Botanical Prospecting for Uranium on the Colorado Plateau

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By HELEN L. CANNON

BOTANICAL PROSPECTING FOR URANIUM ON THE COLORADO PLATEAU

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BOTANICAL PROSPECTING FOR URANIUM ON THE COLORADO PLATEAU

THE DEVELOPMENT OF BOTANICAL METHODS OF PROSPECTING FOR URANIUM ON THE COLORADO PLATEAU

By Helen L. Cannon

ABSTRACT

Botanical methods of prospecting for uranium on the Colorado Plateau have been developed by the U.S. Geological Survey. Detailed investigation has shown that a relation exists between the distribution of mineralized ground and of specific herbaceous plants. The distribution of these plants is controlled by the presence of selenium, sulfur, and other trace elements available in the environment of the uranium deposit. Investigation also has shown that the uranium content of trees rooted in ore is significantly higher than that of trees rooted in barren ground. On the flat-lying sediments at lower altitudes of the Colorado Plateau there is a definite correlation between major plant zones and stratigraphic units. Chemical differences that occur in a mineralized area within a formation produce, on the other hand, recognizable changes in the plant societies, which may be useful as indicators in prospecting. Information concerning the availability of ions in an ore environment and the absorption of these ions by plant species is important in the development of botanical prospecting techniques.

Plants that act as indicators of uranium ore on the Colorado Plateau are controlled by the increased availability of selenium, sulfur, calcium, or phosphorus in the vicinity of ore deposits. The most useful plant species is *Astragalus pattersoni;* the distribution of this plant has led to the discovery of ore deposits in several districts. Prospecting by mapping the distribution of indicator plants is most effective at altitudes below about 7,000 feet where the ore horizon is less than 40 feet below the surface and where the ore contains 0.001 percent or more selenium.

Plants of the mustard family excel in the absorption of uranium but are not as useful in prospecting by plant analysis as coniferous species of deep-root habit and wide distribution. The average uranium content of coniferous trees growing in barren areas is 0.5 ppm (parts per million) compared to 1.5 ppm in mineralized ground. Tree samples may be collected on a grid pattern, analyzed for uranium content by a recently devised chromatographic field test or the older fluorimetric laboratory method, and the values contoured to indicate mineralized ground. The method is applicable in areas of thick forest cover where the ore horizon is at a depth of 70 feet.

Botanical methods of prospecting have been studied and evaluated in 10 districts of the Colorado Plateau. Nearly 11,000 tree samples have been analyzed for uranium, and indicator plants have been mapped along 50 miles of outcrop. Both methods are useful in delineating the extent of mineralized ground. A number of ore bodies were found during the period of appraisal.

INTRODUCTION

A program of exploration and geologic studies concerned with the uranium-vanadium deposits of the Colorado Plateau has been conducted since 1947 by the U.S. Geological Survey under the auspices of the Division of Raw Materials of the U.S. Atomic Energy Commission. Studies of the relations between vegetation and these deposits began in 1947 and continued through 1956. The purpose of the investigation was to discover whether plants rooted in ore are different chemically or taxonomically from plants rooted in barren ground, and whether these differences can be used in prospecting for flat-lying ore deposits that are buried under a considerable thickness of shale and sandstone. Specifically, the investigation was set up to explore the possible significance of an association noted by Beath (1943) between selenium-indicator plants and uranium deposits of the Yellow Cat area in Utah; and also to determine whether the uranium and vanadium content of trees rooted in ore was significantly different from that of trees rooted in barren ground.

As a result of a reconnaissance made by the author in the summer of 1947 in various parts of the Colorado Plateau, detailed work was started in the Yellow Cat area in the summer of 1949, and botanical methods of prospecting have been developed and tested in 10 uranium districts of the Colorado Plateau in different climatic and geologic environments. The project has required expert assistance in the fields of botany, chemistry, and geology and has included, in addition to the full-time efforts of the author, the following field personnel, some of whom are authors of subsequent chapters in this bulletin: geologists—John W. Harbaugh, Louis C. Rove, Jr., Perry F. Narten, William H. Starrett, Frank J. Kleinhampl, Albert J. Froelich, Carl Koteff, and Warren R. Martin; botanists—Mary E. Durrell, Richard M. Stillman, Edward C. Clebsch, Samuel A. Bamberg, D. W. Hess, and Penelope Witte; chemists—Ruth Kreher, Faye H. Neuerburg, and Charles E. Thompson. About 15,000 chemical analyses have been made by personnel under Claude C. Huffman, Jr., John N. Rosholt, and J. Howard McCarthy. Specific acknowledgment for chemical assistance is given on all tables throughout this bulletin.

The U.S. Geological Survey has pioneered research on botanical methods of prospecting for uranium. The analysis of vegetation, however, has been used in the search for other types of mineral deposits in many countries. Tkalich (1938) used plants in prospecting for iron in Russia. A close association was shown to exist between the metal content of surface vegetation and ore bodies at depth by the Swedish Prospecting Co. (1939) in searching for vanadium-bearing shales in Sweden and in prospecting for tin and tungsten deposits in Cornwall, England. Botanical methods were also tried by Rankama (1940) in prospecting for nickel in Finland; by Hedström and Nordström (1945) in studying the chromite deposits of Greece; by Webb and Milman (1951, p. 499) in prospecting for lead and zinc in Nigeria; and by Warren and Howatson (1947) in copper and zinc districts of Canada. For further review see Harbaugh (1953) and Hawkes (1948).

The association of particular plant species, commonly called indicator plants, with mineral deposits or accumulations of a particular element has also been described by many writers. Of greatest importance to our problem was the fine research that has been done on selenium-indicator plants in the Western States and the detailed State-by-State investigations of seleniferous areas that has been carried on by scientists from the U.S. Department of Agriculture (Byers, 1935, 1936; Byers, and others, 1938; Lakin and Byers, 1941, 1948; Miller and Byers, 1937; Williams, Lakin, and Byers, 1940, 1941); the University of Wyoming (Beath, 1937, 1943; Beath, Eppson, and Gilbert, 1935; Beath, Gilbert, and Eppson, 1937, 1939a, 1939b, 1940, 1941; Beath, Draize, Eppson, Gilbert, and McCreary, 1934; Beath, Hagner, and Gilbert, 1946; Knight, 1937); and the University of South Dakota (Moxon and Olson, 1940; Moxon, Olson, Searight, and Sandals, 1938; Moxon, Olson, and Searight, 1939). Our studies have shown that many of these seleniferous areas are also highly radioactive.

Many plants that indicate the presence of gypsum or abundant sulfate in the soils are also of importance in uranium prospecting. Many such plants from the White Sands National Monument were studied and described by Shaffner.[1] They include the following plants also found on the Colorado Plateau—

Abronia angustifolia
Anogra gypsophila
Astragalus allochrous
Cryptantha fulvocanescens
Dithyraea wislizeni
Eriogonum rotundifolium
Lepidium montanum
Oryzopsis hymenoides
Sporobolus giganteus

and species of *Mentzelia*, *Oenothera*, and *Streptanthus*. The usefulness of *Lonicera xylosteum* in prospecting for barite dikes on Alnö

[1] Shaffner, E. R., 1948, Flora of the White Sands Monument of New Mexico: Unpublished master's thesis, New Mexico Coll. Agriculture and Mining.

Island has been ascribed by von Eckermann (1948) to the sulfur content of the dikes. Wild onion has been used for the same reason to trace asphalt outcrops in California (Hoff, 1909, p. 118). Probably the species of the crucifer *Thlaspi*, described as zinc indicators by Vinogradov (1935), and *Eriogonum ovalifolium*, described as a silver indicator by Lidgey (1897) are also controlled by the $CaSO_4$ content of the oxidized ores. Many of these plants are common near uranium deposits.

The occurrence of other indicator plants in the vicinity of ore deposits has been reported in the literature for the last 60 years, but whether the plants are actually controlled by the ore elements, by associated elements, or by changes in the availability of major plant nutrients, is generally unknown. The relation of plants to other types of ore deposits not of immediate concern to the uranium prospector has been described and reviewed by Lidgey (1897), Dorn (1937), Vogt (1942), and others.

The investigation of botanical relations on the Colorado Plateau by the U.S. Geological Survey has resulted in the development of two methods—plant analysis method and indicator-plant method—of botanical prospecting for uranium and an evaluation of the relative effectiveness of each. In addition, the collection and analysis of several thousand samples of native vegetation, controlled plot experiments in a desert environment, and ecologic studies of plant distribution in many districts have yielded basic information on the absorption of uranium and associated elements by different plant groups, changes in availability of plant nutrients in an ore environment, and the effect of an ore deposit on plant distribution. Basic information acquired during the first two seasons has been published (Cannon, 1952).

The two methods of prospecting for uranium that evolved have resulted in the preparation of areal maps on which ground favorable for mineralization is delineated. In the plant-analysis method, isogram maps are compiled from uranium analyses of tree samples collected systematically on a grid pattern; areas of anomalously large amounts of uranium in the samples are favorable for the discovery of mineralized ground. Preliminary tree-analysis data have been published for two districts in New Mexico (Cannon, 1953; Cannon and Starrett, 1956). By the indicator-plant method, maps are made showing the distribution of the key indicator species for a given area. A handbook of methods of botanical prospecting for uranium containing illustrations of key indicator plants has been published (Cannon, 1957). Both methods have been evaluated by prospecting studies in 10 districts of the Colorado Plateau. Samples of more than 10,000 trees have been analyzed for uranium, and indicator-plant studies have been made along 50 miles of outcrop. Reports on district studies and the evaluation of methods form subsequent chapters in this bulletin. The studies indicate that a positive correlation exists between botanical anomalies and mineralized ground.

A list of the complete Latin and common names of the plants referred to in this report is given on pages 45–48.

GEOLOGY AND ORE DEPOSITS OF THE COLORADO PLATEAU

The Colorado Plateau region, or the Colorado Plateaus province of Fenneman (1931), occupies an area between the Rocky Mountains on the east and the Great Basin province on the west and includes parts of Colorado, Utah, Arizona, and New Mexico. The rocks exposed are mostly flat-lying sedimentary strata that range from Pennsylvanian to Tertiary in age and that are pierced in several places by laccolithic mountains and salt plugs, which have tilted and distorted the strata on their flanks. The post-Pennsylvanian rocks are chiefly continental in origin and consist predominantly of alternating sandstone and mudstone sequences, and minor sequences of limestone and gypsum. The resistant sandstone beds form broad mesas, which are deeply dissected by stream erosion.

Uranium minerals are known to occur locally in virtually all the formations exposed on the Colorado Plateau. About 20 formations ranging in age from Pennsylvanian to Tertiary have yielded commercial ore. Minable concentrations of uranium occur chiefly in beds of sandstone, but the deposits in the Todilto limestone are an important exception. The relations between plants and uranium deposits at several stratigraphic positions have been studied in the areas listed in the table below, which also indicates the formation in which the deposits occur. The geographic location of most of these areas is shown in figure 1.

The ore deposits are generally tabular and lie roughly parallel to the bedding. Carnotite and tyuyamunite, composed of oxides of uranium and vanadium, are the principal ore minerals in the oxidized zone, but uraninite and coffinite associated with sulfides are common at depth. According to Garrels and Christ (1959) oxidation above the water table is believed to be necessary for the migration of uranium by solution and redeposition. In the absence of vanadium, arsenic, or phosphate and in the presence of iron or copper sulfides, an abundant migration of uranium may take place. The uranium is transported as either uranyl sulfate or uranyl carbonate and is precipitated as transitory uranyl compounds upon evaporation or adsorbed on ferrous manganese or aluminum hydroxides in the soil

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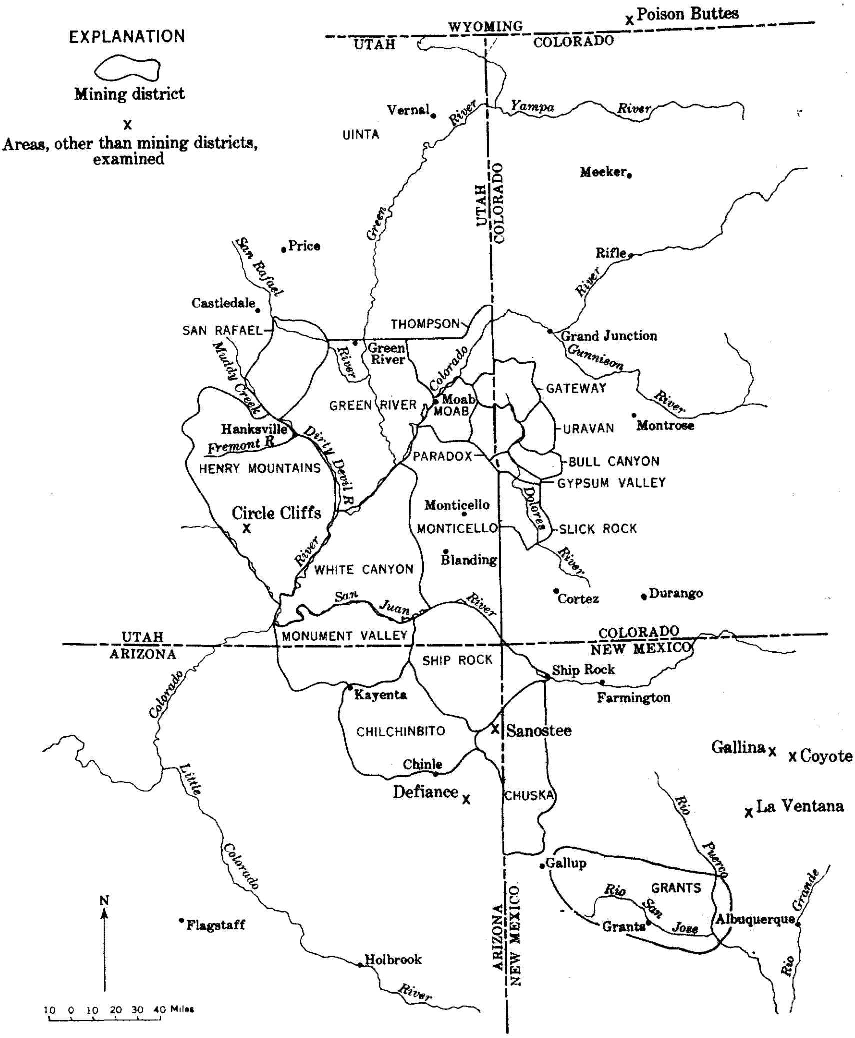

FIGURE 1.—Index map of part of the Colorado Plateau showing mining districts and areas where plant relations have been examined.

or regolith. Uranium is fixed with vanadium, arsenic, and phosphate in insoluble claylike layer compounds.

Investigations by E. M. Shoemaker and others show that uranium ores of the Colorado Plateau contain anomalous amounts of vanadium, sulfur, selenium, cobalt, molybdenum, lead, zinc, nickel, copper, and silver. Several of these elements have been used as geochemical tracers in prospecting for uranium. Differences in the availability of these trace elements and of the major plant nutrients, potassium, *Uranium-bearing formations of the Colorado Plateau and the areas in which plant relations have been studied*

System	Group, formation, or member	Mining districts and other areas in which plant relations have been examined
Tertiary and Quaternary(?).	Santa Fe group	Santa Fe, N. Mex.
Tertiary	Uinta formation	Uinta, Utah.
	Green River formation	Poison Buttes, Wyo.
	Chuska sandstone	Defiance, Ariz.
Cretaceous	Mesaverde group	La Ventana, N. Mex.
	Dakota sandstone	Grants, N. Mex.
Jurassic	Morrison formation:	
	Brushy Basin member	Do.
	Westwater Canyon member.	Do.
	Recapture member	Chuska, Ariz.–N. Mex.
	Salt Wash member	Thompson, Utah.
		Green River, Utah.
		Henry Mountains, Utah.
		Monticello, Utah.
		Gateway, Colo.–Utah.
		Paradox, Colo.–Utah.
		Gypsum Valley, Colo.–Utah.
		Bull Canyon, Colo.
		Slick Rock, Colo.
		Ship Rock, N. Mex.–Ariz.–Utah.
	Todilto limestone	Grants, N. Mex.
		Coyote, N. Mex.
Triassic	Chinle formation:	
	Moss Back member	San Rafael, Utah.
	Shinarump member	White Canyon, Utah.
		Monument Valley, Ariz.–Utah.
		Henry Mountains, Utah.
		Circle Cliffs, Utah.
Permian	Cutler formation	Gallina, N. Mex.

phosphorus, and calcium, in the environment of an ore deposit affect the vegetation, and such effects are the basis for prospecting by botanical means.

GEOGRAPHY AND ECOLOGY

GENERAL SETTING

Geographically the Colorado Plateau is a semiarid country of sandy plains, deeply dissected tablelands, and isolated laccolithic mountains. The surface ranges from 3,500 to 13,000 feet in altitude, and the precipitation ranges from 5 inches on the deserts to 28 inches a year at high altitudes. Total precipitation may differ markedly within a few miles, as it does in the Henry Mountains area (Hunt, 1953, p. 27), from 5 inches on the desert plateau to 15 inches on the mountain slopes. The average altitude of the Colorado Plateau is about 6,500 feet, and the climate is characterized by large diurnal variations in temperature and by cold winters. The major plant zones are discontinuous owing to abrupt changes in altitude in the mountainous areas and consequent variations in temperature and rainfall.

The major plant formations and associations of the Colorado Plateau are shown on plate 1. Important stratigraphic units are shown on plate 2. The association of particular plant types with a given stratigraphic unit is noteworthy. Distribution of the plant associations is related not only to altitude and moisture conditions but also to the chemistry of the geologic formations on which the plants are growing. Where the texture, moisture content, and salinity of the regolith are uniform and closely related to a single geologic entity, a characteristic flora may develop over wide areas. The Mancos shale of Cretaccous age, for instance, commonly weathers to a clay soil of high salt content, which supports a salt desert association of mat saltbush and greasewood with *Eriogonum inflatum*, tansy-mustards, woody asters, wild onions, and other sulfate-tolerant seasonal plants. The Dakota sandstone, which immediately underlies the Mancos shale, on the other hand, is characterized by pinyon, juniper, and sagebrush. The sandstone is commonly covered by a very fine grained loess soil.

Local changes in the flora may develop along the outcrop of any formation in which there is a variation in texture, moisture content, and salinity or in which there is an introduction or redistributon of mineral constituents. In the same way that a knowledge of geology may help the ecologist in interpreting and mapping plant communities, an understanding of plant communities may help the geologist in mapping geologic formations and in locating ore deposits within a favorable formation. For those interested in plant ecology as an aid in prospecting for uranium deposits on the Colorado Plateau, a brief review of the common plant communities, their requirements, and geologic relations in this region is given to form an appropriate background for a discussion of plant species indicative of uranium deposits. Altitudes given for assocation changes include a considerable amount of overlap as differences of 1° latitude may represent a change of as much as 400 feet in altitude (Hopkins, 1938, p. 8) and because the altitude of the break in vegetation may vary by several hundred feet on north-facing and south-facing slopes of the same mountain. Field observations of Colorado Plateau plant associations have been checked against Hunt (1953, p. 28), Shantz and Piemeisel (1940, p. 6), Shantz (1925, p. 16), Nichol (1937, p. 184), and Sampson (1925, p. 27). Ecologic groupings have been used in conformity with Weaver and

Clements (1938, p. 481), Shantz (1925, p. 16), and Sampson (1925, p. 27) insofar as possible.

As defined by Weaver and Clements (1938, p. 89) a "formation" is a major unit of fully developed or climax vegetation and is dependent on climate. Each formation consists of several associations of plant communities which are of regional character. An "association" is uniform in physiognomy and floristic composition and may have 10 or more dominant or controlling species. A large unit that is dominated by a single species is called a "consociation." A subdivision of an association that is dominated by more than one species and controlled by differences in precipitation, evaporation, and temperature is called a "faciation." Where the environment is temporary as in swamps, burns, or cleared areas the names "associes," "consocies," and "facies" are used.

These terms have been used in the ecologic description that follows in order to define exactly what was mapped and to make the information of general use among botanists as well as geologists. The associations of the forest climaxes were not mapped separately; the communities of the northern desert shrub vegetation, on the other hand, were mapped in considerable detail. I suggest that greasewood on the Colorado Plateau might be considered a faciation of the shadscale association rather than of climax rank.

MOUNTAIN FOREST CLIMAXES

TUNDRA FORMATION

An association of sparse alpine vegetation grows above timberline on the windy mountain peaks. The plant cover consists largely of species of *Arenaria*, *Carex*, *Draba*, *Eriogonum*, *Phacelia*, *Phlox*, *Poa*, *Ribes*, and *Silene*, which are of no consequence in botanical prospecting.

The tundra has not been mapped separately from the spruce-fir formation.

SPRUCE-FIR FORMATION

Engelmann spruce (*Picea engelmanni*) and alpine fir (*Abies lasiocarpa*) occupy the coldest and wettest parts of the mountains below timberline at altitudes of about 9,000 to 10,000 feet. The average precipitation is 26 inches, and the vegetation is indicative of the subalpine zone. The forests are generally open, the ground has a good grass cover, and scattered shrubs belong generally to the currant (*Ribes*), willow (*Salix*), and elder (*Sambucus*) genera. No major ore deposits in sedimentary beds are known at this altitude on the Colorado Plateau.

PONDEROSA PINE-DOUGLASFIR FORMATION

Mixed forests of ponderosa pine (*Pinus ponderosa*), Douglasfir (*Pseudotsuga taxifolia*), white fir (*Abies concolor*), Rocky Mountain juniper (*Juniperus scopulorum*), and scrub or Gambel oak (*Quercus gambeli*) extend from about 6,200 to 9,500 feet in the montane zone. Scrub oak and pondersosa pine are dominant to an altitude of about 7,600 feet. Douglasfir persists to timberline. As Douglasfir requires more moisture than ponderosa pine, pine often covers the south-facing slope and fir the north-facing slope of the same canyon. Lodgepole pine (*Pinus contorta* var. *latifolia*) commonly replaces ponderosa pine in areas where the original vegetation has been destroyed by fire. Grassy parks develop in flatter parts of the forests, and stands of aspen (*Populus tremuloides*)—and Douglasfir at higher altitudes—are common as pioneer plants on burned areas or slide-rock. Along breaks and ledges and on flats where there is sufficient sunlight and moisture, the following shrubs may grow:

Amelanchier alnifolia (saskatoon serviceberry)
Arctostaphylos pungens (pointleaf manzanita)
Ceanothus fendleri (fendler ceanothus)
Mahonia fremonti (Fremont mahonia)
Potentilla fruticosa (shrubby bush cinquefoil)
Purshia tridentata (antelope bitterbrush)
Symphoricarpos oreophilus (mountain snowberry)

The herbs commonly include species of *Aster*, *Astragalus*, *Delphinium*, *Erigeron*, *Eriogonum*, *Geranium*, *Gilia*, *Lupinus*, *Penstemon*, *Phlox*, and *Senecio*, depending upon the available sunlight and moisture and the chemistry of the soil. The formation just described is well developed on ore-bearing sandstone of Triassic age on Elk Ridge, Utah and the Chuska Mountains and the Defiance uplift in Arizona; and on sandstone of Jurassic age on Calamity, Outlaw, and other mesas of the Uravan mineral belt in Colorado. In general, sulfur- and selenium-indicator plants are uncommon in the zone of ponderosa pine and Douglasfir largely because of the thick forest cover and lack of sunlight; here tree sampling has been used successfully as a method of prospecting.

PINYON-JUNIPER FORMATION

At altitudes of 5,000 to 8,500 feet juniper and pinyon (*Pinus cembroides* var. *edulis*) are conspicuous on foothill pediments and on mesas capped by sandstone, where the rainfall is low but when ground water is available in or at the base of a sandstone bed. *Juniperus monosperma*, oneseed juniper, is common in the eastern part of the Colorado Plateau, but is replaced by *J. utahensis* in Utah. The trees generally act as phreatophytes; their presence is indicative of ground water, perhaps trapped or perched in the zone of aeration, but at any rate present within about 80 feet of the surface. Pinyon ordinarily dominates over juniper in areas where water is plentiful; pure stands of juniper are common in very dry areas.

The tree cover is open and the undercover is restricted largely to blue grama (*Bouteloua gracilis*) and galleta (*Hilaria jamesi*). Dwarf forms of singleleaf ash (*Fraxinus anomala*) and scrub or Gambel oak (*Quercus gambeli*) are present locally; the latter may be reduced to a ground cover 6 to 8 inches high. The development of the chaparral type of shrub growth on the Colorado Plateau is insignificant. The shrubs that grow in or on the fringes of the zone of pinyon and juniper are plants that prefer a light sandy soil and ground water of low salt content. The shrubs that have been observed in this association are:

Atriplex canescens (fourwing saltbush)
Cercocarpus montanus (true mountainmahogany)
Cowania stansburiana (Stansbury cliffrose)
Ephedra sp. (ephedra or Mormon tea)
Eurotia lanata (common winterfat)
Fallugia paradoxa (apacheplume)
Grayia spinosa (spiny hopsage)
Quercus gambeli (Gambel oak)
Rhus trilobata (skunkbush sumac)
Shepherdia rotundifolia (roundleaf buffaloberry)

Many of these are probably ground-water plants but differ in their water requirements and depth of root penetration.

The herbs include many plants useful as indicators in prospecting. The most common genera are: *Allium*, *Aplopappus*, *Astragalus*, *Calochortus*, *Castilleja*, *Cryptantha*, *Euphorbia*, *Grindelia*, *Lepidium*, *Mentzelia*, *Mirabilis*, *Oenothera*, *Plantago*, *Senecio*, *Solidago*, and *Stanleya*. The pinyon-juniper formation is common on the ore-bearing beds of the Colorado Plateau and is useful both for studies of indicator flora and for tree-sampling (plant analysis) programs.

The juniper, pinyon, and attendant chaparral appear to give way abruptly to sagebrush at the base of the mountains. Actually there is a penetration of sagebrush into the pinyon-juniper and ponderosa pine-Douglasfir formations to an altitude of 7,800 feet wherever the soil is well developed, relatively salt free, and where sufficient water is available to the plants at depths of 4 to 16 feet beneath the ground surface (Shantz, 1925, p. 17). There is a penetration of greasewood in areas of greater salt content. Islands of shadscale and bud sagebrush are of particular importance, because they may be indicative of mineralized ground.

NORTHERN DESERT SHRUB VEGETATION

A northern desert flora grows on the pediments and alluvial fans at the base of the mountains and on the flat sand plains and lower mesas of the Colorado Plateau. The vegetation is characterized by wide expanses of a single species of grayish-green shrub, which may be sagebrush, blackbrush, shadscale, snakeweed, or greasewood, and which presents a monotonous uniform appearance, lacking variety in either color, leaf shape, or general outline. Cottonwoods, salt cedar, fourwing saltbush, or greasewood commonly grow along perennial streams.

The dominance by a single species and the conditions of growth peculiar to each of these communities should be of great interest to anyone who lives for any length of time on the desert. Because the salts and ground-water conditions control the plants, these plants may in turn act as guides to water (Meinzer, 1927; Priklonskii, 1935), grazing, or to lands favorable for agricultural purposes (Fireman and Hayward, 1952). Soil factors affecting the growth of sagebrush, shadscale, saltbush, winterfat, and greasewood were studied by Gates, Stoddart, and Cook (1956). They found that the growth of these species is not dependent upon the texture, pH, exchange capacity, exchangeable potassium or calcium, permability, Ca, Mg, K, Cl, SO_4, CO_3 or carbonate content of the soil but rather is dependent on total salt, exchangeable Na, and soluble Na of the soil and saturation extract conductivity. The interrelation between water availability and salt content may vary with depth below the surface. The tolerance of four dominant plants on the northern deserts is given in the table below.

Relation between vegetation and alkali content of the soil

[Modified from White, 1932, p. 18]

Plant	Total alkali in soil (percent by weight)				Average depth to water (feet)
	1st foot	2d foot	3d foot	4th foot	
Sagebrush	0. 07	0. 14	0. 12	0. 22	4–18
Shadscale	. 26	. 46	. 91	. 71	1–2
Greasewood	. 54	. 70	. 90	. 78	1–2
Pickleweed and seepweed	1. 33	1. 30	1. 62	1. 62	Surface

Alkali injury to plants, according to Harris (1920, p. 34), results largely from diminished water absorption caused by the high osmotic pressure exerted by the concentrated soil solution. When the soil solution becomes more concentrated than that of the root cells, water moves out of the root and plant growth ceases. Those species with a concentrated cell sap have a high tolerance for alkali. Greasewood, a sodium-loving chenopod, thrives in soils containing as much as 1,170 ppm (parts per million) Na_2CO_3, 230 ppm NaCl, and 2,260 ppm Na_2SO_4 (Harris, 1920). A greasewood plant may contain as much as 40 percent Na in the ash (Kearney and Cameron, 1902). The major plant associations characterized by the plants listed in the table above are discussed separately except for greasewood which is considered to be a faciation of the shadscale association on the parts of the Colorado Plateau mapped.

SAGEBRUSH ASSOCIATION

SAGEBRUSH FACIATION

Sagebrush generally merges with the pinyon-juniper formation in the foothills and gives way to species of *Atriplex* on the drier alkaline plains. Stands of sagebrush ordinarily grow at altitudes of 4,000 to 5,500 feet, where precipitation ranges from 10 to 15 inches. It is common on gravel pediments and alluvial fans near the mountains and on sandstone such as the Dakota where a thick soil has formed and the water is plentiful and relatively salt free. The soil on the Dakota is generally a fine-grained loess type of deposit which may be as much as 8 feet thick. Apparently such a soil is ideal for the growth of young sage plants for, although the older roots penetrate to the underlying sandstone, the distribution of sage in many areas is an indicator of plowable loess and hence of land suitable for dry farming. Large areas of sage have been cleared for pinto bean cultivation between Monticello, Utah, and Cortez, Colo. Juniper and pinyon are dominant on the Dakota sandstone where the soil is thin or has been stripped back by wind erosion.

Stands of sage may grow as island communities within the pinyon-juniper formation on higher mesas and within the ponderosa formation of the mountains. Here the total salt content is lower and the sage is not affected by the presence of mineralization as at lower altitudes. On Outlaw Mesa the largest ore bodies were found in sage parks in an otherwise heavily wooded section.

Shvyryoyeva (1955, p. 25) reports that in Russia *Artemisia incana* has a characteristic distribution pattern on each sand unit of Cenozoic age in the Mugodzharsky Mountains so that variations in density have been used to map sand of different origin. On the Colorado Plateau, sage has been used in mapping the boundaries of alluvium by Fred Cater (oral communication, 1949) and also in geologic mapping by R. P. Fischer (oral communication, 1948) because the sagebrush growing on the Dakota sandstone is markedly taller (4 to 7 feet) than that

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growing on sandstone of the Morrison (3 feet) and it is nearly dwarfed on the Summerville formation (1 to 2 feet).

Where conditions are drier, sagebrush may be replaced by *Grayia spinosa* (spiny hopsage) or *Chrysothamnus puberulus* (down rabbitbrush).

BLACKBRUSH-MORMON TEA FACIATION

Where true desert conditions prevail, large areas of sandstone of low salinity on the Colorado Plateau are populated exclusively by *Coleogyne ramosissima* (blackbrush) and *Ephedra* sp. (ephedra or Mormon tea). The vegetation growing in the sand derived from sandstone of Jurassic age on the Green River desert consists of Mormon tea and blackbrush. This faciation gives way abruptly to one of mat saltbush at the contact with the saline Mancos shale (pls. 1 and 2). Over large areas of the Navajo Reservation, Mormon tea is the only shrub in evidence.

LOCAL DOMINANTS

The vegetation growing along many of the streams or washes in the sagebrush association are dominated by *Atriplex canescens* (fourwing saltbush). The recent lavaflows are commonly populated almost entirely by *Fallugia paradoxa* (apacheplume). The species is able to extract the necessary plant nutrients directly from the fresh lava on which no soil has yet formed. Both of these species have been mapped separately as distinct communities.

SHORT GRASS SUBCLIMAX

The prairie grassland formation no longer exists as a fully developed or climax type on the Colorado Plateau as a result of overgrazing and periodic drought but a grass association could be considered as a subclimax of the desert shrub vegetation. The short grass prairie dominants *Bouteloua gracilis* (blue grama), *Stipa comata* (needle and thread), *Stipa neomexicana* (feathergrass), and *Aristida fendleriana* (fendler threeawn) have persisted. *Hilaria jamesi* (galleta) has become a dominant, and pure stands cover the arid plains of northwest New Mexico. The introduced *Bromus tectorum* (cheatgrass brome) is an important part of the grass cover in many areas. The shrub *Ephedra* (Mormon tea) commonly shares dominance with the arid grasses, and herbs described previously as useful indicators grow in grass-covered areas of the Navajo Reservation.

SHADSCALE ASSOCIATION

SHADSCALE FACIATION

Atriplex confertifolia (shadscale saltbush) grows in areas of greater heat and less rainfall than the sagebrush association, and is rooted in more impervious soils of greater salt content. The shrub is common in both the southern and northern deserts and grows from altitudes of 150 to 6,000 feet. In contrast to both sagebrush and greasewood, shadscale is shallow rooted and depends for its water supply upon capillary moisture in the top 2 feet of soil, which is commonly underlain by a hardpan layer (see p. 12). Woody plants associated with shadscale are:

Artemisia spinescens (bud sagebrush)
Atriplex corrugata (mat saltbush)
Eurotia lanata (common winterfat)
Fraxinus anomala (singleleaf ash)
Gutierrezia sarothrae (broom snakeweed)
Tetradymia spinosa (cottonthorn horsebrush)

Eurotia lanata and *Gutierrezia sarothrae* replace shadscale in periods of drought.

The herbaceous plants commonly include—

Aristida fendleriana (fendler threeawn)
Bromus tectorum (cheatgrass brome)
Cryptantha flava (yellow cryptanthe)
Eriogonum inflatum (deserttrumpet eriogonum)
Hilaria jamesi (galleta)
Lepidium montanum (mountain pepperweed)
Oryzopsis hymenoides (Indian ricegrass)
Plantago purshi (woolly Indianwheat)
Solidago petradoria (rock goldenrod)

and species of *Actinea*, *Allium*, *Aplopappus*, *Astragalus*, *Calochortus*, *Euphorbia*, *Grindelia*, *Hedysarum*, *Hymenopappus*, *Mentzelia*, *Oenothera*, and *Senecio*. The shadscale association ordinarily occurs on ore-bearing sandstone that crops out at low altitudes. Communities of selenium- and sulfur-indicator plants, many of which have been listed, are common within the shadscale cover.

MAT SALTBUSH FACIATION

Where the soil is dry and contains an unusual amount of alkali, mat saltbush (*Atriplex corrugata*) may be the only dominant plant species. The plants are low and widely spaced so that the appearance of the desert is monotonous and flat. The species is characteristic of the Mancos shale.

GREASEWOOD FACIATION

Black greasewood (*Sarcobatus vermiculatus*) is a phreatophyte that has a preference for heavy saline soils. The most luxuriant growth occurs where the ground-water table is within 15 feet of the surface, but roots of greasewood can obtain water from a depth of as much as 60 feet (White, 1932, p. 33). Species of *Descurainia* (tansy-mustard) and *Grindelia* (gumweed) are common associates. Greasewood is generally restricted to low poorly drained salt flats, but stands commonly line drainage within the shadscale association, and island communities occur in mineralized parts of the shadscale and juniper cover. All three species are highly tolerant of and absorb large amounts of uranium.

SEEPWEED-PICKLEWEED ASSOCIATION

When the ground-water table is at or near the surface in heavy soils having a salt content of more than 1 percent, both seepweed and pickleweed may be present. The association is not common on the Colorado Plateau, however, and has been noted as an exclusive group of plants only around hot springs and in the drainage from hot springs in New Mexico. These species have not been used in prospecting for uranium.

RELATION OF PLANT GROWTH TO THE CHEMISTRY OF URANIUM DEPOSITS

Plant life reflects the chemistry of the soil in a number of ways. For each group of plants there is an optimum range in nutritional requirement for each element that the plant takes up. If the amount of any element absorbed exceeds or is less than the optimum range for the nutrition of the plant, symptoms of toxicity or deficiency may develop. These symptoms are commonly diagnostic and useful in prospecting for many types of mineral deposits, notably zinc (Cannon, 1955, p. 132) and nickel (Malyuga, 1950). If the differences in availability of major and minor nutrient elements between nonmineralized and mineralized areas are large, some species of plants may be eliminated and others encouraged, so that an indicator flora develops, which can be used in prospecting. Furthermore, the plants that can tolerate mineralized soil contain unusual amounts of ore elements, which may be detected through chemical analysis. All of these effects on plant life reflect the availability of ions in the soil, and the absorption, transport, and eventual use or disposal of the ions by plant species, and so are basically important to the development of botanical prospecting techniques.

AVAILABILITY OF IONS IN THE SOIL

Ions in the soil solution or adsorbed on clay particles, from which they may be easily removed by ion exchange, are considered to be "available" to plants. The ratio of available to total amount of each plant nutrient is generally very small and is dependent upon the pH of the soil, the organic complexes present, the exchange capacity of the soil, and upon the presence of other ions in the soil or regolith in which the plant is rooted. In general, weathering is a selective process in which the surface soils are depleted of plant nutrients. Six parts of potassium to one are lost and nearly half of the nitrogen and phosphorus. The subsoil leachate is usually not in an available form. (Stoltenberg and White, 1953). The amount of an element taken up by a plant is dependent upon that amount available in the soil. To measure this "availability" in the soil is difficult. A crude estimate of the relative availability of ions in the soil can be made by analysis of the water-soluble fraction of the soil. The soil solution contains anions such as nitrates, sulfates, and phosphates and an equal number of cations. The remainder of the metallic ions and potassium are adsorbed on clay particles and on the exchange complex—colloidal salts—(Stout and Overstreet, 1950, p. 308–320). The relative availability of an element can best be gauged by analysis of plant materials to determine the relation of content to optimum range for the species analyzed.

Experimental research on the absorption of metals by plants and the relation between plant distribution and the chemistry of ore deposits has been carried on near Santa Fe, N. Mex., by the author for several years. Plants were grown in plots of desert soil salted with combinations of carnotite ore and plant nutrients to study the availability of uranium, vanadium, and major plant nutrients in a carnotite environment; to learn how uranium and vanadium are absorbed by plants; and to discover the chemical factors that control the distribution of specific plants associated with ore deposits. Sodium vanadate, calcium sulfate, sodium selenite, phosphate, lime, potash, and carnotite were added to plots singly and in combination. Twenty species of plants were grown in these plots and analyzed. A study of the water-soluble fraction of the soils from each plot shows that the amount of an element present in the soil solution is determined largely by the interaction of the other elements present rather than by the addition of the element in question (see table below).

When either sulfur or selenium was added there was an increase in solubility of uranium in the carnotite plots and an increase in solubility of vanadium in the sodium vanadate strip. The relation is apparently reciprocal, as sulfur and selenium are also more soluble in the presence of carnotite. These relations are believed to be a result of oxidation to uranyl sulfate and uranyl selenate in the soil solution in response to irradiation. The oxidation of inorganic and organic solutions in the presence of radiation has been described by Dale (1954) ; sulfur was the most susceptible to reaction of any element that he tested.

Changes in solubility of elements in experimental plot studies, as shown by analyses of water-soluble constituents of soil

Material added	Elements in which solubility—	
	Increased	Decreased
Gypsum	Uranium	Sodium.
Sodium selenite	Uranium, vanadium	Calcium.
Carnotite	Selenium, uranium, phosphorus	Vanadium, iron.
Sodium vanadate	Vanadium, selenium	
Calcium phosphate	Phosphorus, potassium, calcium, iron.	
Lime	Uranium	Iron.
Potash	Potassium, sodium	

ABSORPTION OF IONS BY PLANTS

Major plant nutrients are absorbed by plants in response to the general nutritional requirements of the species. Many inorganic substances, however, are sufficiently similar in chemical behavior to be absorbed by plants whether they are physiologically required in the quantity absorbed or not. The uptake of one element in unusual quantities may thus suppress the uptake of other elements of similar chemical behavior.

A concentration of ions, chiefly H+ and OH−, occurs on the surface of plant root tips, which permits an ion-exchange reaction with clay particles and the release of metals from the clay lattice. Probably metallic ions are accumulated in plants in two ways: either by an ion exchange, in which previously acquired ions are given up in exchange for available external ions, with no resulting increase in the salt content of the tissue (Brooks, 1940) ; or by a process closely linked with the metabolism of the plant, which may increase the salt content of the cells. According to the latter concept (Haertl and Martell, 1956), anions such as citrate, tartrate, malate, and various amino acids, which commonly occur in the solvent aqueous systems of plants, form soluble "chelate" compounds with metals. These acids, secreted by the roots of plants as chelating agents, dissolve and transport the metallic ions into the plant, where the metal is used or stored, and the excess chelate is destroyed. The anions that are characteristic of the metabolic system of particular plant groups thus effectively regulate the quantity of any one group of chemically similar cations that is absorbed.

The cation-exchange capacity of the root is important in the absorption of metals. Plants with a high cation-exchange capacity absorb divalent cations more readily than monovalent cations in competition with soil colloids if the concentration of the element in the soil is not excessive (Mehlich and Drake, 1955, p. 298). Thus, roots of high exchange capacity have more than double the bonding energy for calcium than for potassium, and also absorb the greatest numbers of uranyl and vanadyl (VO) cations from the soil.

The greatest difference in uranium and vanadium absorption between plant groups as shown by 10 species grown at one time in experimental plots was between *Verbesina* of the family Compositae and *Descurainia* of the family Cruciferae. The foliage of *Verbesina* contained in the ash the largest amount of potassium and the lowest amount of uranium and vanadium. *Descurainia* contained the most uranium, vanadium, phosphorus, calcium, and sulfur. The ratio of uranium to vanadium was generally higher in the plants than in the soils. A direct correlation between uranium and vanadium absorption by species was apparent. A comparison of uranium, selenium, and vanadium content of 5 species grown in 3 plots is given in the table below. The amounts absorbed are presumably larger than would be absorbed under natural conditions because large concentrations of various elements were added to the soil in the test plots to emphasize variations in absorption.

Absorption of uranium, vanadium, and selenium varied widely depending on the relation of the individual species to the chemical environment. *Stanleya* grew to magnificent maturity in the selenium plot, where it extracted 174 ppm selenium, but growth and absorption of selenium were restricted by the addition of carnotite. It was not only able to grow but extracted 206 ppm selenium from an additional gypsum plot in which water-soluble selenium could not be detected. Selenium probably substitutes for sulfur in the plant metabolism, and *Stanleya* is a better indicator of seleniferous gypsum than of carnotite ore.

When gypsum and selenium were added to the carnotite plot uranium and vanadium were generally more easily absorbed and transported to the upper part of the plant; when phospate and lime were added absorption of uranium and vanadium was lessened. Results of laboratory experiments with the soil constituents imply that the availability of uranium, vanadium, selenium, and (or) sulfur may be increased in a carnotite environment due to the formation of uranyl sulfate and (or) selenate.

Uranium, vanadium, and selenium content, in parts per million, in the ash of plants from three experimental plots

[Only the above-ground part of the plant was analyzed. Analysts: H. E. Crowe and Claude Huffman, Jr.]

Plant genus	Carnotite plot			Carnotite selenite plot			Sodium selenite plot		
	U	V	Se	U	V	Se	U	V	Se
Descurainia (tansymustard)	265	100	206	490	250	<29	2.8	35	227
Astragalus pattersoni (Patterson loco)	33	25	136	164	95	11,680	2.1	60	5,000
Grindelia (gumweed)	87	105	159	162	84	150	(1)	(1)	(1)
Stanleya (princesplume)	(1)	(1)	(1)	66	50	92	.5	15	174
Verbesina (goldweed)	14	25	13	10	<15	110	------	<15	437
Average content of elements in soil of plot	100-200	400-500	1	200-300	400-500	100-150	5-10	200	100-150

1 The plant was unable to grow in this plot.

	Laboratory No.	Field No.
Descurainia:		
Carnotite plot	D-218779	36-54
Carnotite selenite plot	D-218778	35-54
Sodium selenite plot	D-218777	34-54
Astragalus:		
Carnotite plot	D-218810	67-54
Carnotite selenite plot	D-218809	66-54
Sodium selenite plot	D-218808	65-54
Grindelia:		
Carnotite plot	D-218814	71-54
Carnotite selenite plot	D-218813	70-54
Sodium selenite plot	----------	-----
Stanleya:		
Carnotite plot	----------	-----
Carnotite selenite plot	D-218805	62-54
Sodium selenite plot	D-218804	61-54
Verbesina:		
Carnotite plot	D-218789	46-54
Carnotite selenite plot	D-218788	45-54
Sodium selenite plot	D-218795	52-54

TRANSPORT AND STORAGE OF IONS WITHIN THE PLANT

Results of present-day tracer work by several workers (Epstein, 1956, and Kramer, 1957) demonstrate that ions from the soil solution are absorbed by diffusion along with water into the cytoplasm whence they are transported from cell to cell to all parts of the plant. This process is reversible and the so-called outer space of plants can not accumulate ions in greater amounts than exist in the soil solution. The outer space, however, acts as an ever-present reservoir from which ions may be brought through the vacuolar membrane and accumulated in the inner space of plants by either an active carrier (as iron chelate) or by ion exchange. Thus, plant roots contain ions taken up by all three methods but the upper parts of the plants are dependent on the diffused ions of outer space. Therefore, for rapidly adsorbed ions the actively transported ions may represent a large percentage of the total, while for ions whose rate of adsorption is low, the diffusible and exchangeable ions may be in greater abundance. These differences in rates and methods of absorption cause variations in the metal ratio between roots and the above-ground parts of plants. Generally, more uranium and vanadium are found in roots than in the parts of the plants above ground, although the ratio of these metals in the roots to that of the tops shows considerable variation. If the amount precipitated in the root is large, the root cells may become clogged, and the plant may die.

A study of the uranium and vanadium content of juniper trees and their roots was made in the Thompson district, Utah. It was found that both elements tend to precipitate near the point of intake in the root, that lesser amounts are found in the root approaching the ground surface, and that even smaller amounts are found in the limbs and branches. Forty near-surface juniper roots contained 5.6 times as much uranium and 2 times as much V_2O_5 as the branch tips. Comparative analyses of eight species are given below. The contents of juniper near-surface roots are low compared to those of roots at depth. Two samples of juniper roots at depth contained 70 and 200 times as much uranium and 80 and 150 times as much V_2O_5 respectively as the branch tips. The ratio of uranium and V_2O_5 in roots to that of tops is also much higher in the oak than in the near-surface collections of six other species.

Uranium and vanadium content of roots compared to tops of vegetation in the Thompson district, Utah

[Analysts: F. S. Grimaldi, Ruth Kreher, and Claude Huffman, Jr.]

Field no.	Plant species	Uranium (U), in ash			Vanadium (V_2O_5), in ash		
		Tops (ppm)	Roots (ppm)	Ratio, roots to tops [1]	Tops (ppm)	Roots (ppm)	Ratio, roots to tops [1]
Roots collected at depth from mine							
P 217, 219	*Juniperus monosperma*	7.8	1,600.0	200.0	20	3,000	150.0
P 38, 38	do	2.0	140.0	70.0	50	4,000	80.0
P 26, 27	*Quercus gambeli*	10.0	190.0	19.0	90	1,700	19.0
Near-surface roots							
----------	*Juniperus monosperma* [2]	1.2	7.0	5.6	54	110	2.0
P 24, 25	*Atriplex confertifolia*	3.0	5.0	1.6	10	90	9.0
P 8, 9	*Oryzopsis hymenoides*	30.0	40.0	1.3	70	1,600	23.0
P 56, 57	*Artemisia spinescens*	3.0	5.0	1.6	70	100	1.4
P 54, 55	*bigelovi*	2.0	2.0	1.0	50	5	.1
P 18, 19	*Astragalus preussi*	70.0	70.0	1.0	3,000	2,600	.8
P 16, 17	*Aplopappus armerioides*	40.0	20.0	.5	260	180	.7

[1] Rounded to two significant figures.
[2] Average of 40 samples.

Additional information was obtained from analyses of entire root systems of plants grown in the experimental garden. Plant species that are known to accumulate large amounts of uranium and vanadium in the foliage contained less uranium and vanadium in the roots than species that do not accumulate these elements in the aboveground part of the plant. *Verbesina*, which contained only 3.5 ppm uranium and 10 ppm vanadium in the foliage of the plant, contained 375 ppm uranium and 1,500 ppm vanadium in the roots. The ratio, in this case, of uranium in the roots to uranium in the tops is 3 or

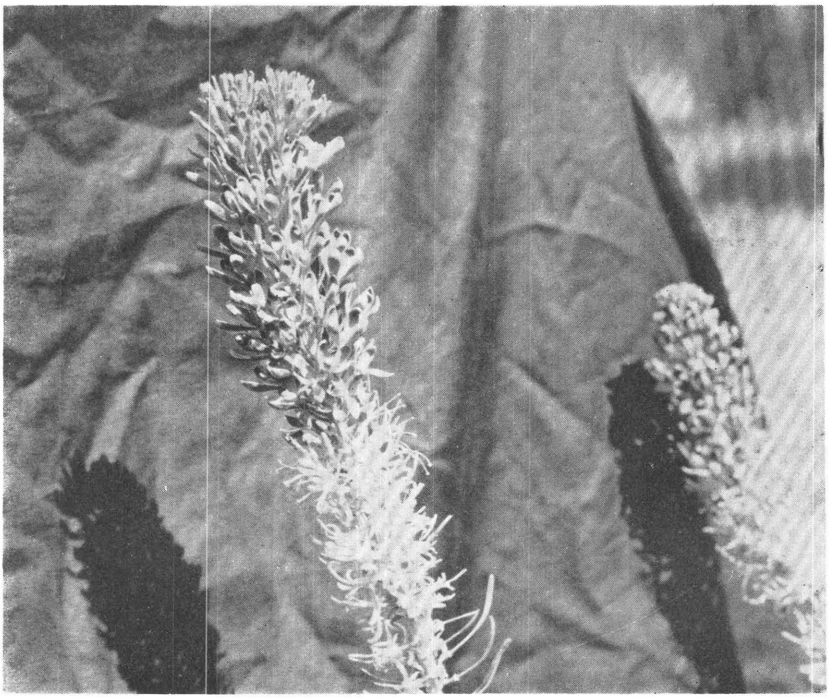
4 times higher than that observed in other plant species in the garden and indicates that the content of uranium and vanadium is low in the foliage because the chemistry of the root system is more favorable for accumulation by ion exchange or active transport than for diffusion. Species of this type are not as useful in prospecting by analysis of branch tips as those that contain less uranium in the roots in relation to the tops.

PHYSIOLOGICAL EFFECTS OF ORE ELEMENTS ON PLANT NUTRITION

Plants growing in the vicinity of uranium-vanadium deposits on the Colorado Plateau are supplied with unusually large amounts of uranium, vanadium, and commonly also molybdenum or selenium. An oversupply of one of these elements may be harmful, as it may prevent another from being absorbed, or if absorbed, from carrying out its normal function in the plant. In general, this results in growth acceleration and a tendency among herbaceous plants to set fruit earlier. Chlorotic and stunted plants have been noted; the affected plants generally have thin and fragmental roots, which contain a yellow deposit. The growth differences described are not widespread and have not been used as guides in prospecting.

In experimental plot studies, stunting is common in plots treated with sodium vanadate, but on the whole growth seems to be stimulated in the carnotite plots; many species grew more luxuriantly and flowered earlier. Peculiar growth phenomena, which apparently can be attributed to irradiation, were observed in the growth of two species. *Grindelia* (gumweed) produced an enlarged basal root stalk on which the basal rosette of leaves was raised 12 inches from the ground. The rosette leaves were greatly increased in length. A similar pattern of growth is described by Gager (1908, p. 230) as occurring in a primrose whose germ cells had been exposed to radiation from radium. *Stanleya pinnata* (desert princesplume) growing in the carnotite plot produced a stalk of imperfect flowers having no petals or stamens and greatly enlarged green sepals (pl. 3).

To test the possibility of irradiation as the determinant, a strongly radioactive and nearly insoluble thorium ore composed largely of the mineral svanbergite [$SrAl_3(PO_4)(SO_4)(OH_6)$] was added to the selenium plot in which the *Stanleya* plants were already in flower. In about a month, the same type of flowers as grew in the carnotite plot began to appear along the flower spike as shown in plate 3. The spikes on most plants also divided, and the growth was greatly stimulated, so that the plants were still blooming and growing in



STANLEYA SHOWING ANOMALOUS GROWTH PRODUCED BY IRRADIATION

Note enlarged sepals and complete lack of stamens and petals in upper half of spike, which grew after the addition of thorium.

November. It seems apparent that the genus *Stanleya* is sensitive to and seriously affected by irradiation of the roots.

PLANT TOLERANCE OF MINERALIZED GROUND

The tolerance exhibited by plant species of mineralized ground on the Colorado Plateau varies somewhat with altitude. The reason for this is probably variations in osmotic pressure in the soil which changes with the salt content. A maximum is reached at lower altitudes where there is less moisture and the salt solutions in the soil are more concentrated. Wadleigh and Gauch (1948) have shown experimentally that an indirect relation exists between the rate of plant growth and the osmotic pressure of the soil. The osmotic pressure is very high in saline soils. Mineralized ground also has a higher salt content and osmotic pressure than the soils of the surrounding area, resulting in a noticeable effect on the distribution of shrubs and herbaceous plants at lower altitudes. Here the plants intolerant of high salt content are unable to grow. These include *Artemisia tridentata* (sagebrush), *Atriplex canescens* (fourwing saltbush), and *Grayia* (hopsage), which are replaced by *Artemisia spinescens* (bud sagebrush), *Atriplex confertifolia* (shadscale saltbush), *Tetradymia spinosa* (cottonthorn horsebrush), and many other salt-tolerant shrubs and herbs. At higher altitudes the effect on plant associations is not distinct and sagebrush parks are common in mineralized as well as barren areas.

Societies of selenium-indicator plants and plants controlled by the increased availability of sulfur, calcium, and phosphorus are found associated with many uranium deposits. Of these, the association of selenium-indicator plants with ores of high selenium content is the most useful in prospecting. Beath (1943) observed the association of these plants with uranium deposits of the Thompson district, Utah, in connection with studies of toxicity of range land. Corroborative data on the usefulness of selenium indicators in this district will be given in a subsequent report.

The seleniferous species of *Astragalus* most indicative of mineralization find the environment of an ore deposit particularly favorable for growth, because the plant species are also accumulators of either molybdenum or vanadium, which are both more abundant in mineralized ground. The amounts of selenium and molybdenum taken up by these plants are toxic to livestock, and numerous mining districts have been set aside by the U.S. Bureau of Land Management for many years as unfit for stock range. Information on seleniferous areas of the United States, selenium accumulating plants, and their effect on livestock has been compiled by Trelease and Beath (1949).

Uranium deposits have been found in many areas that were previously described as seleniferous by Beath (1937, 1943).

PROSPECTING BY MEANS OF INDICATOR PLANTS

The use of a plant species as an indicator in prospecting for metalliferous deposits is based on the assumption that its distribution is controlled or effected in some observable way by the availability of chemical constituents of the ore such as selenium, sulfur, and calcium. Both selenium and sulfur are present in sedimentary rocks, but the concentration varies greatly with the stratigraphic unit and may change from place to place in any one bed. The selenium content of shale of Cretaceous age in the Western United States is appreciable, and remains relatively constant in particular beds or strata over distances of several hundreds of miles. In contrast, selenium is generally present in amounts less than 10 ppm in the barren sandstone of Triassic and Jurassic age in the Colorado Plateau region, but locally, in ore deposits of the same formations, there are concentrations of 100 to 1,000 ppm.

The effectiveness of prospecting by indicator plants depends largely upon the depth to the ore horizon and the contrast in the availability of selenium, sulfur, and other plant nutrients between barren rock and the ore environment. Also the species of indicator plants differ in their root habits, their capacity to absorb selenate and sulfate ions, and in their tolerance of saline soils.

In general, the most useful plants are selenium indicators with long tap roots. Under favorable conditions, the use of *Astragalus* has led to the discovery of ore bodies 70 feet below the surface. *Astragalus* and other seleniferous genera have distinct distribution patterns depending upon the amount of selenium in the ore and the amount required by the plant. Preliminary studies are desirable in advance of prospecting in each new area to determine the species whose distribution is best correlated with mineralized ground.

Differences in the water requirements of coniferous species have also been used in prospecting to determine the position of favorable channels in the sandstone of the Shinarump member of the Chinle formation in the Circle Cliffs area (Kleinhampl and Koteff, 1960). Here the number of pinyon increases with respect to juniper over channels where more water is available in the sandstone. As the position of channels is an important geologic guide to mineralized ground in the Circle Cliffs area, heavy growths of pinyon may be indicative of ore.

CHARACTERISTICS OF INDICATOR PLANTS

A brief description of the characteristics and habits of indicator plants used in prospecting on the Colorado Plateau is given below; a more detailed and illustrated description of 50 species of plants tolerant of mineralized ground has already been published (Cannon, 1957).

The most important group of selenium-indicator plants is included in the genus *Astragalus*, a member of the vetch family. The genus is a large one, and the species vary considerably in selenium absorption. Only certain tribes of the genus are known to be selenium absorbers. A germination test has been devised by Trelease and Beath (1949, p. 20) to determine which species of the genus are selenium absorbers and hence require selenium for growth. Twenty-one species fall into this category; of these, four are associated with ore deposits of the Colorado Plateau. In addition, several other species, some of which are listed in the table below, have been useful in prospecting for mineralized ground of lower selenium content. Careful radiometric surveys show a correlation between all of these species of *Astragalus* and detectable radioactivity of the soil. It is possible that all species of *Astragalus* may require selenium, but for some, the amount may be so small as to escape detection by present analytical methods. Those species that require large amounts of selenium have a characteristic garliclike odor attributable to the organic selenium in the plant. The order of selenium content can be established in a general way by the strength of odor. A discussion of useful species in the order of their importance follows.

Maximum content of four elements found in ash of Astragalus *species*

[Analysts: Claude Huffman, E. J. Fennelly, H. E. Crowe, and W. R. Weston]

Laboratory No.	Field No.	Species	mr/hr [1] (soil)	Ash (percent)	Content of elements in plant ash (ppm)			
					U	V	Mo	Se
------------	P636	*Astragalus pattersoni* [2]	0.25–0.90	11.6	38.0	12	150	1,260
GX-70733	1-92-52	do	.25– .90	13.0	13.6	40	150	46,100
GX-229573	11-55	do	.25– .90	14.2	1.2	--------	1,200	2,850
------------	P18	*preussi* [2]	.13±	19.0	70.0	1,680	30	--------
D-55-1822	1-55	do	.13±	15.2	41.0	175	100	1,000
D-56-2301	42-56	*confertiflorus* [2]	.13±	9.0	--------	900	160	150
GX-220277	78-54	*albulus* [2]	.04	14.6	1.2	--------	<5	33
D-55-5415	219-55	*cobrensis*	.03	14.8	.8	--------	40	33
D-55-1824	4-55	*thompsonae*	.12	34.9	3.6	90	5	14
D-55-5413	215-55	*aculeatus*	.04	22.2	2.7	--------	9	13
D-55-5414	218-55	*nuttallianus*	.02	25.0	.6	--------	20	12

[1] Lowest limit of radioactivity noted in soils in which plant rooted.
[2] Listed by Trelease and Beath (1949, p. 32–38) as selenium absorbers.

Astragalus pattersoni (Patterson loco), plate 4, is a plant 1 to 2 feet high with pealike flowers and pods that rattle when dry. It is not only a most efficient absorber of selenium and molybdenum but is also the most effective indicator of carnotite ore. The plant requires large amounts of selenium and commonly absorbs several thousand parts per million selenium from uranium ores. In plot experiments more than 11,000 ppm selenium was found in the ash of plants collected from soil containing only 30 ppm. The addition of carnotite was found to raise the absorption of selenium. *Astragalus pattersoni* is thus able to extract large amounts of selenium and to act as an indicator of uranium deposits containing as little as 1 ppm selenium. The species is widespread and has been useful in prospecting from the Henry Mountains in Utah to Grants, N. Mex., for deposits in beds ranging in age from Triassic to Miocene.

Astragalus preussi (Preuss' poisonvetch), plate 4, has purple pealike flowers in contrast to the cream-colored flowers of *A. pattersoni* and appears to have a more restricted range; otherwise it is similar in appearance. The absorption of large amounts of vanadium by this species may be a significant factor in the distribution of the plant. *A. preussi* has been used in prospecting in the Thompson, Green River, and Henry Mountains districts of Utah on the Salt Wash member of the Morrison formation.

Other species of *Astragalus* useful in areas of lower selenium content are characterized as follows:

Plant	Flowers	Pods	Leaflets
Astragalus aculeatus	Minute, purple in leaf axils.	Ovoid with prominent sutures.	Five, stiff, spine-tipped.
albulus	Cream-colored	Small, triangular.	Bluish, fine foliage.
argillosus (see pl. 5*A*)	Reddish-purple, short, dense clusters.	Ovoid, compressed.	Linear, long hairs.
cobrensis	Few flowers	Elliptic	Lax stems, linear leaves.
confertiflorus (see pl. 5*B*).	Cream-colored, in dense clusters.	One-celled, small.	Bluish, with silvery hairs.
lonchocarpus	Cream-colored, in dense clusters.	Linear, with long stem.	Long, threadlike.
tenellus	Pale lavender, purple keel.	Small, flattened, pendulous.	Smooth
thompsonae	Large, pinkish-lavender.	Furry, curved, two-celled.	Basal, densely hairy.

Additional genera of plants that require selenium and that may act as indicators of uranium ore where it contains as little as 2 ppm selenium:

Aster venustus (woody aster) with white to pink, daisylike heads and hairy leaves arising from a woody base; common on clay soils and alluvium.

Townsendia incana (hoary townsendia) similar in appearance to *Aster venustus* but matlike in habit, seldom more than 2 inches high. This species grows in the Thompson district, Utah; its seleniferous habit has not been previously described.

Oryzopsis hymenoides (Indian ricegrass) a perennial grass with small ricelike seeds; common throughout the Western United States on soils containing small amounts of selenium.

Stanleya sp. (desert princesplume), common on the Colorado Plateau as a weedy perennial belonging to the mustard family with long spikes of flowers and thin long capsules of seeds extending from the spike. The plant requires both sulfur and selenium but its use as an indicator is limited. The poor reaction of *Stanleya* to soils of high carnotite content, its sensitiveness to irradiation, and its ability to extract selenium from gypsum, all discussed in an earlier section, explain the peculiar distribution of the plant in many districts, and why this plant can be used as a selenium and sulfur tracer downstream from deposits but cannot be used in locating drill holes.

Many uranium ores contain sulfides that oxidize to gypsum above the water table. Sulfur- and calcium-absorbing annuals and bulb plants grow where the gypsum moves upward into the surface soil within reach of shallow rooted plants.

Descurainia (tansy mustard), *Lepidium* (pepperweed), and other plants of the mustard family are indicators of uranium ores that contain gypsum. The family is capable of absorbing large amounts of sulfur, calcium, and sodium and thus is well adapted to life in an alkaline desert environment. *Descurainia* ranked first among all the experimental plants in uranium and vanadium absorption (see p. 20).

Plants of the lily family (Liliaceae) are also indicative of gypsiferous soils. The segolily and wild onion are the most useful indicator plants of this group. In experimental plots, onions grew most luxuriantly in the gypsum plot and second best in the carnotite plot. In the carnotite plot, growth was stimulated so that the plants grew more rapidly than normal.

Grindelia (gumweed) exhibits the greatest tolerance for uranium- and vanadium-rich soils. Seeds were germinated and grown in soils containing about 2 percent vanadium and 0.7 percent uranium. The absorption of uranium, vanadium, and selenium is large from carnotite soils, and the presence of carnotite appears to increase the absorption of selenium tremendously in contrast to its effect on *Stanleya*. As in *Stanleya*, however, the metabolism of the plant is affected by strong radiation, and thus *Grindelia* may not act as an indicator plant in areas where the soils are intensely radioactive.

Species of *Cryptantha*, *Oenothera*, *Mentzelia*, and *Senecio*, are common in mineralized areas because the calcium is more available in a uranium deposit than in the surrounding country rock. These genera are particularly useful in the Grants district, New Mexico.

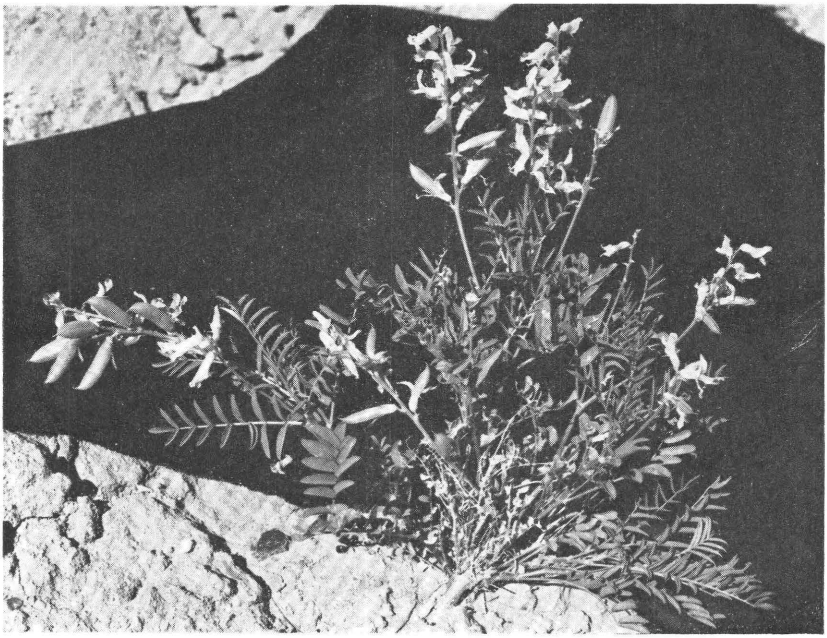
No one calcium- or sulfur-indicator plant should be considered indicative of mineralized ground, as many of the plants are common roadside weeds. A dense population of several of these plant genera is, on the other hand, commonly indicative of soluble salts leaching from a uranium deposit. For instance, in three strongly mineralized areas of the Thompson district, Utah, where ore bodies were found by using indicator-plant information, a dense population of *Allium acuminatum*, *Astragalus pattersoni*, *Calochortus nuttali*, *Cryptantha flava*, *Grindelia squarrosa*, *Lepidium lasciocarpum*, *Oeonothera pallida*, *Oryzopsis hymenoides*, and *Plantago purshi* grew. The many varieties of indicator plants, as well as the population density, is highly significant.

PROSPECTING PROCEDURE

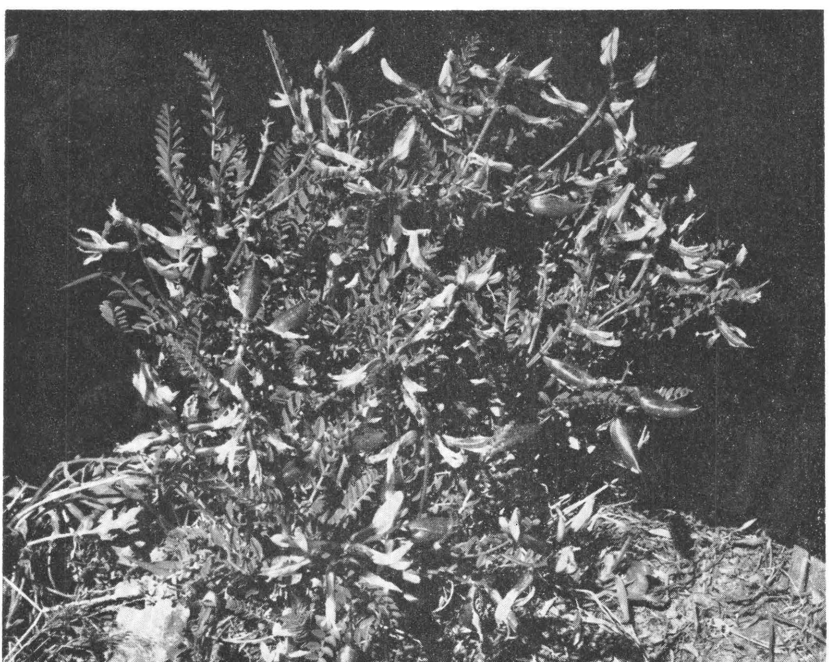
In an area of investigation, preliminary studies are necessary to determine what plant distribution patterns correlate most closely with the extent of the mineralized ground. Such determinations are best made by comparing the entire flora in small plots known to be mineralized with similar plots of barren ground. This preliminary study may evolve into a final mapping of the distribution of a half dozen species that can be plotted by symbol on maps or aerial photographs of the ore-bearing outcrop without the necessity of collection or analysis. A careful study should also be made of the direction of ground-water movement, joint-fracture patterns, folding, and other topographic and structural features of the area in order to interpret from the plant maps the probable migration pattern of water-soluble ions originating in the ore. The resulting delineation of favorable ground can be used as a guide in the exploration for ore. Indicator-plant prospecting is rapid and inexpensive and, therefore, preferred over prospecting by plant analysis if the area is in the proper ecologic zone to permit unobstructed development of the plant community.

PROSPECTING BY MEANS OF PLANT ANALYSIS

Prospecting by plant analysis is based on the detection of anomalous amounts of uranium in trees or shrubs rooted in mineralized

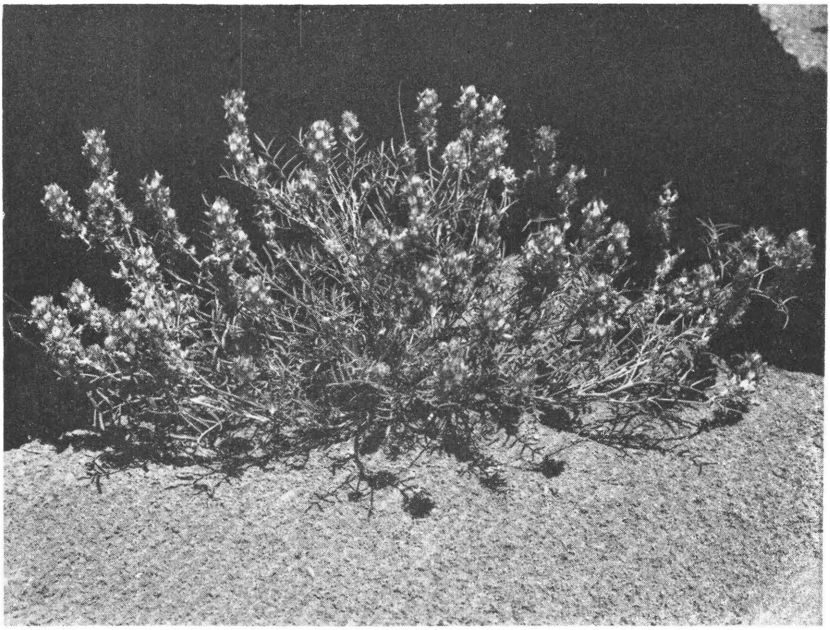


ASTRAGALUS PATTERSONI (cream-colored flowers with purple keel)

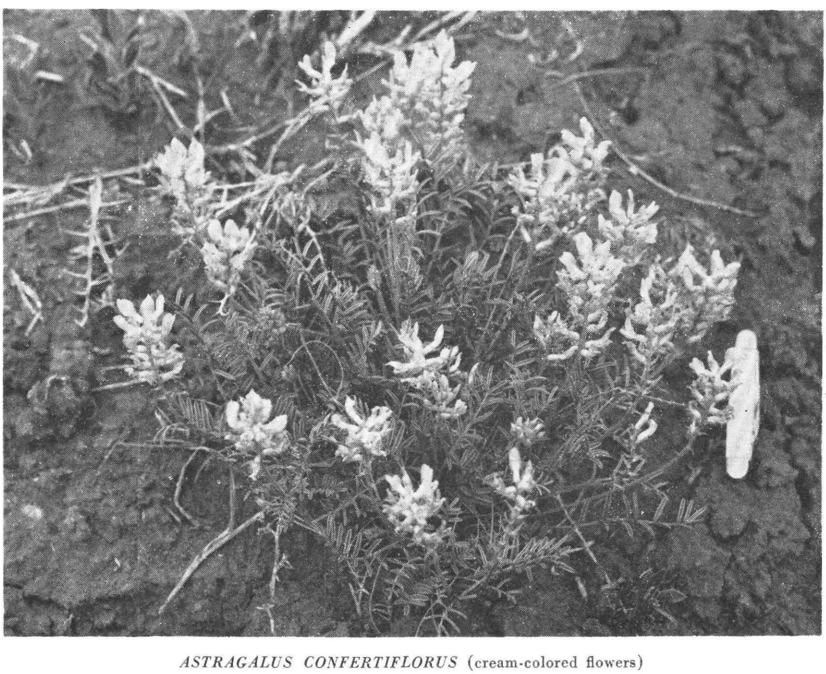


ASTRAGALUS PREUSSI (purple flowers)

INDICATOR SPECIES OF *ASTRAGALUS*



ASTRAGALUS ARGILLOSUS (reddish-purple flowers)



ASTRAGALUS CONFERTIFLORUS (cream-colored flowers)

INDICATOR SPECIES OF *ASTRAGALUS*

ground. The difference is small as the average content of conifers is only 0.5 ppm uranium in the ash. Trees rooted in sandstone-type uranium deposits of the Colorado Plateau have an average content of 1.5 ppm and may contain 50 ppm or more in areas where the ore is highly oxidized. The method is most useful in areas where the tree cover is uniform, and where the ore-bearing bed is preferably 20–30 feet and not more than 70 feet in depth and contains a constant supply of moisture.

Before laying out a tree-sampling project in an area, a preliminary study should first be made of the geology and plant ecology around known deposits. This should include observations on the depth and inclination of the ore-bearing strata, the size and habits of the ore bodies, the presence or absence of a chemical halo in the surrounding barren rock, and the relation of the ore-bearing bed to the water table and the plant roots. The moisture content of the ore bed and of the sandstone and shale between the ore bed and the surface is a controlling factor in the depth of root penetration and may, therefore, indirectly control the absorption of metals from the ore zone. Although the roots of desert trees and shrubs commonly penetrate long distances to reach water, sufficient moisture may be retained in sandstone—ore bearing or barren—above the water table to satisfy the requirements of the plant.

CHOICE OF SAMPLING MEDIUM

GENERAL CONSIDERATIONS

The choice of a sampling medium also involves preliminary studies in the area. Botanical studies should be made of the growth habits of species available for sampling and preliminary samples should be collected from trees growing on both barren and mineralized ground to determine the amount of uranium absorbed by trees in the area under study.

The conifers most useful in prospecting and most common on the Colorado Plateau—pinyon, juniper, ponderosa pine, and Douglasfir—appear from our studies to absorb comparable and consistent amounts of uranium; consequently the anomaly cutoffs determined by the U.S. Geological Survey (written communications by P. F. Narten, 1955, and F. J. Kleinhampl, 1957) may be applied with reasonable success in areas where these species grow.

The ability of a plant to accumulate ions in greater concentration than that in the soil was long believed to be an important factor in prospecting by plant analysis. The use of the term "enrichment factor" was proposed by von Thyssen (1942) as a sort of yardstick for determining the most suitable sampling medium. With the high sensitivity of present analytical methods a large content in the plant sample is generally no longer required. Also, the variations in a particular metal content of a plant may not accurately reflect its content in the soil, but may be related more closely to variations in absorption of some other ion. For instance, those plants that absorb the most uranium on the Colorado Plateau are sulfur- and selenium-indicator plants. Yet the concentration of uranium in these plants is not closely allied to the uranium content of the soil but to the degree of oxidation and to the selenium and sulfur content of the regolith; the uranium content of these plants cannot be used as a reliable indication of mineralized ground.

In alkaline country the ratio of uranium content to the ash content (largely cations) of plants is more constant than the ratio of uranium to the dry weight of the plant (all elements). A juniper and a saltbush containing 5 and 30 percent ash, respectively, and rooted in the same soil, contained 0.1 and 0.6 ppm uranium in the dry weight of the plant, but equal amounts of uranium in the ash; that is, 2.0 ppm. The uranium content of the dry weight of the plant evidently varies considerably with the percentage of ash, but the uranium content of the ash itself remains relatively constant. In the laboratory, analyses for uranium are always made on plant ash, so that the value is more accurate than a conversion to a dry weight basis, and far more revealing to the prospector. Dry weight figures have little merit in botanical prospecting for uranium and probably should not be used. Minor variations in uranium content in the ash nevertheless do exist, and in areas of widescale sampling where it is necessary to use several species of trees, the small differences can be eliminated by using correlation factors or by adjusting the cutoff value between anomalous and background contents for each species.

Several coniferous species of wide areal extent on the Colorado Plateau have deep roots and absorb about the same amounts of uranium, commonly less than 0.5 ppm (in ash) in unmineralized ground, and 1.0 ppm or more in mineralized areas. These species, listed below, have been used as the sampling medium on several projects.

DEPTH OF ROOT PENETRATION

The depth to which the roots of various species penetrate is of importance in botanical prospecting. The semiarid climate of the Colorado Plateau is favorable in this respect for the delineation by botanical techniques of mineralized ground at depths as great as 70 feet beneath the ground surface. This depth is made possible by the necessity for many shrubs or trees, such as pinyon or juniper, to pene-

Trees and shrubs used in analysis prospecting on the Colorado Plateau

Species	Favorable altitude (feet)
Abies lasiocarpa (alpine fir)	9,000–10,000
Pinus ponderosa (ponderosa pine)	
Pseudotsuga taxifolia (common Douglasfir)	7,000–9,000
Abies concolor (white fir)	
Shepherdia rotundifolia (roundleaf buffaloberry)	
Pinus cembroides var. *edulis* (Colorado pinyon pine)	6,000–7,000
Juniperus scopulorum (Rocky Mountain juniper)	
Populus tremuloides (quaking aspen)	
Juniperus utahensis (Utah juniper)	4,000–6,000
monosperma (oneseed juniper)	
Cowania stansburiana (Stansbury cliffrose)	
Atriplex confertifolia (shadscale saltbush)	
canescens (fourwing saltbush)	

trate considerable depths to reach a water-bearing horizon. The effective depth for prospecting by tree analysis varies, though, with ground-water conditions in a particular district. The effective depth was found to be 20 to 30 feet in the Grants, N. Mex., and Elk Ridge, Utah, areas, but 70 feet on La Ventana Mesa, New Mexico, and in Circle Cliffs, Utah.

A slight difference has been noted in the uranium content of trees rooted in ore that lies at a considerable depth compared to trees rooted in near-surface deposits. A tree content of 0.8 ppm uranium was determined as the cutoff between mineralized ground and barren ground on La Ventana Mesa (Cannon and Starrett, 1956) where the mineralized zone is from 60 to 80 feet in depth. In contrast, where the mineralized zone is only 5 to 20 feet in depth in the Grants district, New Mexico (P. F. Narten, written communication, 1955), the cutoff for the same species of tree was established at 1 ppm uranium. Generally, the depth of root penetration appears to have little effect on the amount of uranium transported to the branches.

Actual measurements of root lengths are difficult to make and the root measured may represent only a fraction of the total depth to which the feeder roots ramify. In the course of our study of plant distribution it was found that many woody roots exposed in the mine walls could be traced directly to plants growing on the surface. Depths of root penetration are given in the table below. Additional root lengths reported by others are given in a second column. The roots of the annuals and bulb plants that commonly reflect sulfates in the surface soil may all be measured in inches. Root lengths as much as 21 feet were measured on woody plant species; many unidentifiable roots were noted at depths of from 50 to 75 feet.

It is believed, both from the results of drilling in plant indicated areas and from an experiment conducted in the Carrizo Mountain area, Arizona and New Mexico, that these measurements of woody roots fall considerably short of the total root ramification. A plant of ricegrass growing in dune sand was exhumed and the roots measured at 11 inches. A pit was then dug beside a nearby plant of ricegrass to a depth of 4 feet. The sand was carefully brushed away from the plant and the fine feeder roots were traced to the base of the pit where they disappeared into the sand with no signs of diminishing. A live juniper root was actually dug from a mine wall several hundred feet below the surface (Richard P. Fischer, oral communication, 1947). A 200-foot juniper root was similarly found by miners in the Grants district, New Mexico (Clinton O. Bunn, oral communication, 1957).

In some areas, ore has been found at depths of 100 feet under indicator plants, and junipers have been used successfully in sampling a flat-lying mesa in which the ore horizon (a perched water table) lies at a depth of 65 to 80 feet below the surface (Cannon and Star-

Depth of root penetration of some plant species common on the Colorado Plateau

["sp." following generic name denotes same genus but different species than grows on the Colorado Plateau]

Species	Depth of root penetration measured by author and M. F. Durell (feet)	Reported depths of root penetration (feet)	References
Indicator and tolerant plants			
Elymus condensatus		12	Robinson, 1958.
Hilaria jamesi	5	6	Weaver and Albertson, 1956.
Oryzopsis hymenoides	4+		
Stipa comata		5.5	Do.
Yucca glauca (lateral spread 32 ft).		7.0	Do.
Eriogonum sp		4.0	Hellmers, and others, 1955.
Lepidium montanum	1		
Sisymbrium sp		.6	Cannon, W. A., 1911.
Astragalus cobrensis	6+		
Euphorbia sp		.2	Do.
Mentzelia albicaulis		.4	Do.
Opuntia polyacantha (lateral spread 5.5 ft).		2	Weaver and Albertson, 1956.
Oenothera sp		4.5	Do.
Plantago sp		.5	Cannon, W. A., 1911.
Actinea acaulis	.8		
Artemisia spinescens	5+		
Senecio sp		3.0	Weaver and Albertson, 1956.
Sphaeralcea sp		7.5	Russell, 1950.

Depth of root penetration of some plant species common on the Colorado Plateau—Continued

["sp." following generic name denotes same genus but different species than grows on the Colorado Plateau]

Species	Depth of root penetration measured by author and M. E. Durell (feet)	Reported depths of root penetration (feet)	References
Woody plants used in analysis prospecting			
Juniperus monosperma	19+	200+	Richard P. Fischer, oral communication, 1948. Clinton O. Bunn, oral communication, 1957.
Pinus ponderosa	----------	80	W. D. Grundy, oral communication, 1952.
Ephedra viridis	18	3.3	Cannon, W. A., 1911.
Salix sp	----------	12+	Frederick B. Lotspeich, written communication, 1957.
Quercus sp	----------	28	Hellmers and others, 1955.
gambeli	13	----------	
Atriplex canescens	----------	62	Meinzer, 1927.
confertifolia	5	----------	
Eurotia lanata	----------	3	Shantz and Piemeisel, 1940.
Sarcobatus vermiculatus	19	57	Meinzer, 1927.
Amelanchier utahensis	21	----------	
Cercocarpus sp	----------	5	Hellmers and others, 1955.
Cowania stansburiana	5+	----------	
Ceanothus sp	----------	12+	Do.
Shepherdia sp	----------	50	Cannon, W. A., 1911.
Arctostaphylos glauca	----------	8.5	Hellmers and others, 1955.
sp	----------	17	Do.
Fraxinus anomala	10	----------	
velutina	----------	20	Robinson, 1958.
Symphoricarpos sp	----------	6+	Hellmers and others, 1955.
Artemisia tridentata	----------	30	Woodbury, 1947.
Chrysothamnus nauseosus	----------	15	Meinzer, 1927.
Gutierrezia divaricata	8	----------	

rett, 1956). Successful prospecting at such depths probably results from a combination of deep tap roots that penetrate along fractures in the rocks and the availability of ions in rocks above the ore horizon because of an upward migration of soluble salts.

SAMPLING PROCEDURE

The determination of a sampling pattern depends upon the size and shape of the target area, which in general is equivalent to the horizontal projection of the ore body expected, together with any mineralized halo. In areas where the ore-bearing beds are flat with a uniform forest cover, systematic sampling on a grid pattern may be used. The distance between sampled trees may have an initial spacing of 100 or 200 feet and later a 50-foot spacing in anomalous areas. Where the ore-bearing bed crops out as a sharp cliff, a line traverse parallel to the cliff may be desirable, with particular emphasis on close-spaced samples in talus-covered area.

As the metal content may vary in different morphological parts of the tree, the part sampled is important. Sampling should include collection of material of the same age from the same morphological part of the tree, at the same height from the ground, and from all sides of the tree to assure a composite sample representative of the largest area of root coverage. Warren, Delavault, and Irish (1952) found mature wood to be a consistent sampling medium for the determination of copper and zinc. In testing for minute amounts of uranium, however, Claude Huffman, Jr. (oral communication, 1951), found that ash from leaves and branch tips is more easily mixed and quartered to give reproducible analyses than the ash from branches or trunk wood. For fluorimetric analysis in the laboratory, samples have been collected in quart cardboard containers. Samples collected during the same season and under similar rainfall conditions are desirable.

Special care must be taken to avoid contamination of plant samples as the amounts of uranium found to be significant in prospecting are minute indeed. Contamination by airborne dust in the collecting area or in the laboratory may vitiate the analysis. The air-conditioning system in a large laboratory can easily add 0.5 ppm uranium to the samples being processed; ore trucks can add 1 or 2 ppm uranium to the vegetation over a considerable area; and a mill can increase the uranium content of nearby trees by as much as 1,000 times (Cannon, 1952, p. 758). Contamination on the other hand from nonmineralized dust will increase the apparent ash content of the plant and thus decrease the uranium content. Provisions should be made for washing samples from contaminated collecting areas and for running blanks in the laboratory, particularly on the flux used in a fluorimetric assay.

METHODS OF ANALYSIS

The most precise method of analysis for uranium in plant ash is the fluorimetric method of analysis developed in the U.S. Geological Survey laboratories by Grimaldi, May, and Fletcher (1952), and Grimaldi, May, Fletcher, and Titcomb (1954). By this method the plant ash is mixed with a fluoride carbonate flux and the amount of fluorescence of the resulting flux button is measured photoelectrically by a transmission fluorimeter. When manganese or other elements that may have a quenching effect on the fluorescence are present in quantity, the uranium is extracted chemically before the flux cake is made. A lower limit of sensitivity of about 0.3 ppm in plant ash is possible with this method (Claude Huffman, Jr., written communication, 1956). The initial cost of equipment, the laboratory setup, the sampling and shipping of samples to a central laboratory, and the cost of analysis are all expensive.

The detection of radioactivity in plant ash by alpha count has been used by Anderson and Kurtz (1955, 1956) in prospecting for uraniferous vein deposits in Arizona. The method appears to be sensitive to variations in uranium content down to 10 ppm. Below this amount the radioactivity of uranium is masked by that of potassium, which may constitute 30 percent of the plant ash. The method is applicable to prospecting for vein deposits, but probably not for carnotite deposits of the Colorado Plateau.

A third and more usable analytical method for botanical prospecting on the Colorado Plateau has been developed by Albert P. Marranzino. The method is a modification of a chromatographic method developed for the detection of uranium in natural waters. Designed as a field test to be run on plant ash by the prospector, it is relatively accurate, easy to operate and is sensitive to 1 ppm uranium. All equipment needed can be stocked by the prospector for about $5.00. The method has been tested in the field and appears to be satisfactory for differentiating between mineralized and barren ground. This development makes the analysis of tree ash a feasible and inexpensive method of prospecting. The various methods of analysis for uranium in plants are reviewed and evaluated in a subsequent chapter of this bulletin by F. W. Ward and A. P. Marranzino.

INTERPRETATION OF RESULTS

Isograms of tree-assay data can be drawn on maps of the area to indicate favorable ground. Plant analyses are reported in parts per million of uranium in plant ash; these values may be contoured with an isogram interval of 0.5 ppm. The amount of uranium absorbed by tree roots from mineralized ground varies with the species, and with the type and degree of oxidation of the ore. For juniper and pinyon sampling programs at Circle Cliffs, Utah (Kleinhampl and Koteff, 1960), and at Grants, N. Mex., 1 ppm uranium has been used as the cutoff value between mineralized and barren ground.

At La Ventana, N. Mex., where the tree roots absorb uranium from a mineralized coal, 60 to 80 feet below the mesa surface, a cutoff of 0.8 ppm uranium was used. Working with other coniferous species at higher altitudes, Kleinhampl (written communication, 1957), has obtained slightly different cutoff values for various species. The uranium in the ash of tree foliage, however, is remarkably constant, in contrast to that of the roots. In the presence of uraniferous soil or ground water, the increase in uranium content generally reflects the transition from barren to mineralized ground with reasonable accuracy, although the position of mineralized ground in relation to the vegetation containing anomalous uranium should be determined from a study of the geology and ground-water conditions. The possible migration of soluble salts downdip from the ore deposit is commonly an important factor in the location of drill sites and the delineation of favorable ground. Neither the grade of ore nor the depth to ore can be determined by tree analysis, except in a very broad way; the depth can be assumed to be less than 70 feet and the grade may be assumed to vary in a general way with the content of uranium in the foliage of the trees if the trees are sampled on a grid system in an undisturbed area.

RESULTS OF BOTANICAL PROSPECTING ON THE COLORADO PLATEAU

Botanical prospecting studies have been made in 10 districts of the Colorado Plateau, and in the course of these studies mineralized ground has been located both by plant-analysis and indicator-plant techniques. Prospecting by indicator plants has been tested in the Thompson district, Grand County, Utah, where 1,660 holes were drilled on a grid pattern in an area of 6 square miles after the distribution of indicator plants had been carefully mapped. The holes ranged in depth from 10 to 250 feet. Despite the fact that results obtained in the deeper holes could bear no relation to the plant distribution, the score for the entire drilling program shows 58 percent of the ore holes, 51 percent of the mineralized holes, and only 15 percent of the barren holes were drilled in areas indicated by plants. Five ore bodies were found solely because of the indicator-plant data.

Indicator plants were found to reflect mineralized ground to an average depth of 68 feet, and were dependable guides at depths less than 50 feet. *Astragalus pattersoni* and *A. preussi* are the most reliable indicator plants in the district. Two ore bodies have also been found in the Poison Canyon area of the Grants district by indicator-plant (*A. pattersoni*), distribution on the Morrison formation (P. F. Narten, written communication, 1955). *A. pattersoni* is associated with uranium ores of high selenium content in the Morrison formation in a belt from Thompson, through the Green River and Henry Mountains districts of Utah, and also with ores of the Morrison in the Chuska district, Arizona and New Mexico, and in the Grants and Ship Rock districts, New Mexico, and with deposits of Miocene age in the Santa Fe group.

Nearly 11,000 tree samples have been collected for uranium analysis on the Colorado Plateau, as shown below. Prospecting by plant analysis has been studied in the Grants district, New Mexico, and on Elk Ridge, Utah; in both areas plant anomalies were tested later by limited drilling programs. On Elk Ridge, Utah, radioactive sandstone was found in 80 percent of the plant anomalies tested. Of 108 anomalous localities 55 may contain ore (F. J. Kleinhampl, written communication, 1957). In the Grants district, plant-anomaly maps compiled from juniper and pinyon analyses were furnished to drilling programs of the U.S. Atomic Energy Commission in areas where the U.S. Geological Survey did not undertake exploration. Results of AEC and private drilling indicate that botanical anomalies in the district correlate well with mineralized ground (P. F. Narten, written communication, 1955). Smaller projects of tree sampling have been carried out in seven other areas to establish depth limitations and to investigate absorption variations in different species. A project of sampling *Atriplex confertifolia* (shadscale) on dune sands in the Carrizo Mountain area was not successful because the roots are shallow (see table, p. 33) and the ore-bearing bed underlying the sand was determined by drilling to lie at a depth of 75 feet. Conifer samples on Elk Ridge, on the other hand, effectively indicated ore at depths as great as 40 feet and in Circle Cliffs area as great as 70 feet (Kleinhampl and Koteff, 1960). A good average maximum depth for semiarid parts of the Colorado Plateau is probably 70 feet, but less at higher altitudes.

Extent of U.S. Geological Survey tree-sampling programs on the Colorado Plateau

Locality	Approximate number of trees sampled	Locality	Approximate number of trees sampled
Grants, N. Mex	4,000	La Ventana, N. Mex	200
Elk Ridge, Utah	4,100	Meeker, Colo	200
San Rafael Swell, Utah	700	Circle Cliffs, Utah	100
Gateway, Colo	600		
Carrizo Mountains, Ariz	500	Total	10,800
Thompson, Utah	400		

In the Circle Cliffs area, Kleinhampl and Koteff (1960) found that the ratio between the numbers of pinyon and juniper trees is greater on thicker parts of the Shinarump member of the Chinle formation owing to an increase in available moisture. This conclusion is significant and useful, because the thicker parts of the Shinarump member (containing channels) include the ore.

SUMMARY

Studies of the relations between surface vegetation and the uranium-vanadium deposits of the Colorado Plateau have resulted in the development of two botanical methods of prospecting which utilize different field techniques. Prospecting by indicator plants requires that their distribution be mapped in regions believed to be favorable for the discovery of ore; by the plant-analysis method, samples of tree foliage are collected on a grid or linear pattern and analyzed for uranium. The methods have been tested by collection and analysis of nearly 11,000 tree samples in 9 of the 10 districts of the Colorado Plateau and by studies of indicator plants along 50 miles of outcrop. Both methods have been evaluated by drilling programs succeeding the plant studies.

The uranium-vanadium deposits of the Colorado Plateau occur in sedimentary beds ranging in age from Permian to Tertiary. Ore-bearing beds occur in the plant zones of ponderosa pine and Douglas-fir and pinyon and juniper in the mountainous areas and higher mesas and in the plant zones of sagebrush and shadscale in the desert areas at lower altitudes. Indicator-plant associations found mainly in the shadscale zone and plant analysis in the conifer zones have been useful in prospecting.

Plants growing near ore deposits are affected by differences in the chemistry of the soil. The uranium deposits contain anomalously large amounts of vanadium, selenium, sulfur, molybdenum, cobalt, lead, zinc, nickel, copper and silver. Experimental studies show that the availability of selenium and sulfur for plant absorption is increased in the presence of carnotite and that, similarly, the availability of uranium and vanadium is increased by the presence of selenium and sulfur. These factors are important controls in the distribution of tolerant plants.

Those plant species that absorb and translocate large amounts of uranium to the upper parts of the plant are also found to contain large amounts of vanadium, and either selenium or sulfur. A reciprocal relation with potassium exists.

Uranium and vanadium are concentrated in the roots of plants. The decline in content is marked from the feeder roots, to the near-surface trunk roots, and the tree branches. The amount of uranium, however, found in the branch tips bears a definite relation to the amount of uranium available to the roots from the soil and rock in which the trees are rooted.

Physiological effects on herbaceous plants rooted in mineralized soil have been noted in the field and in plot experiments.

Plants found to be tolerant of mineralized ground and at the same time encouraged by the availability of some element in the ore are most useful in prospecting. The indicator-plant method is dependent upon changes in the local flora growing in mineralized ground. The plant societies are influenced in their distribution mainly by the presence of selenium and secondarily by gypsum, and increased availability of calcium and phosphorus in the ore deposits. The most effective indicator plant, *Astragalus pattersoni*, is able to concentrate enormous amounts of selenium from carnotite-ore deposits that contain very little selenium; this is due to the increased availability of selenium in the presence of carnotite. Prospecting by indicator plants is most effective in lower ecologic plant zones where the cover is open and herbaceous plant societies are free to develop, particularly where the ore contains more than 0.001 percent selenium and is at an average depth of less than 40 feet beneath the surface.

The tree-analysis method is dependent on the absorption and transport of anomalously large amounts of uranium by trees or shrubs rooted in ore at depth to plant parts that are easily sampled. In most areas prospected, amounts of 1 ppm uranium or more in tree foliage are indicative of mineralized ground. The cutoff value varies slightly with the species sampled and with the depth to ore. Maximum root lengths of 21 feet have been measured for plant species in uranium districts of the Colorado Plateau. Root penetration to depths of from 50 to several hundred feet may be inferred from mine observations and from the chemical composition of surface vegetation. Tree analyses may be used effectively to outline mineralized ground to a maximum depth of about 70 feet.

Two methods of analyzing plant ash for uranium content have been perfected in laboratories of the U.S. Geological Survey. The fluorimetric method is the most precise in low ranges, but is also expensive. The chromatographic test is an inexpensive field test designed for the prospector or small commercial laboratory but is least precise in the low ranges of plant content.

A third relation between plants and favorable ground has been reported in the Circle Cliffs area by Kleinhampl and Koteff (1960). The ratio of pinyon to juniper trees is higher on the thicker parts of the Shinarump member or those parts in which mineralized channel fillings occur.

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STANDARD PLANT NAMES USED IN THIS REPORT

In the following list the plants are arranged alphabetically within their families, which are listed in the commonly accepted order of primitive families to complex composites. The Latin and common names are from Kelsey and Dayton (1942), authority and classification are according to Harrington (1954), and abbreviation according to Rydberg (1917).

Family Pinaceae:	
Abies concolor Lindl.	white fir.
lasiocarpa Nutt.	alpine fir.
Juniperus monosperma (Engelm.) Sarg.	oneseed juniper.
scopulorum Sarg.	Rocky Mountain juniper.
utahensis (Engelm.) Lemmon	Utah juniper.
Picea engelmanni Engelm.	Engelmann spruce.
Pinus cembroides var. *edulis* Zucc.	Colorado pinyon pine.
contorta var. *latifolia* S. Wats.	lodgepole pine.
ponderosa Dougl.	ponderosa pine.
Pseudotsuga taxifolia Britt.	common Douglasfir.
Family Gnetaceae:	
Ephedra viridis Coville	green ephedra (Mormon tea).
Family Gramineae:	
Aristida fendleriana Steud.	fendler threeawn.
Bouteloua gracilis (H.B.K.) Lag.	blue grama.
Bromus tectorum L.	cheatgrass brome.
Elymus condensatus Presl.	giant wildrye.
Hilaria jamesi (Torr.) Benth.	galleta.
Oryzopsis hymenoides (R. and S.) Rick.	Indian ricegrass.
Poa sp.	bluegrass.
Sporobolus giganteus Nash	giant dropseed.
Stipa comata Trin. and Rupr.	needleandthread.
neomexicana (Thurb.) Scribn.	New Mexico feathergrass.
Family Cyperaceae:	
Carex sp.	sedge.
Family Liliaceae:	
Allium acuminatum Hook.	tapertip onion.
Calochortus nuttalli Torr.	segolily mariposa.
Yucca glauca Nutt.	small soapweed (Spanish bayonet).
Family Salicaceae:	
Populus sp.	cottonwood.
tremuloides Michx.	quaking aspen.
Salix sp.	willow.

Family Fagaceae:	
Quercus gambeli Nutt.	Gambel oak (scrub oak).
Family Polygonaceae:	
Eriogonum inflatum Torr.	deserttrumpet eriogonum.
ovalifolium Nutt.	cushion eriogonum.
rotundifolium Benth.	roundleaf eriogonum.
Family Chenopodiaceae:	
Allenrolfea occidentalis (S. Wats.) Kuntze	pickleweed.
Atriplex canescens (Pursh) Nutt.	fourwing saltbush.
confertifolia (Torr. and Frem.)	shadscale saltbush.
corrugata S. Wats.	mat saltbush.
gardneri (Moq.)	gardner saltbush.
Eurotia lanata (Pursh) Moq.	common winterfat.
Grayia spinosa (Hook.) Moq.	spiny hopsage.
Sarcobatus vermiculatus (Hook.) Torr.	black greasewood.
Suaeda sp.	seepweed.
Family Nyctaginaceae:	
Abronia angustifolia Greene	narrowleaf sandverbena.
Mirabilis multiflora (Torr.) Gray	Colorado four-o'clock.
Family Caryophyllaceae:	
Arenaria sp.	sandwort.
Silene sp.	silene (catchfly campion).
Family Ranunculaceae:	
Delphinium menziesi D.C.	menziesi larkspur.
Family Berberidaceae:	
Mahonia fremonti Fedde	Fremont mahonia (holly grape).
Family Cruciferae:	
Descurainia sp.	tansymustard.
Dithyraea wislizeni Engelm.	wislizenus spectaclepod.
Draba sp.	draba.
Lepidium lasciocarpum Nutt.	pepperweed.
montanum Nutt.	mountain pepperweed.
Sisymbrium altissimum (L.) Britt.	tumblemustard.
Stanleya pinnata (Pursh) Britt.	desert princesplume.
Streptanthus cordatus Nutt. ex. Torr. and Gray	heartleaf twistflower.
Thlaspi sp.	pennycress.
Family Saxifragaceae:	
Ribes sp.	currant.
Family Rosaceae:	
Amelanchier alnifolia Nutt.	saskatoon serviceberry.
utahensis Koehne	Utah serviceberry.
Cercocarpus montanus Raf.	true mountainmahogany.
Coleogyne ramosissima Torr.	blackbrush.
Cowania stansburiana Torr.	Stansbury cliffrose.
Fallugia paradoxa (D. Don) Endl.	apacheplume.
Potentilla fruticosa L.	shrubby bush cinquefoil.
Purshia tridentata (Pursh) D.C.	antelope bitterbrush.

Family Leguminosae:
Astragalus aculeatus A. Nels. ---------- needleleaf milkvetch.
albulus Woot. and Standl. ---------- white poisonvetch.
allochrous A. Gray---------- halfmoon loco.
argillosus M. E. Jones---------- clay poisonvetch.
cobrensis A. Gray---------- hooded milkvetch.
confertiflorus A. Gray---------- blue poisonvetch.
lonchocarpus Torr. ---------- longseed milkvetch.
nuttallianus D. C. ---------- milkvetch.
pattersoni A. Gray---------- Patterson loco.
preussi A. Gray---------- Preuss' poisonvetch.
tenellus Pursh---------- looseflower milkvetch.
thompsonae S. Wats. ---------- thompson loco.
Hedysarum boreale Nutt. ---------- northern sweetvetch.
Lupinus pusillus Pursh---------- rusty lupine.
Family Geraniaceae:
Geranium sp. ---------- geranium.
Family Euphorbiaceae:
Euphorbia fendleri T. and G. ---------- euphorbia (fendler sandspurge).
Family Anacardiaceae:
Rhus trilobata Nutt. ---------- skunkbush sumac.
Family Rhamnaceae:
Ceanothus fendleri A. Gray---------- fendler ceanothus.
Family Malvaceae:
Sphaeralcea parvifolia A. Nels. ---------- orange globemallow.
Family Loasaceae:
Mentzelia albicaulis Dougl. ex. Hook. --- whitestem mentzelia.
multiflora (Nutt.) Gray---------- desert mentzelia.
Family Cactaceae:
Opuntia polyacantha Haw. ---------- plains pricklypear.
Family Elaeagnaceae:
Shepherdia rotundifolia Parry---------- roundleaf buffaloberry.
Family Onagraceae:
Oenothera pallida Lindl. ---------- pale eveningprimrose.
Family Ericaceae:
Arctostaphylos glauca S. Wats. ---------- bigberry manzanita.
pungens H. B. K. ---------- pointleaf manzanita.
Family Oleaceae:
Fraxinus anomala Torr. ---------- singleleaf ash.
Family Polemoniaceae:
Gilia sp. ---------- gilia.
Phlox diffusa Benth. ---------- spreading phlox.
Family Hydrophyllaceae:
Phacelia corrugata A. Nels. ---------- phacelia (scorpionweed).
Family Boraginaceae:
Cryptantha flava (A. Nels.) Payson---- yellow cryptanthe.
fulvocanescens (Gray) Payson------- white cryptanthe.
Family Scrophulariaceae:
Castilleja angustifolia Pursh---------- narrowleaf paintedcup (paintbrush).
Penstemon sp. ---------- penstemon.
Family Plantaginaceae:
Plantago purshi R. and S. ---------- woolly Indianwheat.

Family Caprifoliaceae:
- *Sambucus* sp. — elder.
- *Symphoricarpos oreophilus* A. Gray — mountain snowberry.

Family Compositae:
- *Actinea acaulis* (Pursh) Spreng. — stemless actinea.
- *Aplopappus armerioides* (Nutt.) Gray — goldenweed.
- *Artemisia bigelovi* A. Gray — bigelow sagebrush.
  - *spinescens* D. C. Eaton — bud sagebrush.
  - *tridentata* Nutt. — big sagebrush.
- *Aster venustus* M. E. Jones — woody aster.
- *Chrysothamnus nauseosus* (Pallas) Britt. — rubber rabbitbrush.
  - *puberulus* (D. C. Eaton) Greene — downy rabbitbrush.
- *Erigeron aphanactis* Greene — fleabane.
- *Grindelia decumbens* Greene — low gumweed.
  - *fastigiata* Greene — erect gumweed.
  - *squarrosa* (Pursh) Dunal — curlycup gumweed.
- *Gutierrezia divaricata* (Nutt.) T. and G. — spreading snakeweed.
  - *sarothrae* (Pursh) Britt. and Rusby — broom snakeweed.
- *Hymenopappus filifolius* Hook. — fineleaf hymenopappus.
- *Senecio uintahensis* (A. Nels.) Greenman — uintah groundsel.
- *Solidago petradoria* Blake — rock goldenrod.
- *Tetradymia spinosa* Hook. and Arn. — cottonthorn horsebrush.
- *Townsendia incana* Nutt. — hoary townsendia.
- *Verbesina* sp. — crownbeard (goldweed).

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