Botanical Prospecting for Uranium in the Circle Cliffs Area Garfield County, Utah

By FRANK J. KLEINHAMPL *and* CARL KOTEFF

BOTANICAL PROSPECTING FOR URANIUM ON THE COLORADO PLATEAU

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By Frank J. Kleinhampl and Carl Koteff

ABSTRACT

The plant-analysis method of botanical prospecting may be used to locate uranium deposits in the Circle Cliffs area where the deposits lie as much as 70 feet beneath the surface of benches developed on the Shinarump member of the Chinle formation. The Shinarump underlying the benches is thicker than 70 feet at many places, however, and thus restricts the use of the plant-analysis prospecting method. The plants *Astragalus pattersoni* and *Stanleya pinnata* broadly define some uraniferous localities adjacent to the contact of the Moenkopi formation and the Shinarump member of the Chinle formation, but the general paucity of *Astragalus* in the Circle Cliffs area limits the usefulness of this genus. *Astragalus pattersoni, Stanleya pinnata,* and *Aster venustus?* may serve as guides to mineralized parts of the Salt Wash sandstone member of the Morrison formation in the Circle Cliffs area. Thick and thin units of sandstone of the Shinarump member generally can be distinguished by studies of the ratios of pinyons to junipers. These studies may supplement drilling to define channel-fill sandstone, which is associated with ore deposits in the Circle Cliffs area. Ratio studies appear to be applicable to other areas throughout the Colorado Plateau where similar geologic and ecologic conditions exist.

INTRODUCTION

During October and part of December 1954, an appraisal was made of the applicability of botanical prospecting methods to the search for uranium in the Circle Cliffs area, Garfield County, Utah (see index map on plate 7). The area was revisited in the spring and fall of 1955. This work was done by the U.S. Geological Survey on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission.

The appraisal was applied primarily to a sandstone of Permian age (probably correlative with the White Rim sandstone member of the Cutler formation, Edward S. Davidson, written communication, 1955) underlying the Kaibab limestone of Permian age, to the Kaibab limestone, to the Shinarump member of the Chinle formation of Late Triassic age, and to the Salt Wash sandstone member of the Morrison formation of Late Jurassic age. Localities studied in detail are shown on plate 7. The frequency of occurrence and distribution of indicator plants was studied with respect to barren and uraniferous ground. An investigation was also made to determine whether or not mineralized rock 50 feet or more beneath the surface could be located by sampling trees and analyzing them for uranium content. The tree-ratio method was studied to determine whether or not the ratios of pinyons to junipers will indicate channel-fill sandstone or differentiate thick and thin units of sandstone.

E. S. Davidson, in charge of geologic mapping of the area for the U.S. Geological Survey, and his coworkers, D. A. Brew and L. D. Carswell were extremely helpful, sharing field camp facilities and contributing analytical data and much geologic knowledge to this report. Acknowledgment is also due L. C. Collins, field assistant in 1954, who mapped some occurrences of indicator plants.

LOCATION

The Circle Cliffs area, part of the Canyon Lands section of the Colorado Plateaus province, lies mostly in Garfield County, south-central Utah (see index map on plate 7). The area is accessible from the west via Escalante, Utah, and Boulder, Utah, through Long Canyon by 39 miles of dirt roads, and from the east via Hanksville, Utah, by 65 miles of dirt roads.

GEOLOGY AND ORE DEPOSITS

The major structural feature of the Circle Cliffs area is a broad doubly plunging anticline with a steep east limb and a gentle west limb. The center of the anticline has been eroded, exposing sedimentary rocks of Permian, Triassic, and Jurassic age. The Shinarump member of the Chinle formation of Late Triassic age underlies a narrow bench which nearly encircles older rocks and which is itself encircled and overlain by younger rocks (pl. 7).

Uranium in the area is found in the Moenkopi formation, in the Shinarump member of the Chinle formation, in other sandstones of the Chinle formation, and in the Salt Wash sandstone member of the Morrison formation. Ore deposits in rocks of Triassic age occur only in a zone that includes the top few feet of the Moenkopi and the bottom few feet of the Shinarump. In places, dissection of the bench formed on the Shinarump has exposed the ore zone, which lies from 20 to 260 feet beneath the surface of the bench. The ore deposits are localized at and near channel banks and irregularities cut in the Moenkopi by post-Moenkopi streams and subsequently filled by sediments of the Shinarump. Lateral extent of the ore deposits is not well known; most are developed by about 200 feet or less of lateral underground workings. Many of the deposits are in pods or discontinuous seams only a few tens of feet in their maximum dimension, but at the Rainy Day mine a drift exposes ore and mineralized rock for about 1,800 feet (Davidson, 1959, p. 436).

Oxidized ore minerals, including metatorbernite, meta-autunite, and metazeunerite, are common in the area (Davidson, 1954). Jarosite and copper carbonate minerals are associated with the oxidized uranium minerals. Uraninite, an unoxidized ore mineral, occurs in the Rainy Day, Lone "B", and probably in the Stud Horse Peaks mines. Pyrite, chalcopyrite, and chalcocite(?) are associated with uraninite.

Selenium, an element necessary for the metabolism of selenium-indicator plants, is present in mineralized rocks of Triassic age in the Circle Cliffs area in amounts ranging from less than 0.5 ppm (parts per million) to at least 6.0 ppm (table 1). These amounts are similar to those found by E. M. Shoemaker, A. T. Miesch, W. L. Newman, and L. B. Riley (1959) in uranium ores from rocks of Late Triassic age in other parts of the Colorado Plateau. These authors also found that, excluding ore from Temple Mountain in central Utah, uranium ore and unmineralized sandstone from formations of Late Triassic age both contain similar amounts of selenium. From their study, they conclude that selenium is dominantly a constituent of the host formations of Late Triassic age and does not appear to have been introduced into ore bodies along with uranium.

TABLE 1.—*Selenium, chemical uranium, and equivalent uranium in ore and mineralized rock samples of Triassic age from the Circle Cliffs area, Garfield County, Utah*

[Asterisk (*) indicates samples collected by E. S. Davidson and analyzed by D. L. Schafer, R. Cox, G. T. Burrow, and J. S. Wahlberg. Other samples collected by E. S. Davidson and analyzed by D. L. Schafer, G. T. Burrow, H. Lipp, J. S. Wahlberg, and M. Finch]

Rock sample			Selenium (parts per million)	Chemical uranium (percent)	Equivalent uranium (percent)
Laboratory serial No.	Field No.	Mine or prospect and locality index No. (see pl. 7)			
222940*	RD-102	Rainy Day mine-18	<0.5	2.60	2.4
222930	SH-2	Stud Horse Peaks mine-1	6.0	1.92	1.1
222932	RD-101	Rainy Day mine-18	<.5	1.05	.98
222937*	SF-1	Silver Falls No. 2 mine-17	1.0	.48	.58
222936*	YJ-1	Yellow Jacket prospects-14	3.0	.29	.31
222939*	SH-1	Stud Horse Peaks mine-1	1.0	.11	.11
222938*	SH-6A	do	1.0	.10	.094
222927	B-2	Salina No. 2 prospect-5	3.0	.10	.49
222941*	RD-2	Rainy Day mine-18	1.0	.099	.090
222935*	HS-1	Hot Shot mine-15	3.0	.079	.32
222929	SH-6B	Stud Horse Peaks mine-1	.5	.044	.034
222933	RM-3	Rocky Mountain mines-18	<.5	.028	.019
222931	RM-4	do	<.5	.018	.017
222942*	RD-3	Rainy Day mine-18	<.5	.005	.009
222943*	RM-2	Rocky Mountain mines-18	<.5	.001	.002
222928	RM-1	do	<.5	.001	<.001

Despite the large number of analyzed samples from the locality of the Rainy Day and Rocky Mountain mines, which introduces a geographic bias in sample distribution, there seems to be a possible correlation of selenium with chemical uranium content and a better correlation of selenium with equivalent uranium (table 1). The latter correlation is similar to that found in the Santa Fe area, New Mexico, where Ralph S. Cannon, Jr., Robert L. Smith, and Helen L. Cannon explain it by a combination of uranium leaching and selenium fixation (Helen L. Cannon, oral communication, 1956). These correlations indicate that the selenium in much of the Circle Cliffs area may be fixed in the uranium deposits and unavailable to selenium-indicator plants. An observation based on the nature of the uraniferous rocks sampled and listed in table 1 may strengthen the hypothesis of selenium fixation. The two samples most out of equilibrium, B–2 and HS–1, are from oxidized deposits (Edward S. Davidson, oral communication, 1955) and are from sandstone. These samples presumably have undergone severe leaching because of their permeability. Uranium may have moved out, leaving an excess of daughter products. Because the selenium content of the two samples is large compared to that in most of the other analyzed samples, it is probable that the selenium nearly represents the original content. If so, and if the rock has been subjected to strong leaching, as indicated by the disequilibrium of uranium and daughter products, it would appear that the selenium is fixed in a relatively insoluble form.

Deposits in the Salt Wash sandstone member of the Morrison formation contain abundant selenium. At the Dream shaft, in the northeast part of the area, carnotite occurs in a carbonaceous siltstone a few feet above the base of the Salt Wash. The selenium content of the ore is extremely high. A sample containing 0.53 percent uranium contains 0.22 percent selenium.[1]

BOTANICAL PROSPECTING

The sandstone of Permian age that underlies the Kaibab limestone, the Kaibab limestone, Moenkopi formation, Chinle formation, Summerville formation, and the Salt Wash sandstone member of the Morrison formation were examined with respect to plant occurrences to determine the feasibility of prospecting for uranium by the indicator-plant and plant-analysis methods (Cannon, 1952, 1954). An earlier cursory examination of the Circle Cliffs area by Helen L. Cannon (oral communication, 1952?) had suggested that at least a few of the primary- and secondary-indicator plants might be useful in delimiting mineralized rock in a zone that includes the top few feet of the Moenkopi formation and the bottom few feet of the Shinarump member of the Chinle formation, and that mineralized areas concealed by the overlying Shinarump member could then be defined by plant analysis.

[1] Sample field no. D–1 and laboratory serial no. 222934; collected by E. S. Davidson and analyzed by D. L. Schafer, R. Cox, G. T. Burrow, and J. S. Wahlberg.

Tommy L. Finnell (oral communication, 1954) suggested that the ratio of pinyons to junipers over relatively thick parts of the Shinarump member might be different from the ratio of pinyons to junipers over relatively thin parts of the Shinarump. This hypothesis was tested in the Circle Cliffs area in places where the Shinarump member underlies flat benches dotted with abundant pinyons and junipers (see pl. 8).

INDICATOR-PLANT METHOD

The indicator-plant method of prospecting utilizes the distribution of indicator species to define areas favorable for the occurrence of uranium-ore deposits. These plants are commonly associated with uranium deposits because their growth, partly dependent on chemical environment, is promoted by the presence of elements associated with uranium. The indicator-plant study made in the Circle Cliffs area utilized only plants listed by Cannon (1957).

Areas where *Astragalus* and *Stanleya* were noted and areas where few or no indicator plants were seen are shown on plate 7. The data are based on observations made in 1954 and in the spring of 1955; the revisit in 1955 verified the earlier findings with only one exception. *Astragalus* seen in 1955, in a locality extending from about one-fourth to one-half mile southwest of the Black Widow mine was not present in the locality in 1954.

Indicator and uranium-tolerant plants found growing on rocks of Triassic and Jurassic age in the Circle Cliffs area are listed below according to their apparent relations to mineralized and barren ground.

Indicator and uranium-tolerant plants found growing in the Circle Cliffs area, arranged according to their relation to uranium-mineralized rock

Controlling element	Plants frequently associated with uranium-mineralized rock	Plants having indeterminate relation to mineralized rock	Plants not restricted to uranium-mineralized rock
Plants growing on rocks of Triassic age			
Selenium	*Astragalus pattersoni.*		
Do		*Oryzopsis hymenoides.*	
Selenium and sulfur	*Stanleya pinnata*		
Calcium			*Cryptantha flava?.*
Do			*Euphorbia fendleri?.*
Do			*Mentzelia multiflora.*
Do			*Eriogonum* sp.
Sulfur (probably)			*Sisymbrium altissimum.*
Potash (probably)			*Elymus salina.*[1]
Uranium tolerant			*Atriplex confertifolia?.*
Do			*Cowania stansburiana?.*

Indicator and uranium-tolerant plants found growing in the Circle Cliffs area, arranged according to their relation to uranium-mineralized rock—Continued

Controlling element	Plants frequently associated with uranium-mineralized rock	Plants having indeterminate relation to mineralized rock	Plants not restricted to uranium-mineralized rock
Plants growing on the Salt Wash sandstone member of the Morrison formation of Jurassic age			
Selenium	*Astragalus pattersoni*?.		
Do		*Aster venustus*	
Do		*Oryzopsis hymenoides.*	
Selenium and sulfur	*Stanleya pinnata*		
Calcium			*Cryptantha flava*?.
Do			*Eriogonum* sp.
Do			*Euphorbia fendleri*?.
Uranium tolerant			*Atriplex confertifolia*?.

[1] Noted by H. L. Cannon during a reconnaissance trip in 1952.

Indicator and uranium-tolerant plants found on rocks of Permian age are listed below, but they are not arranged in the order of the plants above because no special relations to mineralized ground were noted at the time of the investigation.

Indicator and uranium-tolerant plants found growing on rocks of Permian age in the Circle Cliffs

Controlling element	Plant name	Controlling element	Plant name
Selenium	*Oryzopsis hymenoides*	Calcium	*Eriogonum* sp.
Selenium and sulfur.	*Stanleya pinnata.*	Do	*Euphorbia fendleri*?.
Calcium	*Cryptantha flava*?.	Uranium tolerant.	*Atriplex confertifolia*?.

SULFUR- AND CALCIUM-INDICATOR PLANTS

Sulfur- and calcium-indicator plants are ubiquitously distributed on the sandstone of Permian age that underlies the Kaibab limestone, on the Kaibab limestone, Moenkopi formation, Shinarump member of the Chinle formation, shales of the lower part of the Chinle formation, upper part of the Summerville formation, and the lowest 100 feet of the Salt Wash sandstone member of the Morrison formation. The ubiquitous distribution of these plants excludes them from being useful indicator plants in the Circle Cliffs area.

SELENIUM-INDICATOR PLANTS

Astragalus pattersoni, a primary selenium indicator (Cannon, 1957, p. 415), is the only *Astragalus* seen on rocks of Triassic age, and this species is implied wherever *Astragalus* is discussed in the report, unless otherwise specified. A plant, *Hedysarum boreale*, resembling *Astragalus* grows in the area, but can be distinguished from *Astragalus* by its seeds and leaves.

Small numbers of *Astragalus* grow on the Moenkopi formation in Silver Falls Creek canyon. Much of the *Astragalus* noted here could be related to minor amounts of selenium carried into the washes from old mine workings in rocks of Triassic age. Only one occurrence of *Astragalus* in Silver Falls Creek canyon, that at the Duke No. 2 claim, appears to be related to uranium-bearing rock in place. Ore samples from three localities in the Silver Falls area—the Yellow Jacket prospects, Hot Shot mine, and the Silver Falls No. 2 mine—all contained 1.0 ppm or more selenium (table 1). This quantity of selenium can sustain *Astragalus* growth, provided the selenium is in a form available to the plants (Trelease and Beath, 1949; Helen L. Cannon, oral communication, 1954).

Practically no *Astragalus* grew on and adjacent to prospects and mines in rocks of Triassic age in the central, north, and east parts of the Circle Cliffs area. The paucity of *Astragalus* in these parts may be due to the unavailability of selenium to plants; certainly ore and weakly mineralized rock samples generally contain as much selenium as the samples from the Silver Falls locality (table 1). Only rock samples from the Rainy Day and Rocky Mountain mines contain consistently small amounts of selenium. At the Three Pardners mine, *Astragalus* was noted growing on barren red siltstone of the Moenkopi formation about 60 feet below an abandoned adit. The growth is probably due to selenium in mine dump material, which was carried downslope as colluvium, or to selenium in rainwash from the dump.

Astragalus also grows on the Moenkopi formation, away from known uraniferous areas (pl. 7). Abundant *Astragalus* grows just south of the Lamp Stand (north-central part of the area) on red shale of the Moenkopi formation and derived alluvium. Chemical analysis of two of these *Astragalus* plants shows selenium contents of 85 and 250 ppm.[2] The contents are moderately large compared with amounts reported by Trelease and Beath (1949, p. 15) in the same species growing on many types of soils. Perry F. Narten (written communication, 1955) reports that plants of this species contain many thousands of parts per million selenium where they grow on rocks of the Morrison formation in the Poison Canyon area, McKinley County, N. Mex. A sample of gypsum, which is abundant along bedding planes and fractures in the Moenkopi at the Lamp Stand locality, contained less than 0.5 ppm selenium,[3] in-

[2] Sample field nos. KP-569-118 and -119 and laboratory serial nos. 237771 and 237772; collected by E. S. Davidson and analyzed by G. T. Burrow.

[3] Sample field no. ESR-569-45 and laboratory serial no. 238062; collected by E. S. Davidson and analyzed by G. T. Burrow.

dicating that gypsum is probably not now the source of the selenium, but that selenium could be present in the shale in the Moenkopi.

Though the Moenkopi formation weathers to dominantly reddish brown, the lower part of the formation is commonly gray or light yellow and is petroliferous. Pyrite is associated with these petroliferous rocks (Davidson, 1959, p. 438 and 442), and selenium is commonly associated with pyrite and other sulfide minerals (Trelease and Beath, 1949, p. 99 and 106; Goldschmidt, 1954, p. 20), most abundantly with pneumatolytic and high-temperature hydrothermal sulfide ores, but also in unusually large amounts in sedimentary pyrite (Goldschmidt, 1954, p. 533–537). *Astragalus* grows at some of these petroliferous localities, but a detailed study of the plant distribution was not made because no uranium-ore deposits in the Circle Cliffs area are known to be in this part of the Moenkopi formation. The *Astragalus* indicates, however, that the pyrite associated with the petroliferous rocks may indeed be seleniferous.

No *Astragalus* was found growing above the ore zone in the Shinarump member of the Chinle formation anywhere in the Circle Cliffs area, nor was any found on strata of the sandstone of Permian age and overlying Kaibab limestone.

Astragalus pattersoni? is common in the vicinity of the Dream claims where carnotite occurs in a carbonaceous siltstone lens in the Salt Wash sandstone member of the Morrison formation. The plant grows singly and in concentrations northward from the Dream shaft for about three-fourths of a mile. It grows mainly in the lowest 20 feet of sandstone and gray mudstone of the Salt Wash, and grows in lesser numbers on the uppermost beds of the underlying Summerville formation. An ore sample from the Dream shaft contained 0.53 percent uranium and 0.22 percent selenium, a very large concentration of selenium.

Oryzopsis hymenoides, a plant requiring only very small amounts of selenium (Cannon, 1957, p. 467), is widely but sparsely distributed on the sandstone of Permian age, the Kaibab limestone, Salt Wash sandstone member of the Morrison formation, and strata contiguous to the contact of the Shinarump member and the Moenkopi formation.

Aster venustus?, a selenium indicator (Cannon, 1957, p. 469), grows in sparsely distributed concentrations along the lowest 50 feet of the Salt Wash in the vicinity of the Dream shaft.

SELENIUM- AND SULFUR-INDICATOR PLANTS

Stanleya pinnata, a plant requiring both selenium and sulfur (Cannon, 1957, p. 441), generally grows most abundantly in the vicinity of mineralized strata of the Moenkopi and Shinarump, but is not concentrated immediately adjacent to mines and prospects (pl. 7). Locally, *Stanleya* extends laterally hundreds of feet and vertically as much as 45 feet above and 120 feet below mineralized rock at the ore zone.

Stanleya was seen only rarely on mudstone of the Chinle overlying the Shinarump member and was abundant on cliff faces of the Shinarump member in the vicinity of only two prospects. *Stanleya* grew abundantly on some exposures of the sandstone of Permian age and the Kaibab limestone (pl. 7). Edward S. Davidson (oral communication, 1955) says that, in the vicinity of the *Stanleya* growing on rocks of Permian age, anomalous radioactivity of about twice background intensity is associated with a coating of unknown composition on joint surfaces of the rocks.

Sparsely distributed, single *Stanleya* plants are associated with *Astragalus pattersoni?* at the Dream claims.

CONCLUSIONS

In the Circle Cliffs area, sulfur- and calcium-indicator plants are ubiquitous and, therefore, useless for prospecting, because of the calcium carbonate in the Chinle formation and the large amount of gypsum in the Shinarump member of the Chinle formation, the Moenkopi formation, and the Summerville formation.

The selenium indicator *Oryzopsis hymenoides* may be more abundant in the vicinity of mineralized ground, but the change in frequency of occurrence is too subtle for certain detection.

Astragalus and *Stanleya* were not seen growing on the bench underlain by the Shinarump member, but locally were found growing on slopes beneath the bench. Where present they may define broad areas favorable for the occurrence of uranium near the contact of the Moenkopi formation and Shinarump member of the Chinle formation. However, *Astragalus*, because of its general paucity in the Circle Cliffs area, and *Stanleya*, because of its apparent preference for very low grade mineralized rock and intolerance of strongly mineralized ground, should function best as ore guides when used in conjunction with more certain geologic guides to ore, such as channel-fill sandstone.

The general paucity of *Astragalus* on mineralized rocks of Triassic age may be due chiefly to two factors: drought conditions and unavailability of selenium to plants. In the Poison Canyon area, McKinley County, N. Mex., where drought conditions prevail, Perry F. Narten (written communication, 1955) suggests that the local absence of *Astragalus* in parts of the area may be due to prolonged drought which inhibits seed germination and kills old plants. That drought conditions also prevail in the Circle Cliffs area is indicated by climatological data from three stations adjacent to the area (see table below).

Precipitation data, in inches, recorded at three stations adjacent to the Circle Cliffs area

[Data from U.S. Weather Bureau, 1951-55]

Date	Escalante		Fruita		Hanksville	
	Precipitation	Departure from normal	Precipitation	Departure from normal	Precipitation	Departure from normal
October-May 1951-52	8.96	1.94	3.89	−0.62	2.51	−0.43
October-May 1952-53	4.23	−2.79	1.80	−2.71	1.65	−1.29
October-May 1953-54	5.39	−1.63	2.87	−1.64	2.71	−.23
October-May 1954-55	7.31	.29	2.63	−1.88	1.69	−1.25
1952	16.04	3.75	6.18	−1.53	6.09	.74
1953	9.35	−2.94	4.89	−2.82	4.11	−1.24
1954	[1] 11.06	−1.23	[1] 4.11	−3.60	4.41	−.94

[1] Estimated by Weather Bureau.

In the Circle Cliffs area, the drought factor may be less important in affecting the concentration and distribution of *Astragalus* than the availability of selenium to plants, because *Astragalus* grows in relative abundance on the Salt Wash in the vicinity of the Dream claims, which is also in the drought area. The second factor that may be causing the scarcity of *Astragalus*, that of selenium being fixed in the uranium deposits and, consequently, unavailable to plants, is supported by field observations. *Astragalus* is present chiefly in the locality of oldest mining activity for the area, the head of Silver Falls Creek canyon, and downslope from a few mine dumps, where ecesis appears to have succeeded. Selenium becomes readily available to plants where seleniferous ground is disturbed (P. F. Narten, written communication, 1955).

A third factor affecting the concentration and distribution of *Astragalus* may be operable locally—the selenium content of mineralized rock may be too small to support plant growth. At the Rainy Day and Rocky Mountain mines, for example, where no selenium indicators were seen, eight samples of mineralized or ore-grade material from rocks of Triassic age contained less than 0.5 ppm selenium (table 1), the amount at the lower limit of detection by the analytical method used. Amounts less than 0.5 ppm are small compared to selenium contents reported for many rocks and soils supporting seleniferous vegetation in other parts of the Western United States (Trelease and Beath, 1949, p. 110–112). It has been shown, however, that very small amounts of selenium can support selenium-indicator plant growth provided that the selenium is in an available form, as selenate or organic selenium (Beath, 1943; Trelease and Beath, 1949). Helen L. Cannon (oral communication, 1956) was able to grow *Astragalus pattersoni* where only 0.02 ppm selenium in a water-soluble form was added to soil. Furthermore, *Astragalus* indicators may accumulate large amounts (hundreds or thousands of parts per million) of selenium where the rooting medium contains available selenium ranging in amount from a fraction to a few parts per million (Beath, 1943, p. 704; Trelease and Beath, 1949, p. 128). Even plants such as cereals and range grasses, which do not normally take up selenium from seleniferous rock and derived soils, will do so if the selenium is in an available form (Beath, 1943, p. 702).

In the Circle Cliffs area, the general lack of the good selenium indicator, *Astragalus pattersoni*, on mineralized rocks of Triassic age seems to be due chiefly to the unavailability of selenium to plants and, secondarily, to drought conditions. Locally in the area, an extremely small selenium content in mineralized rock may be the factor inhibiting *Astragalus* growth or the growth of other good indicators.

The observation by other workers that selenium content of most uranium-ore deposits and barren sandstone from Upper Triassic formations are very similar (see section on geology and ore deposits) may partly explain the lack of more precise indications of ore deposits by indicator plants.

Astragalus pattersoni?, *Stanleya pinnata*, and *Aster venustus?* may serve as guides to mineralized sandstone in the Salt Wash. *Astralagus preussi*, a good selenium indicator closely related to *Astragalus pattersoni* (Cannon, 1957, p. 417), has been successfully used by prospectors to locate uranium deposits in the Salt Wash of the Trachyte Ranch area, Henry Mountains, Garfield County, Utah (Perry F. Narten and Edward C. Clebsch, written communication, 1954).

PLANT-ANALYSIS METHOD

The plant-analysis method of botanical prospecting for uranium is based on the assumption that plants rooted in a uranium deposit will contain an abnormally large amount of uranium that can be detected by chemical analysis. Uranium assay values of 1.0 ppm or more (in plant ash of branch-tip samples unless otherwise stated) are hereby proposed to define mineralized ground in the Circle Cliffs area. The same value has been used at Deer Flat, San Juan County, Utah (Froelich and Kleinhampl, 1960), and in the Grants area, McKinley County, N. Mex. (Perry F. Narten, written communication, 1955).

Broad, flat benches formed on the Shinarump member overlie the ore horizon in the Circle Cliffs area, and it was thought that plant-analysis prospecting based on grid-pattern sampling of junipers and pinyons growing on the benches could be used to delimit ground favorable for drilling. The ore is near the contact of the Moenkopi and Shinarump, and is generally overlain by channel fillings of the Shinarump ranging in thickness from 20 to 260 feet; consequently, it was necessary to determine the maximum depth at which trees could indicate ore deposits. This was done by collecting branch-tip samples, during 1954, from pinyons and junipers at one barren and four uraniferous areas in the Shinarump. In the uraniferous areas the standstone strata between the ore and sampled horizons range in thickness from 15 to about 70 feet (table 2). Samples were also collected in 1955 from 37 pinyons and junipers growing adjacent to barren drill holes collared in the Shinarump member in the Fourmile Bench area. The assumption is made that the only mineralized zone in the four uraniferous areas ranges from a few feet above to a few feet below the contact of the Moenkopi and Shinarump. Similarly, the maximum depth at which trees could reflect uranium deposits in the Salt Wash was investigated in the vicinity of the Dream claims (table 2). A sample interval of from 50 to 100 feet was used in the areas tested.

Uranium content of most of the plant samples, arranged by area and sample field number, are shown in table 2, and locations of the sampled areas are shown on plate 7. Trees at one barren test area in the Shinarump (table 2) contained well below 1.0 ppm uranium, and most of the trees at the four mineralized areas in the Shinarump contained 1.0 ppm or more uranium. For the barren test area on Fourmile Bench, samples from 32 junipers generally contained well below 1.0 ppm uranium. These ranged in content from 0.1 to 0.9 ppm and had a geometric mean of 0.25 ppm. The five samples of pinyon from this area yielded similar analyses.[4]

The sampled trees growing on the bench formed on the Shinarump appear capable of indicating mineralized rock at least 50 to 70 feet below the surface. This conclusion is based on the assumptions that the known ore horizon, 50 to 70 feet below the sampled horizon, is the only one present, and that those trees assaying 1.0 ppm or more uranium reflect uraniferous ground. Based on the same assumptions and the results of sampling in the four mineralized areas in the Shinarump, sample intervals ranging from 50 to 100 feet appear adequate for locating uranium deposits in rocks of Triassic age in the area. The lateral dimensions of known deposits support this choice of range. Wilbur D. Grundy (oral communication, 1956) noted that a tree, in all likelihood a Rocky Mountain ponderosa pine, growing on the bench formed on the Shinarump just northeast of the Studhorse Peaks has roots that extend downward about 80 feet through a fracture in the Shinarump to a water seep. Pinyon and juniper may be able to grow even deeper roots than the ponderosa because they are more xeric and can grow in warmer and less moist localities. This visual evidence as to the depth of penetration of ponderosa roots further supports the conclusion that pinyon and juniper may indicate mineralized rock as much as 70 feet beneath

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[4] These 37 samples of juniper and pinyon have sample field nos. FK-569-45 consecutively through FK-569-83, excluding nos. 49 and 70, which are samples of another kind of plant. Laboratory serial nos. range from 236761 for sample field no. FK-569-45 consecutively to no. 236799 for sample field no. FK-569-83, excluding serial nos. 236765 and 236786, which correspond to sample field nos. 49 and 70, respectively. Analysts: E. J. Fennelly and Claude Huffman, Jr.

TABLE 2.—*Results of plant-analysis sampling program, Circle Cliffs area, Garfield County, Utah*

[Analysts: Claude Huffman, Jr., and E. J. Fennelly. See plate 7 for location of areas]

Sample field No.	Laboratory serial No.	Kind of tree	Uranium content in ash (parts per million)	Average depth (approximate) to known ore (feet) [1]
Area 17 (barren Shinarump member of the Chinle formation)				
FK-469-1	223502	Pinyon	0.4	7
-2	223503	do	.6	7
-3	223504	Juniper	.2	7
-4	223505	do	.5	7
-5	223506	do	.4	7
-6	223507	do	.6	7
-7	223508	do	.2	7
Area 16, Duke No. 2 claim (Shinarump member of the Chinle formation)				
FK-469-8	223509	Pinyon	4.7	15
-9	223510	do	2.0	25
Area 15, Hot Shot mine (Shinarump member of the Chinle formation)				
FK-469-10	223511	Pinyon	[2] 3.8	50
-11	223512	Juniper	[2] 3.6	50
-12	223513	do	[2] 7.0	50
-13	223514	do	2.0	50
-14	223515	do	[2] 4.8	50
-15	223516	do	2.5	50
-16	223517	do	1.6	50
-17	223518	Pinyon	[2] 16.0	50
Area 12, Lone "B" mine (Shinarump member of the Chinle formation)				
FK-469-18	223519	Juniper	1.5	60
-19	223520	Pinyon	2.1	60
-20	223521	do	1.2	60
-21	223522	do	.5	50
-22	223523	do	.7	60
-23	223524	do	2.5	60
-24	223525	Juniper	.3	50
-25	223526	Pinyon	.8	50
Area 5, Salina No. 2 prospect (Shinarump member of the Chinle formation)				
FK-469-26	223527	Juniper	1.2	60
-27	223528	do	1.8	60
-28	223529	Pinyon	1.4	60
-29	223530	do	1.7	65
-30	223531	Juniper	.8	70
-31	223532	do	.8	70
-32	223533	Pinyon	3.0	60
-33	223534	Juniper	3.5	60
-34	223535	Pinyon	1.9	60
-35	223536	do	1.0	65
Area 19, Dream claims (Salt Wash sandstone member of the Morrison formation)				
FK-469-36	223537	Juniper	1.1	------
-37	223538	do	1.6	------
-38	223539	do	2.3	65
-39	223540	do	.9	80
-40	223541	do	3.4	55
-41	223542	do	2.1	55
-42	223543	do	1.3	------
-43	223544	Pinyon	1.5	110
-44	223545	Juniper	.6	110

[1] In area 17 depth is to contact of Shinarump member and Moenkopi formation.
[2] Probably contaminated; based on magnitude of uranium content of samples.

the surface of the bench formed on the Shinarump. The conclusions concerning depth to which trees may indicate mineralized rock, however reasonable compared to results of other studies (Cannon, 1954; Cannon and Starrett, 1956), are tentative because they are based chiefly on assumptions as to the actual extent of mineralized ground in the control areas.

The tree-analysis data (table 2) indicate that there is no systematic or consistent relation between uranium content of samples of branch tips of trees and depth to ore.

In the Salt Wash sandstone member of the Morrison formation, the position of known mineralized rock does not correlate with the position of sampled trees and their uranium contents. Three trees farthest from the known deposit, contained amounts of uranium similar to the large amounts contained in trees closest to the deposit. Weakly mineralized lenses may occur throughout the Salt Wash in the vicinity of the sampled trees, accounting for the consistently large uranium contents of samples. No anomalous radioactivity was noted anywhere along the outcrop of the Salt Wash except at the Dream shaft and dump; however, mineralized lenses may not be exposed. A second explanation for the large uranium content of these trees may be that they are contaminated by uraniferous dust from mining operations; however, the uranium contents are not so high as to indicate contamination (table 2). The plant-analysis results for this locality are, therefore, indeterminate.

TREE-RATIO METHOD

A new uranium prospecting method using tree ratios was tested in the Circle Cliffs area. The method depends on the different moisture requirements of phreatophytes and on the factors that have localized uranium in sandstone-filled channel scours in rocks of Triassic and Jurassic age on the Colorado Plateau. The scour fillings, by virtue of their high porosity and permeability, generally contain relatively more available water and larger amounts of water than the adjacent mudstone and siltstone; the thick units of sandstone contain larger amounts of water than do thin units. It is expected that plant species requiring large amounts of water will be most abundant where there are large amounts of water. In the Circle Cliffs area the relative abundance of pinyons and junipers was compared with sandstone thicknesses to determine whether any such predictable relations exist.

The ratios of pinyons to junipers were determined by counting the Colorado pinyon pines and Utah junipers that grow on sandstone benches formed on the Shinarump member of the Chinle formation where the unit ranges in thickness from 4 to about 90 feet. The procedure followed was to count all the live pinyons and junipers in eight selected areas, each about two acres in size, and to relate the ratios between the two types of trees to thicknesses of the sandstone. Only a few dead trees were found in the areas of study; consequently, their elimination from the tree counts should have little or no effect on the tree ratios.

Woodin and Lindsey (1954) show that pinyons and junipers have different moisture requirements. They noted that *Pinus edulis* generally grows most prolifically in an altitudinal zone above the oneseed juniper, where it is the dominant tree of the association. They attribute the pinyon's position to a moisture requirement greater than the juniper's. Similarly, Hunt (1953, p. 34) states that *Pinus edulis* generally dominates the zone of pinyon and Utah juniper at its upper extremity. From the observations of Woodin and Lindsey and of Hunt, it appears that the Utah juniper and the oneseed juniper have similar moisture requirements and can be used interchangeably in making studies of the pinyon-juniper ratios. They also observed that Rocky Mountain juniper dominates a juniper-pinyon association above the pinyon zone; consequently, this juniper would probably affect conversely the significance of pinyon-juniper ratios. It is essential, therefore, to identify the species of trees used in ratio study to determine the significance of the ratio.

The ratios of pinyons to junipers determined over different thicknesses of the Shinarump member are given in table 3; plate 7 shows the locations of the ratio studies by area number. In general, the ratio of pinyon to juniper increases with an increase in thickness of sandstone in the Shinarump. The exception at area 5 (table 3) may be explained by a combination of two factors—dip of strata and present topography. Because the dip of the beds at area 5 is to the west, away from a canyon cut through the Shinarump into the Moenkopi, the least amount of water should be available near the bench rim, where the ratio study was made. In addition, the tree

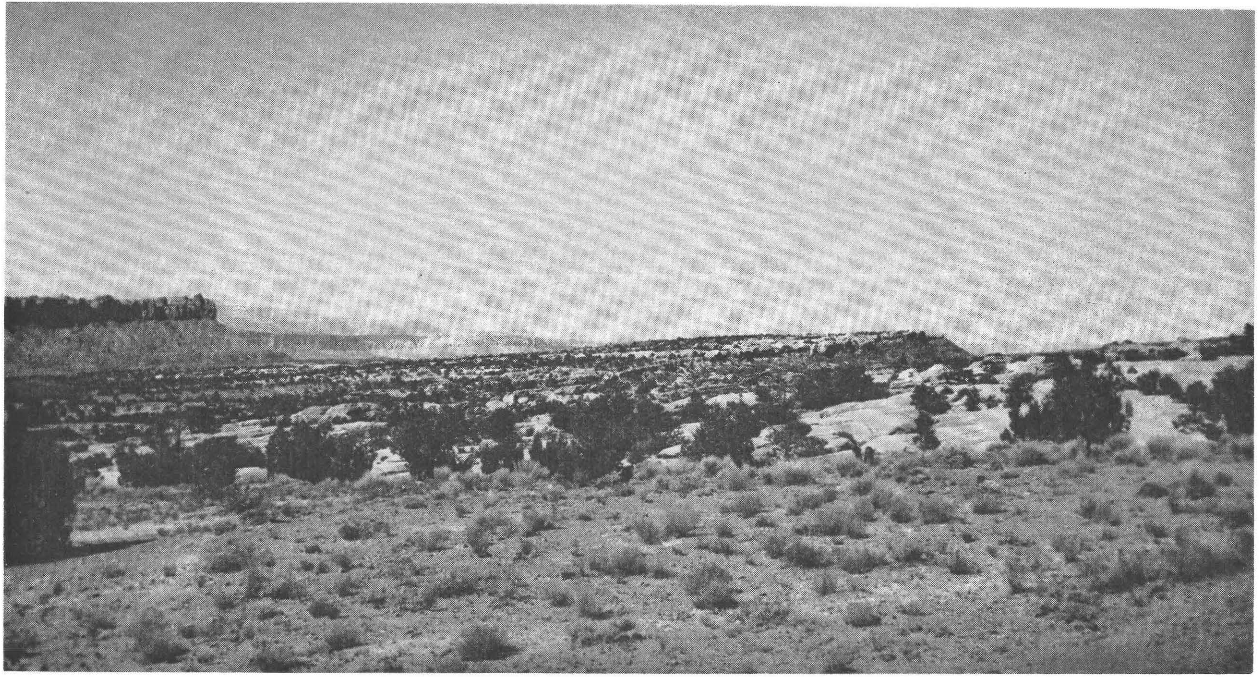
TABLE 3.—*Summary of eight studies of pinyon-juniper ratios made on the Shinarump member of the Chinle formation in the Circle Cliffs area, Garfield County, Utah*

Area No. (See plate 7 for area locations)	Number of trees counted		Pinyon:juniper	Approximate average thickness, in feet, of Shinarump member
	Pinyon	Juniper		
1	34	60	0.57	4
2	70	107	.65	5
3	73	108	.68	8
4	80	87	.92	25
5	11	62	.18	25
6	57	78	.73	30
7	150	114	1.3	58
8	104	100	1.0	85

count was made in an area of nonhomogeneous rock consisting of interbedded, poorly sorted sandstone and shale. The water content of the rocks may be lower here than in an area of homogeneous sandstone, because poorer sorting in nonhomogeneous rocks results in less pore space and decreased permeability. Consequently, the ratio at area 5 cannot be compared with the other ratios.

It appears that a tree-ratio study can differentiate relatively thick units of sandstone from thin ones, but that actual thicknesses cannot be reliably determined. Where the occurrence of uranium deposits is related to relative thicknesses of sandstone, as in the Shinarump, a tree-ratio study may indirectly define ground favorable for uranium deposits. The deposits are generally localized in thick parts of the Shinarump where the thickening was caused by the unit having filled channels cut into the Moenkopi. Conditions favorable for the use of the method are the presence of abundant pinyons and junipers on broad, flat bare little-dissected benches on homogeneous sandstone where ore is associated with either relatively thick or thin parts of the strata comprising the bench. A typical bench formed on the Shinarump in the Circle Cliffs area is shown in plate 8.

Tree-ratio studies should be usable in parts of the Circle Cliffs area, especially in the southern part, and elsewhere on the Colorado Plateau where broad, flat benches on the Shinarump exist. Conditions favorable for use of the method are also favorable for more reliable methods of exploration, such as drilling, but tree-ratio studies cost little, and could be used to outline areas of thick and thin units of sandstone prior to drilling. Figure 4 shows what is probably the best application of a tree-ratio study; it should be most useful in reconnaissance geologic investigations. To be effective, the study must be restricted to small adjacent plots approximately equal in dimension and smaller than local channel widths (fig. 4), because ratios obtained over larger areas tend to mask more diagnostic local ratios. Other factors that may mask diagnostic ratios are present-day gullies cut into the bench, where pinyons are apt to be very abundant; amount and type of soil cover, because casual observation indicates junipers might exceed pinyons where soil is thicker; porosity and permeability of rock, because the Utah and oneseed junipers would be most abundant if the bench were composed of a rock with low porosity and permeability; dip slopes, where junipers may be most abundant updip provided such a direction is away from the greatest concentration of water; and changes in relief, if extreme enough to cause significant differences in amount of precipitation within the area of a study. All of these factors reflect the control that the availability of water has on tree growth. An understanding of local surface- and ground-water conditions is essential to interpretations of tree-ratio studies.



VIEW OF A TYPICAL BENCH IN THE CIRCLE CLIFFS AREA, UTAH

The bench shown in the middle foreground is formed on the Shinarump member of the Chinle formation. The tree-ratio prospecting method would be useful here.

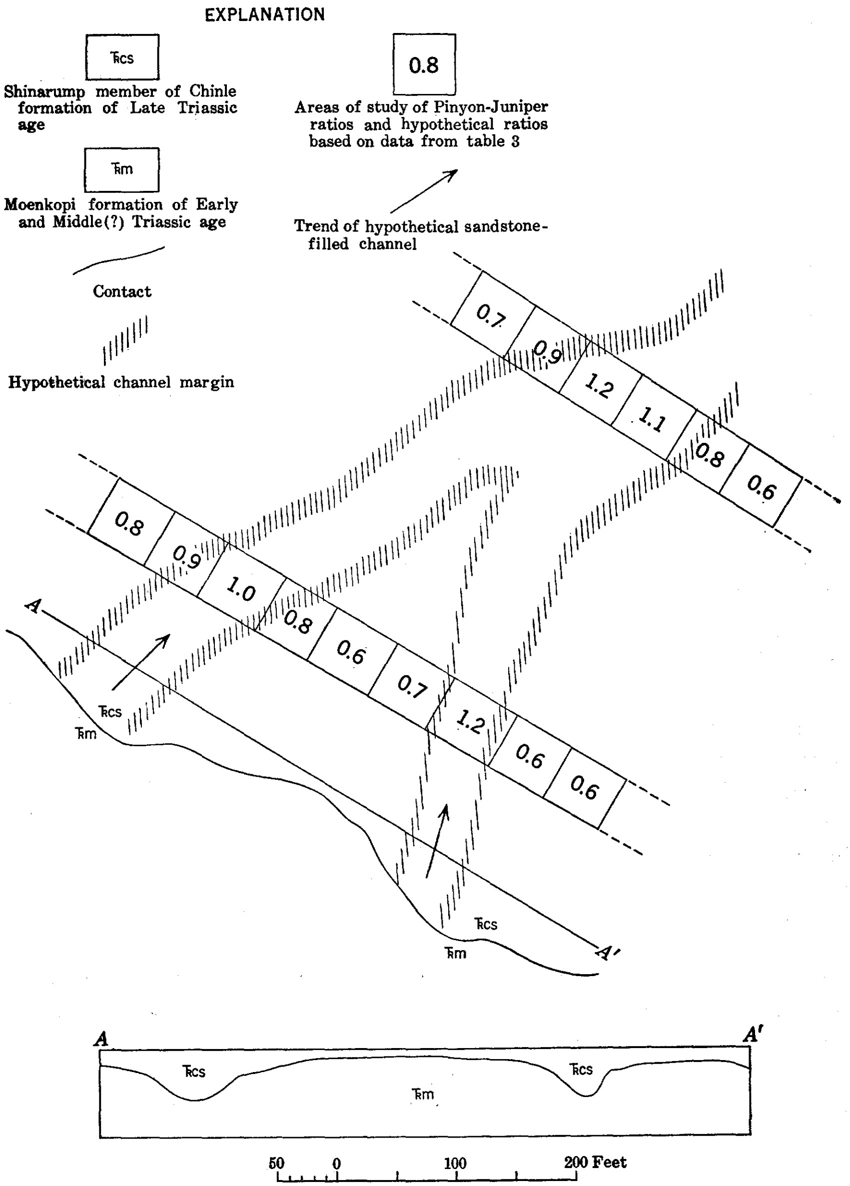


FIGURE 4.—Hypothetical locality showing in plan what is considered the best application of a tree-ratio study.

SUMMARY

Generally, indicator plants may serve as guides to ore in two ways. Ideally, where rock has the attributes favorable for the occurrence of uranium, indicator plants would serve to verify a favorable classification for the rock. Conversely, the absence of indicator plants might serve as a negative guide, or at least reduce slightly the rating of favorableness for containing uranium deposits. In the Circle Cliffs area the lack of indicator plants appears to have no significant effect on the favorableness rating of a rock because good indicators are absent from many mine and prospect localities. Based on this observation and on the fact that the indicator plants seen did not specifically define mineralized ground, it is essential in the Circle Cliffs area to find geologic criteria to clearly differentiate favorable and unfavorable localities. The presence of *Astragalus pattersoni* and *Stanleya pinnata* in the Circle Cliffs area may broadly define areas worthy of additional exploration, particularly where the plant occurrences are in the vicinity of strata that may be hosts for ore deposits. The top of the bench formed on the Shinarump lacks good indicator plants; the better indicator plants are restricted to cliffs and slopes beneath the top where the bench is dissected. Because of this, the maximum depth at which indicator plants can define mineralized ground is presumed to be relatively shallow in the Circle Cliffs area. Also, reliable indicator plants were found growing no more than about 45 feet and, in most places, considerably less than 45 feet above mineralized rock.

The plant-analysis method can probably indicate mineralized rock as much as 70 feet beneath the surface of the bench formed on the Shinarump. Widespread use of the plant-analysis prospecting method in the Circle Cliffs area is precluded by greater depths to the ore zone at many places. A sample interval of from 50 to 100 feet appears to be adequate for locating uranium deposits in rocks of Triassic age in the Circle Cliffs area, because most of the deposits have known lateral dimensions similar to or greater than this sample interval. The 100-foot interval would be most effective in broadly defining favorable ground, which then might be tested by closer spaced sampling or drilling.

The tree-ratio method to determine the relative thickness of sandstone units, and, indirectly, favorable ground, can be used successfully where the sandstone is homogeneous and forms bare rock benches, and where surface- and ground-water conditions are known. The method should be especially useful in reconnaissance investigations.

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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:	
Juniperus monosperma (Engelm.) Sarg.	oneseed juniper.
scopulorum Sarg.	Rocky Mountain juniper.
utahensis (Engelm.) Lemmon	Utah juniper.
Pinus cembroides var. *edulis* Zucc.	Colorado pinyon pine.
edulis	Used by Woodin and Lindsey (1954) for a pinyon pine different from *P. cembroides*. Also used by Hunt (1953, p. 34) for what is probably *P. cembroides*.
ponderosa var. *scopulorum* (Engelm.) Lemmon	Rocky Mountain ponderosa pine.
Family Gramineae:	
Elymus salina M. E. Jones	Salina wildrye.
Oryzopsis hymenoides (R. and S.) Rick	Indian ricegrass.
Family Polygonaceae:	
Eriogonum sp.	an eriogonum.
Family Chenopodiaceae:	
Atriplex confertifolia (Torr. and Frem.)	shadscale saltbush.
Family Cruciferae:	
Sisymbrium altissimum (L.) Britt.	tumblemustard.
Stanleya pinnata (Pursh) Britt.	desert princesplume.
Family Rosaceae:	
Cowania stansburiana Torr.	Stansbury cliffrose.
Family Leguminosae:	
Astragalus pattersoni A. Gray	Patterson loco.
preussi A. Gray	Preuss' poisonvetch.
Hedysarum boreale Nutt.	northern sweetvetch.
Family Euphorbiaceae:	
Euphorbia fendleri T. and G.	Euphorbia (fendler sandspurge).
Family Loasaceae:	
Mentzelia multiflora (Nutt.) Gray	desert mentzelia.
Family Boraginaceae:	
Cryptantha flava (A. Nels.) Payson	yellow cryptanthe.
Family Compositae:	
Aster venustus M. E. Jones	woody aster.