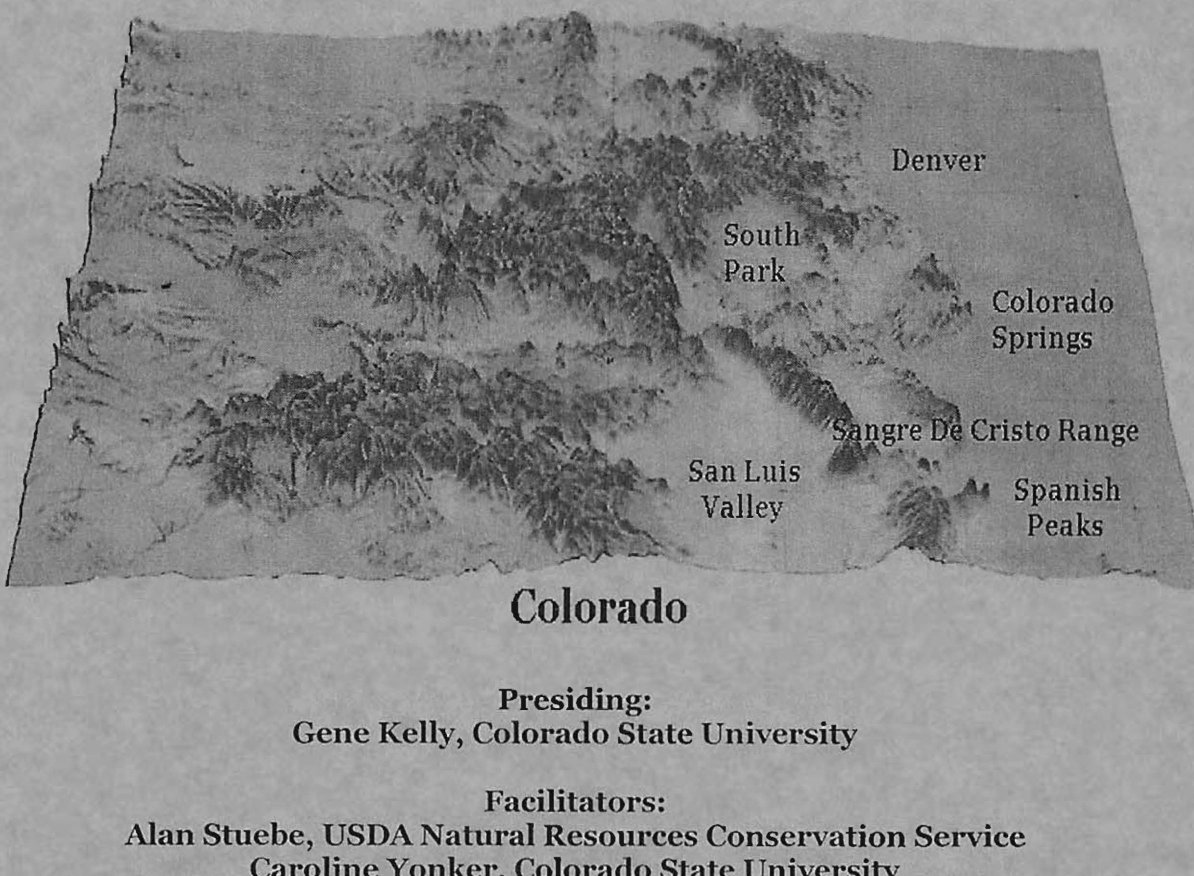
ASA 2003

Soils and Landforms of the Sangre de Cristo Range and Eastern San Luis Valley

Pre-Meeting Field Tour



Colorado

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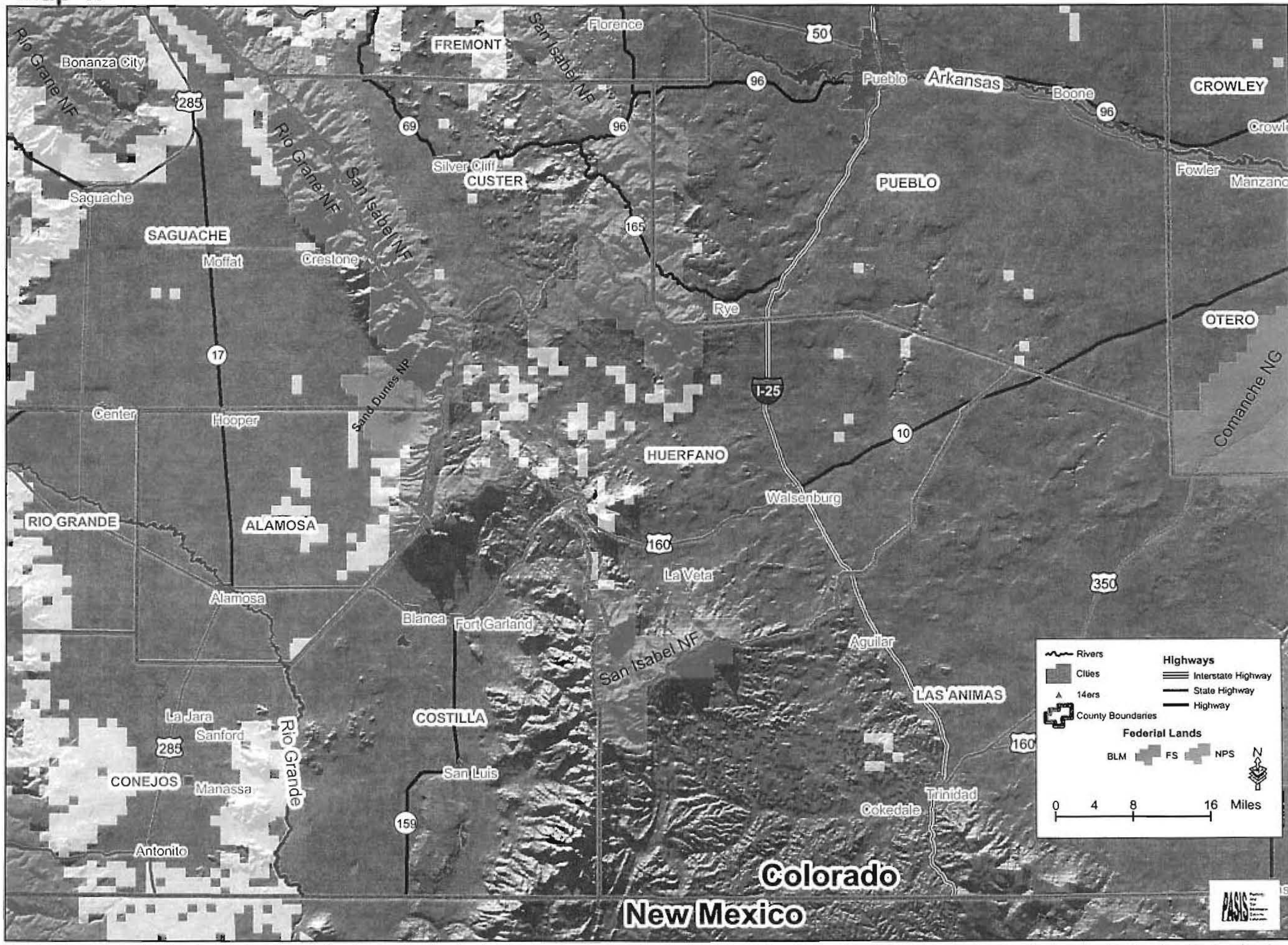
Road Log, Colorado Springs – San Luis Valley

Map 1.



Rio Grande NF
Bonanza City
FREMONT
San Isabel NF
Florence
50
96
Pueblo
Arkansas
Boone
CROWLEY
285
69
Rio Grande NF
San Isabel NF
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Walsenburg
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Alamosa
Blanca
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Aguilar
San Isabel NF
LAS ANIMAS
COSTILLA
La Jara
Sanford
Rio Grande
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CONEJOS
Manassa
San Luis
160
Trinidad
Cokedale
159
Antonito
Colorado
New Mexico
Rivers
Cities
14ers
County Boundaries
Highways
Interstate Highway
State Highway
Highway
Federal Lands
BLM
FS
NPS
N
0
4
8
16
Miles
PASIS

Geologic Time Scale

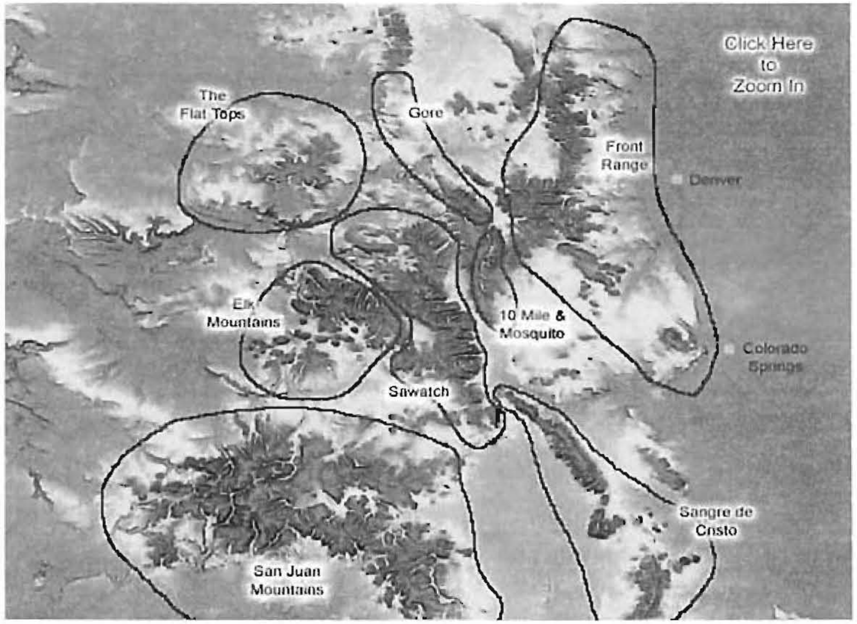
ERA	PERIOD	EPOCH
CENOZOIC	Quaternary	Holocene Pleistocene
	Tertiary	Pliocene Miocene Oligocene Eocene Paleocene
MESOZOIC	Cretaceous Jurassic Triassic	
PALEOZOIC	Permian Pennsylvanian Mississippian Devonian Silurian Ordovician Cambrian	
PRECAMBRIAN		

Road Log Day 1
Colorado Springs – Fort Garland

Mile Marker **Feature/text**

I-25:

Pikes Peak - At 14,110 ft, Pikes Peak ranks 30th in elevation amongst Colorado's 53 "Fourteeners". The state holds thousands of peaks over 11,000 ft, scattered throughout its many mountain ranges.



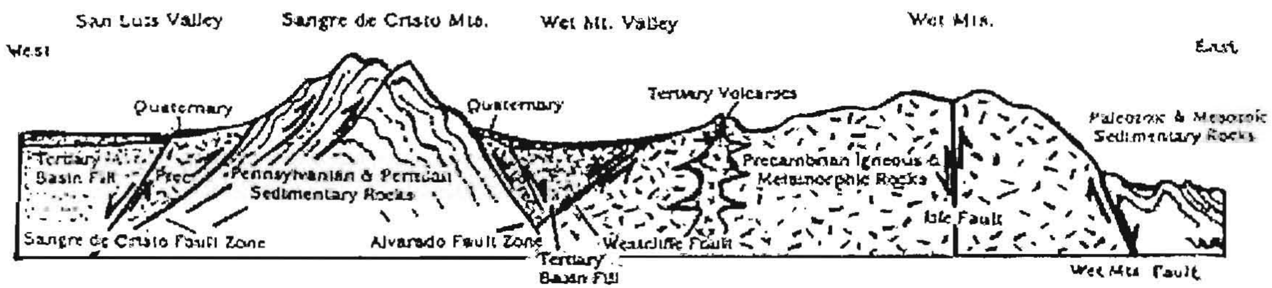
Source: http://www.14ers.com/

Conspicuously higher than its neighbors, Pikes Peak rises farther from its base than any other mountain in the state. Almost the entire mountain consists of Precambrian granite and pegmatite, a highly resistant mass that was uplifted during the Laramide Orogeny (late Cretaceous/early Tertiary) and glaciated during the Pleistocene.

135 End of Front Range - The Front Range of the Rocky Mountains ends abruptly at Cheyenne Mountain. Cheyenne Mountain is the home of the North American Aerospace Defense Command (NORAD), a binational military organization established by Canada and the United States in 1958. NORAD's mission is the surveillance and control of the continental aerospace.

116 Tepee Buttes – These conical hills on the eastern skyline are resistant deposits of limestone within Cretaceous Pierre Shale.

115 View of Wet Mountains - The Wet Mountains, a core of Precambrian rocks, are bordered by the Front Range to the northeast and the Sangre de Cristo Mountains to the southwest.



DIAGRAMMATIC CROSS SECTION, SANGRE DE CRISTO MTS., WET MT. VALLEY, AND WET MTS.

Source: Once *Upon a Geologice Era:Pondering the Deep Past of Custer County* by Wayne Anderson, University of Northern Iowa (http://www.uni.edu/~andersow/once__upon_a_geologic_era.htm)

108-102 Baculite Mesa – The large mesa on the eastern skyline is a remnant of Cretaceous Pierre shale, and is so named for the ammonite Baculites (relative of the modern Chambered Nautilus) it contains.

92 Pueblo-Walsenburg – The highway follows the route of the old Taos Trail. Along the eastern skyline for many miles the Cretaceous limestone forms cuestas.

73 Outcrop of Dakota sandstone – Dakota sandstone is Colorado's most widespread rock unit, and can be traced along the edge of the mountains from Wyoming to New Mexico. It is the lowest of the Cretaceous deposits in the state and comes to the surface along the mountain front where it was upturned during Rocky Mountain uplift (Laramide orogeny) in the early Tertiary.

69 Spanish Peaks - The peaks, which were once described by Spanish conquistadores as "the great isolated double mountain situated at the northernmost limits of the Empire" are visible on the southwestern skyline. They will be described in more detail later in the road log.

60 Huerfano – The isolated cone-shaped hill on the eastern skyline is named Huerfano, the Orphan, and was used as a landmark on the Taos Trail. It is a Tertiary volcanic neck.

56 Volcanic dike – This dike is one of the approximately 500 dikes that are coeval with, and radiate from, the Spanish Peaks. The tallest of the dikes is 100 feet, the widest is 60 feet, and the longest is 15 miles.

Exit to Highway 160

Highway 160:

Driving west out of Walsenburg is a broad sloping plain of Tertiary sedimentary rock that was actually formed from materials derived from the Sangre de Cristo mountains as they were uplifted.

301 Spanish Peaks – The Spanish Peaks, clearly visible to the south, are two large magma intrusions that pushed their way through Cretaceous and Tertiary sediments. Mid-Tertiary in age, they formed after most of the Colorado mountain ranges were in place. The East and West peaks are 12,683 and 13,623 feet in elevation, respectively.

288 Mt. Mestas – This mountain, clearly visible immediately north of the highway, is a Tertiary intrusion through one of the main faults on the eastern margin of the Sangre de Cristo Range. Bare and domelike, it is composed of microgranite (microscopic crystals of quartz, feldspar and mica).

281 Sangre de Cristo Range – The Sangre de Cristos, meaning "Blood of Christ", are so-named for their dominant lithology, Pennsylvanian and Permian age red sedimentary rock. They are the second youngest mountain range in the continental U.S., and owe their jagged appearance to their youth. The range is 235 miles in length, extending from Salida, Colorado to Santa Fe, New Mexico. The following text is excerpted from *Rocky Mountain Geology: South Central Colorado* by James S. Aber, Emporia State University (http://academic.emporia.edu/aberjame/field/rocky_mt/rocky.htm)

Geologic history of the region

The ancient basement rocks of southern Colorado were formed during Proterozoic orogenies, mostly in the middle Proterozoic, 1.0 to 1.8 billion years ago. A great variety of granites and metamorphic rocks make up the Proterozoic crust. These rocks have been uplifted to form the cores of many ranges of the Rocky Mountains, including the Culebra Range of the Sangre de Cristo Mountains. The erosional resistance of the these crystalline rocks supports the high peaks.

The period from late Proterozoic through middle Paleozoic was a time of stable continental conditions in which various sedimentary strata were deposited in shallow seas and low-lying land environments. Limestone, dolostone, sandstone, and shale mark this interval. At times the region underwent erosion, so no rock record was preserved. Rocks of this age are not well exposed in the field geology region.

Beginning in the Pennsylvanian, a significant change took place in Colorado tectonics. A mountain range was uplifted. Known as the **Ancestral Rocky Mountains**, this uplift took place in the same position as the modern Rocky Mountain Front Range, which includes the Sangre de Cristo Range. Substantial uplift combined with rapid erosion to produce immense quantities of coarse clastic sediment--sand and gravel, which was deposited in basins adjacent to the mountain front. These sediments are represented today by thick redbed sequences of Pennsylvanian and Permian age, which are exposed in the foothills along the eastern margin of the Culebra Range. By the end of the Permian, the Ancestral Rocky Mountains had been eroded down to low hills and plains. Through the following Triassic and Jurassic, the region remained continental with accumulation of alluvial and aeolian sediments.

A switch to marine environments took place in the Cretaceous as shallow seas transgressed over the mid-continent region. These marine transgressions resulted from local subsidence of the crust combined with global rises in sealevel. In Colorado, marine sandstone, shale, and chalk accumulated to considerable thickness during the Cretaceous. These strata are well exposed within the Apishapa Uplift and around the margins of the Raton Basin, where more resistant strata form escarpments and hogbacks.

The **Larimide orogeny** began in latest Cretaceous time and continued through the early Tertiary. This orogeny formed the fundamental structures of the modern Rocky Mountains. Mountain ranges were uplifted as tilted crustal blocks bounded by thrust and reverse faults. Proterozoic crust was thrust over Paleozoic and younger strata. Major thrust faults mark the eastern edge of the uplifts, as in the Culebra Range of the Sangre de Cristo Mountains. Uplift of the mountain ranges culminated in the Eocene and was accompanied by subsidence of marginal basins--the Raton Basin, which were filled by great thicknesses of clastic sediment. More than a kilometer of Tertiary sediment is preserved in the Raton Basin in vicinity of Spanish Peaks, for example. Larimide structural deformation was essentially complete in the southern Rocky Mountains by the end of the Eocene.

The mid-Tertiary witnessed a change from crustal compression to crustal extension, as the **Rio Grande rift** system began to open up west of the Sangre de Cristo Mountains. This rift propagated northward from New Mexico into south-central Colorado during the Oligocene and Miocene. Widespread magma intrusions and volcanic eruptions took place in Colorado, New Mexico, and western Texas in connection with rifting. The Raton Basin was a focus for igneous activity within the field-geology region. Thick Tertiary sediments of the basin were intruded at Spanish Peaks, Goemmer Butte, Mount Maestas, Silver Mountain and White Peaks, and great dike systems were formed in connection with several of these intrusions. Most of this igneous activity took place between 27 and 21 million years ago in latest Oligocene and early Miocene times (Penn and Lindsey 1996).

Tectonic activity gradually diminished during the late Tertiary and Quaternary. A few volcanic centers continued to erupt in New Mexico, and the Rio Grande rift zone became relatively stable. Beginning in the Pliocene, the mid-continent region underwent a dramatic rise. Crustal uplift of the entire southern Rocky Mountains and Colorado Plateau regions exceeded one mile (1.6 km) in vertical movement. Rivers entrenched deep canyons, such as the Royal Gorge of the Arkansas River west of Canon City, and massive erosion of the landscape took place. Soft sedimentary strata were washed away leaving more resistant rocks to form the plateaus, buttes, peaks, and ridges of the modern landscape. The history of erosional downcutting is revealed by prominent terraces and pediments within the Cuchara drainage basin.

The most recent geological event of note was the "Ice Age" during the Pleistocene Epoch, 1 million to 10,000 years ago. The high peaks of the Sangre de Cristo Mountains supported numerous small glaciers. These glaciers carved a classic assemblage of alpine landforms, including cirques, horns, aretes, and cols. Lower in the glaciated valleys, various kinds of till and stratified sediments accumulated to form moraines. Small kettle lakes occupy lateral and end moraine complexes. Most of the glacial deposits and landforms date from the last glacial phase, known in the Rocky Mountains as the **Pinedale Stage**. The glaciated terrain is among the most picturesque in the high alpine environment today.

Stream and river downcutting increased during the middle and late Pleistocene. According to Dethier (2001), the Culebra Range and adjacent High Plains experienced stream incision rates of 10-15 cm per 1000 years during the past 600,000 years. This adds up to 6-9 m (20-30 feet) of stream downcutting, which is thought to be a consequence of increased precipitation and runoff from the southern Rocky Mountains rather than a result of crustal uplift.

279 La Veta Pass – Descending west from the pass (elevation 9413 ft), the following rock formations are clearly visible:

276 Sangre de Cristo Formation – The outcrop consists of soft red shale, sandstone and conglomerate of Pennsylvanian and early Permian age.

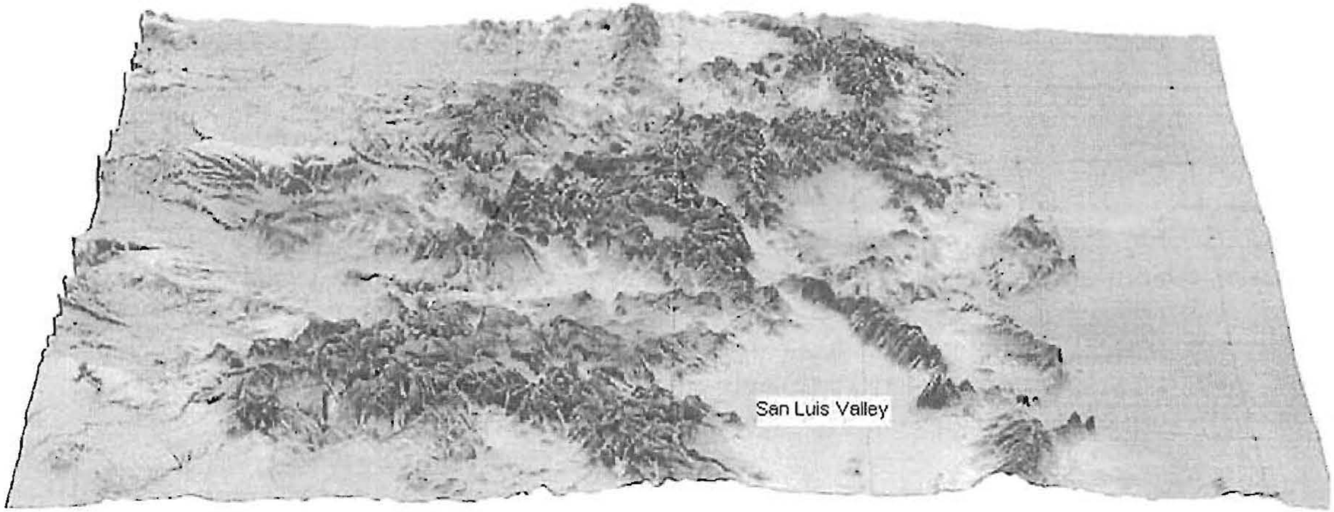
276-273 Sangre de Cristo Formation – The outcrop is the basal portion of the formation and consists of gray, fossiliferous sandstone, shale and limestone of Pennsylvanian age.

273-268 Precambrian rock – The outcrop consists of granite, gneiss, schist. Bright, yellow-green epidote is visible on fracture surfaces at mile marker 268.

268+ Volcanics – The outcrop consists of lavender and purple volcanic rocks of Oligocene age that are associated with the San Luis volcanic field.

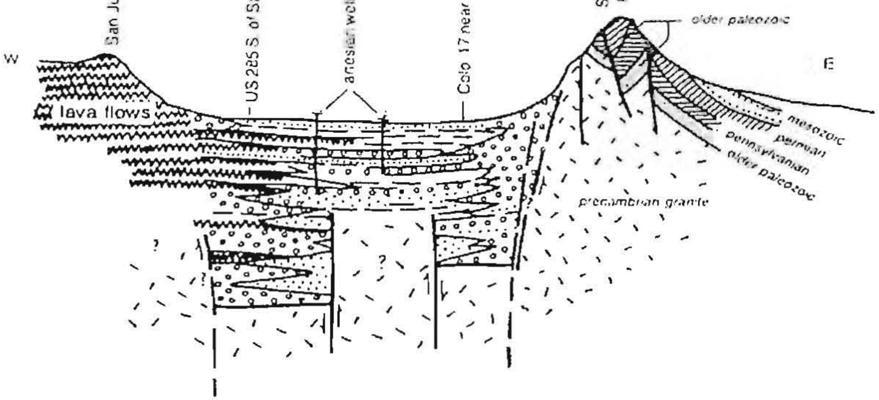
259 Mt. Lindsey and Blanca Peak – These two mountains, clearly visible on the northwestern skyline, consist of Precambrian rock that juts out along the western flank of the Sangre de Cristos. Mt. Lindsey is 14,042 ft in elevation and ranks 43rd amongst Colorado's fourteeners. Blanca Peak is 14,345 ft in elevation and ranks 4th.

San Luis Valley – The San Luis Valley is as large as the state of Connecticut, is a true desert receiving less than 8 inches of precipitation a year, and is considered the world's largest alpine valley. It is approximately 125 mi long and over 65 mi wide; elevation averages 7500 ft.



Source: http://www.14ers.com/

San Luis Valley



Source: Chronic, H. 1980. Roadside Guide to the Geology of Colorado. Mountain Press Publishing Co, Missoula, MT.

The following text is excerpted from *Rocky Mountain Geology: South Central Colorado* by James S. Aber, Emporia State University (http://academic.emporia.edu/aberjame/field/rocky_mt/zapata.htm)

Overview

The San Luis Valley is part of the Rio Grande Rift system that extends from central Colorado southward through New Mexico and West Texas into northern Mexico. The San Luis Valley of southern Colorado has been called the highest, largest, mountain desert in North America (Trimble 2001). The rift system began to form in the Oligocene, as a large graben sank along deep bounding faults. At the same time, tremendous volcanic eruptions and associated intrusions built up the San Juan Mountains to the west and intrusions took place to the east.

The magnitude of structural movements is demonstrated by more than 30,000 feet (9 km) of Oligocene-Holocene sedimentary and volcanic fill beneath the floor of the valley juxtaposed with surrounding ranges rising more than 6000 feet (1800 m) above the valley floor. Since the creation of the valley, large alluvial fans have accumulated against the mountain front. This is most obvious around the flanks of the Sangre de Cristos, where a series of alluvial fans slopes down toward the valley floor. The upper portions of the fans are composed of coarse, cobble and boulder gravel derived from the crystalline mountains. Lower portions of the fans have progressively finer pebble gravel and sand toward the valley floor

Water resources of the San Luis Valley

The San Luis Valley is a true desert, receiving less than 20 cm (8 inches) of precipitation per year. The Rio Grande drains the southern part of the valley through a gorge in volcanic rocks along the Colorado-New Mexico border. In vicinity of Great Sand Dunes, however, the San Luis Valley is a closed depression with no surface outlet for drainage. Surface runoff from the Sangre de Cristos soaks into alluvial fans, and ground water migrates toward the low point at San Luis Lake (< 2300 m altitude). Abundant ground water gives rise to many ephemeral lakes, wetlands, springs and flowing wells, and supports considerable irrigation in the valley.

Throughout most of the San Luis Valley, depth to ground water is less than 12 feet (4 m). Ground water is produced from two major aquifers within the valley (Emery 1971).

- **Unconfined aquifer** -- Up to 200 feet deep consisting of unconsolidated clay, silt, sand, and gravel. Well yields up to 3000 gallons per minute.
- **Confined aquifer** -- From 50 to 30,000 feet deep consisting of unconsolidated sediment interlayered with volcanic strata. Well yields up to 4000 gallons per minute; flowing (artesian) wells.

Excessive use of surface water has led to water logging of soils in many parts of the valley, water-logged soils have become alkaline, and ground water has become highly mineralized from concentration of salts. Although irrigated crop production is good in some areas, much water use is nonbeneficial. Meanwhile, Colorado is obligated to supply water via the Rio Grande southward under terms of the Rio Grande Compact with New Mexico and Texas (Emery 1971). In order to do so, ground water is "salvaged" via high-capacity wells in the northern portion of the valley and transported in canals southward to the Rio Grande.

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Section 2

Bioclimatic- and Litho- sequences

Geomorphic Age and Genesis of Some San Luis Valley, Colorado, Soils

W. D. Nettleton,* B. R. Brasher, J. M. Yenter, and T. W. Priest

ABSTRACT

San Luis Valley is a semibolson in south central Colorado that has varying geomorphic and soil properties. Three sets of geomorphic surfaces were identified corresponding to young, intermediate, and old surfaces. A ^{14}C date of 11 170 YBP on a peat deposit on the valley floor was used to separate Holocene geomorphic surfaces (Set 1) from late-Pleistocene ones (Set 2). The oldest-Pleistocene surfaces (Set 3) studied are believed to be Illinoian in age. They are above the late-Pleistocene age valley floor and are more dissected than the other Pleistocene surfaces. Entisols have formed on the Holocene surfaces (Set 1). These Entisols have some accumulation of organic C and movement of carbonate, but none have calcic horizons. Their sand grains lack clay cutans or other evidence of soil formation. Most of the soils on late-Pleistocene geomorphic surfaces (Set 2) have argillic and calcic horizons, and some have mollic epipedons. Grain argillans on sands are the most common form of illuvial clay and there are calcans in the calcic horizons. Some of the soils have natric horizons. The soils on mid-Pleistocene geomorphic surfaces (Set 3) have a greater clay accumulation than any of the other soils and have calcic horizons. Clay accumulation is largely masked by the carbonate accumulation. The distribution of salt for the most part is in balance with today's arid climate in the valley. The occurrence of carbonate in horizons with illuvial clay, especially in the soils on the oldest surfaces, suggests an arid climate following one or more Pleistocene pluvials. Some of the salt and carbonate may have been added as dust from playas on the valley floor.

THE PURPOSE of this paper was to identify and map the geomorphic surfaces in San Luis Valley (Fig. 1), to characterize the soils found on the surfaces, and to develop soil genesis models for the soils.

San Luis Valley, a semibolson in south central Colorado, is well suited for such a study. Glacial features, some as old as Illinoian (12), have been observed in the mountain ranges on the east and west sides of the valley (2,4,10).

The valley has been subsiding and aggrading since late Miocene time and now contains 600 m of alluvium (10). The Alamosa Formation, the upper part of this alluvium, was considered by Siebenthal (13) to be post-Miocene and preglacial in age. In one of the three soil surveys completed (8,9,23) in the valley since the beginning of the study, a peat deposit was mapped on the eastern side of the valley floor (9). The peat deposit was dateable and provided another measure of the age of the valley floor.

MATERIALS AND METHODS

Landforms and the relative positions of sedimentary deposits were observed during the course of soil surveys of the area (8,9,23). Soils and stratigraphic relationships were examined along auger and spade transects and in backhoe pits to delineate geomorphic surfaces and to assign relative ages. Because of the reconnaissance nature of the survey of the geomorphic surfaces, individual surfaces were not delineated and named. Instead, the surfaces were described as sets, each of which may include more than one individual surface. Youngest surfaces, Set 1, were considered to be those actively eroding or those currently receiving sediment. Oldest known surfaces, Set 3, are of Illinoian age (2,12). Intermediate age surfaces, Set 2, are those inset below the oldest surfaces and either cut or buried by the youngest surfaces.

The valley is cold and dry with cool summers and cold winters. The average precipitation ranges from about 17 cm at Alamosa on the valley floor to about 30 cm on the slopes of the mountains (19).

Besides the three soil surveys that have been published in San Luis Valley (8,9,23) a fourth is in progress. Six pedons are reported from these surveys to show soil development on the three sets of geomorphic surfaces. The six pedons were selected from 16 pedons we have sampled in the valley since 1970.

The soils were sampled and prepared for analysis by the methods described in Soil Survey Investigations Report no. 1 (15). Horizon nomenclature conforms to the designations in use by the National Cooperative Soil Survey (21). The names used for diagnostic horizons and for taxa conform to those used in *Soil Taxonomy* (16) and the 1985 revision (20) and to the *National Soils Handbook* (14).

The particle size distribution analysis was by pipette and sieving (15, method 3A1). The weight of >2-mm coarse fragments was measured by weighing fragments that were <75-mm in diam. and by recalculating the volume estimates of the >75-mm diam. coarse fragments to a weight percent. Calcium carbonate equivalent (15, Method 6E1b), saturation extract (11, Method 3a), electrical conductivity (11, Method 4a), exchangeable sodium percentage (15, Method 5D2), and organic C (15, Method 6A1c) were determined for each soil horizon.

Water retention measurements were taken on Saran-coated natural soil clods at 0.03 MPa (15, Method 4A1). The water available for soil storage was calculated from climatic data by a water balance method (17,18). The average depth of wetting inferred from this calculation is commonly found to coincide with the depth to maximum salt and carbonate accumulation in arid zone soils (1).

The samples collected in 1970 were impregnated with Scotch Cast (Minnesota Mining and Manufacturing Co., St. Paul, MN)[1] by the method of Innes and Pluth (5) for making thin sections. The sections for the 1979 samples were prepared commercially. Terms used to describe the thin sections are for the most part those of Brewer (3).

The ^{14}C date was determined by Teledyne Isotopes (Westwood New Jersey)[1] on a sample of a peat deposit southeast of Alamosa (Fig. 1) after removal of carbonates and humic acids.

RESULTS

Geomorphic Surfaces

Geomorphic surfaces of Set 1 are extensive and include the Holocene surfaces. Common examples are flood plain surfaces with little relief separating them from the constructional surface of the extensive, relict

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Published in Soil Sci. Soc. Am. J. 53:165-170 (1989).

[1] Trade names are provided for the benefit of the reader and do not imply endorsement by the USDA.

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valley floor. These Holocene flood plain surfaces, like the ones on the extensive coalescing alluvial fans on the west, are difficult to separate from the older, nearly level valley floor. One Holocene surface on an extensive bajada (Rio Grande Fan in Fig. 1) diverts the northern streams toward the east side of the valley, but the volume of water from the streams on the west is no longer sufficient to flow across the valley. Sand dunes in the Great Sand Dunes National Monument (Fig. 1) are part of the geomorphic surfaces of Set 1. They lie on the east side of the valley beyond the lake area. The dunes occupy only 1000 km^2, a small part of the valley. Sands in the dunes are mostly quartz with a high percentage of heavy minerals (6).

Geomorphic surface Set 2 includes the relict valley floor, some surfaces that grade to it, and some surfaces that are somewhat older. Besides the relict valley floor, these surfaces are extensive, especially on the northwest side of the valley, and include alluvial fans that occur in two kinds of positions. In one, they merge with the constructional surface of the relict valley floor. In the other, they occur between the mountains and an older set of alluvial fans.

The surface of an extensive peat deposit (mostly Euic Hemic Borosaprists) is one of the geomorphic surfaces of Set 2 on the relict valley floor southeast of Alamosa (Fig. 1, about 8 km east and about 2 km south). The deposit fills the bypassed stream channels

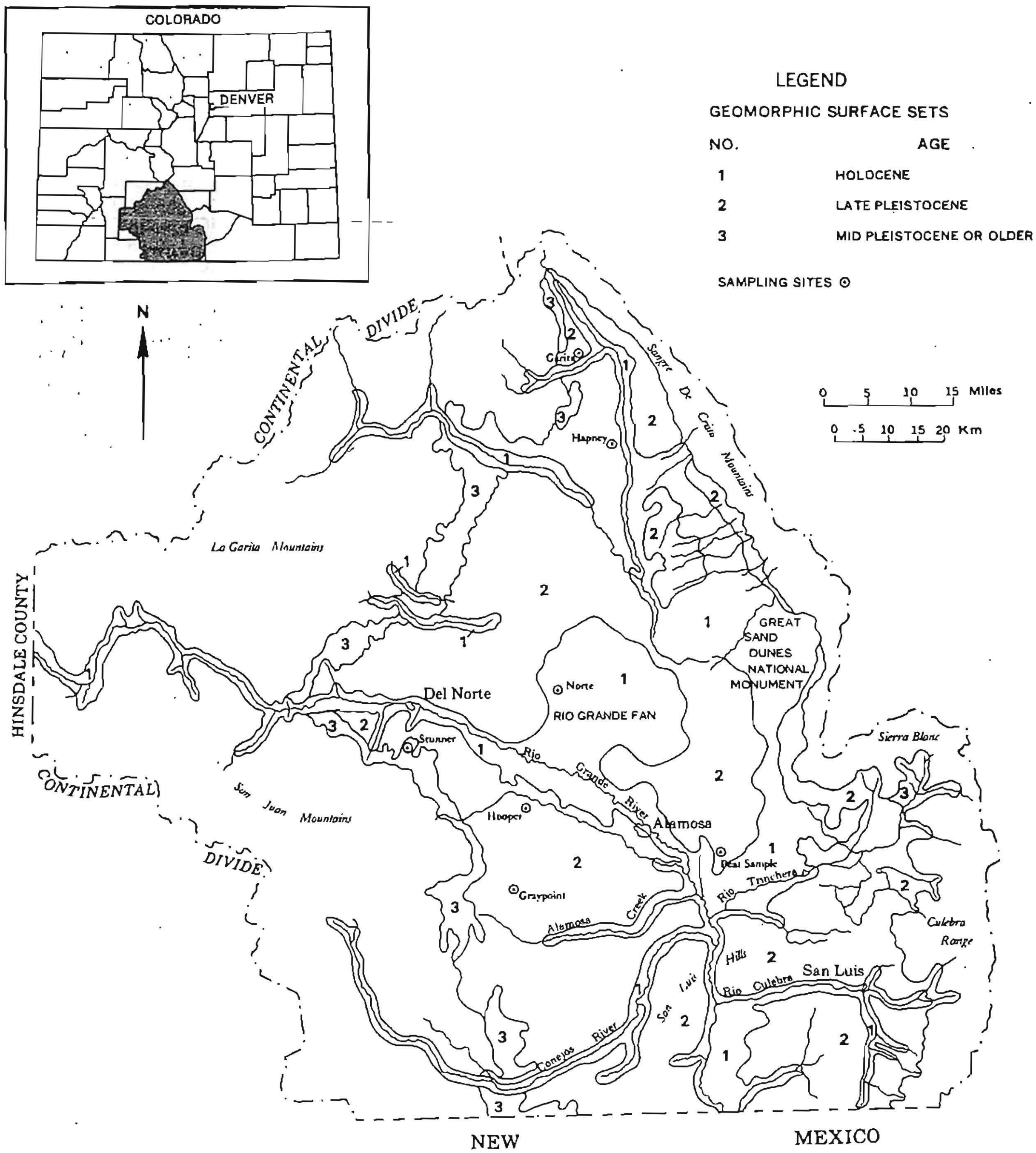

Fig. 1. Location of the pedons and geomorphic surface sets in San Luis Valley and location of the valley within the state of Colorado.

and is about 20 to 40 m across and 1- to 3-m thick. The deposit occurs on the land surface, is surrounded by Natrargids, Fluvents, and Psamments and is presently dry (9). A sample of the Oe2 horizon, 76- to 102-cm depth, at the base of the deposit has a ^{14}C age of 11 170 ± 160 YBP (Isotope no. I-11,771). The peat deposit then is late-Pleistocene and we consider the surrounding higher, mineral soils on the relict valley floor to be late-Pleistocene or older.

Geomorphic surface Set 3 includes surfaces of old alluvial fans that are isolated from the mountains in most places, are well above the valley floor, and are bypassed by modern streams (Fig. 1). Atwood and Mather (2) correlated the part of this older Set of surfaces on the south flank of Sierra Blanca Peak with surfaces believed to be of Illinoian age (12). We saw no evidence of the lacustrine shorelines commonly used in basins of the western USA to identify Pleistocene geomorphic surfaces (7).

For our purposes then, we have divided the geomorphic surfaces of the San Luis Valley into three general sets. Set 1, mostly Holocene, includes surfaces of the present day flood plains and sand dunes and alluvial fan and terrace surfaces graded to present day rivers and streams. Set 2 includes, among other areas, some of those alluvial fan surfaces graded to the constructional surface of the relict valley floor. The nearly featureless, extensive, relict valley floor itself is considered to be late-Pleistocene because of the 11 170 YBP peat deposits that are in bypassed stream channels in parts of it. Set 3, consisting mostly of alluvial fan remnants, is older than the valley floor and based on the work of Scott (12) may be as old as Illinoian.

Fig. 2. Landscape of Norte soils on the Rio Grande Fan, one of the geomorphic surfaces of Set 1. Irrigated wheat (*Triticum aestivum* L.) in the foreground, La Garita Mountains in the background.

Fig. 3. Profiles of soil pedons: (a) Norte (S79CO 109-3), (b) Garita (S79CO 109-2), and (c) Hapney (S79CO 109-1). Tape increments in feet.

Soils

Entisols, like the Norte soils (Fig. 1,2,3a) are typical of the development found on Holocene surfaces (geomorphic surface Set 1). Norte (Table 1), an Aquic Ustorthent, formed in the bajada on the west side of the valley. Soil development consists of a slight accumulation of organic matter and a little movement of carbonate. In an average year, precipitation wets the soil to a depth of about 77 cm (Table 1) or near the depth to maximum salt (electrical conductivity) and carbonate.

The Garita (Fig. 1,3b,4) and Graypoint soils, both Argids on alluvial fan surfaces (geomorphic surface Set 2) are considered to be of late-Pleistocene age. The Garita pedon (Tables 1 and 2), a taxadjunct because it has a weak argillic horizon, also has a calcic horizon. There are grain argillans on sands in the Bt horizon and calcans in the Bk2 horizon. Small amounts of carbonate are dispersed throughout the upper horizons also. In an average year, the soil wets to a depth of about 47 cm, which is near the depth to maximum carbonate (Table 1). The depth to the maximum salt accumulation is below 1 m in this pedon.

Graypoint (Tables 1 and 2), a taxadjunct because it contains more organic matter than is typical for the series, has nearly continuous argillans on sands and bridging between them in the Bt horizon (Fig. 5a). These argillans are about 50-μm thick and moderately well oriented. The Bk horizon has both skelsepic and crystic plasmic fabric. Only crystic is shown in Fig.

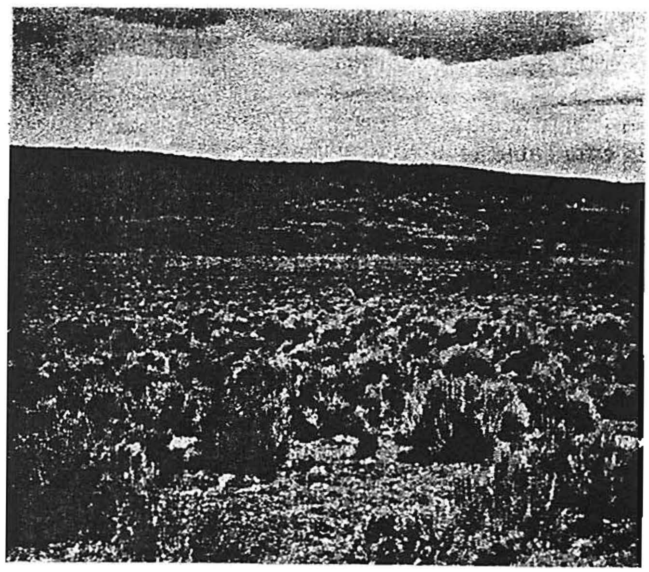

Fig. 4. Landscape of Garita soils under big sagebrush (*Artemisia tridentata* Nutt.) and blue grama (*Bouteloua gracilis*) (foreground) at the north end of the San Luis Valley, one of the geomorphic surfaces of Set 2. Sangre De Cristo Mountains in the background.

Table 1. Physical, chemical, morphological, and site description data for six pedons representing geomorphic surface Sets 1, 2, and 3 in the San Luis Valley of Colorado.†

Horizon	Depth	Clay: Silicate <0.002 mm	Clay: CaCO$_3$ <0.002 mm	Silt 0.002–0.05 mm	Sand 0.05–2 mm	>2 mm	CaCO$_3$ eq. (6Elb)	EC (8Ala)	ESP (5D2)	Depth of wetting‡	Control Section $\bar{x}$ Organic C	Control Section $\bar{x}$ Sand/clay ratio	Munsell color moist	Elevation	Geomorphic position
	cm	%	%	%	%	%	dg kg^{-1}	dS m^{-1}	%	cm	dg kg^{-1}			m	
Geomorphic surface Set 1.															
Norte series (S79CO 109-3), a loamy-skeletal, mixed (calcareous), frigid Aquic Ustorthent															
A	0–20	7.4	—	18.6	74.0	35	1	0.72	1				10 YR 3/4		Holocene
Cl	35–62	4.5	—	14.9	80.6	50	2	1.06	3	77	0.39	10.9	10 YR 5/3	2316	alluvial
2C3	84–106	0.4	—	8.9	90.7	81	1	0.18	5				Variegated colors		fan terrace
Geomorphic surface Set 2															
Garita taxadjunct (S79CO 109–2), a fine-loamy, mixed, frigid Borollic Haplargid															
A	0–5	10.9		33.0	56.1	32	tr	0.86	<1				10 YR 3/4		
Bt	5–18	20.1		33.2	46.7	34	tr	0.14	<1			3.2	10 YR 3/4	2438	Late-
Bk1	33–53	11.1	10	33.9	45.0	43	21	0.22	<1	47	1.18		10 YR 5/4		Pleistocene
2Bk3	80–112	10.4	4	26.2	59.4	70	10	0.99	4				10 YR 7/3		alluvial fan
Graypoint taxadjunct (S70CO 11-7), a fine-loamy over sandy-skeletal, mixed, frigid Borollic Haplargid															
A	0–12	12.8	—	37.5	49.7	15	0	NA	<1				7.5 YR 4/3		Late-
Bt	12–25	28.1	—	35.8	36.1	10	0	NA	<1	77	0.69	6.1	7.5 YR 4/2	2280	Pleistocene
Bk	25–36	5.3	—	5.7	89.0	71	2	NA	5				10 YR 5/3		alluvial fan
Hapney taxadjunct (S79CO 109-1), a fine-loamy, mixed, frigid Aridic Natriboroll															
A	0–8	23.8	—	29.7	46.5	5	0	0.74	1				10 YR 3/1		Late-Pleisto-
Btk2	13–30	30.3	7	28.8	33.9	tr	11	1.73	43	28	0.97	1.4	10 YR 2/1	2295	cene flood
Btk4	43–56	26.8	3	34.5	35.7	1	4	6.53	59				10 YR 2/2		plain on the
Cl	102–152	7.3	—	14.3	78.4	12	tr	4.58	47				10 YR 5/2		valley floor
Hooper series (S70CO 53–1), a fine-loamy, mixed, frigid Typic Natrargid															
E	0–10	8.1	4	19.1	68.8	0	9	14.7	81				10 YR 5/2		Late-Pleisto-
Btk1	10–31	32.0	14	11.8	42.2	0	17	8.7	87				7.5 YR 4/4		cene alluvium
Btk2	31–46	16.4	13	21.3	49.3	3	17	11.4	79	27	0.28	2.3	10 YR 6/2	2250	on the valley
BCk	46–61	13.8	—	16.3	69.9	5	4	8.4	81				10 YR 4/2		floor, water
2Cl	61–77	10.7	—	11.6	77.7	6	3	6.3	75				10 YR 4/2		table at 1 to 3 m
Geomorphic surface Set 3.															
Stunner series (S70CO 53–2), a fine-loamy, mixed, frigid Borollic Haplargid															
A	0–13	12.4	—	39.8	47.8	24	tr	0.36	1				10 YR 4/2	2310	Mid-Pleisto-
Bt1	13–28	42.2		28.6	29.2	3	3	0.68	6				7.5 YR 4/3		cene older
BCtk1	48–58	28.0	13	27.8	31.2	14	20	4.82	12	25	0.84	1.7	7.5 YR 6/4		alluvial fan
BCk1	79–97	15.7	8	34.7	41.6	18	19	8.70	14				7.5 YR 7/4		at the moun-
Cl	132–157	13.8	3	34.2	49.0	21	8	7.70	18				7.5 YR 6/4		tain front

† Method codes following column headings refer to descriptions of methods in Soil Survey Investigations Report no. 1 (15); additionally EC is electrical conductivity, ESP is exchangeable sodium percentage, and the control section average ($\bar{x}$) is calculated for the 0- to 40-cm depth.
‡ Calculated by a water balance method (17, 18).

5b. The calculated average depth of wetting is about 77 cm (Table 1). One would anticipate that the depth to carbonate, 25 cm, more nearly represents the actual depth of wetting because water will not go into the sandy Bk horizon until the soil approaches saturation.

We sampled Hapney (Fig. 1,3c,6) and Hooper soils on the constructional relict valley floor, geomorphic surface Set 2; both soils have natric horizons. Based on the 1973 survey, about three-fourths of these surfaces on the valley floor are occupied by soils having natric horizons (9). Hapney (Tables 1 and 2), a taxadjunct because it has <35% clay in its control section, is representative of soils on the north end of the relict valley floor. Its Bt1 horizon has a ma-skelsepic plasmic fabric (Fig. 7a). There are free grain argillans on most sand grains in the C horizon. Hapney accumulates both carbonate and salt in its argillic horizon. Depth of wetting in an average year, 28 cm (Table 1), is about right for the depth of accumulation of carbonate and salt.

Hooper (Tables 1 and 2), sampled south of the Rio Grande, has many properties like those of the Hapney taxadjunct. Depth of wetting in an average year is also similar. The main difference is that Hooper does not have the color and organic C content required for a Mollisol. The Btk2 horizon of Hooper has some illuviation and grain argillans, but most of the evidence of clay accumulation apparently is masked by carbonate. This masking continues through the BCk horizon, but the 2C1 horizon has well oriented argillans both on sand grains (Fig. 7b) and bridging between them.

Stunner (Fig. 1), a Borollic Haplargid, is on geomorphic surface Set 3, the oldest set of alluvial fan surfaces we examined. It has a greater accumulation of clay than any of the other soils in the study. It also has a calcic horizon and accumulates some salt below 28 cm. This coincides well with the depth of wetting in an average year (Table 1). Clay has accumulated to depths of at least 79 cm. There are illuviation argillans in the Bt1 horizon, but in the BCtk1 and C1 horizons

Table 2. Micromorphological descriptions of five pedons on geomorphic surfaces that represent Sets 2 and 3.†

Horizon	Depth, cm	Related distribution pattern	Plasmic fabric	Other
		Garita taxadjunct (S79CO 109-2), a fine-loamy, mixed, frigid Borollic Haplargid		
Bt	5–18	Porphyric	Insepic	Common free grain argillans. Biotite weathered to vermiculite. Plagioclase, hornblende, mostly unweathered.
Bk2	53–80	Porphyric	Skelsepic-crystic	Common embedded grain argillans. Nearly continuous silt- and clay-size carbonate concretions. Biotite is brown, pleochroic, and weathered to vermiculite, other skeleton grains unweathered.
		Graypoint Taxadjunct (S70CO 11-7), a fine-loamy over sandy-skeletal, mixed, frigid Borollic Haplargid		
Bt	12–25	Porphyric	Skel-insepic	Common illuviation argillans, many embedded grain argillans. Plagioclase and hornblende grains, mostly unweathered.
Bk	25–36	Porphyric	Skelsepic-crystic	Few embedded grain argillans. Many silt- and clay-size carbonate grains as calcans and carbonate concretions.
		Hapney taxadjunct (S79CO 109-1), a fine-loamy, mixed, frigid Aridic Natriboroll		
Btk2	13–30	Porphyric	Ma-skelsepic	Most plasma is stress oriented. Common 2- to 5-mm carbonate nodules. Thin discontinuous illuviation channel argillans. Exfoliating muscovite grains.
Cl	102–152	Iuntic prophyric	Skelsepic	Free grain argillans on most of the sand grains. Common exfoliating biotite grains, hornblende, mostly unweathered, common muscovite, mostly unweathered.
		Hooper series (S70CO 53-1), a fine-loamy, mixed, frigid Typic Natrargid		
Btk1	10–31	Porphyric	Crystic	Common illuviation channel argillans, carbonate nodules, and calcans.
Btk2	31–46	Porphyric	Skel-mosepic	Thick, nearly continuous, illuviation channel argillans, embedded grain argillans. Common carbonate nodules, few calcans.
2Cl	61–77	Iuntic porphyric	In-skelsepic	Abundant free grain argillans. and few calcans. Biotite exfoliating, weathering to vermiculite and kaolinite. Volcanic rock fragments are weathered, hornblende, pyroxene, and plagioclase are relatively unweathered.
		Stunner series (S70CO 53-2), a fine-loamy, mixed, frigid Borollic Haplargid		
Bt1	13–28	Porphyric	Skelsepic	Free grain argillans on most sand grains. Carbonate dispersed throughout. Few exfoliating grains of biotite, few reddish brown pyroxene and light green hornblende grains, common grains of plagioclase and fragments of basalt.
BCtk1	48–58	Porphyric	Crystic	Many carbonate nodules and coatings on bottom sides of gravel. Few carbonate concretions. Common brown and green hornblende, common brown pyroxene, many plagioclase and few quartz grains.
BCKl	79–97	Porphyric	Crystic	Many plagioclase grains and nodules and concretions. Most gravels are coated with carbonate. Common weathered basalt fragments and green and brown hornblende, and few brown biotite grains.

† Terms used for related distribution patterns, plasmic fabrics, and cutans are those of Brewer (3).

clay illuviation is largely masked by carbonate accumulation.

DISCUSSION

Because geomorphic surface Set 1 includes a range of Holocene surfaces, the soils range from Psamments with little development to Ustorthents that have some accumulation of organic matter and carbonate. Most of the soils do not have enough organic matter to be Mollisols or enough carbonate to have calcic horizons.

Soils on geomorphic surfaces of Sets 2 and 3, however, experienced one or more pluvials of the Pleistocene (22). Most of the clay in these soils likely accumulated during the pluvials. The occurrence of carbonate in the horizons with illuvial clay, especially in the oldest soils, suggests an arid climate following one or more Pleistocene pluvials. The distribution of carbonate for the most part is in balance with today's arid climate. The playas on the valley floor are likely sources of carbonate and salt for eolian additions to the soils. The large dune fields on the east side of the valley are evidence of such eolian activity.

The soils on geomorphic surfaces of Set 2 have a wide range of development. The range includes soils

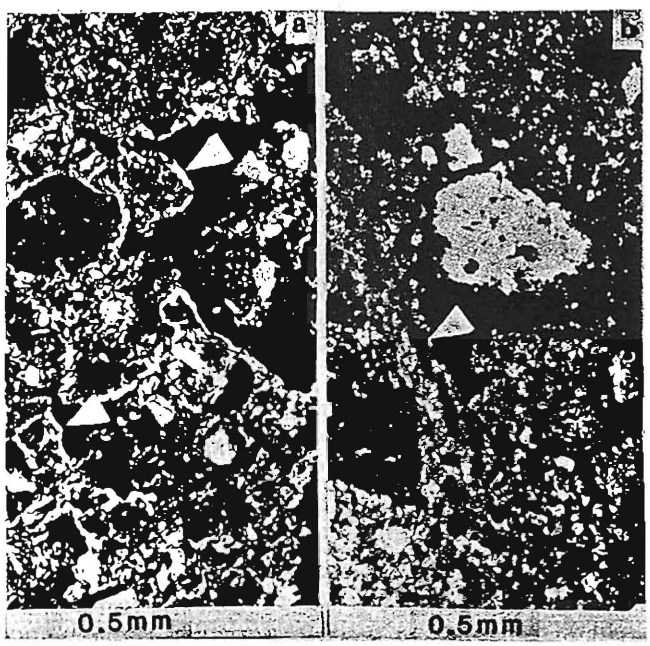

Fig. 5. Photomicrograph of the Graypoint pedon (S79CO 11-7) under crossed polarizers: (a) Grain argillans in the Bt horizon and (b) crystic plasmic fabric in the Bk horizon.

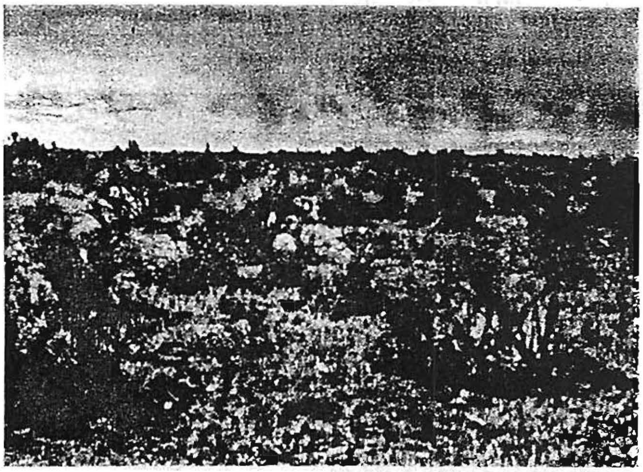

Fig. 6. Landscape of the Hapney soils on the north end of the valley floor. Desert shrub vegetation in a summer rainstorm. One of the geomorphic surfaces of Set 2.

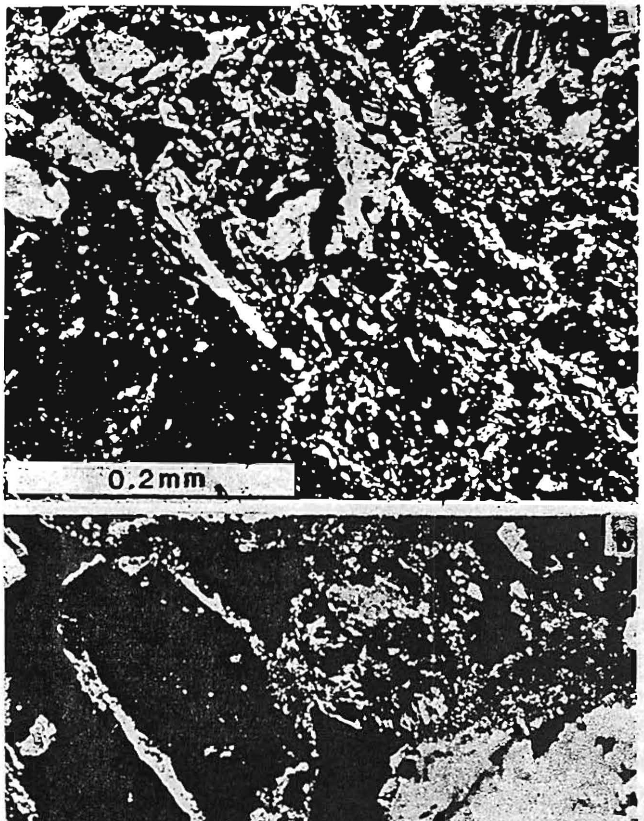

Fig. 7. Photomicrographs of: (a) ma-skelsepic plasmic fabric in the Btk2 horizon of the Hapney pedon under crossed polarizers, and (b) free grain argillans and calcans in the 2C1 horizon of the Hooper pedon (S70CO 53-1) under crossed polarizers.

like Garita that typically have calcic horizons and in some profiles there is also evidence of clay movement. Graypoint soils have strongly developed argillic horizons as evidenced by bridges and nearly continuous argillans on sands in their Bt horizons. Hapney and Hooper, both Natrargids, have the most development of the soils on these late-Pleistocene surfaces. Their argillic horizons contain a maximum of 30 and 32% clay, respectively (Table 1). There are well oriented argillans on sands and clay bridges between in the lower horizons. Of the soils studied, the Stunner soils, Set 3, mid-Pleistocene or older, have accumulated the most clay. They have illuviation argillans in Bt horizons, but in some lower horizons the clay is largely masked by carbonate accumulation.

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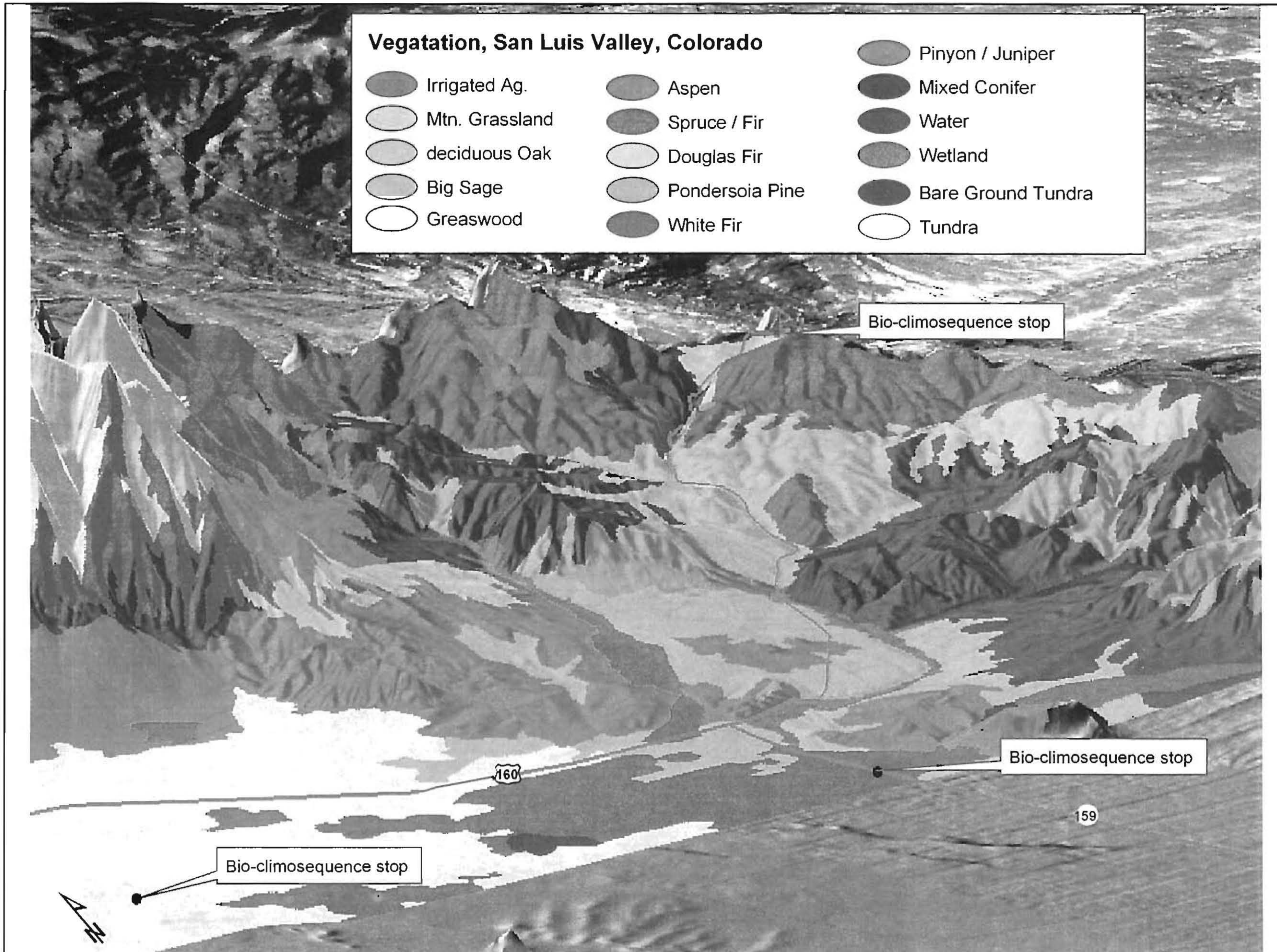

Vegatation, San Luis Valley, Colorado
Irrigated Ag.
Mtn. Grassland
deciduous Oak
Big Sage
Greaswood
Aspen
Spruce / Fir
Douglas Fir
Pondersoia Pine
White Fir
Pinyon / Juniper
Mixed Conifer
Water
Wetland
Bare Ground Tundra
Tundra
Bio-climosequence stop
Bio-climosequence stop
Bio-climosequence stop
160
159
N

Leighcan

Loamy-skeletal, mixed, superactive Typic Dystrocryepts

This series consists of very deep, well-drained soils that formed in till, slope alluvium or colluvium from acid igneous rocks. Leighcan soils are found on mountain slopes (0-70% slopes); elevation ranges from 7 000 to 12 000 ft (2128 to 3648 m). The dominant vegetation includes Engelmann spruce and subalpine fir. Mean annual precipitation is approximately 45 in (114 cm); mean annual temperature is approximately 32°F (0°C).

NSSL data for a site in Rio Grande County (15% slope; ? m elevation):

Horizon	Depth	Color	S	Si	C	Rock Frag	Structure	pH	BD	Soil H_2O	OC	N	CEC	$CaCO_3$
	(cm)	(moist)	(%)	(%)	(%)	(% whole soil)			(g/cm^3)	(cm/cm^{-1})	(%)	(%)		(%)
O	10-0										18.99	0.957	79.1	
E	0-25	7.5YR4/4	24.3	49.8	25.9	49	1fgr	4.8	0.99	0.16	2.66	0.175	37.6	-
Bw1	25-46	7.5YR3/4	58.7	23.6	17.7	65	1fgr	4.8	1.02	0.12	2.03	0.103	29.5	-
Bw2	46-69	7.5YR4/6	68.5	18.8	12.7	69	1fgr	4.8			1.11	0.058	22.3	-
C1	69-112	10YR5/6	69.6	18.5	11.9	68	m	4.8	1.26	0.08	0.64	0.041	16.1	-
C2	112-152	10YR5/8	67.5	19.7	12.8	65	m	4.8			0.52	0.037	17.7	-

Tolvar

Loamy-skeletal, mixed, superactive Ustollic Glossocryalfs

This series consists of very deep, well-drained soils that formed in alluvial fan or slope alluvium derived mainly from granitic rocks. Tolvar soils are found on mountain slopes, toeslopes, footslopes and alluvial fans (10-70% slopes); elevation ranges from 10 000 to 12 000 ft (3040 to 3648 m). The dominant vegetation includes aspen and Douglas fir. Mean annual precipitation is approximately 25 in (64 cm); mean annual temperature is approximately 36°F (2°C).

NSSL data for a site in Montrose County (9% slope; 3110 m elevation):

Horizon	Depth	Color	S	Si	C	Rock Frag	Structure	pH	BD	Soil H_20	OC	N	CEC	$CaCO_3$
	(cm)	(moist)	(%)	(%)	(%)	(% whole soil)			(g/cm^3)	(cm/cm^{-1})	(%)	(%)		(%)
Oi	13-0										28.69	1.067	119.6	
E	0-23	10YR3/4	25.6	58.0	16.4	33	1fgr	6.2	0.97	0.20	2.51	0.138	30.0	-
E/B	23-46	10YR3/4	32.1	53.0	14.9	41	1mgr	6.4			1.17	0.075	22.6	-
B/E	46-69	10YR4/3	38.2	45.4	16.4	61	1msbk	6.4	1.41	0.12	0.58	0.039	20.3	-
Bt1	69-86	10YR 4/4	37.0	42.7	20.3	57	2-3mabk	6.4	1.53	0.12	0.46		20.6	-
Bt2	86-122	10YR4/4	28.9	30.2	40.9	70	2-3mabk	6.4			0.29		31.4	-
BC	122-152	10YR4/4	35.1	30.0	34.9	73	m	6.4	1.30	0.10	0.22		30.9	-

Seitz

Clayey-skeletal, smectitic Ustic Glossocryalfs

This series consists of very deep, well-drained soils that formed in noncalcareous colluvium or slope alluvium derived from rhyolite, andesite, trachite, and interbedded sandstone, shale and basalt. Seitz soils are on hills, ridges, valley sides and mountain slopes (2-65% slopes); elevation ranges from 8 200 to 12 000 ft (2493 to 3648 m). The dominant vegetation includes white fir and Douglas fir. Mean annual precipitation is approximately 18 in (46 cm); mean annual temperature is approximately 34°F (1°C).

NSSL data for a site in Rio Grande County (20% slope; 2706 m elevation):

Horizon	Depth	Color	S	Si	C	Rock Frag	Structure	pH	BD	Soil H_2O	OC	N	CEC	$CaCO_3$
	(cm)	(moist)	(%)	(%)	(%)	(% whole soil)			(g/cm^3)	(cm/cm^{-1})	(%)	(%)		(%)
O	5-0													
E	0-13	10YR4/2	38.4	51.2	10.4	28	1mgr	6.3	1.06	0.17	1.76	0.098	21.7	-
EB	13-23		35.7	33.2	31.1	23	1fsbk	7.0	1.34	0.01	0.98	0.062	44.0	-
Bt1	23-43	10YR4/3	31.7	30.2	38.1	69	2fsbk	7.0			0.71	0.056	61.2	-
Bt2	43-66	10YR4/4	43.1	29.3	27.6	66	2msbk	6.3	1.39	0.13	0.38		57.3	-
Bt3	66-102	10YR5/3	42.8	36.1	21.1	54	1fsbk	6.3			0.22		56.8	-
C	102-152	10YR5/4	43.7	39.6	16.7	22	m	7.0	1.36	0.13	0.14		64.5	-

Uracca

Loamy-skeletal, mixed, superactive frigid Calcidic Argiustolls

This series consists of deep, well-drained soils that formed in fan sediments from mixed igneous and metamorphic rocks. Uracca soils are found on alluvial fans and valley side slopes (8-45 % slopes); elevation ranges from 8 000 to 9 000 ft (2432 to 2736 m). The dominant vegetation includes pinyon pine and juniper. Mean annual precipitation is approximately 12 in (30 cm); mean annual temperature is approximately 43°F (6°C).

Data for a site in Costilla County (11% slope; 2707 m elevation):

Horizon	Depth	Color	Texture	C	Rock Frag	Structure	pH	BD	Soil H_20	OC	N	CEC	$CaCO_3$
	(cm)	(moist)		(%)	(% whole soil)			(g/cm^3)	(cm/cm^{-1})	(%)	(%)		(%)
A	0-4	7.5YR2.5/2	vgr sl	18	40	1fgr	7.0						
ABt	4-11	7.5YR5/3	vcb scl	30	50	2fsbk	6.8						
Bt	11-18	7.5YR4/4	xcb scl	34	70	3fsbk	7.2						
Bw	18-30	7.5YR4/3	xgr sl	14	55	1fsbk	7.2						
2Bw	30-38	7.5YR4/3	gr sl	14	25	1fsbk	7.2						
2Bk	38-54	7.5YR5/3	gr sl	14	25	1fsbk	7.8						
C	54-66	10YR4/3	vcb sl	14	50		7.8						

Platoro

Fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Ustic Haplargids

This series consists of deep, well-drained soils that formed in medium to moderately fine textured alluvial materials derived mainly from basalt and beds of sand and gravel. Platoro soils are on alluvial fans and high terraces (0-15% slopes); elevation ranges from 7 700 to 8 000 ft (2341 to 2432 m). The dominant vegetation is Wyoming big sagebrush, blue grama and prickly pear. Mean annual precipitation is approximately 12 in (30 cm); mean annual temperature is approximately 41°F (5°C).

NSSL data for a site in Costilla County (1% slope; 2400 m elevation):

Horizon	Depth	Color	S	Si	C	Rock Frag	Structure	pH	BD	Soil H_20	OC	N	CEC	$CaCO_3$
	(cm)	(moist)	(%)	(%)	(%)	(% whole soil)			(g/cm^3)	(cm/cm^{-1})	(%)	(%)		(%)
A	0-13	10YR4/2	62.5	26.8	10.7	24	1fgr	7.2	1.66	0.04		0.127	10.2	
BA	13-28	10YR4/3	66.8	20.3	12.9	29	2vf&fsbk	7.2	1.62	0.12		0.069	11.8	
Btk1	28-43	10YR4/3	61.6	16.2	22.2	11	2mpr/2fsbk	7.4	1.62	0.09		0.063		tr
Btk2	43-61	10YR5/4	67.6	14.2	18.2	36	2m&cpr/ 2f&msbk	8.0	1.64	0.12		0.041		1
2Bk1	61-81	10YR5/3	90.2	5.2	4.6	50	1fsbk/sg	7.8				0.030		1
2Bk2	81-102	10YR6/2	95.0	2.2	2.8	55	sg	7.4				0.020		--
2Bk3	102-163	10YR4/4	84.8	8.8	6.4	1	1fsbk/sg	7.4	1.70	0.04		0.018		--
2Bk4	163-200	10YR5/2	90.1	6.5	3.4	46	m/sg	7.4				0.025		tr

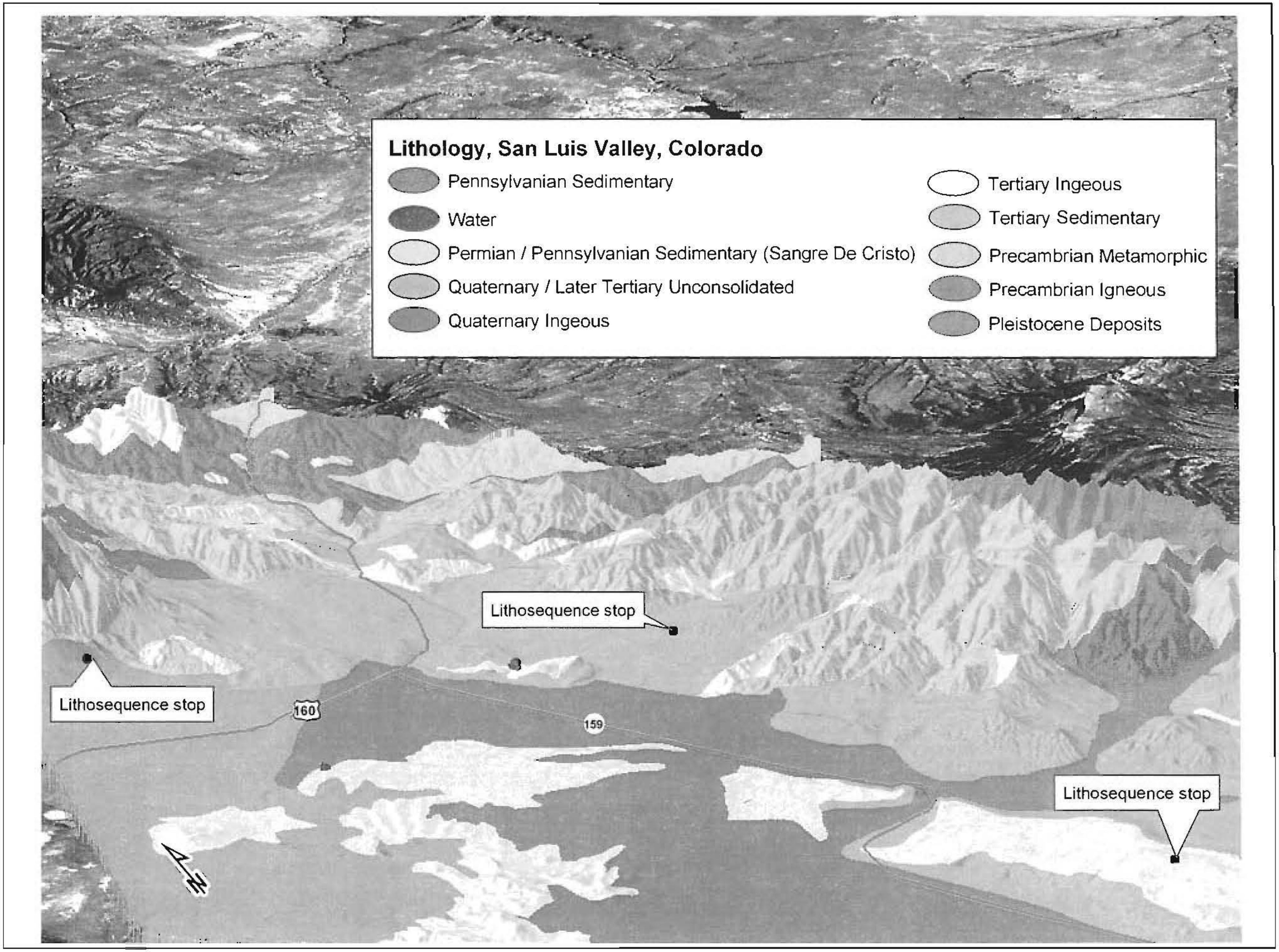
Cososa

Coarse-loamy, mixed, superactive, frigid Typic Haplocalcids

This series consists of deep, well to somewhat excessively drained soils that formed in wind-reworked alluvium from mixed rocks. Cososa soils are on alluvial fans, valley side slopes and wind reworked portions of alluvial terraces (0-20 % slopes); elevation ranges from 7500 to 7700 ft (2280 to 2341 m). The dominant vegetation is rabbitbrush, blue grama and three awn. Mean annual precipitation is approximately 8 in (20 cm); mean annual temperature is approximately 43°F (6 °C).

NSSL data for a site in Costilla County (1% slope; 2295 m elevation):

Horizon	Depth	Color	S	Si	C	Coarse Frag	Structure	pH	BD	Soil H_20	OC	N	CEC	$CaCO_3$
	(cm)	(moist)	(%)	(%)	(%)	(% whole soil)			(g/cm^3)	(cm/cm^{-1})	(%)	(%)		(%)
A1	0-3	10YR4/4	89.6	4.2	6.2	1	1fgr	7.8				0.084		1
A2	3-15	10YR5/3	87.0	7.8	5.2	6	1fgr	7.6				0.046	8.8	tr
Bw	15-36	10YR4/4	88.2	6.2	13.6	17	1f&msbk	7.6	1.52	0.05		0.058	13.3	tr
Bk1	36-53	10YR5/4	84.5	5.6	9.9	16	1f&msbk	7.8	1.75	0.08		0.034		1
Bk2	53-124	7.5YR6/4	69.5	6.4	24.1	15	1fsbk	8.0	1.42	0.16		0.014		11
2Bk3	124-145	10YR5/3	87.3	5.1	7.6	24	sg	8.0				0.020		2
2Bk4	145-188	10YR5/4	93.5	3.0	3.5	53	sg	8.0	1.25	0.27		0.012		2
2Bk5	188+	10YR7/2	65.4	22.8	11.8	13	m	8.2				0.033		20


Lithology, San Luis Valley, Colorado
Pennsylvanian Sedimentary
Water
Permian / Pennsylvanian Sedimentary (Sangre De Cristo)
Quaternary / Later Tertiary Unconsolidated
Quaternary Ingeous
Tertiary Ingeous
Tertiary Sedimentary
Precambrian Metamorphic
Precambrian Igneous
Pleistocene Deposits
Lithosequence stop
Lithosequence stop
Lithosequence stop
160
159
N

Lithosequence site 1 - Quaternary gravels

Coarse-loamy, mixed, frigid Calcidic Argiustoll

This soil formed in slope alluvium and colluvium from acid igneous rocks and is located on a colluvial fan (18% slope) at an elevation of 8900 ft (2705 m). The dominant vegetation includes pinyon pine and Rocky Mountain juniper. Mean annual precipitation is approximately14 in (36 cm); mean annual temperature is approximately 40-43°F (4.5-6°C).

Horizon	Depth	Color	S	Si	C	Rock Frag	Structure	pH	OC	N	CEC	$CaCO_3$
	(cm)	(moist)	(%)	(%)	(%)	(% whole soil)			(%)	(%)		(%)
Oe	2-0											
A	0-20	10YR3/2	60.6	28.5	10.9	7	1msbk/fgr	6.7	4.21	0.277	16.7	
Btk1	20-34	10YR3/3	68.0	20.4	11.6	48	2fsbk	7.9	0.64	0.055	10.1	tr
Btk2	34-57	10YR4/3	76.8	13.4	9.8	52	1msbk	8.1	0.66	0.064	8.4	tr
2Bk	57-	10YR3/2	86.2	6.9	6.9	62	sg	8.2	0.20	0.022	6.2	--

Lithosequence site 2 -Tertiary sedimentary rock

Coarse-loamy, mixed, frigid Pachic Argiustoll

This soil formed in sandstone and conglomerate of the Santa Fe formation and is located on a valley sideslope (15% slope) at an elevation of 8700 ft (2645 m). The dominant vegetation includes pinyon pine and Wyoming big sage. Mean annual precipitation is approximately14 in (36 cm); mean annual temperature is approximately 40-43°F (4.5-6°C).

Horizon	Depth	Color	S	Si	C	Rock Frag	Structure	pH	OC	N	CEC	$CaCO_3$
	(cm)	(moist)	(%)	(%)	(%)	(% whole soil)			(%)	(%)		(%)
Oe	1-0											
A	0-10	10YR3/2	72.9	16.2	10.9	1	1fgr	8.2	2.66	0.196	22.4	1
AB	10-19	10YR3/2	72.8	15.8	11.4	tr	1msbk	8.3	2.69	0.192	23.6	1
Bt	19-39	10YR3/2	74.3	14.3	11.4	5	1mpr/1fsbk	8.3	2.34	0.117	20.3	1
Btk	39-54	10YR2/2	64.9	17.6	17.5	54	2fsbk	8.3	1.14	0.149	26.4	2
BCk	54-70	10YR3/4	73.3	17.1	9.6	66	1msbk	8.4	0.53	0.024	18.2	1
R	70+		77.8	19.0	3.2			8.8			4.8	6

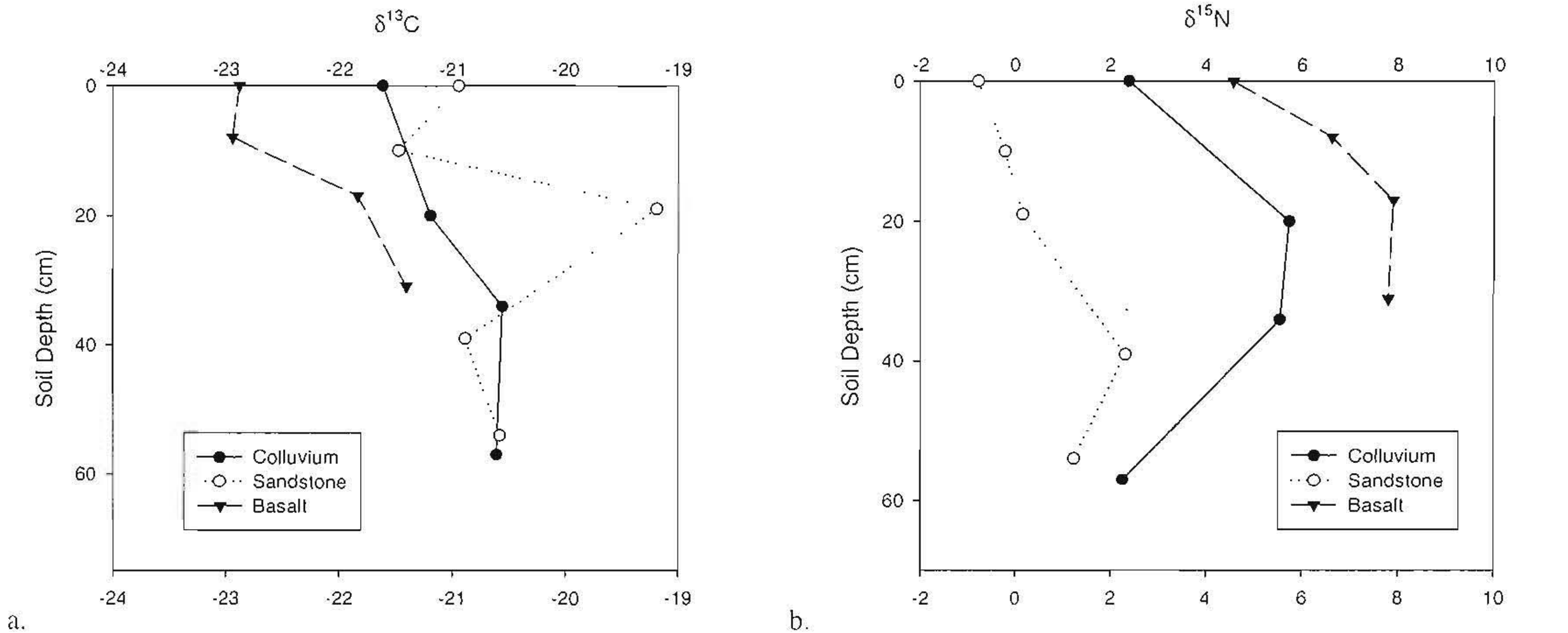
Lithosequence site 3 -Tertiary igneous

Coarse-loamy, mixed, frigid Pachic Argiustoll

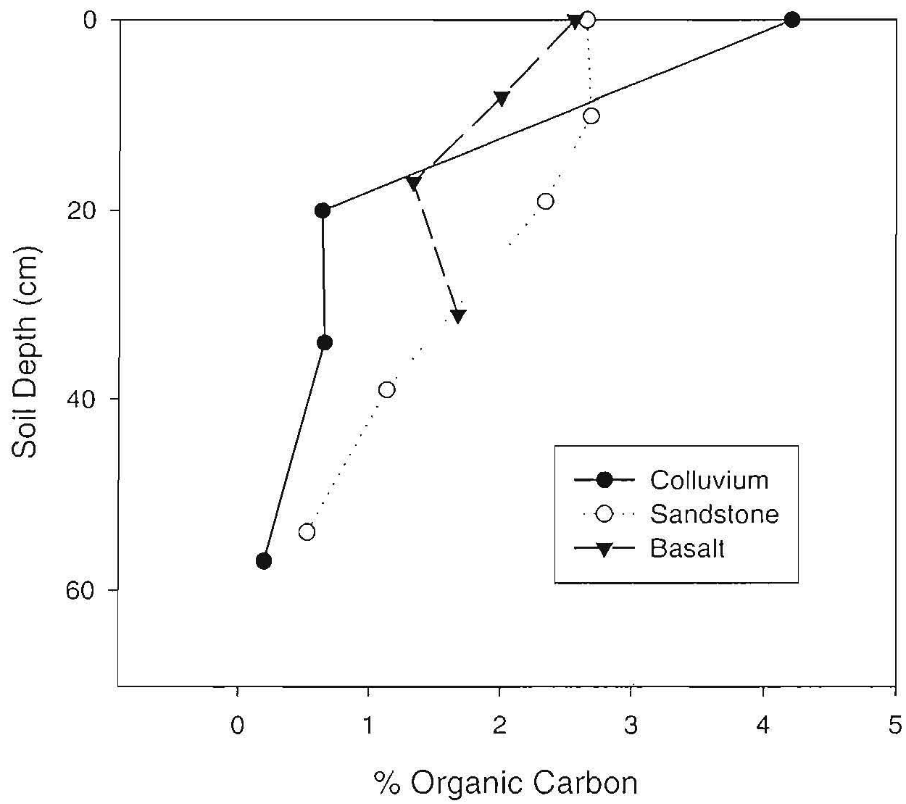
This soil formed in basalt and is located on a mesa (1% slope) at an elevation of 8800 ft (2675 m). The dominant vegetation includes pinyon pine, Wyoming big sage and blue grama. Mean annual precipitation is approximately14 in (36 cm); mean annual temperature is approximately 40-43°F (4.5-6°C).

Horizon	Depth	Color	S	Si	C	Rock Frag	Structure	pH	OC	N	CEC	$CaCO_3$
	(cm)	(moist)	(%)	(%)	(%)	(% whole soil)			(%)	(%)		(%)
Oe	2-0											
A	0-8	10YR3/2	28.2	49.4	22.4	19	2fgr	8.2	2.56	0.257	28.2	5
Btk1	8-17	10YR3/3	33.4	44.5	22.1	15	2mpr/2msbk	8.3	2.00	0.207	25.4	9
Btk2	17-31	10YR4/3	32.3	40.5	27.2	12	2mpr/2msbk	8.3	1.33	0.124	20.9	20
Bk	31-59	10YR6/3	37.8	30.5	31.7	16	m	8.3	1.67	0.100	11.6	53
Cr	59+		71.0	25.9	3.1			8.4		0.002	2.7	4

Comparison of stable isotopic composition of lithosequence soils:



Organic carbon distribution in lithosequence soils:



Organic carbon and nitrogen mass calculated to 100 cm. Bulk density estimated empirically (Rawls, WJ. 1983. Estimating soil bulk density from particle size analysis and organic matter content. Soil Sci 135:123-125).

Horizon	Thickness cm	OC %	N %	BD* g cm^{-3}	C/N	OC g cm^{-2}	N g cm^{-2}
		-------------------- GRANITE --------------------					
Oe	2-0	37.59	1.384	0.224	27		
A	0-20	4.210	0.277	1.09	15	0.918	0.060
Btk1	20-34	0.636	0.054	1.50	12	0.134	0.011
Btk2	34-57	0.657	0.058	1.52	11	0.230	0.020
2Bk	57-100	0.197	0.024	1.58	8	0.134	0.016
						1.415	*0.108*
		-------------------- SANDSTONE --------------------					
O	1-0	23.75	0.933	0.224	25		
A	0-10	2.657	0.194	1.26	14	0.335	0.024
AB	10-19	2.690	0.184	1.27	15	0.307	0.021
Bt	19-39	2.340	0.144	1.30	16	0.608	0.037
Btk	39-54	1.136	0.082	1.44	14	0.245	0.018
Btkm	54-100	0.527	0.052	1.52	10	0.368	0.036
						1.865	*0.137*
		-------------------- BASALT --------------------					
O	2-0	38.13	1.391	0.224	27		
A	0-8	2.564	0.244	1.10	11	0.226	0.021
Btk1	8-17	2.002	0.208	1.19	10	0.214	0.022
Btk2	17-31	1.331	0.161	1.27	8	0.237	0.029
Bk	66-100	1.674	0.234	1.28	7	1.414	0.198
						2.091	*0.270*

Section 3

Irrigation Water Quality, Alamosa River Basin

MINERALOGICAL ALTERATIONS OF SOIL IRRIGATED WITH ACIDIC MINE WATER IN THE ALAMOSA RIVER BASIN

by

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TOC

INTRODUCTION

The headwaters of the Alamosa River originate in the San Juan Mountains, a world class ore-bearing range located to the west of the San Luis Valley. The Alamosa River naturally receives large amounts of heavy metals and acidity from the watershed it drains, but it is also receives the majority of the drainage from the Summitville Gold mine which introduces additional heavy metal-laden and highly acidic water. This could lead to dissolved and particulate metal loading at concentrations greater than background conditions. Downstream of the Terrace Reservoir, the pH of the Alamosa River has been reported to range from 4.2 to 7.0 with no measurable alkalinity (Erdman and Smith, 1996.) The metal loading data for the river shows high concentrations of cobalt (6-13 µg/L), copper (60-350 µg/L), zinc (150-190 µg/L), manganese (360-520 µg/L) and nickel (8-12 µg /L) (Erdman and Smith, 1996.) Smith and others (1995) concluded that there is a significant relationship between the pH of irrigation water and certain metal concentrations. As acidity increases, metal concentrations of copper, manganese and zinc increase.

In contrast, other irrigation waters such as the Rio Grande River and ground water have pH values ranging from 8.8-10.0 and very low concentrations of metals (Erdman and Smith, 1992.) It is common practice in the Alamosa River Basin, downstream of the Terrace Reservoir, to irrigate fields with Alamosa River water as well as Rio Grande River water and ground water.

The soils in the Alamosa Basin are formed over an alluvial outwash from the Platoro and Summitville calderas (Plumlee et al., 1992.) Weathering of the igneous mafic rock in the outwash results in soils which are alkaline with high natural acid buffering capacities (Plumlee et al, 1992.) Over the past decade, the water quality of the Alamosa River has degenerated due to increased mining activity in the 1980's at the Summitville Mine (Erdman and Smith, 1996.) Since the mine closed in 1992, the mine site was declared a United States Environmental Protection Agency (USEPA) Superfund Site. A study of the mineralogy and chemical characteristics of agricultural soils of the Alamos River Basin fills missing data gaps for the USEPA Risk Assessment Analysis of the Summitville Gold mine. The purpose of this study is to determine the mineralogical changes of the soils as a result of the addition of acidic waters to evaluate the long term buffering capacity of the soils. This paper will focus on experimental design and initial field observations from the Alamosa River Basin agricultural soils which have been subjected to a variety of water sources and irrigation practices.

EXPERIMENTAL DESIGN

This study is divided into two phases, Phase I- the Reconnaissance Survey and Phase II- the Detailed Study. This paper will only deal with Phase I, the Reconnaissance Survey. The Phases I research work is conducted across a single soil series, the Graypoint Series of the Alamosa River Basin. The Graypoint Series, classified as a fine-loamy over sandy or sandy-skeletal, mixed, frigid Typic Haplargid, is the dominate soil series in the area (The Soil Survey Staff, 1974.) Phase I looks at six levels of management across the Graypoint series in Conejos County near Capulin, Colorado: (1) virgin soil-never irrigated nor cropped, (2) irrigated and cropped prior to but not after 1984,

(3) flood irrigated with Rio Grande river water and/or deep groundwater and cropped with alfalfa, (4) sprinkler irrigated with Rio Grande river water and/or deep groundwater and cropped with alfalfa, (5) flood irrigated withAlamosa River water and cropped with alfalfa, and (6) sprinkler irrigated with Alamos River water and cropped with alfalfa. The study was initiated in the Spring of 1996, and the Phases I final report will be released to the public by the Colorado Department of Health and Environment December, 1996.

SAMPLING

Six sites were chosen in August, 1995 in the Alamosa River Basin. Each site represents one of the six management schemes. Permission was obtained from local growers before entering the fields to take samples. At each field a pit was dug by backhoe. The soil profile was described using USDA Soil Survey techniques and classified according to the Keys to Soil Taxonomy (The Soil Survey Staff, 1974.) At each site an additional 4 satellitpedons were sampled, one located at each corner of the pit, 10 meters away at a 45 degree angle. The 4 satellitpedons are being used for replication for the first two horizons of the modelpedon. After the description of the profile, samples were taken from each horizon for bulk soil analysis, rock identification, carbonate and oxide concretion identification, and thin section analysis. Chemical and mineralogical analyses are currently being conducted.

SOIL PROFILE DESCRIPTIONS
Graypoint Series

SITE 1
Treatment: virgin soil
Geomorphic position: nearly level stream terrace
Physiography: mountain valley (0-1% slope)
Elevation ~7720 ft.
Drainage class: well drained
Erosion: slight Runoff: none to slight
Classification: loamy- skeletal over sandy skeletal, mixed, frigid,Typic Calciargid
Diagnostic horizons: 11-34 cmargillic; 34-163 cm, calcic
Profile facing east described in sun

A--0 to 11 cm; gravelly sandy loam; brown (10YR 4/3) moist; weak fine granular structure; soft, very friable, non sticky and non plastic; many fine roots throughout; no effervescence; 25%gravels, 2% cobbles; clear smooth boundary.
Bt--11to 34 cm: verygravelly sandy clay loam; brown (7.5YR 4/4) moist; weak mediumsubangular blocky structure; soft very friable, slightly sticky and slightly plastic; clay skins- common thin patchy oped faces; many fines and few medium roots throughout; no effervescence; 45%gravels, 5% cobbles; clear wavy boundary.

2BCk1--34 to 49 cm; extremelygravelly sand; brown (10YR 5/3) moist; single grained; loose; non sticky and non plastic; common fine roots throughout; carbonates - none in matrix, very thin pendant coatings (1-2 mm) on clasts; slight effervescence; 65%gravels, 5% cobbles; clear wavy boundary.

2BCk2--49 to 91 cm; extremelygravelly sand; brown (10YR 5/3) moist; single grained; loose; non sticky and non plastic; few fine roots throughout; carbonates - none in matrix, very thin pendant coatings (1-2 mm) on clasts (slightly greater concentration than 2BCk1); slight effervescence; 60%gravels, 15% cobbles, 3% stones.

Figure 1. Site 1 - virgin soil profile.

SITE 2

Treatment: irrigated and cropped prior to but not after 1984
Geomorphic position: nearly level stream terrace
Physiography: mountain valley (0-1% slope)
Elevation ~7750 ft.
Drainage class: well drained
Erosion: slight Runoff: none to slight
Classification: loamy- skeletal over sandy skeletal, mixed, frigid,Typic Calciargid
Diagnostic horizons: 23-42 cmargillic; 42-81+ cm, calcic
Profile facing east described in sun
Site 5 appears to have been subjected to severe disturbance, possible erosion.

Ap-- 0 to 23 cm; very gravelly sandy clay loam; brown (7.5YR 4/3) moist; weak fine granular structure; soft, very friable, slightly sticky and non plastic; common fine roots throughout; no effervescence; 30%gravels; 5% cobbles; clear wavy boundary.

Bt--23 to 42 cm: very gravelly sandy clay loam; brown (7.5YR 4/4) moist; weaksubangular blocky structure; soft, very friable, slightly sticky and non plastic; common fine and few very fine roots throughout; no effervescence;50% gravels, 5% cobbles; clear wavy boundary.

2BCk1--42 to 81 cm; extremelygravelly sand; brown (7.5YR 5/4) moist; single grained; loose; non sticky and non plastic; common fine roots throughout; carbonates - none in matrix, pendant coatings onlasts; slight effervescence; 60%gravels, 25% cobbles; clear wavy boundary.

2BCk2--81+ cm; extremelygravelly sand; brown (7.5YR 4/2) moist; single grained; loose non sticky and non plastic; few very fine roots throughout; carbonates - none in matrix, pendant coatings onclasts (slightly greater concentration than 2BCk1); slight effervescence;70% pebbles, 10% cobbles; gradual wavy boundary.

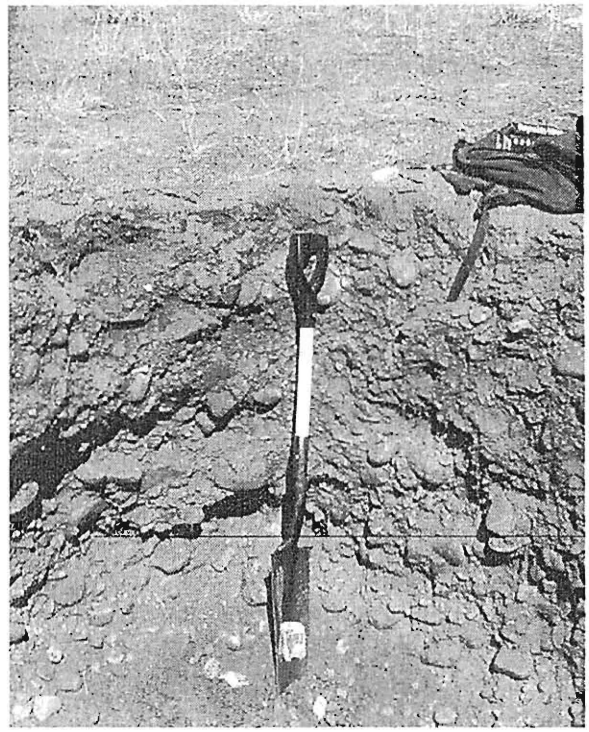

Figure 2. Site 2 - pre-1984 soil profile.

SITE 3

Treatment: flood- irrigated with Rio Grande river water and/or deep ground water
Geomorphic position: nearly level stream terrace
Physiography: mountain valley (0-1% slope)
Elevation ~7675 ft.
Drainage class: well drained
Erosion: slight Runoff: none to slight
Classification: loamy- skeletal over sandy skeletal, mixed, frigid,Typic Calciargid
Diagnostic horizons: 27-45 cmargillic: 27-87+ cm, calcic
Profile facing east described in sun

Ap--0 to 27 cm; gravelly heavy sandy loam; brown (10YR 4/3) moist; weak fine granular structure; soft, very friable, slightly sticky and non plastic; common fine and few coarse roots throughout; no effervescence; 15% gravels, 5% cobbles: abrupt smooth boundary.

Btk--27 to 45 cm; very gravelly sandy clay loam; brown (7.5YR 4/2) moist; moderatesubangular blocky structure; slightly hard, very friable, slightly sticky and slightly plastic; many fine roots throughout; carbonates-disseminated, concentrated toward bottom of horizon; slight effervescence; 45%gravels. 10% cobbles; clear wavy boundary.

Bk--45 to 60 cm; extremely gravelly sandy loam; brown (10YR 4/3) moist; weak subangular blocky structure; slightly hard, very friable, slightly sticky and non plastic; common, very fine roots throughout; strong effervescence; 70% gravels, 5% cobbles; clear wavy boundary.

2BCk1--60 to 87 cm; extremely gravelly sand; brown (10YR 4/3) moist; single grained; loose; non sticky and non plastic; few coarse and few fine roots throughout; carbonates disseminated in matrix, pendant coatings on clasts; slight effervescence; 75% pebbles, 10% cobbles; gradual wavy boundary.

2BCk2--87+ cm; extremely gravelly sand; brown (10YR 5/3) moist; single grained; loose; non sticky and non plastic; few fine and very fine roots throughout; carbonates - pendant coatings on clasts; slight effervescence; 70% pebbles, 15% cobbles.

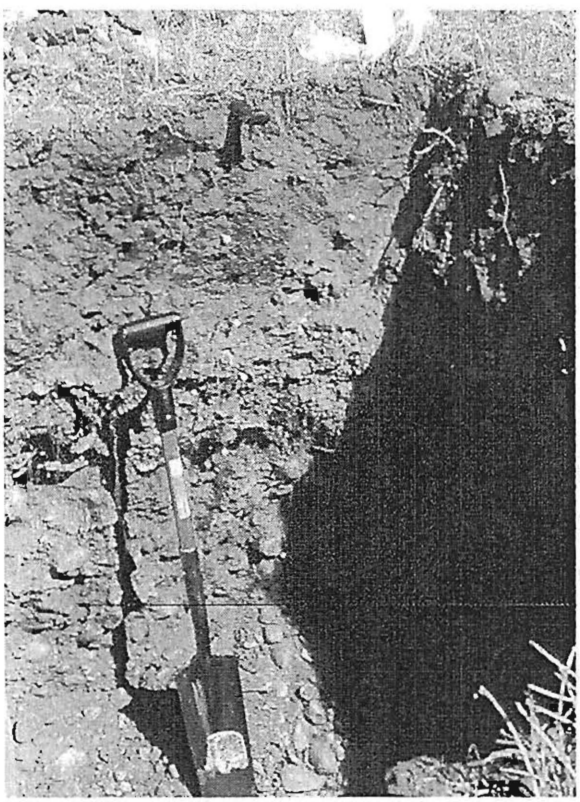

Figure 3. Site 3 - Rio Grande flood irrigated soil profile.

SITE 4

Treatment: sprinkler-irrigated with Rio Grande river water and/or deep ground water
Geomorphic position: nearly level stream terrace
Physiography: mountain valley (0-1% slope)
Elevation ~7675 ft.
Drainage class: well drained
Erosion: slight Runoff: none to slight
Classification: loamy- skeletal over sandy skeletal, mixed, frigid, Typic Calciargid
Diagnostic horizons: 27-42 cm argillic; 27-104 cm, calcic
Profile facing east described in sun

Ap--0 to 27 cm; gravelly cobbly sandy clay loam; brown (10YR 4/3) moist; weak fine granular structure; soft, very friable, slightly sticky and non plastic; many very fine and few fine roots throughout; no effervescence; 40% gravels, 40% cobbles; clear smooth boundary.

Btk--27 to 42 cm; extremely cobbly sandy clay loam; brown (7.5YR 4/4) moist; weak subangular blocky structure; soft, very friable, slightly sticky and slightly plastic; few fine roots throughout; carbonates- very few soft powdery masses in matrix, many pendant coatings on clasts: strong effervescence; 40% gravels, 35% cobbles; clear wavy boundary.

Bk1--42 to 74 cm; extremely gravelly sandy loam; brown (7.5YR 4/4) moist; single grained; loose; non sticky and non plastic; common fine roots throughout; carbonates- very few soft powdery masses in matrix, many pendant coatings on clasts; strong effervescence; 50% gravels, 3% cobbles; clear wavy boundary.

2Bk2--74 to 104 cm; extremely gravelly sand; brown (7.5YR 4/4) moist; single grained; loose; non sticky and non plastic; few fine roots throughout; carbonates- very few bridging sand grains in matrix, many pendant coatings on clasts; slight effervescence; 65% pebbles, 10% cobbles; gradual wavy boundary.

2BC--104+ cm; extremely gravelly sand; reddish brown (5YR 4/3) moist; single grained; loose; non sticky and non plastic; few fine roots throughout; few distinct iron oxide mottles (5YR 6/6); non effervescence; 70% pebbles, 15% cobbles, 5% stones.

Figure 4. Site 4 - Rio Grande sprinkler irrigated soil profile.

SITE 5

Treatment: flood-irrigated withAlamosa River water
Geomorphic position: nearly level stream terrace
Physiography: mountain valley (0-1% slope)
Elevation ~7770 ft.
Drainage class: well drained
Erosion: slight Runoff: none to slight
Classification: loamy- skeletal over sandy skeletal, mixed, frigid,Typic Torriorthent
Diagnostic horizons:cambic
Profile facing east described in sun

Ap—0 to 28 cm; gravelly sandy clay loam: reddish brown (5YR 4/3) moist; weak fine granular structure; slightly hard, friable, slightly sticky and slightly plastic; common very fine roots throughout; no effervescence: 25% gravels, 5% cobbles; abrupt smooth boundary.

Bw1--28 to 57 cm; extremely gravelly sandy loam: reddish brown (5YR 4/3) moist; single grained: loose: non sticky and non plastic; few very fine roots throughout; no effervescence; 70%gravels, 3% cobbles; clear smooth boundary.

Bw2–57 to 79 cm; extremely gravelly loam; yellowish red (5YR 5/6) upper half of the horizon and reddish brown (5YR 4/3) moist; single grained; soft, very friable, slightly sticky and non plastic; common medium and very fine roots throughout; no effervescence; 65 %gravels, 3% cobbles, 5% stones; clear wavy boundary.

2Bw3--79 to 108 cm; extremely gravelly sand; dark reddish brown (5YR 3/3) moist; single grained; loose; non sticky and non plastic; few fine roots throughout; iron and manganese staining on coarse fragments; no effervescence; 80& pebbles, 5% cobbles: gradual wavy boundary.

2Bw4--108+ cm; extremely gravelly sand; dark brown (7.5YR 3/2) moist; single grained; loose; non sticky and non plastic; few very fine roots throughout; very thin carbonate coatings on coarse fragments (unreactive) no effervescence;70% pebbles, 20% cobbles.

Figure 5. Site 5 - Alamosa flood irrigated soil profile.

SITE 6

Treatment: sprinkler-irrigated with Alamosa River water
Geomorphic position: nearly level stream terrace
Physiography: mountain valley (0-1% slope)
Elevation ~7770 ft.
Drainage class: well drained
Erosion: slight Runoff: none to slight
Classification: loamy- skeletal over sandy skeletal, mixed, frigid, Typic Torriorthent
Diagnostic horizons: cambic
Profile facing east described in sun
Plowing to 33 cm could have destroyed the argillic horizon, resulting in classification of the Dunul Series rather than the Graypoint Series.

Ap--0 to 33 cm; very gravelly sandy clay loam; brown (10YR 4/3) moist; weak fine granular structure; soft, very friable, slightly sticky and non plastic; common fine roots throughout; no effervescence; 40% gravels, 10% cobbles and 5% stones; clear smooth boundary.

Bw1--33 to 59 cm; very gravelly sand; dark yellowish brown (10YR 4/4) moist; weak fine subangular blocky to massive structure; loose; non sticky and non plastic; common fine roots throughout; no effervescence; 65% gravels, 10% cobbles, 2% stones; clear wavy boundary.

2Bw2--59 to 87 cm; extremely gravelly sand; dark grayish brown (2.5YR 4/2) moist; massive; loose; non sticky and non plastic; common fine roots throughout; very few faint carbonates (variegated), slight effervescence; 70% gravels; 15% cobbles; gradual wavy boundary.

2Bw3--87 to 120 cm; extremely gravelly sand; dark grayish brown (2.5YR 4/2) moist; single grained; loose; non sticky and non plastic; few very fine roots throughout; very few faint carbonates (variegated), slight effervescence; 80% gravels; 5% cobbles; gradual wavy boundary.

2BC--120+ cm; extremely gravelly sand; dark grayish brown (2.5YR 4/2) moist; single grained; loose; non sticky and non plastic; few very fine roots throughout; very few faint carbonates (variegated), slight effervescence; metal staining reducing zones throughout horizon; 80% gravels, 5% cobbles, 3% stones.

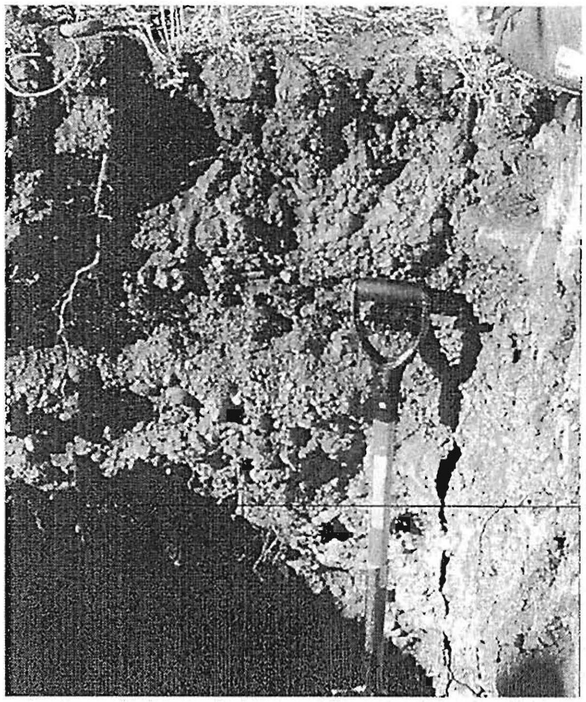

Figure 6. Site 6 - Alamosa sprinkler irrigated soil profile.

DISCUSSION OF FIELD OBSERVATIONS

The degree of weathering in the Graypoint series differs according to which of the six different management schemes the soil is under. Under virgin conditions (site 1), soil formation and weathering are assumed to occur at natural rates typical of arid environments. These weathering processes have slowly developed an argillic horizon from illuviation of clay from the surface. Carbonates have accumulated on the undersides of rock clasts at and below 34 cm with increasing concentration down the soil profile. There are no carbonate concretions in the matrix. The rocks identified from this site show comparatively moderate weathering rinds and are still intact. Site 2 (irrigated and cultivated prior to but not after 1984) also has an argillic horizon and the remnants of a plowed surface horizon which has been subjected to severe disturbance and possible erosion. Carbonates are absent in the upper portion of the profile but can be found on the undersides of rockclasts at and below 42 cm as in site 1. The rocks identified from this site show larger weathering rinds than in site 1 and have some oxide staining but still are intact.

Site 3 and site 4 have greater carbonate accumulation than any of the other sites. This is likely due to the application of high pH irrigation waters moving through the soil profile. There are very few oxide stains on the rocks and weathering of the rocks is least in these two sites. Carbonates are disseminated throughout the matrix for the flood irrigated site (site 3). Under sprinkler irrigation, carbonates can be found in powdery masses within the matrix and as pendant coatings on clasts (site 4). Site 4 also shows the greatest effervescence closest to the surface presumably due to less leaching under sprinkler irrigation.

The greatest signs of weathering occur in sites 5 and 6. This is presumed to be due to the application of the acidic irrigation waters of the Alamosa River. In site 5 there is no accumulation of clay to as an argillic horizon. The high water volume of flood irrigation has moved the clay out of the profile as well as leached the matrix of any reactive carbonates. The undersides of clasts found lower down in the soil profile are covered with a thin white coating that appears to be carbonate but does not react with 1 M HCl. This coating may be silica that has been leached down through the soil profile. These coatings are currently being analyzed. The rocks identified at these two sites are heavily weathered and oxide stained. Iron and manganese staining is prevalent on all rock especially gravels and cobbles. Accelerated weathering compared to control soils, has caused the rocks to breakdown upon handling of the rocks many fall apart in the hand. Significantly larger weathering rinds are present at this site than in any of the other five sites.

Site 6 is also treated with Alamosa River water but through sprinkler irrigation. The lower volume application of acidic irrigation water under sprinklers has left thin coatings of carbonates on the undersides of clasts described as variegated in the soil profile description. As in site 5, site 6 does not have enough clay accumulation to have an argillic horizon. Also in the 2BC horizon rocks are heavily stained with iron and manganese oxides.

It is our observation that the use of Alamosa River water for irrigation has considerably altered the degree of weathering in the soils of the Alamosa River Basin. This is evident in the lack of carbonates in the profile when compared to soils irrigated with other sources of water, the increased iron and manganese staining on rocks, and the increased degradation of the rocks.

Other than field observations very few conclusions can be made at this time. Extensive chemical and physical analyses of the samples from each sites is being conducted in cooperation with Colorado School of Mines and Agro-Engineering of Alamosa, Colorado. Experiments are being conducted to determine the present state of the soils in the Alamosa River Basin and to predict the long-term acid buffering capacity of the soils. Modeling will be used to determine the annual acid and heavy metal loading that these soils will be able to withstand without further degradation. Finally, the study will help local agriculturists make better decisions on how to manage their fields when irrigating with Alamosa River water.

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Section 4

Great Sand Dunes National Monument

THE ROLE OF STREAMS IN THE DEVELOPMENT OF THE GREAT SAND DUNES AND THEIR CONNECTION WITH THE HYDROLOGIC CYCLE

By
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The Great Sand Dunes National Monument is home to a 39 square mile dune field whose complexity belies its relatively small size. The complexity manifests itself as diverse dune development resulting from the interaction of wind and water, and the nature in which their flow is controlled by the local mountain front. The bimodal to complex winds are responsible for creating the dunes, while the streams influence the features of the dune field. Because of the importance of the streams in maintaining the dune system, aspects of the hydrologic cycle at the Great Sand Dunes National Monument Area are studied and monitored to learn how to relate climatic conditions to stream flows and the state of the dune field.

THE ROLE OF STREAMS IN DUNE FIELD DEVELOPMENT

There are two streams that flow along segments of the dune field perimeter. Medano Creek flows along the east and southeastern sides of the dune field and Sand Creek flows along the northwestern side, (see Figure 2). Both completely infiltrate into the ground water system, although Sand Creek occasionally reaches some playa lakes located 10 miles from the mountain front. Discharge has been measured on each stream since 1992 with Parshall flumes placed near where the streams enter monument property. Sand Creek is the larger of the two. Its peak flow has ranged from 54 to 225 cubic feet per second (cfs) and occurs in May and June. Its base flow varies from 0 to 1 cfs. Medano Creek's peak flow has fluctuated from 9 to 65 cfs and base flows are consistently 2-3 cfs.

The streams have a give and take relationship with the dune field. They erode sand from some parts of the dune field and deposit it in others. Each exhibits a net erosion of sand from along the mountain front and deposition on the valley floor during high runoff periods. As flows decrease, the depositional areas dry up, exposing wide, braided channels so that the prevailing winds from the southwest can blow the sand back into the dune field. This results in the dune field having a crescent shape and the thickest sand deposits (up to 750 feet in relief) occurring down wind from the creeks (see figure 1). Each lobe of the crescent is an accumulation of the sand supplied by the streams and the great thickness comes from vertical dune growth allowed by the excess sand and multiple wind directions. Medano Creek is smaller than Sand Creek, but it builds a larger lobe because its erosional section has a longer contact with the dune field.

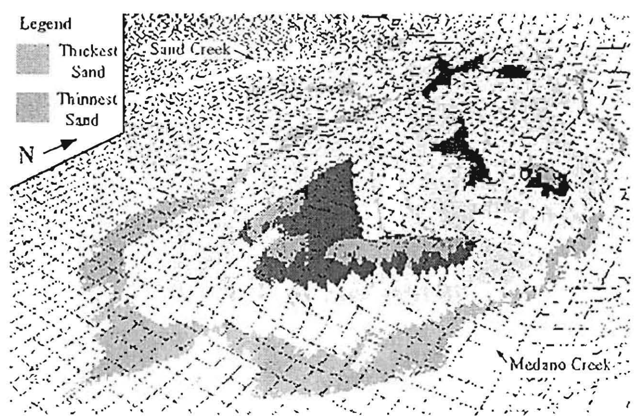

Figure 1. Sand thickness above the San Luis Valley plain. Created by the GIS division of the Rocky Mountain Regional Office, National Park Service.

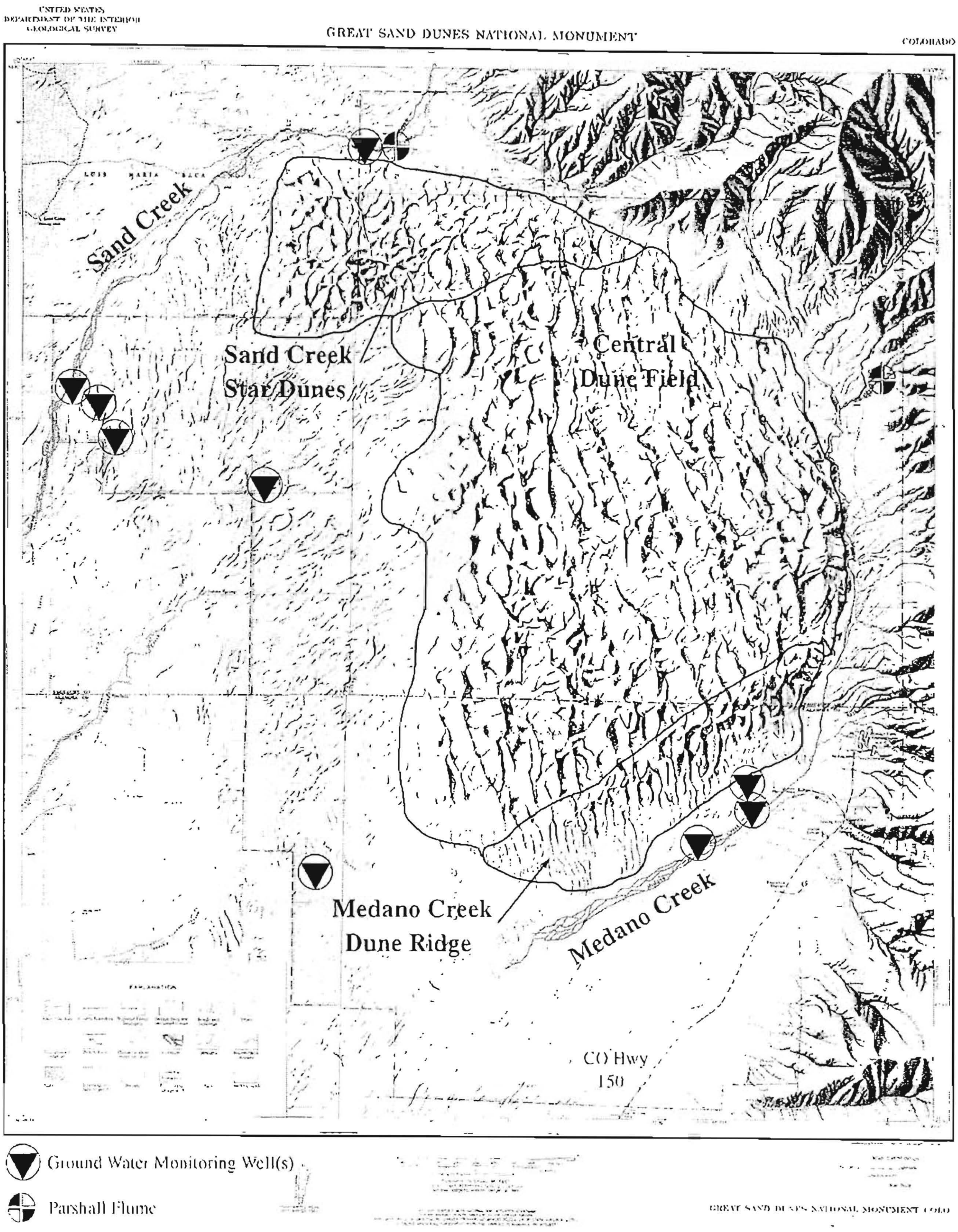

Figure 2. Location of Medano and Sand Creeks, monitoring wells, and Parshall flumes at the Great Sand Dunes National Monument. Modified from USGS map Great Sand Dunes National Monument, Colo.

Medano and Sand Creeks are particularly effective at transporting sand because surge flow can develop in their braided channel sections. Each surge is a pulse of water occurring in regular intervals that can potentially flush more sand down the stream than steady flow. It is a rare phenomena because it requires a high flow regime and a smooth, mobile channel. The fast flow creates bed forms called antidunes. They increase the amount of water stored in the areas where they develop by 20 percent, since they force the water to flow over a sinuous surface instead of a flat surface. The antidunes are not stable and eventually break, releasing the stored water. Since the channel is sandy and creates little turbulence, the pulse of water produced by the collapse of the antidune continues downstream in a discrete packet and picks up more water from other antidune fields (Bean, 1977; Schumm et al., 1982). Surge flow develops better on Medano Creek because its braided channel segment is steeper.

The magnitude of the surge waves depends on water depth. When flows are at the upper discharge levels, the surge wave can be up to one foot high and have a period of 90 seconds. At lower flows, the waves are only a few inches high and have periods less than one minute. In areas where only a thin sheet of water is flowing, several tiny pulses can form in a second.

The action of the creeks contribute to two of three distinct regions of dune development, see figure 2 (Valdez, 1992). The area along Medano Creek is known as the Medano Creek ridge. The thick sand deposits and closely spaced reversing dunes are a direct response to the availability of sand supplied by Medano Creek. Even the close spacing and aggregational nature of the north trending dunes cannot hold all the sand supplied to them, so a second northeast trending ridge fills their troughs and forms the horizon of the ridge. This gives the area an appearance more similar to a sand mountain range than individual dunes. The second area that shows stream affects is known as the Sand Creek star dunes. The many star dunes are the result of a complex wind regime, but a sequence of transverse dunes leading from the Sand Creek floodplain to the star dunes indicate that the source of their sand is Sand Creek. The third area, the central dune field, isn't affected by the streams and as a result displays the simplest dune formation. It has large north trending reversing dunes, with an occasional star dune, that are separated by vegetated troughs. Without the influence of the streams, the entire dune field would probably look like the central dune field and it would likely be oval shaped.

THE CONNECTION OF THE STREAMS TO THE REST OF THE HYDROLOGIC CYCLE

The importance of the streams in the dune system was first realized in the early 1990s. Since then, the National Park Service (NPS) has aspired to better understand their function. Research and monitoring by the NPS and others have laid the groundwork for the these goals to be reached. The first work was intended to explore the scope of the water resources and to start collecting baseline data. After the nature of the water systems was known, then efforts to quantify the effects of the streams and predict how they would react to changes in the local hydrologic cycle were begun.

The stimulus for all the work done since 1990 was a ground water development project proposed on a ranch adjacent to the Great Sand Dunes National Monument. It was designed to withdraw 200,000 acre-feet each year and predicted a lowering of the water table of 150 feet along the monument boundary. The potential for such a drastic change created a real need to understand the relationship between the ground water and the dune field and other natural resources and to predict if those changes were a threat to the goals of the NPS.

The initial projects were intended to determine where the sand moisture within the dunes came from and the type of connection between the streams and ground water. The sand moisture was extracted by flushing a sand core with distilled and deionized water. A chemical analysis of the effluent indicated that the source of the residual moisture was precipitation. Two methods were used to determine the interaction of the streams with ground water. The first was to drill 21 ground water monitoring wells throughout the park and place Parshall flumes on Sand and Medano Creeks. The second used Schlumberger soundings and resistivity testing to map the water table near the creeks. Twelve of the monitoring wells have automated gauging equipment installed while the others are periodically measured manually. The data collected thus far indicates seasonal fluctuations in the water table of up to 10 feet in shallow wells (20 feet) near the Sand and Medano Creeks and fluctuations of < 1 foot in deeper creek wells (100 feet) and wells away from the streams. Most of the wells indicate a simple, surficial aquifer, but the wells drilled into Medano Creek suggest as many as three aquifers levels are within 100 feet of the surface (Hadlock, 1995). The geophysical methods verified the effluent nature of the streams as well as noting differences in hydrologic characteristics of Sand Creek along the mountain front and out in the valley plain (Harmon et al. 1992). It also found areas were Sand Creek was seasonally influent. Both studies predicted that any significant lowering of the water table would increase the gradient between the streams and ground water and decrease the extent and volume of flow, the ability for surge flow to develop, and the ability of these streams to transport sand. With this information in hand, the NPS and other agencies filed an opposition to the water development project and defeated it in water court.

The current research seeks to quantify the role of Medano Creek and predict its effects based on measuring other parameters of the hydrologic cycle. Twenty four survey stations are located every 1,000 feet along the length of Medano Creek's braided channel. Each year, before spring runoff and after the creek has receded, a stream bed profile is surveyed. Changes in the profile are used to calculate the volume of sand moved by the creek during its runoff period and by the wind when the channel is dry. After the first year of the study, the erosion-deposition boundary was found to be 1,000 feet upstream from the dunes parking lot. An average of two feet of sand accumulated in the channel downstream of the parking lot which represents 2 x 107 cubic feet of sand deposited by a flow of 8,500 acre-feet. This project will continue at least two more years to define any exponential changes that may occur with differing runoff levels.

The parts of the hydrologic cycle of interest to the NPS are how the snowpack, storm runoffs, and the position of the water table relate to stream flow rates and duration. A Snotel site was installed near the headwaters of Medano Creek in October of 1995. It measures the water content of the snowpack and precipitation. Although it will take several years to define statistical parameters, its data will be directly compared to runoff characteristics. When combined with information about how the creek is advancing and receding, changes in the water table, and stream discharge, then a better understanding of the hydrologic cycle will exist.

The quest to understand the role of streams in the maintenance of the dune field and how it could be affected by changes in the hydrologic cycle is a work in progress. Hydrologic conditions vary yearly and climatic trends change, therefore all the hydrologic measurement are setup as monitoring projects that operate on an ongoing manner.

The cycle is actually quit simple. It is evident that the snow in the mountains melts, flows down the streams, carries sand, and soaks into the ground (minus the evapotranspiration component). Predicting what changes in any part of the cycle would do to the other parts is not so simple.

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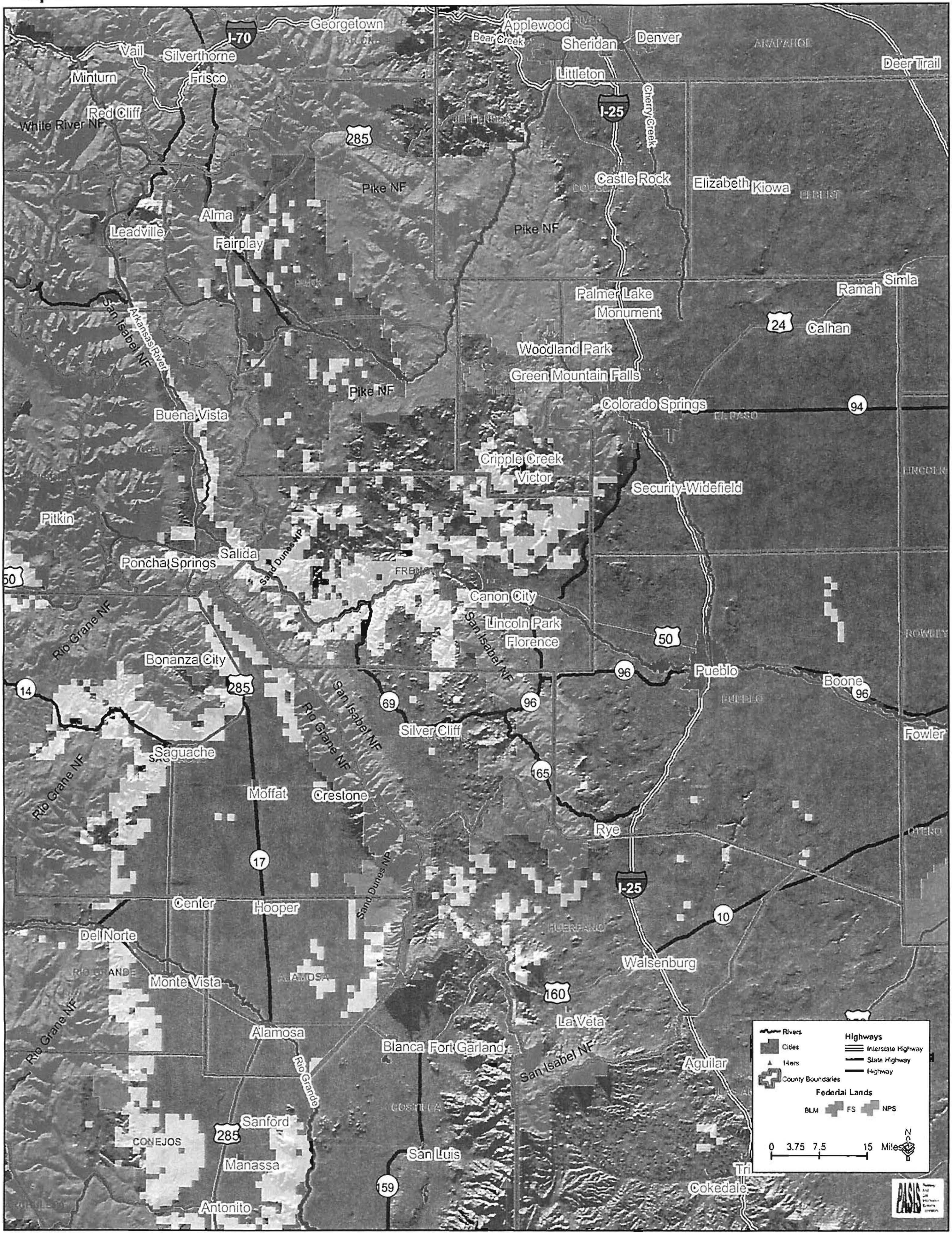
Section 5

Road Log, Mosca – South Park

Map 2.

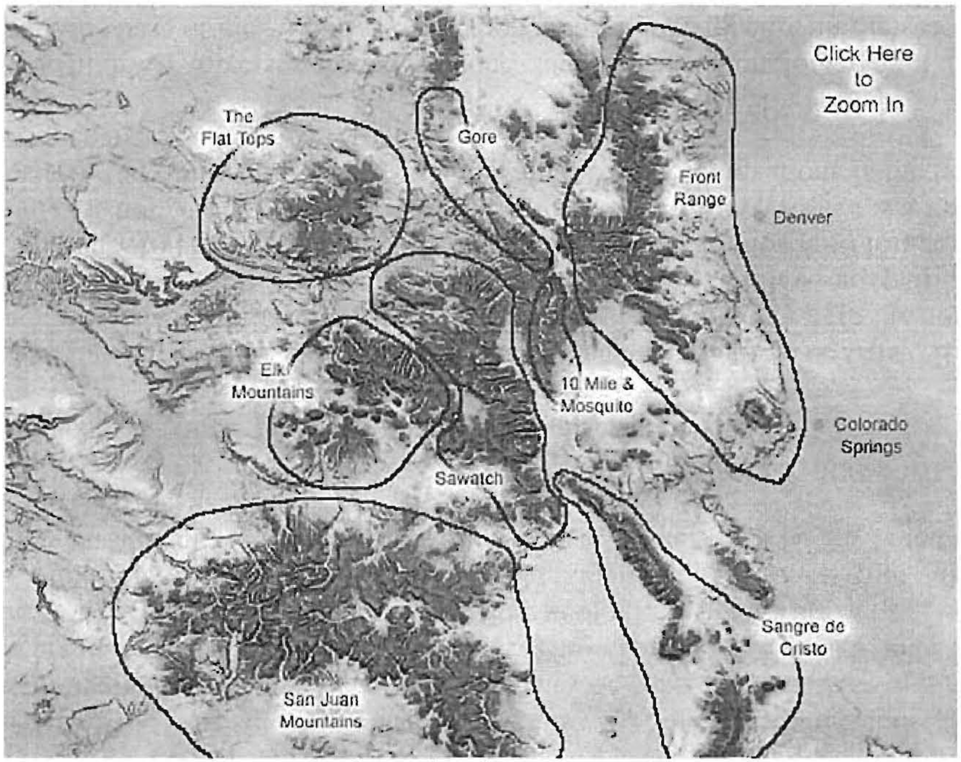

Georgetown
I-70
Vail
Silverthorne
Minturn
Frisco
Red Cliff
White River NF
Applewood
Bear Creek
Sheridan
Denver
ARAPAHOE
Deer Trail
Littleton
I-25
Cherry Creek
285
Castle Rock
Elizabeth
Kiowa
ELBERT
Pike NF
Alma
Leadville
Fairplay
Pike NF
Simla
Ramah
Palmer Lake
Monument
24
Calhan
San Isabel NF
Arkansas River
Woodland Park
Green Mountain Falls
Pike NF
Colorado Springs
94
EL PASO
Buena Vista
Cripple Creek
Victor
Security-Widefield
LINCOLN
Pitkin
Sand Dunes NP
Salida
Poncha Springs
50
FREMONT
Canon City
Rio Grane NF
Lincoln Park
San Isabel NF
Florence
50
CROWLEY
Bonanza City
96
Pueblo
Boone
96
14
285
PUEBLO
San Isabel NF
69
96
Rio Grane NF
Silver Cliff
Fowler
Saguache
165
Rio Grane NF
Moffat
Crestone
Rye
OTERO
17
Sand Dunes NP
I-25
Center
Hooper
10
HUERFANO
Del Norte
RIO GRANDE
Monte Vista
ALAMOSA
Walsenburg
160
Rio Grane NF
La Veta
Alamosa
Blanca
Fort Garland
Rio Grande
San Isabel NF
Aguilar
COSTILLA
Sanford
CONEJOS
285
San Luis
Manassa
159
Cokedale
Antonito
Rivers
Cities
14ers
County Boundaries
Highways
Interstate Highway
State Highway
Highway
Federal Lands
BLM
FS
NPS
0
3.75
7.5
15
Miles
N
PASIS

Geologic Time Scale

ERA	PERIOD	EPOCH
CENOZOIC	Quaternary	Holocene Pleistocene
	Tertiary	Pliocene Miocene Oligocene Eocene Paleocene
MESOZOIC	Cretaceous Jurassic Triassic	
PALEOZOIC	Permian Pennsylvanian Mississippian Devonian Silurian Ordovician Cambrian	
PRECAMBRIAN		

Road Log Day 2
Mosca-South Park

Mile Marker	Feature/text
Highway 17:	
91	UFO Watchtower – "From the fall of 1966 through the spring of 1970 there were hundreds of unidentified flying object sightings and many of the first documented cases of unusual animal deaths (UADs) ever reported. During peak UFO sighting waves in the late '60s dozens of cars would literally line the roads watching the amazing aerial displays of unknown lights/craft as they cavorted around in the sky above the Great Sand Dunes/Dry Lakes area. Several published photographs of these objects/lights were taken by witnesses in 1967. "(Source: http://www.cyberwest.com/cw06/v6alwst1.html)



Source: http://www.14ers.com/

Highway 285:

San Juan Range – Bordering the west side of the San Luis Valley, the San Juan Range consists of a dome of Precambrian rock covered by Tertiary age volcanic rocks. The San Juans may be considered the largest distinct mountain system in the U.S., and cover an area larger than the state of Vermont. They represent the most extensive region of volcanism in Colorado, occurring in several phases throughout much of the geologic period. Three classes of volcanic rock are present in the range, including, lava flows (formed from liquid magma), tuff (formed from volcanic ash and cinder) and breccia (formed from lava fragments). The dramatic form of the San Juans may be attributed to multiple phases of glaciation throughout the Pleistocene.

122 Volcanics – The outcrop consists of purple lava flows of the San Juan Range.

Sawatch Range - Poncha Pass crosses the saddle between the Sawatch and Sangre de Cristo Ranges, and is the divide between the Rio Grande watershed (to the south) and the Arkansas River watershed (to the north). The Sawatch Range and the Mosquito Range - directly north and east across the Arkansas River Valley - are part of the same uplift, such that the sedimentary rock that once overlay them both now dips to the east of the Mosquito Range and to the west of the Sawatch. The river valley is now in the central core of that uplift. The Sawatch Range is a Precambrian core of igneous rock containing younger Tertiary intrusions, some of which are the highest elevations in the range. The range is home to 15 of the state's 53 fourteeners.

130 Tertiary sediments – The highway traverses eroded siltstone, sandstone and conglomerate of Tertiary age. These sediments extend west to the base of the Arkansas Valley where they are capped with Pleistocene gravel and glacial drift. In this proximity, the Arkansas Valley lies at elevation of approximately 7800 ft. The Arkansas River follows a fault valley, the same rift that is responsible for the San Luis Valley.

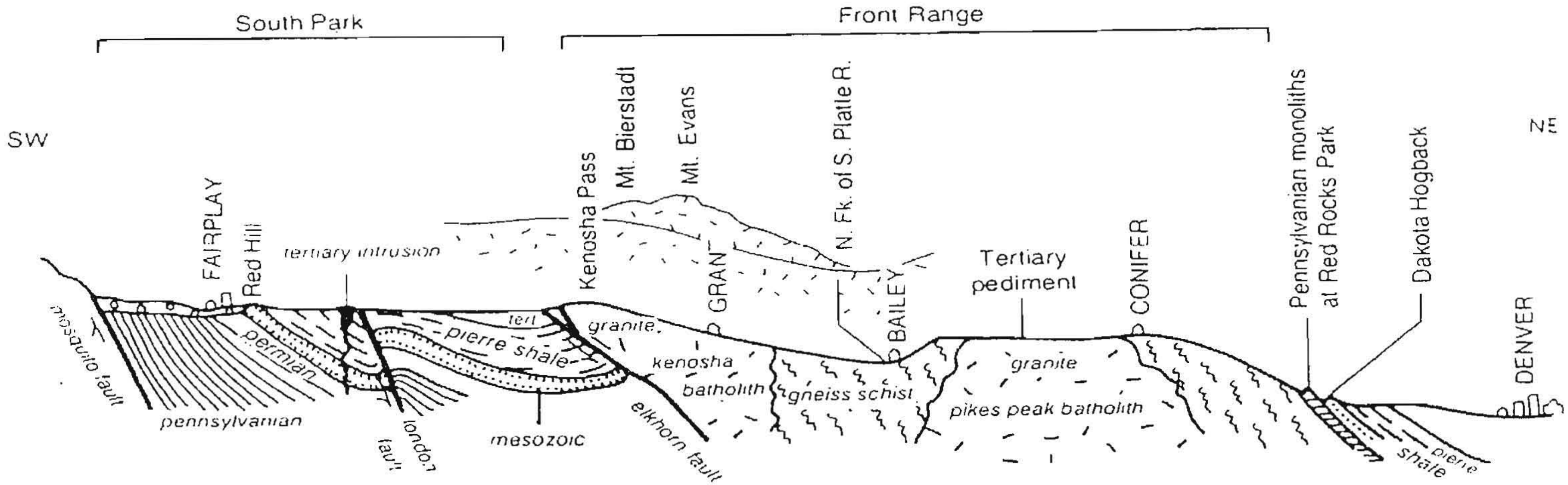
132 Mt. Shavano – Immediately to the west is Mt. Shavano, elevation 14,229 ft. It ranks 17^{th} amongst the state's fourteeners.

139 Mt. Antero - Immediately to the west is Mt. Antero, elevation 14,269 ft. It ranks 10^{th} amongst the state's fourteeners.

142 Mt. Princeton - Immediately to the west is Mt. Princeton, elevation 14,197 ft. It ranks 20^{th} amongst the state's fourteeners. All three of the peaks just noted are Tertiary age intrusions that pushed into, and through, the core of the range after it was uplifted.

225 (note: Here, Highway 285 coincides with Highway 24, and is numbered according to the latter) Trout Creek Pass crosses the Mosquito Range. Immediately preceding and following the summit are outcrops of pre-Pennsylvanian Paleozoic age sediments.

164 South Park – Between the Mosquito Range and the Front Range (to the east) is South Park, a broad intermountain valley approximately 50 mi long and 25 mi wide underlain by Paleozoic and Mesozoic sediments. Visible at the south end of the "park" is the Tertiary age Thirtynine Mile volcanic field. The white deposits on the relatively flat parts of the floor of South Park are evaporite deposits. At the north end of the park, near the old mining town of Fairplay, are extensive gravel deposits that have been dredged to remove placer gold. South Park is drained by the South Platte River.



Source: Chronic, H. 1980. Roadside Guide to the Geology of Colorado. Mountain Press Publishing Co, Missoula, MT.

178 Little Black Mountain – This dome-shaped mountain visible to the west is a laccolith, an igneous intrusion that pushed up between rock layers, causing them to arch upward while not escaping to the surface.

183 Buffalo Peaks – Off to the west are the Buffalo Peaks; volcanic in origin, they are dark because they are largely composed of lava and ash containing very little quartz.

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Section 6

South Park Fen

Water and soil chemistry, floristics, and phytosociology of the extreme rich High Creek fen, in South Park, Colorado, U.S.A.

David J. Cooper

Abstract: An extreme rich fen complex located in South Park, Colorado, is the most southern representative of this ecosystem type known in North America and the first described from the Southern Rocky Mountains. The fen is fed by ground water emerging from glacial outwash and has pH ranging from 7.6 to 8.3 and Ca^{2+} concentrations greater than 50 mg kg^{-1}. The very low precipitation–evapotranspiration ratio in South Park causes Na^{+} and Mg^{2+} salts to accumulate in some soils, forming sodic peats that support halophyte communities. Character species of this fen include *Kobresia simpliciuscula*, *Trichophorum pumilum*, *Carex scirpoidea*, *Carex microglochin*, *Carex livida*, *Utricularia ochroleuca*, *Triglochin palustris*, *Triglochin maritima*, *Salix candida*, *Salix myrtillifolia*, *Salix serissima*, *Thalictrum alpinum*, and *Scorpidium scorpioides*. A hierarchical classification of the vegetation is developed using numerical and table methods and includes 14 aquatic, peatland expanse, and salt flat communities. The most floristically similar fens occur in northern Ontario, northwestern Wyoming, and northern Montana.

Key words: peatland, extreme rich fen, South Park, Colorado, Rocky Mountains.

Résumé : Le complexe de tourbières élevées extrêmement riche, localisé à South Park au Colorado, constitue le représentant le plus méridional de ce type d'écosystème connu en Amérique du Nord, et le premier qui soit décrit dans le sud des Montagnes Rocheuses. Cette tourbière haute est nourrie par une émergence de la nappe phréatique provenant d'un lessivat de glacier et possède un pH de 7,6 à 8,3, avec des teneurs en Ca^{2+} plus grandes que 50 mg kg^{-1}. Le très faible taux de précipitation–évapotranspiration à South Park amène les sels de Na^{+} et de Mg^{2+} à s'accumuler dans certains sols formant des tourbes sodiques qui supportent une végétation d'halophytes. Les espèces caractéristiques de cette tourbière haute incluent les *Kobresia simpliciuscula*, *Trichophorum pumilum*, *Carex scirpoidea*, *Carex microglochin*, *Carex livida*, *Utricularia ochroleuca*, *Triglochin palustris*, *Triglochin maritima*, *Salix candida*, *Salix myrtillifolia*, *Salix serissima*, *Thalictrum alpinum*, et *Scorpidium scorpioides*. L'auteur développe une classification hiérarchique de la végétation en utilisant des méthodes numériques et de tabulation incluant 14 communautés aquatique, de tourbière et de plage salée. Les tourbières les plus ressemblantes floristiquement se retrouvent dans le nord de l'Ontario, le nord-ouest du Wyoming et le nord du Montana.

Mots clés : tourbière, tourbière haute extrêmement riche, South Park, Colorado, Montagnes Rocheuses.
[Traduit par la rédaction]

Introduction

Peatlands that are floristically related to boreal bogs and fens occur as far south in North America as the Southern Rocky Mountains (36–42°N latitude), where they are confined to high elevation (>2500 m) valleys and basins. The dry, warm climate in this region limits peat accumulation to sites where sufficient ground and surface water occurs to maintain soil saturation through the summer (Cooper 1990); thus, all of these peatlands are fens. The chemical characteristics of these fens are largely controlled by watershed bedrock. The bedrock of individual ranges of the southern and central Rocky Mountains is often homogeneous, making the chemical composition of surface waters comparable over large areas. Peatlands in many large areas, such as the Wind River Range in Wyoming, can be similarly classified along the rich to poor gradient (Cooper and Andrus 1994). Differences along the rich to poor gradient appear to occur at a landscape scale between mountain regions of different lithology, not within a single peatland complex.

While ombrotrophic bogs and poor fens are among the most common peatland types in boreal and coastal regions that have high precipitation to evapotranspiration ratios and occur in relatively flat and usually unconfined landscapes (Damman 1986), these ecosystem types are absent in the Southern Rocky Mountains. The common peatland type in Rocky Mountain regions with igneous and metamorphic bedrock and water of low ionic strength is the transitional fen (Cooper 1990, 1991; Cooper and Andrus 1994). However, a few regions in the Rocky Mountains, such as the headwaters of the Teton River in northwestern Montana, the Gros Ventre Range in northwestern Wyoming, and the Mosquito Range and South Park in central Colorado, contain limestone and other calcareous bedrock. Thus, extreme rich fens may occur in the southern and central Rocky Mountains.

The objective of this paper is to describe the water and soil chemistry, flora, and vegetation of High Creek fen in

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South Park, Colorado, which is fed by waters draining a largely calcareous watershed. While the differences in peatland flora and vegetation along the rich to poor gradient have been well studied in several areas of the Holarctic (Sjors 1950, 1963; Malmer 1986; Glaser et al. 1990), the differences between peatlands with similar water chemistry but occurring in regions with different climate and history are less well known. In general, peatlands in the Rocky Mountains of the U.S. have received scant ecological attention and the comparison of a fen from a calcareous region of the interior U.S. with rich and extreme rich fens from other portions of the world is important for understanding the variation in this ecosystem type.

Study area

High Creek fen occurs in South Park, Colorado (Fig. 1) a faulted syncline between the Sawatch and Front Range uplifts (Chronic 1980) that forms one of the large intermountain basins in the Southern Rocky Mountains. The Front Range on the eastern side of South Park is composed of granitic rocks, while the Mosquito Range on the west side is capped with Paleozoic sedimentary rocks, most prominently the Mississippian age Leadville Limestone. Dolomites also occur in the Mosquito Range. On the floor of South Park, sedimentary bedrock is close to the surface and capped by thin Quaternary sediments deposited by Pleistocene glacial outwash and modern streams. Water from the Mosquito Range drains across South Park, forming the headwaters of the South Platte River. The chemical characteristics of surface and ground waters in this region are strongly influenced by calcareous parent materials.

The surrounding mountain ranges produce rainshadows that control many aspects of South Park's climate. The area receives an average of 251 mm of precipitation annually, of which 72% occurs during the May–September growing season (Spahr 1981). Long periods without precipitation are common in both summer and winter, and snow cover, when present, is thin, patchy, and crusted by wind. Average total annual pan evapotranspiration for two sites in the region during 1982–1985 was 865 mm. Potential evapotranspiration is 3.45 times greater than average precipitation (precipitation – potential evapotranspiration ratio of 0.29). The large potential evapotranspiration deficit limits the regional vegetation to short grass and sedge steppe, dominated by *Chondrosum* (*Bouteloua*) *gracilis*, *Artemisia frigida*, and other drought-tolerant species.

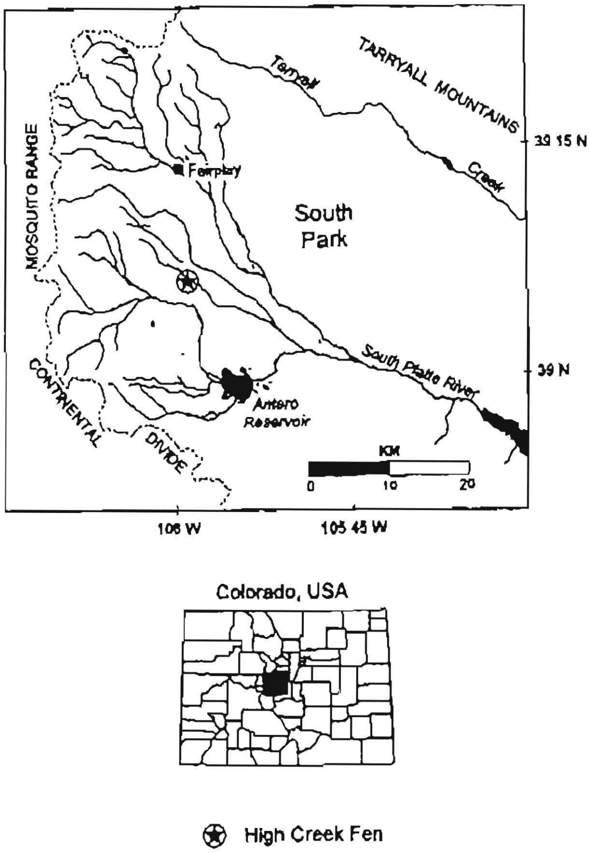
Because of the lack of winter snowpack in South Park, local water tables are recharged by high mountain snowmelt in late May and June. High Creek, like many streams in South Park, flows from the Mosquito Range, infiltrates the South Park valley floor alluvium, and is discharged from glacial outwash deposits at an elevation of 2840 m, forming High Creek fen.

Methods

Water chemistry

The pH and conductance of surface water was measured in the field with a Corning model 104 pH meter with combination electrode and a YSI conductivity–salinity–temperature meter, respectively. Conductance was corrected for H^+ ions and is presented as K_{corr}. Water samples were collected from the major water sources in the study area, passed through 0.45-μm filter paper in the field to remove suspended solids, and later analyzed for Ca^{2+}, Mg^{2+}, Na^+, and K^+ using inductively coupled plasma (ICP) emission spectrography. HCO_3^- was analyzed by titration, and Cl^- and SO_4^{2-} using ion chromatography (Pfaff et al. 1989). All analyses were performed at the Soil Testing Laboratory at Colorado State University, Fort Collins, Colo.

Fig. 1. Location of High Creek fen (star) in Colorado.



Vegetation analysis

Standard phytosociological methods (Mueller-Dombois and Ellenberg 1974) were used to sample the vegetation at High Creek fen. Homogenous stands, 25 m^2 in size, were subjectively chosen without preconceived bias toward plant communities present. A total of 135 stands were sampled, listing all plant species and estimating percent canopy coverage. A vegetation classification was developed using a combination of two-way indicator species analysis using the computer program TWINSPAN (Hill 1979*a*) run with the default values, and Braun-Blanquet table methods (Westhoff and van der Maarel 1978). A summary table presents mean cover and constancy class (I–V) of diagnostic species for each community.

Detrended correspondence analysis (DCA) (Hill 1979*b*) using the computer program CANOCO (ter Braak 1987–1992) was used to indirectly ordinate the vegetation data. One stand ordination and one species ordination were used to examine the relationships among vegetation communities, plant species, and landforms. Plant species were collected, specimens were deposited at the University of Colorado, Boulder, Colo., and nomenclature follows Weber and Wittmann (1992).

Soil chemistry

Once the vegetation classification was completed, soil samples were collected for stands representing the major communities. Each sample was collected from the top 20 cm and air dried, and percent of organic matter determined by loss on ignition. A paste was made from subsamples, and water extracted (Janzen 1993), and concentrations of cations and anions were analyzed using the same methods as for water. Sodium absorption ratio (SAR) was calculated as $[Na^+]/[Ca^{2+} + Mg^{2+}]^{0.5}$ (Janzen 1993).

Table 1. Chemical characteristics of the three main water sources at High Creek Fen.

Source	*n*	pH	K_{corr}	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	SO_4^{2-}	Cl^-
A	3	7.84	437	55.1	29.7	8.4	1.6	252.7	34.7	4.6
B	2	7.84	689	92.8	78.4	9.9	0.8	383.5	89.1	14.1
C	2	8.13	1613	67.2	97.7	25.4	2.7	247.6	815.4	42.6

Note: Conductance in $\mu S\ cm^{-1}$, ions are concentrations in mg kg^{-1}.

Table 2. Chemical characteristics of soils in the study area.

Comm	*n*	OM (%)	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SAR
3.2	2	54.9	19.7	16.1	1.6	0.4	0.3
3.4	1	66.0	6.5	3.7	1.0	0.4	0.4
3.5	2	71.9	8.5	5.5	1.3	0.8	0.5
4.1	2	56.5	6.7	12.0	2.5	1.0	0.8
4.2	2	33.8	11.0	17.7	4.3	2.1	1.1
4.3	2	24.0	15.0	24.7	8.2	0.9	1.9
5.1	2	44.5	5.9	8.2	2.3	0.7	0.8
5.2	2	62.7	4.9	13.6	3.5	2.4	1.2
6.1	2	24.8	9.7	238.5	145.7	12.0	13.0

Note: Percent organic matter is loss on ignition, all ions in mol L^{-1}, and SAR is $[Na^+]/[Ca^{2+} + Mg^{2+}]^{0.5}$. Comm, community type codes (see classification in text).

Table 3. Number and percent of High Creek vascular plants occurring in other floras.

Flora	Shared No.	Shared %	Dist (km)
Pine Butte, Montana (Lesica 1986)	43	36.4	950
Swamp Lake, Wyoming (Fertig and Jones 1992)	37	31.4	650
Idaho (Bursik and Henderson 1995)	35	29.7	1300
Upper Kuskokwim R., Alaska (Drury 1956)	25	21.2	4000
Big Meadows, Colorado (Cooper 1990)	22	18.6	130
Arrigetch Creek, Alaska (Cooper 1986)	15	12.7	4100
W. Alberta (Slack et al. 1980)	11	9.3	1600
Wind River, Wyoming (Cooper and Andrus 1994)	9	7.6	580
Lost River, Minnesota (Glaser et al. 1990)	9	7.6	1200

Note: The High Creek flora contains 118 vascular plant taxa. No. shared, number of taxa shared by two floras. % shared, percent of the High Creek flora occurring in this area. Dist, distance from High Creek fen.

Results

Water chemistry

The chemical composition of water samples was used to identify three main groundwater sources supplying High Creek Fen (Table 1). Water source A enters as discharge from two glacial outwash lobes on the north and northeastern sides of the study area and is a calcium bicarbonate type water. It is suspected to be ground water recharged from Fourmile Creek, the nearest stream north of High Creek fen. It has a pH of 7.84, K_{corr} of 437 $\mu S\ cm^{-1}$, and the lowest ion concentrations of the three water supplies with Ca^{2+} concentrations of approximately 55 mg kg^{-1}.

Water source B enters from the northwest and is suspected to be ground water moving down the High Creek drainage. It is a calcium and magnesium bicarbonate type water. This water has nearly double the Ca^{2+} concentration of water source A, although it has similar pH.

Water source C enters from the southwest in an area of foothills and is a calcium sulfate type water. It has the highest pH, conductance, and cation concentrations of the three water sources identified. It also has the highest Cl^- and SO_4^{-2}, yet the lowest HCO_3^- concentrations. All samples analyzed contained low K^+ concentrations, and Na^+ concentrations were low in all but water source C.

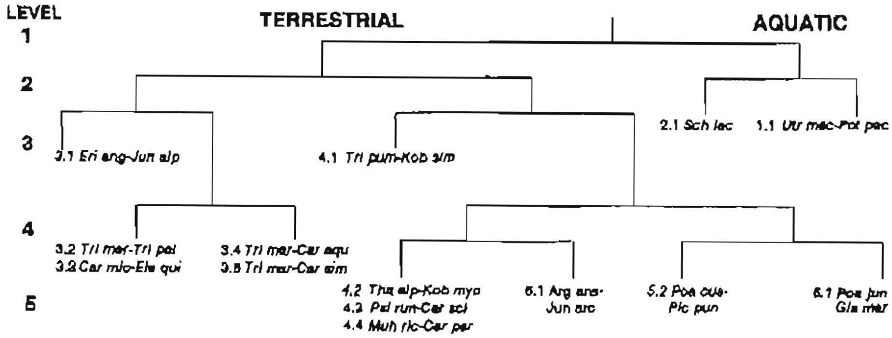
Soil chemistry

All soils sampled, even those from salt flats, contained greater than 20% organic carbon and are classified as organic soils (Soil Survey Staff 1975). Organic carbon content for the 17 samples analyzed ranged from 22.1 to 79.7% with the highest carbon content in the wettest sites, such as water tracks (Table 2). Hummocks dominated by *Kobresia simpliciuscula* have approximately 50–60% organic matter, while hummocks dominated by *Kobresia myosuroides* have 30–40% organic matter, and salt flat soils contain between 20 and 30% organic matter.

Mg^{2+}, Na^+, and K^+ concentrations are highest in the drier stands where capillary water evaporates at the soil surface, leaving solutes behind. Although Ca^{2+} is the most abundant cation in all study area water sources, it does not occur in higher concentrations in drier sites, most likely owing to its precipitating as insoluble calcium carbonate. Water extractable Na^+ concentrations varied from 0.7–10.4 mol L^{-1} in water tracks to 145.7 mol L^{-1} in salt flats. Even higher concentrations of Mg^{2+} occurred, ranging from 4.8–32.1 mol L^{-1} in water tracks to 271.4 mol L^{-1} in a salt flat stand.

SAR is a useful index of sodicity or relative sodium status of soil solutions (Janzen 1993), and varies from approximately 0.4 in water tracks, to 1.0 in hummock communities, to more than 13.0 in some salt flat stands. Soils with SAR values greater than 13 are usually considered to be sodic (Soil Science Society of America 1984) and contain a natric horizon (Soil Survey Staff 1975). Sodic peats are not previously reported for the interior U.S. but may be characteristic of certain extreme rich fen communities occurring in semi-arid regions.

Fig. 2. Hierarchical cluster analysis of the High Creek Fen vegetation generated using TWINSPAN.



Floristic comparison

Table 3 summarizes the percent of High Creek vascular plants occurring in nine other fens, or regional floras where fens are abundant. The size of the area surveyed ranges widely from 60 ha in Big Meadows to areas many times that size, e.g., the state of Idaho. The number of High Creek species occurring in the other floras is low. For example, Big Meadows, located 130 km to the north and at a similar elevation as the study area, contains less than 20% of the High Creek flora and none of the characteristic extreme rich fen taxa. Montana's Pine Butte fen, approximately 950 km distant, has similar water chemistry to High Creek fen but supports only one third of the taxa, while Idaho's peatlands and Wyoming's Swamp Lake fen support less than 30 and 31% of the High Creek taxa, respectively. The two Alaskan sites are large land areas at great distance from the study area, yet they contain more High Creek species than the floras of sites from Alberta, Wind River Range in Wyoming, or Minnesota.

Vegetation classification

The classification presented here is hierarchical with three levels, similar to the order, alliance, and association of the Braun-Blanquet school (Westhoff and van der Maarel 1978). Analysis of the stand data using TWINSPAN identified three major community groups and a total of 14 communities (Fig. 2), and a synoptic table of the communities is presented in Table 4.

Aquatic communities

Submerged aquatic community:
1.1. *Utricularia macrorhiza* – *Potamogeton pectinatus*. This community occupies small pools that have either an organic or a mineral soil bottom. *Potamogeton pectinatus*, *U. macrorhiza*, and *Chara* sp., are constants.

Rooted emergent community:
2.1. *Schoenoplectus lacustris* ssp. *acutus*. This community is characterized by near monospecific stands of *Schoenoplectus lacustris* ssp. *acutus*, with *Eleocharis palustris* and *Triglochin maritima* present in some stands. It occurs in shallow pools up to 30 m in diameter, mostly in the southwestern portion of the study area, where they are fed by water source C. Saline ponds of similar character occur in many high mountain regions of the Holarctic. For example, Store Saltsø, one of the saline lakes of west Greenland (Böcher 1949), has high conductances and even higher ion concentrations than these study area ponds.

Peatland expanse communities

Hollow, water track, and spring fen communities: Hollows occur in the mud bottoms between low hummocks. Water tracks are low-lying linear features with water sheet flowing for most of the summer. Both of these habitats are dominated by species that reproduce well from seed following small-scale disturbance, including *Triglochin palustris*, *Triglochin maritima*, *Eleocharis quinqueflora*, and *Juncus alpino-articulatus*. Spring communities occur where perennial groundwater discharge saturates soils. Stands are typically dense and productive lawns without hummocks.

3.1. *Eriophorum angustifolium* – *Juncus alpino-articulatus*. This community occupies mud-bottomed hollows between peat hummocks maintained by intense freeze–thaw processes. These stands have only widely scattered plants with scant production. *Eriophorum angustifolium* is common in Scandinavian mud-bottom communities (Malmer 1985).

3.2. *Triglochin maritima* – *Triglochin palustris*. This community occurs in water tracks and large areas of bare mud always occur. Tiny pools within the water tracks support populations of *Utricularia ochroleuca* and the bryophyte *Scorpidium scorpioides* is abundant in certain stands that have more constant flows of water.

3.3. *Carex microglochin* – *Eleocharis quinqueflora* occurs in water tracks with less disturbance and less bare mud than the last association. *Eleocharis quinqueflora* is dominant in all stands and supports a more continuous cover than the last community. The sedges *Carex livida* and *Carex microglochin* reach their maxima here.

3.4. *Triglochin maritima* – *Carex aquatilis* stands occur at strong springs, often on slight slopes where water can be seen discharging from the ground and flowing on the soil surface. The soil is firm and *Carex aquatilis* forms a lawn. Some stands have a submerged carpet of *Scorpidium scorpioides*.

3.5. *Triglochin maritima* – *Carex simulata*. Stands of this association occur at strong springs and the ground typically quakes. The sedge carpet is continuous with few breaks. Some stands support a carpet of *Scorpidium scorpioides*.

Table 4. Summary table of mean percent cover and constancy class (I–V) for diagnostic and constant species for the 14 study area communities.

Species	Aquatic		Peatland expanse									Meadow		Salt flat
	Subm	Emer	Hollow	Water track		Spring		Hummock						Sodic
	1.1	2.1	3.1	3.2	3.3	3.4	3.5	4.1	4.2	4.3	4.4	5.1	5.2	6.1
Potamogeton pectinatus	24.6 (V)	2.5 (I)	—	—	—	—	—	—	—	—	—	—	—	—
Chara spp.	8.9 (IV)	1.9 (I)	—	—	—	—	—	—	—	—	—	—	—	—
Utricularia macrorhiza	12.1 (IV)	1.5 (I)	—	—	—	—	—	—	—	—	—	—	—	—
Schoenoplectus lacustris	—	48.1 (V)	—	—	—	—	—	—	—	—	—	—	—	—
Eleocharis palustris	—	8.1 (I)	—	—	—	—	—	—	—	—	—	—	—	—
Juncus alpino-articulatus	—	0.3 (I)	16.8 (V)	—	—	—	—	—	—	—	—	—	—	—
Eriophorum angustifolium	—	—	20.5 (V)	—	—	—	—	—	—	—	—	—	—	—
Triglochin maritima	—	1.3 (I)	0.9 (I)	15.7 (V)	10.0 (V)	5.8 (II)	6.4 (IV)	1.2 (III)	—	2.0 (V)	—	1.2 (I)	—	—
Triglochin palustris	—	—	0.9 (I)	43.2 (V)	4.8 (IV)	7.5 (III)	—	0.1 (I)	—	—	—	—	—	—
Eleocharis quinqueflora	—	—	11.8 (V)	2.5 (I)	40.8 (V)	—	—	0.9 (II)	—	—	—	—	—	—
Scorpidium scorpioides	—	—	—	13.2 (II)	1.2 (I)	18.1 (II)	17.1 (I)	—	—	—	—	—	—	—
Carex aquatilis	—	—	—	—	3.8 (II)	76.2 (V)	6.4 (II)	2.5 (I)	—	—	—	0.5 (I)	—	—
Carex simulata	—	—	—	0.7 (I)	0.8 (II)	5.0 (II)	70.0 (V)	—	—	—	—	—	—	—
Utricularia ochroleuca	—	—	—	1.7 (II)	0.3 (I)	0.8 (II)	—	—	—	—	—	—	—	—
Carex livida	—	—	—	0.4 (I)	4.4 (II)	—	1.4 (I)	0.8 (I)	—	—	—	—	—	—
Carex microglochin	—	—	—	—	3.3 (II)	—	—	2.2 (I)	—	—	—	—	—	—
Salix myrtillifolia	—	—	—	0.1 (I)	—	—	—	1.3 (I)	—	—	—	0.2 (II)	—	—
Salix planifolia	—	—	—	—	—	0.6 (I)	—	—	—	—	—	0.9 (I)	—	—
Pedicularis groenlandica	—	—	—	0.2 (II)	0.1 (I)	0.3 (I)	0.3 (I)	0.1 (I)	—	—	—	—	—	—
Campyliadelphus stellatus	—	—	—	1.8 (I)	—	11.9 (III)	—	1.9 (I)	—	—	—	—	—	—
Kobresia simpliciuscula	—	—	—	—	—	—	—	40.7 (V)	—	—	—	—	—	—
Trichophorum pumilum	—	—	—	—	—	—	—	11.1 (V)	—	—	—	—	—	—
Thalictrum alpinum	—	—	—	—	—	—	—	18.8 (IV)	10.7 (V)	19.0 (V)	—	4.7 (IV)	—	—
Primula egaliksensis	—	—	—	—	—	—	—	0.3 (III)	—	—	—	—	—	—
Salix brachycarpa	—	—	—	—	—	0.6 (II)	—	3.4 (III)	10.0 (V)	—	—	15.4 (IV)	5.0 (I)	—
Salix candida	—	—	—	1.3 (I)	—	3.7 (II)	0.9 (I)	11.3 (IV)	—	—	—	—	—	—
Kobresia myosuroides	—	—	—	—	—	—	—	0.1 (I)	56.7 (V)	—	—	0.8 (II)	—	0.2 (I)
Carex scirpoidea	—	—	—	—	—	—	—	1.7 (II)	5.0 (V)	60.0 (V)	9.0 (III)	1.1 (I)	—	3.2 (II)
Carex parryana	—	—	—	—	—	—	—	—	0.3 (I)	0.3 (I)	50.0 (V)	1.1 (I)	—	1.0 (II)
Deschampsia cespitosa	—	—	—	—	—	—	—	1.6 (III)	4.0 (II)	3.0 (V)	—	3.0 (IV)	1.5 (I)	2.0 (II)
Sisyrinchium pallidum	—	—	—	—	—	—	—	—	0.3 (II)	1.7 (V)	0.5 (III)	0.7 (III)	—	—
Muhlenbergia richardsonis	—	—	—	—	—	—	—	0.1 (I)	1.7 (II)	—	20.0 (III)	2.2 (II)	—	1.2 (II)
Bistorta vivipara	—	—	—	—	—	—	—	0.5 (II)	—	—	—	0.9 (II)	—	—
Juncus arcticus	—	—	—	—	—	—	—	1.3 (II)	3.3 (I)	2.0 (V)	5.0 (III)	52.7 (V)	7.5 (V)	0.2 (I)
Pentaphylloides floribunda	—	—	—	—	—	—	—	1.5 (III)	—	—	—	15.5 (II)	—	6.2 (IV)
Pedicularis crenulata	—	—	—	—	—	—	—	—	2.7 (II)	1.0 (III)	0.5 (I)	1.0 (III)	1.5 (I)	—
Anticlea elegans	—	—	—	—	—	—	—	—	3.3 (II)	—	—	1.9 (III)	—	—
Calamagrostis stricta	—	—	—	—	—	—	—	0.2 (I)	0.7 (I)	3.7 (V)	1.5 (III)	3.3 (III)	—	—
Argentina anserina	—	—	—	—	—	—	—	—	3.7 (I)	9.0 (V)	—	2.9 (I)	—	1.0 (I)

Table 4 (*concluded*).

Species	Aquatic		Peatland expanse									Meadow		Salt flat
	Subm	Emer	Hollow	Water track		Spring		Hummock						Sodic
	1.1	2.1	3.1	3.2	3.3	3.4	3.5	4.1	4.2	4.3	4.4	5.1	5.2	6.1
Packera pauciflora	—	—	—	—	—	—	—	—	—	—	—	0.5 (II)	—	—
Antennaria microphylla	—	—	—	—	—	—	—	—	—	—	—	0.9 (II)	—	9.0 (IV)
Psilochenia runcinata	—	—	—	—	—	—	—	0.6 (I)	3.3 (II)	6.7 (V)	5.0 (III)	1.6 (II)	2.5 (V)	—
Galium boreale	—	—	—	—	—	—	—	—	—	—	—	1.5 (IV)	—	0.6 (I)
Ribes lacustris	—	—	—	—	—	—	—	—	—	—	—	—	4.5 (V)	—
Picea pungens	—	—	—	—	—	—	—	—	—	—	—	0.5 (I)	35.0 (V)	—
Poa cusickii	—	—	—	—	—	—	—	—	—	—	—	—	15.0 (V)	—
Glaux maritima	—	—	—	—	—	—	—	—	—	—	—	—	—	3.6 (II)
Phlox sibirica	—	—	—	—	—	—	—	—	—	—	—	—	—	5.4 (IV)
Plantago eriopoda	—	—	—	—	—	—	—	0.5 (II)	2.3 (III)	1.0 (II)	3.5 (III)	1.8 (I)	2.0 (V)	2.4 (IV)
Poa juncifolia	—	—	—	—	—	—	—	—	—	—	6.0 (III)	—	—	3.2 (IV)
Aster laevis	—	—	—	—	—	—	—	—	—	—	—	—	—	2.2 (IV)
Pyrocomma clementis	—	—	—	—	—	—	—	—	—	—	—	—	—	2.6 (IV)
Puccinellia airoides	—	—	—	—	—	—	—	—	—	—	—	—	3.5 (V)	—
Elymus trachycaulus	—	—	—	—	—	—	—	—	—	—	1.5 (III)	2.9 (II)	10.0 (V)	9.0 (IV)
Critesion jubatum	—	—	—	—	—	—	—	—	—	—	—	—	1.5 (V)	—
Equisetum arvense	—	—	—	—	—	—	—	—	—	—	—	0.3 (I)	5.0 (V)	—

Hummock communities: Peat hummocks are characteristic of several study area communities. The main hummock formers are *K. simpliciuscula*, *K. myosuroides*, *Carex scirpoidea*, and *Carex parryana* ssp. *hallii*, which replace each other along a water table gradient from wetter to drier sites.

4.1. *Trichophorum pumilum* – *Kobresia simpliciuscula*. Stands of this community form hummock complexes in the wettest portion of the study area. Hummocks are 20–50 cm tall formed by the strongly tufted *K. simpliciuscula*, 10–30 cm above the water table and never flooded, and may be snow covered or snow free in winter. Hummock soils contain more than 50% organic carbon.

A ground cover of *Thalictrum alpinum* typically occurs with patches of *Trichophorum pumilum*. The small shrubs *Salix candida*, *Salix brachycarpa*, and *Pentaphylloides floribunda* as well as *Carex microglochin*, *Primula egaliksensis*, and *Triglochin maritima* have high constancy.

Communities dominated by *K. simpliciuscula* are uncommon in the Holarctic, and many are dry alpine sites, such as the *Dryas*–*Kobresia* communities of the White Mountains in interior Alaska described by Gjaerevoll (1954) and the *Dryas*–*Kobresia* association in middle west Greenland described by Böcher (1959). *Kobresia simpliciuscula* dominates wetland communities in a few other areas, however, such as seeps over limestone in Alaska's Brooks Range (Cooper 1986), fens in Ontario (Sjörs 1961), and in Britain where the *Thymus praecox* – *Racomitrium lanuginosum* variant of the *Pinguicula* – *Caricetum dioicae* mire association is dominated by *K. simpliciuscula* and is hummocky in character (Rodwell 1991). In the British community, *Thalictrum alpinum* and *Carex capillaris* are present as well. Hummocks dominated by *K. simpliciuscula* also occur at the Swamp Lake fen in northwestern Wyoming (Fertig and Jones 1992).

4.2. *Thalictrum alpinum* – *Kobresia myosuroides*. *Kobresia myosuroides* is densely tufted, and the main hummock former in sites higher above the summer water table than the last community. Hummock soils have an average of 33.8% organic carbon. Descriptions of *K. myosuroides* dominated communities are all for alpine, arctic–alpine, and arctic tundra sites, except Major and Bamberg's (1967) report from near treeline in Convict Creek Basin, California.

4.3. *Psilochenia runcinata* – *Carex scirpoidea*. Stands dominated by *Carex scirpoidea* occupy drier, more saline margins of the fen where they form low hummock complexes. Along with the high cover of *Carex scirpoidea*, there is high constancy of *Thalictrum alpinum*, *Argentina* (*Potentilla*) *anserina*, *Calamagrostis stricta*, and *Psilochenia* (*Crepis*) *runcinata*. The hummocks are moderately saline, yet contain greater than 20% organic carbon.

4.4. *Muhlenbergia richardsonis* – *Carex parryana* ssp. *hallii*. *Carex parryana* ssp. *hallii* dominates stands that occur on the fringe of the study area and forms low hummocks. This community is closely related to the previous one.

Meadows: Meadows contain many species in common with hummock communities; however, they are not dominated by hummock-forming taxa.

5.1. *Argentina anserina* – *Juncus arcticus*. Stands dominated by *J. arcticus* are characteristic of wetlands throughout

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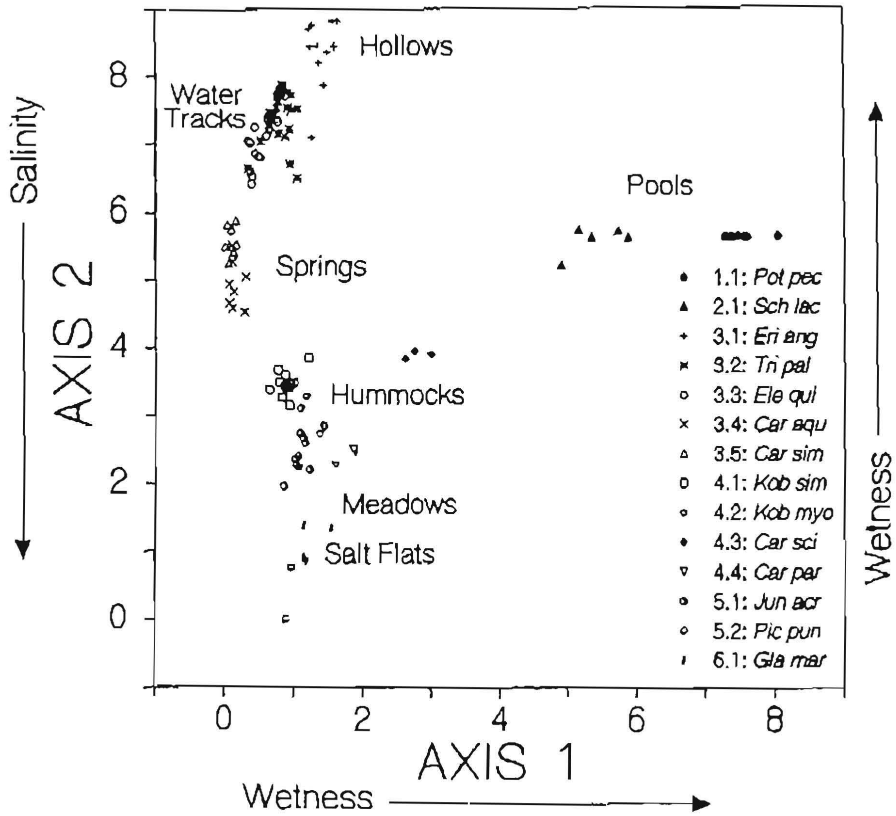
Fig. 3. Detrended correspondence analysis (DCA) of the stand data. Eigenvalue for axis 1 is 0.989, and for axis 2 is 0.831. The axes labels are standard deviation units. Each stand is identified by a symbol representing its community type in the classification. Major landforms are also indicated on the figure.



the western U.S. on soils that may or may not be saline. In the study area, these stands have high water tables, are rarely flooded, and may also be dry for long periods of time. *Juncus arcticus* has high cover in all stands, and *Pentaphylloides floribunda*, *Argentina anserina*, *Salix brachycarpa*, and *Deschampsia cespitosa* have high constancy.

5.2. *Poa cusickii* ssp. *pallida* – *Picea pungens*. Stands dominated by *Picea pungens* occupy terraces higher in elevation than the meadows and hummock complexes. *Picea pungens* forms an open canopy, and stands have an understory of *Poa cusickii* ssp. *pallida*, *J. arcticus*, *Deschampsia cespitosa*, and other taxa similar to the last community as well as to hummock communities.

Salt flats

Sodic peat community:

6.1: *Poa juncifolia* – *Glaux maritima*. Salt flats occur on sites that are highest above the water table, yet are wetted by the capillary fringe. Soluble salts of Na^{2+}, Mg^{2+}, and K^{+} accumulate to much higher concentrations here than in other communities in the study area. SAR values up to 13.0 indicate that these sites are highly saline and the flora halophytic. Soils have greater than 20% organic matter, yet in summer the soil surface is white with salts. Plant cover is generally less than 20% and is dominated by *Glaux maritima* and *Poa juncifolia*.

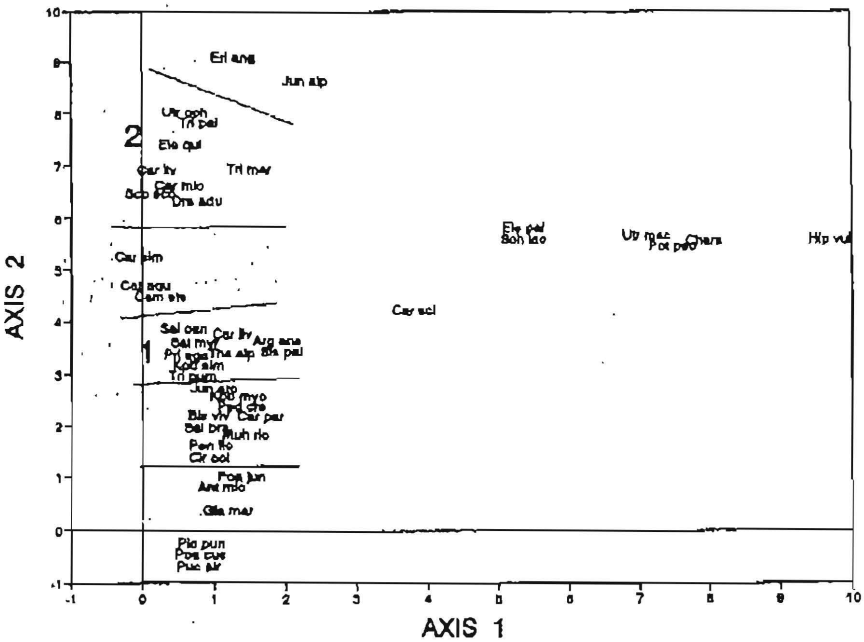
Indirect ordination of the stands and species

Indirect ordination using DCA indicated that the data set is well structured. Axis 1 and axis 2 have eigenvalues of 0.989 and 0.831, respectively, and each has a total gradient length of nearly 9 sd. units.

The stand ordination (Fig. 3) indicates that the difference between aquatic and terrestrial vegetation dominates axis 1. The submerged and emergent vegetation of pools and small streams is on the far right, while the main peat forming communities are on the left. The main floristic similarity between aquatic and terrestrial stands is the presence of *Triglochin maritima* in a few emergent stands. Axis 2 is a complex water table and salinity gradient. Communities near the top left of the ordination occupy hollows, water tracks, and springs where flowing water occurs periodically or constantly. Hummock, meadow, and salt flat communities near the bottom left of the ordination never have standing water, yet have constantly or seasonally saturated soils and strongly calcareous or saline soils.

The species ordination (Fig. 4) illustrates that the richest species concentration occurs in the hummock communities, particularly community 4.1, *Trichophorum pumilum* –

Fig. 4. Detrended correspondence analysis (DCA) of plant species abundance data for the stand data set. The axes labels are standard deviation units. The nine major land forms that species occur in are identified. The two main centroids of rare species occurrence are identified with a 1 and 2 (see text for explanation). The species are Eri ang, *Eriophorum angustifolium*; Jun alp, *Juncus alpino-articulatus*; Utr och, *Utricularia ochroleuca*; Tri pal, *Triglochin palustre*; Ele qui, *Eleocharis quinqueflora*; Car liv, *Carex livida*; Car mic, *Carex microglochin*; Car sim, *Carex simulata*; Car aqu, *Carex aquatilis*; Car sci, *Carex scirpoidea*; Car liv, *Carex livida*; Tri mar, *Triglochin maritima*; Sco sco, *Scorpidium scorpioides*; Dre adu, *Drepanocladus aduncus*; Cam ste, *Campyliadelphus stellatus*; Sal can, *Salix candida*; Sal myr, *Salix myrtillifolia*; Tha alp, *Thalictrum alpinum*; Arg ans, *Argentina anserina*; Sis pal, *Sisyrinchium pallidum*; Pri ega, *Primula egaliksensis*; Kob sim, *Kobresia simpliciuscula*; Tri pum, *Trichophorum pumilum*; Jun arc, *Juncus arcticus*; Kob myo, *Kobresia myosuroides*; Ped cre, *Pedicularis crenulata*; Car par, *Carex parryana*; Bis viv, *Bistorta vivipara*; Sal bra, *Salix brachycarpa*; Muh ric, *Muhlenbergia richardsonis*; Pen flo, *Pentaphylloides floribunda*; Cir col, *Cirsium coloradense*; Poa jun, *Poa juncifolia*; Ant mic, *Antennaria microphylla*; Gla mar, *Glaux maritima*; Pic pun, *Picea pungens*; Poa cus, *Poa cusickii* ssp., *pallida*; Puc air, *Puccinellia airoides*; Ele pal, *Eleocharis palustris*; Sci lac, *Schoenoplectus lacustris* ssp., *acutus*; Utr vul, *Utricularia macrorhiza*; Pot pec, *Potamogeton pectinatus*; Chara, *Chara* spp.; Hip vul, *Hippuris vulgaris*.



Kobresia simpliciuscula. Only a few taxa have their centroids in the hollows, water tracks, and spring communities. Most of the rare plant species have their centroids in two High Creek fen habitats. The first group, indicated by a 1, occur in the *Trichophorum pumilum – Kobresia simpliciuscula* community, including *Trichophorum pumilum*, *Salix myrtillifolia*, *Sisyrinchium pallidum*, *Primula egaliksensis*, and *Salix candida*. The second group, indicated by a 2, occurs in water tracks, and includes *U. ochroleuca*, *Carex livida*, *Scorpidium scorpioides*, and *Carex microglochin*. Although these two habitats are distinctly different, they both are continuously wet.

Discussion

High Creek fen appears to represent the most southerly extreme rich fen in the Rocky Mountain region, and possibly in North America. It is of particular importance because its large size (330 ha), great habitat diversity, and relatively constant water supply supports the full range of fen habitats and taxa.

High Creek fen's surface waters contain higher cation concentrations than those of extreme rich fens reported for Ontario (Sjörs 1961) and central Alberta (Slack et al. 1980), but similar to those of western Alberta (Vitt and Chee 1990). This may be due to the strong evaporative gradients in arid South Park that concentrate salts in the water and peat. Because few peatland water chemistry studies report anion concentrations comparisons with other fens are difficult.

A complex salinity gradient exists because some areas are constantly or regularly flushed with surface water, while others are never flushed and accumulate high salt concentrations. Plants in pools, streams, hollows, water tracks, and springs are growing in soils high in calcium and magnesium salts, while in salt flats at the opposite end of the gradient, soils are dominated by magnesium and sodium salts. The sodic organic soils appear more closely related to coastal brackish marsh peats (Gosselink 1984) than freshwater peats, and the species composition of these sites is dominated by taxa that commonly occur in coastal marshes.

The abundance of Na^+ may inhibit calcicoles, but in addition higher K^+ than Ca^{2+} concentrations in soils inhibit plant uptake of Ca^{2+} (Mengel and Kirkby 1987). While salt flat soils are suitable for Na^+ tolerant plants, they are unsuitable for calcicoles. Soil salt chemistry may be just as important as site hydrology and soil water balance for determining which habitats are suitable for calcicoles such as *Carex microglochin*, *Thalictrum alpinum*, and *K. simpliciuscula*. These species are absent from sodic peats, and instead the halophytes *Glaux maritima*, *Phlox sibirica*, and *Poa juncifolia* occur, creating a distinctive peatland community.

A large group of taxa have their ecological maxima in the Southern Rocky Mountains in South Park's extreme rich fens, including the following: *K. simpliciuscula*, *Carex capillaris*, *Carex dioica* spp. *gynocrates* (*Carex gynocrates*), *Carex microglochin*, *Carex livida*, *Carex scirpoidea*, *J. albescens*, *J. alpino-articulatus*, *Packera pauciflora*, *Primula egaliksensis*, *Ptilagrostis porteri*, *Salix candida*, *Salix myrtillifolia*, *Salix serissima*, *Sisyrinchium pallidum*, *Trichophorum pumilum*, *U. ochroleuca*, and *Scorpidium scorpioides*. Most of these taxa have circumpolar distributions (Hultén 1968), are widespread in arctic, boreal, and montane regions, and reach their austral limits in North America in South Park. Conspicuously absent from High Creek fen are species of Ericaceae, *Sphagnum*, and the characteristic Rocky Mountain wetland plants *Calamagrostis canadensis* and *Psychrophila* (*Caltha*) *leptosepala*. The brown mosses *Scorpidium scorpioides*, *Drepanocladus aduncus*, and *Campyliadelphus stellatus* are common, but their distribution is patchy and limited to springs and water tracks indicating that periodic drought may limit their distribution.

Of the extreme rich fens compared with the study area, the most similar appear to be at Hawley Lake in northern Ontario 2200 km away (Sjörs 1961), and Swamp Lake in northwestern Wyoming 650 km away (Fertig and Jones 1992). These are the only sites where *K. simpliciuscula* and *Carex scirpoidea* are important components of the vegetation. In addition, the presence of *Triglochin maritima*, *Carex microglochin*, *Trichophorum pumilum*, *Salix myrtillifolia*, and *Salix candida* in at least one of the sites indicates their similarity.

The calcareous Pine Butte fen in northwestern Montana (Lesica 1986) shares *Carex livida*, *Carex scirpoidea*, *Carex simulata*, *U. macrorhiza*, *Aster junciformis*, *Triglochin maritima*, *Salix candida* and *Salix serissima* with the study area. However, many circumpolar taxa, such as *Carex microglochin* and *K. simpliciuscula*, are absent.

Alberta and northern Minnesota extreme rich fens (Slack et al. 1980; Karlin and Bliss 1984; Vitt and Chee 1990; Glaser 1987; Glaser et al. 1981; Glaser et al. 1990) have little floristic similarity with the study area, sharing only the mosses *Campyliadelphus stellatus* and *Scorpidium scorpioides*. Scandinavian extreme rich fens share only *Carex microglochin* (Malmer 1985), while several of the calcareous *Pinguiculo – Caricetum dioicae* fen communities in northwestern England share several community dominants, such as *K. simpliciuscula* with the study area (Rodwell 1991).

The low similarity between High Creek fen and other North American fen floras is surprising, since 37% of the study area species have a circumpolar distribution, and an additional 31% occur throughout North America. This is in contrast with the Colorado Front Range alpine tundra flora that, due to its large proportion of circumpolar (25.8%), and North American and western North American taxa (38.1%), shares a large number of species with other alpine and arctic regions (Komárková 1979); including 57–87% with most other alpine stations in the southern and central Rocky Mountain region, and more than 20% with stations in the Alaskan and Canadian arctic.

The reason High Creek fen shares relatively few taxa with other fens may be the discontinuous and patchy distribution of peatlands in areas as far south as Colorado, where peatlands cover only approximately 0.3% of the land (Stevens et al. 1990). Most Colorado peatlands are small and isolated in mountain valleys, or intermountain parks with no connection to the high mountains or to other peatlands. By contrast with Colorado, 38% of Manitoba's land area and 12% of Canada is peatland (Zoltai 1988). While Colorado's alpine tundra flora benefits from the nearly continuous mountain chains that link the Southern Rocky Mountains to the arctic and subarctic (Weber 1965); a connection of this type has been lacking for Colorado's fens. Because the study area shares more species with subarctic regions of Alaska and Ontario than the geographically proximate peatlands of Minnesota and Alberta, it suggests that the long-term floristic connection along the Rocky Mountain chain to Alaska and Asia (Weber 1965) has provided many circumpolar species to the study area, and that either a broader connection to boreal peatlands has been lacking, or most boreal taxa are unable to survive in Colorado's arid climate. In addition, the importance of water and substrate chemistry to peatland plants creates many divergent ecosystem types, while differences between Colorado's alpine tundra on alkaline and acid substrates are few (Komarková 1979).

The high concentration of rare plants in water tracks and on peat hummocks dominated by *K. simpliciuscula* suggests that the constant water supply of these habitats provides an important refugium for species during periodic droughts that are characteristic of interior and southwestern U.S. climates (Kerr 1984; Dean et al. 1984). A reduction in groundwater flow during dry climate periods could reduce available habitat for taxa requiring constantly saturated soils and increase salinity in many portions of the fen. Since the dispersal of new populations to the South Park is unlikely, refugia in the study area, or elsewhere in South Park, may be important for the persistence of the most hydrologically and chemically sensitive species.

The structure of peatland vegetation is often described as being controlled by three main gradients: a poor to rich water chemical gradient, a mire margin to mire expanse chemical gradient, and a hummock to hollow water table depth gradient (Malmer 1985). All communities at High Creek and other South Park fens are well supplied with mineral nutrients, thus, all can be similarly classified as extreme rich. For this same reason, the mire margin to mire expanse gradient appears unimportant. Study area communities are organized along a complex water table and salinity gradient, produced by local patterns of groundwater discharge, sheet flow, and water table and evaporation gradients, which is similar to the hummock–hollow gradient.

Whether extreme rich fens exist throughout the western U.S. is unknown. *Kobresia simpliciuscula*, *Salix candida*, and *Trichophorum pumilum* occur only in extreme rich fens and are reported to occur in Wyoming (Dorn 1988), Utah (Welsh et al. 1987), Idaho (Cronquist et al. 1977), and Oregon (Hitchcock and Cronquist 1973). When a larger number of sites are fully investigated, a more complete picture of the relationships of extreme rich fens in the western U.S. to those found in other regions of the Holarctic can be developed.

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