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by K. E. KOLM

University of Wyoming

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Special Report: Selenium in soils of the Lower Wasatch Formation, Campbell County, Wyoming: Geochemistry, Distribution, and Environmental Hazards

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16. Abstract

Seleniferous Shingle series soils and sandstone outcrops of Section 27, T 48 N, R 71 W, Wyoming are mapped on aerial photography by their association with _Astragalus bisulcatus_. Chemical leachate analyses and atomic absorption methods reveal all studied Samsil and Shingle soils to contain acid, base, and water soluble selenium compounds, and that water extractions showed varied concentration behavior due to soil pH. Acid-soluble selenium is found to be associated with smectite. Statistical analyses confirm that _A. bisulcatus_ presence has a weak influence on soil-lens organic selenium concentration, and determine the importance of other geobotanical factors for convertor presence (selenium not limiting on any soils). Environmental procedures of high-selenium lens burial, convertor plant eradication, and revegetated site monitoring are recommended. Usage of density analysis and photographic enlargement are used to successfully produce both a control area and a Campbell County, Wyoming, regional map of _A. bisulcatus_ supportive soils and outcrops using Skylab photography.

Selenium, Soils, Density Analysis, Photographic Enlargement, Environmental Hazards

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Figure 2. Technical Report Standard Title Page

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ABSTRACT

The soils derived from the Lower Wasatch Formation, Sec. 27, T 48 N, R 71 W, Campbell County, Wyoming, contain considerable selenium concentrations. The purpose of this investigation was to determine the geochemistry and distribution of the seleniferous soils at this study site, and to determine any environmental hazards associated with the disturbance and redistribution of these soils in mining and reclamation or agricultural practices.

Highly seleniferous soils at the study site were mapped by their association with the selenium indicator species Astragalus bisulcatus. This species selectively germinates and grows on Shingle series soils and sandstone outcrops.

Chemical leachate analyses and atomic absorption methods revealed that all soils in this area contain concentrations of acid-, base-, and water-soluble compounds of selenium. Using the techniques of X-ray diffractometry, centrifuge separation, heavy liquid separation, and additional acid leaching on selected samples, acid-soluble selenium compounds were found to be associated with the smectite in the A horizon soils.

An analysis of variance for three separate model equations provided statistical confirmation for the following conclusions:

1) There are significant leachable selenium concentration differences in soil lenses of the entire study area due to the differential effects associated with A. bisulcatus presence (accumulation of organic selenium), soil pH (water leaches variable), and sample randomness.

2) There are significant differences in leachate groups due to solvent strength, soil chemistry, and leachable quantities present in the soils.

3) There are no significant leachable selenium concentration differences between soil lenses of sites A and B. More extensive surficial accumulation of organic selenium compounds by A. bisulcatus is hypothesized.

4) There are no significant leachable selenium concentration differences between the Samsil and Shingle soil types. More geobotanical research is necessary to determine the ecological reasons why A. bisulcatus favors germination and growth exclusively on certain Shingle soils.

5) There is no differential effect of a particular soil or study area with a particular leach. This implies uniformity in both solvent strength used and selenium concentrations leached with each solvent.

6) Shingle soil lens topographic position is significant at site A. Graphed data revealed the cause to be unrelated to erosional transport. Lens variation in selenium quantities due to bedrock source differences is hypothesized.

The serious environmental concern in this study is the control of selenium redistribution in soil to prevent the increase in seleniferous vegetation and eventual deterioration of soils, cropland, and range quality. The following conclusions are appropriate:

1) _A_. _bisulcatus_, due to root decay, contributes to the soils (at approximately 6" depth) small quantities of organic selenium.

2) A. bisulcatus germinates and grows on soils containing 0.2 ppm leachable selenium and less. At the study site leachable selenium will not be a limiting factor for convertor plant germination and growth.

3) For complete environmental assessment, additional selenium analyses of all study area plants are needed to determine range vegetation toxicity (how effective is each individual species in body tissue accumulation of selenium) and the relationships of water-soluble selenium concentrations between soil lens availability and plant uptake.

Because of a potential environmental hazard; the following procedures are recommended:

1) Neither the Samsil nor Shingle soils should be stockpiled due to their significant concentrations of selenium. Other soils, such as the Ulm series soils, should be used for topsoil respreading.

2) If the Samsil and Shingle soils are ever used for topsoil, all selenium convertors should be removed before stock-

piling and all soil lenses containing abnormally high selenium concentrations should be buried.

3) Once reclamation procedures are completed, the land should be carefully monitored for convertor plant invasion. If any seleniferous plants are discovered, they should be eliminated.

It was concluded that selenium compounds at the study site are not being transported downslope by surface runoff. Therefore, there is little danger of surface water deterioration. However, more studies are necessary to determine if significant selenium concentrations are being leached to the water table, therefore, contaminating the groundwater.

Skylab photography was tested as a tool in mapping the Shingle soils and outcrops supporting A. bisulcatus. Density analysis and photographic enlargement were two methods used successfully in localized mapping of the potentially plant-supporting soils (undisturbed). A regional map of these soils was prepared for Campbell County using the Skylab S 190-B photography as a mapping base.

INTRODUCTION

Purpose of Investigation

The Tertiary Wasatch Formation, consisting of continental deposits of drab-colored, grey siltstones and shale, drab-colored, yellowish-grey sandstones, and numerous, thin coal beds (Love, J. D., Weitz, J. L., and Hose, R. K., 1955), overlies the coal-bearing Fort Union Formation in the Powder River Basin. In the strip mining of Fort Union coals, the Wasatch rocks are overburden, and will be disturbed.

Wasatch rocks and their related soils contain selenium (Sharp, W. N., and Gibbons, A. B., 1964; U. S. D. I., 1974). This element is observed to be toxic to living organisms, especially livestock (Trelease, S. F., and Beath, O. A., 1949). In the coal mining areas, a potential environmental hazard exists if selenium concentrations in soils are further increased by the breaking up and weathering of seleniferous overburden. These increased soil concentrations might stimulate selenium convertor plant growth and reproduction, therefore, enhancing the chances of livestock poisoning.

This study was designed to investigate the geochemistry and distribution of the selenium-rich soil lenses derived from the Lower Wasatch Formation and determine changes that might result from their disturbance.

Location and Accessibility

The control area, Section 27, T 48 N, R 71 W, is AMAX's South Belle Ayr Mine Site, Campbell County, Wyoming (Fig. 1). This site, located about 24 kilometers south-southeast of Gillette, can be approached by two improved dirt roads originating at Wyoming highway 59 about 13 kilometers to the northwest and 10 kilometers due west of the area. These roads are generally open all year.

Regional studies encompass all of Campbell County, Wyoming (Fig. 1).

Previous Work

Environmental impact studies have been undertaken in the Powder River Basin because of the increasing mineral resource development (U. S. D. I., 1974). These studies include selenium analyses of 24 rock overburden samples taken from various mine sites. However, no comprehensive publications are yet available relating this trace element to the seleniferous plant supporting capabilities of the Wasatch Formation-derived soils.

The ecologic relationships of various plants species and selenium have been studied extensively (Trelease, S. F., and Beath, O. A., 1949). These studies were an outcome of an urgent need to understand livestock and human poisoning by certain plant species and the economic potential of developing "selenium crops" to retrieve needed quantities of

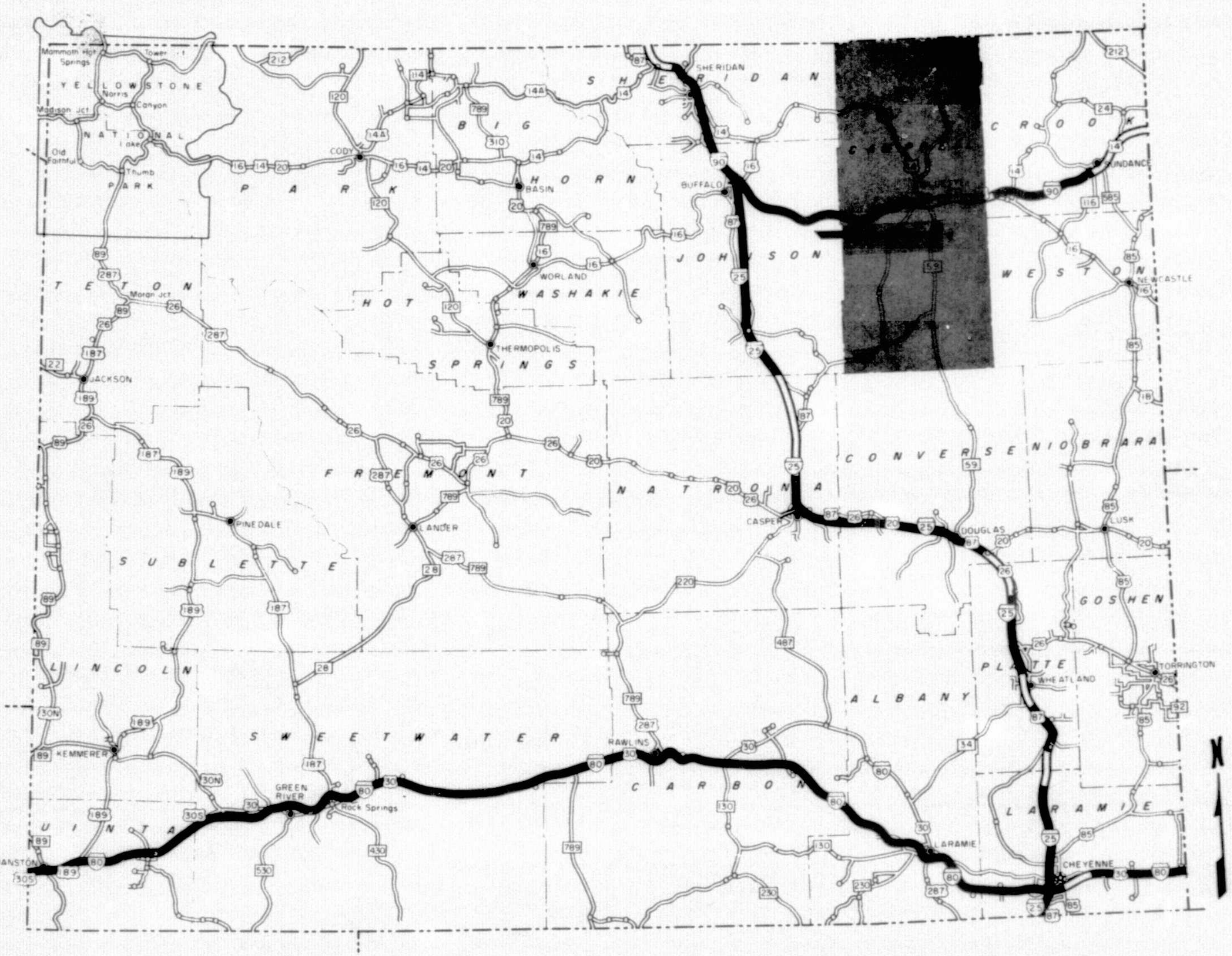


Figure 1. Index map of Wyoming showing the reference site location (arrow) and the area mapped from Skylab photography (shaded area).

this trace element for industrial purposes (Beath, O. A., 1959).

Vegetation coverage estimates based on a Plant Density Index are available for the South Belle Ayr Mine Site (Rogers, J. R., 1974). Using the Parker "Three Step Method", Rogers (1974) also determined the species frequency for the study area.

Extensive geologic studies are published for both Campbell County (Thornbury, W. D., 1965; Robinson, C. S., et al., 1964; Mapel, W. J., et al., 1959; Breckenridge, R. M., et al., 1974) and the area of investigation (Sec. 27, T48 N, R 71 W) (Dobbin, C. E., and Barnett, V. H., 1927; Love, J. D., and Weitz, J. L., 1951; Olive, W. W., 1957). Preliminary soils mapping and analyses at the study site has been recently completed (Rogers, J. R., 1974).

Method of Investigation

Field work was done during the summer of 1974. A reconnaissance investigation using aerial photography (scale 1:24,000) as a mapping base determined the presence of selenium indicator plant species and their relationships to other plant species and soils. A compilation map was then prepared displaying distributions of soil types and selenium indicator species (Plate 1).

Two soil sampling sites were chosen and thirty-five total samples were collected for chemical analysis. The areas differed in the presence or absence of selenium indicator species.

Spectral photometer readings were taken for the various soil units using a filtered, Science and Mechanics, A-3 photometer. These readings, combined with the soil and vegetation information gathered in the field, were the basis for a seleniferous soils map compiled for Section 27, T 48 N, R 71 W, using Skylab S190B color photography (Track 59, Pass 28, September 13, 1973, scale: 1:936,000) (Fig. 2). Techniques, such as density analysis and photographic enlargement, were employed to find the most effective method for mapping from Skylab photography.

Three leachate chemical analyses (acid, base, and water) were conducted on the thirty-five soil samples to determine the presence, geochemistry, and leachability of selenium compounds found in each soil. Four soil samples were further separated into three fractions: clay (0.2-1.0 micron e.s.d.), silt and sand, and heavy minerals (greater than 2.96 specific gravity) and analyzed to determine the mineral associations of acid-soluble selenium compounds.

Three statistical models were tested using an analysis of variance to clarify relationships between individual soil lenses, soil types, study sites, and leachate groups. Mean, variance, and standard deviation were calculated for both the individual soil units and soil series types.

Finally, a regional map was prepared from the Skylab

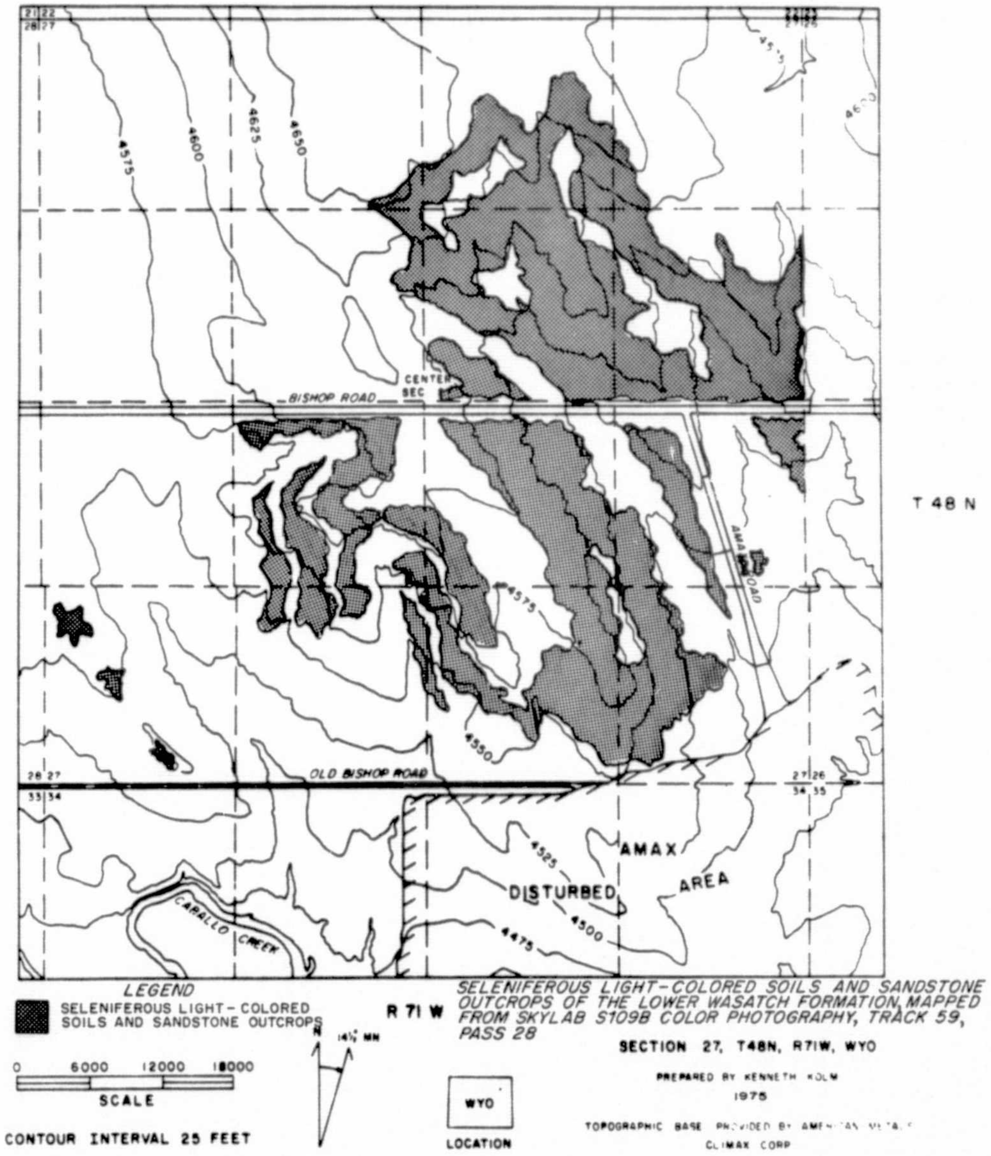


Figure 2. Seleniferous Shingle series soils and sandstone outcrops derived from the Lower Wasatch Formation, mapped from Skylab S190B color photography (Track 59, Pass 28, September 13, 1973, scale: 1: 936,000, Section 27, T 48 N, R 71 W, Wyoming.

photography in order to locate the selenium soil hazard areas in all the coal mining regions of Campbell County (Plate 2).

REGIONAL SETTING

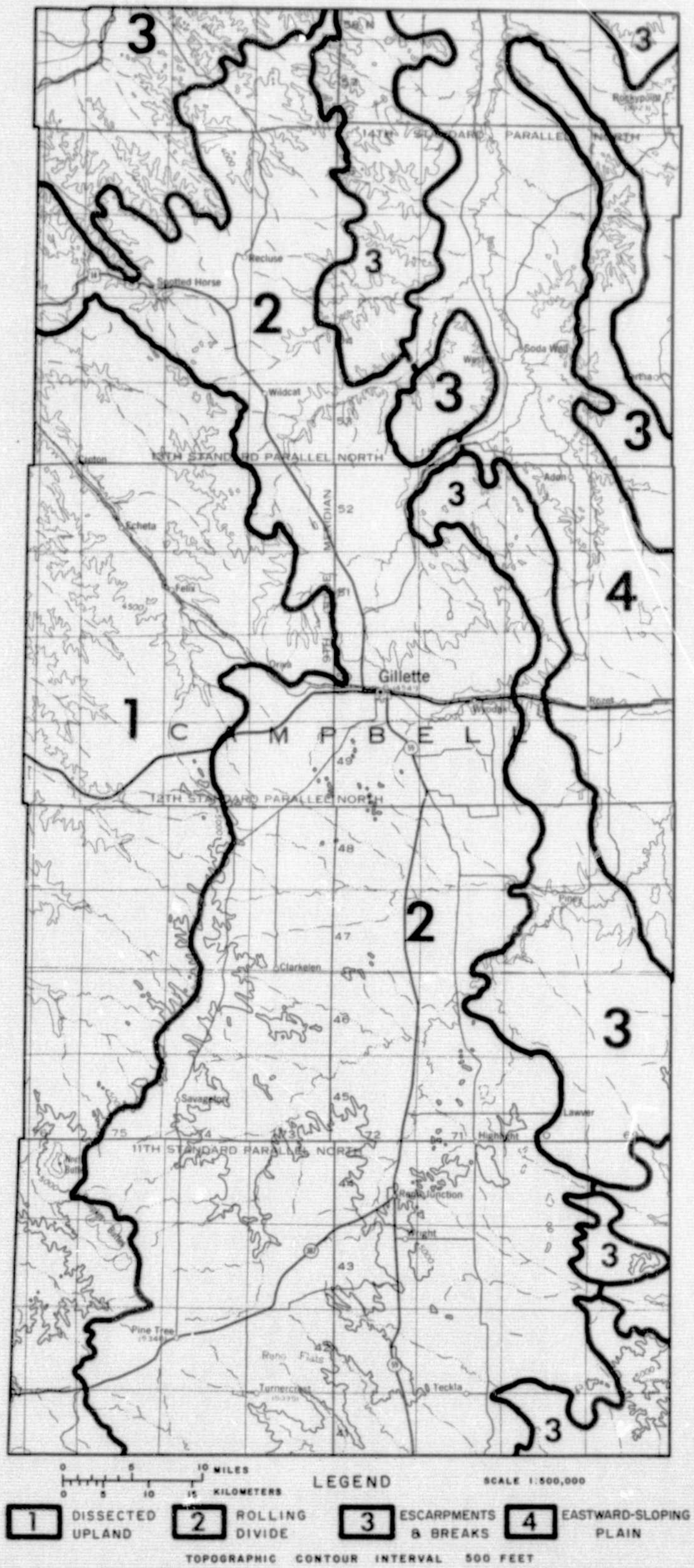
Geomorphology

The area of investigation is located within the Great Plains Geomorphic Province (Thornbury, W. D., 1965). Topographic features characteristic of this region, classified according to average elevation, local relief, and landforms, are described in detail by Breckenridge, R. M., and others (1974), Glassey, T. W., and others (1955), and W. D. Thornbury (1965) (Fig. 3).

The study site is classified as rolling divide (Breckenridge, R. M., et al., 1974) because of its "smooth, low-relief hills and numerous, red scoria hills ranging from 20-100 feet in height" (Fig. 4). Area variations in geomorphic features are caused by 1) differences in the erosional characteristics of the flat-lying, Tertiary bedrock, 2) downward and lateral dissection by fluvial processes through rocks of uniform erosional character, and 3) the burning of coal seams which produces resistant scoria layers (surface burning). Site elevations range from 4500-4650 feet above sea level.

Geology

Structurally, the AMAX study site is located within the Powder River Synclinal Basin described by Robinson, C. S., and others (1964), and Breckenridge, R. M., and others (1974)

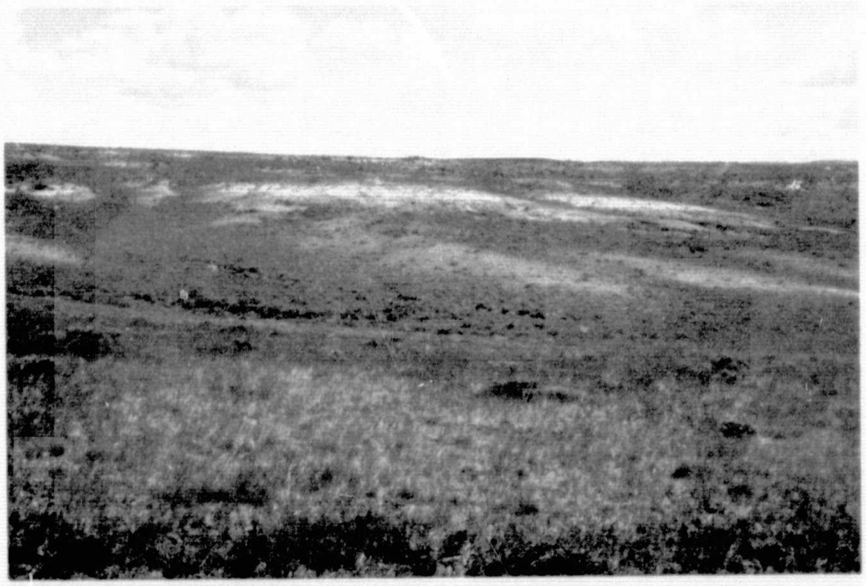


From Topographic Map, State of Wyoming, U.S. Geological Survey, 1967.

Figure 3. Topographic map of Campbell County, Wyoming (from Wyoming Geological Survey, 1974, and U.S. Geological Survey, 1967).

Figure 4. Reference area, Section 27, t 48 N, R 71 W, Wyoming.

a) Site A



b) Site B

(Figs. 5 and 6). The sedimentary Wasatch Formation exposed surficially strikes about N 20° W and dips one or two degrees southwest (Dobbin, C. E., and Barnett, V. H., 1927). No faulting is evident at this site.

Stratigraphically, the investigated area is comprised of relatively flat-lying, Tertiary units unconformably overlying a thick, older sequence of Mesozoic and Paleozoic rocks (Mapel, W. J., et al., 1959; Love, J. D., et al., 1955). Below these sedimentary rocks lie still older, crystalline rocks of the Pre-cambrian "basement" (Breckenridge, R. M., et al., 1974).

The Eocene Wasatch Formation, which covers the land surface at Section 27, T 48 N, R 71 W, consists of the following continental deposits: 1) fine- to medium- grained, friable, well-indurated, drab-colored, yellowish-grey sandstones, 2) drab-colored, grey siltstones and shale, and 3) numerous, thin coal beds (Love, J. D., et al., 1955; Olive, W. W., 1957; Dobbin, C. E., and Barnett, V. H., 1927; Robinson, C. S., et al., 1964). A detailed section measured by Olive (1957) illustrates the lens-like character and variable composition of Wasatch Formation rocks (Table 1).

Soils

Soils of the study site are the product of a semi-arid climate in which vegetation, erosion, and organisms play a

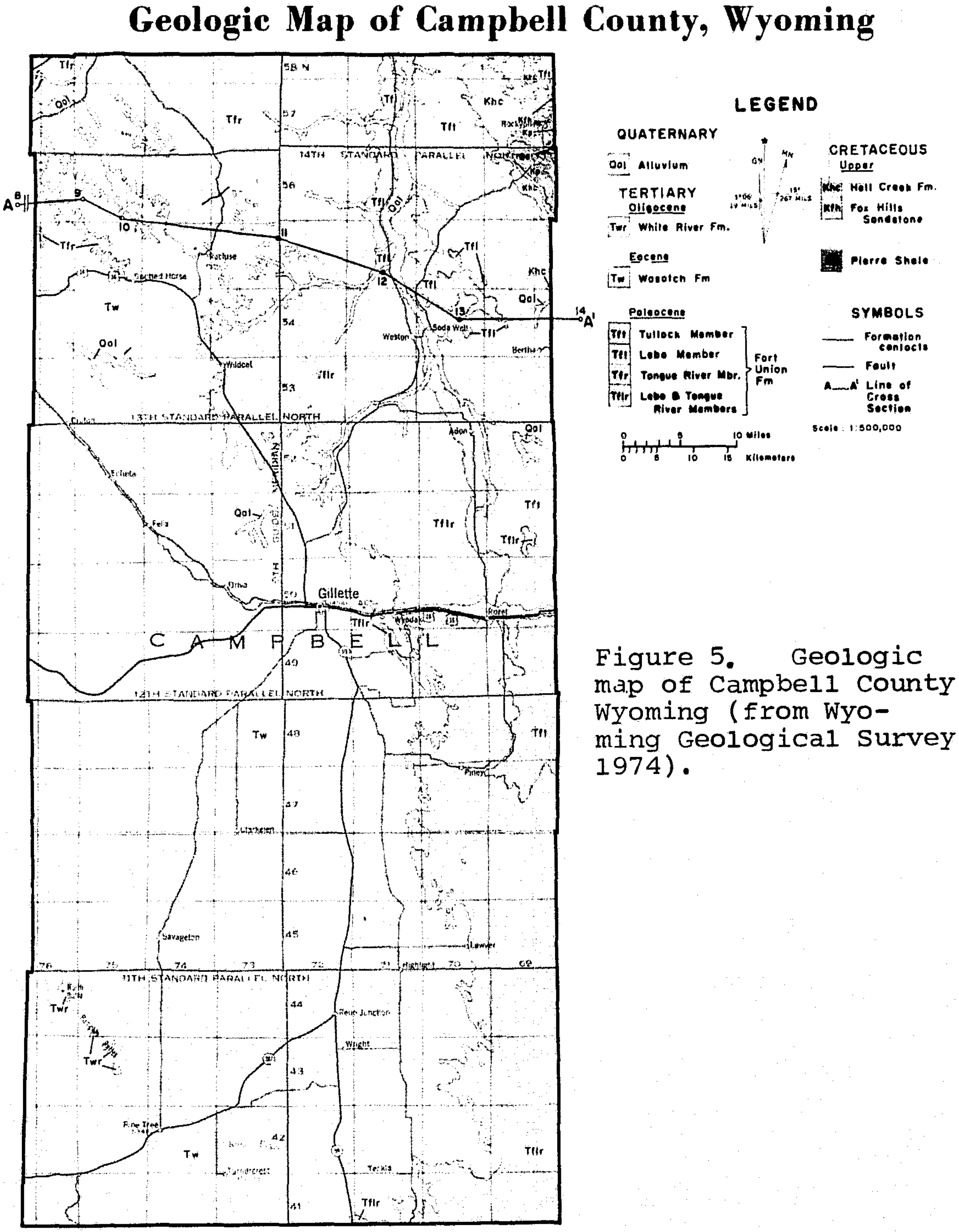


Figure 5. Geologic map of Campbell County, Wyoming (from Wyoming Geological Survey, 1974).

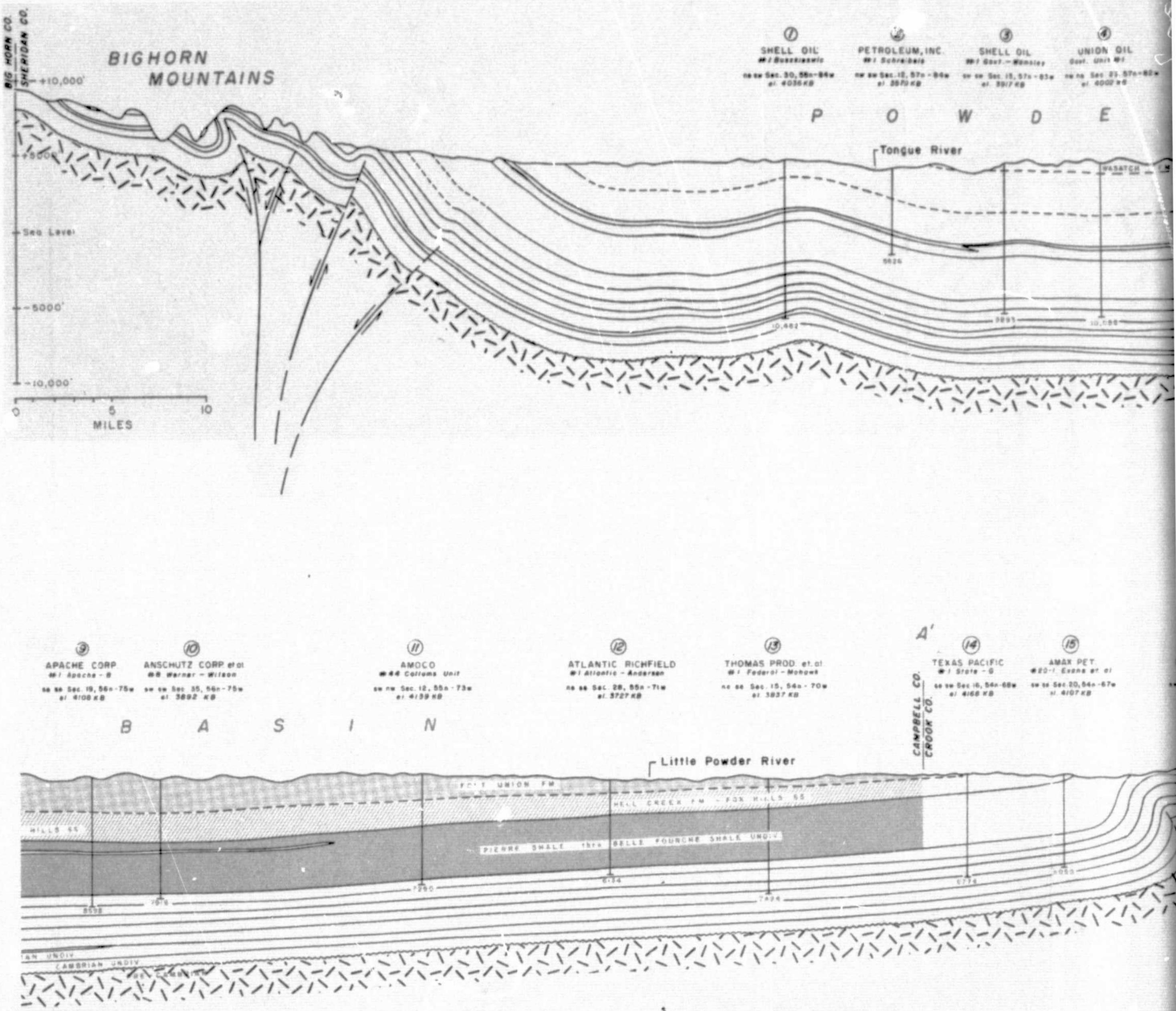


Figure 6. Regional geologic cross-section of the Powder River Basin, Wyoming (from Wyoming Geological Survey, 1974).

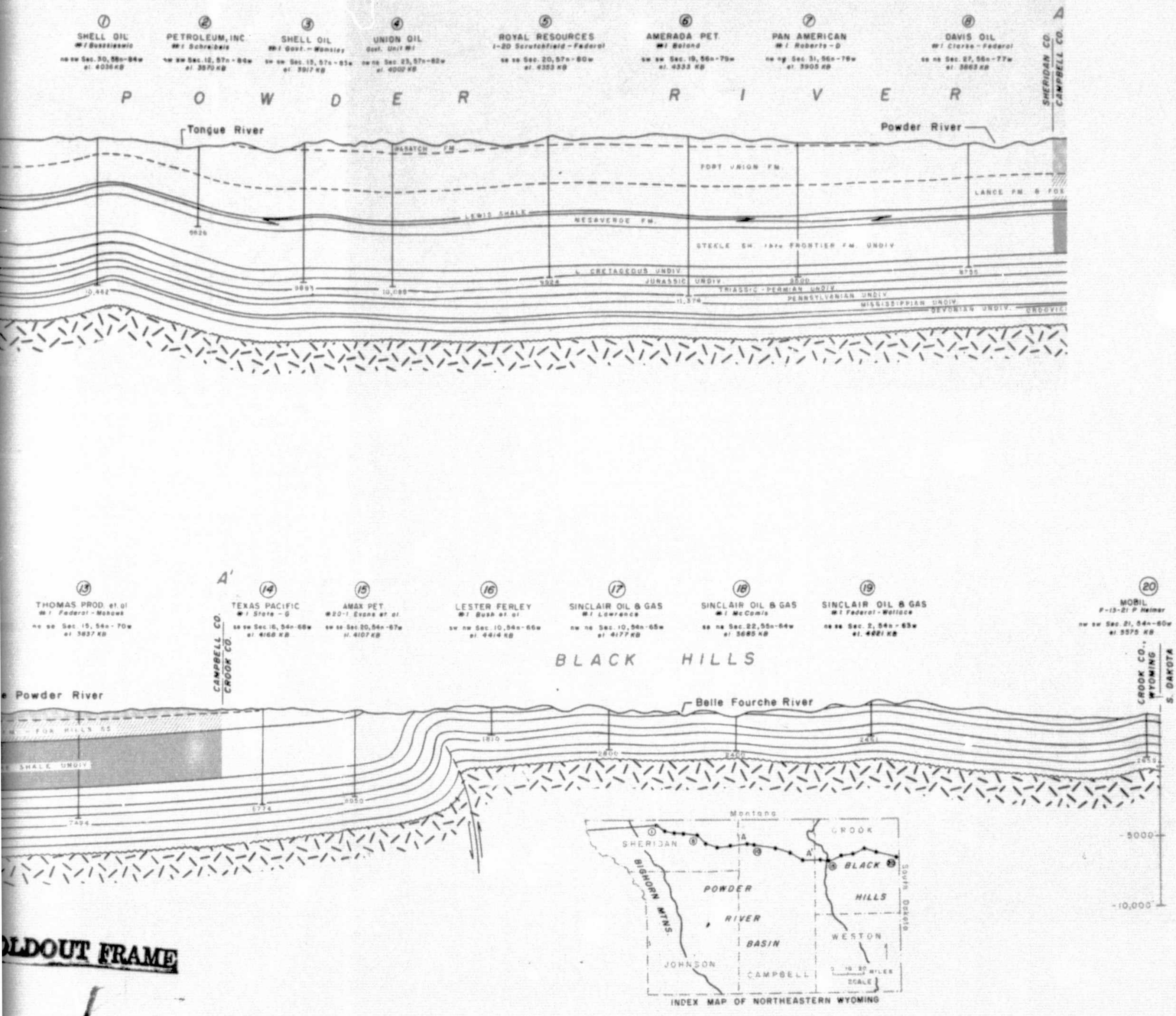


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Table 1. Partial list of measured units through the Wasatch Formation in the south half of Sec. 14, T 53 N, R 75 W, Wyoming (from Olive, W. W., 1957).

Lower Wasatch Formation:	Feet	Inches
Sandstone, friable, pale yellowish-grey	5	7
Shale, olive-grey		6
Coal (local bed), shaly		6
Shale, olive-grey		8
Covered		8
Siltstone, shaly, light olive-grey	6	
Sandstone, well-indurated, ledge-forming, pale-grey; weathering yellowish-orange	16	2
Shale, dark yellowish-brown		1
Coal (local bed)	1	11
Shale, dusky-brown		2
Shale, olive-grey	1	6
Covered	28	6
Sandstone, fine-grained, friable, greyish-yellow; contains lenses of indurated sandstone	30	
Siltstone, shaly, light olive-grey-moderate-yellow stains along bedding planes	2	8
Coal (Felix bed):		
Coal	2	6
Siltstone, shaly, medium-grey	1	3
Coal	2	1
Sandstone, medium-grained, very friable, pinkish-grey, lenticular		11
Coal	1	6
Sandstone, medium-grained, very friable, pinkish-grey, lenticular	3	7
Coal	11	8
Siltstone, shaly, medium-grey		10
Coal	17	6
Shale, dusky-brown		7½
Shale, slightly silty, light olive-grey; contains moderate-yellow vein-like stains	3	1
	140	5½

significant role in the weathering and decomposition of the sedimentary bedrock (U. S. S. C. S., 1955). These soils, which often exhibit a lime carbonate layer at shallow depths, seldom exceed 36 inches in depth. Slope areas usually have a very thin soil cover or consist of exposed bedrock (U. S. S. C. S., 1955).

J. R. Rogers (1974) conducted a preliminary soils study at the AMAX South Belle Ayr Mine Site and classified the various soil units according to such characteristics as appearance, texture, and composition. The two soil types of interest, the Samsil (Fig. 7) and Shingle (Fig. 8) series, are described in detail in Table 2.

Rogers (1974) also notes that both the Shingle and Samsil series soils formed in parent materials weathered residually or transported locally (Figs. 9a and 9b).

Climate and Vegetation

The study site climate, typical of Wyoming's high plains, is temperate and semi-arid (Becker, C. F., and Alyea, J. D., 1964). This area receives 12-14 inches annual precipitation (W. R. R. I., 1974) and has an average growing season of 110-120 days (Breckenridge, R. M., et al., 1974).

At the AMAX site, two major vegetation types: grass-

Figure 7. Samsil series soil developed on a 6-15% slope, Section 27, T 48 N, R 71 W, Wyoming. Pictured is the light-brownish-grey soils less than four inches thick typical of the mixed clayey and calcareous A horizon.

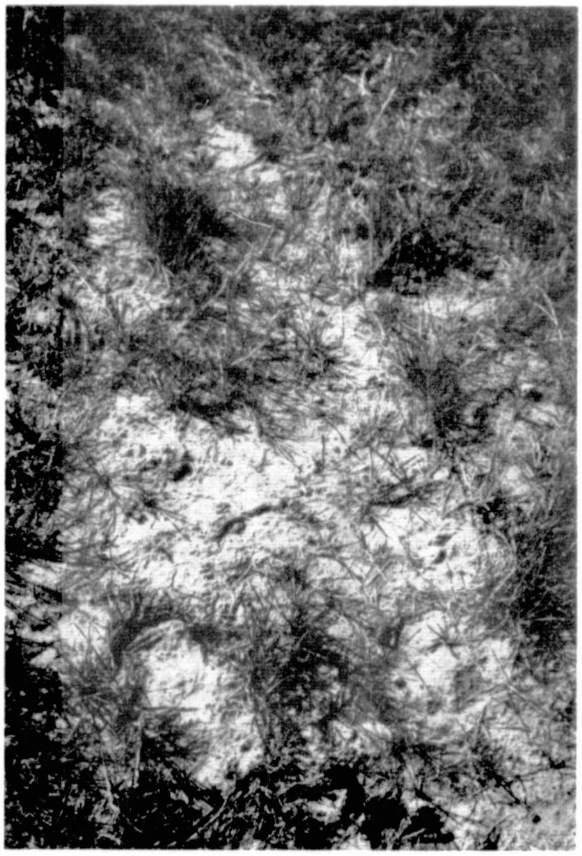


Figure 8. Shingle series soil developed on a 6-15% slope, Section 27, T 48 N, R 71 W, Wyoming. Pictured is the friable, calcareous, light-yellowish-brown, clay loam of the A horizon. The area shown here is about 12 square feet.

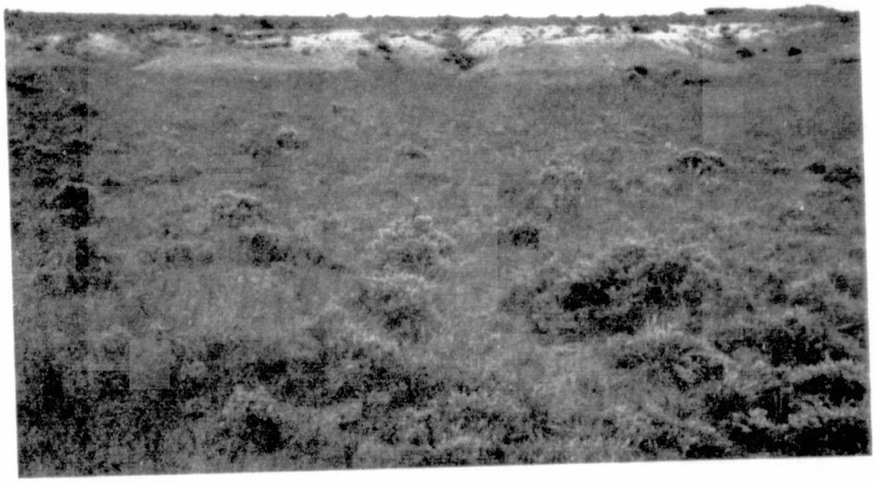
Table 2. Description and preliminary analysis of the Shingle and Samsil series soil types, AMAX South Belle Ayr Mine Site, Sec. 27, T 48 N, R 71 W, Wyoming (from Rogers, J. R., 1974).

Soil Type	General Description
Samsil series:	Clayey, mixed, calcareous, montmorillonitic Lithosols. Light brownish-grey, granular A horizons less than 4 inches thick; friable, clay C horizons; weakly calcareous shale bedrock at depths of less than 20 inches. Neutral- to moderately- alkaline A horizon. Textural Analysis Horizons above the shale range from 50-65% clay. Appearance A1 horizon ranges in hue from 5Y through 10YR. Structure Fine and medium subangular blocky to very fine granular. Setting Slope breaks of dissected shale plains: 2-45% (6-15% at AMAX site). Drainage and Permeability Well drained. Runoff is slow on gentle slopes, rapid on steep slopes. Permeability slow.

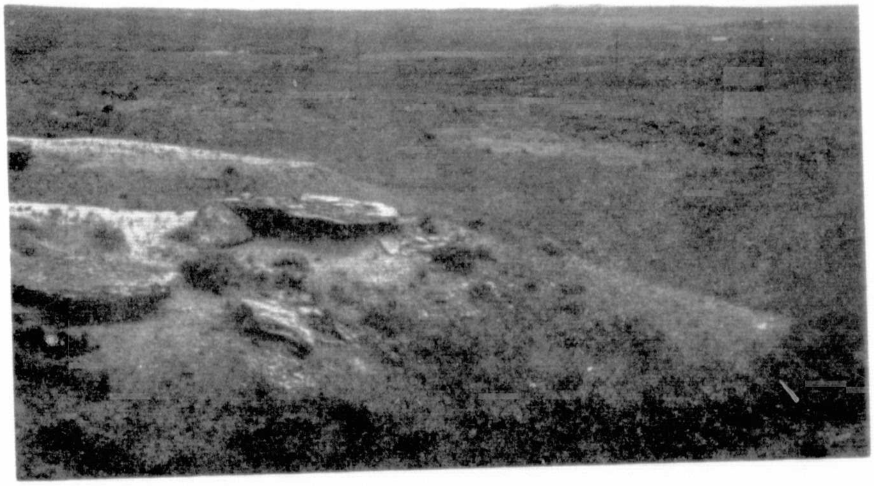
Table 2. Continued.

Soil Type	General Description
Shingle series:	Loamy, mixed (calcareous), mesic Lithosols. Very friable, calcareous A horizons; moderately fine textured, calcareous C horizons; substrata of soft sandstone, loamstone, and siltstone occur at depths of about 15 inches. Mildly- to strongly- alkaline A horizon. Textural Analysis Horizons above the bedrock range from 18-35% clay, 20-55% silt, and 15-55% sand. Sand/clay ratio is less than ¼. Appearance A horizon ranges in hue from 5Y-7.5YR. Structure Granular or crumb, subangular blocky to platy. Setting Moderately- to steeply- sloping ridge crests and side slopes: 5-30% (6-15% at AMAX site). Drainage and Permeability Well drained. Medium- to rapid- runoff. Moderate permeability.

Figure 9. Shingle and Samsil series soils forming in situ. Note the intermingling of outcrops and residual rock fragments with the soils.



a) Area view.



b) Close-up view.

land and sagebrush, are identified and discussed by J. R. Rogers (1974). He found that grasses clearly dominate the composition in both plant communities (about 75% of the total vegetation there), and that four taller-growing, dominant species of needle and thread grass (*Stipa comata*), bluebunch wheatgrass (*Agropyron spicatum*), Canby's bluegrass (*Poa canbyi*), and prairie junegrass (*Koelaria cristata*) are uniformly frequent over the area (Fig. 10). The dominant understory grass is blue grama (*Bouteloua gracilis*).

The sagebrush stands, containing silver sagebrush (*Artemisia cana*) and big sagebrush (*Artemisia tridentata*), form the overstory and blend from dense stands to open grassland (Fig. 11). These species are also found in both vegetation types.

Rogers (1974) inventoried the vegetation cover using a Plant Density Index (percent-of-ground covered by the individual plant species in a given area). He found grassland coverage 45-71%, sagebrush coverage 42-68%, and barren ground 5-25%. Other species combined for less than 1-8% coverage.

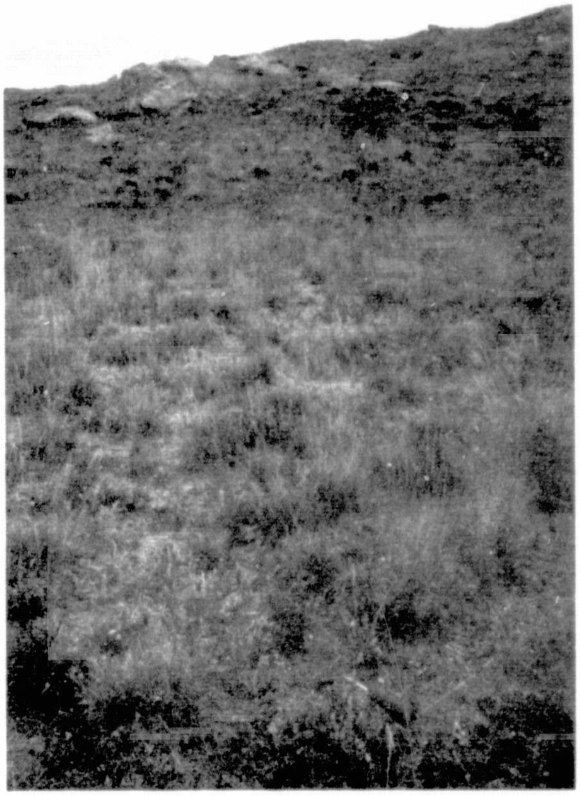


Figure 10. Grassland community found in Section 27, T 48 N, R 71 W, Wyoming. Note the intermingling of sagebrush an A. bisulcatus (by hammer).

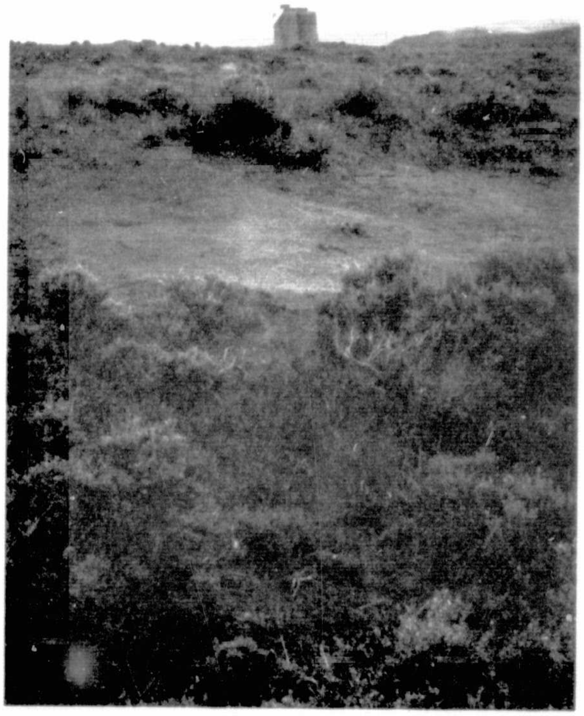


Figure 11. Sagebrush community (in both dense stands and dispersed individuals) T 48 N, R 71 W, Wyoming. Note the intermingling of grassland community.

THE BIOGEOCHEMICAL NATURE OF SELENIUM

Selenium Cycle in Nature

Olson and Moxon (1939) contend that the selenium cycle in nature is a set of complex interactions involving rocks, soil fractions, organisms, and the physical processes involving water and air (Fig. 12). Movement within the cycle depends primarily on the chemical form of the element at the various stages (Olson, O. E., and Moxon, A. L., 1939). For example, organic and water-soluble compounds readily move from soils into plant matter, whereas selenium in association with iron remains locked up in bedrock indefinitely until mechanically removed by erosion or other physical process (Trelease, S. F., and Beath, O. A., 1949).

Selenium in Bedrock and Soils

Selenium is a common trace element associated with most rock types (Turekian, K. K., 1971). Its crustal abundance as listed by Turekian (1971) is highest in carbonates (0.88 ppm) and shales (0.60 ppm), and relatively insignificant in most other rock types (average of 0.05 ppm).

By comparison, the U. S. Dept. of the Interior (with other agencies) (1974) conducted chemical analyses on the Wasatch Formation at various eastern Powder River Basin coal mine sites. The results showed that shales, silt-

<u>LEGEND</u>
Selenium in:
1. Parent Rock
2. Soil (inorganic)
3. Soil Humus
4. Converter Plants
5. Other Plants
6. Animals
7. Atmosphere

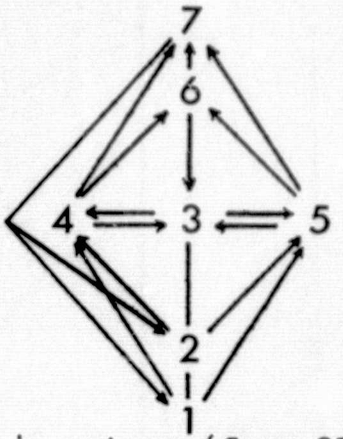


Figure 12. The selenium cycle in nature (from Olson, O. E., and Moxon, A. L., 1939). The interrelations displayed depend upon the chemical form that selenium is in.

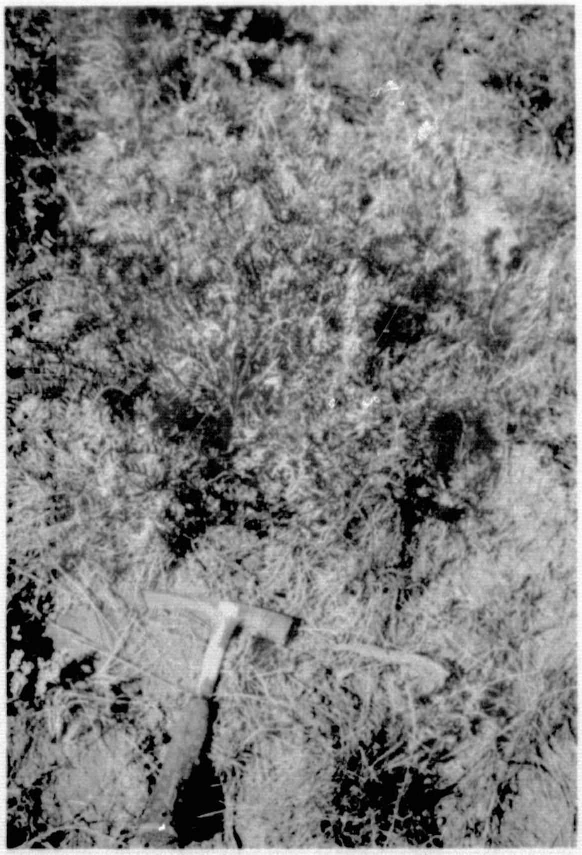


Figure 13. <u>Astragalus bisulcatus</u>, a seleuium indicator and converter species, found at the study area, T 48 N, R 71 W, Wyoming.

stones, and claystones contained selenium concentrations ranging from less than 0.1 ppm to 2.7 ppm, while sandstones contained less than 0.1 ppm.

Hypotheses proposed by Beath, O. A., and others (1935) regarding the selenium origin in Wasatch rocks are the following: 1) selenium compounds may have been ejected as volatiles from a volcano, settled in a Cretaceous sea, and later eroded and redeposited in Tertiary times, or 2) selenium compounds may have been derived slowly during erosion of an igneous land mass in earlier Tertiary time and then redeposited. A third possibility, presented by Trelease and Beath (1949), is the secondary accumulation of selenium by plants in early Tertiary time resulting in areas of concentration within paleosoils, stream channels, and drainage basins.

Geologic materials in Wyoming found to contain high selenium concentrations include the following: limonitic concretions (Beath, O. A., 1937), pyrites (Williams, K. T., and Byers, H. G., 1934), carbonaceous shales (Beath, O. A., 1937), iron-stained bentonite (Trelease, S. F., and Beath, O. A., 1949), ferruginous and carbonaceous sandstones (Trelease, S. F., and Beath, O. A., 1949), impure sulfur (Byers, H. G., 1935), volcanic tuffs (Beath, O. A., et al., 1946), carbonaceous vanadium-uranium ores (Beath, O. A., 1943), and sulfides of copper, silver, iron, and gold (Newberry, J. S., 1881). A high selenium association with iron and calcium is noted by Trelease and Beath (1949).

Beath (1937) found that selenium content in the Wasatch rocks and derived soils varies within the different subunits, and laterally, within different parts of the same subunit. He attributed such variations to the occurrence of high concentrations of selenium in secondary features, such as concretions, and to plant influences, such as the selenium convertor species.

An important key to selenium transport is the interaction of the rock and soil with the physical environment. The semi-arid climate of the Powder River Basin favors soil formation in situ with leaching occurring only in the upper few inches of the soils (Knight, S. H., 1937).

Slope is another important factor for determining selenium origin and movement in the soils. In an area of pronounced relief with outcrop exposure, mechanical disintegration occurs. If selenium is present in the weathered bedrock, the thin soil mantles formed at the base of the outcrops will also contain selenium (Knight, S. H., 1937). Erosion of these thin mantles is minimal in the Powder River Basin due to the paucity of precipitation. However, it is not uncommon to find seleniferous soils that have been carried for short distances and deposited in drainages (Knight, S. H., 1937).

The chemical forms of selenium present in the Wasatch derived soils are undetermined. From previous studies (Beath, O. A., et al., 1935; Beath, O. A., 1937; Williams, K. T., and Byers, H. G., 1934), Trelease and Beath (1949) concluded that a projected soil profile can be constructed for Wyoming's semi-arid basins (Table 3). It is hypothesized that the soils studied at the area of investigation are compositionally similar in structure.

Table 3. Chemical forms of "available" selenium found in a typical soil profile in the semi-arid Wyoming basins (compiled from Trelease, S. F., and Beath, O. A., 1949).

Horizon	Chemical Form	Cause of Occurrence
A	Organic selenium	Plant decay.
	Minor amounts of selenates	Plant decay, water soluble forms leached from bedrock.
	Free selenium, selenides, and basic ferric selenites	Slow, hydrolytic action.
C	Selenates	Unleached area, derived from bedrock.

Selenium in Vegetation

Some plant species are very tolerant to selenium compounds in the soil. These plants are of two types: convertors and secondary absorbers.

Convertors take from the soils and rocks selenium compounds which are required for their metabolism and chemically alter them to organic compounds (Beath, O. A., et al., 1939). They absorb selenium forms that are 1) hydrolysis products of free selenium, selenides, and basic ferric selenites, 2) organic selenium compounds resulting from other concentrator plant decay, and 3) water-soluble selenates (Trelease, S. F., and Beath, O. A., 1949). Members of this plant group found in the Powder River Basin include species of vetch (Astragalus), woody aster (Xylorrhiza), prince's plume (Stanleya), and goldenweed (Oonopsis) (Beath, O. A., 1959).

When the convertors decay, they release organic selenium into the soil. This organic selenium is then available to other convertors and another group of plants, called secondary absorbers (Trelease, S. F., and Beath, O. A., 1949).

Secondary absorbers are plants whose metabolism does not require selenium for survival. However, they will grow on organic selenium-rich soil and will concentrate significant amounts of the toxic, selenium compounds in body tissues (Trelease, S. F., and Beath, O. A., 1949). Members of this classification range from the heavy concentrators of genera Aster, Atriplex, Castilleja, Commandra, Grayia, Oonopsis, Grindelia, Gutierrizia, Machaeranthera, Mentzelia, and Sideranthus, to the occasional users including grasses and economic crops (Trelease, S. F., and Beath,

O. A., 1949). The absorbers, like convertors, release organic selenium to the soil when they decay, thereby perpetuating a toxic environment (Beath, O. A., 1959; Olson, O. E., and Moxon, A. L., 1939).

IDENTIFICATION OF SELENIFEROUS SOILS

Plant Indicator Species

Beath, O. A., and others (1934) discovered that certain of Wyoming's native plants always contain significant amounts of selenium when collected on seleniferous soils. Trelease and Trelease (1938) developed this hypothesis with solution and sand culture experiments on a field collection of plants. They (Trelease, S. F., and Trelease, H. M., 1938) found that the presence of plant species known as "Beath's selenium indicators" confirms the existence of selenium in the soil upon which they grow. Later research concluded that some secondary selenium absorbers can also be used for locating seleniferous regions (Trelease, S. F., and Beath, O. A., 1949).

In the study area, one indicator species, Astragalus bisulcatus, was identified (Fig. 13). A rough estimate of species abundance revealed that A. bisulcatus has a low population density. This was confirmed by Rogers (1974) who used the Parker "Three Step Method" of inventory:

> 1)Lay out a 100' steel tape (transect line) as the measurement area, 2) Lower a 3/4" diameter, hollow loop into position at or near the ground surface along 1' intervals, and 3) Record vegetative component or soil surface condition within the loop (presence-absence data).

Using this method, no indicators or secondary absorbers had been counted.

It was observed that A. bisulcatus grows exclusively on the Shingle soil series and on sandstone outcrops (Figs. 14a and 14b). This implies that the areas where these indicators are found provide the correct kinds and adequate concentrations of selenium compounds as well as all other necessary growth nutrients.

A field map was prepared using aerial photography (scale: 1:24,000) as a mapping base for locating the toxic plants, Shingle soils, and sandstone outcrops (Fig. 15 and Plate 1).

Soils Sampling Procedures

A. bisulcatus is not present over all the Shingle soils of the control study area. Chemical analyses were conducted to test the relationships between all soils that either lack or support selenium indicators and to isolate selenium in its chemical forms as a controlling factor for the plant species distribution.

Two soil sample sites were chosen on the basis that one site contained A. bisulcatus growing on the Shingle soils (but not on the Samsil soils) and, at the second site, A. bisulcatus was absent on all soils.

Site A, located on an east-facing slope near the AMAX road (Plate 1), has A. bisulcatus present (Figs. 13, 14a, 14b, and 15). Four soils of the Shingle series and three

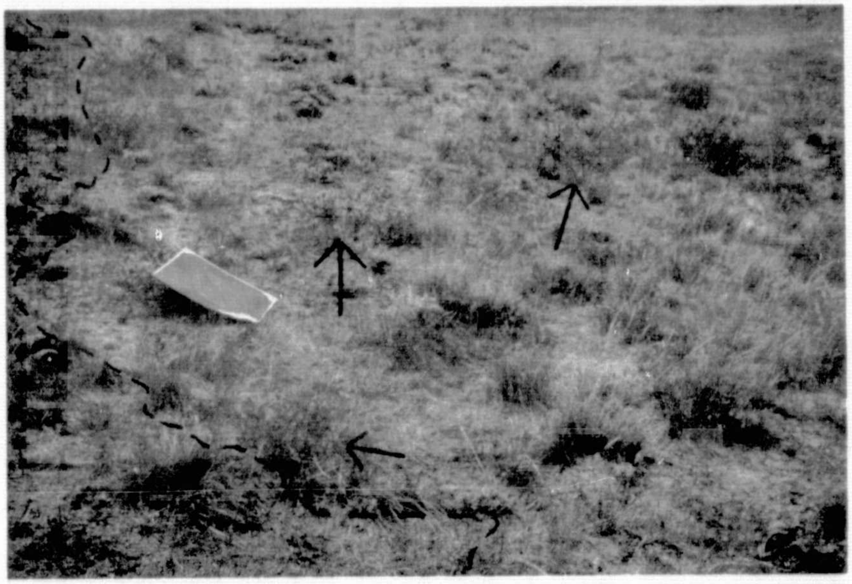


Figure 14a. Astragalus bisulcatus (arrows) growing exclusively on Shingle series soils, T 48 N, R 71 W, Wyoming.

Figure 14b. Astragalus bisulcatus (arrow) growing exclusively on sandstone outcrop, T 48 N, R 71 W, Wyoming.

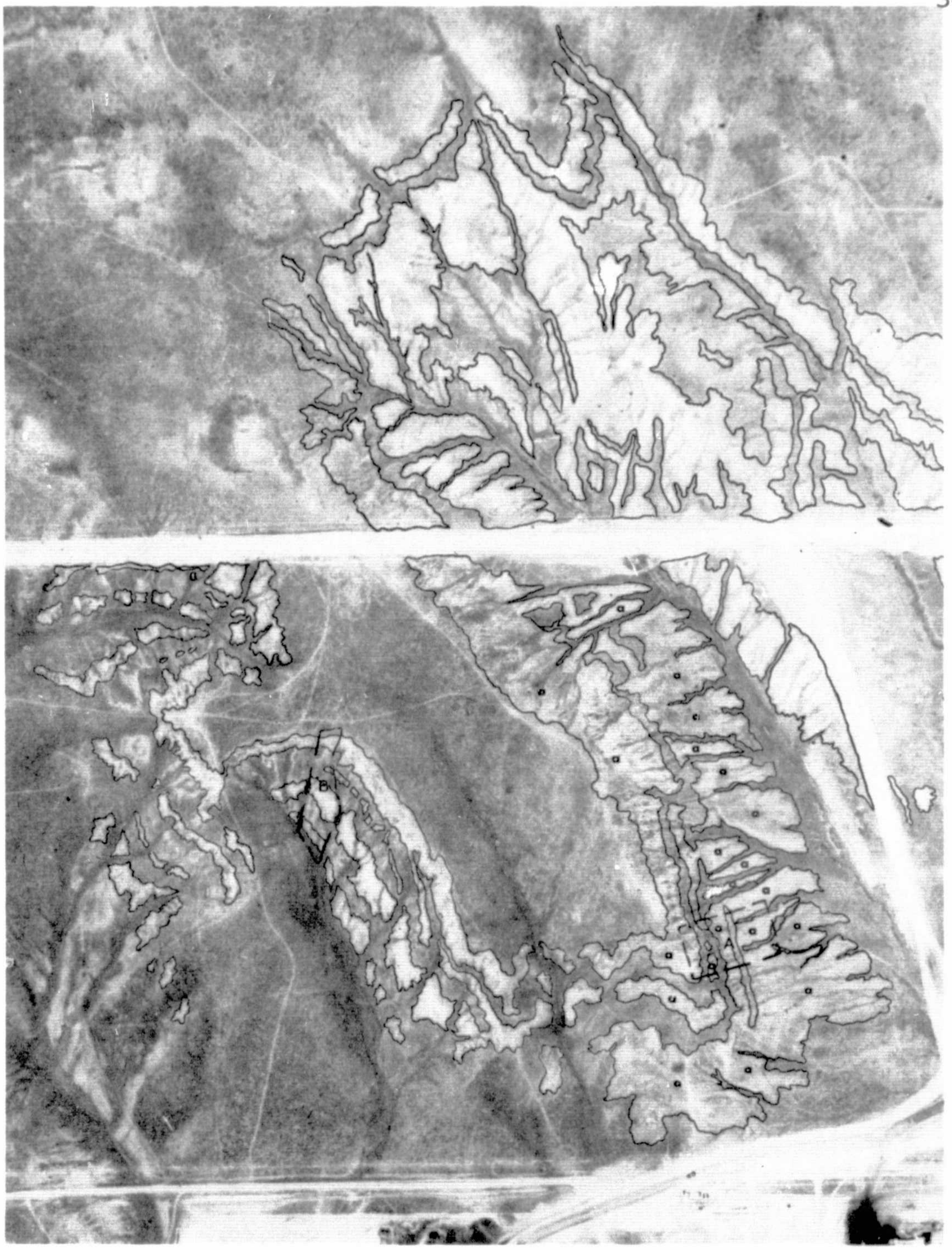


Figure 15. Field map compiled on aerial photography displaying the location of Shingle series soils, sandstone outcrops, and the selenium indicator species <u>Astragalus</u> <u>bisulcatus</u> (a), Section 27, T 48 N, R 71 W, Wyoming (original scale 1: 24,000).

soils of the Samsil series located within the study site were sampled and tested for various forms of selenium. Three replicates for each soil unit were subjectively chosen to cover the population (Fig. 16).

Three soils of the Shingle series and two soils of the Samsil series were sampled and tested for selenium at site B, the area of _A_. _bisulcatus_ absence. Again, three replicates of each soil type were tested (Fig. 17).

Each soil sample was taken at an approximate depth of 6 inches below the surface and represents an area encompassed by a four-inch circle. Analysis of the A horizon was chosen because it is the soil section most likely to be stockpiled and spread for revegetation or reclamation. Also, the influence of _A_. _bisulcatus_ presence is most evident in the A horizon (Olson, O. E., and Moxon, A. L., 1939).

The Shingle and Samsil soils were chosen for comparison due to their geomorphic similarity and primitive stage of development. Results using these poorly developed soil types also provide a clue for the investigator as to the parent material of selenium.

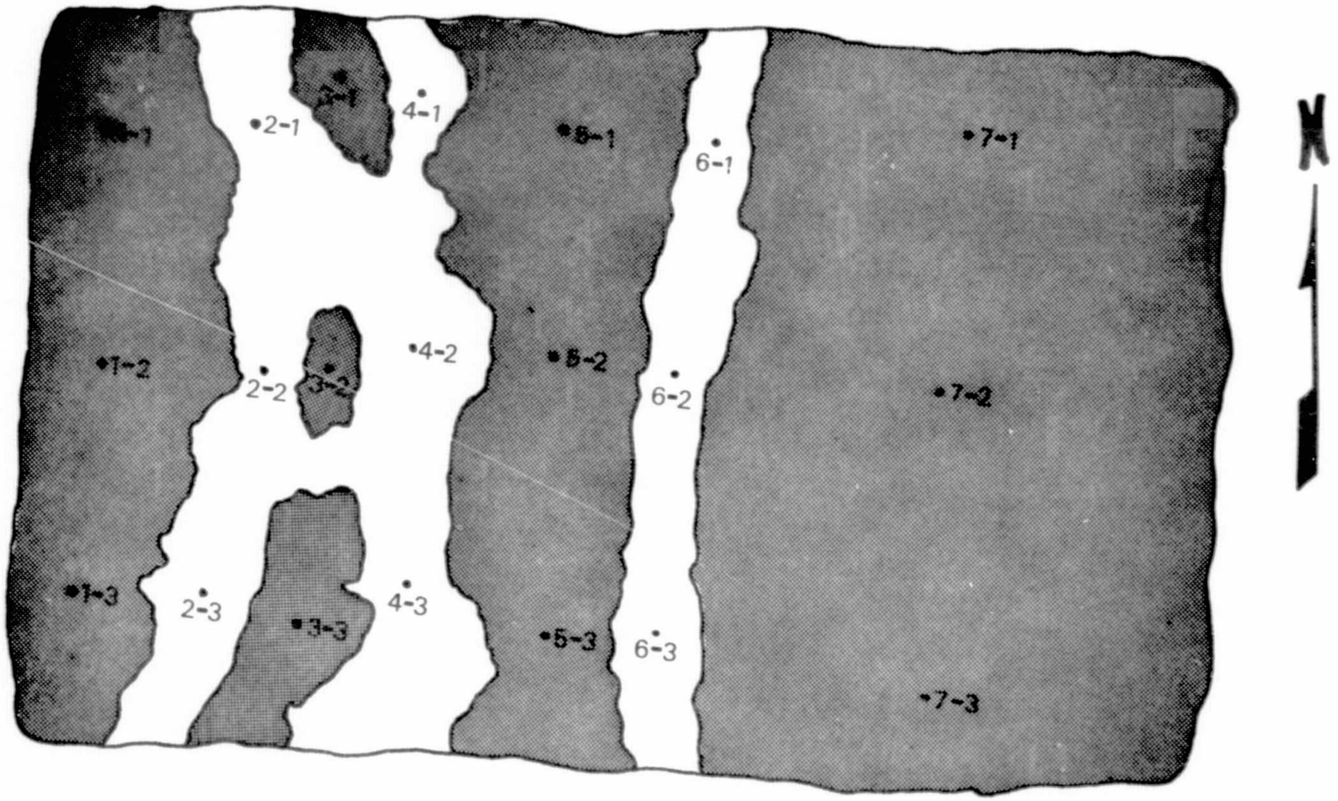


Figure 16. Soil sample map of site A (see Plate 1 for location). Shaded areas are the Shingle series soils. Numbers (unit-replicate) refer to Table 3a.

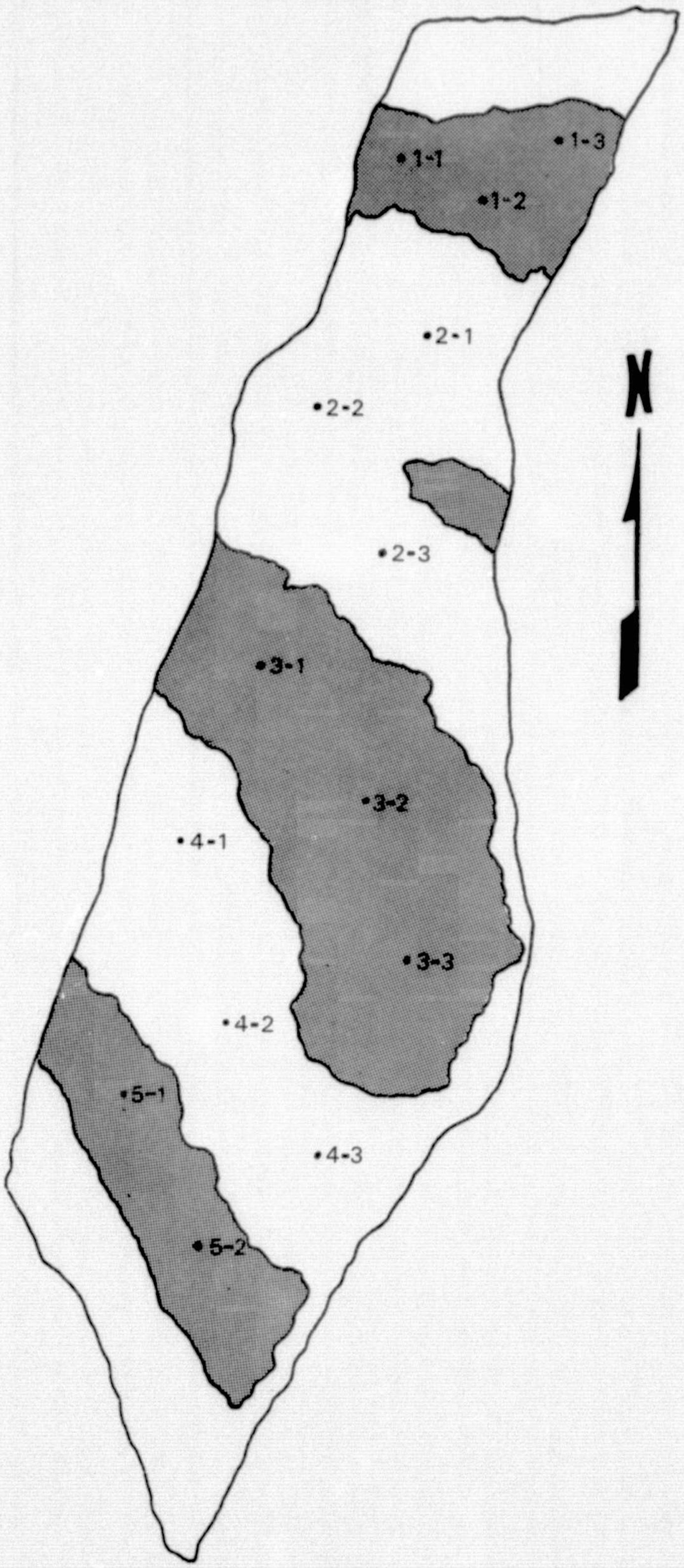


Figure 17. Soil sample map of site B (see Plate 1 for location). Shaded areas are the Shingle series soils. Numbers (unit-replicate) refer to Table 3b.

CHEMICAL ANALYSES OF THE SHINGLE AND SAMSIL SOILS

Analytical Procedures and Results

Three chemical extractions (acid, base, and water) were leached from each soil sample and then tested for concentration of selenium by atomic absorption. The leachate approach was taken for four reasons: 1) to correlate the various extraction results with presence or absence of A. bisulcatus, 2) to determine selenium quantities leached from the soils due to precipitation, 3) to determine the various selenium compounds and concentrations in each soil lens, and then 4) compare all soil lenses with respect to leachate type, soil type, and indicator presence effects.

The water-soluble selenium compounds, including H_2SeO_3, H_2SeO_4, $CaSeO_3$, and $CaSeO_4$ (Trelease, S. F., and Beath, O. A., 1949), are extracted by the addition of 150 mls distilled water to 10 gms of sample previously placed in a Pyrex 125 ml Erlenmeyer flask. This mixture was heated in a steam bath (90°C) for five hours with 5 minutes of shaking- once every hour. Centrifugal separation (2,000 RPM) and filtering (using Whatman 42, ashless, filter paper) of the supernatent liquid using vaccuum methods complete the leach.

The acid extraction, affecting primarily the iron and water-soluble selenium compounds (Trelease, S. F., and

Beath, O. A., 1949), was made by leaching 10 gms of soil (in a plastic 125 ml Erlenmeyer flask) with a series of three 40 ml additions of 1% HCl (volume/volume). Shaking (15 minutes), centrifugal separation (2,000 RPM), and filtering (using Whatman 42, ashless, filter paper) followed each addition. The supernatent liquid was collected after each wash.

The base extraction, using the residue from the acid leach placed in a 300 ml plastic bottle, consisted of one 150 ml addition of 4% NH_4OH, followed by shaking (1 hour), centrifugal separation (2,000 RPM), and filtering (using Whatman 42, ashless, filter paper). The filtrate residue was then washed with 25 mls of 4% NH_4OH. The resultant supernatent liquid contains the leachings of organic compounds left in the soil from dead plants (Trelease, S. F., and Beath, O. A., 1949).

All soil samples used were initially crushed and passed through a size 32 sieve (560 micrometers) to insure a maximum penetration of the leachate. Smaller sizes might bias the results in favor of clay minerals.

The selenium atomic absorption test used in this study is sensitive only to the Se^{+4} oxidation state. Therefore, all the extractions had to be processed as follows:

To 25 mls of sample solution placed in a Pyrex 125 ml Erlenmeyer flask:

1) 1 ml concentrated HCl and 5 mls of 1% $(NH_4)_2S_2O_8$ are added and the mixture is boiled vigorously on a hot plate for fifteen minutes (according to the procedure of Goulden and Brooksbank, 1974). The 1% $(NH_4)_2S_2O_8$ oxidizes organic selenium compounds in the Se(-2) state to the Se (+6) state. HCl is added to acidify the solution so that the 1% ammonium persulfate can effectively oxidize the organics. In the case of base extracts, concentrated HCl is added until pH paper shows acidic response. Another 1 ml of concentrated HCl is then added.
2) 25 mls concentrated HCl is then added and the mixture is gently boiled on a hot plate for 10 minutes (according to the procedure of Lansford, M., and others, 1974). This step reduces Se(+6) to the Se(+4) oxidation state and prepares the solution for atomic absorption testing which requires an acidic medium.
3) The reduced solution is then transfered to a 125-ml Erlenmeyer flask with ground glass neck and attached to the Perkin Elmer, hydride generating apparatus. Reduction to hydrogen selenide is effected by the addition of a sodium borohydride pellet:

a) $NaBH_4 + H^+ + 3H_2O \longrightarrow 4H_2 + Na^+ + H_3BO_3$

b) $3H_2 + H_2SeO_3 \longrightarrow H_2Se + 3H_2O$

The resulting hydride is collected along with hydrogen gas in a balloon attached to the generating apparatus. The solution is magnetically stirred during the generation process. The gases in the balloon are released upon opening of a stopcock and are forced into a tube furnace at 850°C where hydrogen-selenide is decomposed to selenium and the selenium absorption is recorded with a Perkin Elmer 403 Atomic Absorption Spectrophotometer.

The measurement procedure is a modification of the procedure of Goulden and Brooksbank (1974). Details of the procedure are being incorporated in a manuscript in preparation by J. W. Murphy (Unpublished). Ten nanograms of selenium in 25-ml sample are detectable by this procedure.

The atomic absorption test results of the three extractions for each soil lense are summarized in Tables 4a and 4b.

Table 4a. Concentrations of selenium in the acid, base, and water extracts of samples from Site A. Amounts were determined by atomic absorption methods.

Sample # and Description	Leaches (ppb) Acid	Base	Water
Unit 1: Shingle Soil			
1	26	89	21
2	9	43	7
3	12	46	15
Unit 2: Samsil Soil			
1	23	108	7
2	5	22	5
3	9	53	12
Unit 3: Shingle Soil			
1	<1.0	47	25
2	2	62	11
3	8	85	8
Unit 4: Samsil Soil			
1	62	21	21
2	14	34	20
3	6	100	18
Unit 5: Shingle Soil			
1	9	85	24
2	7	70	14
3	26	81	35
Unit 6: Samsil Soil			
1	18	64	14
2	2	15	9
3	31	8	9

Table 4a. Continued.

Unit 7: Shingle Soil			
1	64	227	99
2	115	205	94
3	40	195	59

Table 4b. Concentrations of selenium in the acid, base, and water extracts of Site B. Amounts were determined by atomic absorption methods.

		Leaches (ppb)	
Sample # and Description	Acid	Base	Water
Unit 1: Shingle Soil			
1	18	83	13
2	7	81	2
3	21	78	19
Unit 2: Samsil Soil			
1	20	114	19
2	16	78	9
3	7	126	15
Unit 3: Shingle Soil			
1	22	22	15
2	22	16	1
3	2	10	8
Unit 4: Samsil Soil			
1	39	55	24
2	77	40	49
3	45	43	21
Unit 5: Shingle Soil			
1	7	34	7
2	0	38	<1

Water extractions were tested for pH to determine the cause of apparent disagreement between water and acid leach results. These pH values (Table 5) were then plotted against water/acid ratios (Fig. 18).

The graph documents that Shingle soils, by their capability of increasing the distilled water pH, are alkaline. Water further functions as a mild basic leaching agent for some of the Shingle soils (for example: at site A, unit 5; replicates 1,2, and 3, and site A, unit 3; replicates 1 and 2). When the water acts as a basic leach, values are obtained which are higher than associated acid-leach selenium concentrations (Tables 4a and 4b).

The Samsil soils, ranging from very acidic to very alkaline, generally display "expected" results. Two exceptions (leachate results of site A; unit 6, lens 2, and of site B; unit 2, lens 3) could not be explained by normal experimental error or extreme alkalinity of soil.

Differences in acid- and water-leach procedures was a probable second cause for the "anomalously" high water-soluble selenium quantities. The water-leach method, incorporating heating (increasing reaction rates) over a 5-hour time period (long soil-water contact), may have had a greater effectiveness in selenium extraction than acid-leach methods (no heating, 15 minute contact time between acid and water), especially if acid-leach kinetics are slow. This procedural difference affects all soil sample analyses

Table 5. Water extraction pH measurements.

Site A	pH	Site B	pH
Unit 1		Unit 1	
1	7.6	1	7.1
2	7.6	2	7.1
3	7.8	3	7.3
Unit 2		Unit 2	
1	5.6	1	7.2
2	5.0	2	8.1
3	5.3	3	6.3
Unit 3		Unit 3	
1	7.3	1	7.1
2	7.3	2	7.0
3	7.7	3	7.9
Unit 4		Unit 4	
1	3.9	1	4.3
2	5.5	2	4.5
3	8.0	3	7.3
Unit 5		Unit 5	
1	8.0	1	7.0
2	7.3	2	7.8
3	7.2		
Unit 6			
1	4.4		
2	5.6		
3	4.1		
Unit 7			
1	7.2		
2	7.8		
3	7.1		

Note: Initial distilled water pH is 5.5 .

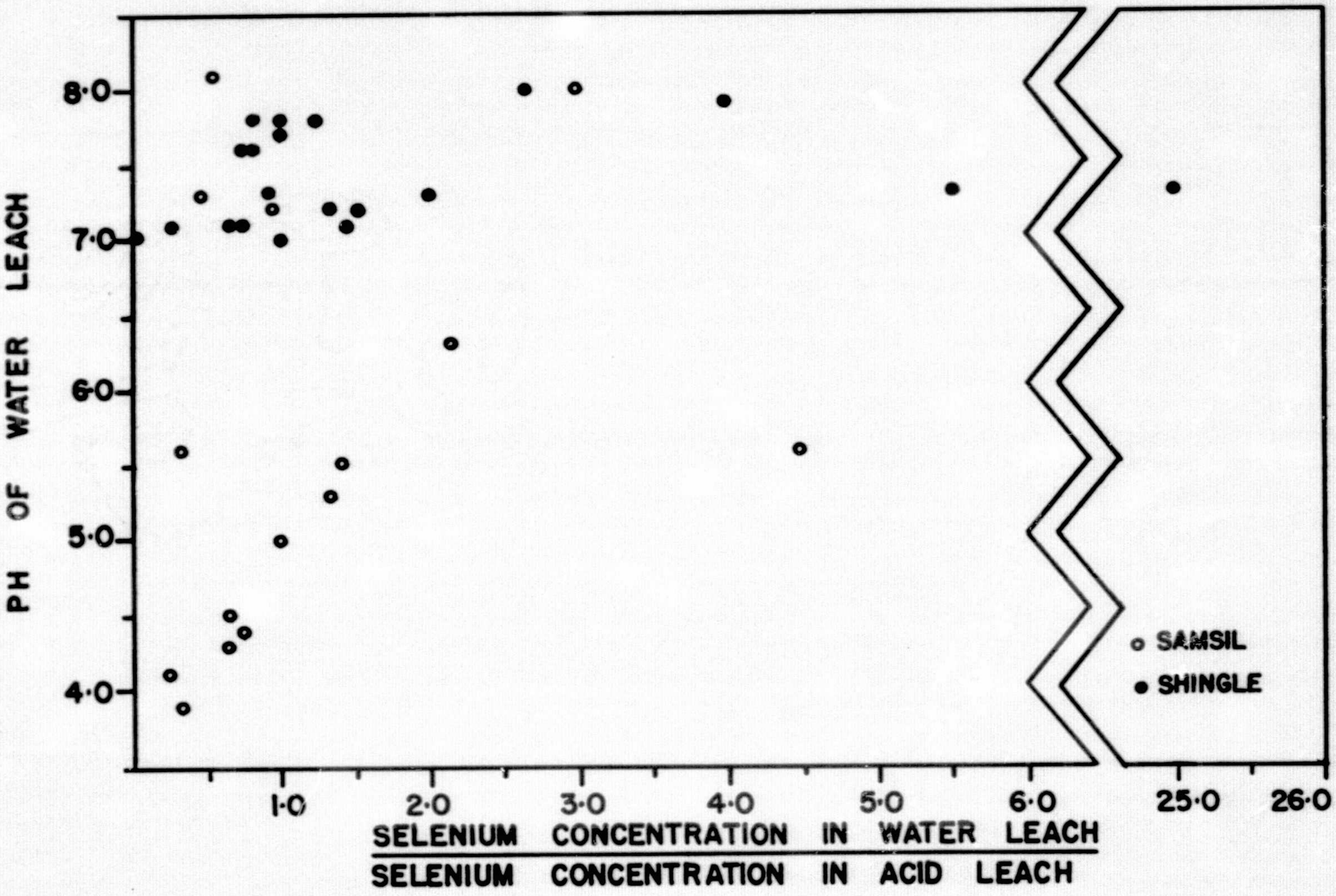


Figure 18. Plot of water leach pH against the ratio of selenium concentration in water leach to selenium concentration in acid leach.

and is used to particularly explain the Samsil soil " exceptions".

Source Determination of Acid-Soluble Selenium Compounds

One Samsil and Shingle soil was chosen from each site on the basis of its having the greatest acid-extracted selenium concentration. These were used for source-determination analyses of acid-soluble compounds. Each of these samples was divided into the three fractions 1) clay (0.2-1.0 micron e.s.d.), 2) silt and sand, and 3) heavy minerals (specific gravity greater than 2.97).

The clay separation techniques used are discussed in detail by Jackson (1956). To separate a 0.2- to 1.0- micron fraction, the sample was dispersed in water and centrifuged at 2,400 RPM for 30 minutes to remove the less than 0.2-micron clay fraction and soluble salts. The resultant supernatent liquid was discarded. The sample was redispersed in water and centrifuged three times at 2,000 RPM for two minutes. The resultant supernatent liquid (containing the 0.2- to 1.0- micron fraction) was saved each time and combined for analysis.

Detailed procedures of heavy mineral separation are described by Carver (1971). The heavy liquid employed was 1,1,2,2, tetrabromethane (specific gravity = 2.97 when pure).

10 gms of each sample were analyzed. The clay fraction

was first isolated and then the residue was analyzed for heavy minerals. The remaining material from both separations was considered the silt and sand fraction (Table 6).

Table 6. Weight of clay, silt and sand, and heavy mineral fractions separated from 10 gms of four selected samples.

Sample	Weight (gms) Clay	Weight (gms) Silt/Sand	Heavy Minerals
Site A; unit 7, replicate 2 (Shingle soil)	0.5	9.3	0.0
Site A; unit 4, replicate 1 (Samsil soil)	1.2	8.5	0.0
Site B; unit 3, replicate 1 (Shingle soil)	0.3	9.4	0.0
Site B; unit 4, replicate 2 (Samsil soil)	1.5	8.3	0.0

Note: Organics and clay fractions less than 0.2 microns account for most of the remaining sample weight.

Preliminary heavy-mineral analyses of two sample sets (one set involving the complete removal of organics using peroxide additions (Jackson, M. L., 1956), the other set remaining untreated) demonstrated the absence of minerals with specific gravities greater than 2.97. It is hypothesized that the A horizons of both soil types are highly oxidized. Therefore, over a long period of time, most heavy minerals have been altered and transported, in solution, to the C horizon.

Each fraction separated (Table 6) was leached with 1%

Table 7. Concentrations of acid-extracted selenium in four fractionated samples. Amounts were determined by atomic absorption methods.

Sample	ppb in fraction	ppb in soil total	% of soil ppb
Clay Fraction			
Site A; unit 7, replicate 2 (Shingle Soil)	425	21	55
Site A; unit 4, replicate 1 (Samsil Soil)	410	50	78
Site B; unit 3, replicate 1 (Shingle Soil)	312	9	60
Site B; unit 4, replicate 2 (Shingle Soil)	184	28	62
Silt/Sand Fraction			
Site A; unit 7, replicate 2 (Shingle Soil)	18	17	45
Site A; unit 4, replicate 1 (Samsil Soil)	16	14	22
Site B; unit 3, replicate 1 (Shingle Soil)	6	6	40
Site B; unit 4, replicate 2 (Samsil Soil)	21	17	38

Note: Total soil ppb are generally lower than earlier leachate results because of water-soluble selenium compound removal occuring with centrifuge techniques.

HCl and tested for selenium by atomic Absorption according to procedures previously described.

Acid-leach results (Table 7) showed that acid-soluble selenium concentrations (55-78%) are associated with clays. Amounts exceeding 0.1 ppm selenium were extracted from clay samples as small as 0.3 gms. It is hypothesized that if particles within both the 1.0- to 2.0- micron and the less than 0.2-micron range had been included in the clay analysis, percentages of total acid-soluble selenium in the clay fractions would increase (with corresponding decreases in silt and sand concentrations). Also, clay weight percentages would be greater and would correspond to weight percentages determined by Rogers (1974).

The Samsil and Shingle clay fractions having the greatest acid-extracted selenium concentrations were separated into three additional fractions based on particle size: 1) less than 0.2 microns, 2) 0.2-1.0 microns, and 3) 1.0-2.0 microns. Each separation was completed using centrifuge techniques described by Jackson (1956).

10 gms of two selected samples being analyzed were fractionated (Table 8). Each clay separation was then leached with 1% HCl and tested for selenium by atomic absorption according to procedures previously described.

Acid-soluble selenium concentrations were observed in all clay groups (Table 9). The highest amounts are in the less than 0.2 micron fraction (especially in the Shingle soil).

X-ray diffractometry was employed to determine clay-fraction compositions in an attempt to discover mineralogic selenium sources in the soils. Clay specimens were pre-

Table 8. Weight of clay fractions separated from 10 gms of two selected samples.

Sample	Micron Fractions (gms) Less Than 0.2	0.2-1.0	1.0-2.0
Site A; unit 7, replicate 2 (Shingle Soil)	1.3	0.9	1.2
Site A; unit 4, replicate 1 (Samsil Soil)	1.9	2.4	1.7

Note: Using this fractionation, the Shingle soil contains 34% clay, and the Samsil soil contains 60% clay.

Table 9. Concentrations of acid-extracted selenium in clay fractions of two selected samples. Amounts were determined by atomic absorption methods.

Sample: Micron Fraction	ppb in fraction	ppb in soil total	% of clay ppb
Less Than 0.2 Fraction			
Site A; unit 7, replicate 2 (Shingle Soil)	81	11	64
Site A; unit 4, replicate 1 (Samsil Soil)	34	7	39
0.2-1.0 Fraction			
Site A; unit 7, replicate 2 (Shingle Soil)	11*	1	9
Site A; unit 4, replicate 1 (Samsil Soil)	29	7	34
1.0-2.0 Fraction			
Site A; unit 7, replicate 2 (Shingle Soil)	33	4	27
Site A; unit 4, replicate 1 (Samsil Soil)	24	4	27

* Result in question.

Table 10. Clay-fraction mineralogic compositions of two selected samples. Percentages are determined by X-ray diffractometry.

Sample: Micron Fraction	Smectite	Illite	Kaolinite
Site A; unit 7, replicate 2 (Shingle soil)			
0.2 fraction	87%	6%	7%
0.2-1.0 fraction	76%	22%	2%
1.0-2.0 fraction	42%	21%	36%
Site A; unit 4, replicate 1 (Samsil soil)			
0.2 fraction	92%	trace	8%
0.2-1.0 fraction	75%	trace	25%
1.0-2.0 fraction	73%	trace	27%

pared for analysis using methods described by Drever (1973). Quantitative estimates of clay mineral percentages were computed using Biscaye's (1965) scheme (Table 10).

Smectite displays a positive correlation with acid-soluble selenium concentrations, whereas kaolinite and illite show the reverse association. Therefore, it is concluded that smectite is the source of acid-soluble selenium in the A horizon soils.

STATISTICAL ANALYSES OF LEACHATE DATA

The analysis of variance statistical test was applied to leachate values (Tables 4a and 4b) to answer the following questions: 1) Are all the soil lenses homogeneous? 2) Are all the soil lenses homogeneous within soil type? 3) Is there a significant difference in sites due to presence or absence of *A. bisulcatus*? 4) Is there a significant difference between soil types? 5) Is there a significant difference between soil types at site A (*A. bisulcatus* present)? 6) Does topographic position determine concentrations of selenium in the soil lens? 7) Are there significant differences in leachate groups? 8) Is there a differential effect of a particular leach with a particular soil or study area? 9) Are variable interactions present between sites, leach type, and soil type which are significant in explaining the leachate results? In order for this test to be valid, it must be assumed that 1) an adequate population sample was tested, 2) the samples and replicates tested were chosen without bias, 3) each parent population (soil lens) was normally distributed, and 4) all error variances were equal.

Three model equations were constructed to answer the nine questions stated above. For each model, degrees-of-freedom, sums-of-squares, estimated mean squares, and the

F-statistics were computed (see appendix A). The F-statistic is evaluated for a gamma = 0.05 significance level.

The first model equation is designed to analyze the variances involving soil type (i), lens number (j), sample site (k), and leachate type (l). Sums-of squares (SS), mean squares (MS), degrees-of-freedom (df), and F-statistic (F) results are listed in Table 11.

Table 11. Analysis of variance table for the following model equation:

$$y_{ijklm} = u + \alpha_i^S + \alpha_k^R + a_{ijk}^G + \alpha_l^L + \alpha_{ik}^{SR} + \alpha_{il}^{SL} + \alpha_{kl}^{RL} + a_{ijkl}^{GL} + \alpha_{ikl}^{SRL} + e_{ijklm} .$$

Source	df	SS	MS	F	Gamma = 0.05
S	1	41.78	41.78	0.29	4.75
R	1	9.38	9.38	0.07	4.75
G*	12	1709.84	142.49	3.63	1.75
L*	2	627.38	313.69	6.36	3.40
SR	1	32.28	32.28	0.23	4.75
SL	2	4.21	2.10	0.04	3.40
RL	2	4.59	2.29	0.05	3.40
GL	24	1183.76	49.32	1.26	1.52
SRL	2	10.68	5.34	0.11	3.40
error	3408	133839.42	39.27		
total	3455	137463.30	39.79		

* Null hypothesis rejected.

Significant F-test values for sources G and L support the hypotheses that 1) there are significant differences in leachate groups (question 7) and 2) all soil lenses are not homogeneous due to some variable effect related to both soil type and site location (question 1). Lack of significant

F-test values for sources S, R, SR, SL, RL, GL, and SRL support the null hypothesis for questions 3, 4, 8, and 9 (Table 16).

The null hypothesis rejection of leachate differences can be explained in terms of solvent strength, soil chemistry, and leachable quantities present. For the acid and base leaches, the concentration and type of acid and base solvents used would determine the effectiveness of the leach. In water leaches, the soil pH affects the quantity and type of material leached. This is illustrated in previous results with the alkaline Shingle soils, for which water leaches (distilled water pH= 5.5) include both water-soluble and base-soluble selenium compounds.

Ignoring solvent strength and soil chemistry, the individual samples can be varied in leachable amounts present. This was observed by Olson and Moxon (1939) and by Beath (1937) in similar research.

Variance ratios of soil types within leachate groups (site differences ignored) and of site areas within leachate groups (soil type ignored) are computed to determine the source of soil lens inhomogeneity (Tables 12 and 13).

The inhomogeneity of soil lenses is apparent in the results of the base and water extracts (Tables 12 and 13). It is hypothesized that because A. bisulcatus creates areas of high organic selenium within the Shingle

Table 12. Variance ratios of soil types within leachate groups. Variances are computed in Appendix B.

	Acid		Base		Water	
	Samsil	Shingle	Samsil	Shingle	Samsil	Shingle
s^2 =	113.70	113.25	484.04	1722.26	50.27	356.45
F =	1.00		3.56*		7.09*	

At gamma = 0.05, degrees-of-freedom = 11, 11: 2.88 is significant*.

Table 13. Variance ratios of site areas within leachate groups. Variances are computed in Appendix B.

	Acid		Base		Water	
Sites:	A	B	A	B	A	B
s^2 =	1050.06	768.60	5326.94	2893.70	1155.54	159.80
F =	1.37		1.84		7.23*	

At gamma = 0.05, degrees-of-freedom = 23, 23: 2.01 is significant*.

soils, and because the distilled water (in the case of the water leach) leaches some basic selenium compounds, Shingle soils of sites A (indicator presence) and B (indicator absence) combined will show a high variance of values in both the water and base extractions (Table 12). Another parameter for site A may be sample closeness to the convertor plants.

A similar situation is noted for the high variability of site A results (Table 13) for both the water and base leaches. This, again, implies the creation of a wide selenium distribution pattern based on presence/absence of plants and soils sampling location with reference to plant location.

High variability in the site A and B acid groups (Table 12) implies 1) an inhomogeneous selenium source in bedrock, 2) inhomogeneous weathering of the source material (perhaps due to differences in soil pH), or 3) both 1 and 2. Analyses of samples taken at depth (in soils and bedrock) would provide necessary information to substantiate this hypothesis.

A final source of variability can be attributed to randomness. This is hypothesized to be present in all samples, especially in the site B, base grouping (Table 13), and the Samsil soils, base grouping (Table 12).

It is curious that Shingle soils display the highest variances for all site A leaches, whereas Samsil soils have the highest variances for site B leaches. The exact cause for this pattern is not yet known. A combination of factors, including bedrock variations, weathering variations, convertor plant and soil fungi influences, soil pH, soil permeability, physical factors (wind, etc.), and random effects, is suggested to explain this phenomena.

The second model equation is designed to analyze variances involving soil type (i), lens number (j), and leachate type (l) at site A (convertor presence). Sums-of-squares (SS), mean squares (MS), degrees-of-freedom (df),

Table 14. Analysis of variance table for the following model equation:

$$Y_{ijlm} = u + \alpha_i^{S} + a_{ij}^{G} + \alpha_l^{L} + \alpha_{il}^{SL} + a_{ijl}^{GL} + e_{ijlm}.$$

Source	df	SS	MS	F	Gamma = 0.05
S	1	38.52	38.52	0.09	4.96
G*	10	4138.72	413.87	3.50	1.83
L*	2	1785.12	892.56	8.05	3.49
SL	2	148.58	74.29	0.67	3.49
GL	20	2217.56	110.88	0.94	1.57
error	612	72407.78	118.31		
total	647	80736.28	124.59		

* Null hypothesis rejected.

and F-statistic (F) results are listed in Table 14.

Significant F-test values for sources G and L directly support the hypotheses that 1) both soil types at site A are not homogeneous within themselves (question 2), and 2) there are significant differences in amounts leached by the various solvents at site A. Lack of significant F-test values for sources S, SL, and GL supports the null hypothesis for questions 5 and 8 (Table 16).

The null hypothesis rejection of soil type homogeneity again suggests that 1) A. bisulcatus presence can create local areas of high selenium concentrations within soil lenses, or 2) content differences in selenium source rock occur, or 3) inhomogeneous weathering occurs, or 4) any combination of these factors exists, or finally 5) random variation between soil lenses exists. Again, bedrock analyses and multilayered soil analyses are needed to support or reject these hypotheses.

The third and final model equation is designed to analize the variances involving only the lens number (j) and the leachate type (l) of site A, Shingle soils. Sums-of-squares (SS), mean squares (MS), degrees-of-freedom (df), and F-statistic (F) results are listed in Table 15).

Table 15. Analysis of variance table for the following model equation:

$$Y_{jlm} = u + \propto_j^E + \propto_l^L + \propto_{jl}^{EL} + e_{jlm}.$$

Source	df	SS	MS	F	Gamma = 0.05
E*	3	13787.25	4595.75	3.61	2.60
L*	2	10590.51	5295.26	4.16	3.00
EL	6	2349.04	391.51	0.31	2.10
error	132	168197.83	1274.23		
total	143	194924.64	1363.11		

* Null hypothesis rejected.

Significant F-test values for sources L and E support the hypotheses that 1) there are differences in leaches within the Shingle soils at site A (question 7), and 2) there is a significant difference in lens position (question 6) of site A, Shingle soils. Again, there is no evidence of differential leach effects with a particular soil lens.

Lens elevation is plotted against the ratio of sample leach (ppb selenium) to average sample leach (ppb selenium) to determine possible causes for soil position importance (Fig. 19). Given both a constant elevation gradient and

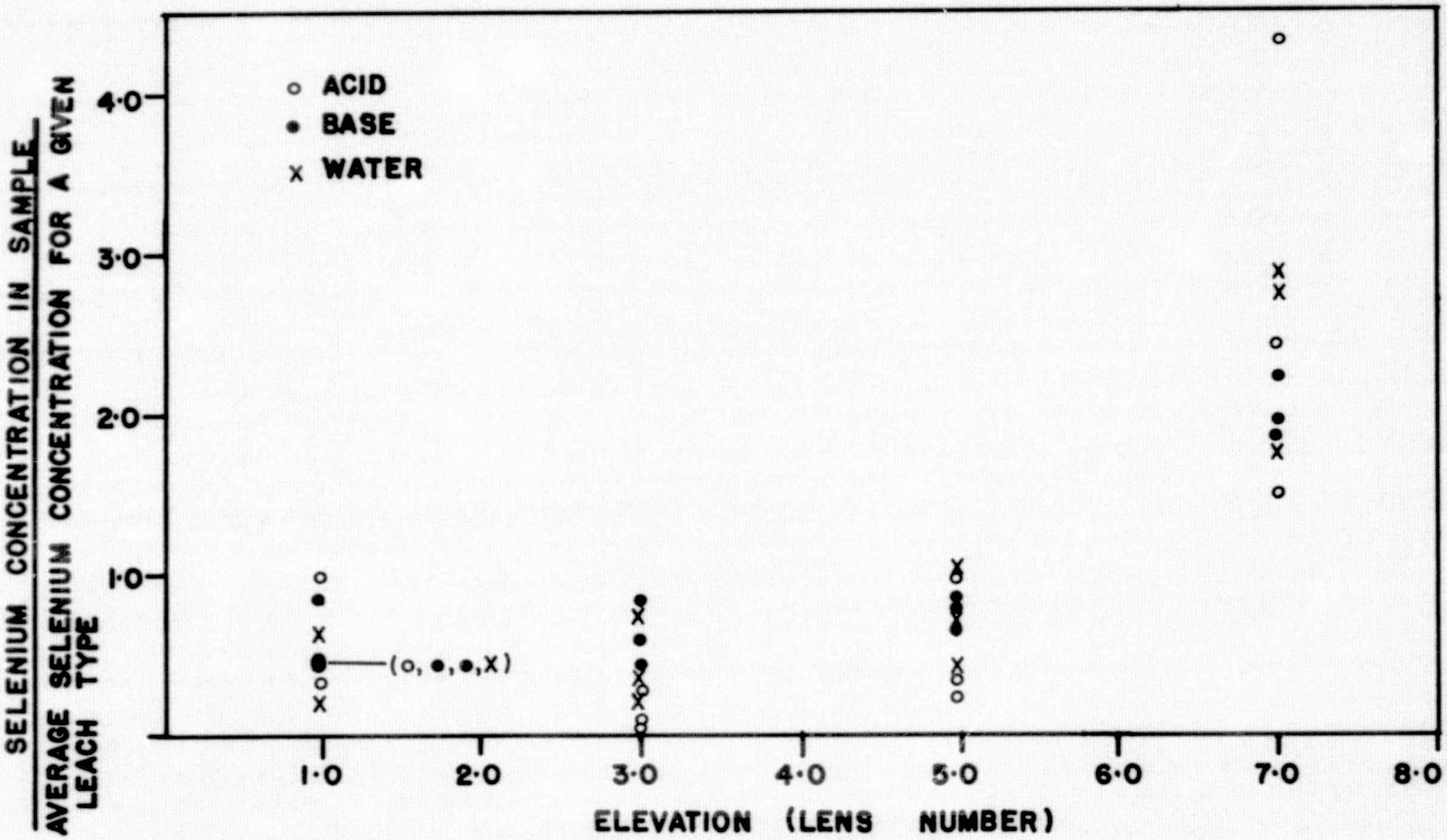


Figure 19. Plot of Site A, Shingle soil lens elevation (lens number 1.0 is topographically the highest area) against the ratio of selenium concentration in sample to average selenium concentration for a given leach type. Note that no smooth regression is present to imply gradual downslope accumulation of selenium.

Table 16. Analysis of variance summary.

Question	Answer
1) Are all the soil lenses homogeneous?	NO
2) Are all the soil lenses homogeneous within soil type?	NO
3) Is there a significant difference in sites?	NO
4) Is there a significant difference between soil types?	NO
5) Is there a significant difference between soil types at site A?	NO
6) Does topographic position determine concentrations in soil lenses?	YES
7) Are there significant differences in leachate groups?	YES
8) Is there a differential effect of a particular leach with a particular soil type or study area?	NO
9) Are variable interactions present between sites, leach type, and soil type which are significant in explaining the leachate results?	NO

<u>Note</u>: Significant difference refers to selenium concentration comparisons between statistical groupings.

convertor population density, it is concluded that lens 7, site A is not accumulating amounts of selenium from the upper lenses (no smooth regression present to imply gradual accumulation). The high concentrations of selenium found in lens 7 appear to have originated from the bedrock. To further support this hypothesis, bedrock cores and downslope soil samples (as opposed to random soil collection) should be analyzed.

ENVIRONMENTAL HAZARDS

Range and Soil Deterioration

The presence of selenium convertor plants is known to cause range and soil quality reduction (Trelease, S. F., and Beath, O. A., 1949). The deterioration process discussed in detail by Trelease and Beath (1949) can be summarized as follows: (1) selenium convertor plants invade a soil with favorable growing conditions (including selenium presence). (2) These plants accumulate inorganic selenium from virgin soils and convert it into water-soluble organic compounds. (3) Upon death and decay of these convertors, the organic compounds are returned to the soil and are readily available for absorption by all plant types. (4) The following year, a larger group of convertors germinate and repeat the same process.

Over a period of time, upper soil enrichment occurs due to many cycles of convertor plant growth and decay (Beath, O. A., et. al., 1934). This increase in soil selenium concentration results in higher amounts absorbed by all vegetation present. For example, it was demonstrated that a soil can be rendered capable of producing toxic wheat by growing seleniferous convertors in it for a period of three years (Beath, O. A., 1937). Furthermore, if irrigation and plowing (selenium convertors turned under) are employed to encourage crop growth in indicator plant-bearing lands previously untilled, the sowed plants will be highly toxic (Beath, O. A., 1937).

Most plants that absorb selenium accumulate quantities which far exceed those found in the supportive soils (Byers, H. G., 1935). Byers (1935) found that wheat growing on soils containing 2.5 ppm of selenium accumulated 45 ppm, and western wheat grass, a native species found in the Powder River Basin, accumulated 60 ppm from a soil containing 6 ppm. A. bisulcatus, one of the most toxic selenium convertors, accumulates as much as 4,000 ppm selenium from soils containing only 1.1 ppm (Beath, O. A., 1937). These values are especially significant because grasses and cereal grains containing 10-30 ppm selenium are documented as producing alkali disease in swine, cattle, and horses. This disease eventually results in death (Trelease, S. F., and Beath, O. A., 1949).

As previously mentioned, A. bisulcatus is growing exclusively on some (but not all) Shingle soils and sandstone outcrops (Figs. 14a and 14b) in the study area. Statistically, there are no selenium concentration differences between soil types, or between Shingle soils which do or do not support A. bisulcatus growth. This implies that some other geobotanical factor (s) besides "available" selenium concentration (water-soluble organic compounds) of these particular soils determines the presence or absence of A. bisulcatus. These factors might include soil moisture (Shingle soils are more moist), seed dispersal, nutrient presence and availability, and plant competition (grazing pressure, etc.) (Daubenmire, R., 1968).

A second implication is that A. bisulcatus has no influence on the tested soils regarding organic selenium accumulation. However, site A soils are found to be inhomogeneous within themselves, implying a small variace effect due to convertor presence. One explanation for this effect might be the accumulation of some organic selenium by root death and decay. Studies encompassing the top one or two inches of soil should be conducted to verify if more extensive accumulation of organic selenium compounds by A. bisulcatus occurs surficially (due to leaves, stems, and flowers).

It is significant that A. bisulcatus germinates and grows on soils containing 0.2 ppm leachable selenium and less. This implies that leachable selenium will not be a limiting factor for the germination and growth of convertor plants at the AMAX site. Additional selenium analyses of all study area plants (including A. bisulcatus) would provide valuable information determining 1) the toxicity of of the range vegetation (ie., how effective is each individual species in body tissue accumulation of selenium, and 2) the relationships of water-soluble selenium concentrations between soil lens availability and plant uptake. This information is essential for complete environmental assessment.

In conclusion, a potential environmental hazard exists if the disturbance of this area is uncontrolled. Therefore, the following mitigating procedures are recommended: 1) before the soils are stockpiled, all selenium convertors (ie., A. bisulcatus) should be removed, and 2) any lenses which contain abnormally high selenium concentrations (Shingle soil unit 7 or Samsil soil unit 2, for example) should be buried (not stockpiled). Convertor plant removal and high selenium lens burial eliminates a major invasion mechanism (seeds) and reduces the potential addition (by plants) and exposure (soil disturbance) of high concentrations of selenium. This will lower the toxicity of revegetative species (potential absorbers).

Furthermore, it is strongly recommended that neither the Samsil nor Shingle soils should be stockpiled due to their significant concentrations of selenium. Other soils, such as the Ulm series soils (Roger, J. R., 1974), should be used for topsoil wherever possible.

Once reclamation procedures are completed, the land should be carefully monitored for convertor plant invasion. Due to the selenium presence in most soils, the revegetated area may provide a favorable climate for convertor germination and growth. More research is necessary to determine if breaking up, mixing, and respreading of the study-site soils creates such an environment. If such species are discovered, their eradication is imperative in maintaining cropland, range, and soil quality.

Surface and Groundwater Deterioration

Beath, O. A., and others (1935) extensively tested small lakes, undrained basins, and springs in Wyoming which were believed to contain high concentrations of selenium. They found that concentrations rarely exceeded 0.1 ppm, even when located in areas surrounded by slopes bearing seleniferous plants of high population density.

Tests conducted throughout Wyoming revealed a wide range of selenium concentrations to exist in well water. A maximum concentration of 9.5 ppm was found in drinking water near Casper (Beath, O. A., 1943). However, there have not yet been any reports of poisoning from well water, nor alkali disease or blind staggers occurence in livestock due to surface water (Trelease, S. F., and Beath, O. A., 1949). Studies determining the long term accumulation effects of sublethal selenium dosages is necessary to thoroughly evaluate potability of water (and foodstuff consumption for humans, also).

It was concluded that selenium compounds are not being transported downslope by surface runoff. Therefore, there is little surface water deterioration danger. However, more studies are necessary to determine if significant selenium concentrations are being leached to the water table. This information is essential in determining whether or not groundwater contamination occurs.

REGIONAL DISTRIBUTION OF SELENIUM SOILS

Discussion of Mapping Methods

It was determined that both Shingle and Samsil soils contain selenium in acid-, base-, and water-soluble forms. For reasons which have yet to be determined, the plant indicator species A. bisulcatus favors germination in the Shingle soils only. Once established, A. bisulcatus progressively reduces the quality of soils and associated range vegetation (Trelease, S. F., and Beath, O. A., 1949). Therefore, a practical application of the knowledge gained through this study is the mapping of potential environmental problem areas by identification of the Shingle series soils which can support A. bisulcatus.

It was initially hypothesized that a regional map locating selenium indicator plants would best illustrate the distribution of soils with favorable growth conditions. However, a field mapping project of this magnitude would require much time and would, therefore, be impractical.

An alternative proposal was to derive a method for mapping these indicator species by interpretation of photography and field checks. This alternative was not feasible for three reasons: 1) the individual indicator plants are not resolvable at scales greater than 1:1,000,

2) the indicator species interspersed with other non-indicator populations renders the low density toxic populations non-resolvable as a contributer to the overall spectral signature, and 3) the reflectances of the continuous grassland and sagebrush communities mask any tonal effect caused by the indicator species (Fig. 20).

A third possibility exists in regional mapping of Shingle soils based on the understanding that these areas are only potential problem areas. For each local site, a plant indicator map might then be prepared to specifically locate the high-selenium lenses within the Shingle soils.

Shingle soils and sandstone outcrops (which support A. bisulcatus) have higher reflectances (in the 300-1,000 nm region) than most other soils and outcrops in the control area. Relative reflectance measurements of Shingle and Samsil soils taken at site B (Fig. 21 and Table 7) confirm this observation. These results indicate that Shingle soils and sandstone outcrops are fairly distinct, mappable units. A reference map of the Shingle units was prepared from aerial photography (Plate 1).

Skylab Photography: A Regional Tool

Upon completion of the local soils map from interpretations of aerial photography, a series of techniques

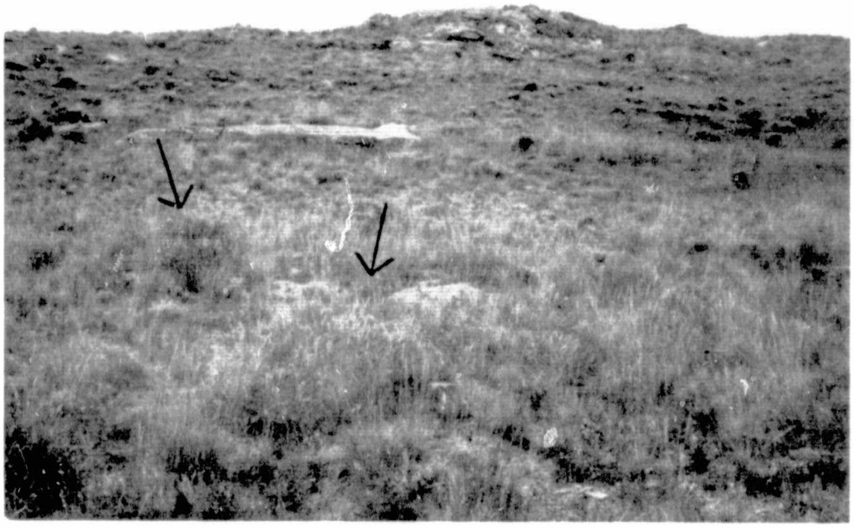


Figure 20. Astragalus bisulcatus (arrows) is shown growing intermingled with two major vegetation communities; grassland and sagebrush. Note the difficulty in separating tonal differences between all members of both communities and Astragalus bisulcatus.

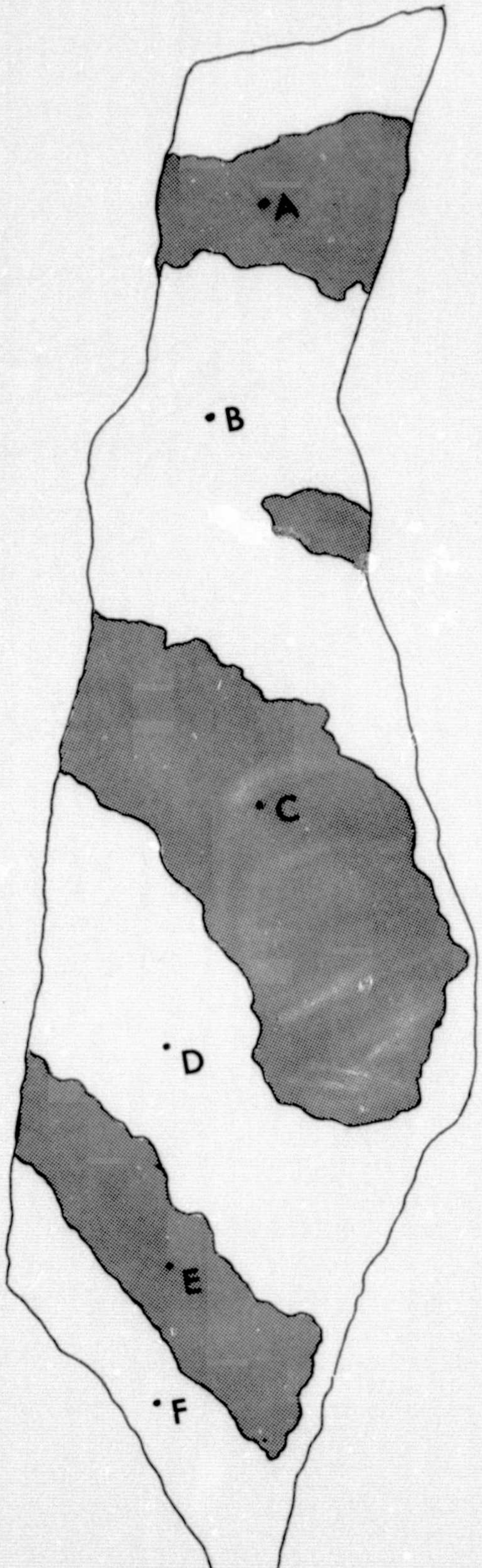


Figure 21. Map displaying the location of photometer readings taken at site B (see Plate 1 for location). Shaded areas are the Shingle series soils. Letters refer to Table 6.

Table 17. Spectral photometer data taken at site B using Science and Mechanics, A-3, photometer filtered with 47B, 57+3961, 22+3966, 25+3961, 30+3961, and 89B Wratten filters.

Sample Description / Filter(s)	47B (390-470)	57+3961 (480-590)	3966+25 (560-1000)	25+3961 (590-660)	3961+30 (570-660)	89B (700-1100)
A) Shingle soil lens	9.5	7.0	9.5	7.2	15.0	10.0
A) Shingle soil lens	12.2	8.8	12.0	8.5	18.0	12.0
B) Samsil soil lens	5.5	3.2	6.0	4.0	8.2	6.8
B) Samsil soil lens	5.0	3.5	5.2	3.8	8.0	6.2
C) Shingle soil lens	7.2	5.0	7.0	5.2	10.8	7.5
C) Shingle soil lens	6.0	4.2	6.0	4.5	10.5	7.2
D) Samsil soil lens	5.0	3.5	5.5	3.7	7.0	5.5
D) Samsil soil lens	5.0	3.5	5.2	3.7	7.8	5.5
E) Shingle soil lens	6.5	5.0	8.5	5.5	11.0	8.5
E) Shingle soil lens	7.5	5.5	7.8	5.0	10.8	7.5
F) Samsil soil lens	5.5	3.0	6.5	4.0	7.2	7.2
F) Samsil soil lens	6.2	3.8	6.2	4.5	9.5	8.2
Reference Gray Card	6.8	4.2	6.0	4.3	9.0	6.5

Time: 10:00 - 12:00 a.m.; Day: June 6, 1974; Sun: bright; Sky: cloudless; Temperature: 74.5°F.; Relative Humidity: 20%; Field of View: 110°; photometer was held two feet above the target.

were employed exploring the potential of Skylab data in regional mapping of the Shingle soils. Skylab, S 190-B, color, positive transparencies (Track 59, Pass 28, September 13, 1973, scale: 1:936,000) were used because of their superior resolution (10-20 m) relative to that of Skylab, S 190-A photography (30-100 m).

Photographic enlargements (10 X) of the S 190-B color positive transparencies provided a base for direct photo-interpretation (Fig. 22). The Shingle lenses and sandstone outcrops are resolved on the enlargements, but, photo-to-map, transfer techniques fail to preserve this detail. Therefore, the soils and outcrop map compiled using the direct transfer technique does not contain nearly all the information that can be derived from the S 190-B photograph (Fig. 2).

Density contouring was used to objectively define gradational boundaries between the Samsil and Shingle series soils. Because the reflectance values of the Shingle soils and sandstone outcrops are greater than those of most other features present, this technique proved useful in defining the general area where indicator species could be present (Figs. 23 and 24).

Image combination by color-addition and/or color-subtraction of S 190-A black-and-white multiband photographs has thus far been unsuccessful because the limited resolution of this photography does not resolve the small soil lenses being studied. If the four multispectral bands of S 190-A photography had resolution equivalent to that of the S 190-B photography, it might have proven useful to enlarge all four transparencies (10 X) and then

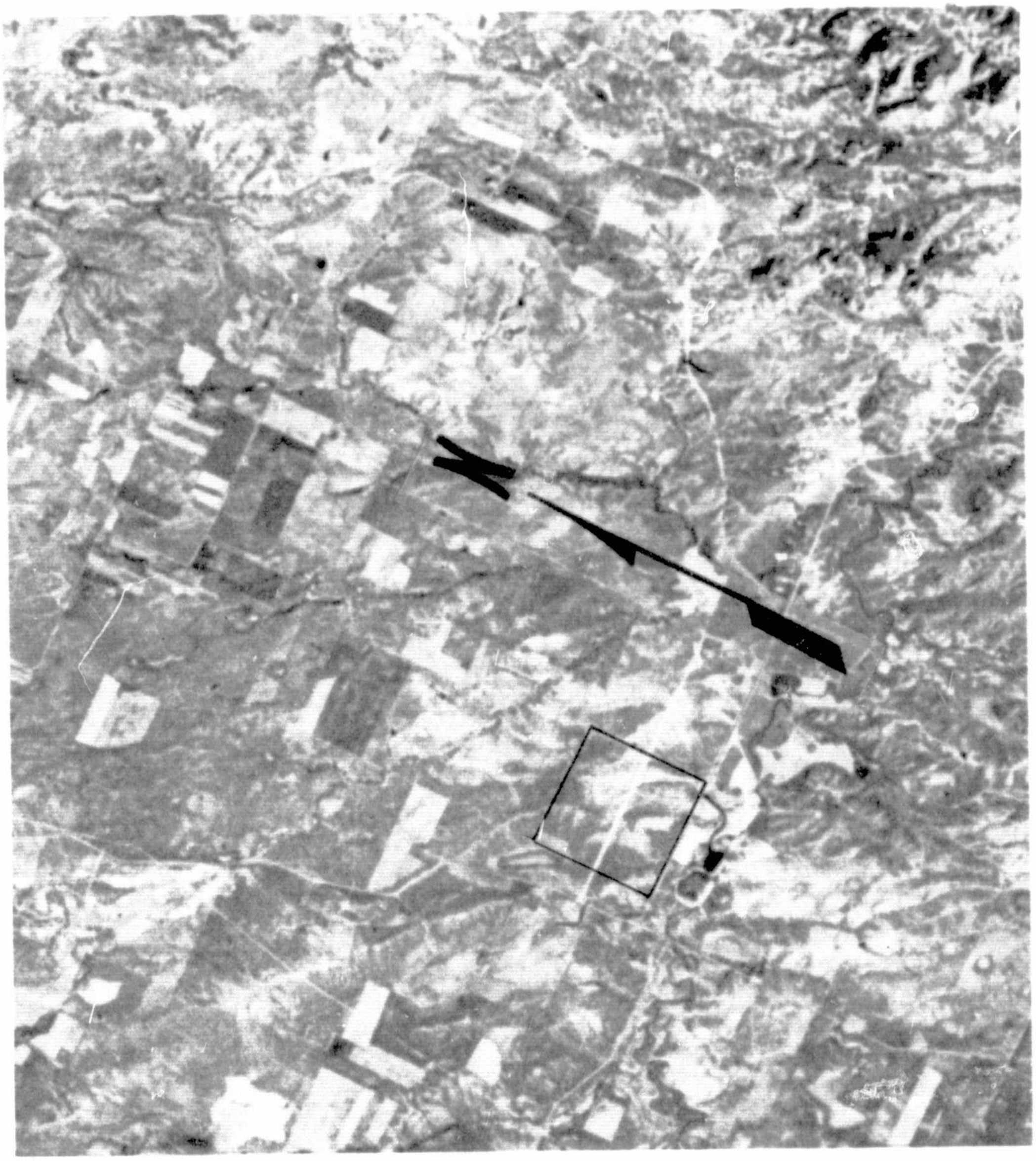


Figure 22. Enlarged S190B photograph used for direct photointerpretation. The control area lies within the square.

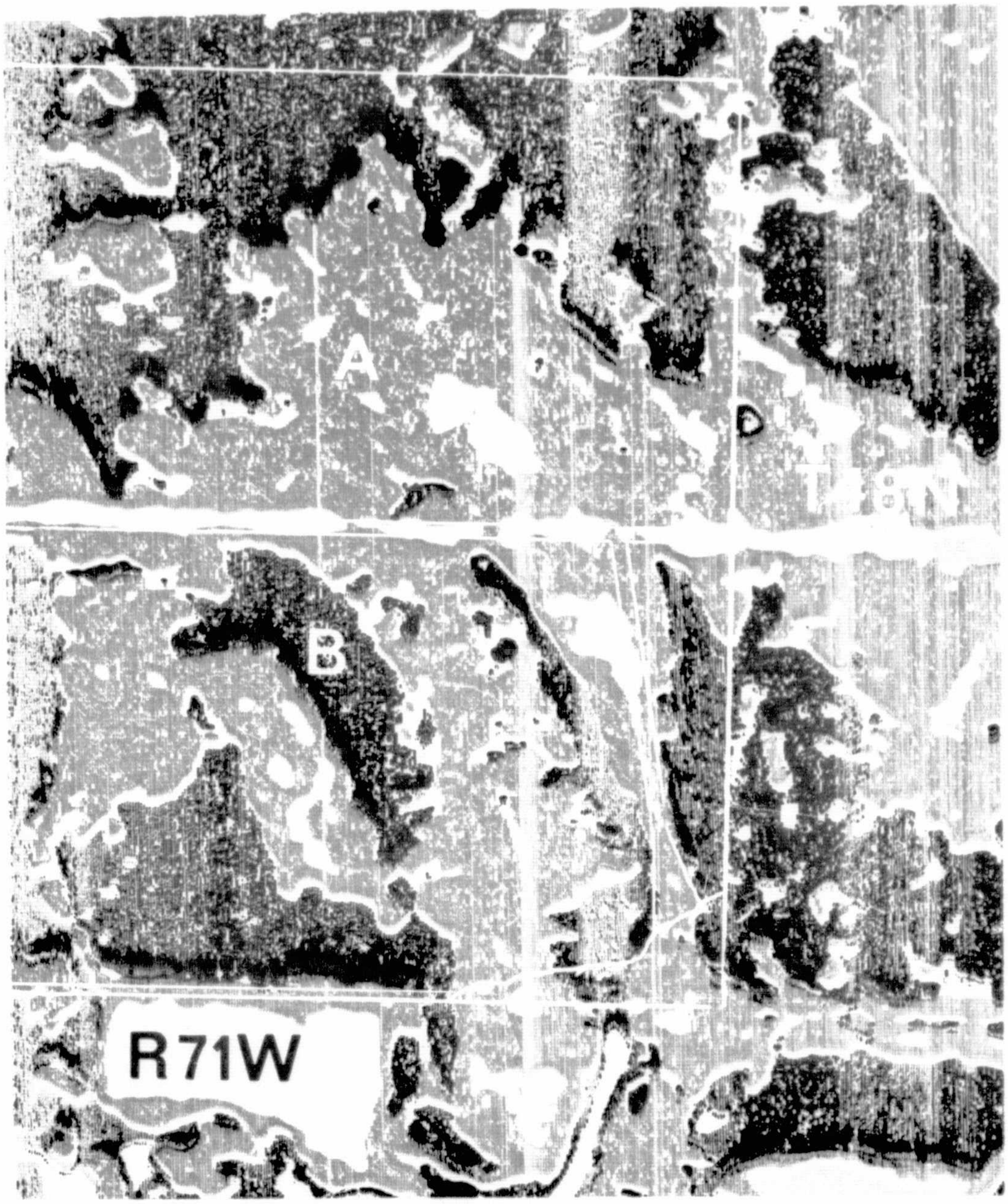


Figure 23. General area of Shingle series soils and sandstone outcrops (A) location in Section 27, T 48 N, R 71 W, Wyoming defined by density contouring from S190B photography. Ulm series soils are also identified (B).

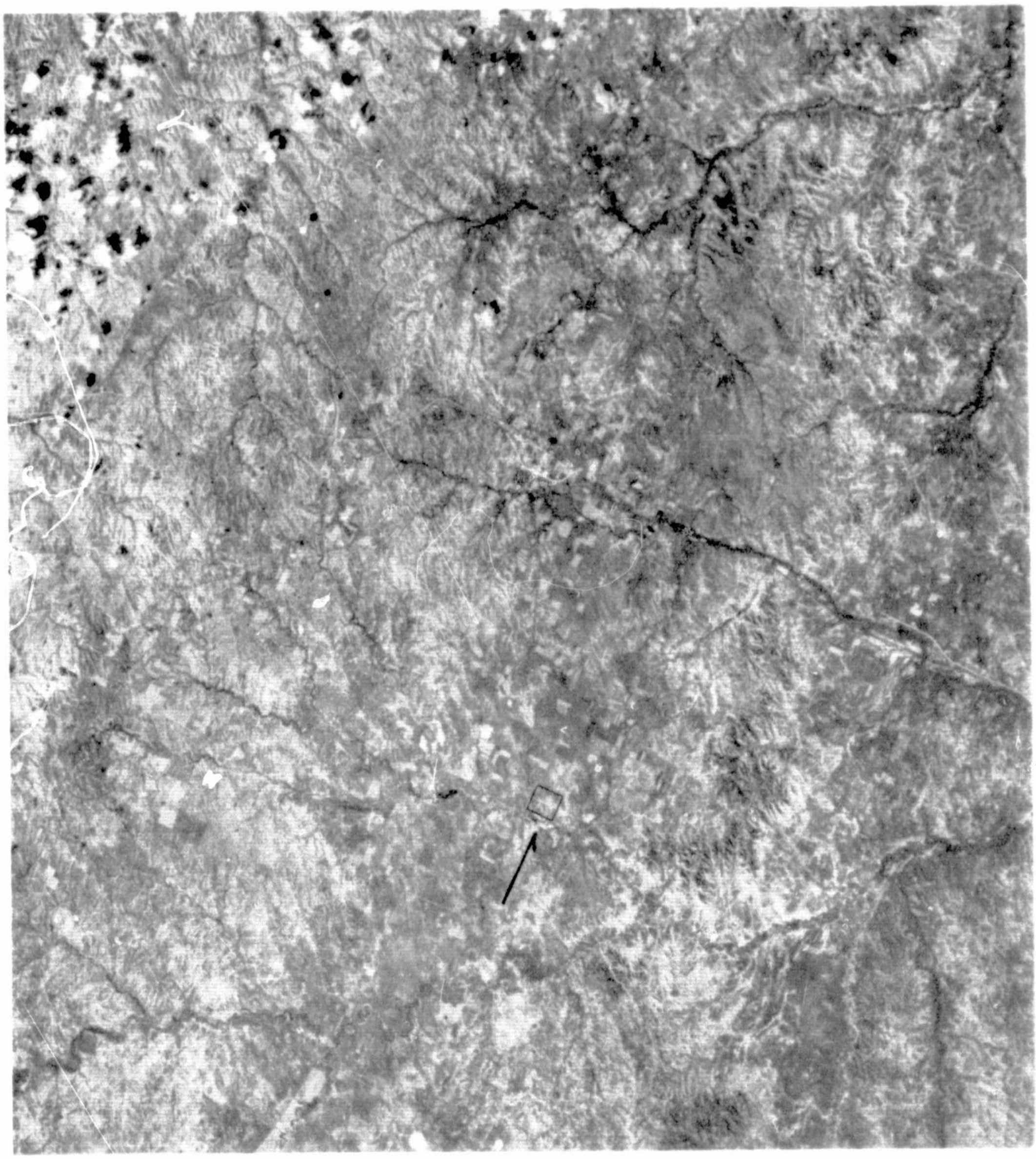


Figure 24. SE ¼ of S190B photograph from which the density contour map was made. Reference area is outlined.

1) combine them together for color-additive or color-subtractive enhancement, or use direct photointerpretation of the red band (where the greatest reflectance differences between Shingle soils and all other features occurs; Table 17).

Edge enhancement techniques were unsuccessful because most of the significant features enhibit little or no relief, low contrast, gradational contacts, and no linearity.

Digital ratioing was not used because the Skylab data were not available in digital form.

The photo-to-map transfer technique from enlarged S 190-B photographs proved most successful in mapping the Shingle soils and sandstone outcrops at the study site. Because of these results, this method was used to prepare a regional map of these soil and rock units for Campbell County (Plate 2). This production of a regional over-view from S 190-B photographs illustrates one of Skylab's greatest applications as both a geologic and environmental tool.

A complete map cannot be prepared from ERTS-1 data because the Shingle soil lenses and outcrops are too small to be resolved by the ERTS scanner.

In summary, Skylab photography could be used successfully to locate highly reflective soils. In the Wasatch formation, these soils were classified as the Shingle series and were found to support the toxic, selenium convertor plant A. bisulcatus.

It is emphasized that the Samsil series soils also contain significant selenium quantities which, if disturbed or mixed with other soils, might also support selenium convertor plants. Therefore, the maps prepared only locate areas where _A_. _bisulcatus_ growth and related soil deterioration is most likely to be present. These maps do not represent a complete inventory of seleniferous soils.

Furthermore, highly seleniferous soils in other areas (Como Bluffs, Wyoming, for example) derived from other geological formations support _A_. _bisulcatus_ and other selenium convertor plants. In these areas, the soils supporting the selenium convertors have very low reflectances (for example, soils derived from the Niobrara shale) (Trelease, S. F., and Beath, O. A., 1949). Therefore, the relationship of convertor plant location and high-reflectant soils cannot be generalized. Each geological formation and geographical locality must be considered independently.

CONCLUSIONS AND RECOMMENDATIONS

In Sec. 27, T 48 N, R 71 W, a unique correlation of Shingle soils and sandstone outcrops with A. bisulcatus presence was noted.

Chemical leachate analyses revealed that all soils present contained acid-, base-, and water-soluble compounds of selenium.

Acid-soluble selenium compounds were found to be associated with the smectite in the A horizon soils. Further studies and core analyses are needed to determine 1) what minerals in the bedrock carry selenium (ie., what is the actual source of selenium), and 2) what is the ultimate source of the mobile selenium compounds (ie., volcanic ash or natural erosional processes).

An analysis of variance for three separate model equations provided statistical confirmation for the following conclusions:

1) Some soil lenses contained significantly higher quantities of leachable selenium than others. This was the result of 1) A. bisulcatus presence (accumulation of organic selenium created base-leach variabilities), 2) differential soil lens pH (water leaches variable), and 3) random sample variations. Other possible factors in need of further study include bedrock selenium source variations

and weathering inhomogeneities of both soil and bedrock type.

2) More selenium compounds were leached in a basic environment than in acidic or neutral environments, suggesting that more leachable selenium is in an organic form.

3) There are no significant leachable selenium concentration differences between soil lenses of sites A (Shingle soils with _A_. _bisulcatus_ present) and B (no selenium indicators present). The influence of _A_. _bisulcatus_ presence is weak enough to be masked in site comparisons. Studies encompassing the top one or two inches of soil should be conducted to verify if more extensive accumulation of organic selenium compounds by _A_. _bisulcatus_ occurs surficially.

4) There are no significant leachable selenium concentration differences between the Samsil and Shingle soil types. Again, the influence of _A_. _bisulcatus_ presence is weak enough to be masked in soil type comparisons. More geobotanical research is necessary to determine the ecological reasons why _A_. _bisulcatus_ favors germination and growth exclusively on certain Shingle soils.

5) Various Shingle soil lenses supporting _A_. _bisulcatus_ were found to be quite variable. It is recommended that bedrock core analyses and soils sampling be undertaken to substantiate the hypothesis that the variation is primarily due to bedrock sources.

The serious environmental concern in this study is the control of selenium redistribution in soil to prevent the increase in seleniferous vegetation and eventual deterioration of soils, cropland, and range quality. In this regard, the following conclusions are appropriate:

1) A. bisulcatus, due to root decay, contributes to the soils (at approximately 6" depth) small quantities of organic selenium. Studies of the top one or two inches of soil should be conducted to verify if more extensive accumulation of organic selenium compounds by A. bisulcatus occurs surficially.

2) A. bisulcatus germinates and grows on soils containing 0.2 ppm leachable selenium and less. At the study site leachable selenium will not be a limiting factor for convertor plant germination and growth.

3) For complete environmental assessment, additional selenium analyses of all study area plants are needed to determine range vegetation toxicity (how effective is each individual species in body tissue accumulation of selenium) and the relationships of water-soluble selenium concentrations between soil lens availability and plant uptake.

Because of a potential environmental hazard; the following procedures are recommended:

1) Neither the Samsil nor Shingle soils should be stockpiled due to their significant concentrations of selen-

ium. Other soils, such as the Ulm series soils, should be used for topsoil respreading.

2) If the Samsil and Shingle soils are ever used for topsoil, all selenium convertors should be removed before stockpiling and all soil lenses containing abnormally high selenium concentrations should be buried.

3) Once reclamation procedures are completed, the land should be carefully monitored for convertor plant invasion. If any seleniferous plants are discovered, they should be eliminated.

A second environmental concern in this study is the deterioration of natural waters due to selenium redistribution in soil. It was concluded that selenium compounds at the study site are not being transported downslope by surface runoff. Therefore, there is little danger of surface water deterioration. However, more studies are necessary to determine if significant selenium concentrations are being leached to the water table. This information is essential in determining if groundwater contamination occurs.

Skylab photography was tested as a tool in mapping the Shingle soils and outcrops supporting _A_. _bisulcatus_. Density analysis and photographic enlargement were two methods used successfully in localized mapping of the potentially plant-supporting soils (undisturbed). A regional map of these soils was prepared for Campbell County using the Skylab S 190-B photography as a mapping base.

It is emphasized that Samsil series soils also contain significant selenium quantities which, if disturbed or mixed with other soils, might also support selenium convertor plants. Therefore, the maps prepared only locate areas where A. bisulcatus growth and related soil deterioration is likely to be present and are not a complete inventory of seleniferous soils.

The relationship of convertor-plant location and high-reflectant soils cannot be generalized. Each geological formation and geographical locality must be considered independently.

Hopefully, the information supplied by this study will aid ranching and mining interests in future land-use management and reclamation procedures.

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APPENDICES

APPENDIX A

Analysis of Variance Computations

Model 1:

$$y_{ijklm} = u + \alpha_i^{S} + \alpha_k^{R} + a_{ijk}^{G} + \alpha_l^{L} + \alpha_{ik}^{SR} + \alpha_{il}^{SL} + \alpha_{kl}^{RL} + a_{ijkl}^{GL} + \alpha_{ikl}^{SRL} + e_{ijklm}\,.$$

Source	df	SS
S	I-1	$\sum_i \frac{T_{i....}^2}{JKLM} - \frac{T_{.....}^2}{IJKLM}$
R	K-1	$\sum_k \frac{T_{..k..}^2}{IJLM} - \frac{T_{.....}^2}{IJKLM}$
G	IK(J-1)	$\sum\sum\sum_{ijk} \frac{T_{ijk..}^2}{LM} - \sum\sum_{ik} \frac{T_{i.k..}^2}{JLM}$
L	L-1	$\sum_l \frac{T_{...l.}^2}{IJKM} - \frac{T_{.....}^2}{IJKLM}$
SR	(I-1)(K-1)	$\sum\sum_{ik} \frac{T_{i.k..}^2}{JLM} - \sum_i \frac{T_{i....}^2}{JKLM} - \sum_k \frac{T_{..k..}^2}{IJLM} + \frac{T_{.....}^2}{IJKLM}$
SL	(I-1)(L-1)	$\sum\sum_{il} \frac{T_{i..l.}^2}{JKM} - \sum_i \frac{T_{i....}^2}{JKLM} - \sum_l \frac{T_{...l.}^2}{IJKM} + \frac{T_{.....}^2}{IJKLM}$
RL	(K-1)(L-1)	$\sum\sum_{kl} \frac{T_{..kl.}^2}{IJM} - \sum_k \frac{T_{..k..}^2}{IJLM} - \sum_l \frac{T_{...l.}^2}{IJKM} + \frac{T_{.....}^2}{IJKLM}$

Model 1, continued.

Source	df	SS
GL	IK(J-1)(L-1)	$\sum\sum\sum\sum_{ijkl} \frac{Tijkl.^2}{M} - \sum\sum\sum_{ijk} \frac{Tijk..^2}{LM} - \sum\sum\sum_{ikl} \frac{Ti.kl.^2}{JM} - \sum\sum_{ik} \frac{Ti.k..^2}{JLM}$
SRL	(I-1)(K-1)(L-1)	$\sum\sum\sum_{ikl} \frac{Ti.kl.^2}{JM} - \sum\sum_{kl} \frac{T..kl.^2}{IJM} - \sum\sum_{ik} \frac{Ti.k..^2}{JLM} + \sum_{k} \frac{T..k..^2}{IJLM} - \sum\sum_{il} \frac{Ti..l.^2}{JKM} +$ $\sum_{l} \frac{T...l.^2}{IJKM} + \sum_{i} \frac{Ti....^2}{JKLM} - \frac{T.....^2}{IJKLM}$
error	IJKLM-IJKL	$\sum\sum\sum\sum\sum_{ijklm} X_{ijklm}^2 - \sum\sum\sum\sum_{ijkl} \frac{Tijkl.^2}{M}$
total	IJKLM-1	$\sum\sum\sum\sum\sum_{ijklm} X_{ijklm}^2 - \frac{T.....^2}{IJKLM}$

Source	EMS	F
S	$JKLM\sigma_S^2 + LM\sigma_G^2 + \sigma^2$	MS_S/MS_G
R	$IJLM\sigma_R^2 + LM\sigma_G^2 + \sigma^2$	MS_R/MS_G
G	$LM\sigma_G^2 + \sigma^2$	MS_G/MS_E
L	$IJKM\sigma_L^2 + M\sigma_{GL}^2 + \sigma^2$	MS_L/MS_{GL}
SR	$LM\sigma_G^2 + JLM\sigma_{SR}^2 + \sigma^2$	MS_{SR}/MS_G

Model 1, continued.

Source	EMS	F
SL	$JKM\sigma_{SL}^2 + M\sigma_{GL}^2 + \sigma^2$	MS_{SL}/MS_{GL}
RL	$IJM\sigma_{RL}^2 + M\sigma_{GL}^2 + \sigma^2$	MS_{RL}/MS_{GL}
GL	$M\sigma_{GL}^2 + \sigma^2$	MS_{GL}/MS_E
SRL	$M\sigma_{GL}^2 + JM\sigma_{SRL}^2 + \sigma^2$	MS_{SRL}/MS_{GL}
error	σ^2	

Model 2:

$$y_{ijlm} = u + \alpha_i^S + a_{ij}^G + \alpha_l^L + \alpha_{il}^{SL} + a_{ijl}^{GL} + e_{ijlm} .$$

Source	df	SS
S	I-1	$\sum_i \frac{T_{i...}^2}{JLM} - \frac{T_{....}^2}{IJLM}$
G	I(J-1)	$\sum_i\sum_j \frac{T_{ij..}^2}{LM} - \sum_i \frac{T_{i...}^2}{JLM}$
L	L-1	$\sum_l \frac{T_{..l.}^2}{IJM} - \frac{T_{....}^2}{IJLM}$

Model 2, continued.

Source	df	SS
SL	(I-1)(L-1)	$\sum\sum_{il} \frac{T_{i.l.}^2}{JM} - \sum_{i} \frac{T_{i...}^2}{JLM} - \sum_{l} \frac{T_{..l.}^2}{IJM} + \frac{T_{....}^2}{IJLM}$
GL	I(J-1)(L-1)	$\sum\sum\sum_{ijl} \frac{T_{ijl.}^2}{M} - \sum\sum_{ij} \frac{T_{ij..}^2}{LM} - \sum\sum_{il} \frac{T_{i.l.}^2}{JM} + \sum_{i} \frac{T_{i...}^2}{JLM}$
error	IJLM-IJL	$\sum\sum\sum\sum_{ijlm} X_{ijlm}^2 - \sum\sum\sum_{ijl} \frac{T_{ijl.}^2}{M}$
total	IJLM-1	$\sum\sum\sum\sum_{ijlm} X_{ijlm}^2 - \frac{T_{....}^2}{IJLM}$

Source	EMS	F
S	$JLM\sigma_S^2 + LM\sigma_G^2 + \sigma^2$	MS_S/MS_G
G	$LM\sigma_G^2 + \sigma^2$	MS_G/MS_E
L	$ILM\sigma_L^2 + M\sigma_{GL}^2 + \sigma^2$	MS_L/MS_{GL}
SL	$JM\sigma_{SL}^2 + M\sigma_{GL}^2 + \sigma^2$	MS_{SL}/MS_{GL}
GL	$M\sigma_{GL}^2 + \sigma^2$	MS_{GL}/MS_E
error	σ^2	

Model 3:

$$Y_{jlm} = u + \alpha_j^{E} + \alpha_l^{L} + \alpha_{jl}^{EL} + e_{jlm} \, .$$

Source	df	SS
E	J-1	$\sum_j \frac{T_{j..}^2}{LM} - \frac{T_{...}^2}{JLM}$
L	L-1	$\sum_l \frac{T_{.l.}^2}{JM} - \frac{T_{...}^2}{JLM}$
EL	(J-1)(L-1)	$\sum\sum_{jl} \frac{T_{jl.}^2}{M} - \sum_l \frac{T_{.l.}^2}{JM} - \sum_j \frac{T_{j..}^2}{LM} + \frac{T_{...}^2}{JLM}$
error	JLM-JL	$\sum\sum\sum_{jlm} X_{jlm}^2 - \sum\sum_{jl} \frac{T_{jl.}^2}{M}$
total	JLM-1	$\sum\sum\sum_{jlm} X_{jlm}^2 - \frac{T_{...}^2}{JLM}$

Source	EMS	F
E	$LM\sigma_E^2 + \sigma^2$	MS_E/MS_{Error}
L	$JM\sigma_L^2 + \sigma^2$	MS_L/MS_{Error}
EL	$M\sigma_{EL}^2 + \sigma^2$	MS_{EL}/MS_{Error}
error	σ^2	

Data Table Used in Analysis of Variance Computations

Soil Type (i)			Leachate (l)			
	Site (k)	Acid	Base		Water	
	A	B	A	B	A	B
Shingle:						
Unit (j)	Replicates (m):					
1	26,9,12	18,7,21	89,43,46	83,81,78	21,7,15	13,2,19
3	1,2,8	22,22,2	47,62,85	22,16,10	25,11,8	15,1,8
5	9,7,26	7,0	85,70,81	34,38	24,14,35	7,1
7	64,115,40	Absent	227,205,195	Absent	99,94,59	Absent
Samsil:						
Unit						
2	23,5,9	20,16,7	108,22,53	114,78,126	7,5,12	19,9,15
4	62,14,6	39,77,45	21,34,100	55,40,43	21,20,18	24,49,21
6	18,2,31	Absent	64,15,8	Absent	14,9,9	Absent

APPENDIX B

Mean, Variance, and Standard Deviation Tables: Individual Soil Lenses

Site A:

Sample Set		Leaches	
	Acid	Base	Water
Unit 1: Shingle			
Mean	16	59	14
Var.	82	662	49
Std. Dev.	9	26	7
Unit 2: Samsil			
Mean	12	61	8
Var.	89	1897	13
Std. Dev.	9	44	4
Unit 3: Shingle			
Mean	3	65	15
Var.	17	366	82
Std. Dev.	4	19	9
Unit 4: Samsil			
Mean	27	45	20
Var.	917	2585	2
Std. Dev.	30	51	2
Unit 5: Shingle			
Mean	14	79	24
Var.	109	60	110
Std. Dev.	10	8	11
Unit 6: Samsil			
Mean	17	29	11
Var.	211	931	8
Std. Dev.	15	31	3
Unit 7: Shingle			
Mean	73	209	84
Var.	1467	268	475
Std. Dev.	38	16	22

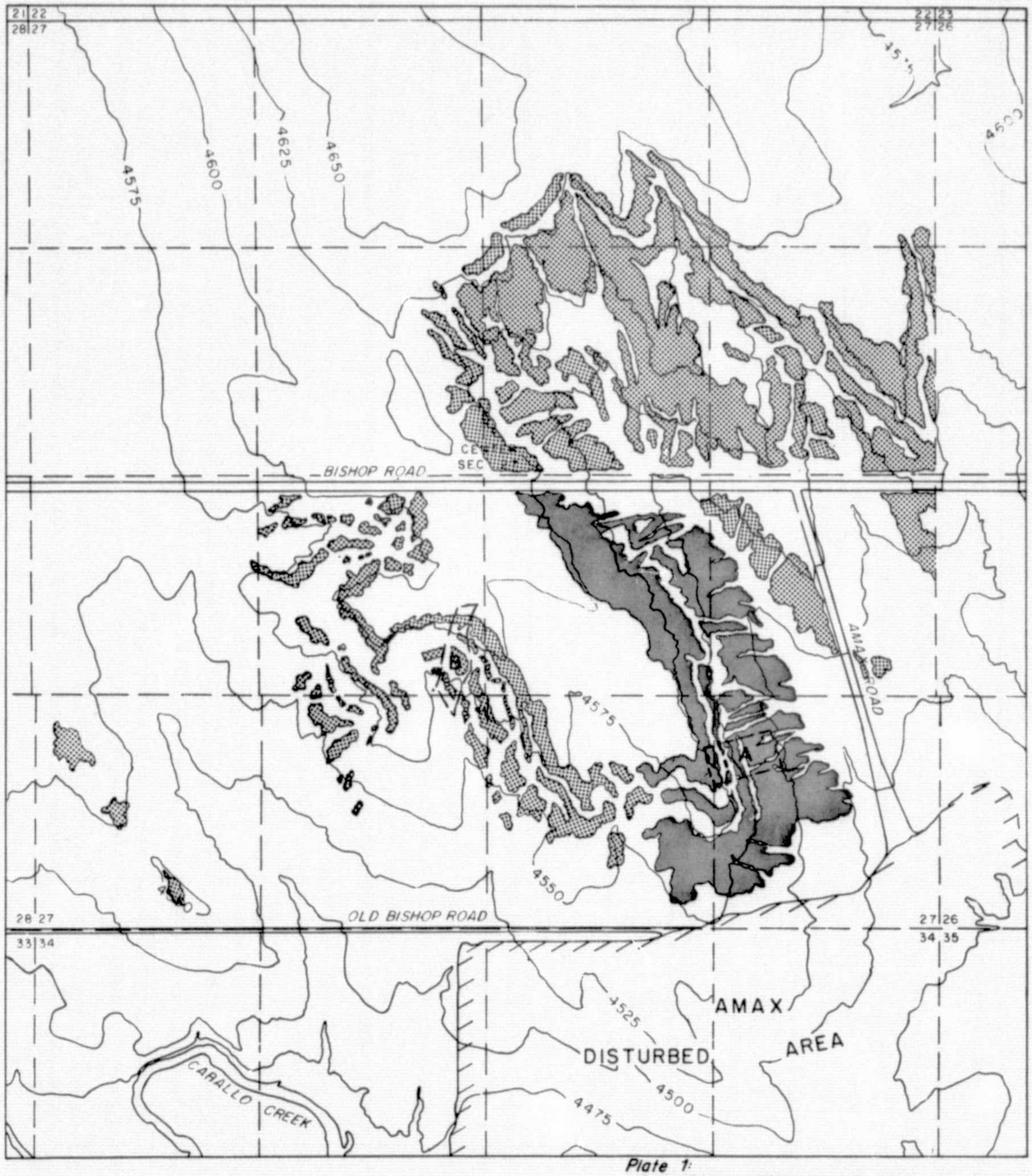
Site B:

Sample Set	Leaches Acid	Base	Water
Unit 1: Shingle			
Mean	15	81	11
Var.	54	6	74
Std. Dev.	7	3	9
Unit 2: Samsil			
Mean	14	106	14
Var.	44	624	25
Std. Dev.	7	25	5
Unit 3: Shingle			
Mean	15	16	8
Var.	133	36	49
Std. Dev.	12	6	7
Unit 4: Samsil			
Mean	54	46	31
Var.	417	63	236
Std. Dev.	20	8	15
Unit 5: Shingle			
Mean	4	36	4
Var.	25	8	25
Std. Dev.	5	3	5

Mean, Variance, and Standard Deviation Tables: General Combinations of Sites A and B

Sample Set	Leaches Acid	Base	Water
For Site B:			
All Samsil Units:			
Mean	34	76	23
Var.	722	1800	145
Std. Dev.	28	42	12
All Shingle Units:			
Mean	11	44	8
Var.	46	1094	15
Std. Dev.	7	33	4

Sample Set	Acid	Leaches Base	Water
For Site A:			
All Samsil Units:			
Mean	9	45	13
Var.	59	256	37
Std. Dev.	8	16	6
All Shingle Units:			
Mean	27	103	34
Var.	991	5071	1118
Std. Dev.	31	71	33
For Sites A and B Combined:			
All Samsil Units:			
Mean	26	60	18
Var.	114	484	50
Std. Dev.	11	22	7
All Shingle Units:			
Mean	19	74	21
Var.	113	1722	356
Std. Dev.	11	42	19

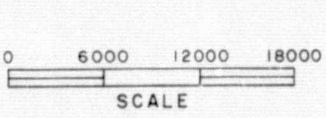


R 71 W

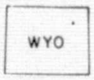
Plate 1:
Seleniferous soils, outcrops, and plant indicators in the Lower Tertiary Wasatch Formation, mapped from Field Observation on Aerial Photography
SECTION 27, T48N, R71W, WYO.

PREPARED BY KENNETH KOLM
1975

TOPOGRAPHIC BASE PROVIDED BY AMERICAN METALS CLIMAX CORP.



CONTOUR INTERVAL 25 FEET



LOCATION

LEGEND

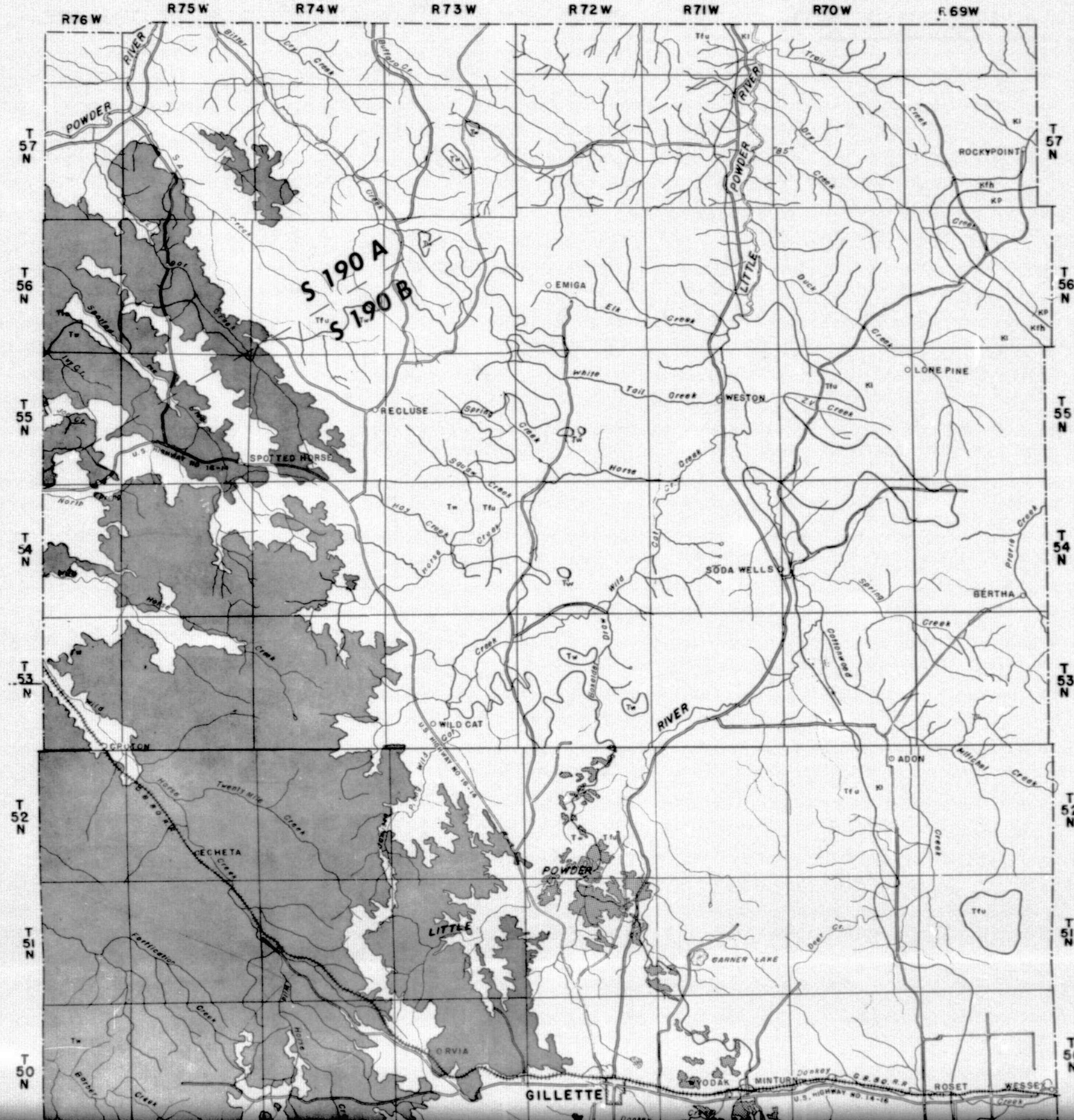
■ Seleniferous Shingle series soils and sandstone outcrops supporting the plant indicator species *Astragalus bisulcatus*

▨ Seleniferous Shingle series soils and sandstone outcrops; no selenium indicator species observed

⬚ Boundary of soil sample study sites

97b

FOLDOUT FRAME 1



FOLDOUT FRAME

2

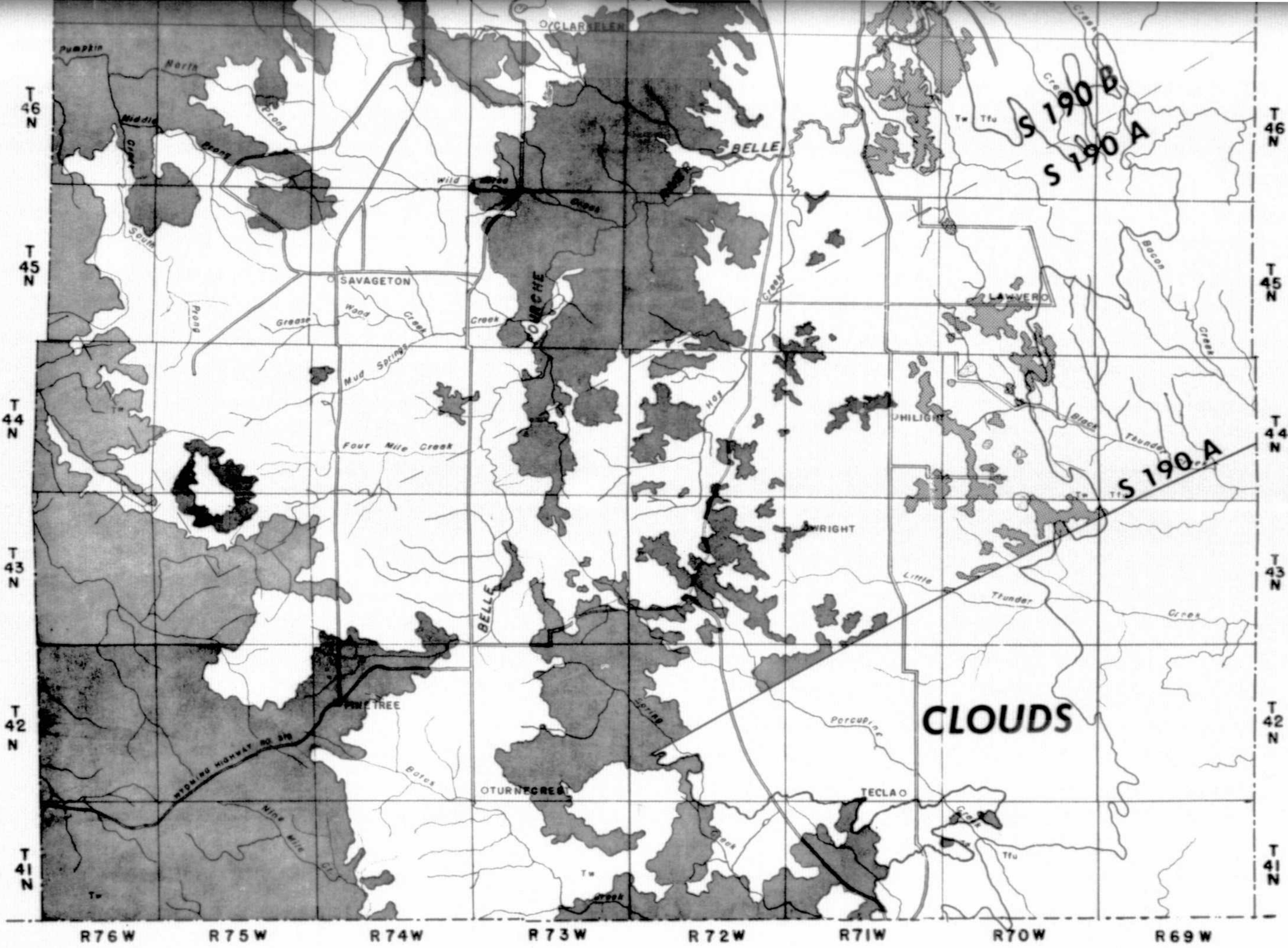


Plate 2:

Possible Selenium-rich Shingle Series Soils and Sandstone Outcrops of the Wasatch Formation, Campbell County, Wyoming, Interpreted from Skylab Photography

by

KENNETH E. KOLM

1975

Compiled on Geologic Base(Geological Survey of Wyoming, 1936) from Interpretations of S 190 A and S 190 B Photography(Track 59, Pass 28, September 13, 1973) and S 190 A Photography(Track 5, Pass 10, June 13, 1973).

LEGEND

POSSIBLE SELENIUM-RICH SOILS

▨ Shingle series soils and sandstone outcrops

■ Badlands containing shingle series soils and sandstone outcrops

BOUNDARIES

– – – Limits of Coverage

——— Cloud Coverage

MILES

FOLDOUT FRAME

3