GEOMORPHIC AND GEOCHEMICAL CHARACTERISTICS OF FIVE ALPINE FENS IN THE SAN JUAN MOUNTAINS, COLORADO

A Thesis

by

BREE KATHLEEN MCCLENNING

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Approved by:

Co-Chairs of Committee, John R. Giardino
Franco Marcantonio
Committee Member, Bryan Boulanger
Head of Department, John R. Giardino

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ABSTRACT

Fens are abundant in the San Juan Mountains. By exploring the geomorphology and geochemistry of fen wetlands, the functions that fens serve can be better understood. In this research, two main studies were conducted involving the geomorphology and geochemistry of fens.

The first study involved a complex investigation of the geomorphology of five fen sites in the San Juan Mountains near Silverton, Colorado. Geomorphic maps were constructed for each fen site at a scale of ~1:3,000. A geomorphic classification scheme was then made based on fen location, and fens were placed in one of three categories: 1) valley-bottom, 2) valley-side, and 3) terrace. Fen circularity and elongation values were calculated for thirty fens to determine morphometry. A pattern for elongation of fens emerged between the three types of alpine fens with valley-bottom fens having an average elongation value of 1.7, valley-side 2.4, and terrace 1.9. Valley-side fens are more elongated than valley-bottom and terrace fens, which exhibit similar elongation values.

In addition, sediment samples at each site were sectioned along visual breaks in the sediment column and were sieved. Mean phi values were calculated for each section and at each site. The mean phi values at California Gulch, Glacial Lake Ironton, Howardsville, Red Mountain Pass North, and Red Mountain Pass South, are 0.2112, 0.9045, 1.6028, 0.0178, and 1.0516, respectively. Overall, coarse-grained particles are associated with valley-side fens, and medium-grained particles are associated with valley-bottom and terrace fens.

The second part of the study involved investigating the geochemistry of fen sediment. The geochemistry portion of this research focused on concentration and isotopic ratios of Pb and the amount of ^{137}Cs in fen sediment to better understand variations of Pb with depth and calculate approximate sedimentation rates. Based on isotopic ratios of Pb, binary mixing was determined with the presence of ore mineralized Pb and non-ore mineralized. Binary mixing of two types of ore-mineralized Pb is present at the Howardsville fen and both ore-mineralized and non-ore mineralized Pb is present at the Red Mountain Pass North fen. Based on ^{137}Cs in fen sediment at Howardsville, an average rate of deposition of sediment is approximately 0.16 cm/yr, with a visible change in sedimentation rates pre- and post-1960s.

DEDICATION

I would like to dedicate my entire thesis to my late grandfather, Elmer L. Brewer. He encouraged me every step of the way for as long as he could. Being the eldest of many children and supporting a large family of his own, my grandfather did not have the educational opportunities that I have. He is one of the most intelligent, hard-working men that I have ever known. My grandfather always told me "An education is one thing that nobody can ever take away." Thank you, Grandpa Brewer. Amor Siempre, the Apple of your eye.

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CHAPTER I

INTRODUCTION AND PROBLEM STATEMENT

INTRODUCTION

Fens are dynamic systems which are thought to be heavily influenced by multiple parameters such as geomorphology, hydrology, geochemistry, climatology, and ecology. The San Juan Mountains in Colorado contain thousands of fens, yet unfortunately, few studies have been conducted that explore beyond the vegetational aspects of these forms. Understanding the geomorphology and geochemistry is necessary to appreciate the role fens play in alpine environments.

This research is two-fold and seeks to answer two main questions: 1) What geomorphic function do fens serve in alpine environments? 2) Is land use change associated with lead (Pb) deposition in alpine fen systems? These research questions are accompanied by three objectives.

OBJECTIVES

Three main objectives were used to answer the research questions: 1) evaluate the impact of changing land use on fens, 2) establish a geomorphic classification of fens in alpine environments, and 3) determine the rate of the deposition of fen sediments.

To complete the objectives and answer the two main questions, the following tools were used: 1) geomorphic maps to determine inputs and outputs from surrounding landforms, 2) soil lithology and grain-size analysis to determine sedimentary characteristics, 3) refractive seismic profiling to determine the underlying shape and depth to bedrock, 4) Pb isotopes and concentrations as indicators of source (ore mineralized Pb versus non-ore mineralized Pb), 5) ^{137}Cs and ^{210}Pb$_{xs}$ from fen sediments to estimate rates of sedimentation.

STUDY AREA LOCATION

Five study sites containing fens in the San Juan Mountains of southern Colorado were chosen for this research (Figure 1). The San Juan Mountains have elevations in excess of 4,300 m with numerous fens situated along valley floors and adjacent slopes.

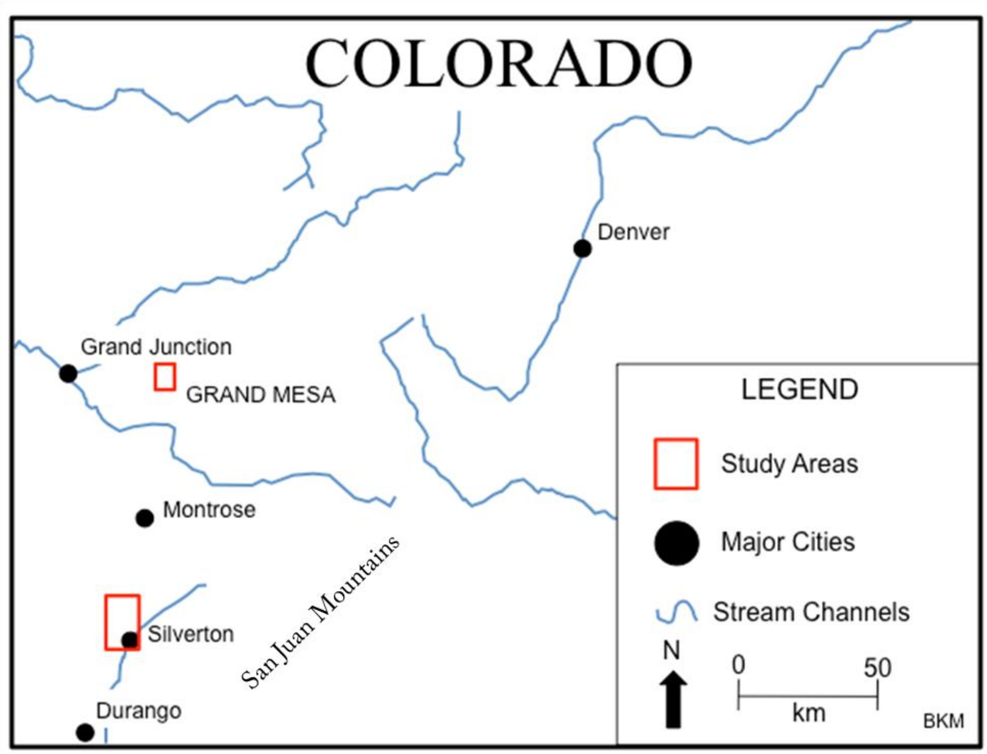


FIGURE 1. Location map of research area with the study sites outlined with a red box.

Fen sites are located in San Juan and Ouray Counties and are within the Animas and Uncompahgre watersheds. Each study site contains at least one fen and is located around the Silverton Caldera, near Silverton, Colorado (Figure 2), which is situated at an elevation of 2,800 m. The study sites are located in areas near streams and former mining operations.

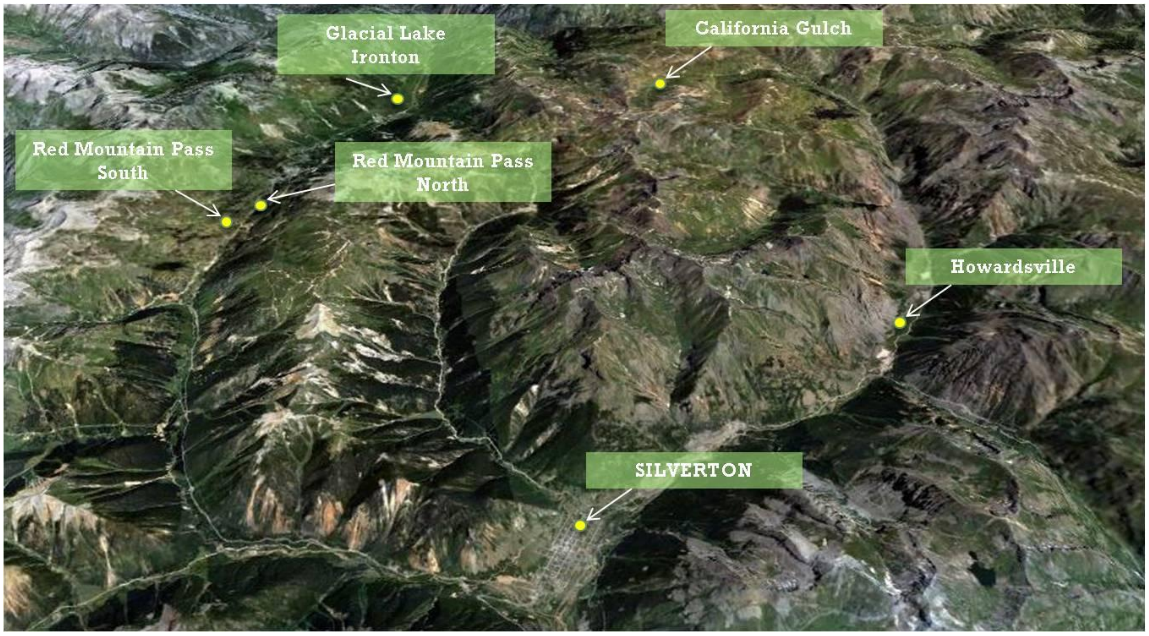


FIGURE 2. Study sites in reference to Silverton, Colorado and the Silverton Caldera (Google Maps, 2012).

Fens are found in the following localities: California Gulch, Ironton, Howardsville, and Red Mountain Pass. The following names were given to each fen site: California Gulch, Glacial Lake Ironton, Howardsville, Red Mountain Pass North, and Red Mountain Pass South.

CHAPTER II

LITERATURE REVIEW

INTRODUCTION

The study of fens extends across the globe with much research devoted to the ecology and restoration of fens. Unfortunately, few studies have been conducted that explore beyond the vegetational aspects of these forms. A review of fens in terms of ecology and restoration, geomorphology and hydrology, geomorphic mapping, trace metal geochemistry, and land use was conducted for this thesis.

FENS

Ecology and Restoration

Vegetation and restoration of fens are important aspects of peatlands. Some types of flora are found exclusively in fens, hence why many restoration efforts have been conducted to restore fens. Much research has been conducted evaluating fens for type of vegetation present (Austin, 2008) and restoration of damaged peatlands (Johnson and Valppu, 2003; Cooper and MacDonald, 2000).

Austin (2008) surveyed 88 fens for vegetation and impacts resulting from human activities. The author determined that nearly half of the fens were affected by humans in the form of ditches, drainages, floods, and damage from use of vehicles. Austin (2008) concluded that restoration opportunities for fens are plentiful.

Johnson and Valppu (2003) sought to investigate the success of a sedge meadow restoration. The authors were primarily concerned with looking at the donor soil and crop cover within small-scale plots, plant transplants, and monitoring of large-scale soil applications. Johnson and Valppu (2003) were then able to make recommendations for the restoration of peatlands.

Cooper and MacDonald (2000) sought to develop restoration methods for extensively-mined peatlands. The purpose of their research was to figure out what fen species naturally recolonize on mined surfaces and to test revegetation techniques. The authors tested restoration methods in 27 plots. The study by Cooper and MacDonald (2000) was designed to evaluate the recovery of mined fens in addition to testing techniques for the restoration of dominant plant species within mined areas.

Geomorphology and Hydrology

The understanding of geomorphology of fens varies around the world. Much of the work involving fens has been carried out in the central United States.

Some researchers studying fens use a hydrogeomorphic approach (Brinson, 1993; Hauer and Smith, 1998; Faber-Langendoen, 2005), whereas others use a combination of, or solely a geomorphic or hydrologic approach (Almendinger and Leete, 1998; Rocchio, 2005a; Watters and Stanley, 2006; Warburton and Evans, 2010; De Mars and Garritsen, 1997; Devito et al., 1997; Vitek and Rose, 1980). Researchers conclude that changes to the fens, whether anthropogenic or not, via hydrology, glaciation, and geomorphology affect fens.

Almendinger and Leete (1998) seek to understand rare fen vegetation by acknowledging the role of hydrology. Six calcareous fens were surveyed in the Minnesota River Basin, where the authors determined that hydrogeology, geology, and landforms affect calcareous fens (Almendinger and Leete, 1998).

Fen research outside of temperate areas of the Midwestern United States, such as in alpine regions, has been conducted, with much work completed in Colorado (Austin, 2008; Chimner et al., 2008; Cooper et al., 2006). As with post-glaciated Midwestern states, glaciation greatly affects high elevation landforms via erosion and deposition, affecting the formation of fens (Rocchio, 2005a).

Geomorphology and hydrology are combined by Brinson (1993) to provide an additional view of the formation and sustainment of fens. Brinson (1993) coined the term "hydrogeomorphic approach" (HGM), which incorporates hydrology and geomorphology. The HGM approach encompasses three aspects: hydrological source, hydrological regime, and geomorphic setting. This method of assessing wetlands is often used to analyze and mitigate wetlands that are damaged by anthropogenic activities (Hauer and Smith, 1998).

A hydrogeomorphic approach was applied in a study of riverine wetlands by Hauer and Smith (1998). The function of fens in alluvial floodplains is listed in four main categories: 1) hydrological, 2) biogeochemical, 3) vegetation maintenance, and 4) faunal maintenance and provision. In summary, Hauer and Smith (1998) found fens to perform a variety of functions including: 1) dynamic and long term surface and subsurface water storage, moderation of groundwater flow of discharge, 2) nutrient cycling, removal of imported elements and compounds, retention of particulates, organic carbon export, 3) maintenance of characteristic plant community and characteristic detrital biomass, and 4) provide habitat for wildlife, maintain faunal food webs along with regional and landscape biodiversity. According to Hauer and Smith (1998), wetland function is greatly influenced by the hydrology and geomorphology of the region.

Fens were studied by Faber-Langendoen (2005) from a hydrogeomorphic perspective. These fens formed in depressions and along slow moving rivers and lakes, which provided the necessary water supply required to sustain them.

Fens have a fluctuating water table, which is affected by geomorphology, climate, local weather, and subsurface flow; therefore, a fluctuating water table influences local groundwater flow to the fen system (Faber-Langendoen, 2005). A hydrogeomorphic approach was effective in assessing fens.

Hydrology and geomorphology are addressed by Rocchio (2005a) in an assessment of fens, which examines post-glaciated regions. These regions create viable geomorphic features, such as moraines and kettle lakes, which create ungulating topography suitable for fen formation. Rocchio (2005a) included a geomorphic assessment in his review of Rocky Mountain fens in addition to an in-depth look at fen ecology.

Rocchio (2005a) addresses key issues such as land use change and how it affects fens. For example, Rocchio (2005a) discusses the anthropogenic impacts of water diversions, ditches, peat mining, and livestock management on the hydrology of fens. By altering hydrology, peat oxidation and decomposition, subsurface water storage capacity, landforms (the fens themselves), and ecological aspects (such as vegetation) are all negatively affected by a change in the hydrologic regime.

Geomorphology has been used to explain fens from an ecological perspective (Watters and Stanley, 2006). Understanding of surface drainage networks in peatlands is limited; thus, Watters and Stanley (2006) attempt to better understand the geomorphology and hydrology of fens by studying the flow of water through fens.

Peat deposits are found to affect cross-sectional and planform features of streams by influencing the path, velocity, and stability of streams. The rate of erosion of peat deposits was investigated and the impact of transport of peat blocks on fluvial systems was studied by Warburton and Evans (2010). The authors illustrate that these blocks create obstacles in channels and influence local flow, channel bed topography, bank stability, and physical habitat of streams; thus, peat blocks are important geomorphologic components of fluvial systems that affect an array of geomorphic and hydrologic properties of these systems (Warburton and Evans, 2010).

Water quality and groundwater flow were found to affect a fen meadow reserve. Water quality and groundwater flow are interrelated and affected the fen meadow over a 65 year period (De Mars and Garritsen, 1997). The hydrological setting was modeled in detail using FLOWNET® to simulate groundwater flow, and water samples were analyzed using Inductively Coupled Mass Spectrometry (De Mars and Garritsen, 1997). De Mars and Garritsen (1997) used this information to investigate impacts on fen meadows from changes in water management and groundwater pollution. Water quality was found to affect the type of vegetation within the fen meadow, but overall, polluted waters and groundwater flow were not a major threat to the fen during the time of study (De Mars and Garritsen, 1997).

Devito et al. (1997) conclude that hydrology greatly affects the function of fens. Fen studies demonstrate that local groundwater systems are directly related to hydrologic flow in peatlands (Devito et al., 1997). For example, when a water deficit occurs during drought conditions or lack of local groundwater flow, the direction of subsurface water flow can be reversed (Devito et al., 1997). If water is exiting the fen via evapotranspiration and subsurface flow, and no water is entering the fen, then the flow is out of the fen rather than into it (Devito et al., 1997). Devito et al. (1997) demonstrate the important link between hydrology and wetlands.

Vitek and Rose (1980) studied a fen by investigating a variety of parameters including: fen morphology, hydrology, solifluction, peat thickness, and erosion and deposition rates. The authors attempted to conclude how the Ute Creek patterned fen formed after investigating the geomorphology and hydrology of patterned fens.

Geomorphic Mapping

Mapping is an integral part to understanding landscapes and landforms at a variety of spatial scales. One method of assessing fens is geomorphic mapping. Geomorphic mapping has been conducted at a variety of scales for a variety of purposes (Vitek et al., 1996; Mihai, et al., 2008; Griffiths and Abraham, 2008; Demek et al., 1972). According to Vitek et al. (1996) maps are a fundamental, time-tested tool used to analyze landscapes.

Geomorphic maps are key to any regional landscape study (Mihai, et al., 2008). Mihai (et al., 2008) explore the use of standardized legends and GIS to construct geomorphic maps. As geomorphic mapping evolved over the last fifty plus years, the

IGU congress of 1956 attempted to standardize map legends and encourage the use of standard geomorphic methods (Mihai, et al., 2008). Since that time, geomorphic maps have evolved; however, deviations from standardized legends are necessary to convey data from a variety of landscapes.

Trace Metal Geochemistry

Trace metal geochemistry is an integral part of understanding fens as archives of Pb. The literature incorporating Pb and fens is not very extensive. Though several articles discuss the interaction of geochemistry and vegetation, few directly focus on the geochemical characteristics of Pb in fen sediment like that of Stanton et al. (2007).

Bendell-Young and Pick (1993) found that components such as the geochemistry of peat and fen waters affect the release and uptake of heavy metals in fens. Concentrations of aluminum (Al) within fens were measured in peat, surface water, and pore-water. The authors concluded that variable amounts of Al exist in each fen (Bendell-Young and Pick, 1993). Furthermore, the concentrations in each of the previous components are influenced by the role of hydrology in these fens (Bendell-Young and Pick, 1993). In this study a link was found between peat acting as a reservoir for elements, such as Al, rather than a permanent sink which suggests there may be some recycling of Al back into surface waters (Bendell-Young and Pick, 1993). Thus, the link between wetland geochemistry and the release and uptake of heavy metals was confirmed by Bendell-Young and Pick (1993).

A multi-faceted study was prompted highlighting peat pore-water and solid-phase geochemistry because of the lack of occurrence of trace metals versus depth in a profile that incorporates nutrients, major elements, and redox-sensitive species (Koretsky et al., 2007). Lateral variations among peat pore-water and solid-phase geochemical profiles were found to exist in addition to the possibility for trace metals to be remobilized after deposition (Koretsky et al., 2007). Remobilization depends on a variety of factors including hydrology, geomorphology, climate, macrofauna, and macrophytes (Koretsky et al., 2007). This study highlights the interconnectedness of components in fen systems.

Stanton et al. (2007) analyzed sediment cores and water samples in five wetlands to determine the capability of the wetlands to retain and/or release metals in an area with extensive acid mine drainage. Heavy metal content in sediments (within the Animas watershed of Colorado) varied with Pb concentration ranging from 190 ppm to 1,600 ppm (Stanton et al., 2007). Stanton et al. (2007) determined that the wetlands appear to concentrate some of the trace metals with enrichment of elements in the upper 60 cm and greater than 80 cm in depth.

Additionally, Stanton et al. (2007) concluded that wetland sediments vary in their ability to act as sinks for dissolved metals, and wetlands around Mineral and Cement Creeks contain non-mining and mining related acid mine drainage, in addition to eolian deposition of mining material from mine and mill waste areas.

Fens often act as sinks and filters for contaminants, so investigating isotopic ratios of Pb in the sediment sheds light on the source (i.e., atmospheric, natural particulate, or ore) of Pb and indicates the history of deposition of the various sources of Pb to the fens. Pb is found in natural forms and isotopic ratios act as tracers of eroded material, showing that natural Pb contains a higher $^{206}Pb/^{207}Pb$ ratio and a lower concentration than contaminant ore Pb (Marcantonio et al., 1999).

In addition to using Pb in fen sediment as an archive of deposition, ^{137}Cs can be utilized as a method for estimating rates of deposition of sediment.

No natural form of ^{137}Cs exists; therefore, ^{137}Cs is an effective tool for determining sedimentation and erosion rates in a variety of environments (Ritchie and McHenry, 1990). ^{137}Cs, which originates from radioactive fallout, strongly adheres to sediment particles making it a useful chronostratigraphic tool (Ritchie and McHenry, 1990). Determining the peak in ^{137}Cs allows it to be used as a means of dating sediment from 1963 +/- 2 years (Robbins and Edginton, 1975).

LAND USE

Prior to mining, the San Juan Mountains were inhabited by people of a different culture. Ute tribes extended across much of Colorado and into northern New Mexico and Utah (Blair et al., 1996). The Utes operated in small, family units and migrated seasonally. As the Ute community evolved, partially as a result of trade with Spanish settlers, four tribes became established in southwest Colorado: the Muache, Capote, Weeminuche, and Tabeguache (Uncompahgre; Blair et al., 1996). As white settlers moved to the area, the Utes were eventually forced to disperse or be displaced to allow room for settlers and mining communities (Blair et al., 1996).

Land use in the San Juan Mountains evolved with the dispersal of the Utes and onset of mining in the late 1800s. During times of mining, populations were booming in the communities around the Silverton Caldera. Settlements closest to the fens included Ironton, the Red Mountain District, Silverton, Howardsville, and Animas Forks.

Ironton Park and the Red Mountain area were full of mining activity from 1888-1893. Settlements at Ironton and Red Mountain boomed after the railroad made its way to Ironton Park in 1888. Both settlements had a population of approximately 1,000 people (Blair et al., 1996). Animas Forks, nearest to the California Gulch fen, was established in 1877 and reached a population of nearly 1,500. The town of Silverton grew to 3,000 in the late 1800s (Blair et al., 1996). After mining ceased, populations dispersed and now only Silverton is left with permanent residents, approximately 600 people year-round.

Though mining has ceased, over 5,400 inactive mines, prospect pits, and other mining-related features are present in the Animas watershed of southwest Colorado (Wright et al., 2007). These features have lasting effects on the environment, including flora and fauna.

Many sources of Pb are found in streambeds in the Animas watershed. A mixture of mineral deposits, unmined altered rock, unmineralized rock underlying the watershed, mine waste, and tailings are all present in the streambeds (Church et al., 2007b). Because of a high silver (Ag) association with galena (PbS), galena has been mined in all of the local mining districts since mining began (Church et al., 2007b).

Church et al. (2007b) found that mining and milling practices affected the geochemistry of streambed sediment in the Animas River more than the sediment in Cement and Mineral Creeks. The authors found that isotopic compositions of Pb in deposits are closer in value to that found in mill tailings than pre-mining streambeds. The pre-mining geochemical baseline for Pb downstream from the former town of Eureka is approximately 400 ppm, with the amount of Pb post-mining being greater than 400 ppm (Church et al., 2007b).

CHAPTER III

STUDY AREA DESCRIPTION

INTRODUCTION

The study sites are within the San Juan Mountains of Colorado, near the town of Silverton, which sits at the southern edge of the Silverton Caldera. Each study site is situated around the Silverton Caldera, with the exception of California Gulch to the west of the caldera rim.

Roads tend to follow the caldera rim; therefore, each study site is easily accessible by Highway 550 or a county road.

Bedrock is exposed across the landscape. The landscape is dotted with fens, which are situated in valleys that were carved out by glaciers. The fens reside on alluvium, which later filled the valleys after glaciation. Depth to bedrock in the valleys varies with location as does depth to the water table.

GEOLOGY AND GEOMORPHOLOGY OF THE SAN JUAN MOUNTAINS

The San Juan Mountains in southwest Colorado consist of Precambrian crystalline basement rocks that are overlain by Paleozoic, Mesozoic, and Eocene-aged sedimentary rocks along with a Tertiary-aged volcanic covering (Church et al., 2007b). Though now eroded, a complex of calderas (including the San Juan and Silverton Calderas) produced an Oligocene-aged volcanic layer approximately 1 km thick. The volcanic layer was heavily faulted, altered hydrothermally, and mineralized in the Oligocene and Miocene which resulted in the deposition of sulfide minerals (Church et al., 2007b).

The formation of the Silverton Caldera, which encompasses the area of research, produced faults and fractures essential to the flow of water, including the migration of water high in mineral content and acidity (Blair et al., 1996). Such features provided hydrothermal solutions that led to the deposition of minerals, such as galena (PbS), pyrite (FeS_2), and milky quartz (SiO_2; Blair et al., 1996). Weathering of these sulfide minerals, above ground and within mines, leads to the release of sulfuric acid which dissolves other sulfide minerals and releases trace elements into the environment (Church et al., 2007a). Transported via water flow, trace elements such as Pb are carried across the landscape and to other streams, often times accumulating in toxic levels.

Pb within galena is abundant in the San Juan Mountains, especially around Red Mountain Pass (Moore, 2004), and is found in two main forms: ore mineralized Pb and non-ore mineralized Pb. Both ore mineralized and non-ore mineralized are natural forms of Pb found within the surrounding rock. Ore mineralized Pb is released pre- and post-mining activities via smelters and the transportation of ores, waste rock, and tailings. Non-ore mineralized Pb is released via erosion of bedrock. Though Pb can be released as non-ore mineralized rock, the San Juan Mountains have a rich history of sulfide mineral mining dating back to1871 (Church et al., 2007a).

After the formation of the Silverton Caldera, glaciation took place in the Pleistocene and later carved out valleys in the San Juan Mountains (Vincent et al., 2007). In the Quaternary, uplift continued and streams continued to cut canyons that were later filled with glaciers (Moore, 2004). After the retreat of glaciers, streams shaped the landscape (Moore, 2004).

Based on Carbon-14 dating of bog and lake sediments, it is postulated that deglaciation took place approximately 18,000-15,000 years ago (Maher, 1972; Carrara et al., 1984). Since that time, weathering, erosion, and deposition have reshaped the landscape, resulting in mass movement, canyons, and terraces, providing areas for wetlands to form.

HYDROLOGY

Hydrology is a major process affecting the formation and survival of fens in this post-glaciated region. Flowing water influences the formation of landforms in the San Juan Mountains via erosion and deposition. Valleys are filled with alluvium, and features resulting from glaciation remain, which are all conducive to the formation of fens (Rocchio, 2005a). The survival of fens in alpine environments can be attributed to large valleys where wetlands are sustained by hydrology via alluvial aquifers and springs (Rocchio, 2005a; Rocchio, 2005b).

Hydrology in the San Juan Mountains is controlled by climate and geomorphology (Rocchio, 2005a). Summer precipitation and snowmelt replenish groundwater and surface water, which allow fens to thrive. Groundwater levels are important in sustaining fens and are dependent upon factors such as bedrock, topography, soil, and seasons. In areas with deep alluvium, surface water can collect in alluvial aquifers to support fens (Rocchio, 2005b). Fens are most likely to form near confining beds, groundwater discharge areas, and permanent bodies of water (i.e., lakes, ponds, and streams; Rocchio, 2005a). Permanent bodies of water, such as Mineral Creek, Red Mountain Creek, and the Animas River, are confined by the Silverton Caldera and flow nearly parallel along the boundary of the caldera (Stanton et al., 2007). Along the margins of these streams, you will find fens.

CLIMATOLOGY

Average annual maximum and minimum temperatures in Silverton, Colorado are 11.2° C and -7.5° C, respectively (WRCC, 2006). Mean annual precipitation and annual air temperature varies with location of each fen site. Mean annual precipitation at California Gulch, Glacial Lake Ironton, Howardsville, Red Mountain Pass North, and Red Mountain Pass South are 76 cm to 114 cm, 76 cm to 107 cm, 51 cm to 102 cm, 66 cm to 94 cm, and 76 cm to 114 cm, respectively (NRCS, 2011). The average annual temperature ranges between 0°-3° Celsius with frost free days ranging from 30-75 (NRCS, 2011).

SOILS

Soil in the fen study sites are characterized by parent material, slope, composition, drainage, depth to restrictive features and the water table.

Parent material is primarily from alluvium with slopes of 0°-3°, with the exception of the Red Mountain Pass North area, which has greater slopes. Composition varies at sites from a combination of partially decomposed plant material (peat), loam, sand, clay, gravel, and cobble (NRCS, 2011).

Drainage is generally poor to very poor (with the exception of Red Mountain Pass North) and depth to bedrock is usually greater than 203 cm with the exception of Glacial Lake Ironton, which has a depth to bedrock of 102-203 cm (NRCS, 2011). Depth to water table is approximately 15-51 cm, with the exception of the Red Mountain Pass North area, which can be up to 203 cm (NRCS, 2011).

VEGETATION

Fen vegetation in the study area varies with elevation but overall is dominated by sedges (*Carex spp*.) and willow shrubs (*Salix spp*.). In addition to grasses (*Carex spp*.). and shrubs (*Salix spp.*), forbs, flowers, and trees and abundant. Forbs include woodland strawberries (*Fragaria vesca*), shrubby cinquefoil (*Potentilla fruticosa*), and Parry's goldenrod (*Oreochrysum parryi*). Trees vary and are dependent on elevation but include spruce (*Picea spp*.), pine (*Pinus spp*.), aspen (*Populus spp*.), and birch (*Betula spp*.).

Flowers are present along the margin of some fens and include blue columbine (*Aquilegia coerulea*), fireweed (*Chamerion angustifolium*), bluebell (*Mertensia spp.*), buttercup (*Ranunculus spp*.), geranium (*Geranium spp*.), senecio (*Senecio spp*.), queen's crown (*Clementsia rhodantha*), aster (*Erigeron spp*.), and cow parsnip (*Heracleum sphondilium*).

ACCESS TO STUDY AREA

Five study sites were selected in the San Juan Mountains south of Ouray, Colorado to analyze the geomorphology and geochemistry of fens. Fen sediments were used to measure the concentration of ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{210}Pb, and ^{137}Cs, and characterize the soil. Each fen site is part of a larger fen complex, with each fen site approximately 0.0003 km^2 to 0.18 km^2 in area and 3,000 m to 3,600 m in elevation. The fen complexes are located in San Juan and Ouray Counties which are within the Animas and Uncompahgre Watersheds.

Of the five selected study sites, one fen, the Glacial Lake Ironton fen, does not exhibit the characteristics of a true fen. For example, the first 40 cm of the soil profile is not rich in peat.

California Gulch

Near the origin of the Animas River sits California Gulch at an elevation of approximately 3,600 m with an area of 0.002 km^2 (Photograph 1). The California Gulch fen complex is located northwest of Animas Forks at 37º55’47” N, 107º36’16” W. This fen complex is reached by traveling north of Silverton on County Road 2, then by traveling northwest on County Road 19 once reaching Animas Forks.

PHOTOGRAPH 1. Looking south-southwest at California Gulch, including the West Fork Animas River.

Glacial Lake Ironton

The Glacial Lake Ironton fen complex rests on alluvium in a former lake bed within a glacial valley at an elevation of approximately 3,000 m and 0.0003 km^2 in area (Photograph 2).

PHOTOGRAPH 2. Glacial Lake Ironton fen, surrounded by willow shrubs and covered in grasses and exposed soil. Photograph taken looking to the north-northwest.

Numerous fens are located within the Glacial Lake Ironton fen complex, but the sample site chosen is likely a former fen, located at 37º56’22” N, 107º40’19” W, west of Highway 550 (Million Dollar Highway). Highway 550 cuts through the fen complex to the west of Mineral Creek in an area surrounded by former mining efforts.

Howardsville

At an elevation of 3,000 m and area of 0.005 km^2 sits the Howardsville fen complex between the former mining towns of Eureka and Howardsville (Photograph 3).

PHOTOGRAPH 3. Howardsville fen site, looking upstream, with the Animas River on the left side of the photograph.

This fen complex is located west of County Road 2 at 39º50’39” N, 107º35’6” W. The Howardsville fen complex is reached by traveling north of Silverton on County Road 2.

Red Mountain Pass North and Red Mountain Pass South

Located less than 700 m from the Red Mountain Pass North fen complex, (Photograph 4) is the Red Mountain Pass South fen complex (Photograph 5), both of which sit at an approximate elevation of 3,400 m.

PHOTOGRAPH 4. Looking to the north at Red Mountain Pass North fen.

PHOTOGRAPH 5. Red Mountain Pass South fen, with roche moutonnée in the background. Photograph taken looking to the west.

The northern fen complex is 0.018 km^2 in area and located at 37º54’10” N, 107º42’31” W. The fen is cut by, but predominantly east of Highway 550. The southern complex is 0.014 km^2 in area and located at 37º53’44” N, 107º42’50” W, west of Highway 550. Red Mountain Pass South is within the Animas Watershed, unlike Red Mountain Pass North which is within the Uncompahgre Watershed.

CHAPTER IV

METHODS

INTRODUCTION

This research seeks to better understand the function fens serve in alpine environments by looking at landforms and deposition of sediment containing heavy-metals. Geomorphic and topographic maps are used to better understand the influence of landforms, and Pb isotopic ratios and concentrations are used as indicators of source of Pb (ore mineralized Pb versus non-ore mineralized Pb), along with ^{137}Cs and ^{210}Pb from fen sediments to estimate rates of sedimentation.

Three primary objectives were used to evaluate the geomorphic function fens serve in alpine environments: 1) evaluate the impact of changing land use on fens, 2) establish a geomorphic classification of fens in alpine environments, and 3) determine the rate of deposition of sediments in fens. To fulfill the first objective, Pb concentration and isotopic ratios of fen sediment were measured, the presence of binary mixing was analyzed, and changes in land use were evaluated. The second objective was fulfilled by mapping geomorphic features, analyzing fen morphometry, collecting and evaluating sediment, and refractive seismic profiling. The third objective was fulfilled by calculating the rate of sedimentation using ^{137}Cs and ^{210}Pb$_{xs}$.

To complete the objectives, the following tools were used: 1) geomorphic maps to determine inputs and outputs from surrounding landforms, 2) soil lithology and grain-size analysis to determine sedimentary characteristics, 3) refractive seismic profiling to determine the underlying shape and depth to bedrock, 4) Pb isotopes and concentrations as indicators of source (ore mineralized Pb versus non-ore mineralized Pb), 5) ^{137}Cs and $^{210}Pb_{xs}$ from fen sediments to estimate rates of sedimentation.

GEOMORPHOLOGY

Geomorphic Mapping

Knight et al. (2011; p. 179) state: “Landforms are the building blocks of landscapes.” Geomorphic mapping is a very practical method used to evaluate landscapes. Knight et al. (2011) suggest that geomorphic mapping helps to do the following: 1) identify and interpret landscape patterns, 2) identify geomorphological processes and events, resulting in geohazards, and 3) evaluate sensitivity of relict landscapes to climate. Based on geomorphic mapping, morphometry of landforms can be delineated by researchers.

Geomorphic maps in the study area were mapped at a scale of 1:3,000. Symbols, legends, and field methods were modeled after de Graaff et al. (1987), Demek (1972), Federal Geographic Data Committee (2006), and Gardiner and Dackombe (1983).

Prior to fieldwork, topographic and geologic maps were scanned from original copies at a scale of 1:24,000. Digital topographic maps and orthorectified aerial photographs at a scale of 1:3,000 were utilized using ArcGIS® and used as a mapping reference in the field and were compared with topographic and geologic maps to create preliminary working maps prior to fieldwork.

The geomorphology of the San Juan Mountain study sites was mapped using hundreds of photographs and a compilation of sketches. Upon returning from fieldwork, aerial photographs were printed at a scale of 1:3,000 on 140 cm x 90 cm paper and geomorphic features were drawn on the aerial photographs, followed by hand drawing each geomorphic map using a Wacom Tablet® and Adobe Illustrator CS5®.

Morphometry

Fen morphometry was calculated at a scale of ~1:10,000 using ArcGIS® and orthorectified photographs from the NRCS (2011). Fen length, width, perimeter, and area were calculated using ArcGIS®. Upon collecting the data, the circularity of thirty fens, including five fens from the study sites, and elongation of each fen were calculated.

Circularity is based on the area of each fen divided by the area of a circle, replacing the circumference with the perimeter of each fen (Equation 1).

EQUATION 1
Circularity of a fen.

$$F_C = \frac{A_f}{A_c}$$

Where:

A_f is the area of the fen
A_c is the circularity of the fen based on fen perimeter

A value of zero indicates a line and a perfect circle is indicated by a circularity value of one. Though perimeter was incorporated into the equation of circularity, it was not used in the equation for elongation because the perimeter of each fen is not actually a perfect circle. A better estimate of elongation is one that does not incorporate perimeter.

Elongation was calculated for each fen based on the length of each fen divided by the width (Equation 2).

EQUATION 2
Elongation of a fen.

$$F_e = \frac{L}{W}$$

Where:
L is the length of the fen based on the long axis
W is the width of the fen, perpendicular to the long axis

The larger the value of elongation, the more elliptical the fen is. In theory, when the length of the fen equals the width, a circle is present. By calculating the elongation and circularity of each fen, the general shape of each fen can be determined.

Sediment Sampling

Soil varies across landscapes. A multitude of parameters must be taken into account when describing soils. This includes topography, parent material, climate, and time (SSDS, 1993). In addition to the aforementioned properties, vegetation is a good descriptor of soils as it varies throughout the landscape (SSDS, 1993). Sediment sampling was conducted following Goudie et al. (1981) and SSDS (1993).

At each sample site, a hole ~40 cm in diameter was excavated to a depth of 100 cm. Sediment was removed at each sample site using a sharpshooter shovel. Varying compositions (i.e., dense peat and roots) caused difficulty in sediment extraction and dictated how much sediment from each site was able to be extracted. After removing sediment, it was immediately sealed with plastic wrap and labeled. Upon returning from the field, the basic sedimentological characteristics of each sample were evaluated by using photographs, a Munsel chart, and cutting into each soil sample to produce a fresh surface. Soil samples from each of the five sites were compared with soil data from the NRCS (2011), and sub-basin soil maps were created using ArcGIS®.

Each sample was then subsampled based on visual changes in color and lithology. Subsamples were weighed and then sieved with U.S.A. Standard Testing Sieve screens with mesh sizes of 1.19 mm, 0.59 mm, 0.42 mm, 0.25 mm, and 0.07 mm (#16, #30, #40, #60, and #200). From these data, cumulative frequency diagrams were produced for each subsample using an Excel® program created by Balsillie et al. (2002) to show the distribution of grain-size and calculate the standard deviation and mean phi.

Refractive Seismicity

Following Pelton (2005) and Burger et al. (2006) a seismic refraction profile of three fens was conducted using a StrataView® seismograph. Seismic lines with up to 24 geophones were utilized and placed parallel to the long and short axes of each of the three fens. A large hammer and metal plate were used to trigger ground vibrations on each side of the seismic lines with approximately seven hits being used 2 m to 3 m from the end of each line. Depending on the sample site, geometric settings varied.

GEOCHEMISTRY

Sampling of Fen Sediments for Pb and Cs

To understand how land use change is associated with the deposition of heavy metals in alpine fens, Pb isotopic ratios and concentrations were used as indicators of source (ore mineralized Pb and non-ore mineralized Pb). ^{137}Cs and ^{210}Pb$_{xs}$ from fen sediments were used to estimate rates of deposition.

Approximately 36 cm of sediment was removed from each fen study site using a sharpshooter shovel (Photograph 6).

PHOTOGRAPH 6. Removal of sediment using a sharpshooter shovel.

Each sediment sample was further subsampled in 2 cm increments with approximately 15-18 subsamples per sediment sample (Photograph 7). Samples were immediately sub-sampled after extraction to avoid compression and expansion. To prevent contamination of samples, tools were thoroughly cleansed three times using distilled water between sampling. At a later time, an additional 30-40 cm of fen sediment was extracted at each fen sample site for analysis of ^{137}Cs and ^{210}Pb$_{xs}$, following the aforementioned procedure.

PHOTOGRAPH 7. Sediment sample from the California Gulch fen with top of the unit on the left side of the photograph.

Pb Concentrations and Isotopic Ratios

Sediment samples were prepared for analysis in a Class 1000 R. Ken Williams Radiogenic Isotope Geochemistry Facility. A portion of each sediment sample was dried in 50 ml plastic centrifuge tubes using an oven heated to approximately 55°C for two days, then ground to a consistent grain-size using a metal spatula. Sample weight was recorded and sediment samples were transferred to small plastic containers and a few drops of concentrated HNO_3 were added to each container.

After adding acid to each container, the containers remained sealed overnight and were heated to approximately 50°C on a hot plate. The next day, container lids were removed and the samples were heated overnight to approximately 32°C to allow the acid to evaporate. Using a small amount of 2% HNO_3, samples were transferred to clean 50 ml plastic centrifuge tubes. From that point, samples were diluted to 50 ml using 2% HNO_3, and centrifuged for approximately 20 minutes at 1500 rpm to remove any remaining suspended solids.

Once centrifuging was complete, approximately 0.3 g of ^{205}Pb spike was added to clean 50 ml centrifuge tubes. Following this step, 50 μl of each solution was pipetted from the centrifuge tubes and placed into the tubes containing the ^{205}Pb spike, then further diluted to 30 ml using 2% HNO_3. Next, 10 ml of the diluted and centrifuged solution was pipetted and added to clean centrifuge tubes.

Samples were analyzed using Inductively Coupled Plasma Mass Spectrometry (Element XR ICP-MS at Texas A&M University). The ICP-MS measured the isotopic ratios of $^{206}Pb/^{207}Pb$ and $^{206}Pb/^{208}Pb$, and Pb concentration in each sample. The fractionation factor for each sample set was determined by running multiple NIST 981 standards during each sample run (approximately 1 standard was run per 5 samples).

^{137}Cs and $^{210}Pb_{xs}$ Detection

To analyze for ^{137}Cs and ^{210}Pb$_{xs}$ in the sediment, samples were transferred to 50 ml centrifuge tubes. Samples were positioned in drying racks which were then placed in an oven at 50°C for one to two weeks until samples were dry. After drying, samples were weighed and ground to an even consistency using a clean mortar and pestle which was thoroughly cleaned using distilled water before proceeding to the next sample. Sediment samples were then transferred to the University of Texas-Austin for analysis using standard methods (Alison et al., 2007). Organic matter was removed via burning and the remaining sediment was tested for ^{137}Cs and ^{210}Pb by using gamma spectrometry and low-energy germanium planar detectors. Samples were placed in petri dishes and counted 24-48 hours after ^{210}Pb was allowed to ingrow, then the amount of ^{210}Pb$_{xs}$ was calculated. ^{137}Cs activities were determined using various keV photopeaks.

CHAPTER V

DESCRIPTION OF FENS

INTRODUCTION

The term wetland encompasses a variety of landforms, but two more prominent types of wetlands include bogs and fens. Fens are found throughout the world and are sustained by groundwater and surface water, unlike bogs which are sustained by surface water (Bedford and Godwin, 2003). Fens must additionally contain at least 40 cm of peat within a soil profile. In the San Juan Mountains of Colorado, the majority of wetlands are fens, not bogs, and do not necessarily contain water at the surface year-round. Fens in the San Juan Mountains generally form on or near slopes, or low lying areas where water is discharged and often remains on the surface (Rocchio, 2005a).

Wetlands provide an environment to support a variety of functions which benefit not only flora and fauna, but also humans. Wetlands provide transition zones between landscapes, habitat for a variety of flora and fauna, and recreational and educational areas (Hite and Cheng, 1996). Wetlands often serve as environmental buffer zones, which assist with flood control, and protect property. Additionally, wetlands filter contaminants that are found in municipal waste water, acid mine drainage, agricultural runoff, and are recharge zones for local water systems (Hite and Cheng, 1996).

More notably, wetlands function as contaminant traps from surface runoff. Sediment containing contaminants, such as heavy metals, get trapped along with grease and oil from highways.

The ability of wetlands to act as traps varies seasonally with the fluctuating water supply (Mulamoottil et al., 1996). Wetlands are additionally influenced by the input and output of materials, which varies with a several factors such as landscape, season, and water supply.

Fens are dynamic systems found throughout the world, including alpine environments. In contrast to bogs, which are fed by atmospheric and surface water, fens are additionally fed by groundwater (Bedford and Godwin, 2003). Fens have the potential to be composed of 95% water (Charman, 2002), and fens contain at least 40 cm of organic material (Rocchio, 2005a).

Fens are recorders of landscape history. Fens perform multiple functions within their environment such as recording rates of sedimentation, acting as sources and sinks for sediments containing heavy metals, and providing buffer zones and habitat to a variety of flora and fauna. In general, fens are viewed as recorders of information regarding the past and present environment in which they reside (Charman, 2002).

The function of fens is greatly influenced by the geomorphology, hydrology (Charman, 2002), and geochemistry of the region. Multiple factors, such as mining, construction of major roads and trails, animal grazing and burrowing, and altering of the landscape by humans, impact the natural function in of a fen. It is of the utmost importance to understand the role and interactions of geomorphology and geochemistry in fen environments to better understand the past, present, and future of these systems.

FEN SYSTEMS

Fens serve as sources and sinks for material. Essentially, fens act as regulators of material and energy flowing into and out of them (Figure 3).

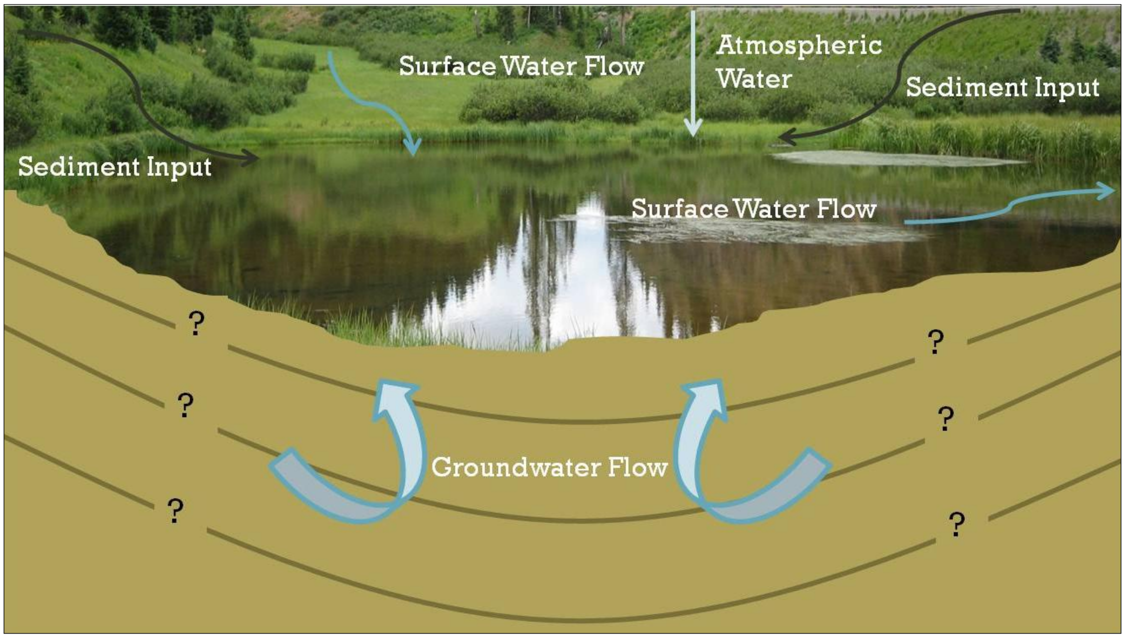


FIGURE 3. Fens as sources and sinks, featuring atmospheric water, surface water, and groundwater inputs and outputs.

For example, atmospheric water can enter a fen and stay there or become part of the groundwater system, evaporate, be taken up by plants and transpired, or continue as surface water. Similarly surface water can flow through a fen, into it and remain there, or have the same fate atmospheric water might. In terms of groundwater, it can stay in the form of groundwater, come to the surface of the fen, evaporate, be taken up by plants and transpired, or enter stream water and travel laterally through and out of a fen. Additionally, sediment containing Pb and other heavy metals can be deposited in a fen and stay there or travel via wind or surface water flow.

CHAPTER VI

DATA

INTRODUCTION

Data were collected at all sample sites and analyzed for Pb and Cs content, along with a grain-size analysis and the compilation of geomorphic maps and photographs.

Photographs and field sketches were compared to create maps at a scale of ~1:3,000. Grain-size from one soil sample taken at each site was analyzed and plotted as a cumulative frequency graph. The geochemical data was compiled and graphed to analyze isotopic ratios and composition of Pb and Cesium within the fen sediment.

GEOMORPHOLOGY

California Gulch

The California Gulch fen (Photographs 8 and 9) slopes to the east-southeast at 2° to 4° (NRCS, 2011), draining into the West Fork Animas River. A large pond marks the uppermost portion of the fen. The California Gulch fen resides on the slope of a glacial valley, south of the headwaters of the west fork of the Animas River, and is surrounded by former mines and adits. The landscape is above the tree line with a wide valley floor and steep valley slopes inclined 5º to 8° (NRCS, 2011). The valley floor slopes 1º to 3º (NRCS, 2011) and is covered sporadically with fens containing sedges and small ponds, wildflowers, and exposed igneous bedrock. The West Fork Animas River flows through the valley, which cuts through exposed extrusive igneous bedrock of the Eureka and Burns Members (Luedke and Burbank, 1987).

PHOTOGRAPH 8. The upper portion of the California Gulch fen, including the upper-most pond. Photograph taken looking to the east-southeast.

PHOTOGRAPH 9. View of the California Gulch fen, looking to the west-northwest. Past mining activity is visible in the background along with orange-colored water draining to the West Fork Animas River in the foreground.

Though dominated by extrusive igneous rocks, California Gulch contains intrusive igneous features such as dikes and/or sheets of porphyritic quartz latite, mineralized faults, and surficial deposits composed of alluvium, colluvium, talus, alluvial fan deposits, and glacial drift (Luedke and Burbank, 1987).

Glacial Lake Ironton

Glacial Lake Ironton is a former glacial lake composed of alluvium, sloping to the north-northeast at approximately 2° with valley slopes ranging from 4º to 8° (NRCS, 2011). The Glacial Lake Ironton fen complex (Photograph 10) contains a variety of sedges, willow shrubs, and pines within the alluvium substrate.

PHOTOGRAPH 10. View from Glacial Lake Ironton fen sampling site looking towards Red Mountain.

A variety of igneous and surficial deposits are present on the surrounding slopes, with the former glacial lake bed dominated by alluvium. Extrusive igneous rocks, such as the Henson, Burns, Eureka, and San Juan Members are visible along with mineralized veins, faults, and hydrothermally altered rock (Burbank and Luedke, 1964). As shown by geologic and topographic maps, the northern downslope end of the former glacial lake bed is cut and covered on the surface by an alluvial cone deposit. Additional surficial deposits, such as talus and glacial drift, are present along the base of the slopes surrounding the fen complex (Burbank and Luedke, 1964).

Unlike California Gulch and Howardsville, sedimentary units such as the Molas Formation and Ouray Limestones, and mineralized sedimentary rock units of the Leadville and Ouray Limestones, are visible (Burbank and Luedke, 1964).

Howardsville

The Howardsville fen complex is situated on a river terrace east of the Animas River (Photograph 11). Valley slopes range from 4º to 8° (NRCS, 2011). Slopes are mostly bare northwest of the fen complex with grasses and a forested area to the southeast. The Howardsville fen is covered primarily with sedges and willow shrubs.

PHOTOGRAPH 11. Looking east towards the Howardsville fen from the west side of the Animas River.

Upper valley slopes to the northwest and southeast are dominated by extrusive igneous rocks such as the Burns and Eureka Members, some of which were hydrothermally altered (Luedke and Burbank, 2000). The lower portion of valley slopes and the river terrace are dominated by surficial deposits such as alluvium, talus, alluvial-cone deposits, alluvial-fans, and glacial drift. The eastern slope is cut by a hydrothermally altered intrusive igneous dike and mineralized faults and veins (Luedke and Burbank, 2000).

Red Mountain Pass North

The Red Mountain Pass North fen is predominantly sloping 1° to 4° degrees to the south-southwest (NRCS, 2011). The fen complex contains three small ponds and drains to the southwest, then slopes to the north at the lowermost pond into a tributary of Red Mountain Creek. The lowermost pond contains orange-colored water that can be seen draining from the pond to Red Mountain Creek though a small stream, which runs north through a culvert under County Road 31.

The Red Mountain Pass North fen is situated on alluvium, which lines the lower portion of valley slopes and the glacial valley, and extends from Red Mountain Pass South to the area nearest the National Bell Mine.

The surrounding slope of the Burns Formation is composed of breccias, tuffs, and rhyodacitic bedrock. The far eastern portion of the fen complex is influenced by colluvium and the Burns Formation, whereas west of the National Bell Mine, the fen complex is influenced by the Burns Formation that contains intensely altered bedrock resulting in ore bodies.

Red Mountain Pass North contains primarily sedges, with shrubs and wildflowers along the margin of the fens. The surrounding landscape reaches slopes up to 8° (NRCS, 2011). Former mines can be found sporadically throughout the landscape which is dominated by extrusive and intrusive igneous rocks, such as the Burns Formation and porphyritic quartz latite. Colluvium, mineralized rock, and mineralized faults and veins are also visible. The fen complex is covered with surficial deposits that are exclusively alluvium (Burbank and Luedke, 1964).

Material inputs, such as bedrock and sediment, west of the fen tend to be intercepted by Highway 550, but materials transported by wind and water appear to be delivered to the fen. The majority of material inputs appear to be from the eastern slopes. Evidenced by ponds, seeps, and potential flow paths, materials such as bedrock and sediment are capable of being transported to the fen via water erosion.

Red Mountain Pass South

Further south, the Red Mountain Pass South fen slopes 1° to 3° to the south-southeast and surrounding landscape reaches slopes up to 8° (NRCS, 2011). The fen complex contains primarily sedges, with shrubs and wildflowers along the margin of the fen. The fen complex is cut by an old dirt road and human-made ditches, which separate the eastern portion of the fen complex from the western portion. A small stream runs from the southwest portion of the fen and converges with water in the ditches and a stream that flows parallel to Highway 550. Once flowing together, the water crosses under the highway via a culvert and flows together with an orange-colored tributary of Mineral Creek.

The orange-colored tributary of Mineral Creek flows through colluvium and the Burns Formation before joining with water from the fen complex. Longfellow Mine and Koehler Tunnel are east of the fen complex and drains orange-colored waters into a retention pond and Mineral Creek (Photographs 12 and 13).

PHOTOGRAPH 6. Photograph of Longfellow Mine and a retention pond at the base of the mine and Koehler Tunnel. Photograph taken looking to the north-northeast.

PHOTOGRAPH 7. Photograph of Koehler Tunnel with acid mine drainage flowing into the retention pond at the base of the tunnel and Longfellow Mine. Photograph taken looking to the east.

Former mines can be found sporadically throughout the landscape which is dominated by extrusive and intrusive igneous rocks, such as the Burns Formation and porphyritic quartz latite. Colluvium, mineralized rock, and mineralized faults and veins are also visible. Red Mountain Pass South contains surficial deposits that are exclusively alluvium (Burbank and Luedke, 1964).

SEDIMENT

Characteristics

At the California Gulch sampling site, sediment to a depth of 65 cm was extracted downslope of one of the major ponds within the fen complex. The surface of the fen complex is covered with sedges and sphagnum moss, with wildflowers along the margins. The root zone extends approximately 10 cm below the ground surface into very moist soil with non-living roots present to a depth of 25.5 cm. Peat is present to a depth of 65 cm.

According to the Munsel classification scheme, the color of the soil is very dark gray (10YR/3/1). The California Gulch sediment sample contains fine-grains with a lighter colored band around 26 cm. This is consistent with the Henson Unit, which contains slightly decomposed plant material at the surface, and transitions into a stoney sandy clay loam (NRCS, 2011).

The Henson unit is present at elevations ranging from 3,500 m to 4,100 m on mountain slopes and in mountain valleys, receiving 90 cm to 115 cm of precipitation per year into well-drained soil (Soil 339; Figure 4). Depth to water table is greater than 203 cm. Slopes range from 17° to 31° on parent material consisting of colluvium and/or slope alluvium that is derived from rhyolite (NRCS, 2011).

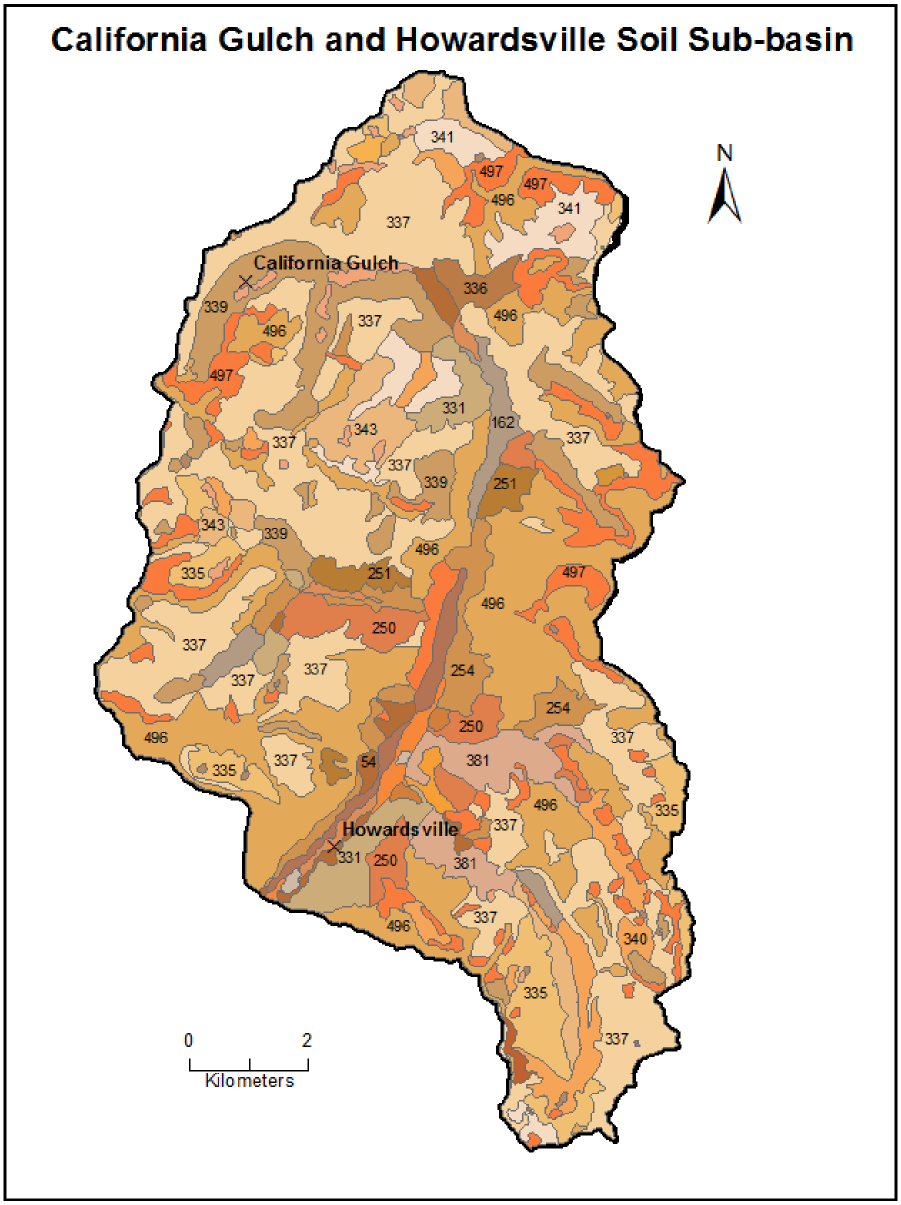


FIGURE 4. Sub-basin soil map of California Gulch and Howardsville, with key.

SOIL NUMBER	SOIL NAME	SLOPE (°)
53	Cryaquolls-Typic Cryaquents complex	1-3
54	Quazar very cobbly loam	3-14
56	Typic Cryaquents-Cryaquolls-Cryofibrists complex	0-3
121	Henson very gravelly loam	17-31
145	Rock outcrop	0-50
150	Rubble land	0-50
171	Whitecross-Rock outcrop complex	24-37
254	Cryorthents-Rubble land complex	17-37
331	Needleton stony loam	17-33
335	Whitecross-Rock outcrop complex	17-37
337	Whitecross-Rock outcrop complex	24-37
339	Henson very gravelly loam	17-31
341	Moran very gravelly loam	17-33
343	Telluride-Rock outcrop complex	24-37
381	Needleton-Snowdon-Rock outcrop complex	17-39
496	Rock outcrop	0-45
497	Rubble land	9-45

FIGURE 4, continued

The Glacial Lake Ironton sampling site was fairly dry when a sediment sample was extracted; therefore, it was difficult to extract sediment to a depth greater than 40 cm (Photograph 14).

PHOTOGRAPH 8. Sediment sample of the Glacial Lake Ironton fen with the top of the unit on the right side of the photograph.

Sedges and shrubs were thick, covering a hummocky terrain. Plant tops and roots are contained within the first 3 cm of fine-grained to sandy sediment and the bottom portion of the sediment sample increases in sand content and the is yellowish-brown (10YR/5/6). With depth, orange streaks are present in the sediment. There is a lack of 40 cm of peat upon analyzing sediment from Glacial Lake Ironton, therefore it appears that the sample was not extracted from a fen, but from the outskirts of an area containing multiple fens within a fen complex.

Sampled sediment was extracted from the Cryaquolls-Borohemists complex, which is present in the valley floor (Soil 109; Figure 5). Elevations range from 3,000 m to 4,300 m on slopes of 0° to 3°. Average precipitation is 75 cm to 105 cm into poorly drained soil, with a depth to the water table approximately 15 cm to 90 cm below the surface. Parent material consists of alluvium and herbaceous organic material covering alluvium (NRCS, 2011).

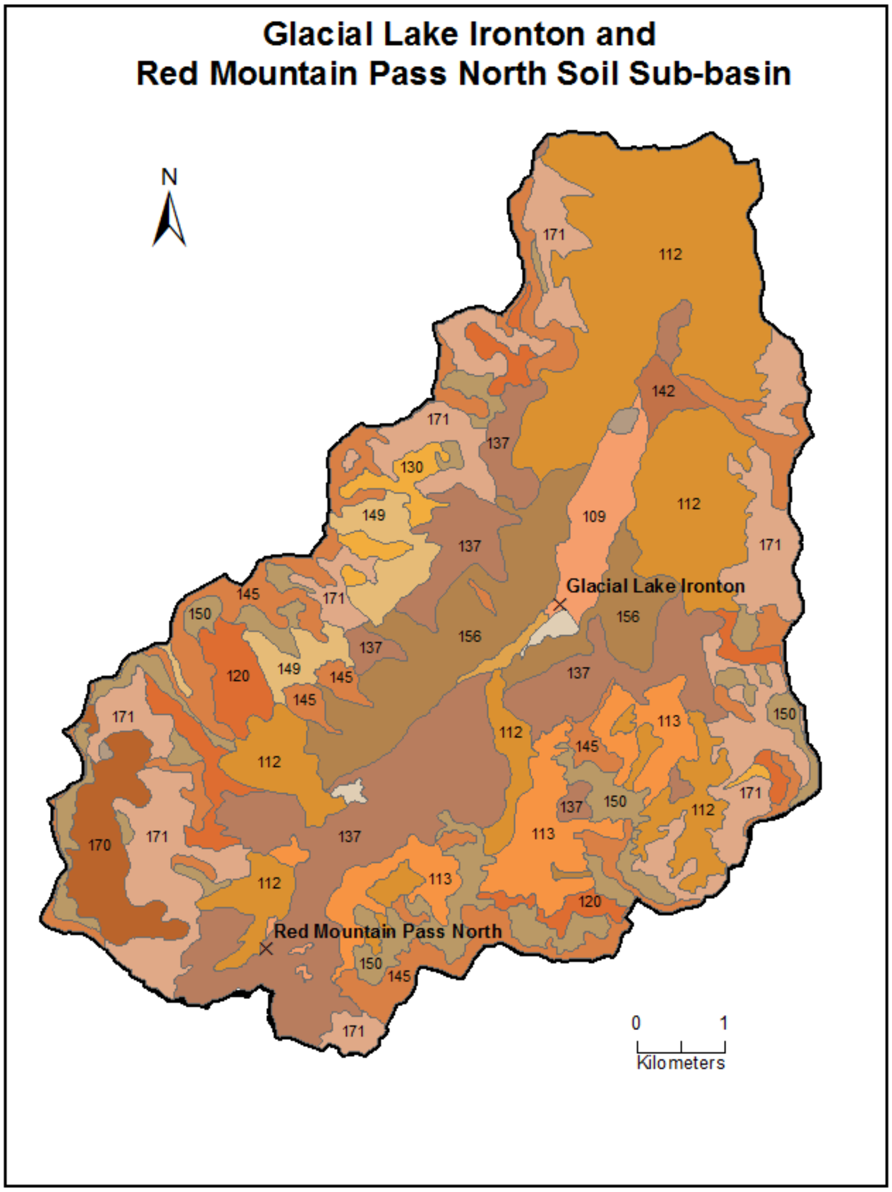


FIGURE 5. Sub-basin soil map of Glacial Lake Ironton and Red Mountain Pass North.

SOIL NUMBER	SOIL NAME	SLOPE (°)
56	Typic Cryaquents-Cryaquolls-Cryofibrists complex	0-3
109	Cryaquolls-Borohemists complex	0-3
111	Cryoborolls-Cryaquolls association	0-9
112	Cryorthents-Rock outcrop complex	27-50
113	Cryorthents-Rubble land complex	17-37
114	Dumps, mine	
120	Henson loam	17-37
130	Moran-Telluride-Rock outcrop complex	3-22
137	Needleton-Snowdon complex	14-33
142	Quazar, cool-Varden complex	9-33
145	Rock outcrop	0-50
149	Rock outcrop-Telluride association	22-50
150	Rubble land	0-50
156	Scout family	6-31
170	Whitecross-Rock outcrop complex	9-24
171	Whitecross-Rock outcrop complex	24-37

FIGURE 5, continued

The Howardsville fen complex contains very wet, fine-grained sediment, with a covering of sedges. Near 35 cm depth, gravels are present and as digging continued, standing water filled to 40 cm and rocks and sand prevented further digging at 50 cm (Photograph 15). Sediment to a depth of 36 cm was extracted. The sediment sample contained organic-rich sediment with orange streaks and sand (Photograph 16). Overall, the color is very dark brown (10YR/3/2).

PHOTOGRAPH 15. Sample extraction at the Howardsville fen with standing water and gravels present.

PHOTOGRAPH 16. Sediment sample of the Howardsville fen with the top of the unit on the left side of the photograph.

The Howardsville sediment sample is part of the Cryaquolls-Typic Cryaquents complex, which is present on flood plains and valley floors at elevations ranging from 2,600 m to 3,000 m with slopes of 0.5° to 3° (Soil 53; Figure 4). The Cryaquolls-Typic Cryaquents complex receives 50 cm to 100 cm of precipitation per year in poorly drained soils with average depth to the water table between 15 cm and 50 cm. Soils are derived from alluvium (NRCS, 2011).

At Red Mountain Pass North, sediment was sampled upslope of the pond nearest the road and is covered in sedges with flowers and shrubs along the fen margin.

Approximately 70 cm of sediment at depth was extracted and contains a root structure less dense than that of the Red Mountain Pass South site, and is only approximately 5 cm thick (Photograph 17). The coloring is very dark grayish brown (10YR/3/2).

PHOTOGRAPH 9. Sediment sample of the Red Mountain Pass North fen with the top of the unit on the left side of the photograph.

Fine-grained sediment, along with woody debris and dense roots, are present in the organic brown sediment to a depth of 13 cm. Sediment began to crumble between 35 cm and 37 cm, followed by a clay layer with a root zone around 40 cm depth. Large samples of wood were found at 64 cm depth. As digging continued, a strong sulfur smell was present and the sampling hole began to fill with water.

A sub-basin soil map (Soil 137; Figure 5) reveals that Red Mountain Pass North is characterized by the Needleton-Snowdon complex situated at slopes of 14° to 33° at elevations of 2,700 m to 3,600 m, respectively. This complex is found on mountain slopes, alluvial fans, and ridges. Annual precipitation into well-drained soils is 66 cm to 94 cm, with depth to the water table between 0 cm and 200 cm. The Needleton-Snowdon complex is derived from parent material of slope alluvium and/or colluvium both from non-volcanic breccia, and slope alluvium derived from rhyolite (NRCS, 2011).

Approximately 68 cm of very dark gray (10YR/3/1) sediment at depth was extracted from the Red Mountain Pass South fen complex (Photograph 18).

PHOTOGRAPH 18. Sediment sample of the Red Mountain Pass South fen with the top of the unit on the left side of the photograph.

The sediment is characterized by a very dense root system to a depth of 8 cm with gravel, potentially from road construction, appearing around 6 cm in depth. Peat is present in the fine-grained sediment with another layer of gravels appearing at 40 cm. As digging continued the sampling hole began to fill with water until a depth of 60 cm was reached. At 60 cm from the surface, wood was found along with more gravel.

The Red Mountain Pass South fen complex is part of the Typic Cryaquents-Cryaquolls-Cryofibrists complex (Soil 56; Figure 6). Very low slopes of 0° to 3° are present at an elevation of 2,800 m to 4,000 m. Parent material consists of alluvium and organic material. Additionally, depth to the water table is 0 cm to 91 cm. (NRCS, 2011).

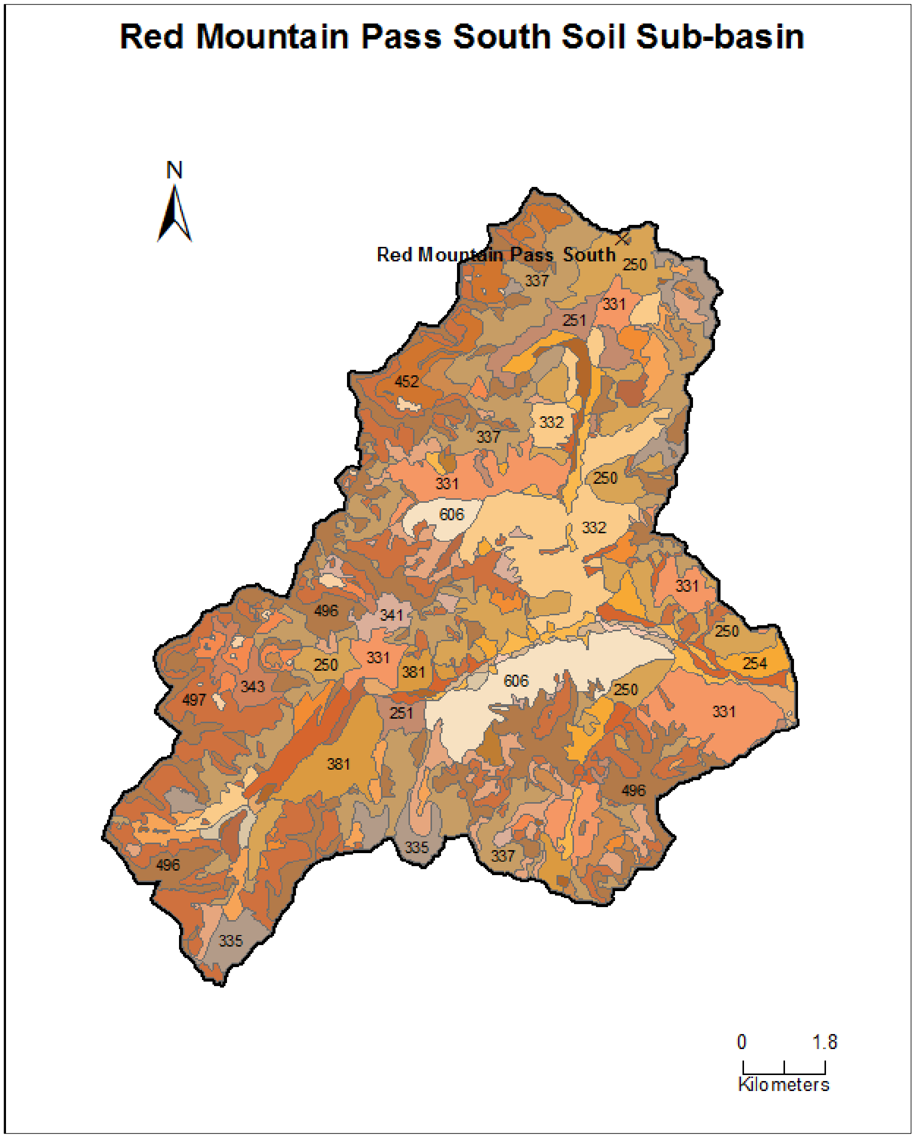


FIGURE 6. Sub-basin soil map of Red Mountain Pass South.

SOIL NUMBER	SOIL NAME	SLOPE (°)
53	Cryaquolls-Typic Cryaquents complex	1-3
54	Quazar very cobbly loam	3-14
56	Typic Cryaquents-Cryaquolls-Cryofibrists complex	0-3
121	Henson very gravelly loam	17-31
145	Rock outcrop	0-50
150	Rubble land	0-50
171	Whitecross-Rock outcrop complex	24-37
254	Cryorthents-Rubble land complex	17-37
331	Needleton stony loam	17-33
335	Whitecross-Rock outcrop complex	17-37
337	Whitecross-Rock outcrop complex	24-37
339	Henson very gravelly loam	17-31
341	Moran very gravelly loam	17-33
343	Telluride-Rock outcrop complex	24-37
381	Needleton-Snowdon-Rock outcrop complex	17-39
496	Rock outcrop	0-45
497	Rubble land	9-45
606	Snowdon-Needleton Complex	24-42

FIGURE 6, continued

Grain-Size Analysis

Grain-size analysis was used to evaluate the texture and mean grain-size in one soil profile at each study site and within subsamples at each study site. The grain-size analysis method was used to better understand grain-size distribution throughout the soil column at each fen site.

Mean grain-size (ϕ) and standard deviation varied at each study site (Table 1; Appendix A). Sample means ranged from 0.0178 ϕ to 1.6028 ϕ, and standard deviation from 1.0182 to 1.8092. Grain-sizes ranged from medium-grained to coarse-grained sand.

Subsample means ranged from -0.2277 ϕ to 1.5100 ϕ, and standard deviation from 0.6657 to 1.8060. Sand sizes ranged from very coarse to fine-grained.

TABLE 1
Sieve data for all sample sites and sections

Sample	Depth (cm)	Mean (ϕ)	Standard Deviation (σ)	Grain-size
CG	*0-65.5*	*0.2112*	*1.1985*	coarse-grained sand
CG	0-25	0.4560	1.2822	coarse-grained sand
CG	25-36	0.3952	1.3326	coarse-grained sand
CG	36-43	0.0951	1.1236	coarse-grained sand
CG	43-50	0.1572	1.1781	coarse-grained sand
CG	50-55	0.1353	1.1645	coarse-grained sand
CG	55-65.5	0.1351	1.1576	coarse-grained sand
GLI	*0-16*	*0.9045*	*1.4853*	coarse-grained sand
HV	*0-36*	*1.6028*	*1.8092*	*medium-grained sand*
HV	0-9	0.6466	1.5466	coarse-grained sand
HV	9-31	1.5100	1.8060	medium-grained sand
HV	31-36	2.4122	1.6233	fine-grained sand
RMP N	*0-70*	*0.0178*	*1.0182*	coarse-grained sand
RMP N	0-15	0.1351	1.1345	coarse-grained sand
RMP N	15-60	-0.2277	0.6657	very coarse-grained sand
RMP N	60-70	-0.0881	0.8868	very coarse-grained sand
RMP S	*0-68*	*1.0516*	*1.7385*	*medium-grained sand*
RMP S	0-38	0.0852	1.6891	coarse-grained sand
RMP S	26-28	1.5343	1.7035	medium-grained sand
RMP S	38-68	1.3245	1.7706	medium-grained sand

Italics indicates data for entire profile

At the California Gulch fen site the soil profile (0-65.5 cm) consists entirely of coarse-grained sand with a mean of 0.2112 ϕ and a standard deviation of 1.1985. Subsamples at depths of 0-25 cm, 25-36 cm, 36-43 cm, 43-50 cm, 50-55 cm, and 55-

65.5 cm have means of 0.4560 ϕ, 0.3952 ϕ, 0.0951 ϕ, 0.1572 ϕ, 0.1353 ϕ, and 0.1351 ϕ, respectively. Standard deviations range from 1.1236-1.3326.

The Glacial Lake Ironton soil profile (0-16 cm) contains medium-grained sand. The mean and standard deviation are 0.9045 ϕ and 1.4853.

The Howardsville soil profile (0-36 cm) contains medium-grained sand with a mean of 1.6028 ϕ and a standard deviation of 1.8092. A subsample from a depth of 0-9 cm contains a mean of 0.6466 ϕ and standard deviation of 1.5466. From 9-31 cm, the mean and standard deviation are 1.5100 ϕ and 1.8060. At a depth of 31-36 cm the mean and standard deviation are 2.4122 ϕ and 1.6233.

At Red Mountain Pass North, the soil profile (0-70 cm) is coarse-grained sand with a mean and standard deviation of 0.0178 ϕ and 1.0182. Subsamples at depths of 0-15 cm, 15-60 cm, and 60-70 cm have means of 0.1351 ϕ, -0.2277 ϕ, and -0.0881 ϕ, respectively. Standard deviations range from 0.6657-1.1345.

The soil profile at Red Mountain Pass South consists of medium-grained sand and has a mean of 1.0516 ϕ and a standard deviation of 1.7385. A subsample from 0-38 cm has a mean of 0.8523 ϕ and a standard deviation of 1.6891. From 38-68 cm, the mean and standard deviation are 1.3245 ϕ and 1.7706.

Within the Red Mountain Pass South sample, a visual change in grain-size was noted in the soil profile so a subsample from 26-28 cm was sieved. The mean is 1.5343 ϕ and standard deviation is 1.7035.

MORPHOMETRY

Some researchers approach wetland classification from a non-geomorphological perspective, such as Cowardin et al. (1979), who created a hierarchical classification scheme based on ecology. Few researchers consider the topography, geology, soil, and geomorphology of a region when classifying wetlands. Euliss et al. (2004) take a spatio-temporal approach and acknowledge the importance of geomorphology in a spatio-temporal continuum. The authors suggest that their approach to classifying wetlands can be used in locations other than prairie pothole regions of the United States. Alternatively, Evans and Warburton (2007) model mires following Charman (2002), which include fens and bogs, and include generic hydro-morphological characteristics. At this time, no classification scheme is universal; therefore, a geomorphic and hydrologic approach was taken to classify fens at the five study sites in the San Juan Mountains.

Based on an extensive study of the fens, it appears that three types of fens can be identified. Using geomorphic characteristics, each of the studied fens was placed into one of three categories: 1) valley-bottom, 2) valley-side, and 3) terrace. The classification scheme is based on the geomorphic location of each fen.

Fens are affected by surface water and groundwater flow (Figure 7). When water table levels are high an abundant amount of water enters each fen, but when levels are low, water flows out of the fen and into the surrounding environment. Fens are very sensitive to changes in local hydrologic patterns.

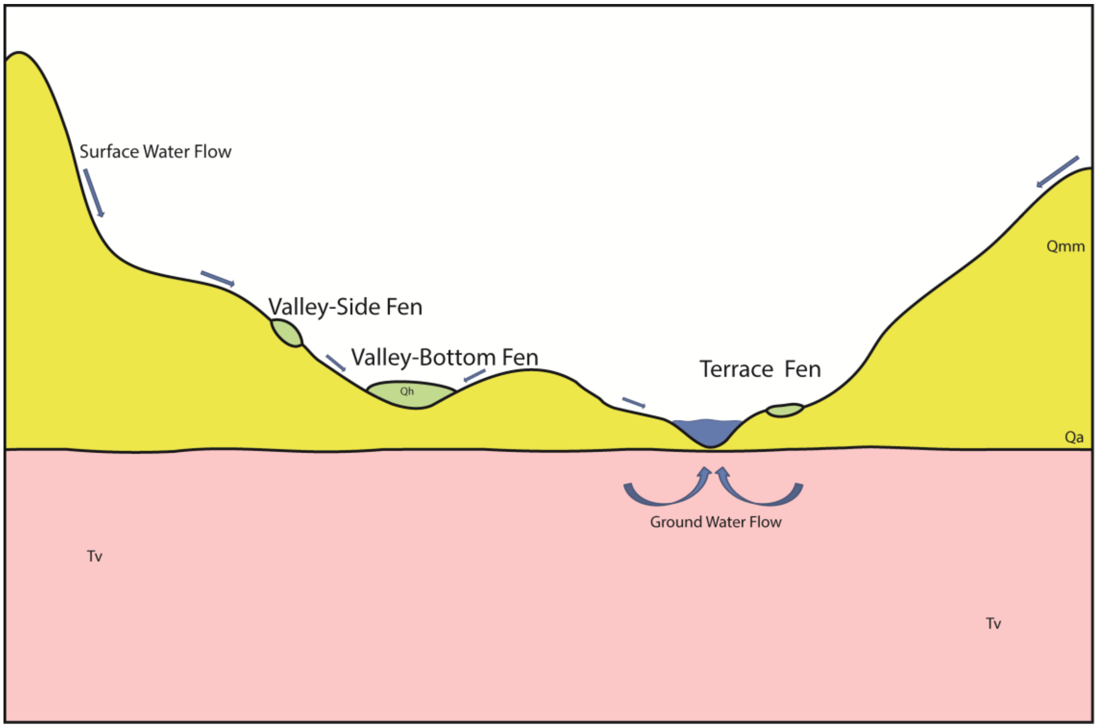


FIGURE 7. Classification of fens based on geomorphic location. (Qa=Quaternary alluvium, Qh=Quaternary Holocene sediment, Qmm=Quaternary mass movement, Tv=Tertiary volcanic bedrock).

In the five study sites within the San Juan Mountains, fens are found either in valley-bottoms where groundwater and surface water flow through, along valley-sides where groundwater discharges and surface water flows, or on a terrace where groundwater, surface water, and a river supplies the fens with sufficient water.

Glacial Lake Ironton and Red Mountain Pass South fen complexes are considered valley-bottom fens. Both complexes formed in alluvium-filled glacial valleys and are surrounded by fairly steep valley sides.

California Gulch and Red Mountain Pass North fen complexes, which also formed in alluvium-filled valleys, are considered valley-side fens as they slope towards the valley floor. Lastly, the Howardsville fen is considered a terrace fen because it resides on a terrace adjacent to the Animas River.

In addition to classifying each of the five fen complexes based on morphometry and geomorphic location (Table 2), an additional twenty-five fens were delineated using orthorectified photographs and ArcGIS®. A total of ten fens from each of the classification categories were chosen and morphometric properties were calculated for all thirty fens (Table 3).

TABLE 2
Site, classification, fen elongation, and area associated with each of the five main fens.

Site	Classification	F_e	Area (km^2)
CG	valley-side	2.6	0.002
RMPS	valley-bottom	2.1	0.014
GLI	valley-bottom	1.2	0.0003
RMPN	valley-side	2.6	0.018
HV	terrace	1.9	0.005
$\bar{x}$		2.1	0.008

TABLE 3
Fen Morphometry: area, circularity, and elongation values of thirty fens.

ID	Area of fen (km^2)	Circularity	Elongation
Valley-bottom	0.001	0.9	1.2
Valley-bottom	0.003	0.3	2.0
Valley-bottom	0.007	0.7	1.2
Valley-bottom	0.007	0.7	2.1
Valley-bottom	0.001	0.7	1.5
Valley-bottom	0.002	0.8	1.8
Valley-bottom	0.014	0.7	2.1
Valley-bottom	0.0003	0.9	1.2
Valley-bottom	0.002	0.6	1.9
Valley-bottom	0.003	0.3	2.2
mean	0.004	0.7	1.7
median	0.003	0.7	1.9

TABLE 3, Continued

ID	Area of fen (km^2)	Circularity	Elongation
Valley-side	0.005	0.6	2.8
Valley-side	0.001	0.6	2.2
Valley-side	0.004	0.7	2.3
Valley-side	0.004	0.6	2.4
Valley-side	0.002	0.8	2.3
Valley-side	0.004	0.6	2.4
Valley-side	0.002	0.4	2.6
Valley-side	0.018	0.4	2.6
Valley-side	0.001	0.9	2.3
Valley-side	0.005	0.7	2.2
mean	0.004	0.6	2.4
median	0.004	0.6	2.4

TABLE 3, Continued

ID	Area of fen (km^2)	Circularity	Elongation
Terrace	0.008	0.7	2.2
Terrace	0.003	0.5	2.1
Terrace	0.002	0.6	1.8
Terrace	0.009	0.5	1.9
Terrace	0.008	0.6	1.6
Terrace	0.003	0.5	2.0
Terrace	0.005	0.5	1.9
Terrace	0.001	0.7	1.7
Terrace	0.001	0.7	2.2
Terrace	0.001	0.9	1.7
mean	0.004	0.6	1.9
median	0.003	0.6	1.9

The mean circularity and elongation for valley-bottom fens is 0.7, which is similar to terrace fens with a mean and median of 0.6. Valley-side fens have a similar circularity to terrace fens with a mean and median of 0.6. Valley-bottom fens exhibit the greatest circularity, followed by terrace and valley-side fens. This can likely be attributed to the degree of slope at each location.

In terms of elongation, valley-bottom fens have a mean of 1.7 and a median of 1.9, whereas terrace fens have a mean and median of 1.9. In contrast, valley-side fens have a mean and median elongation of 2.4. Valley-side fens are more elongated than both valley-bottom and terrace fens, which tend to be more circular. This again is likely attributed to the degree of slope at each location.

A general trend in the value of circularity between the three types of alpine fens was not noted, but a pattern emerged for the elongation of fens. Valley-bottom fens have an elongation value ranging from 1.2 to 2.2. Valley-side fens have elongation values that range from 2.2 to 2.8, and terrace fens have values ranging from 1.6 to 2.2. Valley-bottom fens have the greatest range in values, which are more similar to terrace fens than valley-side fens. Valley-side fens are the only type of fen that has an elongation value exceeding 2.2. A conclusion can be drawn that states valley-side fens are more elongated than valley-bottom and terrace fens which exhibit similar elongation values.

REFRACTIVE SEISMICITY

To determine depth to bedrock, seismic data from each seismic channel were plotted on a point graph to determine the first arrival point of the refractive wave. Unfortunately, the data were inconclusive. Some channels showed an excellent signal, whereas others needed extensive filtering. Differences in signals are perhaps a result of a greater depth of alluvium than previously thought, boulders, thick peat, or amount of saturation. Unfortunately, this method did not work and depth to bedrock was not able to be determined.

GEOCHEMISTRY

Pb in the San Juan Mountains is found in two main forms: ore mineralized Pb and non-ore mineralized Pb. Each is a natural form of Pb found within the surrounding rock. Ore mineralized Pb is released during mining activities via smelters and the transportation of ores, waste rock, and tailings. Non-ore mineralized Pb is released via erosion of bedrock.

Pb in fen sediment can be found in both ore and non-ore mineralized forms, which can lead to the presence of binary mixing of Pb, the mixing of Pb from more than one source. To determine if binary mixing is present, it is necessary to conduct an isotopic analysis based on ^{206}Pb, ^{207}Pb, and ^{208}Pb ratios.

By plotting depth of the sediment layer versus Pb concentration (ppm) and ^{206}Pb/^{207}Pb, the presence of binary mixing becomes visible. This is confirmed by plotting ^{206}Pb/^{207}Pb versus 1/Pb (ppm^{-1}) and ^{206}Pb/^{208}Pb versus ^{206}Pb/^{207}Pb, and calculating r^2.

In a plot of concentration and isotopic ratio versus depth, lower concentration values and higher isotopic ratios are indicative of non-ore mineralized Pb, whereas higher concentrations of Pb and lower isotopic ratios are indicative of ore-mineralized Pb. The presence of both scenarios on a graph would indicate multiple sources of Pb.

Binary mixing can be confirmed by plotting ^{206}Pb/^{207}Pb versus 1/Pb (ppm^{-1}) and ^{206}Pb/^{208}Pb versus ^{206}Pb/^{207}Pb, then calculating r^2. A high r^2 value in a plot of ^{206}Pb/^{207}Pb versus 1/Pb (ppm^{-1}) indicates the likelihood of the presence of binary mixing. A low r^2 value indicates the presence of more than two sources of Pb. In a plot of ^{206}Pb/^{207}Pb versus ^{206}Pb/^{208}Pb, a high r^2 value indicates mixing between two sources of Pb.

Lead

Pb isotopic ratios and concentrations are shown in Table 4 for all fen sediments. Values of depth versus ^{206}Pb/^{207}Pb and Pb concentration were plotted for each fen, with the exception of California Gulch. ^{206}Pb/^{207}Pb versus 1/Pb (ppm^{-1}) was plotted for all study sites (Figure 8).

TABLE 4
Fen sediment data from isotopic analysis using ICP-MS.

SAMPLE	DEPTH (cm)	Pb CONCENTRATION (ppm)	1/Pb (ppm^{-1})	^{206}Pb/^{207}Pb	^{206}Pb/^{208}Pb
CG	1	97	0.0103	1.1987	0.4868
CG	3	82	0.0122	1.1940	0.4863
CG	5	89	0.0113	1.1947	0.4864
CG	7	136	0.0073	1.1964	0.4872
CG	9	39	0.0253	1.1992	0.4898
CG	11	106	0.0095	1.1967	0.487
CG	13	63	0.0016	1.1959	0.4872
CG	15	52	0.0193	1.1962	0.4878
CG	17	46	0.0219	1.1960	0.4877
CG	19	42	0.0238	1.1992	0.4900
CG	21	56	0.0178	1.1962	0.4878
CG	23	71	0.0141	1.1971	0.4878
CG	25	92	0.0108	1.1961	0.4871
CG	27	100	0.0100	1.1970	0.4873
CG	29	91	0.0110	1.1957	0.4875
GLI	1	383	0.0026	1.1983	0.4886
GLI	3	373	0.0027	1.1947	0.4868
GLI	5	210	0.0048	1.1938	0.4869
GLI	7	293	0.0034	1.1948	0.4868
GLI	9	317	0.0032	1.1975	0.4887
GLI	11	393	0.0025	1.1948	0.4868
GLI	13	276	0.0036	1.1951	0.4874
GLI	15	246	0.0041	1.1964	0.4870
GLI	17	281	0.0036	1.1962	0.4872
GLI	19	452	0.0022	1.1953	0.4863
GLI	21	371	0.0027	1.1938	0.4867
GLI	23	314	0.0032	1.195	0.4864
GLI	25	305	0.0033	1.1933	0.4872
GLI	27	193	0.0052	1.1918	0.4868
GLI	29	396	0.0025	1.1917	0.4863

TABLE 4, Continued

SAMPLE	DEPTH (cm)	Pb CONCENTRATION (ppm)	1/Pb (ppm^{-1})	^{206}Pb/^{207}Pb	^{206}Pb/^{208}Pb
HV	1	169	0.0059	1.1988	0.4870
HV	3	184	0.0054	1.1995	0.4866
HV	5	369	0.0027	1.1999	0.4802
HV	9	251	0.0040	1.1997	0.4855
HV	11	241	0.0042	1.2003	0.4824
HV	13	229	0.0044	1.1979	0.4841
HV	15	204	0.0049	1.1989	0.4865
HV	17	99	0.0101	1.2031	0.4892
HV	19	137	0.0073	1.2044	0.4895

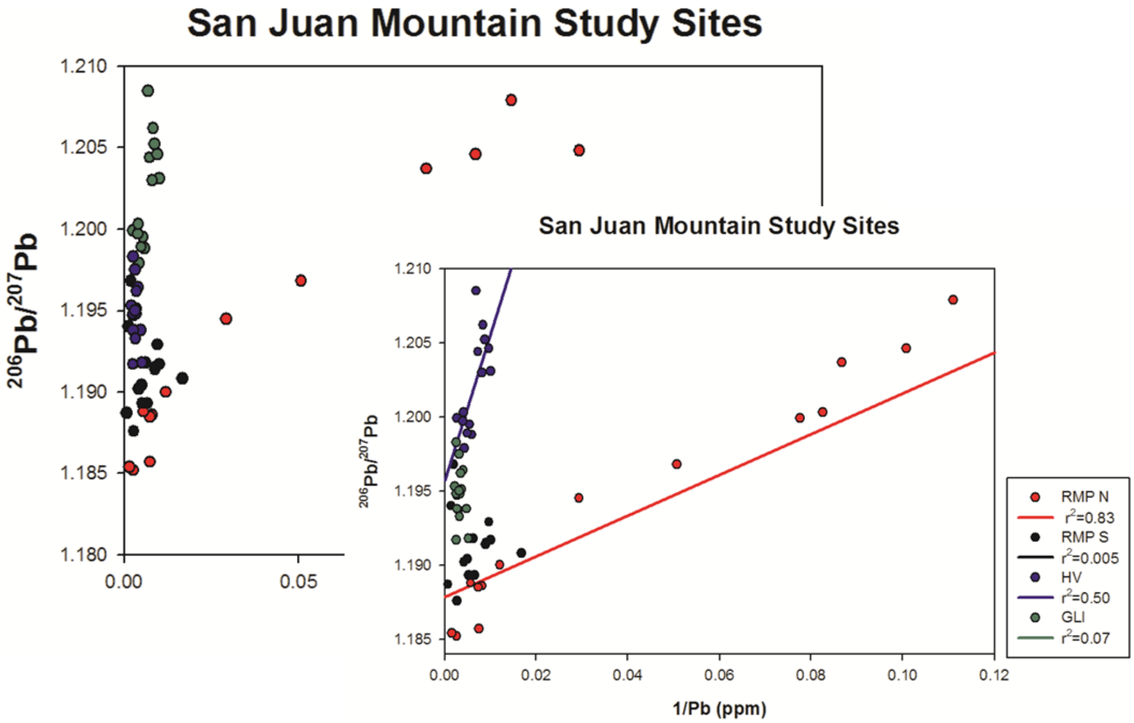


FIGURE 8. Normal and magnified views of ^{206}Pb/^{207}Pb versus 1/Pb displaying r^2 values for San Juan Mountain study sites.

A plot of $^{206}Pb/^{207}Pb$ versus $^{206}Pb/^{208}Pb$ of all study sites is also shown (Figure 9). Unfortunately, Pb concentration data for California Gulch has a large error when compared to the other study sites, so a depth versus $^{206}Pb/^{207}Pb$ and Pb concentration plot was not completed for that data set. Analysis of concentration was completed to determine whether a correlation exists between the variables and if non-ore mineralized Pb or ore mineralized Pb is present in fen sediments.

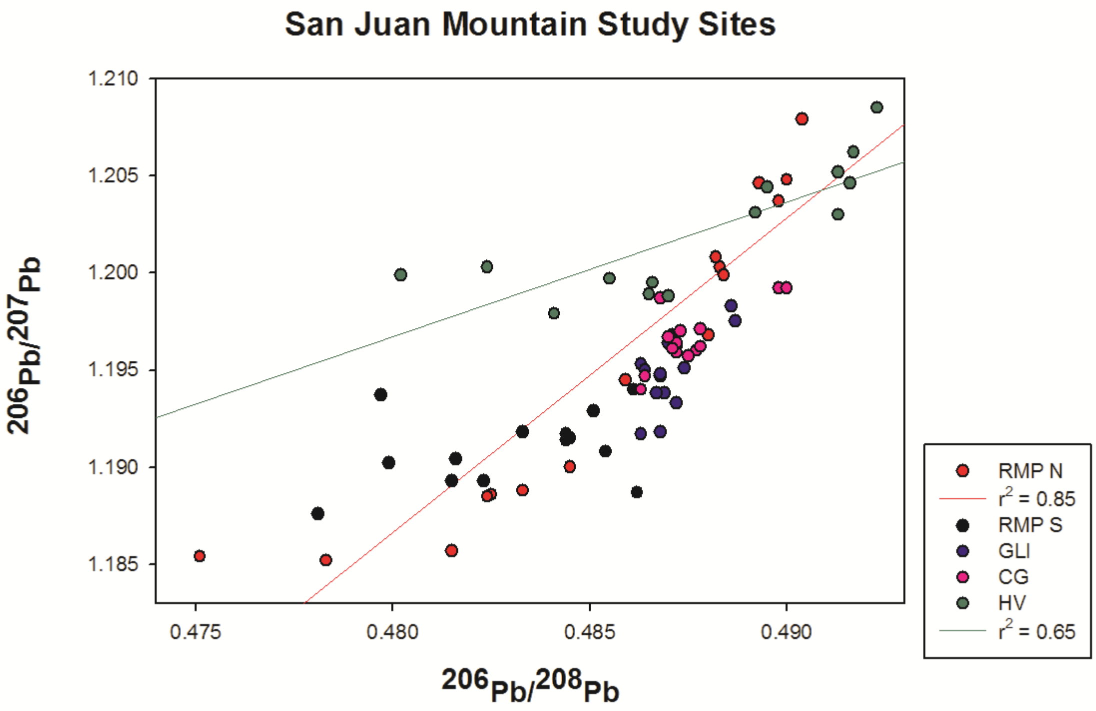


FIGURE 9. Graph of $^{206}Pb/^{207}Pb$ versus $^{206}Pb/^{208}Pb$ for study sites, displaying r^2 values for Red Mountain Pass North and Howardsville.

At all sites, except for Red Mountain Pass North and Howardsville, all ^{206}Pb/^{207}Pb ratios are within error of each other, therefore suggesting little to no variation of Pb with depth.

California Gulch sediment contains isotopic ratios of ^{206}Pb/^{207}Pb ranging from 1.194-1.199 (Figure 10).

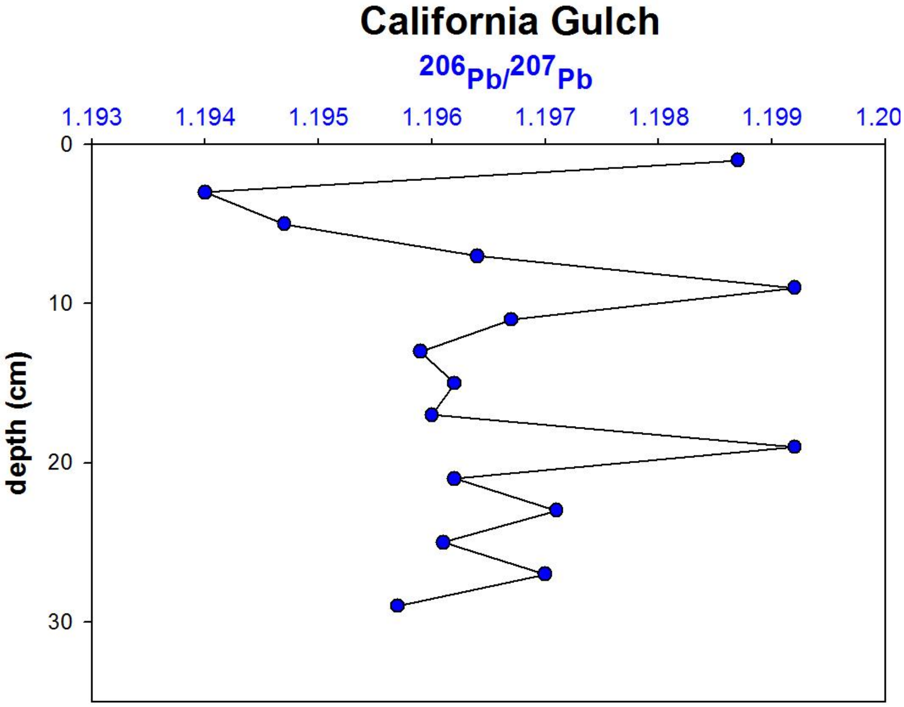


FIGURE 10. Plot of ^{206}Pb/^{207}Pb versus depth from surface at California Gulch.

Glacial Lake Ironton sediment contains concentrations of Pb ranging from 192 ppm to 451 ppm (Figure 11). Isotopic ratios vary little and range from 1.192 to 1.198. Overall, Pb concentrations alternate from 383 ppm at the surface to 452 ppm at 19 cm to

193 ppm at 27 cm and then greatly increase from 27 cm to 29 cm with values of 193 ppm to 396 ppm.

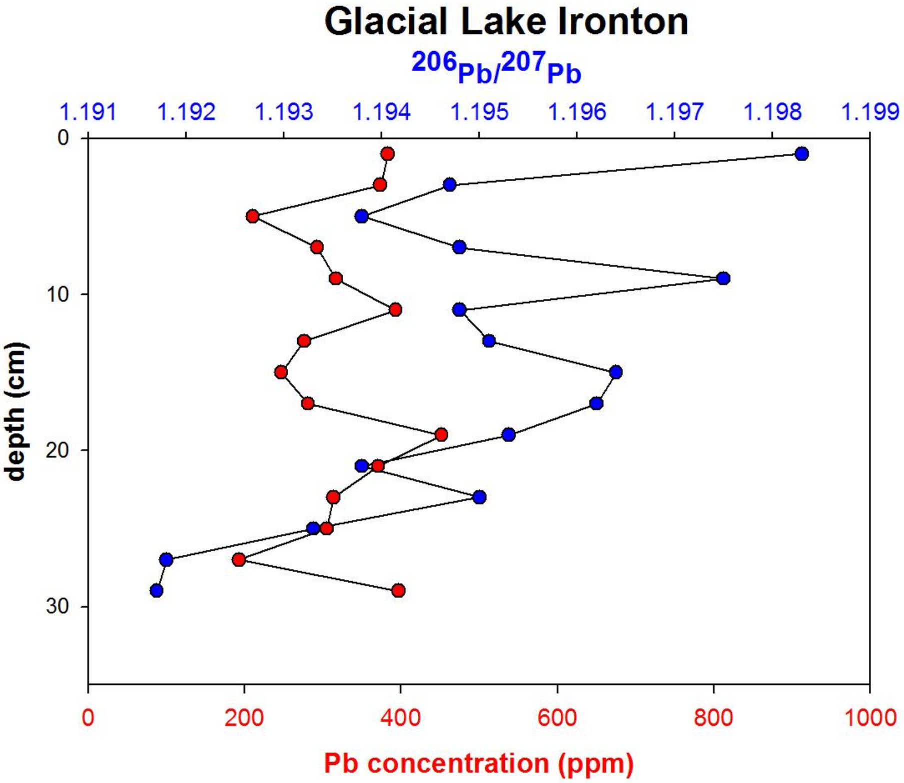


FIGURE 11. Plot of ^{206}Pb/^{207}Pb and concentration versus depth from surface at Glacial Lake Ironton.

Howardsville sediment contains concentrations of Pb ranging from 98 ppm to 368 ppm and ^{206}Pb/^{207}Pb ratios that vary significantly between 1.198 and 1.209 (Figure 12). A sharp increase in Pb concentration occurs between the surface and 5 cm below the surface, with an increase of Pb concentration from 169 ppm to 369 ppm. Little variation in Pb concentration is seen between 5 cm and 15 cm. A gradual decrease of Pb concentrations occur from 15 cm to 29 cm with concentrations varying from 204 ppm to 145 ppm, and an increase of $^{206}Pb/^{207}Pb$ ratios occurs from 15 cm to 29 cm with values of 1.199 to 1.209.

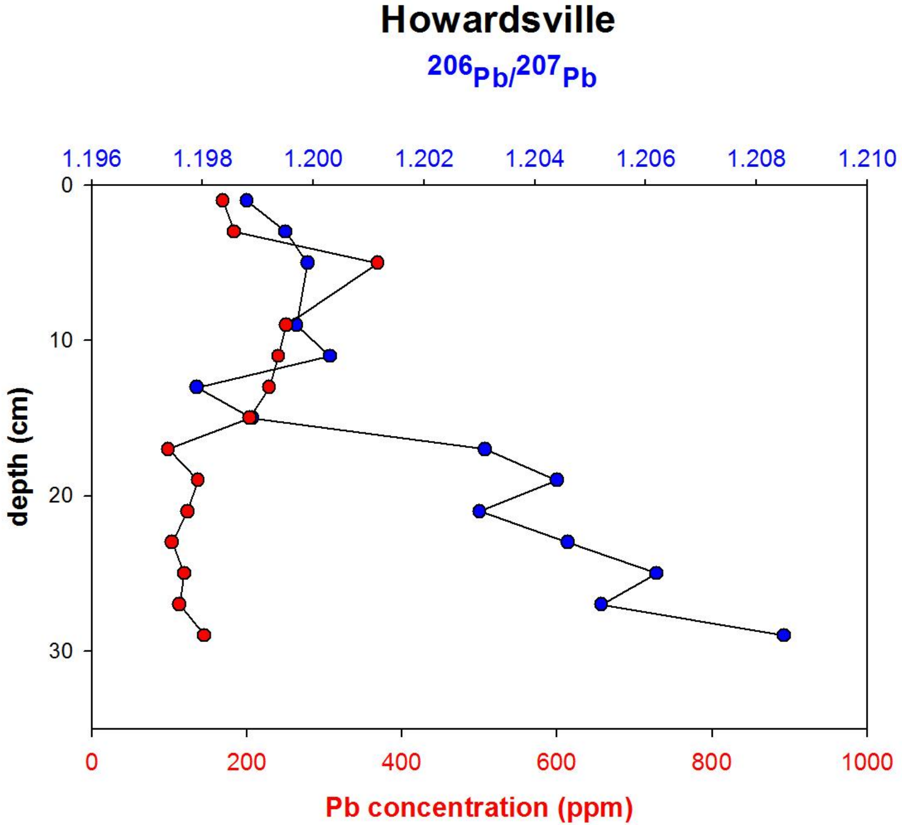


FIGURE 12. Plot of $^{206}Pb/^{207}Pb$ and concentration versus depth from surface at Howardsville.

Red Mountain Pass North sediment (Figure 13) contains a wide-range of concentrations of Pb ranging from 6 ppm to 634 ppm and $^{206}Pb/^{207}Pb$ ratios of 1.185 to 1.203. A sharp increase in Pb concentration and slight increase in $^{206}Pb/^{207}Pb$ ratios occur between the surface and 3 cm below the surface. Pb concentration values range from 376 ppm to 634 ppm. A very sharp decrease in Pb concentration of 634 ppm at 3 cm, to 133 ppm at 5 cm is apparent. Between 5 cm and 11 cm, Pb concentrations alternate from 133 ppm to 176 ppm, followed by an increase of ^{206}Pb/^{207}Pb ratios ranging from 1.186 to 1.190. A sharp decrease in Pb concentration is visible between 11 cm and 13 cm with values of 176 ppm to 34 ppm, followed by a very gradual decrease of Pb concentration from 13 cm to 29 cm, reaching a value of 12 ppm. Alternately, a large increase in ^{206}Pb/^{207}Pb from 11 cm to 17 cm occurs with values ranging from 1.190 to 1.200.

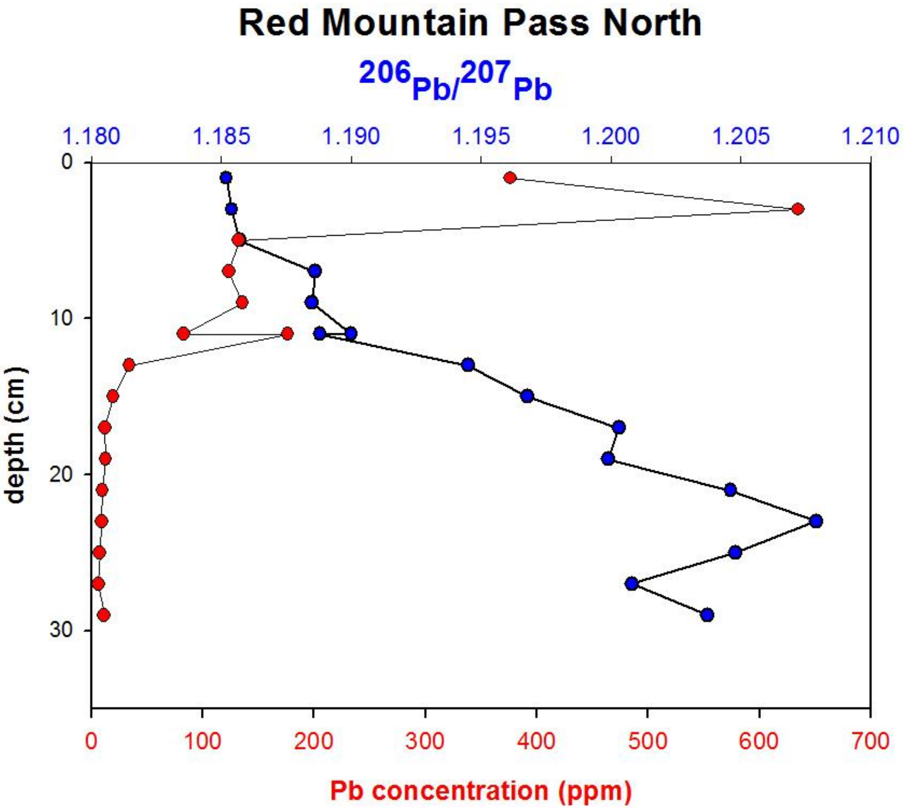


FIGURE 13. Plot of ^{206}Pb/^{207}Pb and concentration versus depth from surface at Red Mountain Pass North.

Red Mountain Pass South sediment (Figure 14) contains highly variable Pb concentrations ranging from 59 ppm to 1345 ppm and ^{206}Pb/^{207}Pb ratios of 1.187 to 1.197. In general, Pb concentrations greatly increase from the surface to 11 cm with values ranging from 202 ppm to 1345 ppm then sharply decrease from 1345 ppm at 11 cm to 99 ppm at 29 cm. ^{206}Pb/^{207}Pb ratios tend to increase from the surface with a value of 1.190 to 7 cm with a value of 1.197. Ratios then decrease to a value of 1.188 at 13 cm, followed by both increasing and decreasing values to 1.192 at 29 cm.

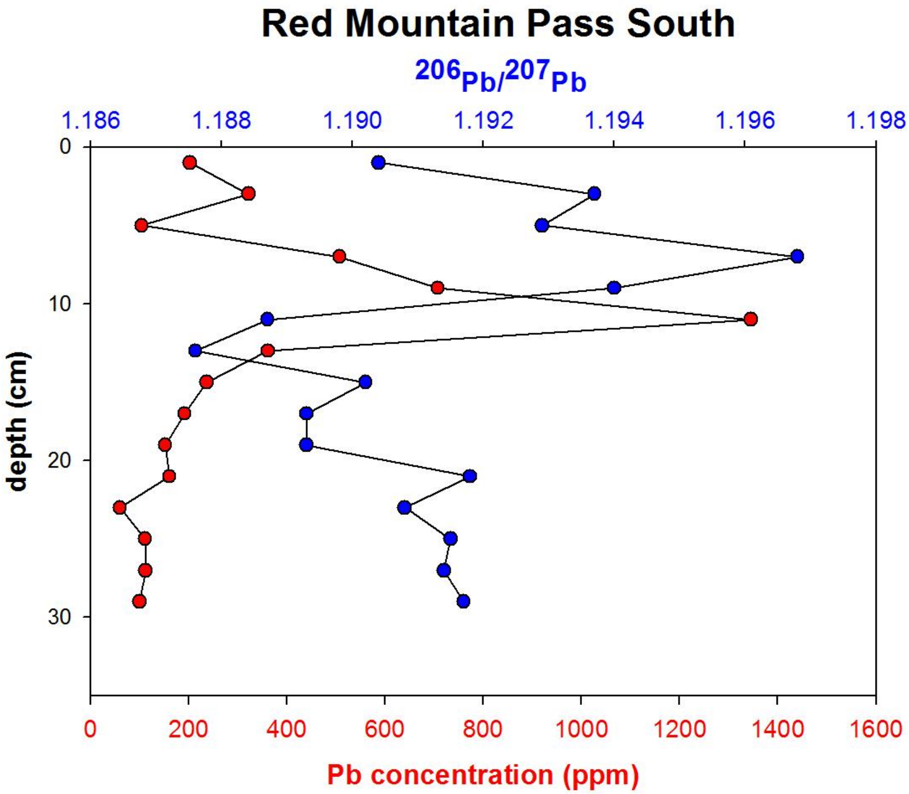


FIGURE 14. Plot of ^{206}Pb/^{207}Pb and concentration versus depth from surface at Red Mountain Pass South.

^{137}Cs and ^{210}Pb

In addition to using isotopic ratios of Pb as environmental tracers, ^{210}Pb and ^{137}Cs are useful in environmental studies. ^{210}Pb has a half-life of 22.8 years (Church et al., 2007b). This form of Pb is easily incorporated into sediment being deposited, thus allowing layers of sediment to be dated consecutively (Church et al., 2007b).

Like ^{210}Pb, ^{137}Cs is considered a reliable method for dating of sediment. ^{137}Cs is considered a thermonuclear byproduct that is related to nuclear atmospheric testing during the late 1950s and early 1960s (Church et al., 2007b). There has not been any atmospheric nuclear testing since this time making ^{137}Cs a reliable method for dating of sediment.

^{210}Pb$_{xs}$ is used to validate ^{137}Cs results and it works as an indicator that where it is present, the sediment is less than 150 years old. Since ^{210}Pb has a short half life it should reach zero relatively quickly (Church et al., 2007b). In terms of concentration of ^{137}Cs at each study site, a peak of ^{137}Cs is expected with depth before the amount of ^{137}Cs declines to zero, with a peak indicating the year 1963 +/- 2 years (Robbins and Edgington, 1975).

From the analysis of ^{210}Pb$_{xs}$ and ^{137}Cs, average sedimentation rates were derived (Figure 15; Table 5). A discernible ^{137}Cs peak was reached in sediment samples at all fen sample sites, except for Red Mountain Pass North. This was the result of a lack in sufficient sediment within the sediment sample (non-organic material). Sedimentation rates based on ^{137}Cs range from 0.04 cm/yr to 0.19 cm/yr, whereas, sedimentation rates based on ^{210}Pb$_{xs}$ range from 0.04 cm/yr to 0.23 cm/yr (Table 6).

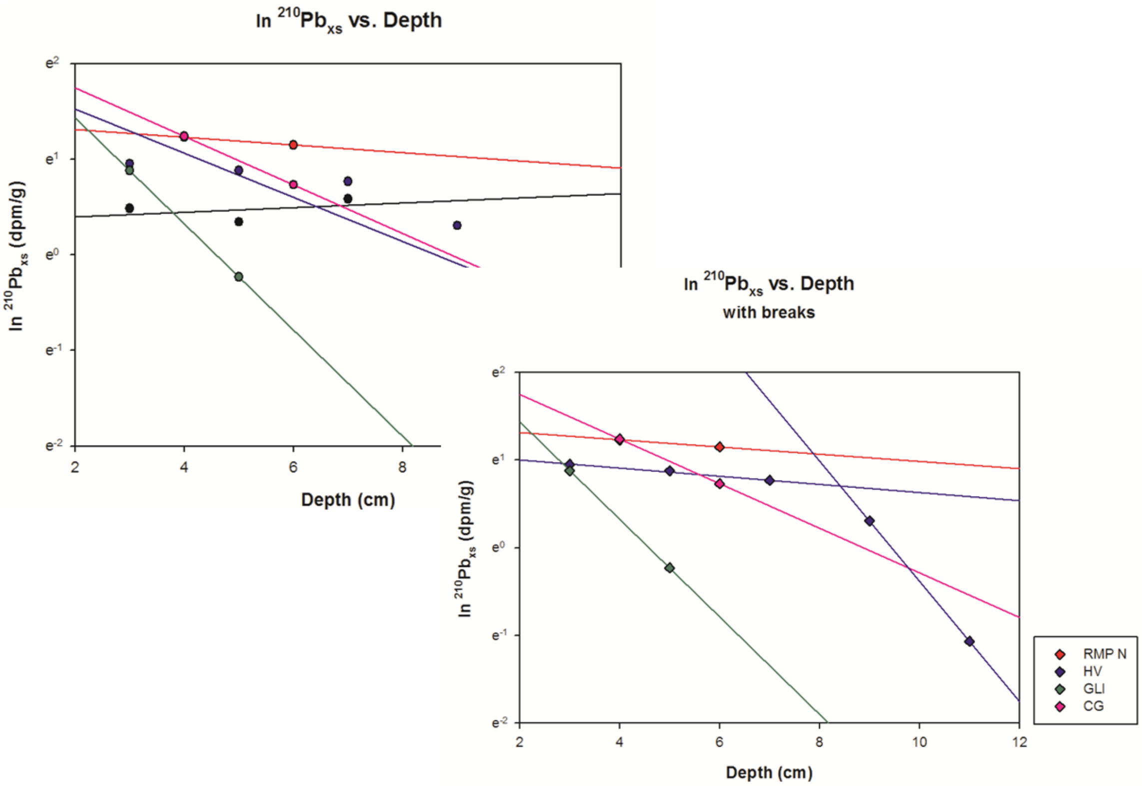


FIGURE 15. Plot of the natural log of ^{210}Pb$_{xs}$ versus depth, with visible breaks in data points near 8 cm depth.

TABLE 5
Results of ^{210}Pb, ^{210}Pb$_{xs}$, and ^{137}Cs analysis in fen sediments at each study site.

SAMPLE ID	DEPTH (cm)	^{210}Pb	^{210}Pb$_{xs}$	^{137}Cs
CG	2	14.27	11.65	1.31
CG	4	33.44	31.58	9.38
CG	6	9.61	7.98	4.74
CG	8	2.30	1.00	0.43
GLI	1	6.27	2.42	0.91
GLI	3	13.39	11.08	6.27
GLI	5	5.52	2.21	6.14
GLI	7	5.10	0.71	0.93
HV	1	12.73	9.88	1.18
HV	3	15.94	13.33	1.33
HV	5	14.40	11.14	2.07
HV	7	11.40	8.59	5.22
HV	9	6.98	3.88	6.99
HV	11	5.13	1.41	0.62
HV	13	4.00	0.57	0.00
RMP N	2	22.26	21.81	1.11
RMP N	4	31.31	30.49	3.17
RMP N	6	23.89	23.34	4.56
RMP S	1	14.22	12.19	0.78
RMP S	3	8.96	5.05	0.73
RMP S	5	7.13	4.08	0.38
RMP S	7	8.81	5.96	0.05

TABLE 6
Average sedimentation rates at each sample site based on ^{210}Pb$_{xs}$ and ^{137}Cs.

SAMPLE ID	*^{210}Pb$_{xs}$ (cm/yr)	**^{137}Cs (cm/yr)
RMP N	0.23	0.13
RMP S	N/A	0.04
HV	0.10	0.19
GLI	0.05	0.08
CG	0.04	0.08

* First ^{210}Pb$_{xs}$ value was removed

**137Cs value is based on 1963 +/- 2 years

The natural log of $^{210}Pb_{xs}$ was plotted versus depth on a natural logarithmic scale to validate sedimentation rates based on ^{137}Cs and to look for natural breaks in average sedimentation rates. In comparison with $^{210}Pb_{xs}$, Red Mountain Pass North has a ^{137}Cs based sedimentation rate of 0.13 cm/yr, which is nearly half that of $^{210}Pb_{xs}$ (0.23 cm/yr). Howardsville has a discernible peak in ^{137}Cs with a sedimentation rate of 0.19 cm/yr, which is nearly twice that of $^{210}Pb_{xs}$ (0.10 cm/yr). Both Glacial Lake Ironton and California Gulch have sedimentation rates based on ^{137}Cs of 0.08 cm/yr versus $^{210}Pb_{xs}$ rates of 0.05 cm/yr and 0.04 cm/yr, respectively.

TEMPORAL TIME LINE OF CHANGE

The San Juan Mountains have undergone geologic and human-induced changes throughout time, with more rapid changes occurring in the last two hundred years (Blair et al., 1996). The San Juan Mountains were formerly inhabited by Utes until 1873 when the Brunot Treaty allowed settlement in the San Juan Mountains (Western Mining History, 2010). Many Ute tribes moved with the onset of mining of ores and coal (Blair et al., 1996).

Mining was booming in the late 19th Century (Blair et al., 1996), and continued to increase with the construction of the railroad in 1882 (Western Mining History, 2010). Large changes in population were seen as mining increased and the populations grew.

In the town of Silverton, the population was 2,500 in 1883. It remained steady through 1886, but began to grow with the addition of mines, mills, and smelters (Appendix B; Sanborn Map Company, 1883, 1886, and 1910). In 1910, the town of Silverton had a population of 3,000 people with the addition of mining activities.

Populations dispersed eighty-one years later, in 1991, when Sunnyside Mine closed (Jones, 2007).

During times when mining was booming, acidic waters seeped into mines and the surrounding environment, corroding anything made of iron (Blair et al., 1996), and polluting surface water and groundwater. These effects are visible in the form of orange-colored streams, even in areas where mining has ceased (Photograph 19).

PHOTOGRAPH 19. Orange-colored stream, east side of Highway 550 and Red Mountain Pass South. Photograph taken looking to the south.

Pollution of water and sediment continued into the 1970s with the flooding of the Animas River near Silverton in September of 1970. The Animas River at Howardsville had a maximum discharge on September 6, 1970 of 33.1 m^3/s, with a normal average discharge of 2.8 m^3/s (Roeske et al., 1978). As a result of mining an unknown amount of tailings on the surface of the landscape became entrained by water, which was then sent flowing into the Animas River.

Flooding is not an unknown phenomenon to the region. Larger floods have been recorded on the Animas River. On October 5, 1911 the Animas River had a discharge of 7,079 ft^3/s. Whereas, a flood on June 29, 1927 produced a discharge of 566 ft^3/s. Additional large floods include one on May 14, 1941 with 297 ft^3/s, June 6, 1956 with a discharge of 265 ft^3/s, and May 25, 2005 with a discharge of 242 ft^3/s, to name a few (USGS, 2012).

Between 1973 and 1974 melting snow pack caused tailing ponds to break, which released 100,000 tons of tailings and mud into the Animas River, heading towards the town of Silverton (Evans, 2010). Mining ceased for one month of clean-up, but resumed for six more years until a similar event occurred again (Evans, 2010).

Mining towns, such as Eureka and Howardsville, collapsed with the cessation of mining, but Silverton held on by supporting tourism. Land use has changed from the mining of ores and coals to the mining of peat, creation of off-road vehicles, and the creation of trails, which have all helped sustain the former mining town of Silverton.

Though mining has ceased, lasting effects are still visible with abandoned mines, adits, tunnels, acid mine drainage, waste rock, and tailings dumps. Changes in land use have greatly impacted the environment and forever changed the landscape.

Mining in the area has ceased and land use has changed with growing tourism. Land within the United States National Forest allows trails for vehicle use, giving ease of access to areas containing fens. At each of the study sites in the San Juan Mountains, off-road vehicles and trails, along with major roadways, cut through fens. Fen systems, including local hydrologic regime and the surrounding environment, are altered. Currently, steps are being taken to remediate some of these issues and protect many of the 2,000 fens located in the San Juan Mountains, in addition to mitigating the lasting effects of mining (Chimner et al., 2010).

CHAPTER VII

ANALYSIS

INTRODUCTION

Upon analyzing geomorphic and geochemical data, it has become apparent that the fen study sites are complex. Fens in each of the five study sites formed in Quaternary-age deposits and receive input of materials from a variety of sources.

The topography of a region plays a tremendous role as to what enters and exits fens. Steep slopes tend to funnel material, such as sediment and rocks of a variety of grain-sizes, via wind and water erosion, to lower-lying areas, whereas low-lying areas, such as fens, tend to retain material. Landforms, such as roche moutonnée, often block or alter the transport of material.

The valley-bottom fens, Glacial Lake Ironton and Red Mountain Pass South, are both surrounded by steep slopes and have water flowing to and through them via surface water flow. The water is likely to carry loose rocks, sediment, and heavy metals to the fens, which may or may not reside in the fen. Valley-side fens, such as California Gulch and Red Mountain Pass North, reside at the base of valley slopes and are greatly influenced by stream water and form where groundwater flows from the base of slopes. Howardsville, a terrace fen, is most influenced by the Animas River which supplies it with water during high flow times.

Both topography and geology influence what materials are input and output from fens and affect depth to water table. The role of geology within the study sites involves the type of rock surrounding the fens and available for transport, biproducts of past mining, faults and fractures, the ability to transport water, and the material available for fens to form in.

Elements from the surrounding rock are often leached via water and carried to fens via streams. Water tends to seep from fractures and into fens. Geology, in terms of composition of bedrock, directly affects the heavy metal content of water and sediment within fens.

The depth to the water table for the California Gulch fen is greater than 200 cm and Red Mountain Pass North fen is up to 203 cm (NRCS, 2011). It is likely that the depth to the Red Mountain Pass North fen is nearer 203 cm based on the fact both fens are valley-side fens. The fens are likely sustained by water seeping from bedrock at the base of slopes. Alternatively, Glacial Lake Ironton has an estimated depth to bedrock of 15 cm to 90 cm and Red Mountain Pass South is up to 91 cm (NRCS, 2011). Both of these fens are valley-bottom fens, which likely receive their groundwater from directly below them. Lastly, Howardsville is a terrace fen with an estimated depth to groundwater of 15 cm to 50 cm (NRCS, 2011).

Geologic influences must be examined in addition to depth to the water table to understand how the fens are sustained. California Gulch receives surface water channeled from the igneous rock to the west, whereas Red Mountain Pass North receives water from the surface which flows around roche moutonnée and bedrock from high above the landscape. Glacial Lake Ironton and Red Mountain Pass receive additional water from streams that cut through the alluvium and from streams running down the slope of igneous rock. Lastly, Howardsville receives additional water that flows over Quaternary deposits and across the road to the terrace.

By studying soil maps and soil characteristics, a better understanding of the sedimentary characteristics of fens can be developed. Characteristics of sediment influence the ability of a fen to act as a source and a sink for materials and influences what volume of water can permeate through the fen. Though this study did not focus on investigating physical properties of soil, it did look at sedimentary characteristics to attempt to describe sediment layers in the fens.

Inputs into fens varied with location and a variety of lithologic properties were found. For example, four of the five sediment samples contained at least 40 cm of peat, which indicates the presence of a fen, whereas another site contained gravels near the surface, which after a visual examination, appeared to have originated from gravel used to make Highway 550. Additionally, orange streaks were found in some sediment layers, which would indicate a time when oxidation occurred and water levels were perhaps low.

GEOMORPHOLOGY

California Gulch

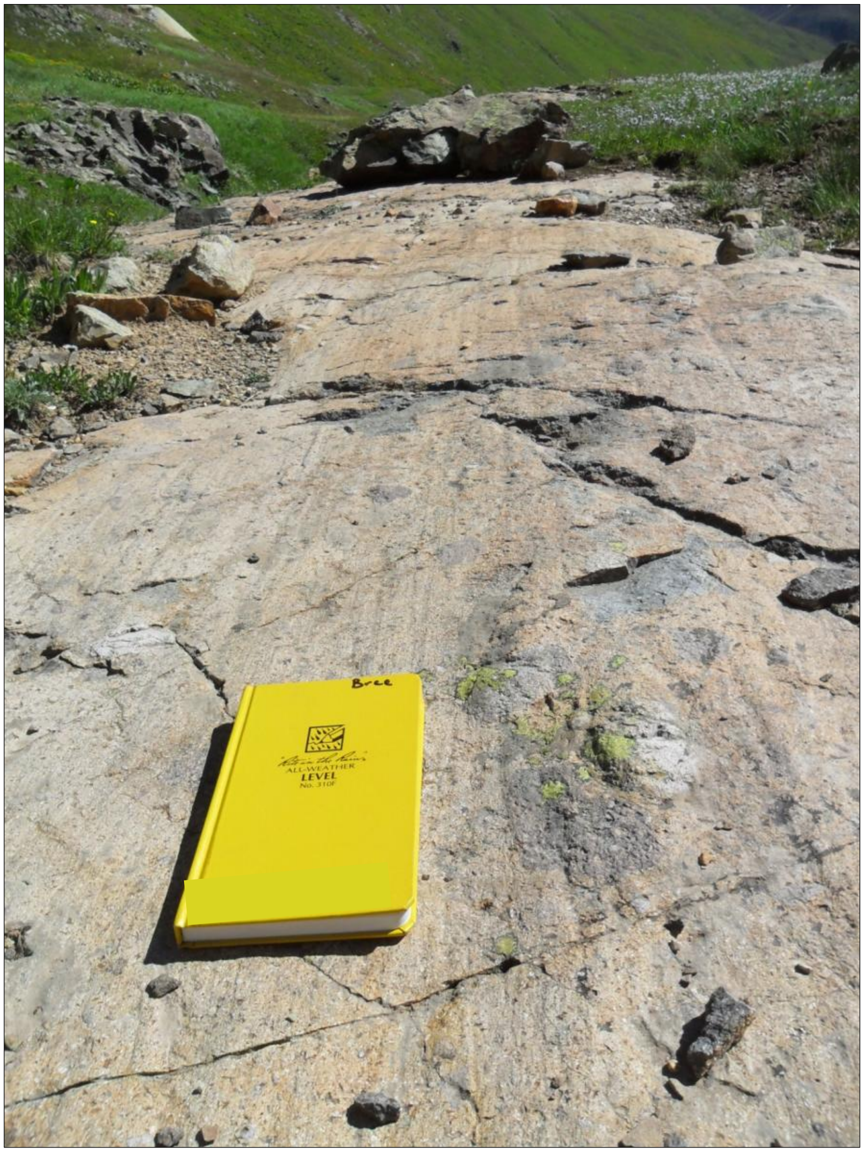
The geomorphology of the fen complex at California Gulch was mapped at a scale of ~1:3,000 with a 20 m contour interval. The California Gulch fen is west of the West Fork Animas River, which flows through a narrow valley bottom (APPENDIX C). Southwest of the mapping area, large cirques are present along with hydrothermally altered rock.

California Gulch is characterized by valley sides with convex and concave slopes. The western portion of the valley is characterized by convex slopes along County Road 19. The western slopes contain numerous intermittent areas of exposed extrusive igneous rock, some of which are along concave slopes. The eastern slopes of the valley are characterized by a combination of convex and concave slopes.

The eastern edge of the valley contains areas where rockfall, primarily boulders, provide a path for rainwater and snowmelt to flow and carry loose rock toward the valley bottom (White, 1981). This pattern can also be seen on the western slopes.

The valley bottom at California Gulch contains numerous outcrops of extrusive igneous rock and colluvium. Ponds have formed within the colluvium. Numerous minor stream channels, primarily 1st order, are visible in the eastern portion of the mapping area, some of which begin on the valley slopes and flow to the West Fork Animas River.

The West Fork Animas River is narrow with exposed bedrock along the margins. The river flows through Quaternary deposits and igneous bedrock. Igneous rock crops out along bends within the river with the majority of outcrops on the east side of the river. Many of the outcrops have slopes greater than 40° and show hydrothermal alteration. Some of the outcrops are low-lying with rounded tops and contain visible glacial striae (Photograph 20).



PHOTOGRAPH 20. Photograph of glacial striae at California Gulch with field notebook parallel to striae, facing north-northeast.

Adjacent to the western side of the West Fork Animas River is the California Gulch fen. The fen is situated on sloping ground adjacent to a large igneous rock outcrop to the southwest, a smaller one in the center portion of the fen, and a third outcrop on the northeast lower side of the fen.

The upper portion of the fen contains a pond with small, empty burrows upslope of it (Photograph 21).

PHOTOGRAPH 21. Photograph of empty burrows upslope of a filled pond at the California Gulch fen site. Photo taken looking to the east-southeast.

The burrows potentially contain water during times when excess water is present. At the time of analysis, the California Gulch fen was very moist at the surface. The fen gently slopes and drains to the West Fork Animas River. An orange-colored stream, which originates from a mine adit on the western portion of the valley slope, flows to the California Gulch fen. The orange-colored stream flows from the adit, over County Road

19, over a break in slope, and through the fen where it drains into the Animas River (Photograph 22).

PHOTOGRAPH 22. Orange-colored stream originating from a mine adit west of County Road 19, flowing through the California Gulch fen and into the West Fork Animas River. Photograph taken from across the West Fork Animas River.

Aside from natural landscape features, man-made features such as waste rock piles and roads are present (Photograph 23).

PHOTOGRAPH 23. View looking north-northwest at the California Gulch site. Waste rock and County Road 19 are visible.

County Road 19 parallels the West Fork Animas River along the western valley side and forks southwest of the fen, leading off-road vehicles around a 180° bend and up the valley side. East of the fork in the road are three mine adits southwest of the fen, approximately 5 m to 35 m above County Road 19. The northernmost mine adit nearest the road is the one that contains an orange-colored stream flowing from it (Photograph 24).

PHOTOGRAPH 24. View of a closed mine tunnel with orange-colored water flowing from it.

Glacial Lake Ironton

The Glacial Lake Ironton fen complex is characterized by a valley with slopes covered in trees. The Glacial Lake Ironton fen complex formed in the alluvium on the bed of a former glacial lake (APPENDIX C). The sampling site is west of Highway 550 and in an area surrounded by willow shrubs. The sampling site resides west of Red Mountain Creek, which flows northeast through the eastern portion of the former glacial lake. Red Mountain Creek and the Glacial Lake Ironton study site are separated by Highway 550, which traverses right of center through the former glacial lake.

Glacial Lake Ironton slopes are fairly gentle in rise with the western portion of the mapping area being covered entirely by trees, whereas the eastern portion is fairly steep, but also covered with trees. Most exposed bedrock is hidden by the trees, but two extrusive igneous rock outcrops are visible on the western portion of the mapping area. Trees are encroaching on the former glacial lake on either side of the valley.

The eastern portion of the valley contains an orange-colored stream, which originates from Gray Copper Gulch on Red Mountain, and flows to the north-northeast until it enters Red Mountain Creek in the northeast corner of the study area.

Red Mountain Creek is an orange-colored stream that flows on the western portion of a former tailings pond in the study area, then to the north-northeast. In the area along the former tailings pond, the creek was straightened and lined with large cobbles (Photograph 25), now both iron coated and non-iron coated, along the sides of the stream. The creek passes under a bridge for County Road 20 (Photograph 26). Red

Mountain Creek then abruptly forms a braided stream, with gravel and sand bars, both containing iron- and non-iron coated cobbles, gravels, and sands.

PHOTOGRAPH 25. Red Mountain Creek at Glacial Lake Ironton, west of a former tailings pond, looking downstream.

PHOTOGRAPH 26. View of Red Mountain Creek at Glacial Lake Ironton, taken from County Road 20, looking upstream.

The western edge of Red Mountain Creek contains bank-cut sides along with convex and concave slopes. As the gradient decreases, the banks become tree-lined on both sides of the stream. Between the stream and Highway 550 reside gravels and shrubs in sporadic locations.

The areas east and west of Highway 550 were dry with areas of mudcracks (Photograph 27) and gravels. Moving nearer the northern edge of the mapping area, two ponds with streams flowing north become apparent and grassy vegetation increases, with wetlands beginning to appear just north of the mapping area.

PHOTOGRAPH 27. Mudcracks northwest of the Glacial Lake Ironton sampling site.

In addition to natural landforms and features, anthropogenic processes are present. Northwest of the former tailings pond are two mine adits, which sit above an off-highway vehicle trail and County Road 20W, both of which follow along the western boundary of the former glacial lake. Other human-made features are visible, such as gravels from the road, which have traveled downslope to the valley floor. East of Highway 550 and Red Mountain Creek is a small gravel parking lot for off-road vehicles, which leads to numerous trails up the eastern portion of the mapping area. North of this area, along Highway 550, is a culvert that is draining orange-colored water from the western portion of the valley bottom to the eastern half (Photograph 28).

PHOTOGRAPH 28. Culvert under Highway 550 draining orange-colored water from the west side to the east side of the former glacial lake.

From the southern edge of the mapping area to the northern culvert, no other culverts or outlets are seen that would allow the migration of water laterally across the valley bottom. Highway 550 impedes flow along with the large, former tailings pond.

Howardsville

The Howardsville fen (Photograph 29) resides in an alluvium-filled valley with steep cliffs to the west and forested areas to the east (APPENDIX C). The geomorphology of the area is dominated by stream processes. The Animas River flows to the southwest in the study area, west of the Howardsville fen. The river is characterized by alluvial deposits along with sand and gravel bars.

PHOTOGRAPH 29. The Howardsville terrace fen, with a beaver dam visible in the center of the photograph. Photograph was taken looking upstream of the Animas River valley.

The western portion of the geomorphic map (Photograph 30) represents cliffs covered in talus, specifically alluvial talus. Alluvial talus consists of rocks of a variety of sizes and shapes, carried by rain and snow melt to valley floors (White, 1981). The talus extends onto the alluvium-filled valley floor.

PHOTOGRAPH 30. Photograph of Howardsville fen with steep cliffs to the north-northwest along with talus and small trees on the slopes.

The eastern portion of the mapping area represents two debris flows. Both extend onto the valley floor, into the Howardsville fen.

The Howardsville fen is northwest of Galena Mountain and east of the Animas River. The fen is situated on very wet alluvium (at the time of analysis) and is almost entirely surrounded by open water, with the exception of the southeast portion, which is along the eastern edge of the valley. A beaver dam is present within the waters of the fen and is surrounded by fine-grained sediment, gravel, and cobble. Numerous water flow paths start from the fen and extend towards the river. In addition, streams in the northern portion of the mapping area flow towards the Animas River.

County Road 2 was constructed through the debris flow and talus on the eastern half of the valley and parallels the Animas River. During heavy rain mudslides cover the roadway. Additionally, an off-road vehicle trail parallels the western half of the valley and cuts through the rockfall and alluvial talus.

Red Mountain Pass North

Dominated by glacial and hydrologic processes, Red Mountain Pass North is surrounded by extrusive igneous rock, roche moutonnée, and alluvium. The Red Mountain Pass North fen resides on alluvium (APPENDIX C). The fen complex contains three ponds, two small ones in the upper portion, and one large pond in the lower portion. The fen is surrounded by extrusive igneous rock.

West of the fen are numerous roche moutonnée. Potential water flow paths pass around them. Bedrock and loose debris are exposed at the base of this are with concave, convex, and slopes greater than 40°. Slopes are gentler to the east, but within the southeastern portion of the map are breaks in slope along hillsides and rock outcrops, with an area of rockfall. Mineral Creek flows through the study area to the lower and largest pond in the fen complex. Mineral Creek then flows through a culvert under county Road 31 and to the northeast. The upper reach of the creek flows parallel to Highway 550, which cuts through the fen complex.

Altered igneous rock, associated with ore, is present east of the Red Mountain Pass North fen. An off-highway vehicle trail is accessed via County Road 31 and traverses southeast, up the altered igneous rock. The road leads to a deforested area adjacent to Hero Mine.

Human-made features other than mines and roads are visible. North of the fen is an area where gravel has been deposited alongside County Road 31 (Photograph 31).

PHOTOGRAPH 31. Piles of gravel along County Road 31, north of the Red Mountain Pass fen. View of Red Mountain in the background.

An additional old gravel trail, now only suitable for walking, can be followed from County Road 31, south of the two northern ponds, and adjacent to Mineral Creek (Photographs 32 and 33). The gravel trail traverses a small hummock that cuts through the north-central portion of the fen complex, and allows water to seep through it towards the lower pond.

PHOTOGRAPH 10. Gravel trail, primarily covered in grasses, along the margin of Red Mountain Pass North fen. Photograph taken looking to the west-southwest.

PHOTOGRAPH 33. Gravel on a trail along the margin of the Red Mountain Pass North fen.

Red Mountain Pass South

The Red Mountain Pass South fen is formed in alluvium beneath steep slopes containing igneous rock and roche moutonnée to the west and mining activities to the east (APPENDIX C). The fen complex contains two streams, one originating in the northeast corner of the fen and the other in the southwest corner, that converge via a culvert and are channeled under Highway 550 to Mineral Creek. The converged streams flow south, parallel to Highway 550.

Along the north-northwest portion of the fen are concave, convex, and slopes steeper than 40°. Igneous rock and loose debris are visible and transported downslope.

Above the edge of the fen reside many flow paths, areas of exposed igneous rock, and depressions between roche moutonnée. Along the eastern portion of the fen runs Highway 550 which includes an abrupt change in slope along the roadway that allows gravels to enter the fen. East of Highway 550 are steep slopes greater than 40°.

County Road 16 follows the western edge of the fen up and into the steep slopes to the south and west. An old gravel road cuts through the center of the fen and contains human-made ditches on either side. One ditch contains flowing water and intersects with one stream in the southern portion of the fen and one stream flowing in the eastern portion, parallel to Highway 550. The streams and ditch intersect in the southwest corner of the fen and flow into Mineral Creek.

Northeast of the fen is a gravel area to the west of Highway 550 for parking off-road vehicles. East of the fen and Highway 550 is County Road 14, which travels to the south, away from Longfellow Mine.

Longfellow Mine is situated above an orange-colored retention pond that has surface water entering it from the base of the Longfellow Mine area. To the east are very steep slopes with boulders, cobbles, and gravels traveling down slope from exposed quartz-latite bedrock.

Koehler Tunnel is visible from County Road 14 at the base of the steep and exposed bedrock. An orange-colored stream flows from the tunnel to the retention pond. Across from the retention pond is the base of a hill composed of extrusive igneous rock. The origin of the water is unknown, but a stream of orange-colored water flows around the base of the hill to the north then flows into a ditch parallel to Highway 550 and joins Mineral Creek, which then flows to the southwest.

MORPHOMETRY AND GRAIN-SIZE

Upon analyzing one soil profile from each of the five fen sites and comparing overall grain-size to fen type, a correlation was found. Valley-bottom and terrace fens contain medium- to coarse-grained sand and valley-side fens contain coarse- to very coarse-grained sand particles.

A soil sample 65.5 cm in depth was analyzed for grain-size at California Gulch and a soil sample 70 cm in depth was analyzed for Red Mountain Pass North. Soil profiles at California Gulch and Red Mountain Pass North contain coarse to very-coarse sand grains. Both fens are considered valley-side fens.

A shallow soil sample 16 cm in depth was sampled at Glacial Lake Ironton and exhibits a coarse-grained texture. Red Mountain Pass South and Howardsville soils were analyzed to a depth of 68 cm and 36 cm, respectively, and contain medium-grained sand. The Glacial Lake Ironton sample does not contain as much soil as the other samples, therefore results from Glacial Lake Ironton may not be reliable.

Glacial Lake Ironton and Red Mountain Pass South are both considered valley-bottom fens, whereas, Howardsville is considered a terrace fen. Valley-bottom and terrace fens contain medium-grained sand particles.

Overall, it appears that valley-side fens can be classified as having coarse-grained sand particles and valley-bottom and terrace fens can be classified as having medium-grained sand particles.

One would suppose that larger grain-sizes would be found in valley-bottom fens and assume that the larger grains were funneled to the flatter surface; however, this appears to be incorrect, though a larger number of samples are needed to confirm this postulation.

In terms of valley-side fens, geomorphic maps in APPENDIX C show the location where soil profiles were extracted at California Gulch and Red Mountain Pass North relative to local geomorphic features. California Gulch slopes approximately 2º where the sample was extracted. The sample location is less than 50 m from a major break in slope. Red Mountain Pass North slopes 1º to 4º, with a slope closer to 1º where the sample was extracted.

The possibility arises that surface water flow and slope influence the deposition of larger grain-sizes in the valley-side fens. The velocity of water slows when it reaches a break in slope and likely deposits coarse grains on the sloping fens.

The valley-bottom and terrace fens have slopes approximately 1º to 2º where samples were extracted. However, in contrast, the location of where the samples were extracted is a much greater distance away from the valley sides, which slope up to 8º.

Fine- to medium-grained sediment is deposited at the terrace fen, Howardsville, and at the valley-bottom fens, Glacial Lake Ironton and Red Mountain Pass South, overall medium-sized grains are deposited. The potential exists for water to be able to carry medium-grained particles to the fens at these sampling localities, but not coarser-grains.

It appears that an abrupt change in slope and surface water flow effect the size of grains that will be deposited in each type of fen.

GEOCHEMISTRY

Binary Mixing

Pb isotopes are essential for use as environmental tracers in wetland sediment. Pb is found to separate from parent uranium and thorium isotopes when a mineral deposit forms (Church et al., 2007b). The isotopic composition of Pb within the related hydrothermal fluid is considered to be "frozen" in the sulfide minerals, which is generally in the form of galena (Church et al., 2007b).

To determine the presence of binary mixing (mixing of Pb from two sources) at each study site, a graph of $^{206}Pb/^{207}Pb$ versus 1/Pb (ppm^{-1}) was plotted along with $^{206}Pb/^{207}Pb$ versus $^{206}Pb/^{208}Pb$. Additional plots include Pb concentration and isotopic ratio versus depth, which were plotted to support findings of ore versus non-ore mineralized Pb. Simple linear regression (best-fit-line method) was performed to determine whether there was the presence of binary mixing at each sample site.

Overall, by plotting $^{206}Pb/^{207}Pb$ versus 1/Pb and calculating the coefficient of determination, r^2 (Table 7) at each study site, it was determined that data from Glacial Lake Ironton and Red Mountain Pass are not significant. At the Howardsville and Red Mountain Pass North sites, variability is significant and binary mixing is supported by plotting $^{206}Pb/^{207}Pb$ versus 1/Pb and determining the value of r^2.

TABLE 7
Analysis of coefficient of determination for study sites.

SAMPLE	r^2 of $^{206}Pb/^{207}Pb$ vs. 1/Pb	r^2 of $^{206}Pb/^{207}Pb$ vs. $^{206}Pb/^{208}Pb$
RMP N	0.8	0.9
RMP S	0	0.3
HV	0.5	0.7
GLI	0.1	0.5
CG	N/A	0.6

Binary mixing is found in fen sediment in the Red Mountain Pass North fen site. An r^2 value of 0.83 strongly supports the presence of binary mixing of one ore and one non-ore mineralized Pb, which is consistent with the $^{206}Pb/^{207}Pb$ and concentration versus depth graph. At Howardsville, an r^2 value of 0.50 points towards, but does not strongly support the presence of binary mixing. There are likely more than two ores present with some non-ore mineralized Pb.

Additionally, in terms of $^{206}Pb/^{207}Pb$ versus $^{206}Pb/^{208}Pb$, Red Mountain Pass North contains mixing of Pb from two different sources, whereas Howardsville contains the mixing of Pb from one to two sources. Values of r^2 at Red Mountain Pass North and Howardsville are 0.85 and 0.65, respectively. In summary, Red Mountain Pass North represents fen sediment that contains the mixing of ore mineralized and non-ore mineralized Pb. The Howardsville fen sediment likely contains ore mineralized Pb from more than two sources, with some non-ore mineralized Pb. These assumptions are made based on isotopic data and concentration, along with r^2 values, with high r^2 values indicating binary mixing and low values indicating more than two sources of Pb.

In analyzing the Howardsville data in more detail, a visible increase in Pb concentration versus depth is seen at approximately 15 cm and a decrease at 5 cm, with overall slight changes in isotopic ratios of ~1.198-1.210. At these depths, a change in the source of ore mineralized Pb likely occurs, and can be associated with the years 1932 and 1985, respectively, based on a depositional rate of 0.19 cm/yr. Keep in mind that there is uncertainty based in the Pb and Cs chronology, i.e., based on ^{137}Cs data, the year 1963 (+/- 2) should be associated with 13 cm, but based on a depositional rate of 0.19 cm/yr, the year 1943 is derived.

A constant depositional rate should not be assumed at each study site, but for the purpose of this study it is assumed, and at 15 cm and 5 cm, the years 1932 and 1985 represent a change in deposition of Pb in the form of ore-mineralized Pb.

At Red Mountain Pass North, an increase in Pb concentration is visible at 10 cm depth and again at 5 cm depth. A large change in isotopic ratios is visible and ranges from ~1.180-1.210 at Red Mountain Pass North. It appears that at 5 cm there is a change from the deposition of sediment containing non-ore mineralized Pb to ore mineralized Pb. The year 1973 is associated with 5 cm depth, and 10 cm depth is associated with the year 1934 (based on ^{137}Cs data and a depositional rate of 0.13 cm/yr). Thus, the years 1934 and 1973 represent times when a change in deposition of ore and non-ore mineralized Pb occurred.

Conclusions supporting these data can be made by comparing the proximity of each fen to mines, smelters, tunnels, and adits. Red Mountain Pass North and is surrounded by mining features, which drain to the fen. The potential for windblown and water eroded Pb is likely causing the presence of multiple ores at the Red Mountain Pass North fen.

Hero Mine is located directly adjacent to the Red Mountain Pass North fen, with Red Mountain to the east. An assumption can be made that the ore mineralized Pb, indicated by plotting $^{206}Pb/^{207}Pb$ versus 1/Pb, is coming from the Hero Mine, which is topographically higher and to the east of the fen complex. It is probable that the non-ore mineralized Pb originates from Red Mountain and was carried to the fen via water or wind transport.

The Howardsville fen complex is located in the Animas River valley, between the former mining towns of Eureka and Howardsville. Like Red Mountain Pass North, the Howardsville fen is surrounded by multiple mines, smelters, tunnels, and adits, which drain to the fen complex and Animas River flowing to the west of the fen. It is highly likely that multiple ore mineralized Pb sources mixed and were deposited in the fen sediment. There is the potential for some non-ore mineralized Pb, possibly from Galena Mountain to the southeast, and ore-mineralized Pb from nearby mining features to be transported to the fen by wind.

Comparative Data

Data by Church et al. (2007b) was used to calculate $^{206}Pb/^{207}Pb$ and $^{206}Pb/^{208}Pb$ ratios pre- and post-mining. Sediment from streambeds of the Animas River, Cement Creek, and Mineral Creek were collected and analyzed for Pb by Church et al. (2007b). Additionally, pre-mining sediment was collected and analyzed for Pb. Pb concentrations increased post-mining in comparison to pre-mining geochemical data.

A plot of ^{206}Pb/^{207}Pb versus ^{206}Pb/^{208}Pb pre-mining indicates a linear relationship with values of ^{206}Pb/^{207}Pb ranging from ~1.180-1.220 and ^{206}Pb/^{207}Pb values ranging from ~0.484-0.496 (Figure 16).

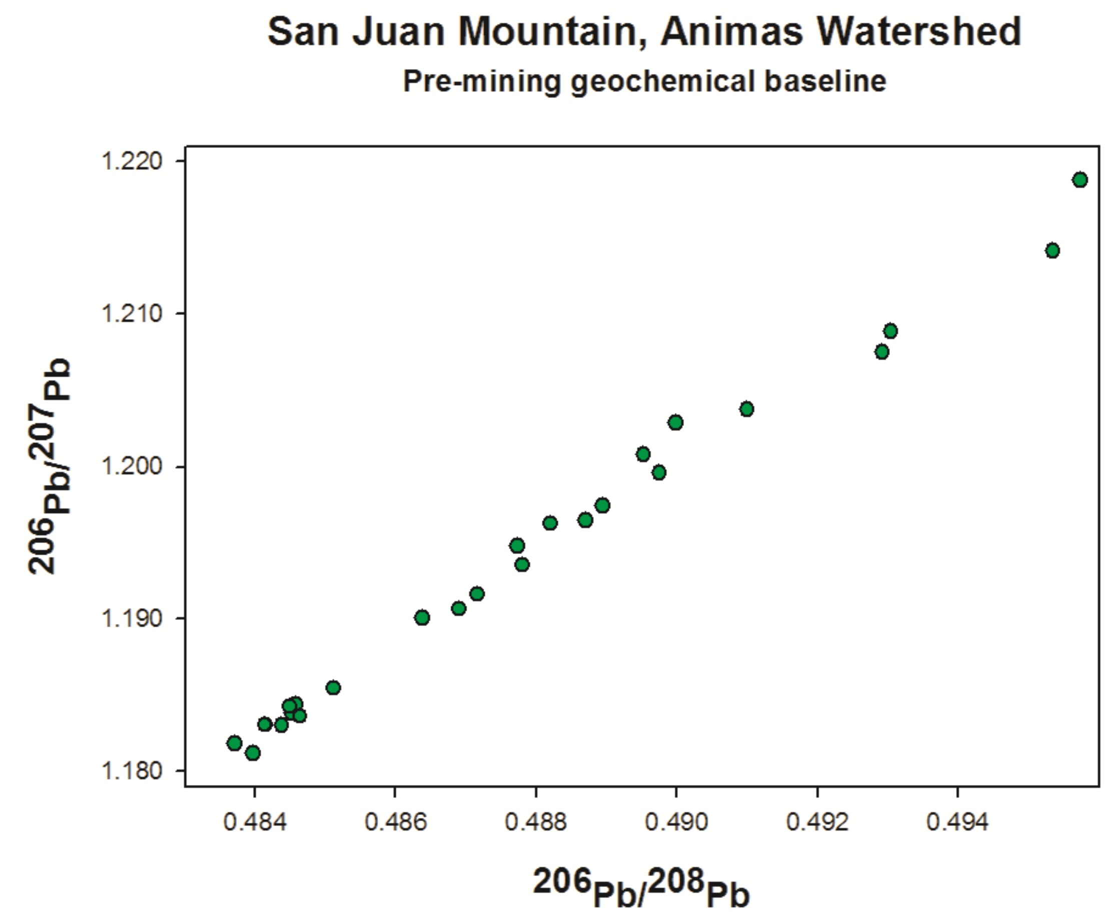


FIGURE 16. Plot of ^{206}Pb/^{207}Pb and ^{206}Pb/^{208}Pb pre-mining based on data by Church et al. (2007b).

Additionally, a linear relationship is seen in a plot of $^{206}Pb/^{207}Pb$ versus $^{206}Pb/^{208}Pb$ post-mining with $^{206}Pb/^{207}Pb$ values ranging from ~1.176-1.192 and values of $^{206}Pb/^{208}Pb$ ranging from ~0.483- 0.488 (Figure 17).

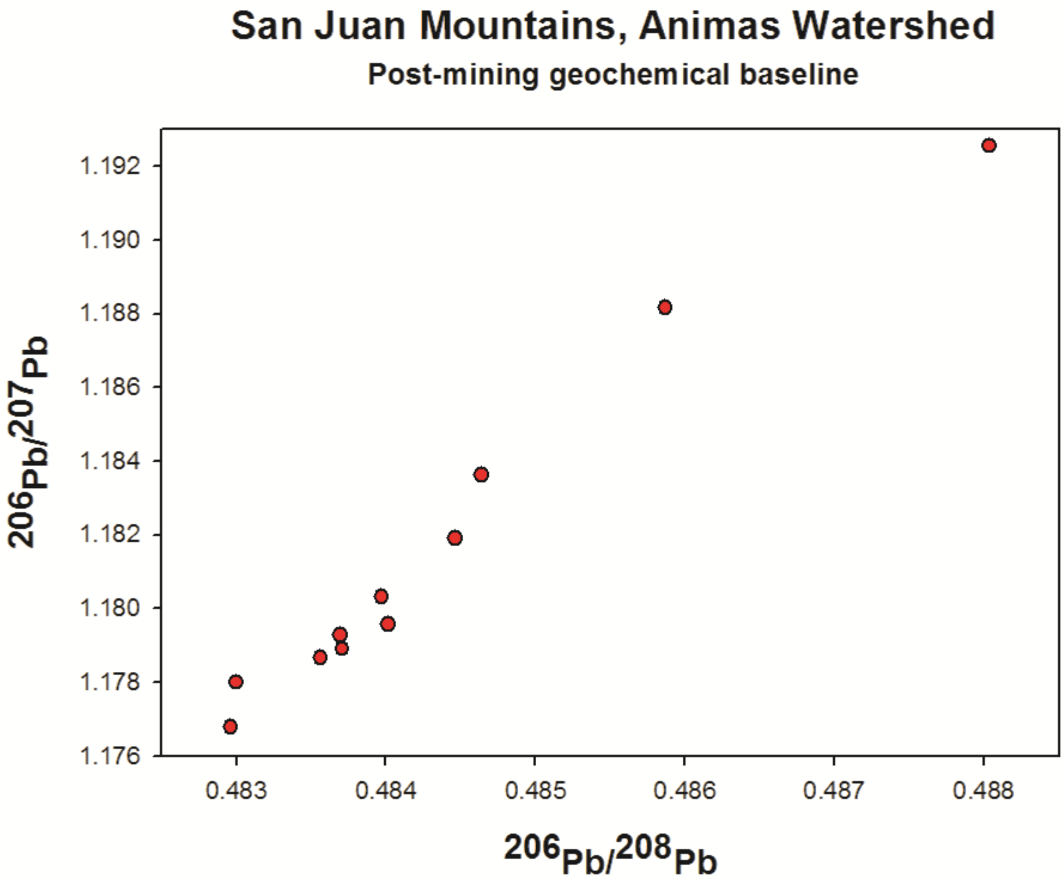


FIGURE 17. Plot of $^{206}Pb/^{207}Pb$ and $^{206}Pb/^{208}Pb$ post-mining based on data by Church et al. (2007b).

In comparison, a plot of $^{206}Pb/^{207}Pb$ versus $^{206}Pb/^{208}Pb$ for the five study sites in this research indicates values of $^{206}Pb/^{207}Pb$ range from ~1.185-1.210 and values of

^{206}Pb/^{208}Pb ranging from ~0.475-0.500. A linear relationship is seen at Red Mountain Pass North with a moderate linear relationship at Howardsville, as indicated by r^2 values.

A plot from data collected by Church et al. (2007b) of ^{206}Pb/^{207}Pb versus 1/Pb, pre- and post-mining (Figures 18 and 19) reveals greater concentrations of ore-mineralized Pb post-mining. Ratios of ^{206}Pb/^{207}Pb range from ~1.180- 1.220 pre-mining and ~1.176-1.192 post-mining. Pre-mining 1/Pb (ppm^{-1}) concentrations range from ~0.002-0.017, and ~0.0001- 0.0008 post-mining. This supports the findings of Church et al. (2007b) that Pb concentrations increased post-mining in comparison to pre-mining geochemical data.

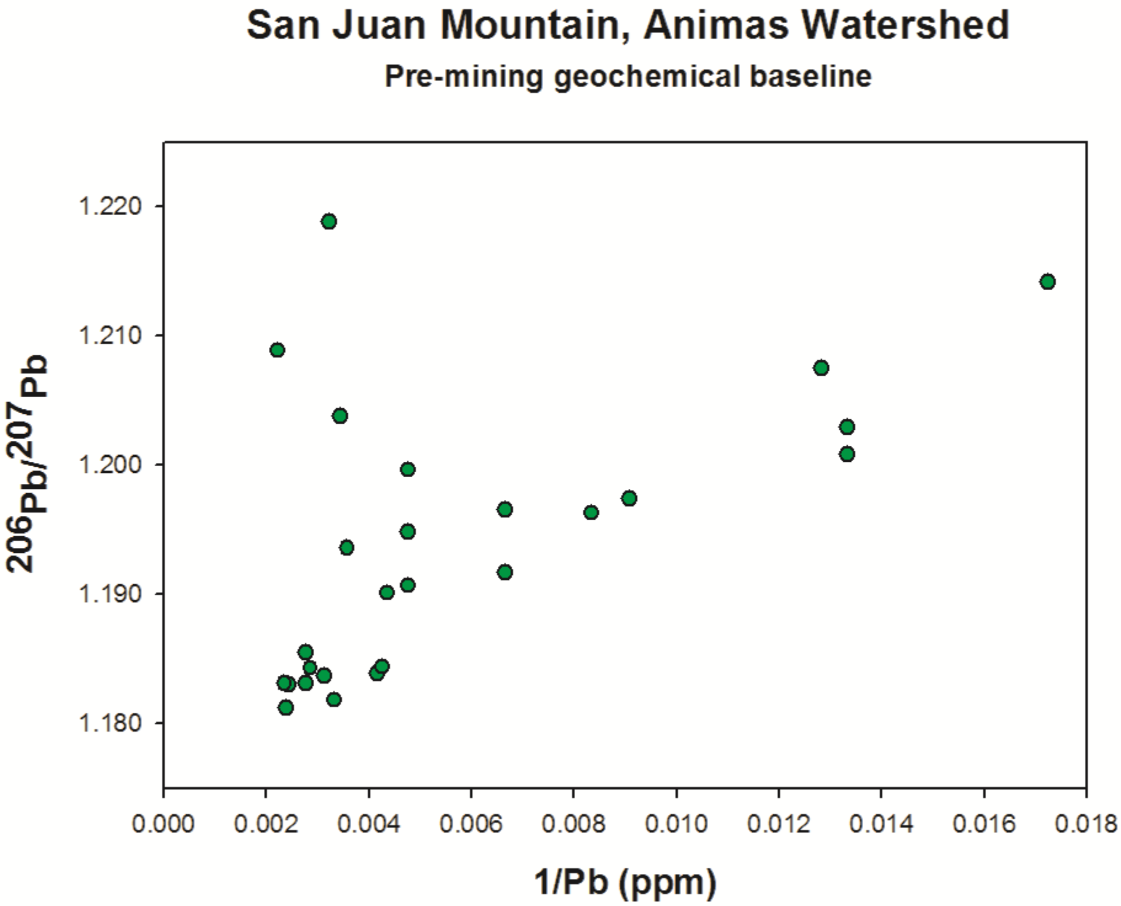


FIGURE 18. Plot of ^{206}Pb/^{207}Pb versus 1/Pb pre-mining based on data by Church et al. (2007b).

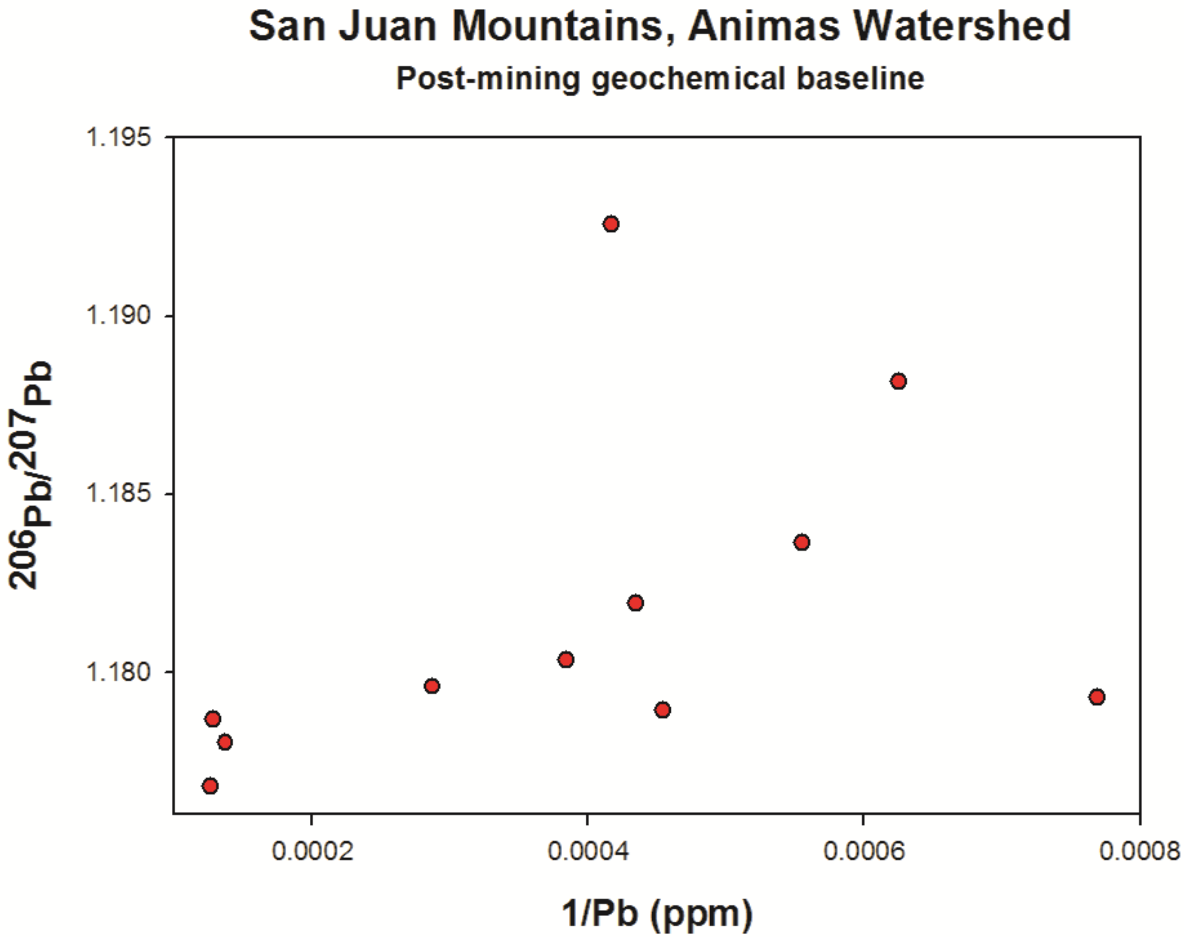


FIGURE 19. Plot of ^{206}Pb/^{207}Pb versus 1/Pb post-mining based on data by Church et al. (2007b).

In comparison, ^{206}Pb/^{207}Pb at the five study sites in this research range from 1.185-1.209. Concentrations of 1/Pb (ppm^{-1}) range from 0.0007-0.158, with the majority of concentrations of 1/Pb (ppm^{-1}) being less than 0.016. In comparison to pre- and post-mining data from Church et al. (2007b), it appears that the isotopic signature and concentration in Pb at each study site in this research are closer to the post-mining concentrations rather than pre-mining concentrations.

At the five study sites in this research, Pb appears to be coming from three sources. There appears to be a high concentration and high isotopic ratio of Pb at ~1.19. At ~1.21 a low concentration and high ratio of Pb appear along with a high concentration and low ratio of Pb. Data from Church et al. (2007b) was used to attempt to find similar isotopic signatures.

There are six sites associated with data collected by Church et al. (2007b). The sites are all upstream of Howardsville, near the former mining town of Eureka. The sites analyzed by Church et al. (2007b) have ^{206}Pb/^{207}Pb ratios between 1.182 and 1.184, and concentrations ranging from 300 ppm to 400 ppm. The isotopic ratios are lower than those currently found at Howardsville (1.198-1.208) with overall concentrations greater than that at Howardsville (98 ppm to 368 ppm).

Based on isotopic signatures at the aforementioned sites, it does not appear that the Pb from the study conducted by Church et al. (2007b) is the same as the Pb associated with this study.

^{137}Cs and ^{210}Pb

Concentrations of ^{137}Cs and ^{210}Pb in fen sediments were measured for each study site, in addition to excess ^{210}Pb. As a result of an anomaly in the data, ^{210}Pb was calculated with the removal of the first calculated value of ^{210}Pb.

Sedimentation rates based on ^{210}Pb$_{xs}$ appear to be slow prior to 1963 and then rates dramatically increase at approximately 8 cm depth. A natural break in sedimentation rate is especially visible in the Howardsville fen sediment. A natural break indicates a major event or minor events changing the sedimentation rate. The pre-1963 sedimentation rate at Howardsville is 0.06 cm/yr and post-1963 is 0.28 cm/yr; thus, the data support a dramatic change in sedimentation rates. By taking the average of the pre- and post-1963 rates (based on $^{210}Pb_{xs}$), the average rate of sedimentation is 0.17 cm/yr, which is close to the ^{137}Cs calculated rate of 0.19cm/year. In terms of other fen sites, natural breaks are also visible at Red Mountain Pass North, but more data are needed to validate pre- and post-1963 sedimentation rates.

With the analysis of ^{137}Cs and $^{210}Pb_{xs,}$ an average rate of sedimentation and age dating of horizons within fen sediment can be calculated. The Howardsville fen complex sample contained enough sediment to discern a peak in ^{137}Cs. At a depth of 9 cm a peak of 6.99 dpm/g is reached followed by 0.00 dpm/g at a depth of 13 cm. With the exception of $^{210}Pb_{xs}$ at 3 cm, the amount of $^{210}Pb_{xs}$ gradually decreases, but we do not reach a point where the value reaches zero. The fact that a value of zero is not reached, indicates depths representing a time period greater than 150 years from present.

From this information, it can be assumed that 9 cm represents the year 1963 (+/- 2 yrs) and 13 cm represents the year of 1953, before nuclear fallout became discernible. If this postulation is correct, then an average sedimentation rate of 0.19 cm/yr can be calculated based on ^{137}Cs. Although an average sedimentation rate was calculated, it is likely that sedimentation rates varied over time. Nevertheless, we can estimate an age model based on the sedimentation rates calculated. The interval at Howardsville from 0-9 cm should represent the years 2011-1964 (+/- 2 years) based on a sedimentation rate of 0.19 cm/yr. The interval from 9-31 cm and 31-36 cm likely represents the years 1964-1848 and 1848-1822, assuming an even depositional rate. But, sedimentation rates based on $^{210}Pb_{xs}$ appear to be slow prior to 1963 and then rates dramatically increase at approximately 8 cm depth.

Data for the other sample sites is not consistent enough to draw conclusions from, except for fen sediment from Red Mountain Pass North. Although there was not enough sediment to find a peak in ^{137}Cs, it can be assumed that a peak occurred after 6 cm as discerned by a sharp decline in values of ^{137}Cs and $^{210}Pb_{xs}$.

If the assumption is made that a peak in ^{137}Cs is found at all sites, the average sedimentation rate for each fen complex can be calculated. The following sedimentation rates were calculated as: California Gulch, 0.08 cm/yr; Glacial Lake Ironton, 0.08 cm/yr; Red Mountain Pass North, 0.13 cm/yr, and Red Mountain Pass South, 0.04 cm/yr.

To validate findings, the aforementioned data was compared with $^{210}Pb_{xs}$. Howardsville presents the strongest data with an average sedimentation rate of 0.19 cm/yr (based on ^{137}Cs) and 0.23 cm/yr (based on $^{210}Pb_{xs}$). California Gulch has an average $^{210}Pb_{xs}$ sedimentation rate of 0.04 cm/yr and ^{137}Cs rate of 0.08 cm/yr. Additionally, Glacial Lake Ironton represents an area with a sedimentation rate of 0.05 cm/yr based on $^{210}Pb_{x}$ and 0.08 cm/yr relative to ^{137}Cs testing. Calculations for the other study sites do not present strong evidence for a valid ^{137}Cs sedimentation rate based on $^{210}Pb_{xs}$ values.

When looking at sedimentation rates, especially when they appear to be slower pre-1963 and faster post-1963, a question arises: what is causing a difference in sedimentation rates at each site? It appears that one major event or multiple smaller events likely occurred in the mid-to-late sixties or early-to-mid seventies.

In terms of what is responsible for an increase in sedimentation rates at Howardsville post-1963 based on the availability of data, it is possible that with flooding of the Animas River north of Howardsville, tailings and other products of mining were introduced into the river system and deposited at the edge of the terrace where the Howardsville fen resides. A dam break resulting from melting snow pack between 1973 and 1974, released tons of tailing and mud into the Animas River, which could have been deposited at the Howardsville fen site.

Location appears to play a role in sedimentation at fen sampling sites. The Howardsville fen formed on a terrace, which is surrounded by steep valley walls and is often inundated during large flooding events. The location of this fen allows for an influx of sediment to enter the fen, likely causing a greater sedimentation rate, and a differing texture, in comparison with the other sample sites.

The soil profile at Howardsville has an overall medium-grain sand texture. In the subsamples at Howardsville, texture alternates (beginning at the surface moving downward) from coarse-grained sand, medium-grained sand, to fine-grained sand. Different flooding events and downslope movement of material (i.e., mudslides during large-rain events) could be the reason for differences in grain-size.

Red Mountain Pass North is located on a valley side where materials are often being transported via water flow and aeolian transport downslope and through the fen, which would explain an additionally high sedimentation rate. Grain-size at Red Mountain Pass North ranges from coarse-grained at the surface to very-coarse grained at depth.

The soil profile at California Gulch is composed of coarse-grained sand. The fen receives input from sediment from the valley sides, but the valley sides contain much more bedrock and much less sediment than is available at Howardsville. Thus, a lesser amount of fine-grained sediment is available for the California Gulch fen.

The Glacial Lake Ironton soil profile consists of coarse-grained sand. The fen site is susceptible to surface water flow and the input of sediment from either the western edge of the former glacial lake area, or windblown sediment from the eastern half. Highway 550 prevents material from being deposited from the eastern half of the former glacial lake to the western half and vice versa. It appears that windblown sediment is not the primary mode of deposition of material.

The soil profile at Red Mountain Pass South has alternating textures of coarse-grained sand at the surface to medium-grained sand at depth, with a medium-grained texture layer within the coarse-grained texture.

Red Mountain Pass South fen is located west of Highway 550, in a valley that is surrounded by roche moutonnée with material being transported via water flow from streams and ditches in the fens and potentially gravel from the highway.

LAND USE

Land use changes such as the addition of a major highway, trails, county roads, cattle grazing, and increased precipitation could have caused a change in the sedimentation rate at each of the fen sites post-1963.

The fen study sites are all affected by anthropogenic influences such as roads, trails, and mines. By studying aerial photographs, it becomes visible that roads affect drainage patterns and impede the free-flow of materials and water across landscapes. This is visible at Glacial Red Mountain Pass North, and Red Mountain Pass South. Highway 550 traverses through Glacial Lake Ironton and Red Mountain Pass North, and appears to have possibly been built atop the eastern edge of Red Mountain Pass South.

Mining activities are apparent at each study site. Orange-colored waters containing heavy metals, such as Pb, flow from many mine adits. Orange-colored waters are seen flowing at California Gulch, Red Mountain Pass North, and Red Mountain Pass South. Adits and tunnels work as direct connections between groundwater and the surface. Water fills tunnels, which then make their way to the surface as oxidized waters that are released into the environment through openings at the surface.

Not all orange-colored streams with heavy metals can be attributed to mining. There is a need to recognize that not all destruction and deterioration results from humans and that nature plays a role. We cannot always identify the source of destruction and deterioration: anthropogenic versus natural. For example, at Glacial Lake Ironton, orange-colored waters are seen flowing from Red Mountain, which contains hydrothermally altered rock, down Grey Copper Gulch to the former glacial lake. Though orange-colored waters are flowing from Red Mountain, not all are a result of human activity.

CHAPTER VIII

CONCLUSIONS

INTRODUCTION

Changes in land use from mining to tourism appear to have a direct impact on fens in the alpine regions of southwest Colorado. Difficulties arise when attempting to draw conclusions as to what specific land use change had an effect on each fen study site, but assumptions can be made. There are ten main conclusions that can be drawn from the data.

STATEMENT OF PROBLEM

This research sought to answer two main questions: 1) What geomorphic function do fens serve in alpine environments? 2) Is land use change associated with lead (Pb) deposition in alpine fen systems?

After analyzing five alpine fen complexes within the San Juan Mountains of Colorado, it is more evident as to the association land use change has with the geomorphic function fens serve and Pb deposition

OBJECTIVES

Land use change has a direct impact on fens. Through this research the following objectives were accomplished: 1) evaluated the impact of changing land use on fens, 2) established a geomorphic classification of fens in alpine environments, and 3) determined the rate of deposition of sediment in fens. These objectives were accomplished by creating geomorphic maps to determine inputs and outputs from surrounding landforms, analyzing soil lithology and grain-size to determine sedimentary characteristics, using Pb isotopes and concentrations as indicators of source (ore mineralized Pb versus non-ore mineralized Pb), and using ^{137}Cs and ^{210}Pb$_{xs}$ from fen sediments to estimate rates of sedimentation.

CONCLUSION

Upon analyzing the topography, geology, and soil of each study site, it is apparent that they each serve a role in the function of fens. The question remains: what geomorphic function do fens serve in alpine environments? Based on analyses of data, the following can be concluded:

1) Fens serve as sources and sinks for material and act as open systems for the input and output of material, such as rock, soil, water, and heavy metals.
2) Fens record events via sedimentation.
3) Based on location and morphometric properties, such as elongation and circularity, thirty fens were classified as valley-bottom, valley-side, or terrace fens.
4) Valley-bottom fens have an average elongation value of 1.7, valley-side 2.4, and terrace 1.9. Valley-side fens are more elongated than valley-bottom and terrace fens, which exhibit similar elongation values.
5) There is not a lot of variability of isotopic ratios at sites except for Red Mountain Pass North and Howardsville.
6) Sedimentation rates based on ^{137}Cs are discernible for all study sites, excluding the Red Mountain Pass South fen site, with an overall average sedimentation rate of 0.16 cm/yr.

7) An average sedimentation rate at Howardsville is 0.19 cm/yr, along with a distinct change in sedimentation rates pre- and post-1963, 0.06 cm/yr and 0.28 cm/yr respectively.
8) There is evidence for the absence and presence of binary mixing at study sites and the presence of ore mineralized Pb and non-ore mineralized Pb, based on graphs of $^{206}Pb/^{207}Pb$ and concentration versus depth, $^{206}Pb/^{207}Pb$ versus 1/Pb, $^{206}Pb/^{207}Pb$ versus $^{206}Pb/^{208}Pb$, and linear regression values.
9) Land use change has an impact on the geochemistry of fens in alpine environments, but there is not enough evidence to correlate specific events with fen sedimentation rates.
10) Proximity of fens to mines, smelters, adits, tunnels, and hydrothermally altered rock is likely correlated to the presence of ore mineralized Pb and non-ore mineralized Pb, with the addition of ease of access of materials via water and wind erosion.

SUGGESTIONS FOR FUTURE STUDY

Much future work exists, especially in terms of determining rates of deposition of sediment, classifying fens, analyzing grain-size, and analyzing historical data such as Plat Books and population data. More data, thus more samples, are needed to verify correlations between fen type and each of these parameters.

In addition, a seismic survey can be conducted that determines depth to bedrock at a variety of fens.

Lastly, fen restoration is currently a topic of interest. A multi-variable approach should be undertaken that includes investigating soil properties, flow regime, depth to bedrock, land use change, and applied to fen restoration. Fen remediation efforts will benefit as will the scientific community.

FEN DEVELOPMENT IN THE SAN JUAN MOUNTAINS

The San Juan Mountains have undergone great changes in usage over the last two hundred years, which in turn has altered fens. Fens develop slowly and are sensitive systems. It is of the utmost importance to take these data and conclusions and apply them to fen systems to better understand the direct link between changes in land use and the effect they have on fens. Fens are dynamic, complex systems that are affected by many variables and in turn affect the environment in which they form. Fens act as sources and sinks, which provide an open system for the flow of material and energy. Fens even record events via soil deposition, though more data is needed to directly correlate layers to specific events. Characteristics of fens vary across landscapes. It appears topographic location affects elongation, and fens in the study area can be classified as valley-bottom, valley-side, and terrace fens, based on morphometric characteristics.

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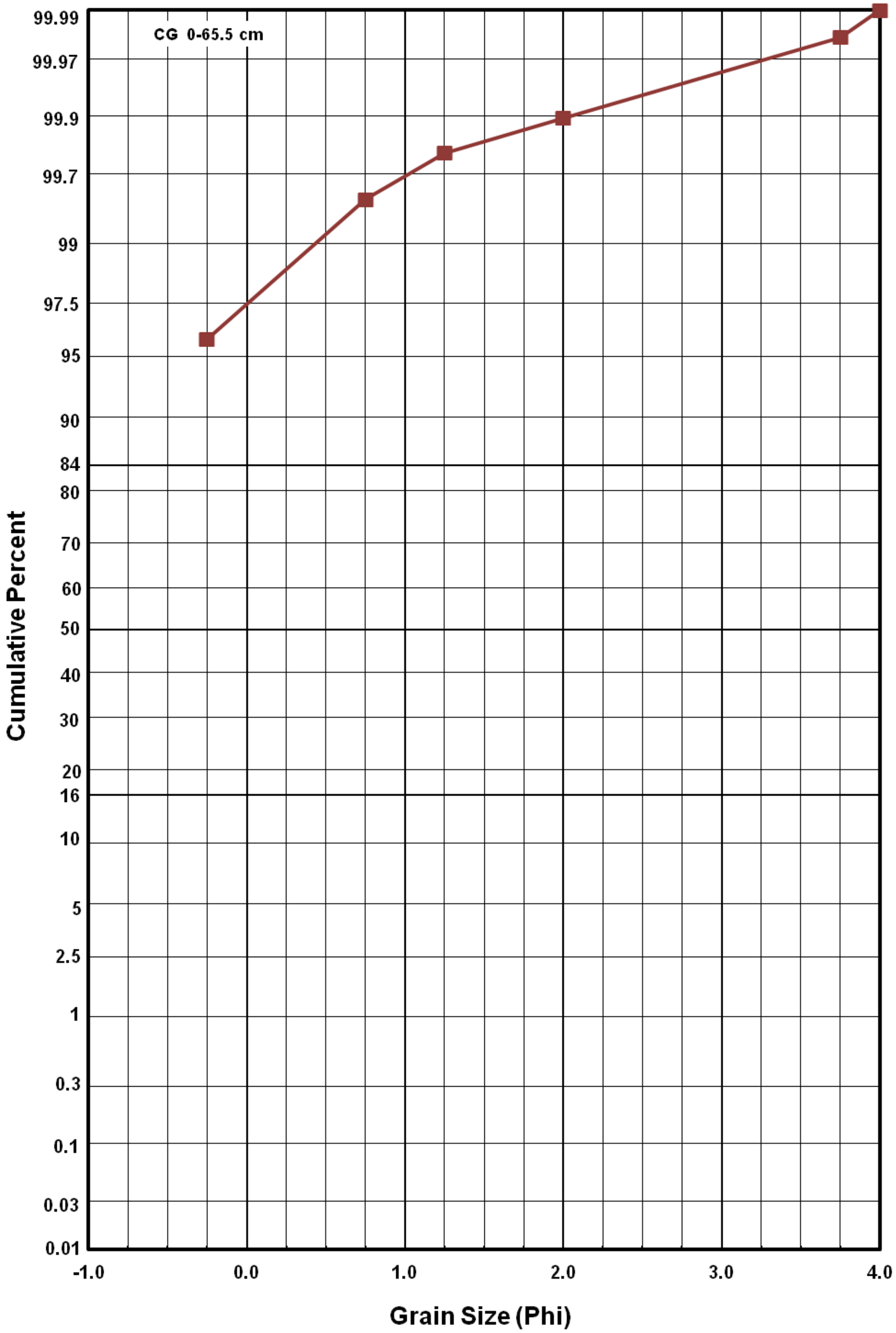
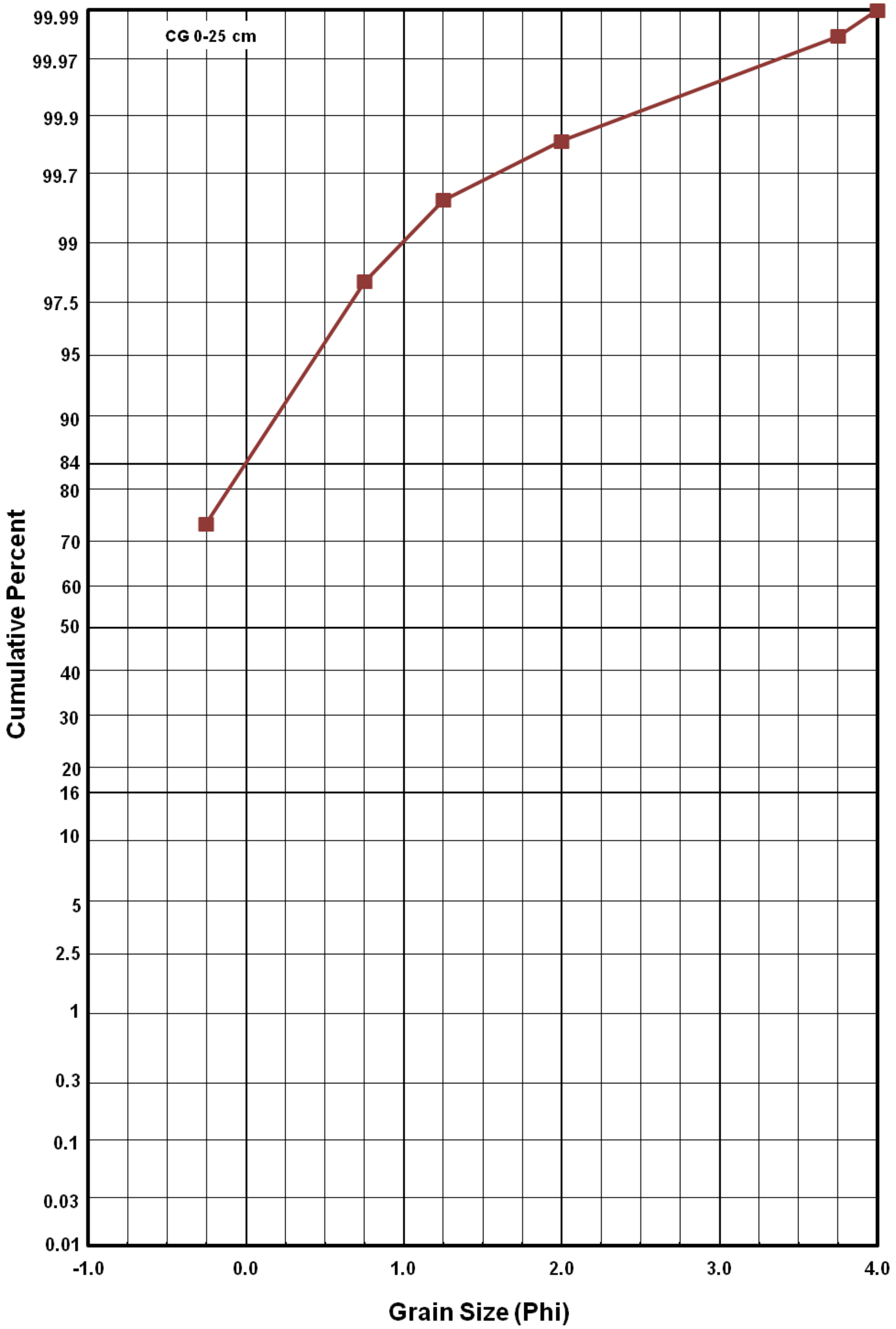
APPENDIX A

ANALYSIS OF GRAIN-SIZE DATA



CG 0-65.5 cm
Cumulative Percent
99.99
99.97
99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)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Cumulative Percent
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99.97
99.9
99.7
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97.5
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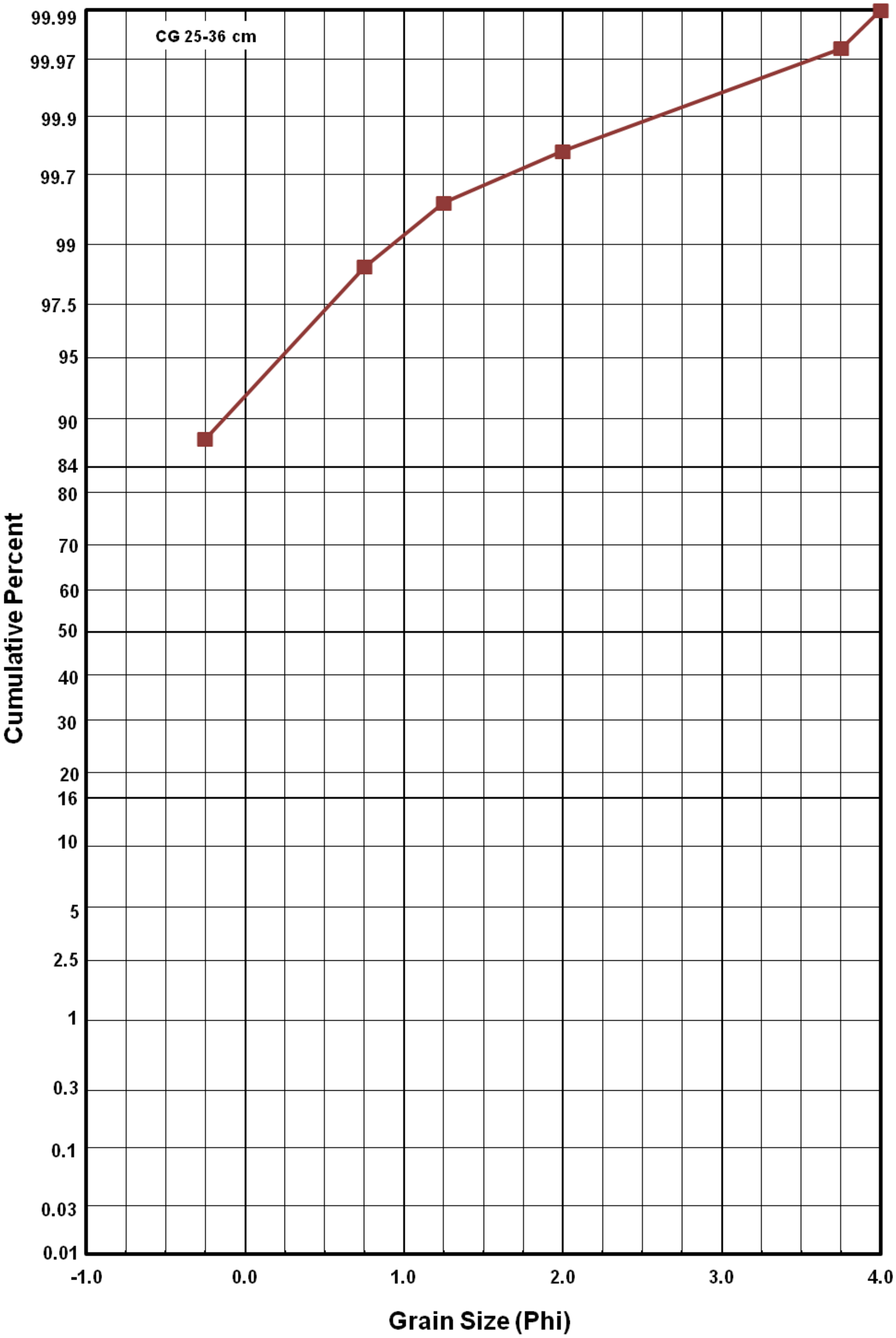
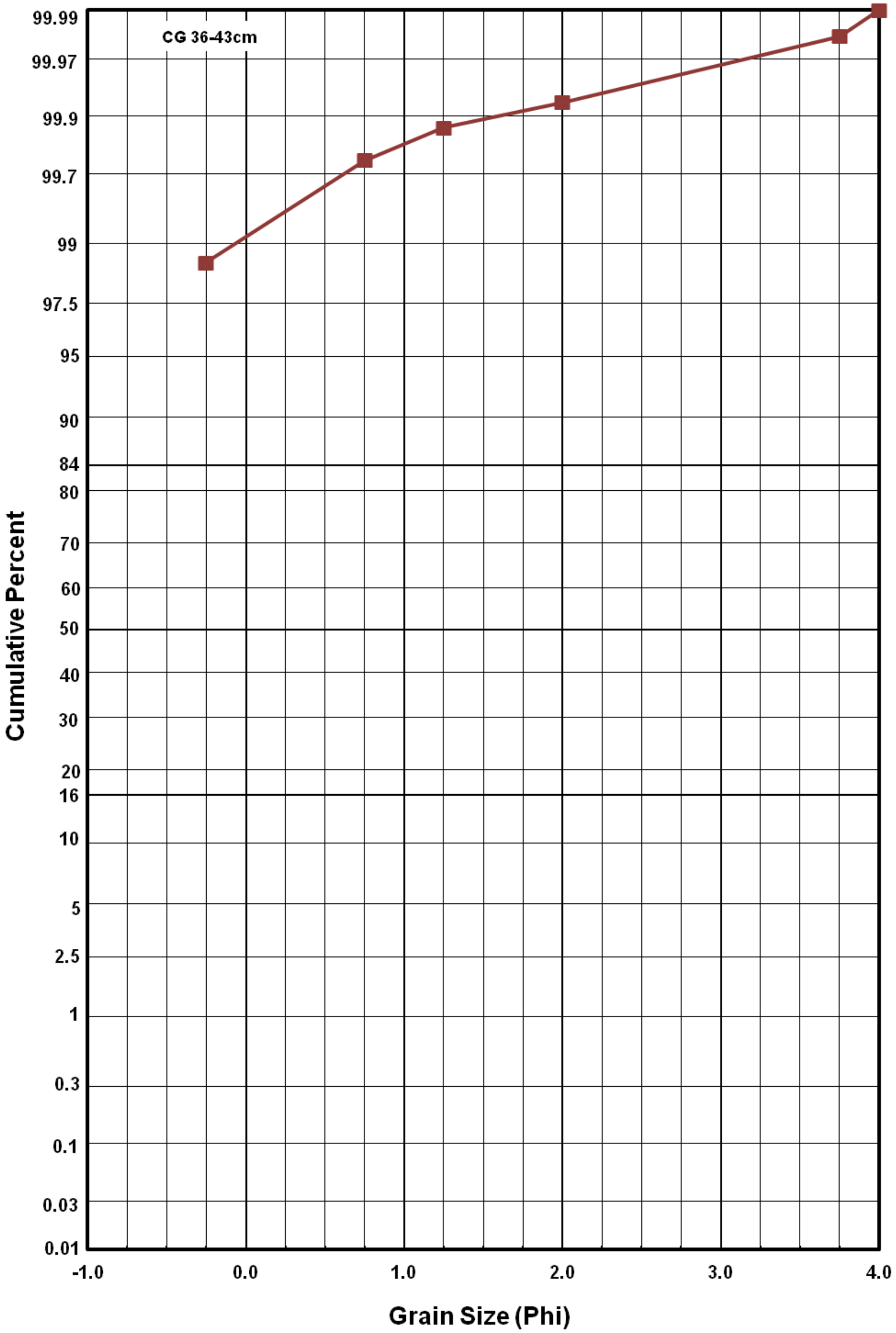
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)


CG 25-36 cm
Cumulative Percent
99.99
99.97
99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)


CG 36-43cm
Cumulative Percent
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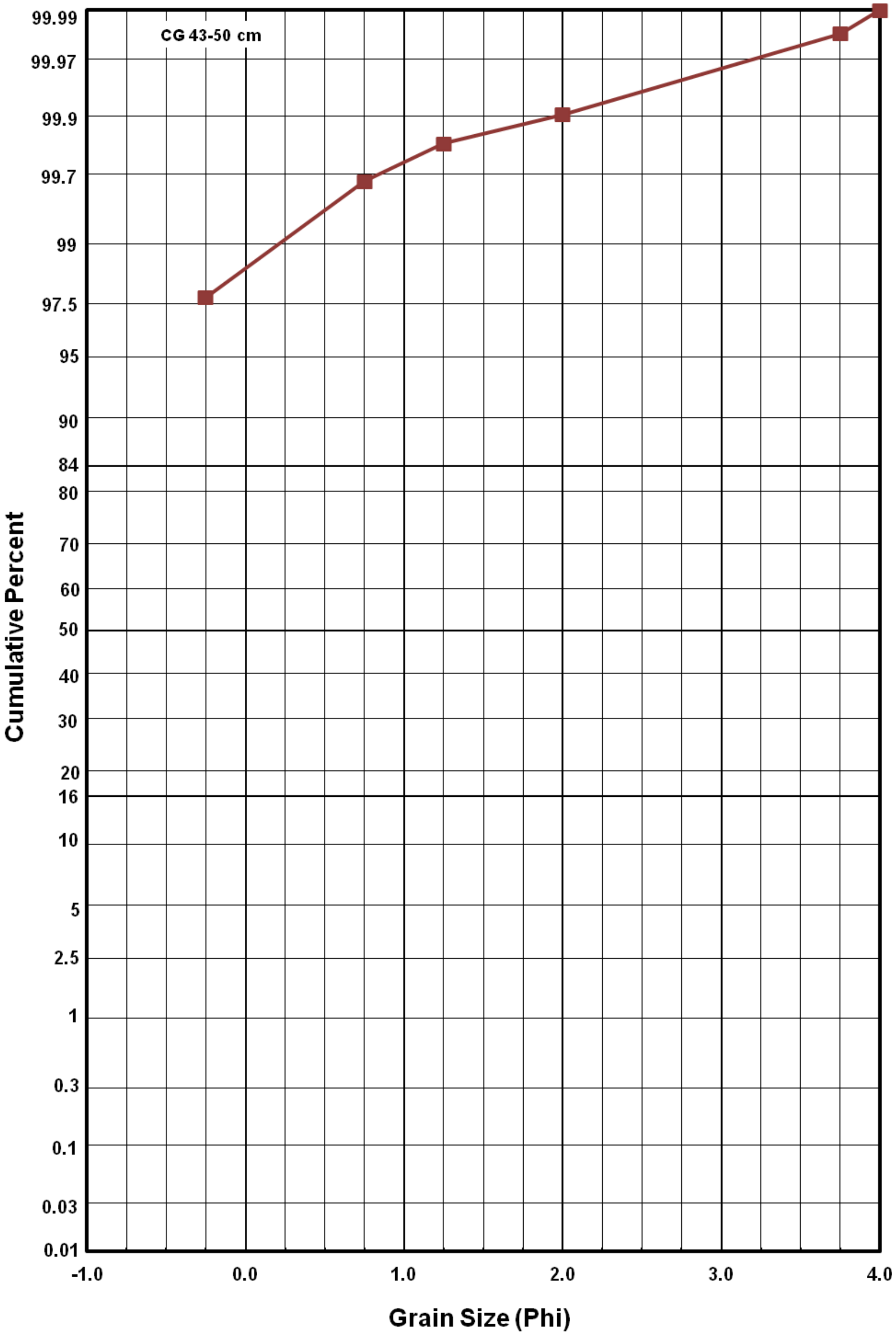
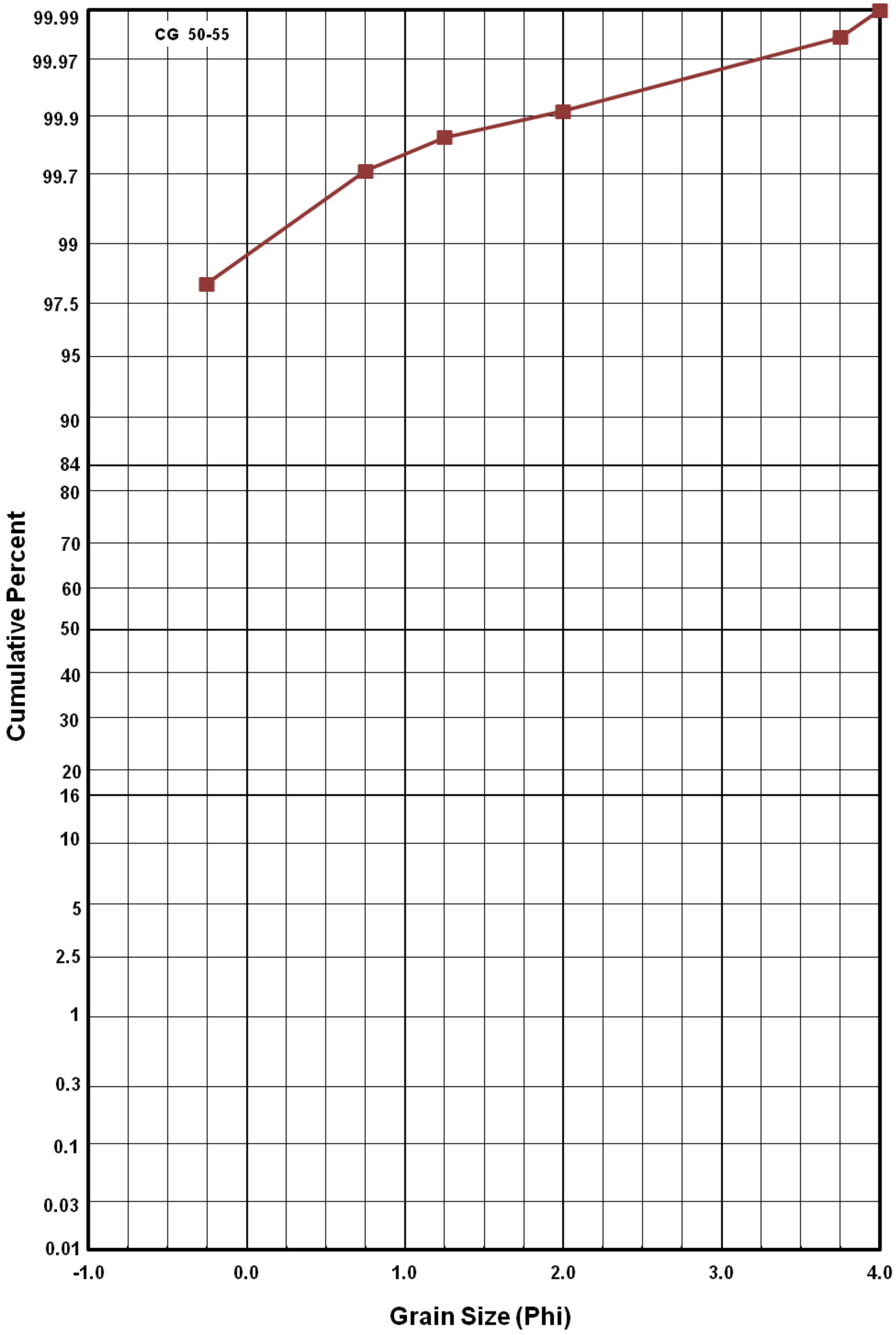
99.97
99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)


CG 43-50 cm
Cumulative Percent
99.99
99.97
99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)


CG 50-55
Cumulative Percent
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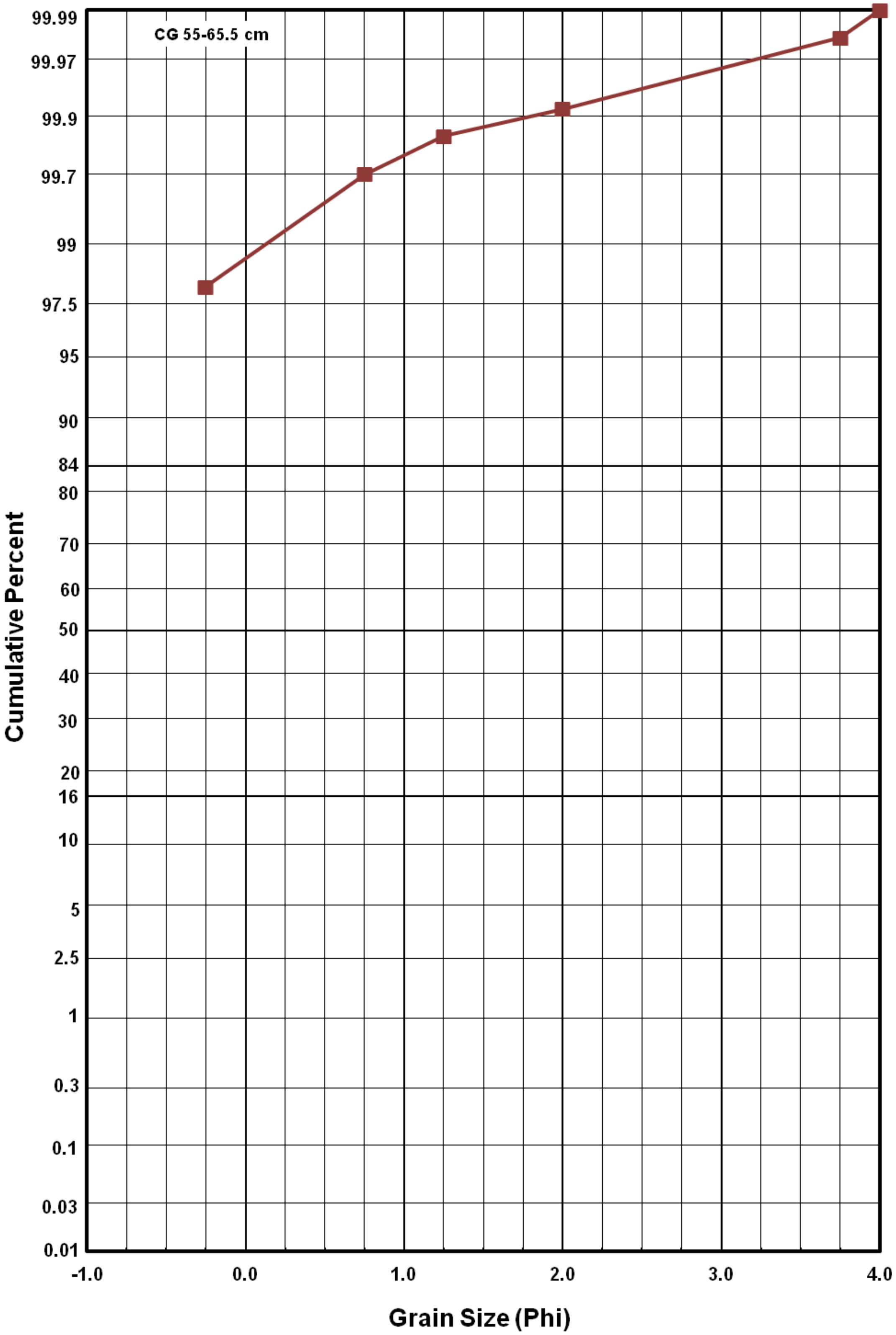
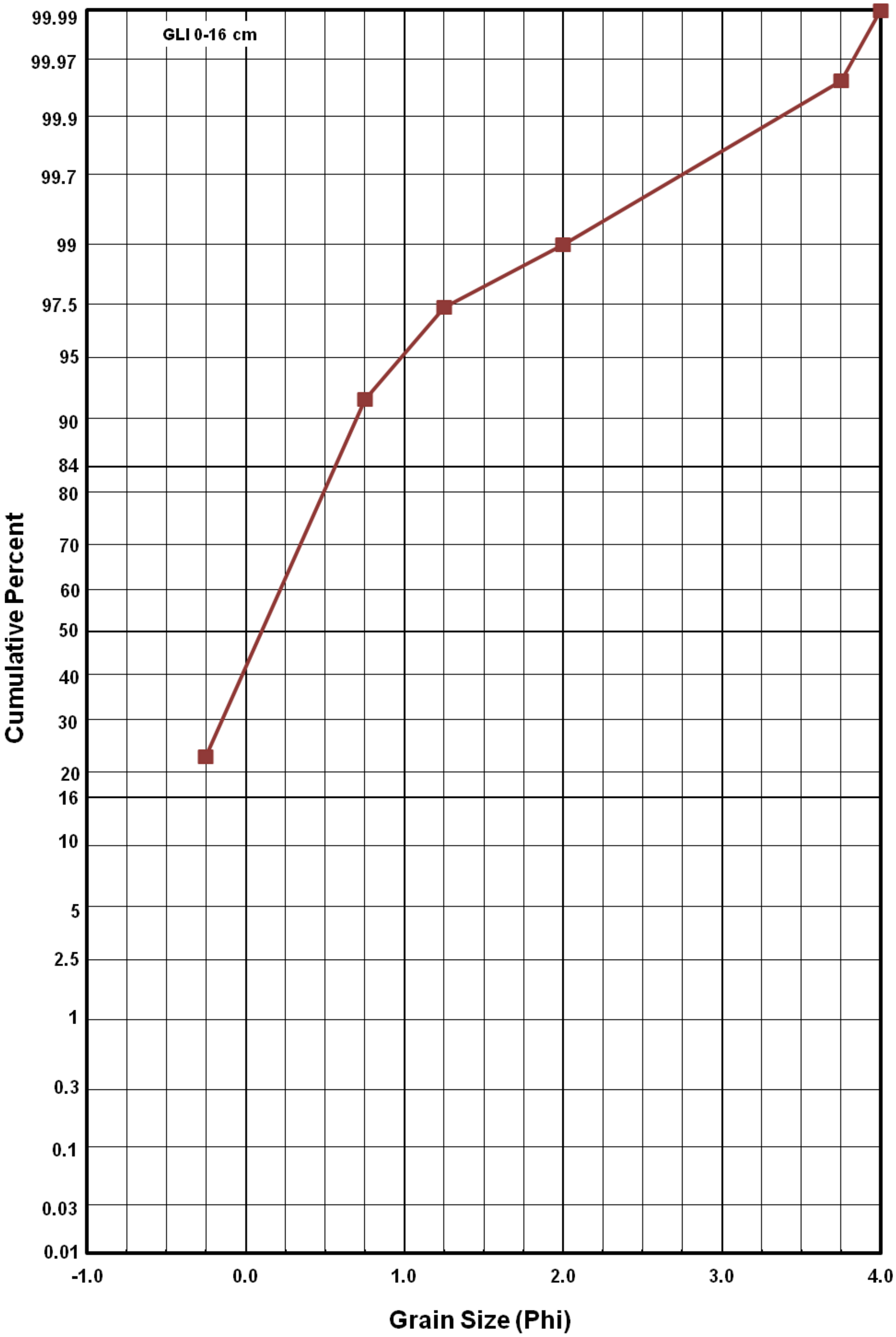
99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)


CG 55-65.5 cm
Cumulative Percent
99.99
99.97
99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)


GLI 0-16 cm
Cumulative Percent
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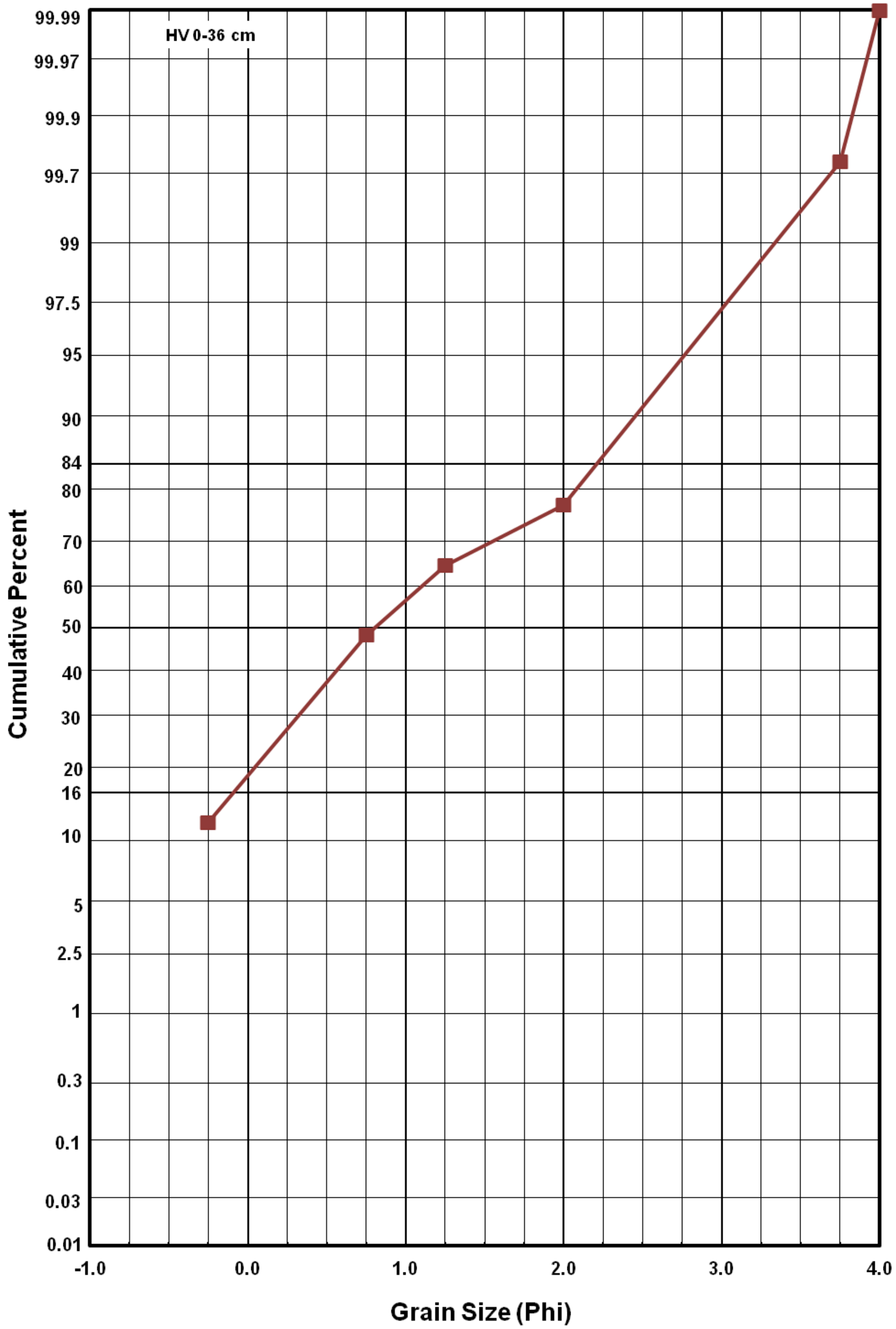
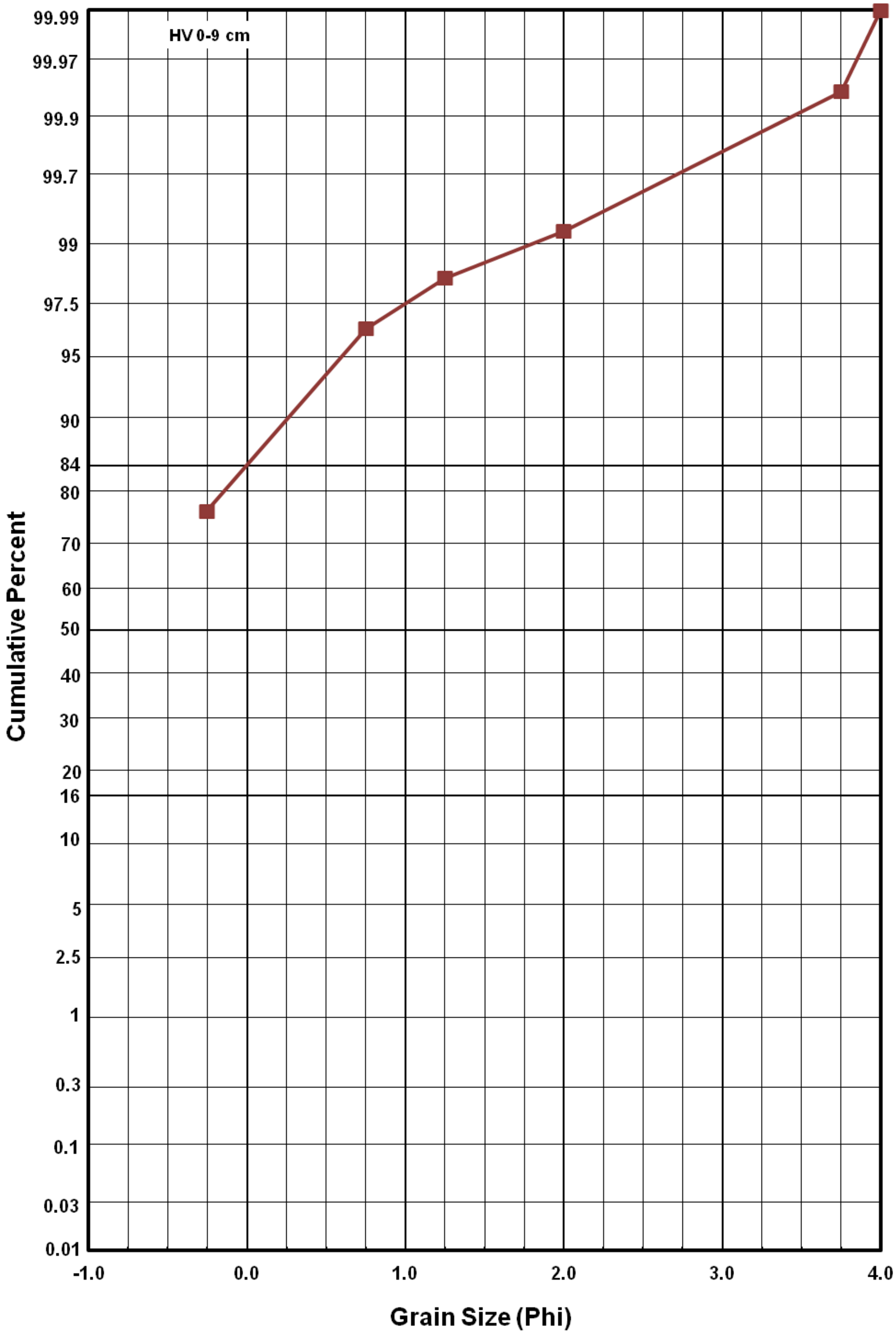
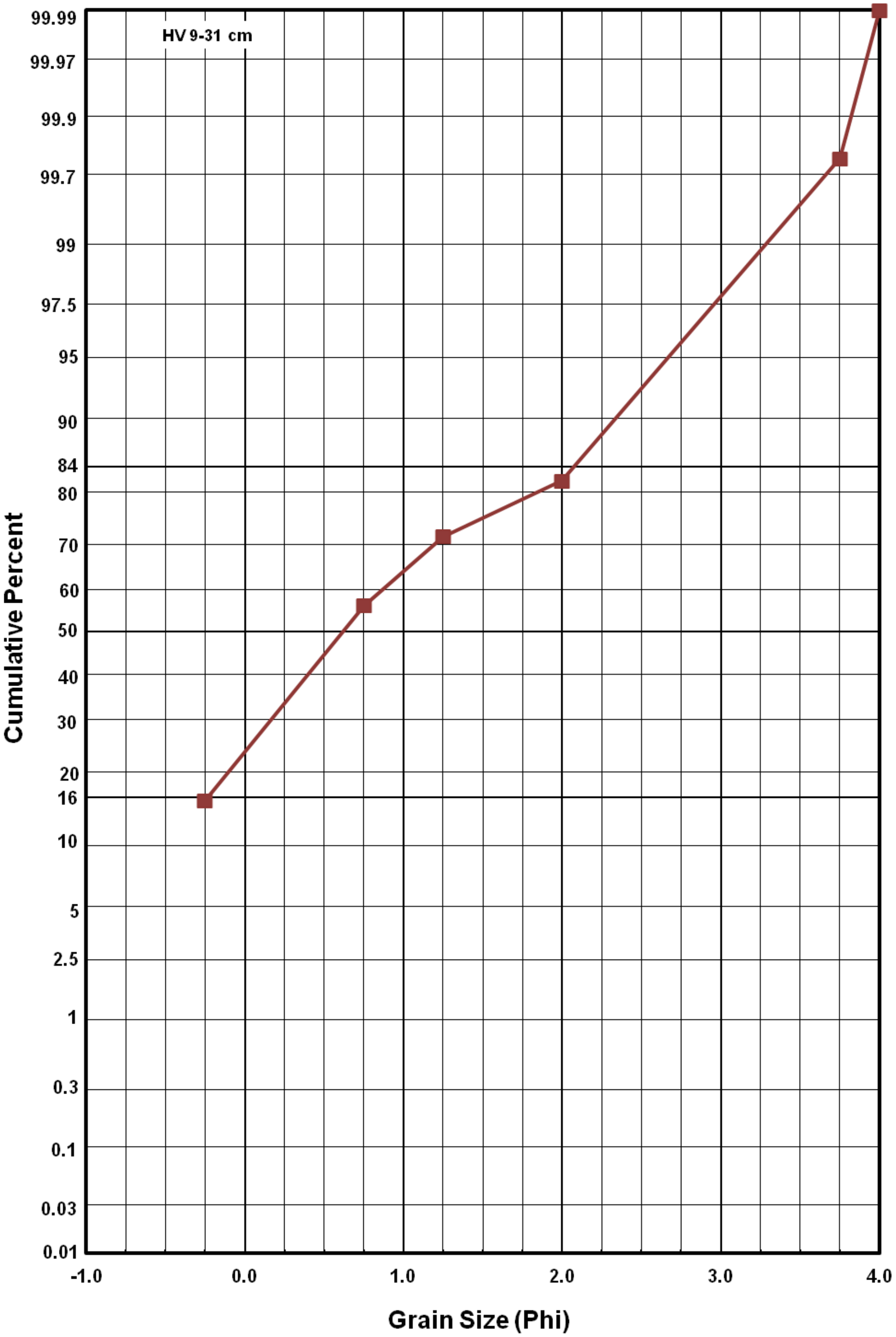
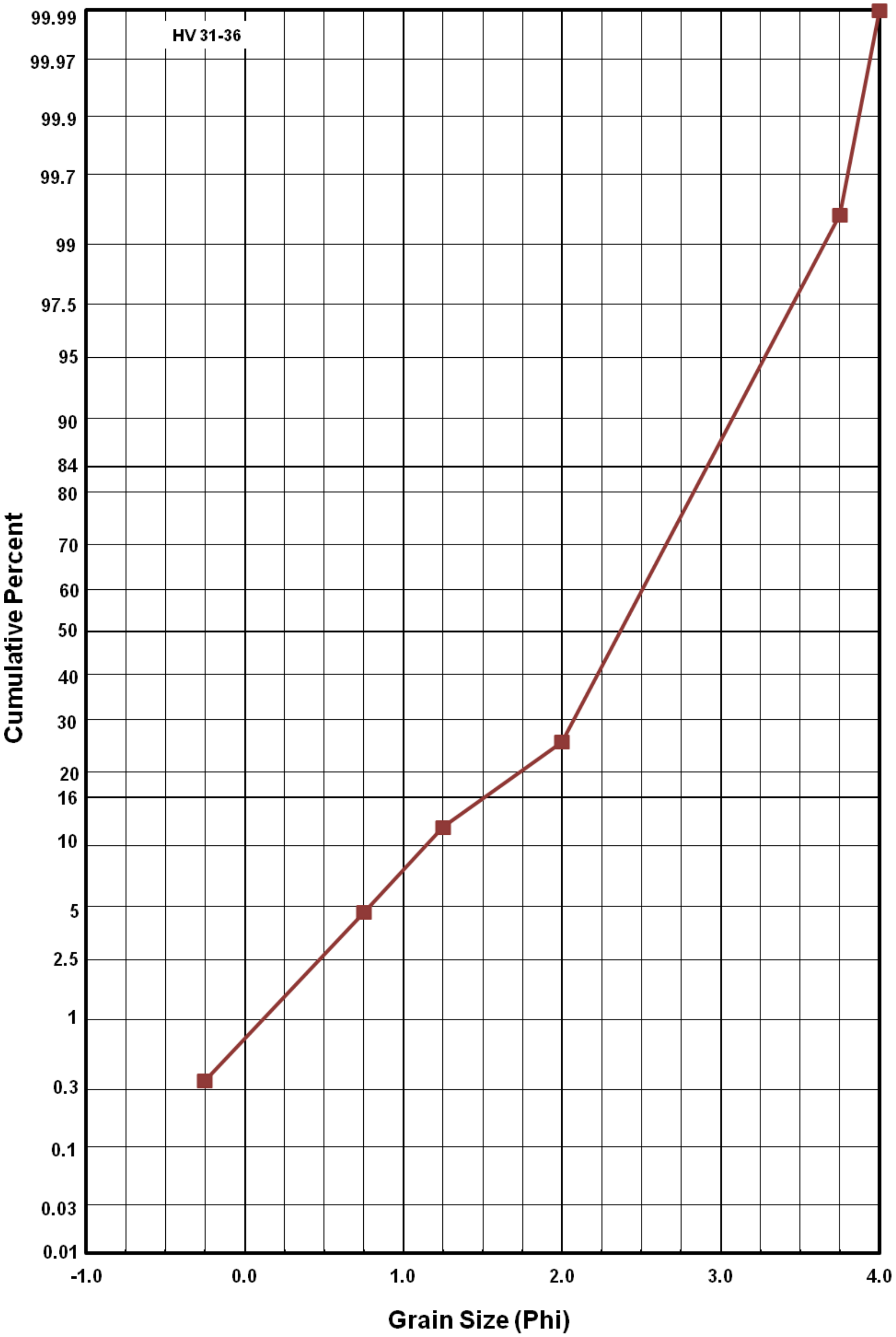
99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)


HV 0-36 cm
Cumulative Percent
99.99
99.97
99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)


HV 0-9 cm
99.99
99.97
99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
Cumulative Percent
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)


HV 9-31 cm
99.99
99.97
99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
Cumulative Percent
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)


HV 31-36
Cumulative Percent
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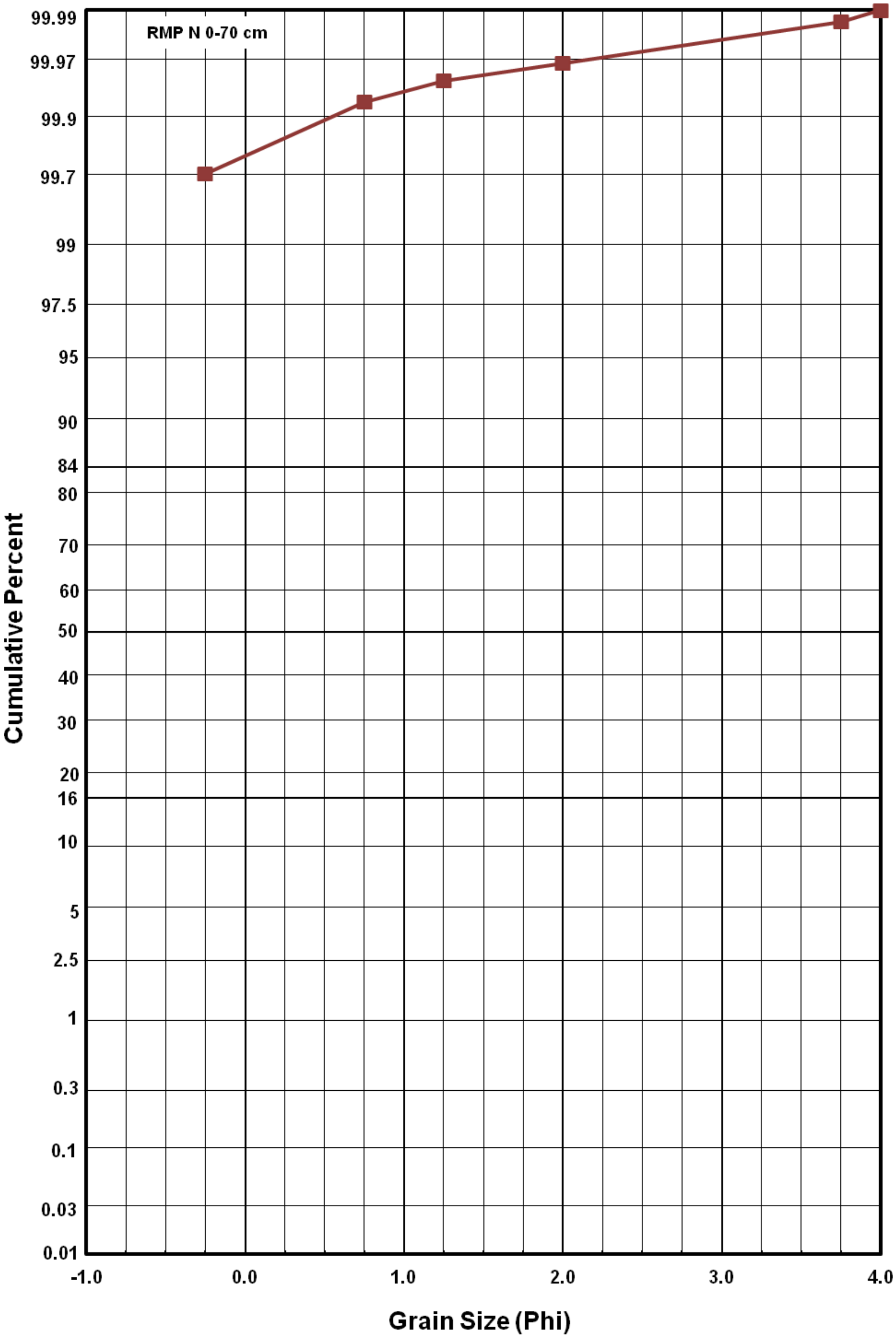
99.97
99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)


RMP N 0-70 cm
Cumulative Percent
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99.7
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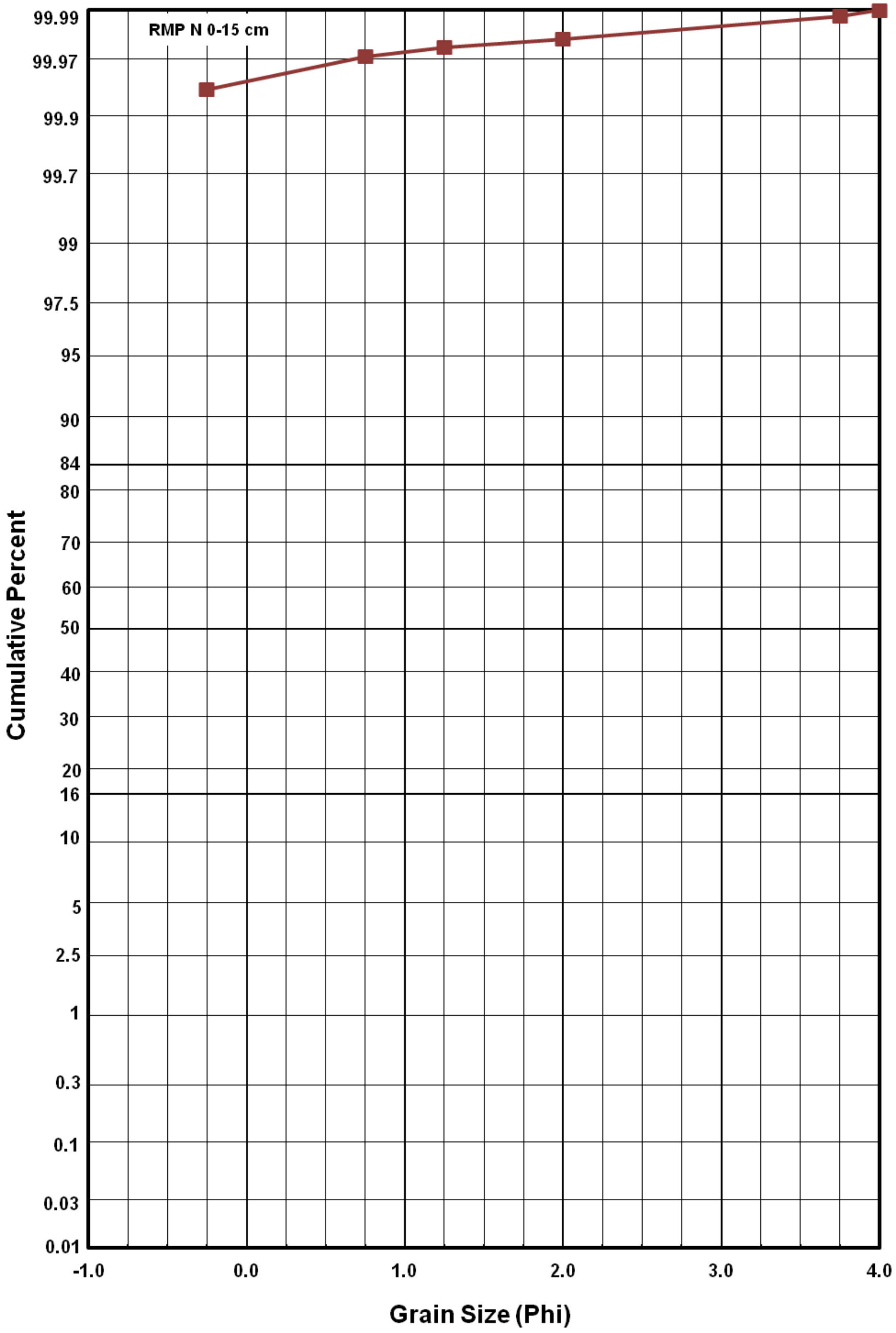
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)


RMP N 0-15 cm
Cumulative Percent
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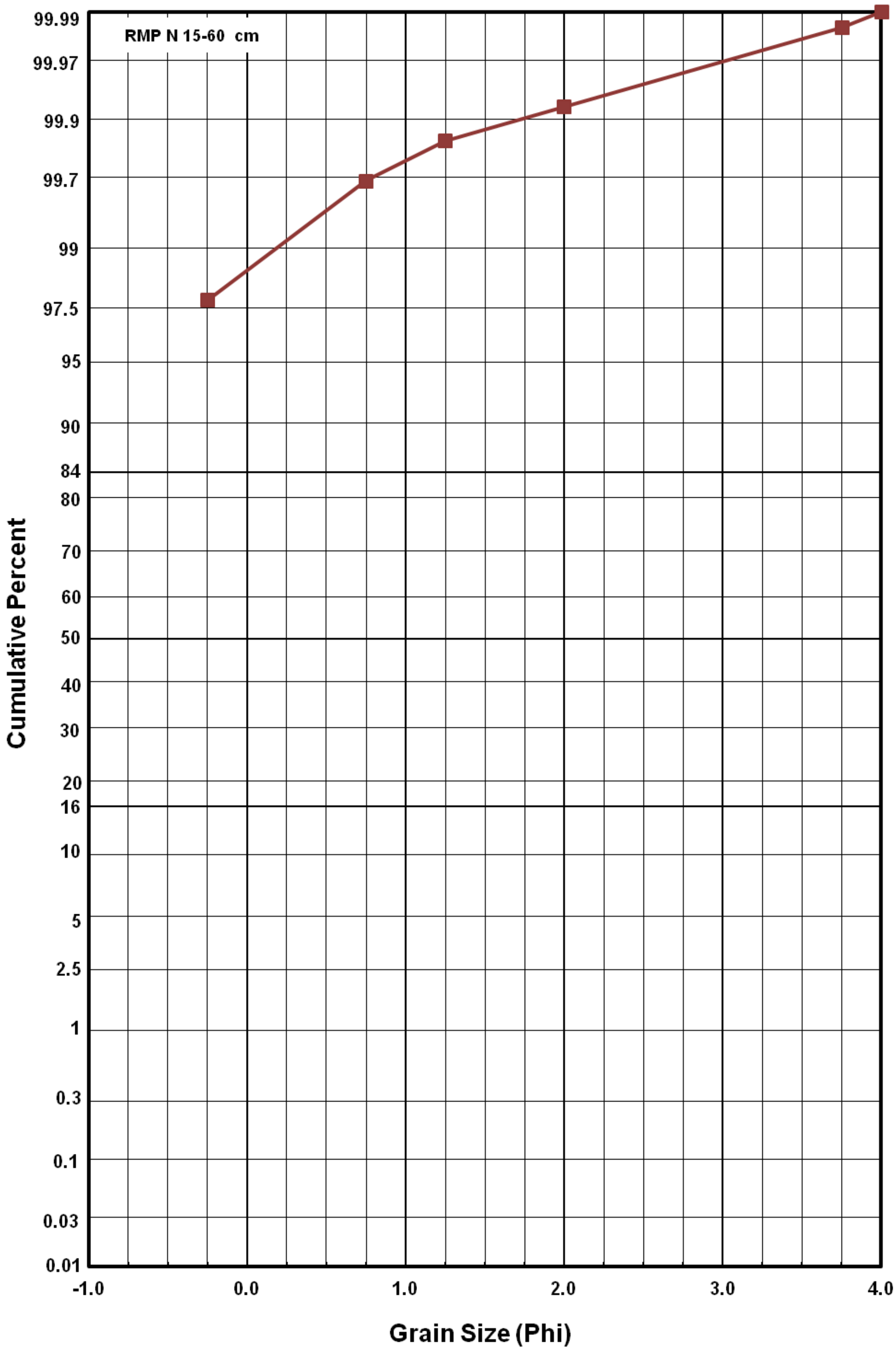
99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)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Cumulative Percent
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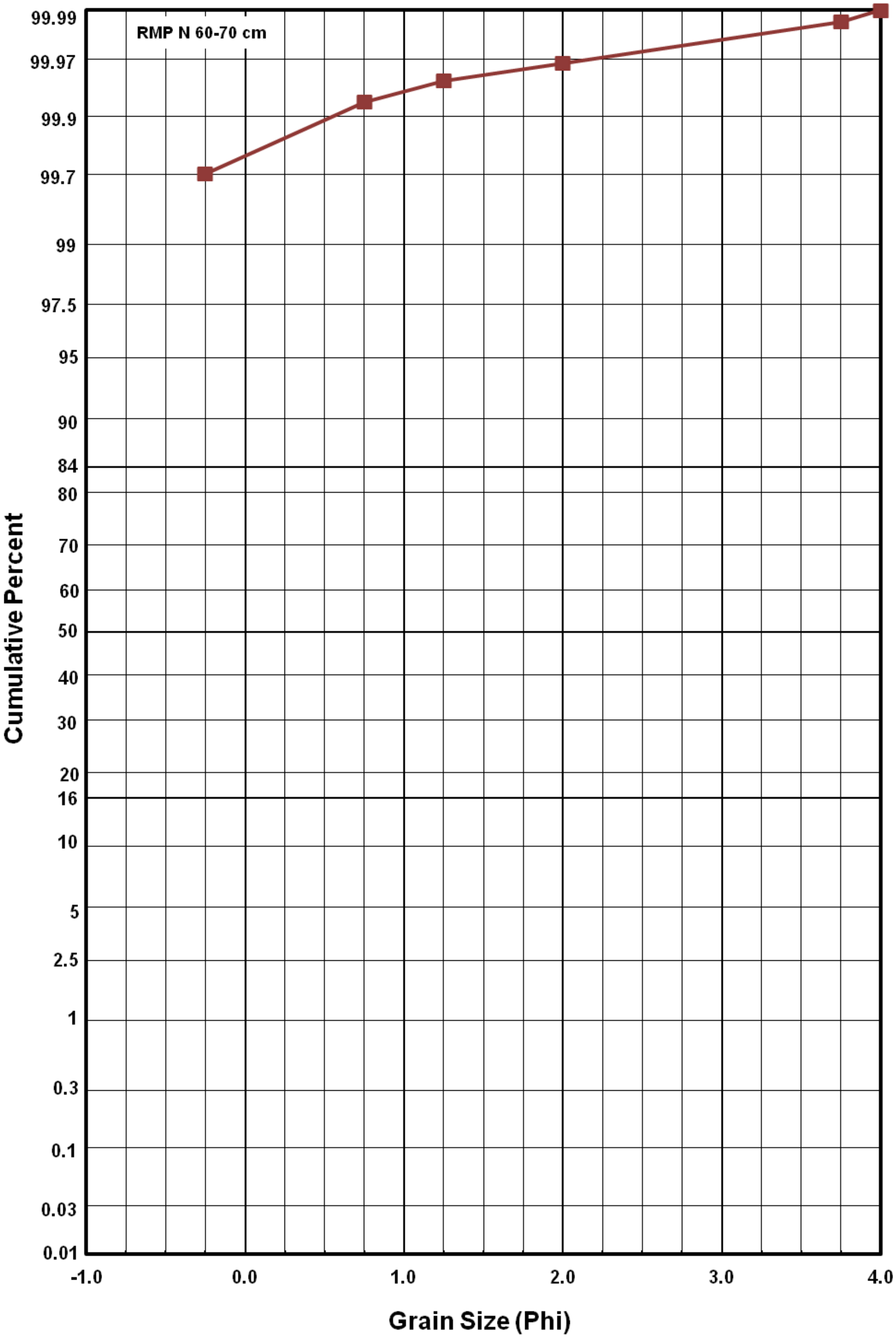
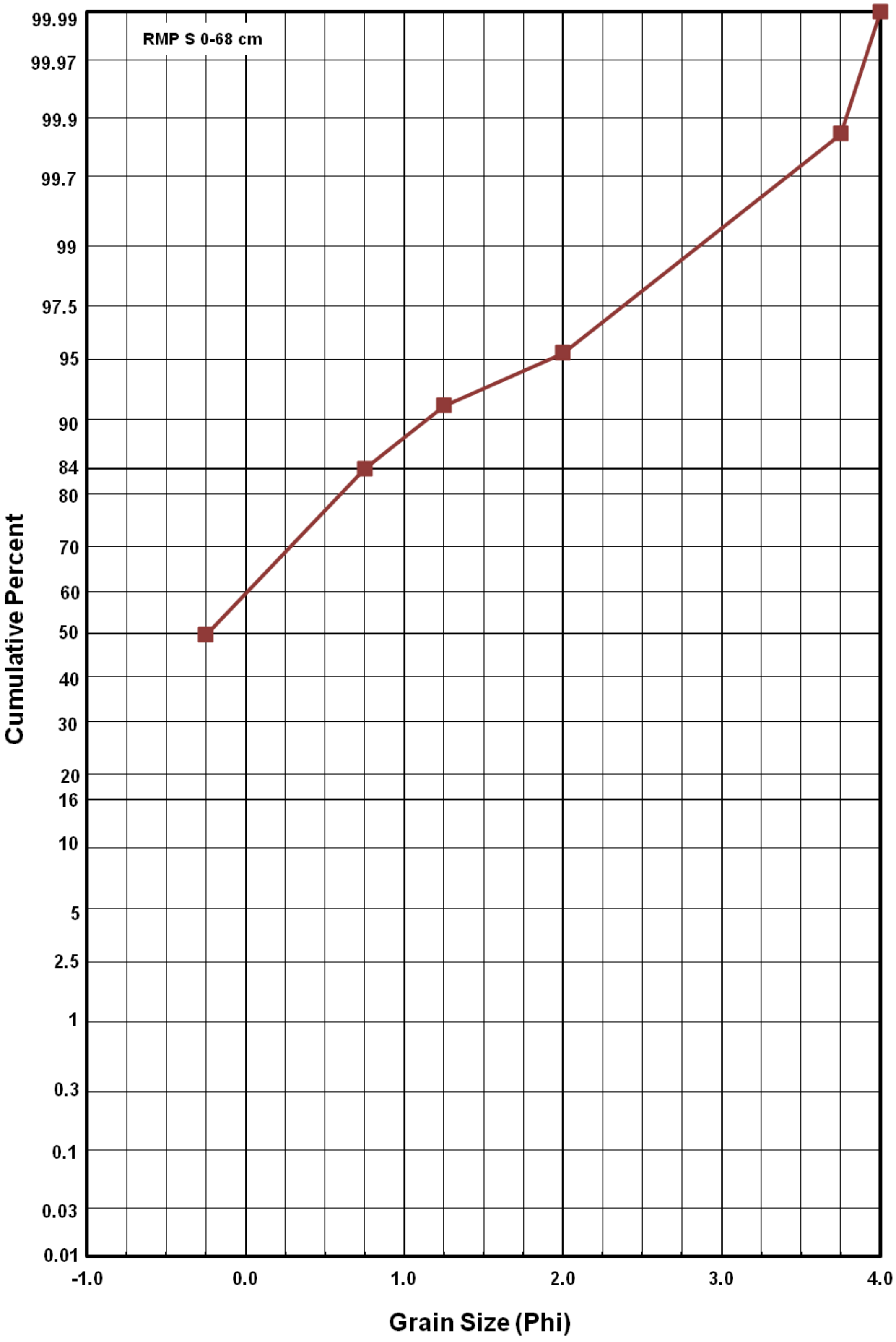
99.97
99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)


RMP N 60-70 cm
99.99
99.97
99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
Cumulative Percent
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)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Cumulative Percent
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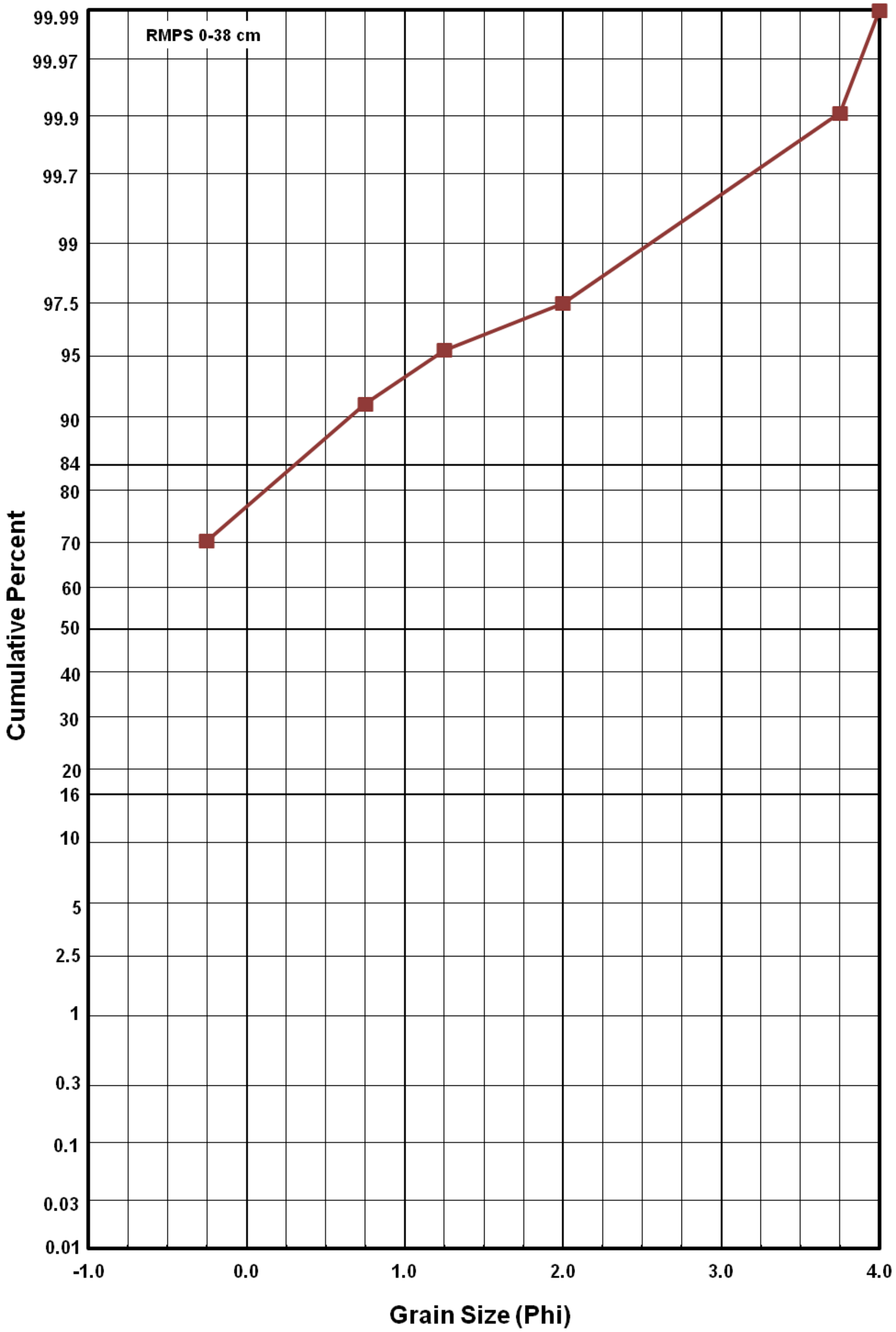
99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)


RMPS 0-38 cm
Cumulative Percent
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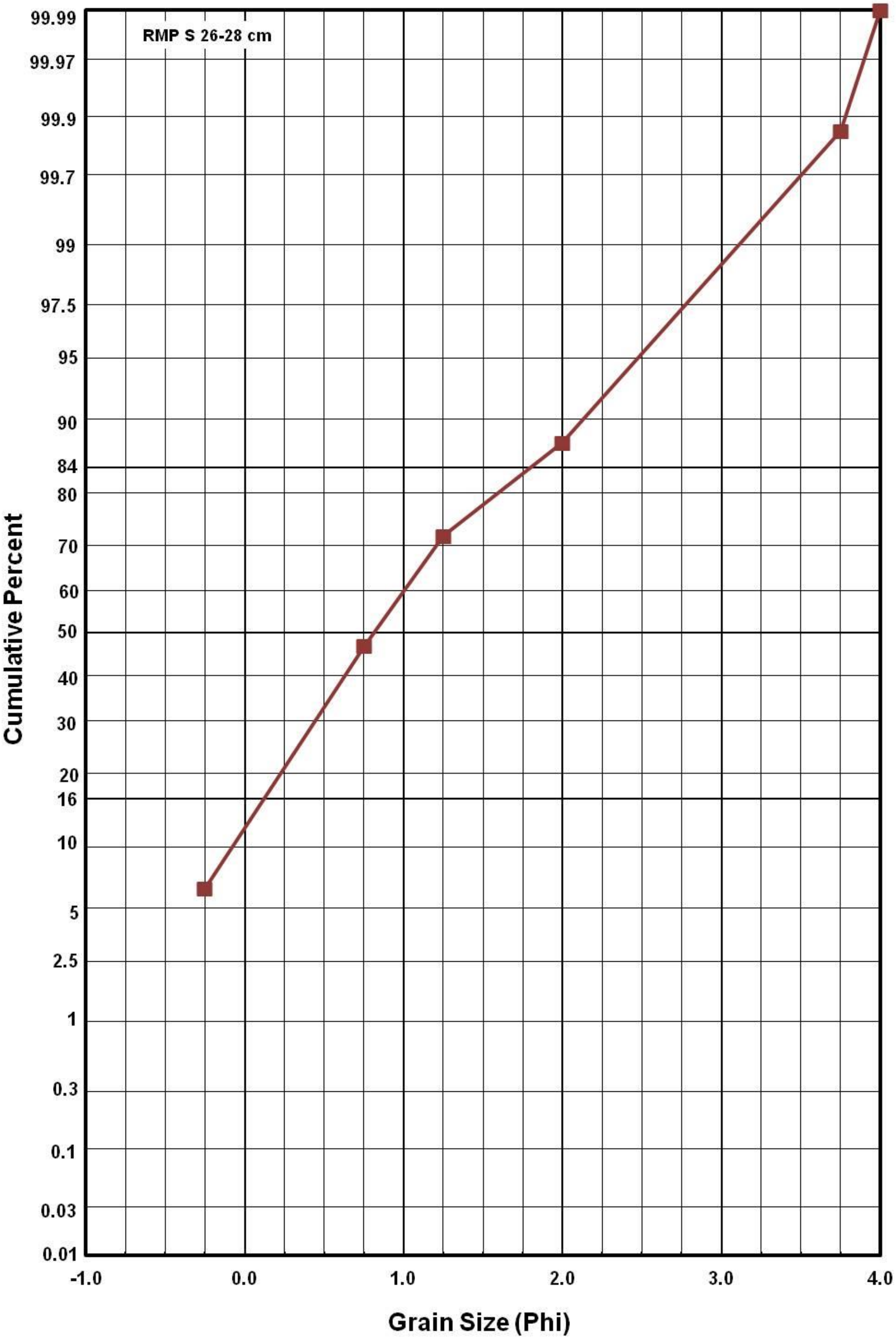
99.97
99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)


RMP S 26-28 cm
Cumulative Percent
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99.9
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
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0.01
-1.0
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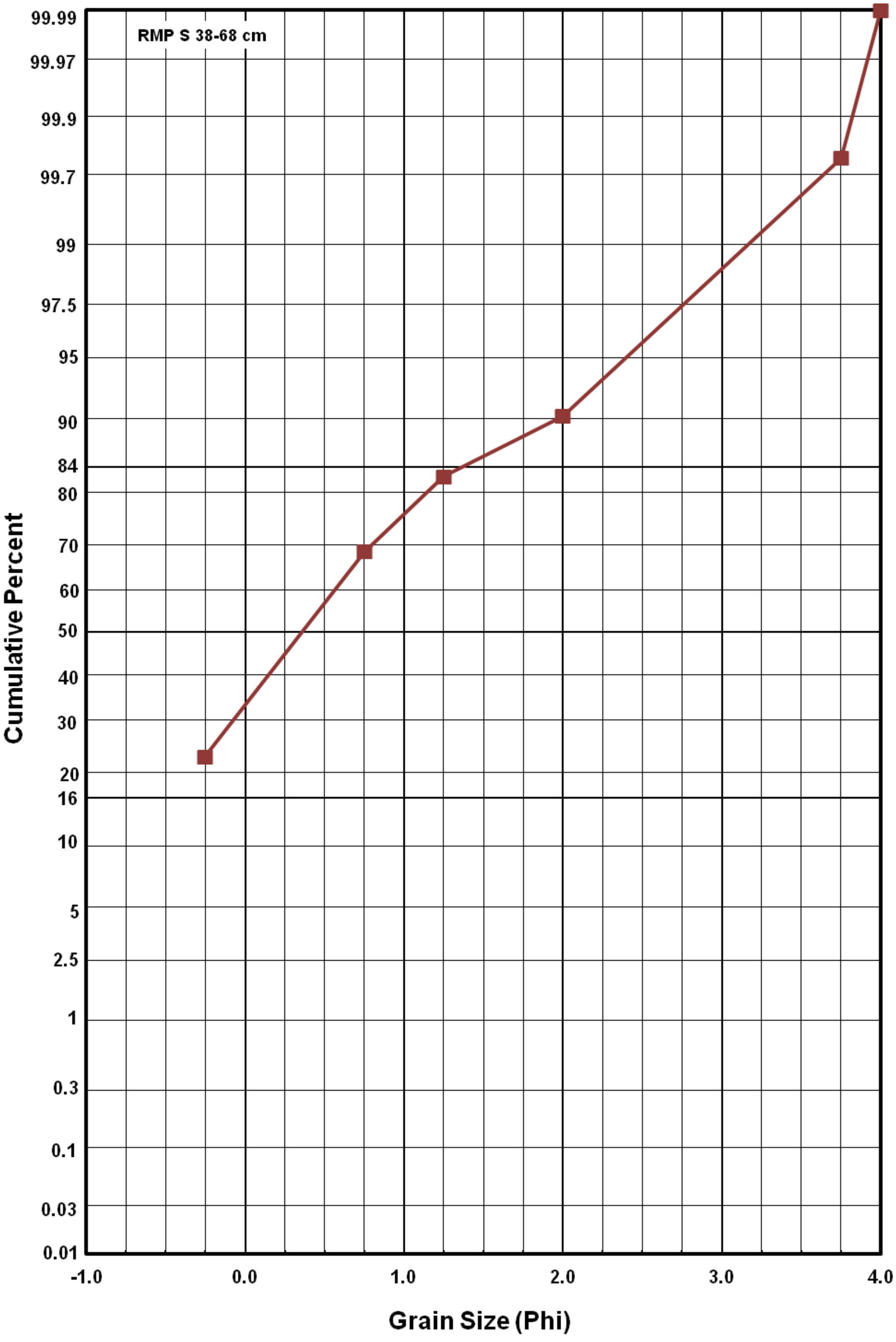
1.0
2.0
3.0
4.0
Grain Size (Phi)


RMP S 38-68 cm
Cumulative Percent
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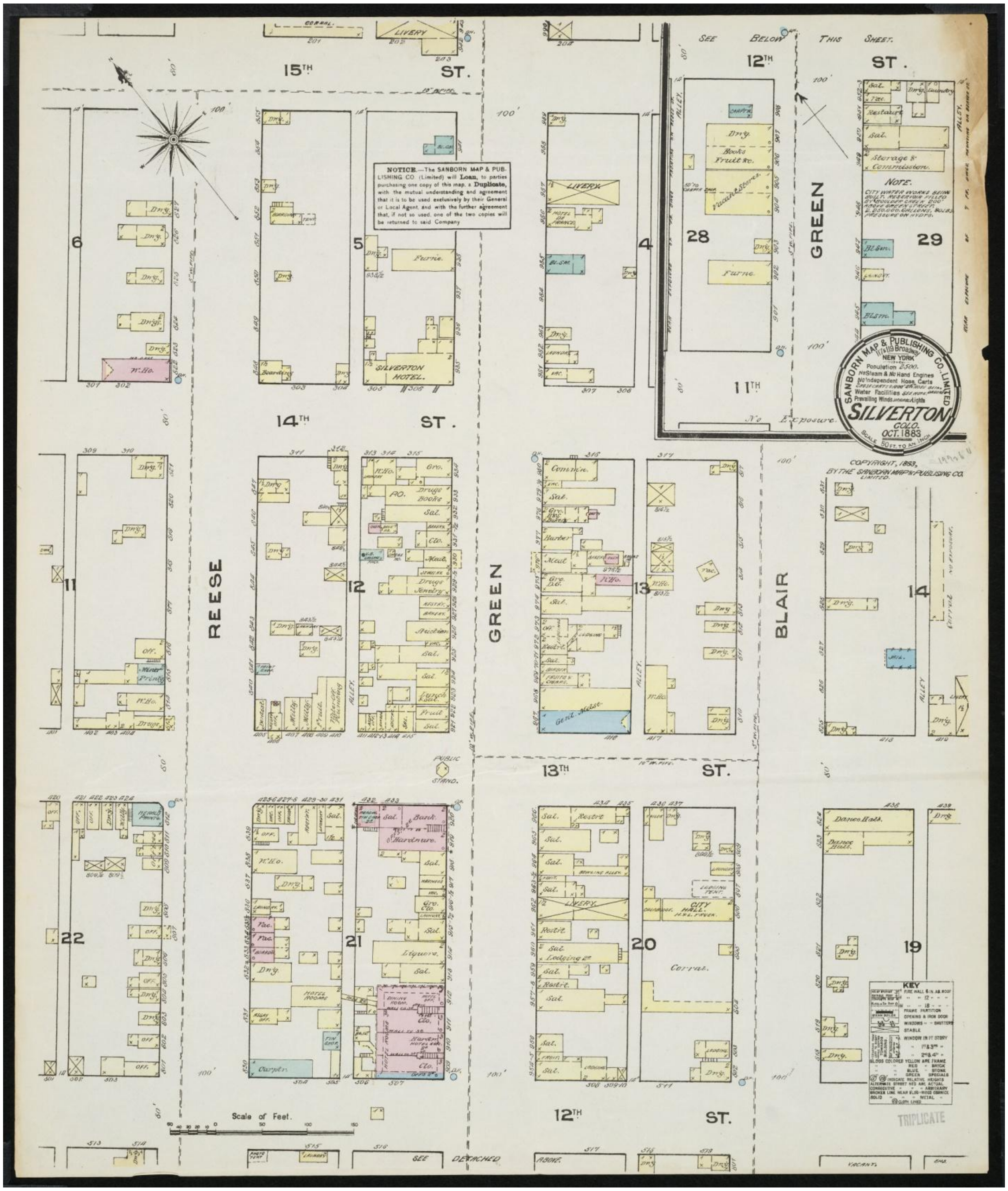
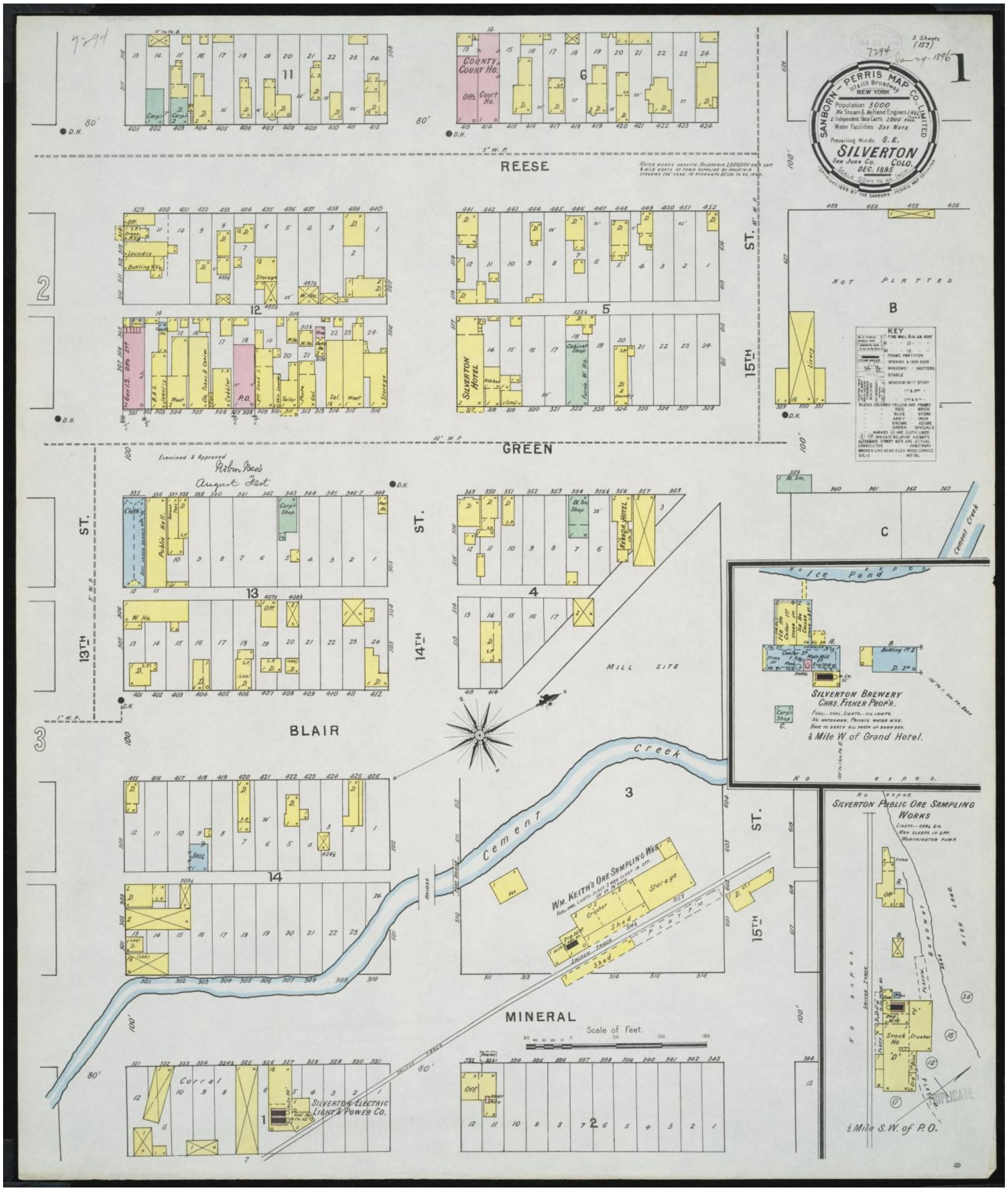
99.7
99
97.5
95
90
84
80
70
60
50
40
30
20
16
10
5
2.5
1
0.3
0.1
0.03
0.01
-1.0
0.0
1.0
2.0
3.0
4.0
Grain Size (Phi)

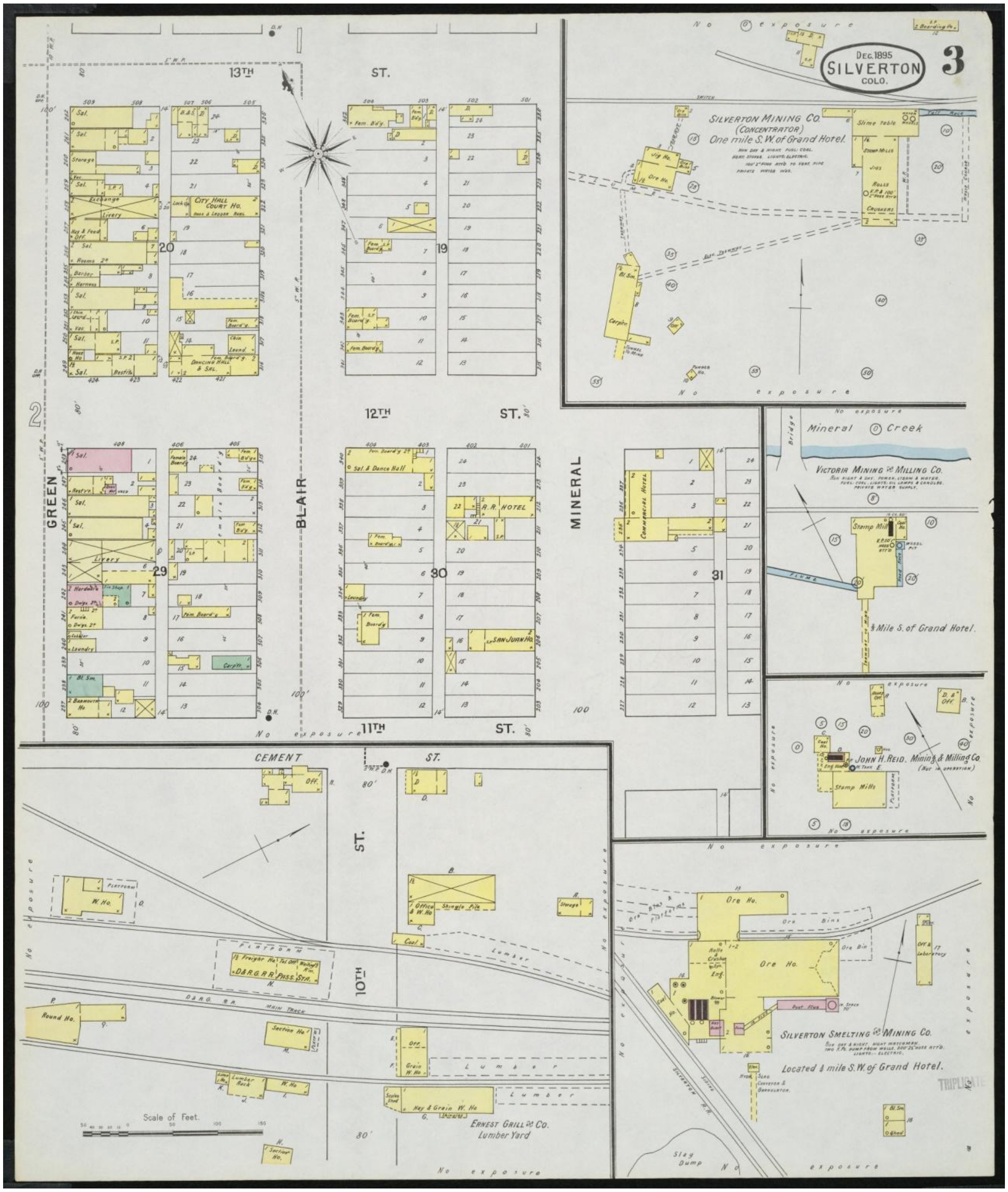
APPENDIX B

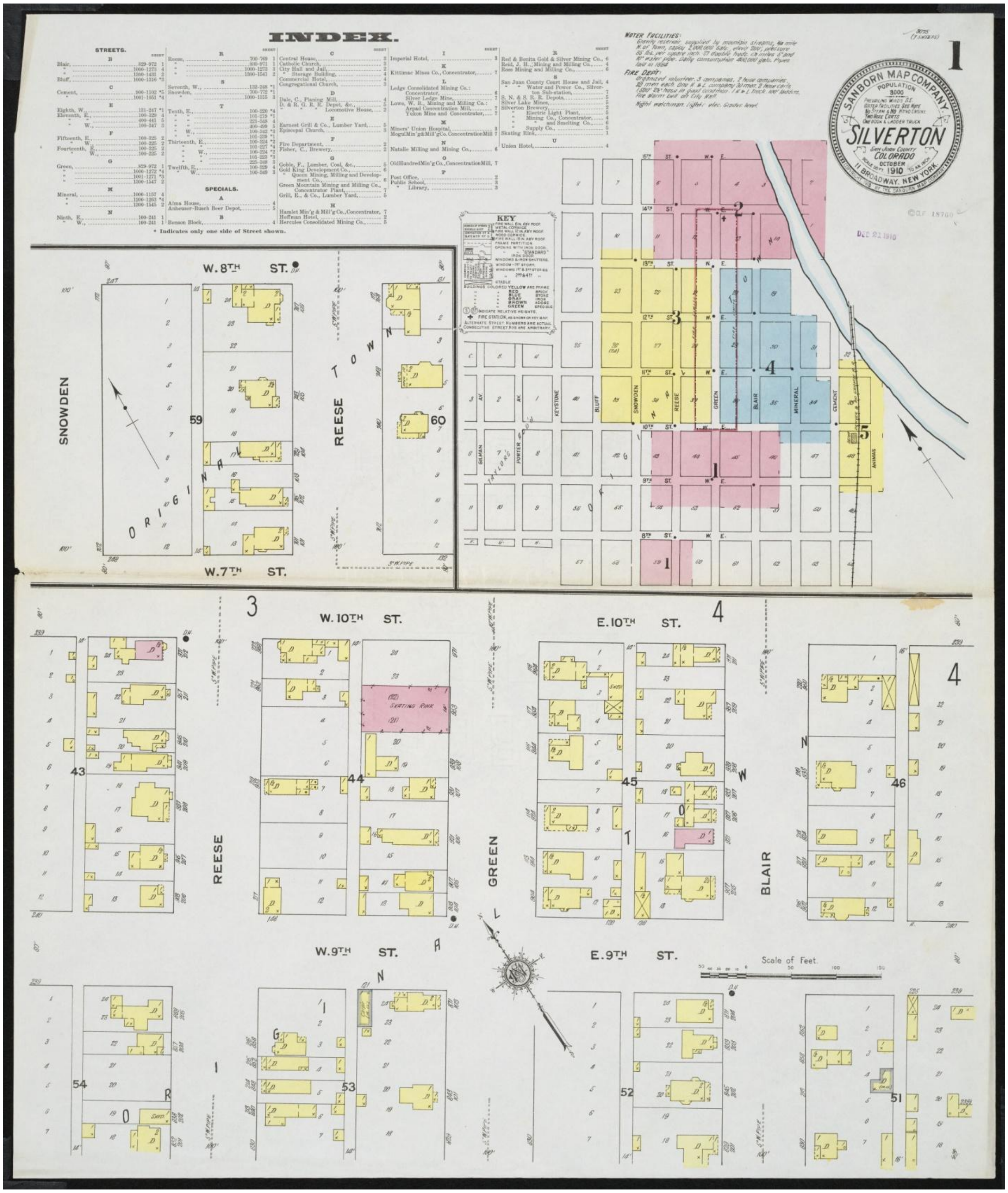
SANBORN MAPS OF SILVERTON




SANBORN – PERRIS MAP CO., LIMITED
117 & 119 Broadway
NEW YORK
Population 3000
No Steam & No Hand Engines 1 H & L Truck
2 Independent Hose Carts 2000' Hose.
Water Facilities See Note
Prevailing Winds S. E.
SILVERTON
San Juan Co. Colo.
DEC. 1895
Scale 50 ft. to an inch.
Copyright 1896 by the Sanborn-Perris Map Co. Limited
1
3 Sheets (157)
7294
Jan-29-1896
REESE
GREEN
BLAIR
MINERAL
13TH ST.
14TH ST.
15TH ST.
COUNTY COURT HO.
SILVERTON HOTEL
P.O.
Public Hall
JAIL
Livery
NOT PLATTED
KEY
Examined & Approved
MILL SITE
Cement Creek
Ice Pond
SILVERTON BREWERY
CHAS. FISHER PROP'R.
¼ Mile W. of Grand Hotel.
SILVERTON PUBLIC ORE SAMPLING WORKS
WM. KEITH'S ORE SAMPLING WKS.
SILVERTON ELECTRIC LIGHT & POWER CO.
Corral
Scale of Feet.
½ Mile S.W. of P.O.
DUPLICATE


2
DEC. 1895
SILVERTON
COLO.
13TH ST.
12TH ST.
11TH ST.
10TH ST.
BLUFF
SNOWDEN
REESE
GREEN
23
22
21
26
27
28
39
38
37
3
WALKER HO.
PUBLIC SCHOOL
CENTRAL HO.
GRAND HOTEL
CONGR'L CHURCH
R.C. CHURCH
Scale of Feet
TRIPLICATE

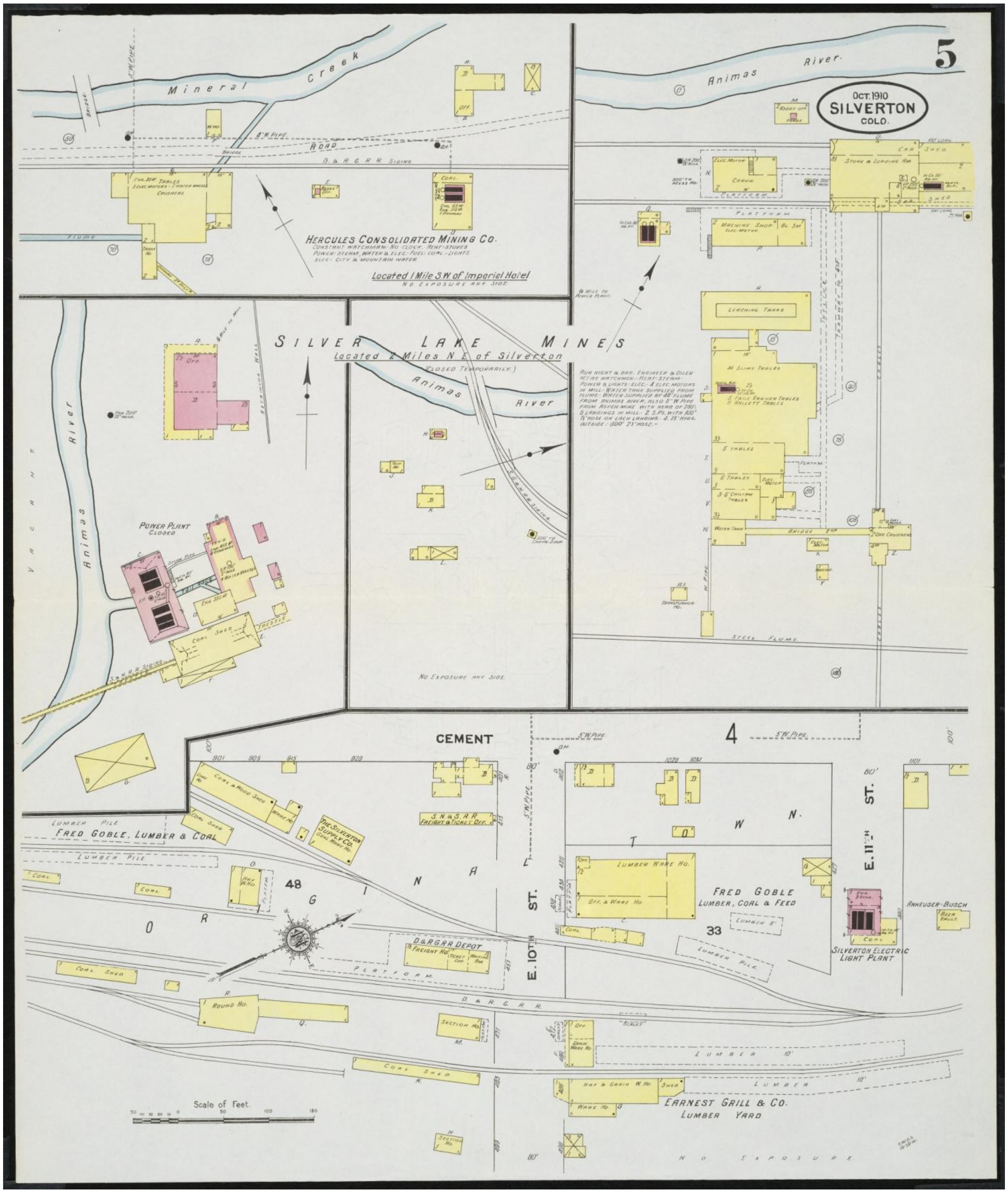

Dec. 1895
SILVERTON
COLO.
3
13TH ST.
12TH ST.
11TH ST.
GREEN
BLAIR
MINERAL
CEMENT ST.
10TH ST.
CITY HALL COURT HO.
DANCING HALL & SAL.
Sal. & Dance Hall
R.R. HOTEL
SAN JUAN HO.
Commercial Hotel
Livery
Hardware
Laundry
Carp'r.
Bl. Sm.
Fem. Board'g
20
19
29
30
31
2
No exposure
SILVERTON MINING CO. (CONCENTRATOR)
One mile S.W. of Grand Hotel.
Mineral Creek
VICTORIA MINING & MILLING CO.
Stamp Mill
⅛ Mile S. of Grand Hotel.
JOHN H. REID. Mining & Milling Co. (Not in operation)
Stamp Mills
Ore Ho.
SILVERTON SMELTING & MINING CO.
Located ⅛ mile S.W. of Grand Hotel.
Slag Dump
Laboratory
Round Ho.
D.&R.G.R.R. PASS. STA.
Freight Ho.
Section Ho.
Lumber Rack
Hay & Grain W. Ho.
ERNEST GRILL & CO. Lumber Yard
Office & W. Ho.
Shingle Pile
Coal
Lumber
Scale of Feet.
TRIPLICATE

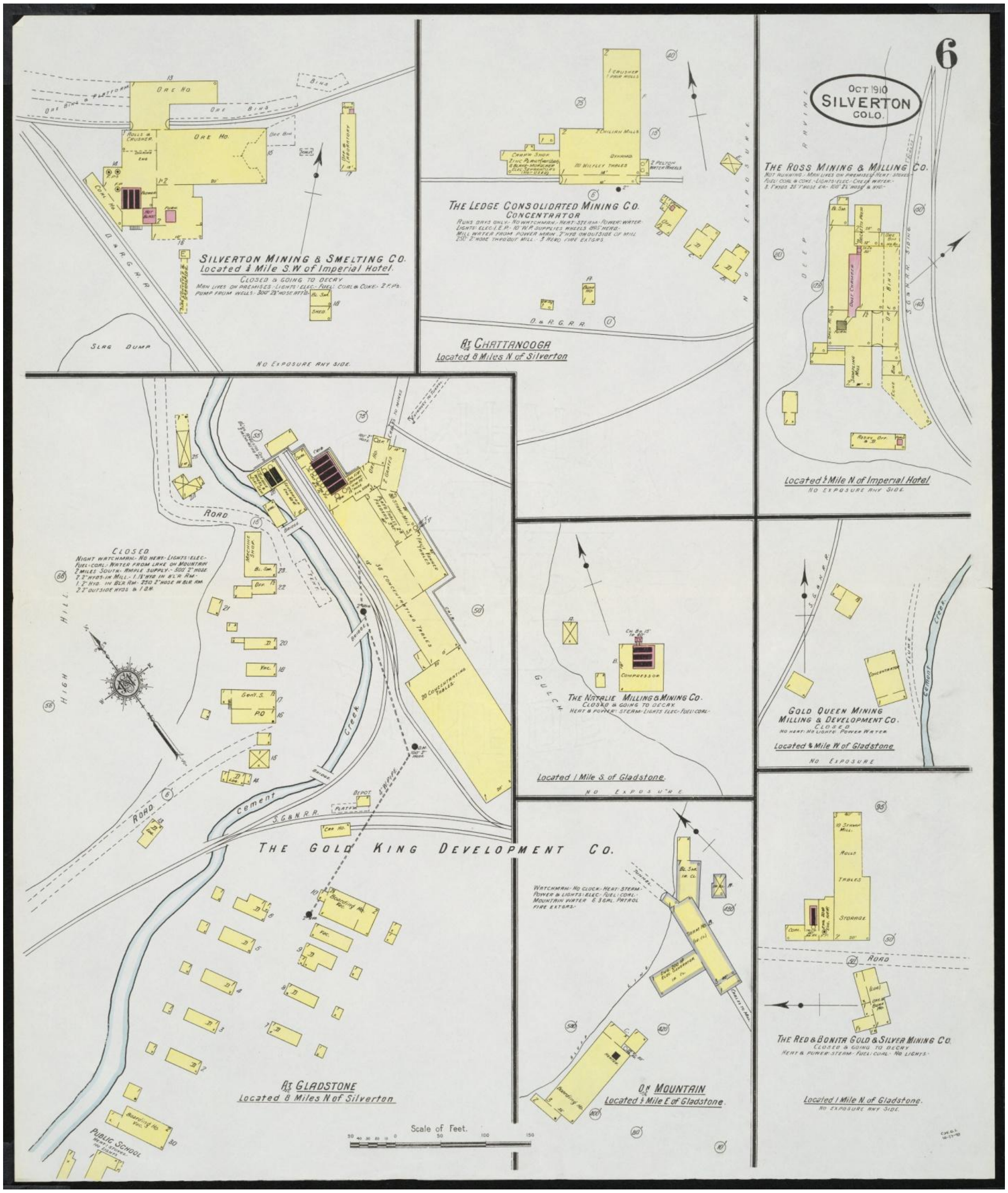

INDEX.
1
SANBORN MAP COMPANY
SILVERTON
COLORADO
OCTOBER 1910
11 BROADWAY, NEW YORK
KEY
W. 8TH ST.
W. 7TH ST.
SNOWDEN
REESE
ORIGINAL TOWN
59
60
W. 10TH ST.
E. 10TH ST.
W. 9TH ST.
E. 9TH ST.
GREEN
BLAIR
43
44
45
46
54
53
52
51
3
4
Scale of Feet.

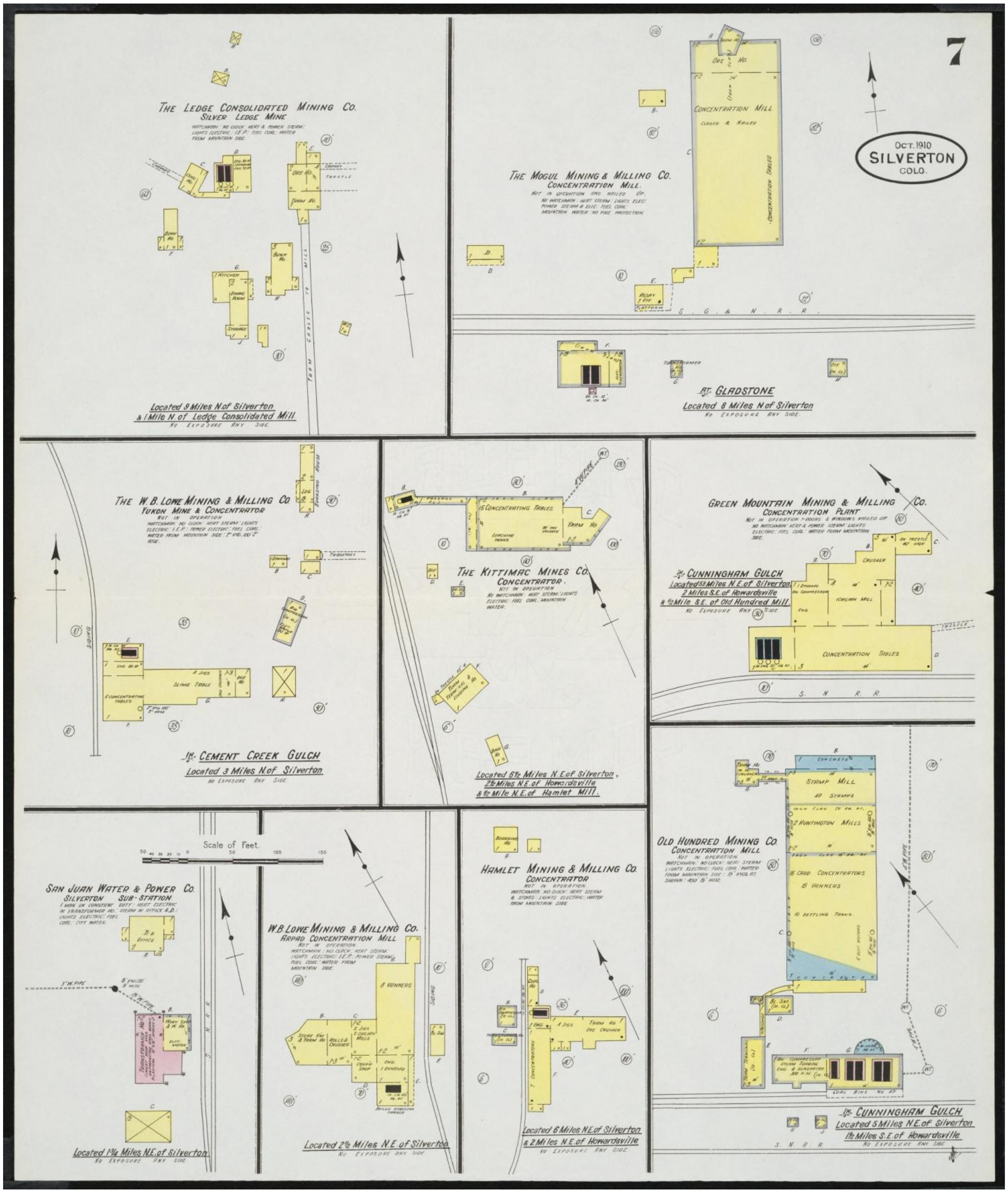
2
Oct. 1910
SILVERTON
COLO.
REESE
GREEN
BLAIR
MINERAL
W. 13TH ST.
W. 14TH ST.
W. 15TH ST.
E. 13TH
E. 14TH
E. 15TH ST.
CITY HALL & HOSE HO.
HOFFMAN HOTEL
P.O.
Cement Creek
SILVERTON BREWERY CHAS. FISHER
Ice Pond
Located 3/4 Mile W. of Imperial Hotel.
STANLEY PLACER
REESE'S ADD'N
Not Plotted
Locomotive Ho.
Scale of Feet.


3
OCT. 1910
SILVERTON
COLO.
Miners Union Hospital
W. 13TH ST.
W. 12TH ST.
W. 11TH ST.
W. 10TH ST.
BLUFF
SNOWDEN
REESE
GREEN
Public School
Public Library
Episcl. Church
Congl. Church
R.C. Church
Imperial Hotel
Central Ho.
ORIGINAL TOWN
Scale of Feet.
2
1
4
10
11
21
22
23
26
27
28
37
38
39


Oct. 1910
SILVERTON
COLO.
4
E. 13TH ST.
E. 12TH ST.
E. 11TH ST.
E. 10TH ST.
GREEN
BLAIR
MINERAL
CEMENT
LIVERY
BENSON BLOCK
City Storage
COMMERCIAL HOTEL
UNION HOTEL
ALMA HOUSE
CHARLES DALE, PLANING MILL
Machine Shop
Planing Mill
SILVERTON MINING CO. (CONCENTRATOR)
Slime Tables
Stamp Mills
Dump
Located 1 Mile S.W. of Imperial Hotel
County Jail
Located ¼ Mile N. of Imperial Hotel
SAN JUAN COUNTY COURT HO.
Cement Creek
JOHN H. REID MINING & MILLING CO.
Stamp Mills
Located 1 Mile S. of Imperial Hotel
No Exposure
Scale of Feet.
1
2
3
5
19
20
29
30
31
34
35
36
46
47

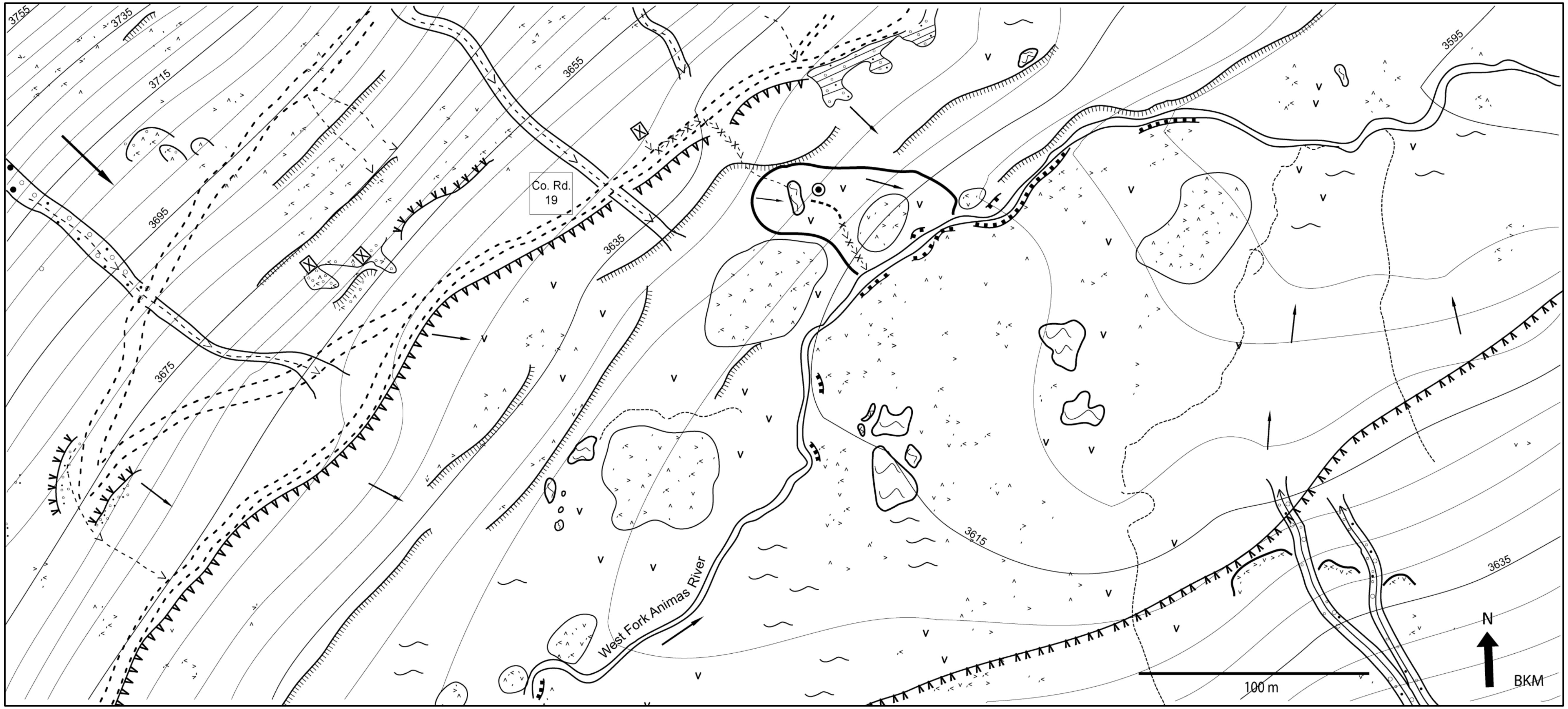

5
Oct. 1910
SILVERTON
COLO.
Mineral Creek
Animas River
Bridge
8" W. Pipe
Road
D. & R. G. R. R. Siding
Flume
Eng. 30 H.P. Tables
3 Elec. Motors - 2 Water Wheels
Crushers
Assay Off.
Coal
Off.
W. Ho.
HERCULES CONSOLIDATED MINING CO.
Constant watchman - No clock. Heat: stoves
Power: steam, water & elec. - Fuel: coal - Lights
elec.: city & mountain water.
Located 1 Mile S.W. of Imperial Hotel
No exposure any side.
Elec. Motor
Carpr.
Platform
300' to Mess Ho.
Store & Loading Rm.
Car Shed
Machine Shop
Elec. Motor
Bl. Sm.
Leaching Tanks
Tramway to Ore
½ Mile to Power Plant
SILVER LAKE MINES
Located 2 Miles N.E. of Silverton
(Closed temporarily.)
Run night & day. Engineer & oiler act as watchmen. - Heat: steam - Power & lights: elec. - 4 elec. motors in mill. - Water tank supplied from flume. - Water supplied by 48" flume from Animas River, also 8" W. pipe from Aspen Mine with head of 250'. 8 landings in mill. - 2 S.Ps. with 100' 1½" hose on each landing. - 4. 2½" hyds. outside - 500' 2½" hose.
44 Slime Tables
5 Frue Vanner Tables
11 Hallett Tables
5 Tables
6 Tables
3-6' Chilian Tables
Elec. Motor
Water Tank
Bridge
2 Ore Crushers
Transformer Ho.
W. Pipe
Steel Flume
Cables
½ Mile to Mill
Retaining Wall
Power Plant
Closed
Eng. 350 H.P.
Coal Shed
Trestle
S. & N. R. R. Siding
Animas River
Off.
No exposure any side.
CEMENT
Lumber Pile
FRED GOBLE, LUMBER & COAL
Coal & Wood Shed
Coal Shed
Ware Ho.
The Silverton Supply Co. Genl. Ware Ho.
S. N. & S. R. R. Freight & Ticket Off.
5" W. Pipe
Hay W. Ho.
48
ORIGINAL TOWN
D. & R. G. R. R. Depot
Freight Ho.
Ticket Off.
Waiting Rm.
Platform
D. & R. G. R. R.
Round Ho.
Coal Shed
Section Ho.
E. 10TH ST.
E. 11TH ST.
4
33
Lumber Ware Ho.
Off. & Ware Ho.
FRED GOBLE
LUMBER, COAL & FEED
Lumber Pile
Silverton Electric Light Plant
Anheuser-Busch
Beer Vault
Scales
Grain Ware Ho.
Lumber 10'
Hay & Grain W. Ho.
Shed
Ware Ho.
EARNEST GRILL & CO.
LUMBER YARD
No Exposure
Scale of Feet.
50 40 30 20 10 0 50 100 150


6
OCT 1910
SILVERTON
COLO.
SILVERTON MINING & SMELTING CO.
Located ¼ Mile S.W of Imperial Hotel.
CLOSED & GOING TO DECAY
MAN LIVES ON PREMISES - LIGHTS: ELEC. - FUEL: COAL & COKE - 2 F.P's.
PUMP FROM WELLS - 300' 2½" HOSE ATT'D.
ORE HO.
ORE BINS
ORE BINS & PLATFORM
ROLLS & CRUSHER
COAL HO.
OFF. & LABORATORY
D. & R. G. R. R.
SLAG DUMP
NO EXPOSURE ANY SIDE.
THE LEDGE CONSOLIDATED MINING CO.
CONCENTRATOR
RUNS DAYS ONLY - NO WATCHMAN - HEAT: STEAM - POWER: WATER
LIGHTS: ELEC. I.E.P. - 10" W.P. SUPPLIES WHEELS 895' HEAD -
MILL WATER FROM POWER MAIN - 2" HYD ON OUTSIDE OF MILL
250' 2" HOSE THRO'OUT MILL - 3 AERO FIRE EXTGRS
1 CRUSHER 1 PAIR ROLLS
2 CHILIAN MILLS
20 WILFLEY TABLES
DYNAMO
2 PELTON WATER WHEELS
CARP'R SHOP
ZINC PLANT
D. & R. G. R. R.
NO EXPOSURE
AT CHATTANOOGA
Located 8 Miles N of Silverton
THE ROSS MINING & MILLING CO.
NOT RUNNING - MAN LIVES ON PREMISES - HEAT: STOVES -
FUEL: COAL & COKE - LIGHTS: ELEC. - CREEK WATER -
3. 1" HYDS 25' 1" HOSE EA. - 100' 2½" HOSE & HYD.
DEEP RAVINE
DUST CHAMBER
SAMPLING MILL
ORE BINS
S. G. & N. R. R. SIDING
ASSAY OFF.
Located ½ Mile N. of Imperial Hotel
NO EXPOSURE ANY SIDE.
CLOSED.
NIGHT WATCHMAN - NO HEAT - LIGHTS: ELEC. -
FUEL: COAL - WATER FROM LAKE ON MOUNTAIN
2 MILES SOUTH - AMPLE SUPPLY - 500' 2" HOSE
2 2" HYDS. IN MILL - 1 1½" HYD IN B'L'R RM -
1 2" HYD. IN BLR. RM. - 250 2" HOSE IN BLR. RM.
2 2" OUTSIDE HYDS & 1 O.H.
HIGH HILL
ROAD
MACHINE SHOP
GEN'L S.
P.O.
30 CONCENTRATING TABLES
20 CONCENTRATING TABLES
STAMP MILL
BRIDGE
Cement Creek
S. G. & N. R. R.
DEPOT
PLATF'M
CAR HO.
4" W. PIPE
THE GOLD KING DEVELOPMENT CO.
Boarding Ho.
PUBLIC SCHOOL
AT GLADSTONE
Located 8 Miles N of Silverton
Scale of Feet.
50 40 30 20 10 0 50 100 150
THE NATALIE MILLING & MINING CO.
CLOSED & GOING TO DECAY
HEAT & POWER: STEAM - LIGHTS ELEC. - FUEL: COAL -
COMPRESSOR
GULCH
Located 1 Mile S. of Gladstone.
NO EXPOSURE
GOLD QUEEN MINING
MILLING & DEVELOPMENT CO.
CLOSED
NO HEAT - NO LIGHTS - POWER WATER
CONCENTRATOR
FLUME
Cement Creek
S. G. & N. R. R.
Located ¼ Mile W. of Gladstone
NO EXPOSURE
WATCHMAN - NO CLOCK - HEAT: STEAM -
POWER & LIGHTS: ELEC. - FUEL: COAL -
MOUNTAIN WATER 6. 3 GAL. PATROL
FIRE EXTGRS.
TUNNEL
TRAM HO.
ELEC. GENERATOR
CABLES TO MILL
BLUFF LINE
Boarding Ho.
ON MOUNTAIN
Located ¾ Mile E. of Gladstone.
10 STAMP MILL
ROLLS
TABLES
STORAGE
ROAD
THE RED & BONITA GOLD & SILVER MINING CO.
CLOSED & GOING TO DECAY
HEAT & POWER: STEAM - FUEL: COAL - NO LIGHTS.
Located 1 Mile N. of Gladstone.
NO EXPOSURE ANY SIDE.

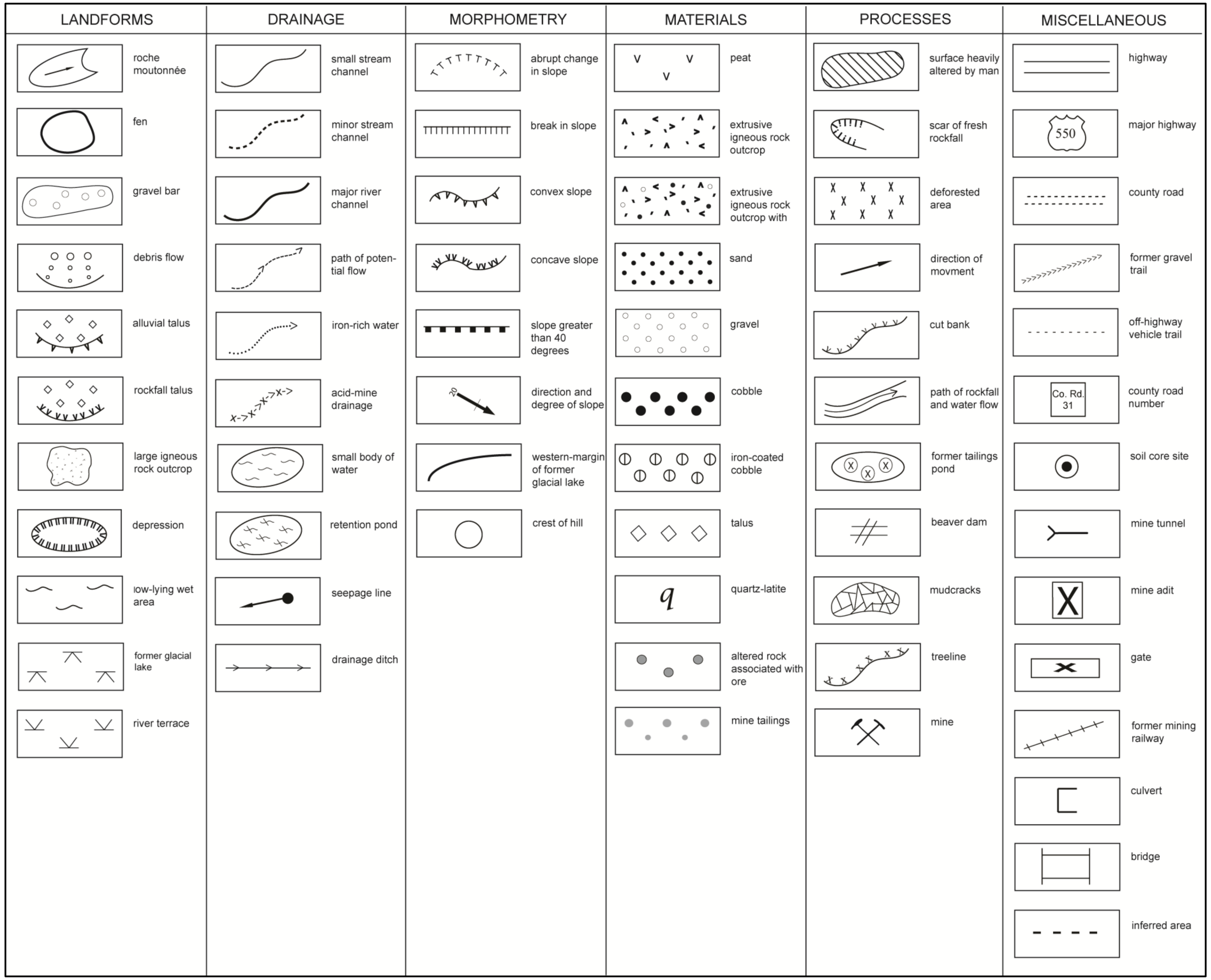

7
Oct. 1910
SILVERTON
COLO.
THE LEDGE CONSOLIDATED MINING CO.
SILVER LEDGE MINE
WATCHMAN: NO CLOCK: HEAT & POWER STEAM: LIGHTS ELECTRIC: I.E.P.: FUEL COAL: WATER FROM MOUNTAIN SIDE.
ORE HO.
TRAM HO.
BUNK HO.
KITCHEN
DINING ROOM
STORAGE
TRESTLE
TRAM CABLES TO MILL
Located 9 Miles N. of Silverton
& 1 Mile N. of Ledge Consolidated Mill.
NO EXPOSURE ANY SIDE.
THE MOGUL MINING & MILLING CO.
CONCENTRATION MILL.
NOT IN OPERATION AND NAILED UP.
NO WATCHMAN: HEAT STEAM: LIGHTS ELEC: POWER STEAM & ELEC: FUEL COAL: MOUNTAIN WATER: NO FIRE PROTECTION.
ORE HO.
CONCENTRATION MILL
CLOSED & NAILED
CONCENTRATION TABLES
ASSAY OFF.
PLATFORM
S. G. & N. R. R.
TRANSFORMER HO.
OFF.
AT GLADSTONE
Located 8 Miles N of Silverton
NO EXPOSURE ANY SIDE.
THE W. B. LOWE MINING & MILLING CO
YUKON MINE & CONCENTRATOR
NOT IN OPERATION
WATCHMAN: NO CLOCK: HEAT STEAM: LIGHTS ELECTRIC: I.E.P.: POWER ELECTRIC: FUEL COAL: WATER FROM MOUNTAIN SIDE: 2" HYD. 100' 2" HOSE.
LOG
BOARDING HOUSE
TRAMWAY
SIDING
SLIME TABLE
4 JIGS
ORE HO.
6 CONCENTRATING TABLES
IN CEMENT CREEK GULCH
Located 3 Miles N. of Silverton
NO EXPOSURE ANY SIDE.
THE KITTIMAC MINES CO.
CONCENTRATOR.
NOT IN OPERATION
NO WATCHMAN: HEAT STEAM: LIGHTS ELECTRIC: FUEL COAL: MOUNTAIN WATER.
15 CONCENTRATING TABLES
LEACHING TANKS
TRAM HO
PASSAGE
4" W. PIPE
TRAM TERMINAL & LOADING HO
BUNK HO.
Located 6½ Miles N.E. of Silverton,
2½ Miles N.E. of Howardsville
& ½ Mile N.E. of Hamlet Mill.
GREEN MOUNTAIN MINING & MILLING CO.
CONCENTRATION PLANT
NOT IN OPERATION - DOORS & WINDOWS NAILED UP
NO WATCHMAN: HEAT & POWER STEAM: LIGHTS ELECTRIC: FUEL COAL: WATER FROM MOUNTAIN SIDE.
CRUSHER
ON TRESTLE 40' HIGH
CHILIAN MILL
ENG.
CONCENTRATION TABLES
TRESTLE
S. N. R. R.
IN CUNNINGHAM GULCH
Located 5½ Miles N.E. of Silverton
2 Miles S.E. of Howardsville
& ½ Mile S.E. of Old Hundred Mill.
NO EXPOSURE ANY SIDE.
Scale of Feet.
50 40 30 20 10 0 50 100 150
SAN JUAN WATER & POWER CO.
SILVERTON SUB-STATION
1 MAN ON CONSTANT DUTY: HEAT ELECTRIC IN TRANSFORMER HO.: STEAM IN OFFICE & D.: LIGHTS ELECTRIC: FUEL COAL: CITY WATER.
D. & OFFICE
3" W. PIPE
TRANSFORMER HO.
WORK SHOP & W. HO.
ELEC. MOTOR
S. N. R. R.
Located 1¾ Miles N.E. of Silverton
NO EXPOSURE ANY SIDE
W.B. LOWE MINING & MILLING CO.
ARPAD CONCENTRATION MILL
NOT IN OPERATION.
WATCHMAN: NO CLOCK: HEAT STEAM: LIGHTS ELECTRIC: I.E.P.: POWER STEAM: FUEL COAL: WATER FROM MOUNTAIN SIDE.
8 VANNERS
STORE RM & TRAM HO.
ROLLS & CRUSHER
2 JIGS 2 CHILIAN MILLS
CARP'S SHOP
ENG. 1 DYNAMO
BOILER HOMESTON FURNACE
SIDING
Located 2½ Miles N.E. of Silverton
NO EXPOSURE ANY SIDE
HAMLET MINING & MILLING CO.
CONCENTRATOR
NOT IN OPERATION.
WATCHMAN: NO CLOCK: HEAT STEAM & STOVES: LIGHTS ELECTRIC: WATER FROM MOUNTAIN SIDE
BOARDING HO.
4 JIGS
TRAM HO. ORE CRUSHER
7 CONCENTRATORS
TRANSFORMER HO.
Located 6 Miles N.E. of Silverton
& 2 Miles N.E. of Howardsville
NO EXPOSURE ANY SIDE
OLD HUNDRED MINING CO.
CONCENTRATION MILL
NOT IN OPERATION.
WATCHMAN: NO CLOCK: HEAT STEAM: LIGHTS ELECTRIC: FUEL COAL: WATER FROM MOUNTAIN SIDE: 1½" HYDS. AS SHOWN: 400' 1½" HOSE.
CONCRETE
STAMP MILL
40 STAMPS
2 HUNTINGTON MILLS
16 CARD CONCENTRATORS
15 VANNERS
10 SETTLING TANKS
4" W. PIPE
BL. SM.
TRAM TERMINAL
COMPRESSOR STEAM TURBINE ENG. & GENERATOR 300 K.W.
COAL BINS NO RF.
S. N. R. R.
IN CUNNINGHAM GULCH
Located 5 Miles N.E. of Silverton
1½ Miles S.E. of Howardsville
NO EXPOSURE ANY SIDE

APPENDIX C

MAPS

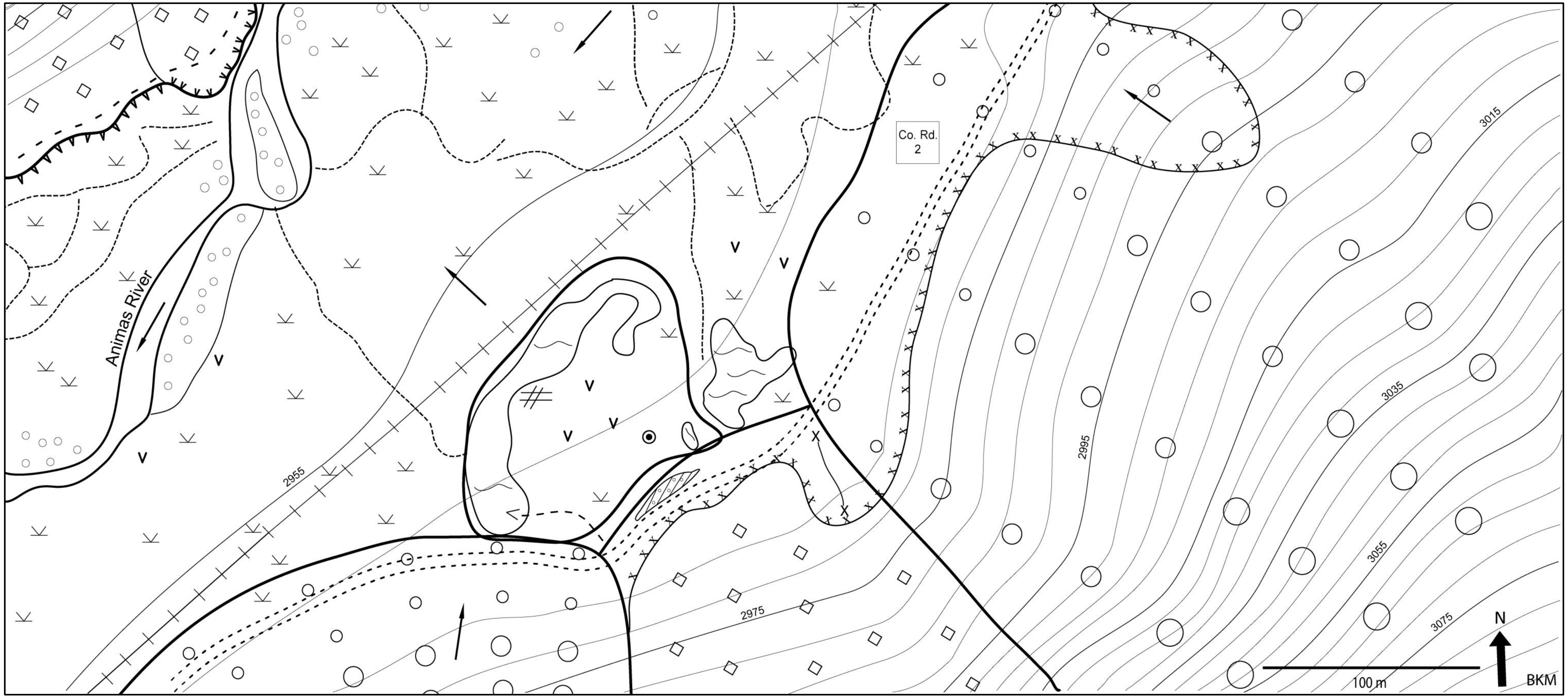


Geomorphic map of California Gulch

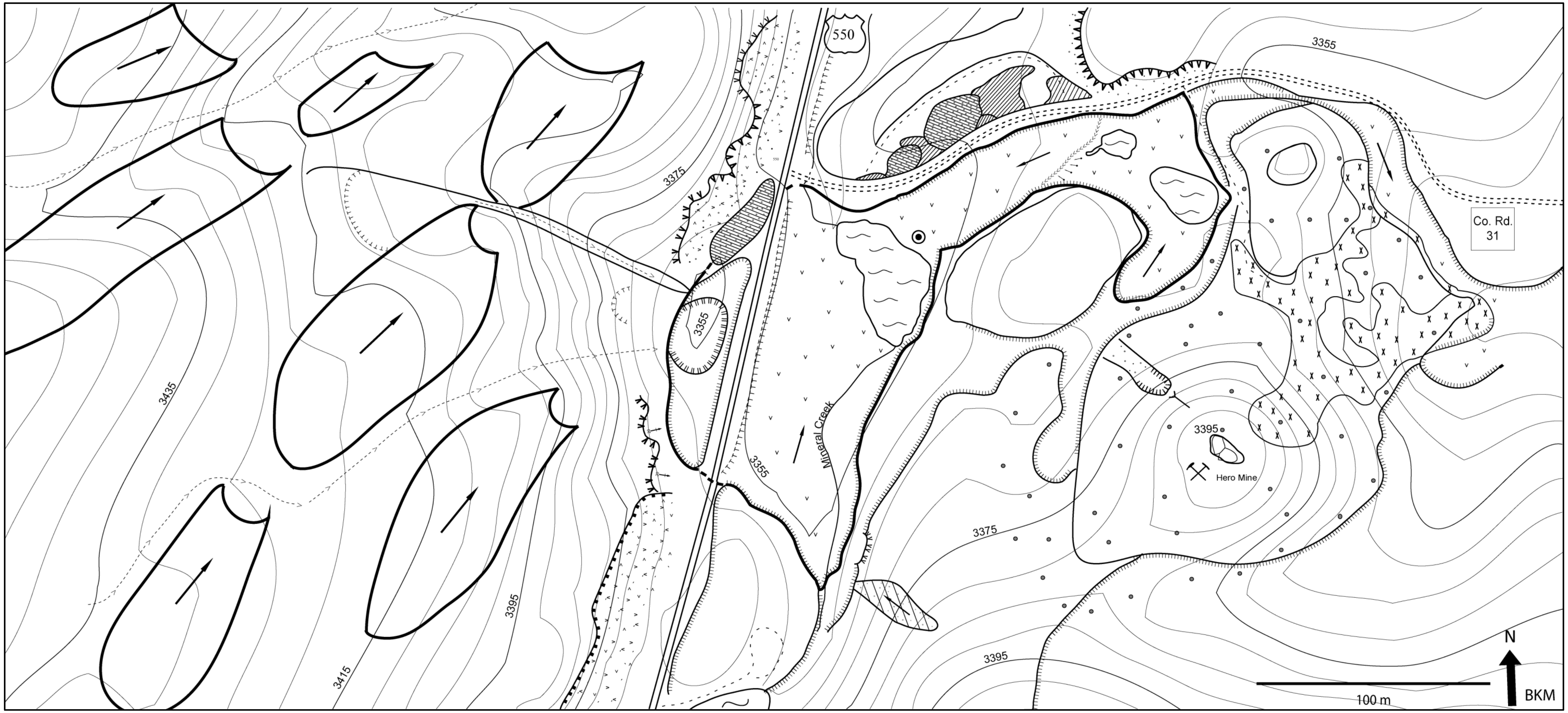


Legend for geomorphic maps

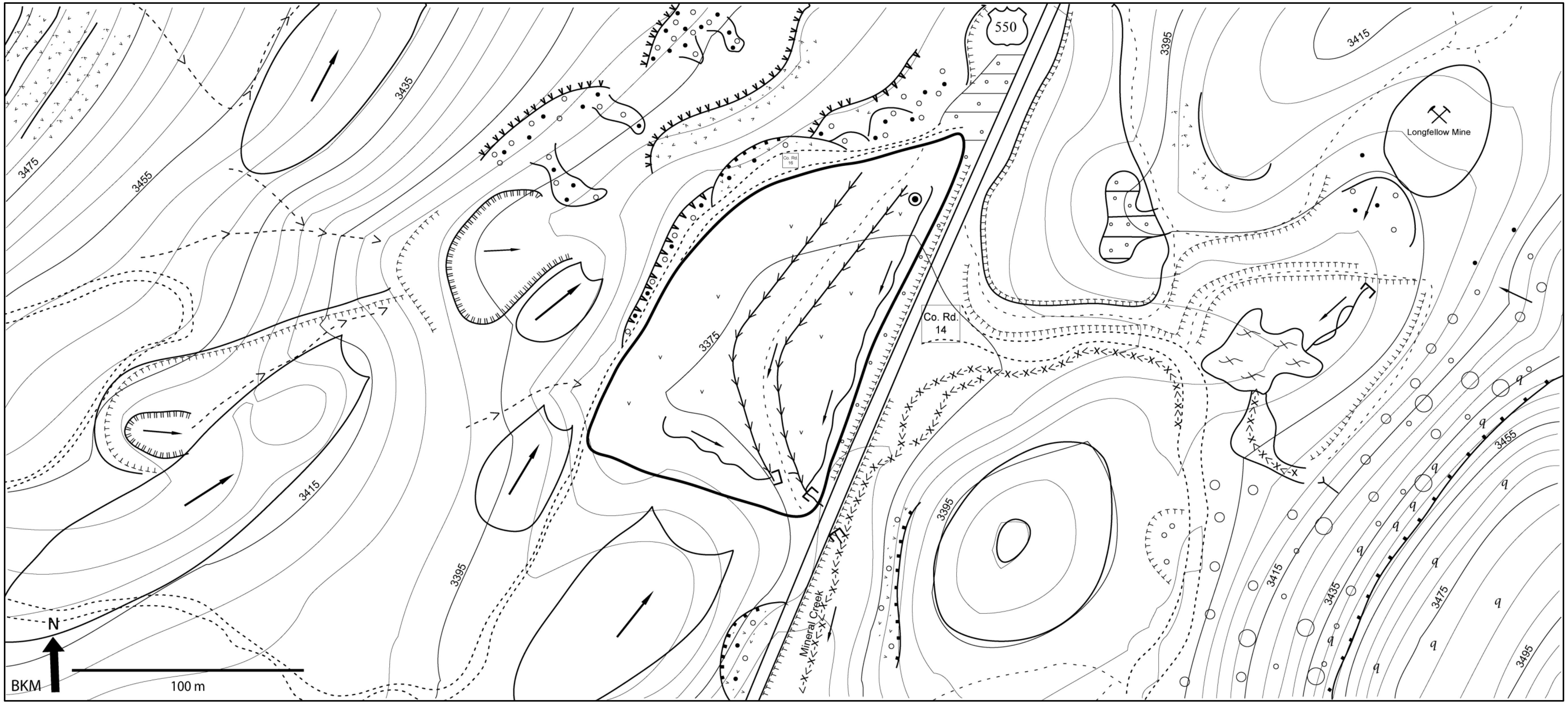
Geomorphic map of Glacial Lake Ironton



Geomorphic map of Howardsville



Geomorphic map of Red Mountain Pass North



Geomorphic map of Red Mountain Pass South