "bare" area in a forest. The apparently bare area may actually support small annual plants or perennials that die to the ground each year, thus ridding themselves of a year's accumulation of metal. The trees nearest to a copper or zinc area may exhibit interveinal iron chlorosis because the excess metals interfere with the production of chlorophyll. Trees under such environmental stress have also been observed to turn colour earlier in the fall than those farther from the mineralized area. It is possible that the latter phenomenon, if widespread, may be useful in remote sensing.

Stunted, bushy forms of **Tephrosia longipes** and plants of **Combretum zeyheri** with enlarged fruits have been described by Wild (1968) as true morphological copper ecotypes in Rhodesia. Whether the plants observed in the field have reached a stage of ecotonal development or not is unimportant to the prospector as long as the growth differences can be observed. Stunted trees that tend to be spreading, and of a uniform height, surround the grassy zone of a typical Rhodesian metal anomaly (Wild, 1970). Progressive stunting and chlorosis with increased metal content were observed in rows of vegetables which had been planted across high-zinc areas in drained mucks at Manning, New York (Cannon, 1955).

Measurements made by Jacobsen (1967) of several species in a Rhodesian sampling program showed a progressive decrease in the height of nonspecialized species with increasing soil copper. Studies by Howard-Williams (1971) of the seeds and flowers of **Becium homblei** showed differences in seed weight and corolla shape between populations growing in widely different soil types; the greatest reduction in size occurred in plants growing in heavy-metal soils. Antonovics et al. (1971) have shown that tolerant races of plants are generally dwarfed or prostrate and require less calcium and phosphate.

Geobotanical studies I recently conducted at the Pine-Nut molybdenum deposit in Nevada demonstrated anomalous growth phenomena in several species. The length of the internodes in **Ephedra nevadensis** was greatly extended, producing a wandlike appearance in the plant; and flowers of **Peraphyllum ramossissima** (squaw apple) were white instead of their normal pink colour.

Antonovics et al. (1971) suggested that the morphological changes reported by Malyuga (1964) may well be genetic. The following experience demonstrates that morphological changes are not necessarily genetic, but may be caused by elemental imbalance.

Twenty some years ago I conducted an experimental plot study of mineral uptake by native plants over a period of three years. The plots were treated as shown in Figure 18A.1. Many diverse growth habits were observed. As splits of the same seed collection were sown in each plot, all differences were attributable to the imbalance of nutrients or trace metals rather than to genetic variations. **Euphorbia fendleri** (Fig. 18A.2) grew with an upright habit in the gypsum plot but was completely prostrate and developed nodules on the stems at the crown of the plant in the lime plot. California poppies in the lime plot developed light yellow edges on the petals and some completely yellow flowers, but had dark orange flowers in plots to which phosphate had been added.

GYPSUM & CARNOTITE	GYPSUM	GYPSUM & VANADIUM
SELENIUM & CARNOTITE	SELENIUM	SELENIUM & VANADIUM
CARNOTITE	SELENIUM & THORIUM	VANADIUM
PHOSPHATE & URANIUM	PHOSPHATE	PHOSPHATE & VANADIUM
LIME & CARNOTITE	LIME	LIME & VANADIUM

Carnotite = $K(UO_2)\ (VO_4) \cdot nH_2O$

Thorium = $SrAl_3$ (rare earths) $(PO_4)\ (SO_4)\ (OH_6)$

Vanadium = $Na_2H_2V_6O_{17}$

Selenium = Na_2SeO_3

Figure 18A.1. *Plan of experimental plot study conducted in 1956-58.*

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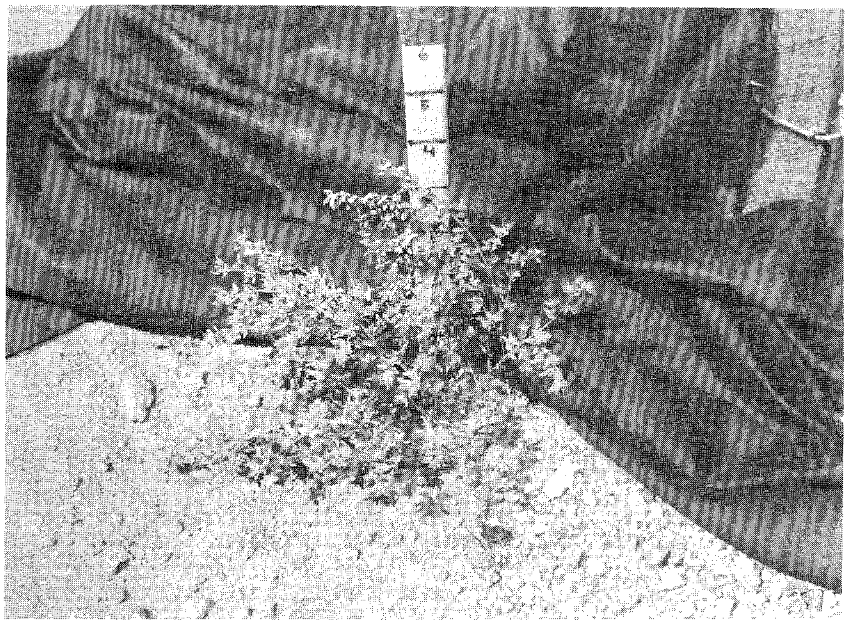
Morphological changes in several species growing in irradiated soil plots were observed. One of the most interesting results was the discovery that **Astragalus pattersoni**, the most useful uranium indicator plant (formerly believed to be entirely dependent on selenium) grew to maturity in the selenium plot, but also in the carnotite plot to which no selenium had been added. **Stanleya** was strongly affected by radiation. Where radioactive ores were added to the soil where the plant spikes were already in flower, the new flowers ceased to produce petals or stamens within a few days, and eventually the pistil produced a new plant asexually.

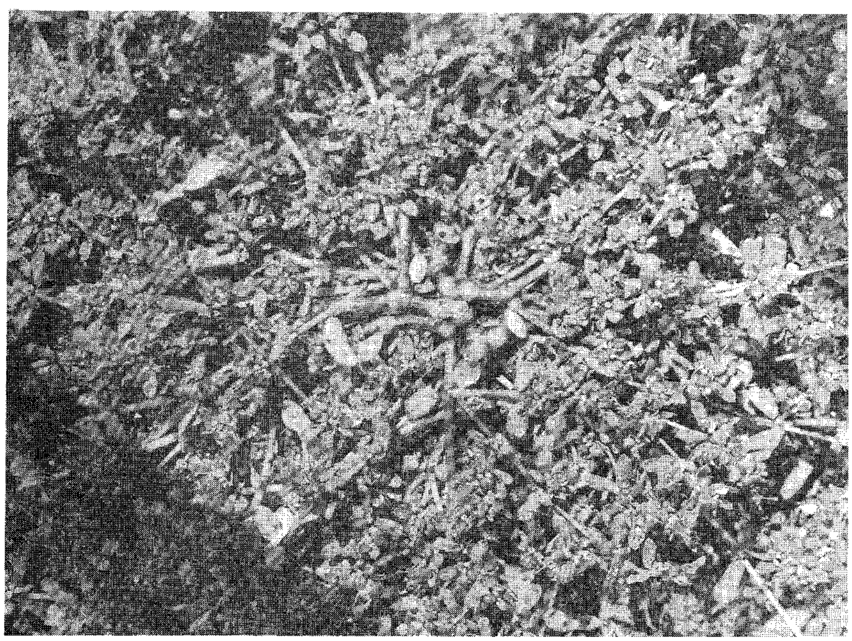
RECENT USES OF GEOBOTANY FOR SPECIFIC METALS

Copper

Many lower forms of plants are useful in prospecting or at least have been shown to be tolerant of metalliferous soils. The use of indicator "copper mosses" and several liverworts in prospecting was described in the early literature. The resistance to copper of species from several other moss genera has also been described by Ernst (1965), but the plants have not been given indicator status. Certain fungi, bacteria, and algae have also been observed to be associated with copper soils, and the black crust formed by blue-green algae has been used in prospecting (Wild, 1968).



a. Upright in gypsum plot (GSC 203492-E)



b. Prostrate with nodules in lime plot (GSC 203492-H)

Figure 18A.2. ***Euphorbia fendleri*** *in plots treated with gypsum and lime.*

A small herb, **Eriogonum ovalifolium**, was reported by Lidgey (1897) to be an indicator of silver in Montana (Fig. 18A.3). This plant was observed by Grimes and Earhart (1975) to be the dominant ground cover in a number of bare areas of otherwise forested country in Montana. The areas have since proved to be mineralized with Cu, Pb, Ag, and Zn. Plant samples contained as much as 500 ppm Cu in the dry weight of the leaves and more than 1000 ppm in the roots. As much as 15 ppm Ag in the leaves was detected at another locality. The distribution of several varieties of the species is being studied in different geochemical environments.

In similar clearings in Zambia, Reilly (1967) reported that the indicators **Becium homblei, Vernonia glaberrima, Triumfetta welwitschii,** and **Cryptosepalum maraviense** accumulate copper in their leaves. Grasses growing in the mineralized soil did not accumulate copper. Negative indicators, or cuprifuge plants, were intolerant of soils containing more than 20-40 ppm Cu. Although **Becium homblei,** a mint (Fig. 18A.4), was formerly believed to grow only on soils containing more than 100 ppm Cu, Howard-Williams (1970) reported that the plant has been found in barren ground in both Zambia and Rhodesia, but is confined to certain well defined climatic boundaries. It is also able to grow on high-nickel, lead, and arsenic soils. Ecologic studies show that **Becium homblei** is the dominant forb in a typical grass association but is restricted to soils of high copper content where it is in competition with **Becium obovatum,** which is not tolerant of low-Ca, low-pH, and high-metal soils. Thus, the isolated occurrences of **Becium homblei** are believed to be relict stands. The plant has large underground rootstalks from which leafy shoots arise during each wet season and die off each dry season, thereby ridding itself of the copper. Because of this growth habit, **Becium homblei** is also able to survive periodic man-made bush fires (Howard-Williams, 1972).

Other potential indicator plants were studied by Jacobsen (1968) in the Mangula mining district of Rhodesia. In order to appraise the usefulness of various species, he calculated the specific indicator value (I_{Cu}) for a range of copper soils by dividing the plant's tolerance span (Cu maximum minus Cu minimum) by its average soil-copper value (Cu_0). Plants with the lowest I_{Cu} values (<12.) are the best indicators for their respective range of soil Cu values. Some of these local indicators for high-copper soils are listed in Table 18A.2. Wild (1968) has also made a study of geobotanical anomalies in Rhodesia and states categorically that "the only taxon definitely distinct at the specific level that is confined to copper soils in Rhodesia is **Becium homblei,** although this species occurs on non-copper soils in Katanga." This suggested to Wild that the plant is in an intermediate stage of development as an endemic. Wild has recognized several subspecies morphological ecotypes as being at an even earlier stage of development: a glabrous, narrow-leafed form of **Justicia elegantula,** S. Moore; an olive-brown **Pogonarthria squarrosa** Pilg.; a stunted bush, **Tephrosia lurida** Sond.; and a form of **Combretum zeyheri** Sond. with unusually large fruits and wavy-winged bracts. These ectoypes appear to be distinct taxa at some infraspecific level and are useful indicators. A species of **Combretum** has also proved useful in indicating copper-ore deposits in South Africa (Cole, 1971a).

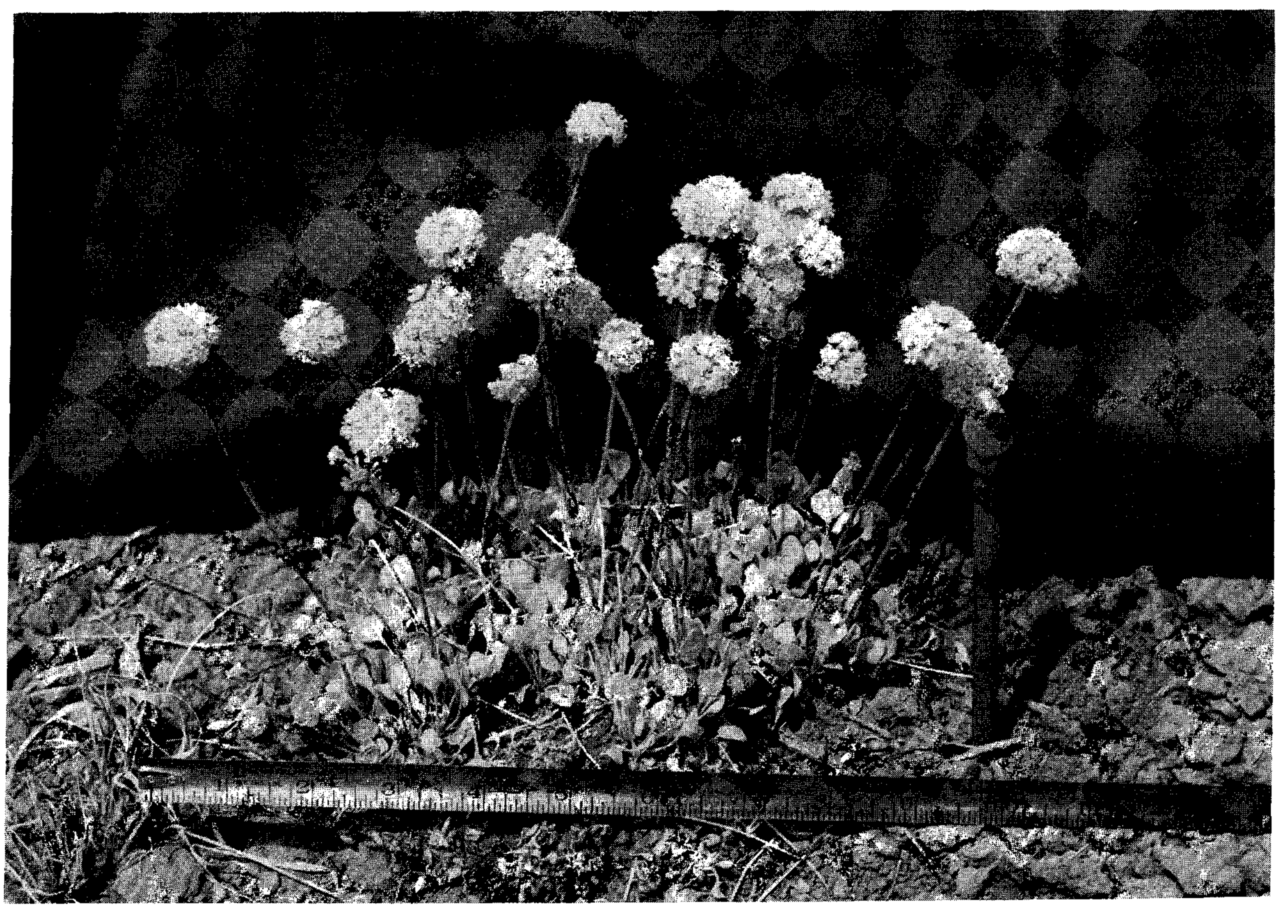


Figure 18A.3. ***Eriogonum ovalifolium*** *silver plant, growing on mineralized soil in Montana. (GSC 203492-G)*

Figure 18A.4. ***Becium homblei,*** *a copper indicator plant in Rhodesia. (GSC 203492-J)*

Table 18A.2

Local indicator plants for high copper soils in Rhodesia (Jacobsen, 1968)

Species	Copper indicator value (I_{Cu})
>5000 ppm Cu in soil	
Bulbostylis contexta	2.07
Eragrostis racemosa	4.07
Monocymbium ceressiiforme	2.82
Trachypogon spicatus	3.91
1900-5000 ppm	
Albizia antunesiana	3.66
Burkea africa	5.34
Ficus burkei	4.09
Heeria reticulata	3.72

Brooks (1977) has analyzed 48 herbarium specimens of 19 species of **Haumaniastrum** (formerly **Acrocephalus**) and reports high-copper and also high-cobalt contents in **H. robertii,** a well known copper indicator plant in Africa, and also in **H. katangense** and **H. homblei.** He suggests that the role of the latter two species as indicator plants should be studied further.

Lewis et al. (1971) have studied the distribution of 25 species in soils of known copper contents in the Monte Alto copper district in Brazil, and reported that 3 plants, **Croton mortbensis, Psidium aracá,** and **Eugenia** sp. grew only in soils containing 175 ppm or more of copper and may be useful indicator plants.

Nicolls et al. (1965) made a thorough study of the geobotanical relationships in the Dugald River area of Australia, making an assessment of all factors thought to govern plant distribution in the area. The characteristic plant associations are replaced over the lodes by a treeless plant assemblage consisting of **Bulbostylis barbata** and **Fimbristylis** sp. nov., which reflect high Cu values in the surface soil; **Polycarpea glabra** and **Tephrosia** sp. nov., most closely related to copper and zinc toxicities; and **Tephrosia** sp. nov., which is tolerant of high lead as well as copper and zinc. The authors demonstrate that the indicator plants are able to exclude copper at relatively low levels in the soil but that large amounts of Cu are absorbed from soils of high Cu content. Analyses of the soils for major nutrients suggest that phosphorus, which increases over the lodes, may have an important influence on plant distribution.

Cobalt

The extraordinary cobalt uptake by **Nyssa sylvatica** var. **biflora,** reported by Beeson et al. (1955), has been confirmed by Brooks et al. (1977) in herbarium specimens from the United States and Southeast Asia. Brooks has also shown that the accumulation of cobalt by other species of **Nyssa** is extraordinarily high, and although the plants also accumulate nickel, the Co/Ni ratio in the plants is 2 or more. The latter ratio is rare in the plant kingdom. A second genus of the Nyssaceae, **Camptotheca,** also accumulates cobalt, but not to the extent of **Nyssa.** As the plants are able to absorb large amounts of cobalt from normal soils, they should be useful in assessing the cobalt status of agricultural soils, but are not indicative of economic cobalt deposits. On the other hand, Brooks' (1977) discovery of unprecendented levels of cobalt in **Haumaniastium robertii,** known previously as a copper indicator plant, raises the question of whether this plant is actually an indicator of cobalt rather than copper. The values range from 1368 to 10 222 ppm cobalt (on a dry weight basis), with a mean of 4304 ppm in six leaf specimens; this is an order of magnitude greater than any values previously reported for cobaltophytes! Brooks' noteworthy method of analyzing small pieces of herbarium specimens sent to him from many countries is providing much new information on the distribution and identification of metal tolerant plants, and should stimulate further research by botanists all over the world.

Zinc and Lead

Denaeyer-De Smet (1970) has found the accumulation of zinc in zinc indicator plants to be generally high but to vary greatly according to species. She studied the accumulation of zinc by nine species growing in high-zinc areas (Fig. 18A.5). The zinc obligate, **Thlaspi sylvestre** ssp **calaminare,** contained 15 700 ppm zinc in the dry weight of the leaves – ten times that of the other species. The leaves and the roots of **Silene cucubalus** var. **humilis** accumulated roughly equal amounts of zinc (1860 ppm). The zinc-vague trees, **Salix caprea, Betula verrucosa** and **Populus tremula** accumulated 1285-1439 ppm zinc in the leaves and became chlorotic. **Armeria halleri** concentrated the zinc strongly in the roots; when the **A. halleri** plants were transplanted from high-zinc soils to normal soils, the zinc rapidly decreased in both the leaves and the roots. Lefebvre (1968), studying several species of **Armeria,** reported the occurrence of ecotype populations having a hereditary tolerance of heavy metals. These ecotypes are able to produce new roots in the presence of high concentrations of zinc, whereas their counterparts obtained from normal soils could not.

Five areas of naturally occurring lead-poisoned soil downslope from known deposits have been found in Norway by Låg and Bølviken (1974). In less advanced stages of poisoning, **Vaccinium** ssp (blueberry) is replaced by **Deschampsia flexuosa** (hair grass). In advanced stages of poisoning, the vegetation is stunted, chlorotic, lacks fruit, or disappears

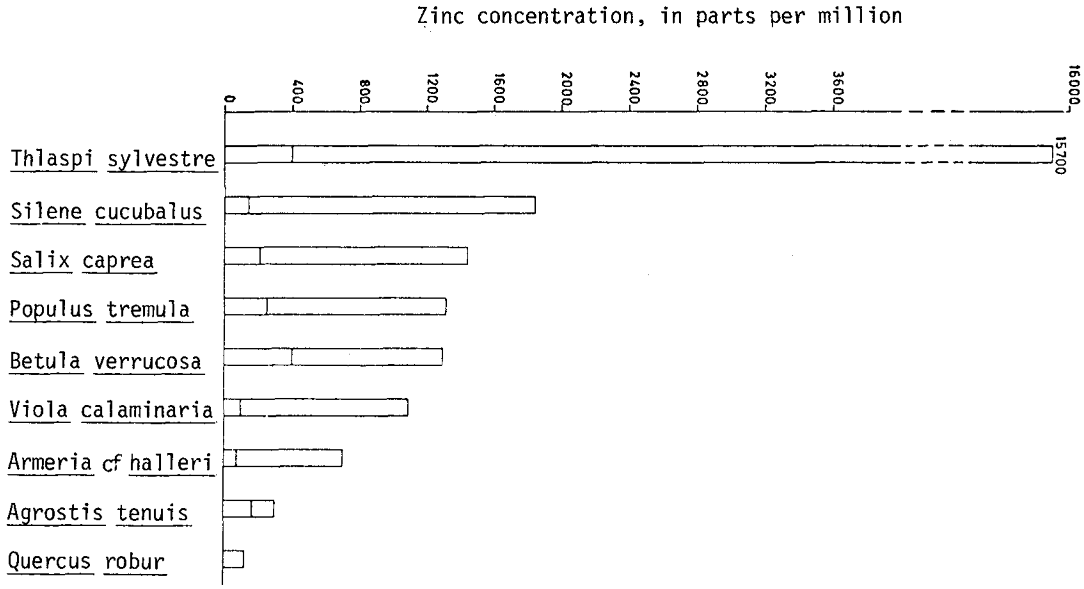


Figure 18A.5. *Graph showing amounts of zinc in the leaves of different species collected from the same zinc-rich biotype at Plombiéres, Belgium (taken from Denaeyer-De Smet, 1970).*

entirely. The largest such bare area is 100 m^2. The soil here lacks a bleached horizon, is stony, has no covering of sphagnum moss, and averages 24 500 ppm lead. Among the plants that were analyzed, a fern, **Dryopteris lianaeana,** contained more lead (253 ppm) than **Deschampsia flexuosa** (99 ppm). The vegetation of these areas includes no indicator plants, but the authors suggest that the recognition of atypical plant communities and bare areas in otherwise forested country may prove to be an effective prospecting method.

Work by Nicolls et al. (1965) in Australia showed the indicator plant **Eriachne mucronata** to be far more tolerant of high-lead areas than other plants.

Serpentine: Nickel and Chromium

Unusual floras of narrowly endemic species occur on serpentine rocks throughout the world. The areas are commonly characterized by dwarf pine, dwarf shrubs, mosses, lichens, ferns, and certain genera of the laurel, pink, chickweed, and borage families. The endemic floras of soils derived from ultramafic rock in northwest Washington, British Columbia, and Oregon were described in detail by Kruckeberg (1969). He believed that the restriction of these plant species to serpentine rocks is largely determined by their ability to extract enough calcium from acid clay soil, as the Mg/Ca ratio is very high. Although he describes the vegetation in the nickeliferous area of Grants County, Oregon, he does not consider soil metal content as a possible control, nor does he give analyses for Ni or Cr.

Lee et al. (1975) undertook a statistical approach to the problem of controls for the serpentine flora in New Zealand. Soils were collected at random sample sites near two endemic species, **Myosotis monroi** Cheesem. and **Pimelea suteri** Kirk (Fig. 18A.6) and also near three nonendemic species. The five groups of samples were analyzed for Ca, Co, Cr, Cu, K, Mg, Mn, Ni, and Zn, and the data were treated statistically by discriminant analysis. The greatest difference between endemic and nonendemic plants was their magnesium content, and the second greatest difference was nickel. The endemic plants appear to be characterized by an ability to survive in soils having high Mg/Ca ratios and elevated levels of nickel.

The serpentine flora of the Great Dyke in Rhodesia has been studied in detail by Wild (1965). He found that nickel-bearing serpentine produced a depauperate and stunted flora whereas serpentine of low nickel content did not. He attributed the sterility observed in several species to nickel poisoning. The percentage of nickel and chromium in serpentines is often very high, and nickel is accumulated by certain species of plants in very large amounts. Severne (1974) reported a significant negative correlation between nickel and calcium in a nickel accumulator, **Hybanthus floribundus,** in Western Australia. This suggests that Ni can substitute for Ca, a thought which is supported by the recent finding of nickel in pectinates. Possibly nickel is essential to these plants.

Malyuga (1964) listed three indicator plants for nickel: **Alyssum bertolonii,** found in Italy; **Alyssum murale** in Georgia (U.S.S.R.); and **Asplenium adulterium** in Norway. Many nickel accumulator plants have been investigated since that time, and a few of them including 11 additional species of **Alyssum,** have been demonstrated to be indicators of high-nickel ground (R.R. Brooks and O. Verghano Gambi; pers. comm., 1977). **Sebertia acuminata** of the Sapotaceae is endemic to New Caledonia, occurs only on soils derived from ultrabasic rocks, and is found most often on high-nickel soils (Jaffré et al., 1976). A study by Lee and others (1972) of two known hyperaccumulators of nickel from New Caledonia demonstrated that the nickel content of **Hybanthus austrocaledonicus** could be correlated with the total soil nickel content but that the nickel content of **Homalium kanaliense** could not; the latter, therefore, could not be used in prospecting. The ecotype **Hybanthus floribundus** ssp **curvifolius** is restricted to high-nickel soils in Western Australia (Severne, 1974). Lee and others (1977b) have recently found high chromium, in an epiphytic moss that grows on **Homalium guillainii,** a hyperaccumulator of nickel. The moss, **Aerobryopsis longissima** (Doz. and Molk.) Fleisch, had a mean chromium content of 5000 ppm, nearly twenty times that of its host.

Jaffré and Schmid (1974) reported that a tree of the Rubiaceae, **Psychotia douarrei** (C. Brown) Däniker, from New Caledonia, accumulates higher levels of nickel than had ever been reported in a plant. The nickel content ranged from 1.8-4.7 per cent in the dry weight of

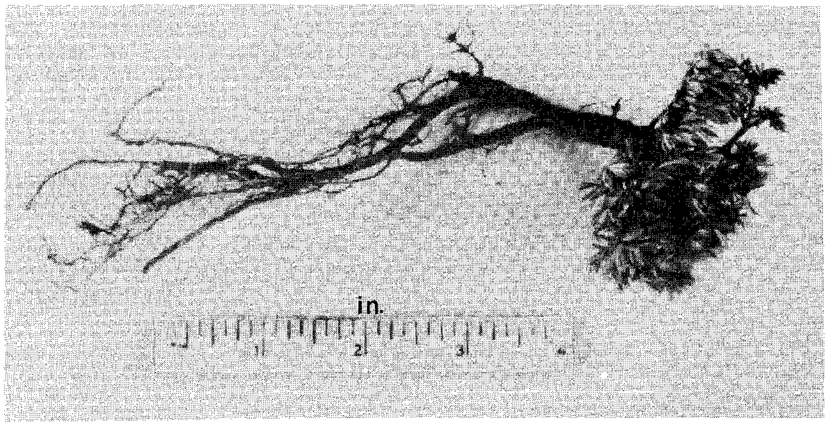


Figure 18A.6. ***Pimelea suteri****, endemic serpentine plant in New Zealand. (GSC 203492-B)*

the leaves to as much as 9.2 per cent in the roots. They suggested that the nickel uptake is not passive but is actively associated with the plant's physiologic processes.

Brooks et al. (1976) have recently analyzed leaves of 2000 herbarium specimens which included 232 species of **Homalium** and **Hybanthus** from throughout the world. Five additional species of hyperaccumulators (> 1000 ppm Ni, dry weight) were found, all from New Caledonia. As nickel contents greater than 1000 ppm dry weight only occur in plants growing over ultrabasic rocks, the analyses of the 2000 samples have pinpointed a number of Ni-bearing ultrabasic areas. As shown by the work of Lee et al. (1977a), however, the nickel content of a particular hyperaccumulator may or may not correlate with the total content of the soil. Soil analyses for the newly discovered species are therefore, necessary before their true status as indicators of nickel mineralization can be evaluated.

Wild (1971) has described a new species, **Dicoma niccolifera** Wild, a composite, as being almost entirely confined to nickel-bearing soils. It occurs in Zambia and Rhodesia. He believed the species to be an older relict species isolated by biotype depletion rather than adapted modification of another more common species. The plant has been used as a reliable indicator of nickel in Rhodesia. Wild (1970) also found several other species that could be used locally as nickel indicators, although elsewhere they were not confined to nickel soils. **Albizia amara** was a striking indicator of 11 nickel anomalies; it is not normally associated with serpentine. **Turraea nicotica** is of value as an indicator of both serpentine and amphibolite nickel anomalies. **Combretum molle** occurred in all nickel anomalies, and commonly as stunted, pure stands. **Combretum molle** also is common on copper soils, as are the metal-resistant grasses **Loudetia simplex, L. flavida, Aristida leucophaea, Andropogon gayanus,** and others.

SUMMARY

Recognition of sparsely populated or depauperate vegetated areas associated with highly mineralized soil has advanced in the last ten years, and much progress has been made in determining the occurrence and controls of stands of obligate, relict, and evolved ecotypes that may be useful in prospecting.

Plants that tolerate highly metalliferous soils are commonly either deciduous plants that have a high uptake of metals but die to the ground each year, or plants that concentrate the metal in the walls of the root cells but are able to avoid blockage by the continued growth of adventitious roots. The rapid evolution of races of highly tolerant plants in mineralized areas from the few hardy individuals that occur in normal populations has been established. Many of the previously known indicator plants have been shown to be specialized races or ecotypes characterized by an unusual tolerance for a particular metal.

Fewer obligate indicator species have been recognized in the past ten years than during the previous periods, but greater emphasis has been placed on the observation of plant communities as an aid in prospecting. Typical plant communities related to copper, lead, and zinc mineralization with several species in common have been found in widely separated areas of Europe.

Stunting, chlorosis, and morphological effects are common in mineralized areas. Some of these aberrant plants have been shown to be true morphological ecotypes; others are known to result from an imbalance of nutrients. The latter effects can be reversed. Both are useful in prospecting.

Several new nickel accumulators and indicators have been reported from New Caledonia, Western Australia, Zambia, Rhodesia, Europe, and Indonesia.

Analyses by R.R. Brooks of several thousand samples of herbarium specimens of well known indicator plants collected throughout the world have shown many to be true accumulators of specific metals. His analyses have pinpointed two or three previously unknown ultrabasic areas in Indonesia.

The geologist who is prospecting a new area would be advised to look for open areas where the vegetative cover consists of fewer than the normal number of species. The plants may be stunted or prostrate, and the plant community may consist of species unusual for the general area. If such plants are deep-rooted, their presence may offer a means of metal detection not possible from surface soils alone.

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