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Progress Report on Selenium in the Manning Canyon Shale, Central Utah

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ABSTRACT.—More than 20 years ago Beath (1939) located a number of seleniferous areas in the western United States by means of indicator plants. Unusual concentrations of selenium, up to 96 ppm, were reported from shale of the Mississippian Manning Canyon Shale, in Provo Canyon, about 40 miles south of Salt Lake City, Utah.

The present study, limited to 3 months of part-time work, investigates some broad features of concentration, distribution, and lithologic association of selenium within the Manning Canyon Formation, especially at its type section in Soldier Canyon, in the Oquirrh Range, 25 miles northwest of Provo Canyon.

Selenium is present in unusual concentrations in shaly strata throughout the 1600 foot thickness of the formation. High concentrations of selenium are most common in dark-colored, carbonaceous, calcareous, soft, usually gypsiferous and often iron-oxide stained or pyritic shale. Such rocks, interbedded with shaly limestone and nearly pure limestone, carry a mean concentration of 18 ppm with a standard deviation of 8 ppm. Ten to 20 percent of the type section is composed of such rock.

Association of organic matter, pyrite, often oxidized, plus gypsum in some of the most seleniferous beds, indicates possible derivation of selenium from organic matter, and its reconstitution in part as a sulfide, and subsequent oxidation to selenite or selenate.

In hard shale, shaly limestone, and limestone, which constitute a large portion of the Manning Canyon Shale, concentration of selenium decreases to a value below 1 ppm.

The Manning Canyon Shale at Lake Mountain, 20 miles south of Soldier Canyon, supports no selenium indicator plants, a situation wholly different than in Soldier Canyon or Provo Canyon. The Lake Mountain section represents a more terrestrial environment as shown by the greater abundance of coarse clastic rocks and fossil terrestrial plants. A sampled section across one of the better known fossil plant localities yielded the lowest selenium concentrations for shales recorded during the study. Since lithologies at Soldier Canyon are more representative of brackish and marine conditions, it follows that concentration of selenium is more allied to marine or brackish water processes than to terrestrial processes.

Hydrothermal activity, manifestly weak in the portions of the stratigraphic sections studied, may have modified the original distribution of selenium. Evaluation of this effect awaits further study.

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The writer was assisted in the field on one occasion by R. W. Moyle and W. D. Tidwell.

INTRODUCTION

Historical Sketch

In 1934 researchers at the Department of Research Chemistry of the University of Wyoming linked the occurrence of selenium in certain native range plants to toxic effects produced in animals which grazed upon them (Beath, et. al., 1934a). The vegetation in question was confined primarily to Cretaceous or Eocene formations. During the same year, several hundred acres of woody aster and narrow-leafed vetch were observed growing on soils derived from the Chugwater Formation of Permian and Triassic age in central Albany County, Wyoming (Beath, 1934b). Further investigation revealed that two members of the Chugwater Formation supported toxic seleniferous vegetation. A sandstone member near the middle of the formation yielded up to 10 ppm and averaged 2.4 ppm selenium. The second, near the base of the formation, yielded lesser amounts.

Finding selenium in Permian and Triassic rocks greatly enlarged the problem of selenium distribution. Beath and coworkers (1937) traced selenium bearing rocks from the Chugwater Formation in southeastern Wyoming to rocks of equivalent or nearly equivalent age near the western border of the state. Seleniferous rocks were found in the Permian Phosphoria formation as well.

Beath and his colleagues extended their studies into most of the western United States. Many new areas of seleniferous rocks were discovered by recognition of four genera, *Astragalus, Stanleya, Xylorrhiza,* and *Oonopsis,* which were defined as "indicator" plants (Beath, et. al., 1939a p. 259).

> The significance of selenium indicator plants is particularly important in locating seleniferous areas not heretofore recognized in the West. . . We have selected for detailed study certain areas where one or more indicator plants occur. . . The areas include. . . carbonaceous and limy shales of late Mississippian or early Pennsylvanian age in Provo Canyon, Wasatch Mountains, Utah.

The same author in a subsequent paper (Beath, et. al., 1939b, p. 312) states:

> The seleniferous shale in Provo Canyon is either late Mississippian or early Pennsylvanian in age. The distinctive odor, characteristic of some seleniferous plants, led Dr. David Love, U. S. Geological Survey, field assistant, to believe that this formation supported seleniferous vegetation. Dr. Love had previously collected seleniferous vegetation in Wyoming under our direction. *Aster glaucus* rooted in these shales was seleniferous. . .

A stratigraphic section, (Table 1) together with the content of selenium associated with each stratum was published (Beath, et. al., 1939a, p. 266)

TABLE 1
Stratigraphic section of a portion of the Manning Canyon Shale at the Canyon Glen Campgrounds, Provo Canyon, Utah.

Bed No.	*Lithology*	*Thickness in feet*	*Selenium ppm.*
20	Shale, chocolate-brown at base, grades to dark black thinner-bedded shale	25	3.6
19	Limestone, forms massive cliff above water flume; is dark black to blue-gray, some sandy limestone present	67½	1.5
18	Shale, very black, has seams of yellowish-brown ferruginous material at very top and at various places in bed	19	34.3
17	Limestone, very shaly, blue to black with brown and yellowish-brown seams	55	0.6
16	Shale, light-brown to dark chocolate-brown, gypsiferous in seams. Forms first shale outcrop near flume	17	25.1
15	Limestone, blue to gray, some shale which is brownish; the bed grades from true limestone at base to sandy and shaly limestone at top	25	12.0
14	Shale, variegated, mainly black with some chocolate-brown colors	24	96.3
13	Limestone, very shaly, dark blue to black	29	2.6
12	Shale, very dark black, thin-bedded	20	7.0
11	Limestone, gray to black; hard	7½	0.5
10	Limestone, very sandy, weathers light-brown	2½	0.5
9	Shale, limy in part, dark black to gray	20	0.6
8	Sandstone, reddish-brown to buff, coarse grains or grit up to 4 mm. in diameter	10½	
7	Limestone, shaly, dark brown, contains numerous small lingulids	11	1.0
6	Limestone, blue to dark black, hard. weathers blue-gray	14	1.0
5	Shale, chocolate-brown, bedding 1 in. to 4 in.; shales are lighter color towards the top, and various fresh—or brackish-water pelecypods present	12	7.5
4	Shale, dark black, carbonaceous in part, and ferruginous in part, bedding less than 1 inch	3	1.8
3	Limestone, dark blue, in part shaly	4½	
2	Sandstone, reddish-brown, very gritty, with coarse fragments up to 5 mm. in diameter	4	1.4
1	Limestone, blue, which extends to bottom of railroad cut, or to railroad tracks	7	0.4
	Total thickness	377½ ft.	

Robertson (1940) investigated distribution of selenium and the possibility of selenium poisoning in Utah. His work dealt with occurrence of selenium in the Manning Canyon Shale and its associated vegetation in part, but no systematic, detailed stratigraphic work was undertaken.

Recent Work

Study of selenium in the Manning Canyon Shale remained for two decades where Beath left it. However, other important studies, helpful to the geochemist, have been made. Moyle (1958) studied the paleoecology of the Manning Canyon Shale. Five sections were measured in central Utah in localities where the formation is best exposed, and five other partial sections, including the Provo Canyon section, were studied as well. The Soldier Canyon section, Tooele County, Utah, 4 miles southeast of the town of Stockton and 25 miles northwest of Provo, is the best exposed and most complete outcrop of the formation. Here the formation is over 1,600 feet thick, and consists mainly of shale and lesser amounts of interbedded limestone. Even smaller amounts of interbedded sandstone and quartzite are present. Clay shale characterizes the lower 600 feet, silty shale and shaly limestone typify the upper 1,000 feet. Fresh, brackish, and shallow, warm marine water conditions are evidenced by typical marine or terrestrial assemblages. Study of the lithologies demonstrates the cyclic nature of deposition with three regressions and two transgressions, punctuated with many minor changes.

Tidwell (1962) described an Early Pennsylvanian flora from the upper shales of the formation. These plants were probably deposited near their site of growth. *Alethopteris, Neuropteris,* and *Calamites* occurred, in order of decreasing abundance. The rock types and flora suggest a fresh or brackish swamp environment.

Prince (1963) studied Mississippian coal cyclothems in the middle one-third of the formation, and measured a detailed stratigraphic section, 285 feet thick. The two described coal cyclothems exhibit characters which compare favorably with mid-continent cyclothems, and probably reflect similar environments.

Purpose and Scope of the Present Investigation

Heretofore investigation of occurrence of selenium in sedimentary rocks of the United States has been conducted primarily by plant and soil chemists (Beath, 1934a to 1946; Moxon et. al. 1938) and by economic geologists studying distribution of selenium and other elements in the Colorado Plateau (Newman, 1962). The former studies were conducted to determine distribution of selenium and the possibility of selenium poisoning of livestock. The latter studies were made primarily to shed light on genesis of uranium deposits.

Discovery of unusually high concentrations of selenium in a considerable portion of the Manning Canyon Formation by Beath (1939a) suggests that distribution of the element, its forms of occurrence, and the environments of its deposition should be studied in detail. Green (1959) reports an average of between 0.3 to 0.6 ppm selenium in shales. Beath (1939a) reports as much as 96.3 ppm in a shale bed 24 feet thick in the Manning Canyon Shale at Canyon Glen Campgrounds in Provo Canyon.

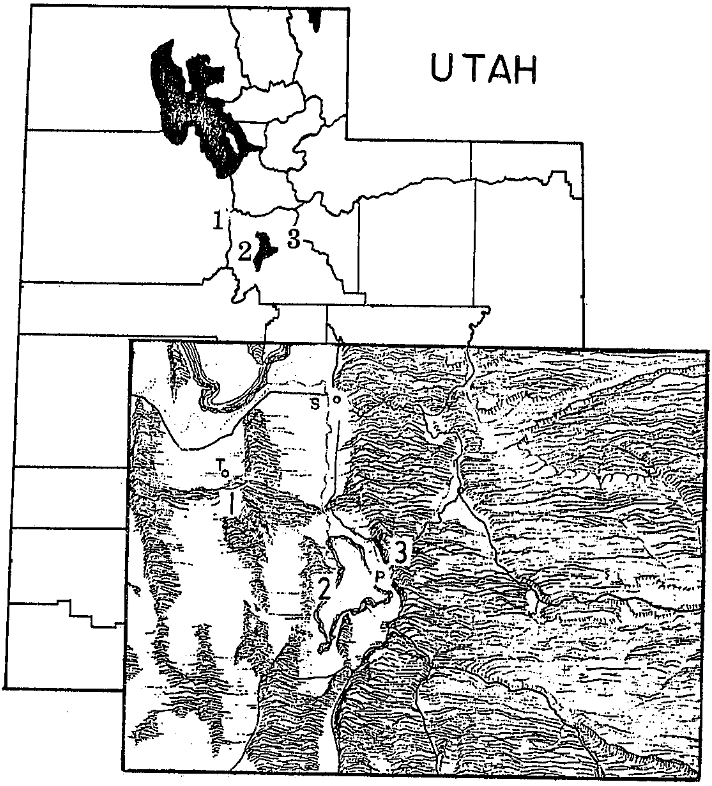
The principal objectives of the present study were the following:

1). To attempt corroboration of Beath's work at the site of the original discovery, i.e., at Canyon Glen Campgrounds, Provo Canyon, Utah.

2). To obtain greater stratigraphic detail in the occurrence of selenium as a function of lithologic type.

3). To isolate, within the most seleniferous strata, the materials which yield the highest concentrations of the element.

4). To use 'indicator" plants, for possible extension of the study beyond the Provo Canyon and Soldier Canyon sections.



TEXT-FIGURE 1.—Index map of sections studied. S, Salt Lake City; P, Provo; T, Tooele; 1, Soldier Canyon in the Oquirrh Range; 2, Lake Mountain; 3, Canyon Glen Campground, Provo Canyon in the Wasatch Mountains.

Field and Laboratory Work

Sections at Canyon Glen Campgrounds in Provo Canyon, at Soldier Canyon, and at Lake Mountain were collected during the summer of 1963. Channel samples, at a depth of 6 inches to as much as 3½ feet, but averaging about 18 inches, were taken across shale beds of the Manning Canyon Shale and details of lithology were noted. Changes in color, texture, mineralogy, and weathering characteristics as well as presence of indicator plants were used for stratigraphic subdivision. In general, only shale beds were sampled; limestones and sandstones were sampled in a few instances but these latter rocks yielded much less selenium than associated shales.

The writer, W. D. Tidwell, and R. W. Moyle, visited the section at Soldier Canyon and Lake Mountain in August 1963.

The method of analysis for selenium in the present study was adapted from Robinson (1934). A 10 gram sample of shale with 10 ml of a 10% solution, by volume, of bromine in concentrated hydrobromic acid, and an additional 10 ml of concentrated hydrobromic acid, were prepared in a Corning C-3440 pyrex glass distilling apparatus. The resulting distillate was collected until 10-12 ml was obtained. Bromine distilled in the first stages was reduced by passing sulfur dioxide gas through the solution until the bromine color disappeared. The selenium tetrabromide was reduced by addition of 0.1 to 0.25 gram hydroxylamine hydrochloride. Subsequent heating of the solution on a water bath accelerated production of red selenium.

Estimation of concentration was by visual comparison with standardized samples with 3, 7, 10, 15, 25, 35, and 50 ppm concentrations.

Precision is such that 95% or more of the values range plus or minus 15% of the value given in the tables (Table 2 and following). Systematic error, rather than random error, is believed to be generally lower than the true value inasmuch as certain losses of selenium, thought to be small in comparison with amounts obtained, occurred. Incompleteness of oxidation of selenium by bromine, loss of selenium tetrabromide during distillation, and loss of the same during reduction of bromine to bromide are believed to be the principal sources of error. Reduction of excess bromine was carried out in a cold-water bath to minimize escape of the volatile selenium tetrabromide.

Analysis of plant material was performed by overnight decomposition of 10 grams of air dried sample in 15-20 ml of 30% hydrogen peroxide. The mixture was then evaporated to dryness in a water bath and the residue treated in the same manner as shale samples.

SELENIUM AT CANYON GLEN CAMPGROUNDS

Stratigraphic distribution.—In general, but with some notable exceptions, the results of Beath and others concerning the selenium occurrence in the Manning Canyon Formation has been verified. Selenium is present in unusual concentrations (Table 2). However, important differences exist both as to the absolute value of maximum concentrations, and to the stratigraphic distribution of selenium. For instance Beath (Table 1, bed 14) reports 96.3 ppm in a variegated shale 24 feet thick. The present writer obtained 15, 20, and 20 ppm at 7, 6, and 10 feet, respectively, in the same shale (Table 2, beds 32, 33, and 34).

It is possible that the selenium is not evenly distributed along the strata, or that sampling and analytical errors alone or combined with the foregoing, may have caused the disagreement. Values reported in the present study may be too low due to analytical errors, and it may well be that Beath's sampling caused him to report values too high. It is not known precisely how Beath sampled the section, but if samples were taken from near the surface, it is quite possible that local enrichment by accumulation of selenium-rich decayed vegetable matter may have occurred in the upper part of the profile.

Of the 156½ feet of shales measured by the writer, 73 feet, or 43%, contained values in the range 1-9 ppm; 49½ feet, or 32%, contained values in the range 10-19 ppm; 36½ feet, 23%, contained values in the range 20-29 ppm; and 3 feet, 2%, contained values in the range 30-39 ppm.

TABLE 2.

Detailed stratigraphic section of selected portions of the Manning Canyon Shale, Canyon Glen Campgrounds, Provo Canyon, Utah.*

Bed No.	*Description*	*Sample Number*	*Feet Above Base*	*Thickness in feet*	*PPM Selenium*
41	Shale, resembles bed 40	MC-CG 41-0-0 1963	157-182	25	1

TABLE 2 (CONT.)

40	Shale, gray, calcareous, soft, but not crumbly. Slope former. *Stanleya sp.*	MC-CG 40-0-0 1963	154-157	3	1
39	Limestone, blue gray, slabby, weathers gray, ledge former		151-154	3	Not sampled
38	Shale, gray, medium hardness, fissile, ragged outcrops	MC-CG 38-0-0 1963	142-151	9	1
37	Limestone, shaly, black gray, weathers light brown gray, shaly partings, ragged outcrops.	MC-CG 37-0-0 1963	136-142	6	Not analyzed
36	Shale, gray, soft, crumbly, slope former. *Stanleya* sp., *Aster glaucus.*	MC-CG 36-0-0 1963	132-136	4	10
35	Limestone, shaly, some interbedded shale, blue gray, slope former. *Aster glaucus.*		125-132	7	Not sampled
34	Shale, brownish black, soft, crumbly; gypsum present in 1/16 inch criss-crossing veinlets; calcareous, slope former.	MC-CG 34-0-0 1963	115-125	10	20
33	Shale, black with numerous ferruginous layers, soft, crumbly, slope former, *Stanleya* sp., *Aster glaucus;* calcareous, gypsiferous.	MC-CG 33-0-0 1963	109-115	6	20
32	Shale, brownish gray, soft, crumbly, slope former, *Stanleya* sp. and *Aster glaucus,* calcareous, gypsiferous.	MC-CG 32-0-0 1963	102-109	7	15
31	Limestone, shaly, brown, jagged ledge former	MC-CG 31-0-0 1963	92-102	10	5
30	Shale, brownish black, soft, crumbly, calcareous, slope former. *Stanleya* sp.	MC-CG 30-0-0 1963	91-92	1	15
29	Limestone, shaly to 3 inch beds, brownish black, ledge former		73-91	18	Not sampled
28	Shale, black, resembles bed 26. *Stanley* sp.	MC-CG 28-0-0 1963	68-73	5	20
27	Limestone, blue gray, slabby, ledge former		66-68	2	Not sampled
26	Shale, black, soft, crumbly, contemporary plant roots throughout, slope former	MC-CG 26-0-0 1963	55-66	11	20
25	Limestone, blue black, slabs 1 inch to 6 inches thick, ledge former		49-55	6	Not sampled
24	Shale, gray black, soft, crumbly, slope former	MC-CG 24-0-0 1963	44-49	5	15
23	Limestone, black, shaly on bottom to dense, very fine-grained on top, resembles coal from a distance, ledge former		39-44	5	Not sampled
22	Limestone, blue gray, 3 inch bedding, weathers gray, ledge former		37-39	2	Not sampled

TABLE 2 (CONT.)

21	Shale, resembles bed 19	MC-CG 21-0-0 1963	36-37	1	30
20	Shale, black, gypsiferous, calcareous, traces of limonite on bedding planes Soft, crumbly. Slope former. *Astragalus* sp. (?)	MC-CG 20-0-0 1963	36-37	1	30
19	Shale, mouse gray, brown tint, soft, crumbly, slope former	MC-CG 19-0-0 1963	34½-35	½	20
18	Shale, black, numerous contemporary plant rootlets, soft, crumbly, white efflorescence.	MC-CG 18-0-0 1963	33½-34½	1	30
17	Limestone, blue gray, slabby, ledge former		32-33½	1½	Not sampled
16	Shale, mouse gray, brown tint, resembles bed 13	MC-CG 16-0-0 1963	23-32	9	10
15	Shale, black, limonitic, soft, crumbly, slope former.	MC-CG 15-0-0 1963	19-23	4	20
14	Shale, black, chippy, soft, siliceous-calcareous concretions with disseminated pyrite, slope former.	MC-CG 14-0-0 1963	14-19	5	15
13	Shale, mouse gray, brown tint, soft, crumbly, slope former.	MC-CG 13-0-0 1963	0-14	14	7

Base of the above portion of the section was taken at the lowermost exposure of shale in the bottom of the largest ravine north of the railroad track crossing Provo River at the campgrounds.

Strike of beds: N 70° W; dip, 30° north.

A fault whose relative movement is not observable interrupts the section.

12	Limestone, blue gray, massive, ledge former		84-96	12	Not sampled
11	Shale, chocolate color, ferruginous near top and bottom, soft, crumbly, slope former. *Stanleya* sp.	MC-CG 11-0-0 1963	81½-84	2½	5
10	Limestone. Resembles 8		80-81½	1½	Not sampled
9	Shale, resembles bed 7 *Stanleya* sp.	MC-CG 9-0-0 1963	78-80	2	5
8	Limestone, dark gray,. ferruginous seams, massive, ledge former.		76½-78	1½	Not sampled
7	Shale, black with red and yellow mottling, stringers of gypsum, soft, crumbly, slope former.	MC-CG 7-0-0 1963	75-76½	1½	10
6	Limestone, blue-gray, massive, ledge former.		69-75	6	Not sampled
5	Shale, black with yellow brown to red brown veinlets, soft, crumbly, calcareous, slope former. *Stanleya* sp.	MC-CG 5-0-0 1963	67-69	2	10
4	Sandstone, red-brown to buff, coarse grained to gritty, weathers reddish brown, ledge former.	MC-CG 4-0-0 1963	52-67	15	Not sampled

TABLE 2 (CONT.)

3	Shale, black, crumbly, upper three feet lighter in color, calcareous, slope former. *Stanleya* sp.	MC-CG 3-0-0 1963	37-52	15	10 (?)
2	Limestone, blue gray, massive, cliff former.		12-37	25	Not sampled
1	Shale, brown, bedding ½ inch grading to 2 inches at top; calcareous, weathers brown, slope former.	MC-CG 1-0-0 1963	0-12	12	5

*Begin section at base of 12 foot shale bed exposed in railroad cut about 100 feet west of railroad bridge crossing Provo River. NW ¼, Sec. 4, T. 6 S., R. 3 E.

Strike: N 70° W; dip, 25° North.

Fifty feet of section underlying the massive limestone ledge cropping out above the flume is not described or sampled. The beds above and below carry only small amounts of selenium, and in the limited time available, this lower section, consisting mostly of shales and shaly limestones, was not sampled or described.

Maximum values obtained by the writer were associated with carbonaceous, black, gypsiferous, often limonitic or hematitic, shales (Table 2). Samples MC-CG 18-0-0, 19-0-0, 20-0-0, and 21-0-0, yielded 30, 20, 30, and 30 ppm respectively. High values, though not maximum, were obtained from samples MC-CG 14-0-0, 15-0-0, and 16-0-0, of 15, 20, and 10 ppm respectively.

Maximum concentrations of selenium are associated with dark colored, soft friable, gypsiferous, calcareous, and often limonitic or hematitic shales. Usually, but not always, the so called indicator plants, *Stanleya* sp. and *Aster glaucus* are rooted in the strata. *Astragalus* is found only occasionally.

Shales that are hard and chippy bear less selenium; limestones and sandstones are generally impoverished. The more calcareous shales become the less selenium is noted. The more carbonaceous, ferruginous or pyritic, gypsiferous, and friable a sediment becomes the greater will be the concentration of selenium.

Within one of the most seleniferous beds (samples MC-CG 33-0-0, Table 2, and MC-CG 33-0-10, Table 3), the selenium seem to be most highly concentrated in red or yellow lenses, stringers, or more diffuse splotchy areas derived from oxidation of pyrite. A maximum of 40 ppm was found in red, ferruginous shale intermingled with dark, carbonaceous, gypsiferous shale (Table 3). In a limonitic, hematitic veinlet carrying remnants of pyrite, and surrounded by an incrustation of gypsum up to $\frac{1}{8}$ inch thick, 35 ppm of selenium was obtained. In an adjoining dark colored carbonaceous shale, free of gypsum and iron oxides, 10 ppm was obtained at a depth of 24 inches (MC-CG 33-0-8, Table 3).

TABLE 3

A profile down the dip of a seleniferous bed, 33, and some further samples from the same bed at Canyon Glen Campgrounds, Provo Canyon.*

Description	*Sample Number*	*Depth from Surface in Inches*	*Thickness In Inches*	*PPM Selenium*
Shale, carbonaceous, stringers of hematite and limonite, soft, crumbly.	MC-CG 33-0-1 1963	0-6	6	20
As above	MC-CG 33-0-2 1963	6-12	6	25

TABLE 3 (CONT.)

As above	MC-CG 33-0-3 1963	12-20	8	20
As above, but a little less friable.	MC-CG 33-0-4	20-28	8	10
As above	MC-CG 33-0-5 1963	28-36	8	10
As above	MC-CG 33-0-6 1963	36-44	8	20
Shale, all carbonaceous, no ferruginous mottling.	MC-CG† 33-0-7 1963	24		10
Shale, ferruginous, red, soft, friable.	MC-CG† 33-0-8 1963	24		40
Limonite-hematite veinlet surrounded by gypsum, 1/16 inch thick in turn surrounded by carbonaceous shale.	MC-CG† 33-0-9 1963			35
Gypsum veinlets in bed 34-0-0. No calcite with sample.	MC-CG†† 33-0-10 1963			20
Siliceous, calcareous, pyritic nodule. Size of grapefruit. Value of selenium concentration is a minimum value.	MC-CG††† 14-0-1 1963			15

*Samples were taken down dip to a depth of 44 inches to determine the variation of selenium concentration as a function of depth on a given bed. The stratum chosen was midway in bed 33-0-0, and is a six inch layer of black shale mottled with iron oxide stains. The shale is soft and friable and becomes more compact with depth. Samples were taken on 6 to 8 inch intervals.

†Selected samples from the same bed along the outcrop band.

††From bed MC-CG 33-0-0:

†††From bed MC-CG 14-0-0:

This association of organic matter, pyrite, and iron oxide with gypsum suggests that the selenium may have been derived from organic sources. Subsequent reducing conditions during deposition and diagenesis favored accumulation of pyrite in veinlets, and enrichment of selenium in the sulfide phase. Later, oxidation of pyrite may have produced the iron oxides and gypsum. It seems likely then, if the foregoing is true, that selenium is distributed among the organic matter, pyrite, and oxidized products as an oxide, a selenite or a selenate.

It is by no means impossible that selenium was introduced by hydrothermal activity. However, evidence of such activity at Canyon Glen is slight. Widespread development of crosscutting veins, wall rock alteration, and the development of sulfide minerals, other than pyrite, typical of hydrothermal deposits of the region, are not observed. Further study will be necessary to evaluate such effects. At present it seems that hydrothermal effects, if present, are superimposed on the more important deposition and diagenetic processes that concentrated the selenium.

Concentration Versus Depth.—In a sample profile of bed 33-0-0 of the Canyon Glen section, concentration of selenium, as a function of depth, is such that a maximum value of 25 ppm occurs within the first 12 inches, and decreases to about 10 ppm at about 30 inches, then increases to about 20 ppm at 40 inches (See Table 3). It is believed that the indicator plants draw selenium toward the surface from depths up to 36 inches, the depth of penetration of roots, and causes enrichment in the upper 12 inches of the weathering profile. Weathering of leaves, stems, and fruit of seleniferous vegetation doubtlessly contributes to enrichment near the surface. Concentration at about 18 inches is roughly equal to that at about 36 inches. For that reason, sampling, subsequent to analysis of the depth profile, was made at a depth of about 18 inches in the soft shales.

Indicator Plants.—*Aster glaucus* (woody aster) collected on bed 33 contained a minimum of 100 ppm (Table 4), and *Stanleya* sp. rooted in the same bed contained a minimum of 50 ppm. Except in localities where downslope movements confuse the stratigraphic profile, these plants are systematically distributed on the seleniferous beds, and in general, the most seleniferous beds produce the greatest density of plant population. This condition is somewhat modified by ecological conditions such as availability of moisture, ability to gain and maintain roots due to steepness of the erosion surface, etc. In general, presence of these plants indicates availability of selenium in the strata in which they are rooted. Lack of the plants usually, but not always, indicates low concentrations of selenium in the strata.

Correlation of indicator plants with seleniferous beds at Canyon Glen is sufficiently positive to suggest that the same relationships might be present at the type locality at Soldier Canyon.

TABLE 4

Analysis of selected plant specimens collected on highly seleniferous beds of the Manning Canyon Shale at Canyon Glen Campgrounds, Provo Canyon, Utah*

		PPM Selenium
MC-CG 33-0-10	*Aster glaucus.* Collected from bed 33. Leaves, stems and buds. Strong smell in foliage when prepared for digestion	100
MC-CG 33-0-11	*Stanleya* sp. Collected from beds 32 and 33. Strong, disagreeable odor when vegetation was crushed. Some leaves brown, bloom was gone. Hillside very dry where plants were collected.	50
MC-CG 24-0-1	*Aster glaucus.* Collected from bed 24. Foliage luxuriant. Grew in shady, damp location near the river. Sample included leaves, stem, and flowers.	100
MC-CG 24-0-2	*Oonopsis* (?) sp. Collected from bed 24. Dandelion like plant, but lacks the stems and flowers of dandelion. Resembles *Oonopsis condensatus,* but lacks the flowers shown in the description of that species. Sample was not crackling dry when prepared. Considerable water was present in tissue.	10

*Ten grams of air dried vegetation was ground and digested with 30% hydrogen peroxide by leaving overnight, then evaporating to dryness on a water bath. The material thus derived was treated in the same manner as employed for soils, except that twice the usual amount of bromine was added to assist in oxidation of organic matter during distillation.

SELENIUM AT SOLDIER CANYON

Since the Manning Canyon Shale is more than 1600 feet thick at Soldier Canyon, much too thick to sample in detail for the present study, three detailed sections were measured and described. The lowermost two are about 20 feet thick, and the uppermost is 75 feet thick. Selection of upper and lower detailed sections was based on occurrence of indicator plants rooted in soft, friable, dark-colored, gypsiferous, sometimes ferruginous shales, i.e., the combination of factors found most favorable to high concentrations of selenium at the Canyon Glen Campgrounds Section.

The middle detailed section is the upper coal cyclothem described by Prince (1963). Samples used for analysis were from Prince's collection on file at Brigham Young University. A principal objective was to determine, if possible, variation of selenium concentration within the cyclothem.

The Lower Section.—Measurement, description, and analysis of the lowermost section is summarized in table 5. Similar to conditions and concentrations at Canyon Glen Campgrounds, a maximum of 30 ppm selenium was found in a dark-colored, mottled red and yellow and gray, soft, friable, gypsiferous shale (Sample MC-SC 47-0-0). Indicator plants were present but not abundant. Specimens of *Stanleya* sp. had been grazed by livestock: flower plumes were removed, and the upper, more tender foliage, was missing.

Indicator plants and dark-colored shales are distributed throughout the lower portion of the formation at Soldier Canyon and suggest a broader distribution of selenium than indicated in table 5.

Bed MC-SC 45-0-0 is a black, soft shale which contains considerable brown calcite with pseudomorphs of limonite after pyrite. The bed, in addition, shows some loss of coherence as though it may have been altered hydrothermally. The sample contains 10 ppm selenium. Comparison with overlying beds (Table 5) indicates that the effect of hydrothermal alteration is to impoverish the rock in selenium. Further study is needed for a more definite evaluation.

TABLE 5

Detailed stratigraphic section of a portion of the Lower Manning Canyon Shale at the type locality, Soldier Canyon, Tooele County, Utah.*

Bed No.	*Description*	*Sample Number*	*Feet Above Base*	*Thickness in feet*	*PPM Selenium*
48	Shale, red, chippy, fissile, slope former.	MC-SC 48-0-0 1963	17-20	3	15
47	Shale, black, variegated with red, yellow, gray, soft, friable, slope former.	MC-SC 47-0-0 1963	13-17	4	30
46	Shale, red brown, soft friable, slope former	MC-SC 46-0-0 1963	9-13	4	15
45	Shale, black, soft, friable, slope former; brown calcite occurs with pseudomorphs of limonite after pyrite; loss of some coherence of the rock.	MC-SC 45-0-0 1963	5-9	4	10
44	Shale, purplish black, calcite stringer, soft, friable, slope former.	MC-SC 44-0-0 1963	0-5	5	10

*The section is in the lowermost part of the type section at Soldier Canyon. Bed 44 overlies Unit 2 of Moyle. (1958). Strike: N. 70°W, dip 45° North. *Stanleya* sp. occurs in this part of the section, but is not as abundant as in other parts of the section. NE ¼ Sec. 33, T. 4 S., R. 4 W.

Selenium in the Coal Cyclothem. Investigation of selenium in the coal cyclothems described and studied by Prince (1963) was not very successful. In spite of the presence of indicator plants, concentrations of selenium throughout the cyclothem proved to be low, i.e., 10 ppm or less (Table 6). Most of the concentrations appeared to be less than 5 ppm, and at these levels the method of analysis employed is not sufficiently definitive. It was hoped that greater concentrations of selenium would be present than were actually found, and that the differences from one part of the cyclothem to another would be more marked. A cyclic repetition of the selenium was not established.

TABLE 6

Detailed stratigraphic section of a middle portion of the Manning Canyon Shale, Soldier Canyon, Utah. (Prince, 1963)*

Unit No.	*Description*	*Thickness Inches*	*Feet Above Base*	*PPM Selenium*
154	Quartzite, medium to light gray. Marks the base of the upper partial cyclothem.	12	190.3	Not sampled
153	Siltstone, brown, shaly, and nodular.	2	189.3	Not sampled
152	Shale, black, dense, noncalcareous.	10	189.2	10
151	Clay, medium gray to light green, waxy.	1	188.3	5
150	Shale, medium gray to light green, noncalcareous.	2	188.2	5
149	Siltstone, brown, slightly calcareous, thin 1" beds, hard and compact.	6	188.1	2
148	Shale, nodular, green to brown, slightly calcareous. ¼ to ½ inch beds.	18	187.6	5
147	Shale, medium gray to dark green, noncalcareous.	12	186.1	1
146	Shale, light green, weathers brown, calcareous, papery to ¼ inch beds, somewhat nodular	9	185.1	8
145	Shale, medium gray to green, slightly calcareous.	28	184.3	3
144	Siltstone, medium gray, weathers light gray, nodular.	3	182.0	No sample
143	Shale, black, noncalcareous, paper thin to ¼ inch beds.	30	181.8	5
142	Shale, black, weathers gray, waxy, noncalcareous, chippy, hard.	6	179.3	3
141	Shale, black, weathers gray, waxy, clayey, very thin beds.	9	178.6	No sample
140	Shale, medium gray to gray, weathers light gray, nodular, noncalcareous.	14	178.0	5
139	Shale, black, dense, silty, somewhat nodular, noncalcareous, ½ inch beds.	7	176.8	10
138	Shale, light gray to medium gray, weathers same with orange mottling, bedding very thin to paper thin.	8	176.3	5
137	Limestone, black, dense, laterally persistent. Key bed for upper cyclothem. Ostracods, pelecypods, low-spired gastropods, brackish marine.	12	175.6	3
136	Shale, roof shale, consists of the following: top 2½ inches, shaly limestone, 3 inches red shale, 2 inches shaly limestone, 3½ inches shale, 2 inches red shale.**	13	174.6	1

TABLE 6 (CONT.)

135	Coal, brown to dark brown lignite, banded, associated with gypsum, and limonitic on weathered surface.	4	173.5	15 (?) Value represents a minimum value.
134	Underclay, black to dark gray, irregular to no bedding, very waxy and carbonaceous.	6	173.2	1
133	Shale, dark gray, silty to sandy, noncalcareous.	2	172.7	1
132	Sandstone, light gray, medium to fine-grained, noncalcareous.	6	172.5	Not sampled
131	Quartzite, light gray to buff, fine to medium grained, orange limonite mottling, thin bedded, crossbedded in part. This and underlying quartzite beds marks the base of the upper complete cyclothem.	33	172.0	Not sampled

*This section is from the upper coal cyclothem in the middle part of the Manning Canyon Shale. Measurements are to the base of the "medial limestone" member, which is approximately 460 feet above the base of the formation. The descriptions given are modified from those given by Prince (1963). SE ¼, NE ¼, Sec. 33, T. 4 S., R. 4 W.
**Sample of shaly limestone only.

The Upper Section.—Indicator plants, *Stanleya* sp., rooted in soft, black, gypsiferous, and sometimes ferruginous shales led the writer to investigate a part of the upper Manning Canyon Shale at Soldier Canyon. (Table 7).

The section consists of 58 feet of shale and 17 feet of limestone. The weighted mean concentration of selenium in the shales is 13 ppm. (Sum of products of thickness times concentration, and the sum divided by the total thickness.) The high value is 45 ppm, associated with bed 41, Table 7; a brownish black, soft, limonitic, gypsiferous shale 1 foot thick. Two other beds are noteworthy for concentration of selenium. Beds 36 and 35 of Table 7, 2 feet and 8 feet thick, have 30 ppm and 25 ppm selenium, respectively. These shales are also brownish black, soft, friable, gypsiferous. *Stanleya* sp. is rooted into each bed.

The presence of indicator plants, such as *Stanleya* sp., and other dark colored, soft shales in the upper part of the Manning Canyon Shale suggest that selenium is more widespread than indicated by the limited measured section. Values shown in table 7 suggest that the upper part of the Manning Canyon Shale is the most seleniferous part of the formation. At Canyon Glen, 156½ feet of shale averages 10.5 ppm; at Soldier Canyon, the section in table 7 averages 13.1 ppm in a 58 foot section. Maximum concentrations of selenium, up to 100 times normal abundance of the element in shale, is associated with soft, black to brownish black, gypsiferous calcareous, often limonitic or hematitic shale.

TABLE 7

Detailed stratigraphic section of an upper portion of the Manning Canyon Shale at the type locality, Soldier Canyon, Tooele County, Utah.*

Bed No.	*Description*	*Sample Number*	*Feet Above Base*	*Thickness in feet*	*PPM Selenium*
42	Limestone, blue gray, thin bedded, shaly, ledge former.		70-75	5	Not sampled
41	Shale, black brown, fissile, soft, limonitic, gypsiferous, calcareous.	MC-SC 41-0-0 1963	29-70	1	45

TABLE 7 (CONT.)

40	Shale, brownish gray, somewhat hard, fissile, bedding up to ¼ inch.	MC-SC 40-0-0 1963	66½-69	2½	20
39	Shale, gray brown, hard. Limonitic and gypsiferous. *Stanleya* sp. rooted in bed nearby.	MC-SC 39-0-0 1963	65-66½	1½	20
38	Limestone, shaly, blue gray, bedding ¼ inch to 6 inches, jagged ledge former.		53-65	12	Not sampled
37	Shale, resembles 36, but not as black or as gypsiferous.	MC-SC 37-0-0 1963	50-53	3	5
36	Shale, brownish black, soft, bedding ⅛ to ¼ inch. Gypsiferous Not limonitic. Two *Stanleya* sp. rooted in bed.	MC-SC 36-0-0 1963	48-50	2	30
35	Shale, gray brown, soft. *Stanleya* sp.	MC-SC 35-0-0 1963	40-48	8	25
34	Shale, gray, fissile, slope former.	MC-SC 34-0-0 1963	20-40	20	10
33	Shale, gray brown, soft, friable, gypsiferous, limonitic in part.	MC-SC 33-0-0 1963	16-20	4	10
32	Shale, gray, fissile, chippy, slope former.	MC-SC 32-0-0 1963	8-16	8	8
31	Shale, black, papery thin, limonitic stains.	MC-SC 31-0-0 1963	4-8	4	7
30	Shale, medium gray, soft, friable, slope former.	MC-SC 30-0-0 1963	2-4	2	5
29	Shale, black, fissile, hard. No hematite or limonite or gypsum. Slope former.	MC-SC 29-0-0 1963	1-2	1	5
28	Shale, black mottled with yellow and orange, fissile, slope former. *Stanleya* sp. rooted in bed.	MC-SC 28-0-0 1963	0-1	1	10
27	Limestone, blue gray, shaly, thin bedded, jagged ledge former.		0 to minus 10		Not sampled

*This section lies approximately 1200 feet above the base of the formation, and is roughly equivalent to unit 26 of Moyle (1958). The analyzed section is two spurs (200 yards) east of Moyle's section. The formation is thinner on the spur where Moyle measured his section than it is at the present locality because of structural complications in his section. NE ¼ Sec. 33, T. 4 S., R. 4 W.

SELENIUM AT LAKE MOUNTAIN

Lake Mountain is 20 miles south of Soldier Canyon, and 20 miles due west of Provo Canyon (Text-fig. 1). Indicator plants are wholly lacking in the sections visited by the writer on Lake Mountain. The author walked over most of the section described by Moyle (1958) and Tidwell (1962), and not a single indicator plant was found. Either other ecological conditions make the growth of such plants unfavorable or the selenium content of the formation is too low to support such a flora. Perhaps indicator plants find the concentration of the selenium from 1 to 10 ppm too low to meet requirements for growth.

Data summarized in table 8 show that the concentration of selenium in the stratigraphic vicinity of the early Pennsylvanian flora described by Tidwell (1962) is very low. The highest value, associated with bed 4 of Table 8 is 7 ppm. In general the concentration is near 1 ppm, the least concentrations of selenium of the five sections studied.

It is thought by Tidwell (personal communication) and by Moyle (1958) that the Lake Mountain section represents terrestrial deposition to a greater degree than the other sections. Sandstones are more abundant at Lake Mountain, and so are fossil terrestrial plants.

It is possible that terrestrial conditions are less favorable to concentration of selenium than brackish or marine conditions. Since the brackish to marine rocks of the upper part of the Manning Canyon Shale at Soldier Canyon are the most seleniferous section yet encountered, and since equivalent rocks at Lake Mountain seem to be more terrestrial and are least seleniferous, it is suggested that concentration of selenium is somehow related to brackish water or marine conditions.

TABLE 8

Section across plant-bearing strata in the Manning Canyon Shale, Jackrabbit Quarry, Lake Mountain, Utah (Tidwell, 1962).*

Bed No.	*Description*	*Sample Number*	*Feet Above Base*	*Thickness in feet*	*PPM Selenium*
12	Shale, pinkish brown, weathered, approaches surface on shallow side of quarry on the east.		71-73	2	Not sampled
11	Shale, pinkish brown, fissile, laminated.	MC-LM 11-0-0 1963	66-71	5	1
10	Shale, resembles 11	MC-LM 10-0-0 1963	60-66	6	1
9	Shale, resembles 11	MC-LM 9-0-0 1963	53-60	7	1
8	Shale, pinkish brown, laminated, weathers in slabs. Plants found by Tidwell in this bed and in 7.	MC-LM 8-0-0 1963	46-53	7	1
7	Shale, pink, laminated, weathers in slabs ¼ inch to 6 inches, some unidentifiable plant remains. Lower part of most productive fossil plant beds.	MC-LM 7-0-0 1963	41-46	5	1
6	Shale, brownish pink, variegated, crumbly. Limonitic stains.	MC-LM 6-0-0 1963	37-41	4	2
5	Shale, brown gray, limonitic on surface, crumbly.	MC-LM 5-0-0 1963	30-37	7	5
4	Shale, gray, some limonite, but not as much as in 3-0-0. Crumbly.	MC-LM 4-0-0 1963	22-30	8	7
3	Shale, gray with yellow iron oxide stain abundant, crumbly.	MC-LM 3-0-0 1963	13-22	9	3

TABLE 8 (CONT.)

2	Shale, yellowish gray, beds crumpled by folding, part of bed cut out by folding; dip changes to east.	MC-LM 2-0-0 1963	6-13	7	1
1	Shale, variegated with brown, gray, and yellow, bed is crumpled by folding.	MC-LM 1-0-0 1963	0-6	6	3

*Section begins on top of blue-gray limestone which weathers pink on the west side of the quarry. The dip of the bed is nearly vertical, and the strike is about N 2° E. Beds 7 and 8 correlate with those beds which have yielded numerous *Alethopteris, Neuropteris,* and *Calamites* (Tidwell, 1962). SW ¼, SW ¼ Sec. 7, T. 7 S., R. 1 E.

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