

SOIL-GEOLOGY SELENIUM RELATIONSHIPS IN DISTURBED AND NATIVE ECOSYSTEMS¹

by

C.P. Skinner and G.F. Vance²

Abstract: The importance of soil-geology relationships involving selenium (Se) was evaluated in disturbed and native environments at Fort Carson Military Reservation. The military base covers approximately 56,000 ha (138,000 acres) and is located east of the Rocky Mountain Front Range in southeastern Colorado where Se occurs naturally in geological formations. Identification of areas where Se occurs in potentially high concentrations can facilitate efforts to reduce impacts associated with soil erosion and Se transport from within Fort Carson to surrounding lands. We studied soil-geology relationships that potentially contribute to Se distribution and transport at Fort Carson. Combining geographic information system (GIS) coverages for geology, soils and vegetation at Fort Carson resulted in 43 descriptive mapping units. Soil samples collected from 92 sites represented about 99% of the study area. Identification of specific geologic formations and related soil series indicated that soils with Se levels above the 0.5 mg/kg phosphate-extractable Se suitability criteria were formed on parent materials primarily of Cretaceous-aged shales and Quaternary-aged alluvium underlain by Cretaceous-aged shale. Seleniferous soils were predominately calcareous clays, silts and loams, or sediments derived from shales and eolian deposits. Selenium in surface soils of one watershed increased in concentration with increasing distance downslope. Identification of areas likely to support seleniferous soils (e.g., low-lying areas within the landscape, soils formed in Cretaceous-aged fine-texture shales in close proximity to water) would be useful for making environmental management decisions regarding revegetation or remediation programs.

Additional Key Words: Soil series, geological formations, GIS, erosion, wetlands

Introduction

Selenium (Se) is commonly associated with arid lands in the western United States, occurring naturally in soils and geologic materials, particularly materials of Cretaceous age (Burau 1989, Presser and Swain 1990, Dreher and Finkelman 1992). The mean Se concentration for soils in the western U.S. is 0.23 mg/kg (Shacklette and Boerngen 1984).

Soils with total Se concentrations greater than 2 mg/kg have the potential for the production of vegetation containing Se levels that could cause selenosis in wildlife and domestic animals (Thorton 1981). While Se is required in small amounts for adequate animal nutrition, the distinction between healthy and lethal dosages occurs

within a narrow range. Recognized suitability levels for concern are based on animal consumption over an extended period of time. The critical level established for Wyoming soils that support growth of plants with Se levels above the suitability limit is generally within a range of extractable Se from 0.3- to 0.8-mg/kg dry soil weight using ammonium bicarbonate-DTPA or hot water (with CaCl_2) agents (WDEQ-LQD 1996). It is also well known that aquatic Se is extremely problematic to wildlife and fish due to bioavailable Se at levels as low as 2 to 10 ppb.

Selenium exists in many forms and oxidation states in the natural environment. Selenide (S^{2-}) and elemental Se (Se^0) are the dominant species, and are immobile and biologically unavailable in subsurface environments. When eroded from geologic and soil materials and exposed to oxidizing atmospheric conditions, selenite (SeO_3^{2-}) and selenate (SeO_4^{2-}) become the dominant species. In well-oxidized, alkaline environments, SeO_4^{2-} is thermodynamically stable. However, SeO_4^{2-} is more soluble than SeO_3^{2-} , is not as strongly adsorbed and, therefore, is more mobile than SeO_3^{2-} and easily leached. Selenite, which is less soluble than SeO_4^{2-} , occurs in mildly oxidizing, neutral pH environments where the mobility of SeO_3^{2-} is limited by its affinity to be strongly

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adsorbed by particles or be reduced to Se^0 in chemical or biological processes. Selenium mobility is greater in alkaline environments such as in calcareous soils (Balistrieri and Chao 1987, Bar-Yosef and Meek 1987, Burau 1989, Presser and Swain 1990, Neal 1990, Fio et al. 1991).

Several factors can influence the solubility and mobility of Se in the soil environment including soil parent material, geologic formation, soil texture, clay mineralogy, pH, redox reactions, presence of metals or nitrates, soil organic content, microbial activity, rainfall or seasonal leaching, and volatilization (Table 1).

Seiler (1996, 1998) suggested three mechanisms by which Se is transferred from seleniferous rocks to soils and groundwater. The simplest origin of Se is from pedochemical weathering of the parent rock as soils are formed; groundwater coming in contact with the soil and rock can also solubilize Se. In the San Joaquin Valley of California, the most important Se transfer process occurs when irrigation of upland agricultural areas contributes downslope flow to areas through processes of active weathering, alluvial fan building and local drainage. Importation of surface waters, such as movement of seleniferous waters from the Colorado River that pass through Upper Cretaceous sedimentary rocks to the Salton Sea, can transport seleniferous waters over hundreds of miles. Importation can also occur via anthropogenic sources, such as discharge and transport of seleniferous waters from industrial processes.

A recent study using data from Brough's (1996) analysis of playa soils from the Powder River Basin in northeastern Wyoming, together with x-ray diffraction analyses of the playa minerals, suggested there is a relationship between Se concentration and the primarily illite/smectite and kaolinite clay minerals (Skinner et al. 1997). Each of these clay minerals has been shown to adsorb Se at different levels under varying pH conditions (Bar-Yosef and Meek 1987, see Table 1). Seleniferous soils formed in the eastern half of the Fort Carson study area are predominantly comprised of calcareous clay and shale that provide a source of fine-textured materials that have high water retention and slow permeability. Soil texture and composition of clay minerals and organic matter determine whether soluble forms of Se will be leached through the soil profile or be retained either by evaporation or adsorption to soil particles. Since SeO_3^{2-} adsorption decreases with increased pH and arid soils tend to be alkaline, Se could either be maintained in a soluble form in solution or concentrated in dry soils.

Muun (1995) suggested that pedogenic and geomorphic processes appear to influence the distribution and concentration of Se, with soil parent material being

the primary factor in well-drained soils or on slopes where weathering or transport is limited. If soils are affected by a high water table (e.g., from a playa lake) Se distribution may fluctuate with the water table and may accumulate above the area of flooding. Presser and Swain (1990) found that SeO_4^{2-} concentrated in salts of weathered upper Cretaceous-Paleocene marine sedimentary shales in the San Joaquin Valley of California.

Selenate, the more mobile and biologically available form of Se (Balistrieri and Chao 1987, Burau 1989, Fio et al. 1991), will move readily through sandy soils while SeO_3^{2-} is adsorbed by clay and organic matter particles (see Table 1 adsorption, clays and parent material). In the predominantly arid climate of Fort Carson, Se released into the environment by the dissolution of weathered geologic materials would have sufficient time to react with soil colloids and clays, tending to concentrate over time.

Our objective was to collect a representative sampling of the described study area in order to identify seleniferous soil-geology relationships for facilitating the design of land management programs for the U.S. Army at Fort Carson, Colorado. This was accomplished using 92 sampling sites within descriptive mapping units developed for the military installation.

Materials and Methods

Site Description

Fort Carson covers over 56,000 ha (138,000 acres), has an arid climate and is situated east of the southern Rocky Mountain Front Range of Colorado (Figure 1). About 60% of the military base is comprised of Cretaceous-aged limestone, sandstone and shale. The terrain varies from elevations as high as 2,040 m (6,691 ft) in shrub and tree-lined ridges of the Rocky Mountain foothills along the western boundary, to the short grass prairie of the High Plains at an elevation of 1,660 m (5,445 ft) in the eastern extent of the military base.

Numerous, intense summer rainstorms, together with frequent disturbance by military activities, subject the landscape to massive amounts of erosion, with transport and deposition of seleniferous materials throughout the Fort Carson boundary. Upon weathering of rock materials, Se oxidation and formation of selenite (SeO_3^{2-}) and selenate (SeO_4^{2-}) species increases the potential for mobility through water processes and uptake by plants that may then be consumed by domestic animals, wildlife and humans (Neal 1990). Bioavailability of Se as an issue of land management requires location and identification of environmental Se sources and receptors.

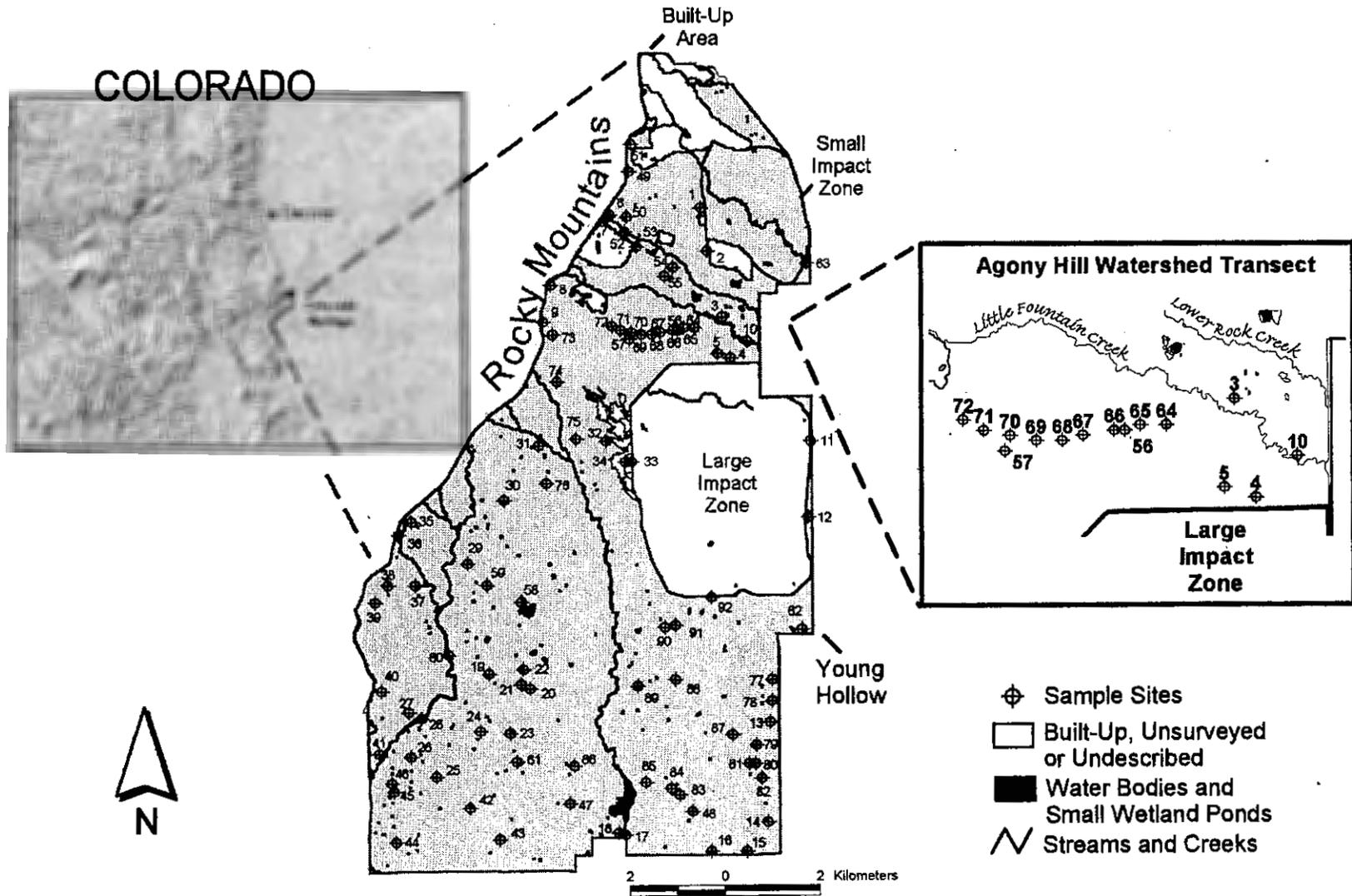


Figure 1. Location of Fort Carson study area with respect to the Colorado Rocky Mountains, and distribution of 92 sampling sites.

Table 1. Factors affecting selenium relations in soils, plants and waters.

Adsorption	Balistreri and Chao 1987 Bar-Yosef and Meek 1987	Blaylock et al. 1995 Fio et al. 1991
Anion Competition	Adams and Pickett 1998	Balistreri and Chao 1987
Atmosphere	Cahill and Eldred 1998	Haygarth et al. 1995
Calcium/Gypsum Amendments and Extractions	Agnihotri et al. 1998 Seby et al. 1997	Singh 1994 Woodbury et al. 1999 (plant uptake)
Clays, Texture	Arvy 1992 Bar-Yosef and Meek 1987 Dreher and Finkelman 1992	Johnson 1991 Neal 1990
Climate, Leaching, Rainfall, Soil Moisture, Water Stress	Arvy 1992 Bureau 1989 Seiler 1998 Tennant and Wu 2000 (plant uptake)	Wahl et al. 1994 Zawislanski et al. 1992 Zhang and Frankenberger, Jr. 1999 Zhang et al. 1999
Geologic Material, Geomorphology	Bureau 1989 Dreher and Finkelman 1992 Munn 1995	Presser and Swain 1990 Seiler 1996, 1998
Metals	Arvy 1992 Myneni et al. 1997	Neal 1990
Microbial Processes	Azaizeh et al. 1997 de Souza et al. 1999 (plant uptake) Dowdle and Oremland 1998	Dungan and Frankenberger, Jr. 1998 Losi and Frankenberger, Jr. 1998
pH	Balistreri and Chao 1987 Bar-Yosef and Meek 1987 Blaylock et al. 1995 Bureau 1989	Haygarth et al. 1995 Johnson 1991 Neal 1990 Poole et al. 1994
Parent Material, Organic Matter	Ajwa et al. 1998 Bureau 1989 Johnson 1991	Munn 1995 Tokunaga et al. 1996
Plant Growth Stage	Milachinovic et al. 1998 (plant uptake)	
Redox Reactions	Jayaweera and Biggar 1996 Neal 1990 Myuneni et al. 1997 Peters et al. 1997	Poole et al. 1994 Tokunaga et al. 1997 Tokunaga et al. 1998 Wahl et al. 1994
Roots, Rhizosphere	Azaizeh et al. 1997 Blaylock and James 1994 de Souza et al. 1999	Haygarth et al. 1993 Wu et al. 1996
Salts, Salinity	Dreher and Finkelman 1992 Grieve et al. 1999 (plant uptake)	Presser and Swain 1990 Zawislanski et al. 1992
Se Species	Balistreri and Chao 1987 Fio et al. 1991 Jayaweera and Biggar 1996 Martens and Suarez 1997	Neal 1990 Sharmasarkar and Vance 1995 Yamada et al. 1998
Season	Nishri et al. 1999	
Volatilization	Hansen et al. 1998 Stork et al. 1999	Martens and Suarez 1999 Zhang and Frankenberger, Jr. 1999

GIS Construction

GIS coverages for the Fort Carson study area were quite detailed, so that overlaying coverages produced data layer maps that were not suitable for the identification of sampling sites. Therefore, the soil series coverage representing 65 soil units was consolidated into three soil mapping units (i.e., 'Ustolls', 'Torriorthents and Ustalfs' and 'Aridisols') based on similar parent materials, geomorphic features and pedogenic processes (Figure 2). The geology coverage representing 23 geologic units was consolidated into five mapping units (i.e., 'Shale', 'Limestone', 'Alluvium, Loess and Eolian Sand', 'Morrison, Lykins, Lyon and Fountain Formations' and 'Landslide Deposits and Dakota Sandstone') based on similarity of origin and/or landscape proximity (Figure 3). A vegetation coverage that included mapping units for grass, scrub (e.g., shrubs) and trees was added to the soil-geology GIS coverages, resulting in the formation of the final 43 different mapping units. The combination of these coverages resulted in adequate detail reduction to produce useful data and a readable map, while preserving sufficient detail for identification of general soil-geology relationships, and permitting GIS queries to identify specific soil and geology attributes.

A total of 92 sites, including a transect with 11 sites in one watershed, were sampled (see Figure 1). A majority (32 out of 43) of the final mapping units was sampled, representing approximately 98.6% of the study area described by mapping units. Areas excluded from sampling were those described as built-up areas, military impact zones and safety fans, badlands and unsurveyed areas.

Soil Sampling

Soil samples from each site were collected in increments of 0-25, 25-50, 50-75 and 75-100 cm depths and placed into plastic soil collection bags. Samples were air-dried at room temperature (~22°C), and passed through a 2-mm sieve to remove rocks, pebbles and larger pieces of plant material. Air-dried soil samples weighing 5.0 grams were placed into 50-ml centrifuge tubes to which 25-ml 1.0 M di-basic phosphate (K_2HPO_4) extracting solution was added (Spackman et al. 1994). Tubes were placed into a reciprocating shaker for 2 hours, at about 120 oscillations per minute to keep the soil suspended, then centrifuged at 2000-rpm for 15 minutes. Supernatants were filtered into clean plastic centrifuge tubes through a Whatman 40 filter paper and stored at 4° C for analysis within 24 hours.

Se Analysis

A 3-ml aliquot of each extract was placed into a 50-ml glass test tube, to which 12-ml deionized-distilled water and 1-ml 30% H_2O_2 were added. Tubes were placed into a hot water bath and heated for 20 minutes at 85° to 90°C, after which 10-ml conc. HCl was added to each sample followed by a second 20-minute heating in a hot water bath at 85° to 90°C. The samples were allowed to cool for 12 hours and their Se concentrations determined using hydride generation-atomic absorption spectrometry (HG-AAS) according to the methods of Steward et al. (1994) and Spackman et al. (1994).

GIS Database Queries and Analyses

Selenium concentration data were tabulated in an Excel spreadsheet that was attached as a table to the GIS sampling site layer in ArcView, permitting database queries and identification of trends in distribution.

Results

Sites with seleniferous soils were not widely distributed, occurring in a few areas influenced by the presence of water at some time during the year and primarily within the eastern half of the study area (Figure 4). Soil series units that exhibited Se concentrations above the critical level were located primarily along a stream to the north and areas on the western and southeastern boundaries of the large impact zone, and within a small area along the southwestern boundary of the installation. Seventy one out of 92 sites occurred in areas of disturbance attributed mainly to military activities and natural erosion of geological parent materials.

Soils at 10 of the 92 sampling sites were seleniferous (i.e., soils with extractable Se concentrations > 0.5 mg/kg) (Table 2). Nine out of the ten sites with seleniferous soils were located on disturbed lands. The ArcView query revealed that these sites were located in soil series of Heldt clay loam (Haplocambids), Kim loam (Torriorthents), Limon clay (Torriorthents), the Razor-Midway complex (Haplocambids), and Wiley silt loam (Haplargids). Five out of eight Heldt clay loam samples were seleniferous, as were the single sample of Kim loam, the two samples of Limon clay, one out of three Razor-Midway complex samples, and one sample out of two in Wiley silt loam (3-9% slopes). Together, the soil series units for these samples represented only 6.2%, or 2,785 ha (6,879 acres) of the Fort Carson area with described soils (Heldt clay loam, 2.8%; Kim loam, 0.2%; Limon clay, 0.7%; Razor-Midway complex, 8.4%; Wiley silt loam, 0.8%).

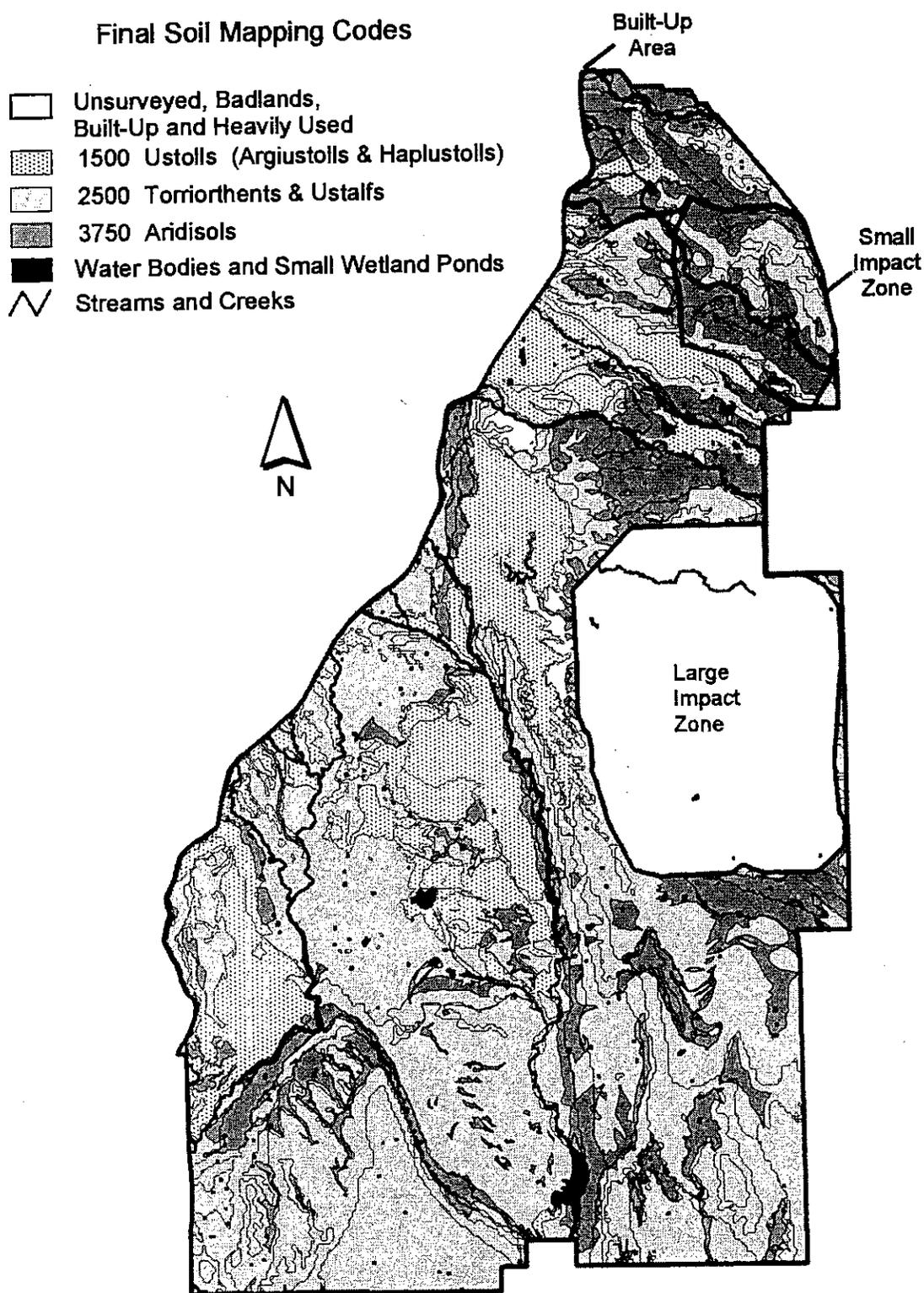


Figure 2. Distribution of three final soil mapping codes at Fort Carson, Colorado.

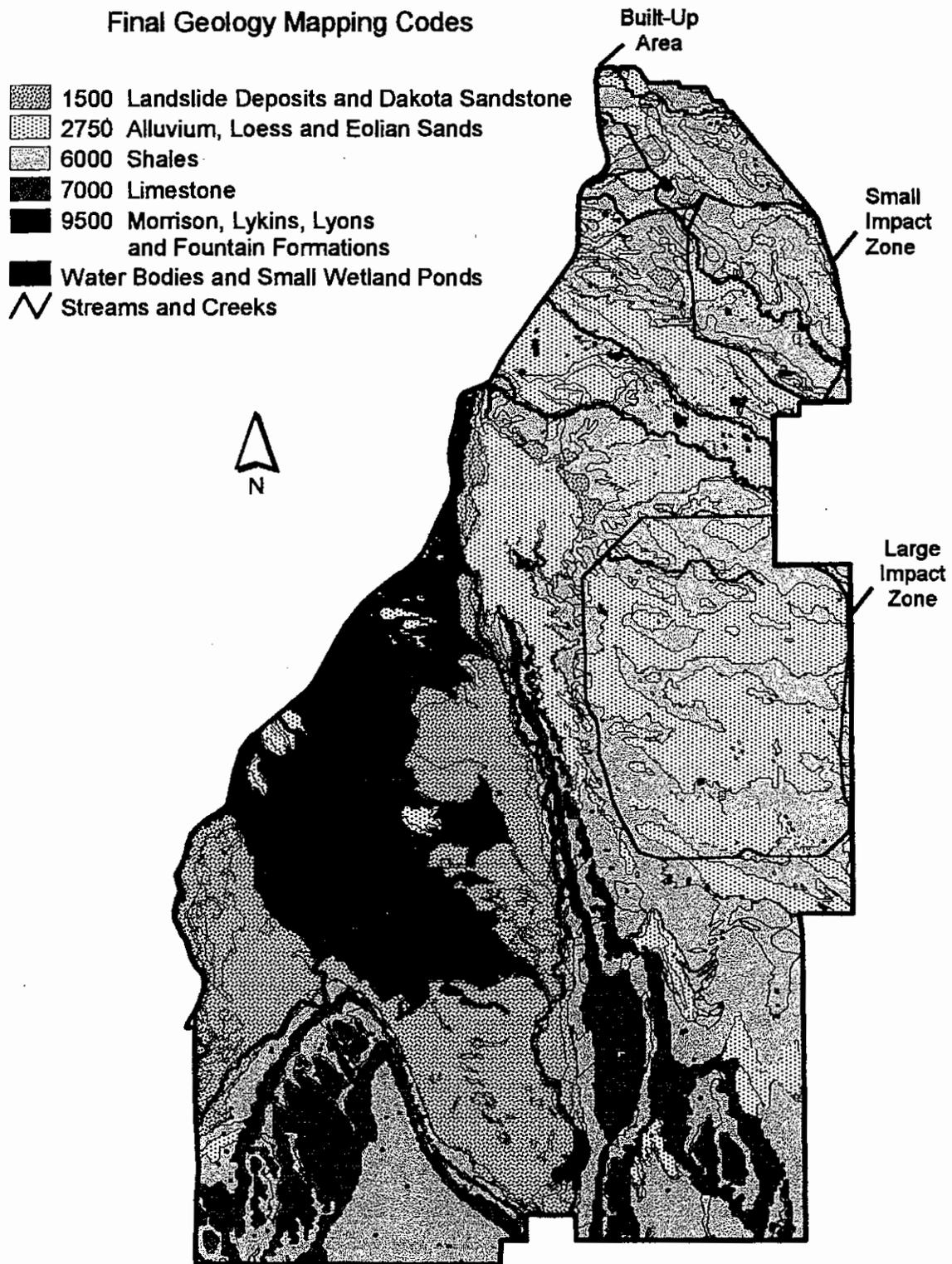


Figure 3. Distribution of five final geology mapping codes at Fort Carson, Colorado.

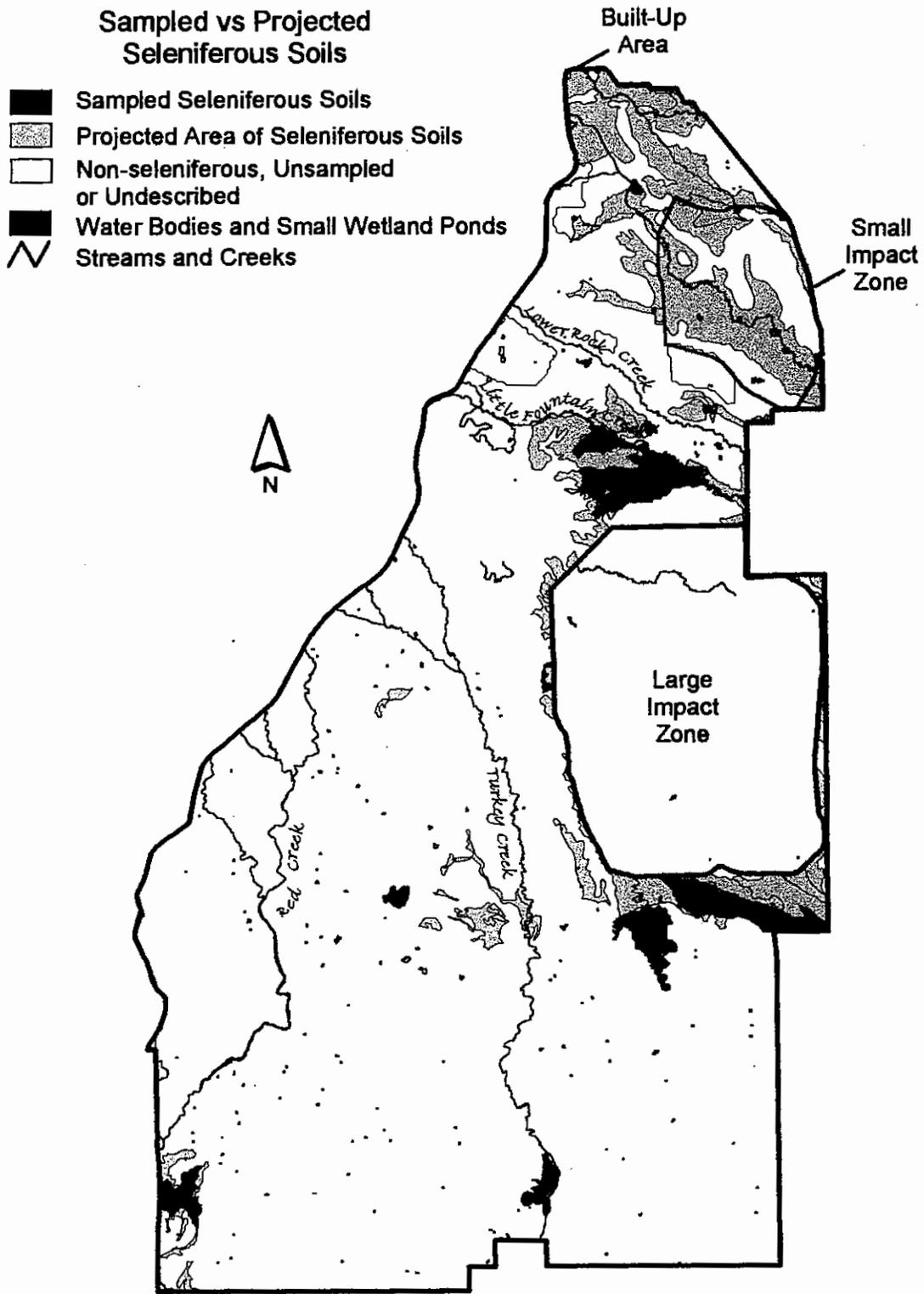


Figure 4. Soil mapping unit area containing sites with soil Se > 0.5 mg/kg compared to projected seleniferous areas based on similar soil units alone.

Table 2. Sampled versus projected area of soils with > 0.5 mg Se/kg

	Heldt Clay Loam	Kim Loam	Limon Clay	Razor-Midway Complex (Clay Loam)	Wiley Silt Loam	Totals
Soil Mapping Unit Code	3750	2500	2500	3750, 2500	3750	
Soil Description	Haplocambids	Torriorthents	Torriorthents	Haplocambids Torriorthents	Haplargids	
Number of Sites Sampled (Seleniferous)	8 (5)	1 (1)	2 (2)	3 (1)	2 (1)	16 (10)
Sampled Polygon area (ha)	959	97	244	1,452	33	2,785
Projected Area (ha)	1,233	458	331	3,747	351	6,120
Sampled % of Total Area	2.1	0.24	0.51	3.2	0.12	6.2
Projected % of Total Area	2.8	1.0	0.71	8.4	0.81	14

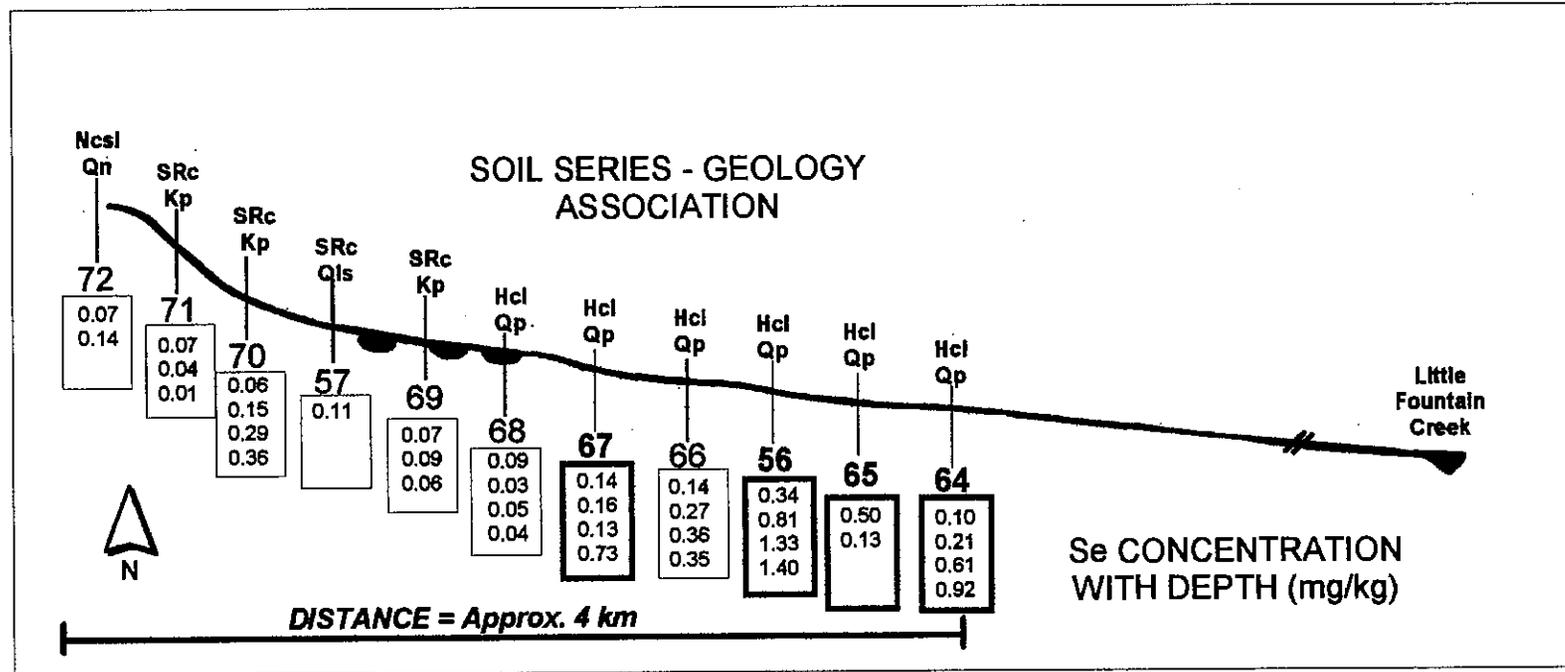
Kim loam soils formed in Cretaceous-aged Smoky Hills shale exhibited the highest maximum Se concentration. Sites in Heldt clay loam soils formed on Piney Creek alluvium underlain by Cretaceous-aged Pierre shale had the next highest Se concentrations. Four of six transect sites with Heldt clay loam Aridisols formed on Quaternary age Piney Creek alluvium underlain by Cretaceous-aged Pierre shale were seleniferous (Figure 5). These sites were located in downslope positions where surface runoff and Se accumulated in fine-textured soils. Sites located in coarse, rocky upland positions where soils were formed on

parent materials or alluviums eroded from granitic geologic sources were found to be non-seleniferous.

Two geology codes were represented by the seleniferous soil samples. All, with the exception of one of the Limon clay samples, occurred within "Shale" geology mapping units. The one Limon clay sample occurred within a unit of "Alluvium, Loess and Eolian Sand". Geologic units represented by seleniferous sites included units in the Smoky Hills shale, Graneros shale, Pierre shale, and Piney Creek alluvium underlain by Pierre shale (Table 3).

Table 3. Maximum, minimum and average Se concentration for sites with seleniferous soils.

Site No.	Soil Se (mg/kg)			Soil Classification	Geology Classification
	Max	Min	Avg		
91	1.7	0.56	1.1	Kim Loam	Smoky Hills Shale
45	1.2	0.12	0.47	Limon Clay	Graneros Shale
62					Piney Creek Alluvium
67	1.6	0.10	0.66	Heldt Clay Loam	Piney Creek Alluvium (underlain by Pierre Shale)
92					
65					
56					
64	1.6	0.10	0.66	Heldt Clay Loam	Piney Creek Alluvium (underlain by Pierre Shale)
11	0.82	0.23	0.52	Razor-Midway Complex (Clay Loam)	Pierre Shale
34	1.0	0.90	0.95	Wiley Silt Loam	Smoky Hills Shale



SOIL SE CONC. (mg/kg)

- 64
 Seleniferous Soils
- 72
 Nonseleniferous Soils
- Ponds
- Creek

SOIL SERIES

- Ncsl Nederland cobbly sandy loam 9-25% slopes
 SRc Schamber-Razor complex 8-50% slopes
 Hcl Heldt clay loam 0-3% slopes

GEOLOGIC MATERIAL or FORMATION

- Qn Nussbaum alluvium (unconformity; major uplift)
 Kp Pierre shale
 Qls Landslide deposits
 Qp Piney Creek alluvium (unconformity)

Figure 5. Comparison of Se concentrations by soil series and geologic formation for sampling sites in the Agony Hill watershed transect area.

Extrapolation of Se-containing Areas to Potentially Seleniferous Areas

Querying the ArcView database for areas with soils similar to sites with seleniferous soils resulted in projected potentially seleniferous areas of approximately 6,120 ha (15,116 acres), or 13.7% of the described mapping unit area (see Figure 4). These units were distributed primarily within floodplains and along streams in the northern portion of the Fort Carson study area, areas surrounding the large impact zone, along the southwestern boundary of the installation, and several small areas within the interior of the military base.

When geologic materials for sampled seleniferous sites were identified by GIS query, the projected potentially seleniferous area based on similar geologic materials totaled 22,448 ha (55,446 acres), or 40% of the study area (Figure 6). Using the soil-geology combinations associated with seleniferous soils, similar soil-geology relationships across the study area would account for 9,500 ha (23,500 acres), or 17% of the study area (Figure 7).

Discussion

Geologic formation and erosion of seleniferous materials is instrumental in determining where Se accumulates in the soil environment. Sedimentary rock, particularly Cretaceous sandstones, shales, and volcanic ashes, have been found to have high levels of Se (Wells 1965, Burau 1989, Presser and Swain 1990, Dreher and Finkelman 1992). Geologic materials in sites where Se levels exceeded the critical level for soils (≥ 0.5 mg Se/kg) within Fort Carson were primarily Cretaceous age shales along streams and creeks. If the source of Se in these areas is locally present seleniferous geologic materials, continuous influxes of seleniferous erosional deposits would occur over time as a result of flooding and the subsequent scouring of the landscape during storms, increasing the potential for Se oxidation, solubility and transport. If Cretaceous-aged geologic materials alone were used as the only factor to identify areas with potentially seleniferous soils, 60% of the study area would have the potential to be seleniferous.

Two factors "presence of water and erosion" are significantly involved in the mobility and transport of Se within Fort Carson. Coarse-textured soils with potentially greater permeability occurred primarily on hilltops and side slopes where runoff potential and/or erosion is likely greater than infiltration of precipitation. Soils on low-lying slopes, however, would be the receptors of transported eroded soils and accumulation of sediments. Fine-textured soils in low-lying positions below the

hillslopes would have greater water-holding capacity and, thus, greater potential for interaction of seleniferous materials with water resulting in dissolution of Se. However, with evapotranspiration an increase in the relative concentration of ions in solution would be expected; over time, these ions would be immobilized when water for transport is insufficient. Recurring periods of heavy precipitation and subsequent transport across the landscape would reactivate mobility of seleniferous materials in the environment.

ArcView queries located areas with soil Se concentrations above the critical level primarily within the arid eastern half of the study area. The seleniferous soils were identified as Torriorthents (Entisols with little soil development), Haplocambids (Aridisols, with little organic matter in very fine sands) and Haplargids (Aridisols, with an argillic horizon and a cold soil regime) all located in areas that have been heavily disturbed by military equipment.

Land disturbances as a result of military activities, together with intense summer rains, facilitate erosion and the potential for Se transport in soils that already have a moderately high erosive nature. Numerous streams dissecting the mountains and foothills in Fort Carson become potential Se transport mechanisms as they carve paths through the landscape. Sediments are distributed within the floodplains of the streams and creeks and deposited on top of other soils and geologic formations.

During and after torrential summer rainstorms in southeastern Colorado, the streams carry large amounts of eroded sand and rock fragments from upstream, and sediments scoured by the tumbling and abrasive action of rocks move along stream beds and riverbanks. In flood conditions, movement of waters across the landscape can occur along great distances, and fine silts and clays are deposited across the low-lying plains. Flowing from higher elevations in the western half of the study area to lower elevations in the eastern half of the study area, stream flow eventually decreases, and energy to carry the load of eroded materials subsides.

Heavy deposits of sediment accumulate in areas where soils already exhibit runoff at slow to medium rates, particularly where erosion control ponds have been constructed. This increases the amount of water that is retained and, consequently, retention of potentially Se-laden waters in soils for extended periods of time. Water levels eventually subside due to infiltration, evaporation or runoff; but fine-textured soils, especially whose primary components are clay particles, have a greater capacity for holding and retaining water. In the arid environment of Fort Carson, evapotranspiration of water

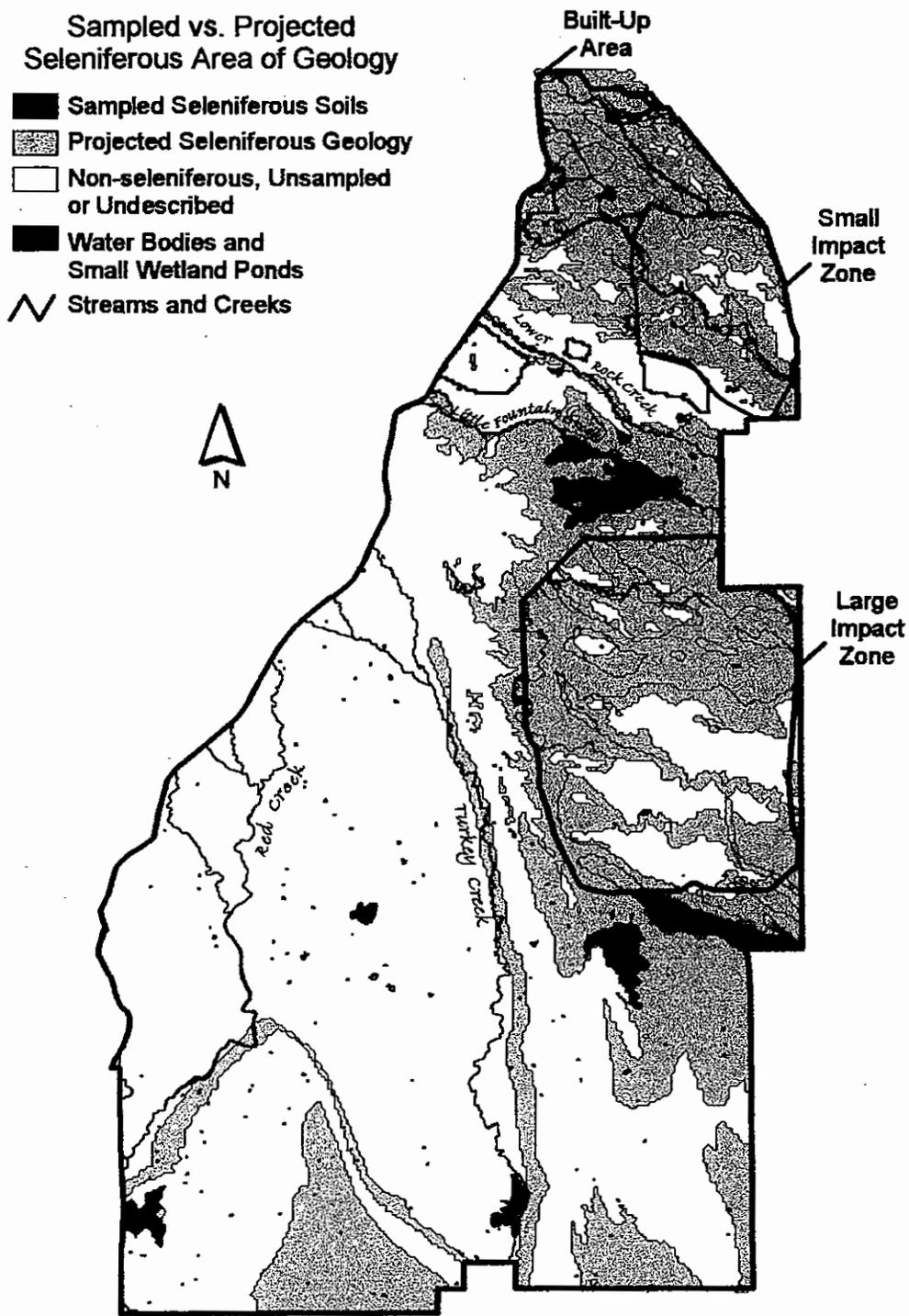


Figure 6. Geology mapping unit area containing sites with soil Se > 0.5 mg/kg compared to projected seleniferous areas based on similar geology units alone.

**Sampled vs. Projected Seleniferous
Areas of Soil-Geology Combinations**

-  Sampled Seleniferous Areas
-  Projected Seleniferous Soil-Geology
-  Non-Seleniferous, Unsampled
or Undescribed
-  Water Bodies and Small Wetland Ponds
-  Streams and Creeks

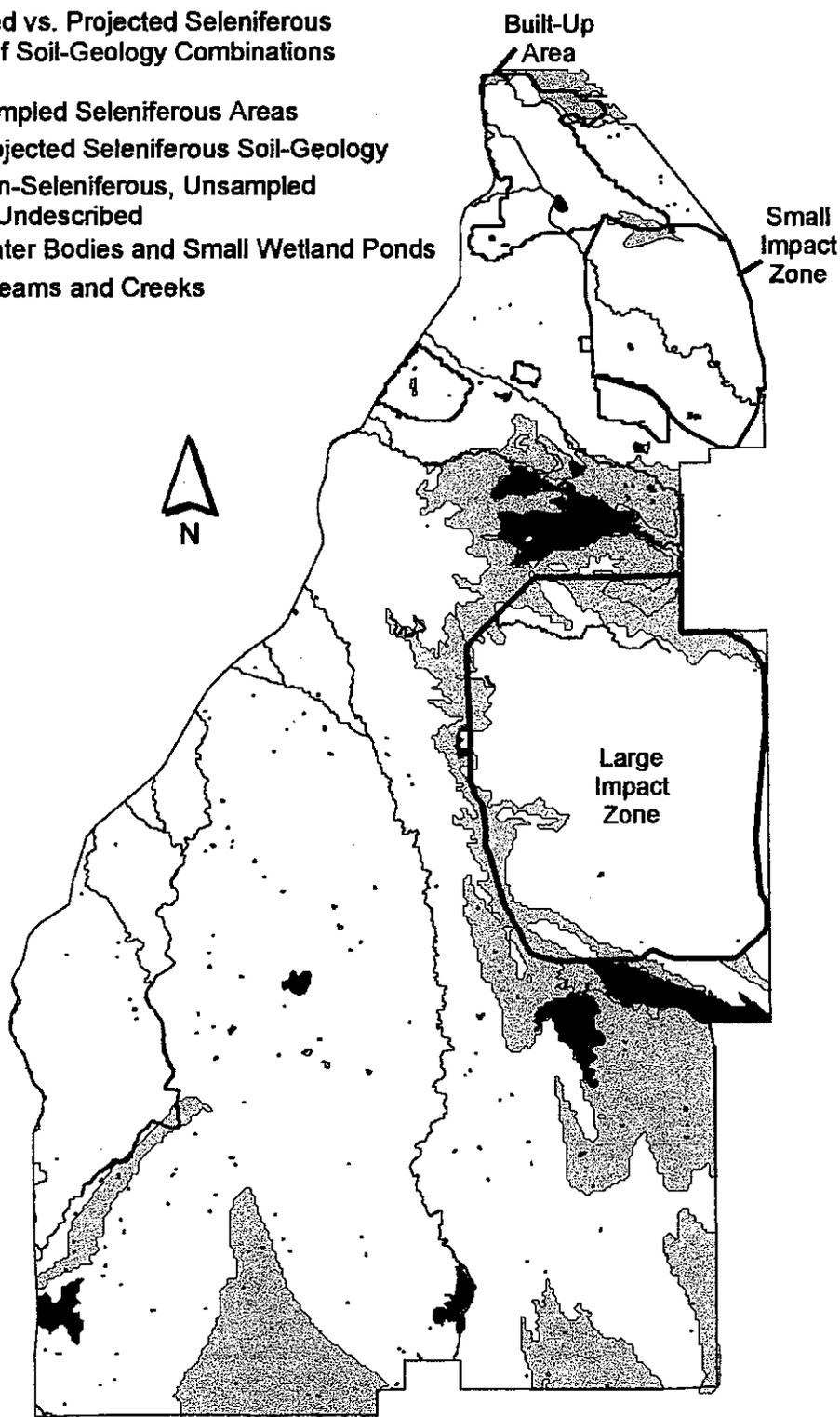


Figure 7. Soil-Geology combination mapping unit area containing sites with soil Se > 0.5 mg/kg compared to projected seleniferous areas based on similar soil-geology combinations alone.

can further concentrate Se in the soils and soil solution. Thus, transport and deposition of seleniferous materials from west to east, and concentration in fine-textured sediments of the High Plains account for the distribution of seleniferous soils along streams and creeks in the eastern half of Fort Carson.

Landslide deposits and granitic alluvial fans associated with the slopes of the Rocky Mountain foothills at the western boundary of Fort Carson form coarse-textured soils, particularly because smaller particles are easily transported downslope, and moved by streams to low-lying areas east of the mountain front. These soils have larger pore spaces that readily permit infiltration and have lower water retention. Consequently, any seleniferous materials or erosional deposits within the coarse textured soils tend to exhibit rapid infiltration and transport of Se deeper into the soil profile, as runoff down the hill slopes, and/or subsurface flow downslope into low-lying areas. Transport of larger, coarser particles over the landscape, particularly during intense rainstorms, scours and erodes other soils and geologic materials. Elevated levels of Se may also occur in coarser textured soils (Carnevale et al. 1988), particularly if rainstorm infiltration is sufficient to bring the water table close to the surface where soluble forms of Se can come in contact with the soils.

Soils with moderate permeability (Wiley silt loam and Kim loam) had the highest average Se concentrations (all other soils had slow permeability), suggesting that permeability is a factor in concentration of soil Se. Soils with slow permeability result in greater runoff and evaporation, while moderately permeable soils permit movement of colloids and water into the soil profile. However, lower slopes and slow permeability also suggest potential for accumulation of fine soil particles (e.g., clays) that can retain water easily and block infiltration of water into the soil pores. Higher slopes and slow permeability suggest a greater opportunity for runoff and evaporation of colloids and water before they can infiltrate into the soils. Moderately permeable soils with slopes neither low nor high suggest that colloids and water can infiltrate into these soils and accumulate in the soil profile. The seleniferous soils in Heldt clay loam had slopes of 0-3%. Lower slopes and fine-textured soils provide an environment conducive to poor drainage, water retention and, in an arid environment, potential for concentration of Se upon evaporation of water from soils. The majority of sites sampled in the Heldt clay loam (five out of eight samples), many of which occurred within the Agony Hill transect, exhibited Se levels greater than the critical level for soils (see Figure 5).

Erosion is a primary factor that must be taken into consideration for Se in the environment to become

mobilized and concentrated in soils, but erosion plus geologic material, soil texture and landscape position can give a clearer picture of the potential for seleniferous soils to form. Fine-textured soils and geologic materials with the propensity to be seleniferous and easily eroded provide the parent material that enhances the formation of seleniferous soils. A query of seleniferous sampling sites in Fort Carson indicated that the geology of the sites was primarily shale or alluvium overlying shale. Shales are sediments composed of soft layers of fine-textured particles that are not well lithified, crumble easily to form soils, and readily weather into gentle slopes, rather than remaining as rock outcrops like sandstone and limestone (Tarbuck and Lutgens 1984).

Low-lying shale landforms that characterize the eastern half of Fort Carson provide the setting for weathering, deposition and accumulation of Se in sediments and waters. Geologic materials upon which seleniferous soils have formed include terraces, alluvial fan sediments, clayey alluvium, residuum and eolian deposits that have been influenced by erosion processes. Thus, that these materials may be seleniferous as a result of exposure and oxidation of Se during the erosion process is highly likely. The fact that one sample was seleniferous out of many samples of similar soils suggests not only that Se distribution can be quite variable, but also that transport of other eroded soils or geologic materials nearby can influence Se concentration.

Summary and Conclusions

The Fort Carson terrain is complex in nature with several potential geologic sources of Se that can accumulate in soils. Spatial distribution of sampling sites with Se concentrations that exceed the critical level of 0.5 mg Se/kg suggests relationships exist between soils and slope of formation, soil texture and geologic formations. Based on measured Se levels and descriptive mapping unit codes of sampling sites, extrapolation to unsampled areas suggests the eastern half and southwestern quarter of the study area have the greatest potential for having seleniferous soils and geology. Identification of areas likely to support seleniferous soils would assist revegetation and remediation efforts designed to prevent future Se problems.

Sites with seleniferous soils occurred primarily within units where soils were formed on Cretaceous-aged Graneros and Smoky Hills shales, or Piney Creek alluvium underlain by Cretaceous-aged Pierre shale. These sites were predominantly located along streams, creeks, or areas influenced at least temporarily by the presence of water (e.g., erosion control ponds). Soil Se increased with depth and in distance downslope to low-lying positions in the watershed drainage. The Heldt clay

loam soils-Piney Creek alluvium combination was the most common soil-geology unit supporting sites with seleniferous soils.

Soils formed from the silts, clays and weathered shales result in a texture conducive to significant water retention and Se concentration in an arid environment. Due to the nature of military activities that exacerbate natural erosion processes in areas with Se levels above the suitability limits, there is significant potential for seleniferous materials to be transported throughout the landscape. Of concern would be erosion of potentially seleniferous materials within the large impact zone, and transport and deposition of seleniferous sediments from numerous small streams off the installation and into Fountain Creek where eventual transport and deposition into the Arkansas River might occur.

Geologic formations identified by GIS queries where soils contained critical levels of Se were predominantly Cretaceous age shales, or Quaternary alluvium underlain by Cretaceous age shales. However, the Cretaceous age Pierre shale exhibited only one sample in 11 that was seleniferous. The locations of the soils sampled on Pierre shale were of high slopes or rocky soils, conditions that would permit rapid runoff or infiltration of waters, rather than accumulation of erosional deposits and concentration of Se in the soils.

Combinations of soils and geology can be an important factor in identifying potentially seleniferous soils rather than simply soil or geology alone. Since only one seleniferous sample out of 11 was collected from soils in the Pierre shale, further sampling should be done to determine whether this Cretaceous age material would be expected to be seleniferous in other areas particularly depending on the slope of the sampling site.

It is important to note that soils within the impact zones were not surveyed nor included in the descriptive mapping units. Consequently, based on our projections, the potential exists for a greater area of seleniferous soils to occur within the Fort Carson study area if soils within the impact zone are similar to the five potentially seleniferous soil series described in our study. This can pose a problem for environmental protection if continued disturbance within the impact zone increases mobility of Se by erosion of soils and transport by water during frequent torrential seasonal storms and floods.

Further research should include determination of the depth of alluvial floodplain deposits in relation to contact with geologic formations to better analyze the Se sources and transport processes within the study area. Determination of transport pathways should be mapped

to provide a clearer picture of the potential sources of seleniferous materials. Alluvial deposits may be sufficiently shallow for plants to root directly into seleniferous materials lying below the deposits. Alluvial deposits also may be a complex combination of many geologic materials, some potentially seleniferous, and transported through other seleniferous areas, complicating identification of the Se sources. Additional sampling should be done within projected areas of concern as a means of field testing the results of this study.

Further sampling of transects is recommended for potentially seleniferous areas. Samples from soils similar to those from this study within the Graneros shale would make likely areas for such sampling. Soils formed on low slopes (0-5% for most of the soils sampled in this study), fine-textured soils formed on shales (e.g., clays, loams and clay loams) that can retain soil moisture and concentrate Se, and those formed on geologic materials of Cretaceous age suggest potential for soils to be seleniferous.

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