Geomorphic History of the Santa Maria Canyon, San Juan Mountains, Colorado

Maria S. Panfil
Carleton College
Northfield, MN 55057

Introduction

The Santa Maria Canyon is a small, steep-sided canyon that parallels the Rio Grande Valley for 12 km between Antelope Park and Clear Creek Park (Figure 1). Separated from the Rio Grande Valley by Long Ridge, the canyon at one time connected drainage between Clear Creek Park and the Rio Grande River below Hogback Mountain.

The project focused on mapping and describing geomorphic features in the canyon and using them to identify, sequence, and model events in the valley's formation. Evidence suggests three major episodes in the valley's history: glacial deposits and erratics indicate glaciation, paleochannels and boulder deposits indicate flooding, and young alluvial fill indicates recent and active hillslope erosion.

Project Methods

Field work emphasized reconnaissance mapping to identify geomorphic features and to sequence the events that caused them. I made observations on foot and from aerial photographs (USDA, 1985). Test pits provided further information about landform type. I collected basalt and andesite clasts to measure weathering rind thickness as a relative dating indicator. Carson (pers. comm., 1992) measured rind thicknesses and included Santa Maria Canyon stones in the set he collected from the Antelope Park area.

In order to model the hydraulics indicated by paleochannels and boulder deposits, I measured cross-sections and boulder diameters. Cross-sections were made with a hand level and stadia rod and were supplemented with information from the Workman Creek Quadrangle (USGS, 1963). I determined slopes from the quadrangle map and survey data taken with a Total Station. To determine maximum boulder size, I measured the three axes of the 10 largest boulders found in sections 50 m long and spanning the width of the channels.

I calculated velocity, depth, and discharge using averages of the median boulder axes, channel cross-sections and slope, and the paleohydraulic methods of Baker (1974), Williams (1983), and the empirical method of Costa (1983).

Glaciation

Ice covered the Southern Rocky Mountains twice in the last 150,000 years. The earlier event is thought to correlate with the Bull Lake Glaciation of Wyoming, occurring between 140,000 and 150,000 yr B.P.(Porter et al., 1983). The younger event was at a maximum between around 23,500 yr B.P. and 10,000 yr B.P. and is thought to correlate with the Pinedale event of Wyoming (Madole, 1986 and Elias et al., 1991). Atwood and Mather (1932) concluded that ice from the Rio Grande Glacier flowed over Antelope Mountain and Long Ridge and into the Santa Maria Canyon during the earlier event. Thinner ice during the more recent glaciation reached an elevation of 9,400 ft (2865 m) on Antelope Mountain and Long Ridge, too low an elevation to flow into the canyon. Atwood and Mather (1932) did not map any glacial deposits in the Santa Maria Canyon.

Erratics and a small deposit of glacial drift 2 km upvalley of the Canyon mouth indicate glaciation of the Santa Maria Canyon (Figure 2). We found crystalline erratics on top of Antelope Mountain (elevation 3100 m (10172 ft)) on the northeast ridge above the canyon mouth. I also found erratics on a low bedrock ridge in the middle canyon (elevation 2804 m (9,200 ft)). The drift deposit consisted of 4 small hillocks elongated parallel to valley orientation.

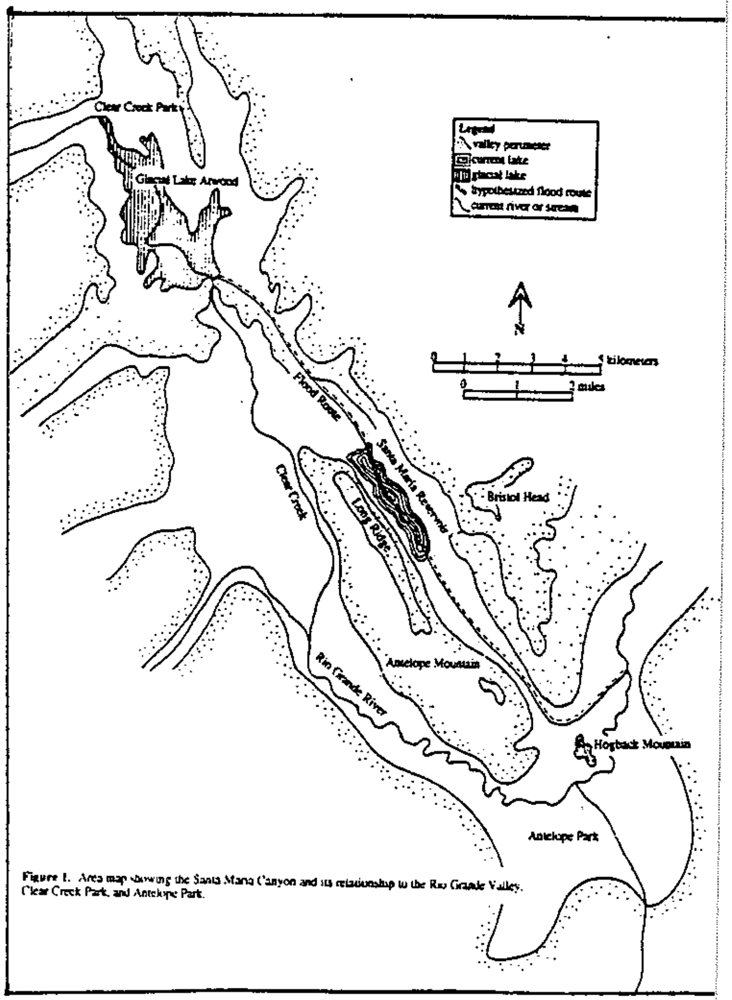

Figure 1. Area map showing the Santa Maria Canyon and its relationship to the Rio Grande Valley, Clear Creek Park, and Antelope Park.

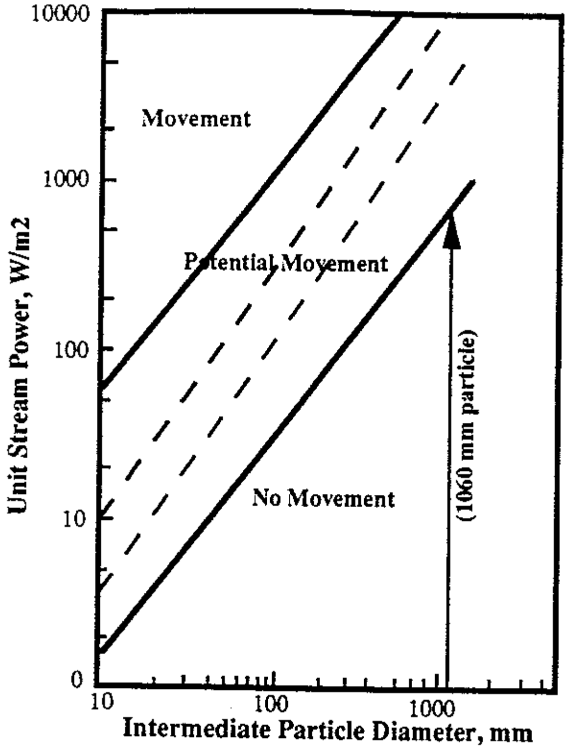

Figure 3: Approximation of the likelihood of particle movement for a given particle diameter and unit stream power. (Source: Williams 1983).

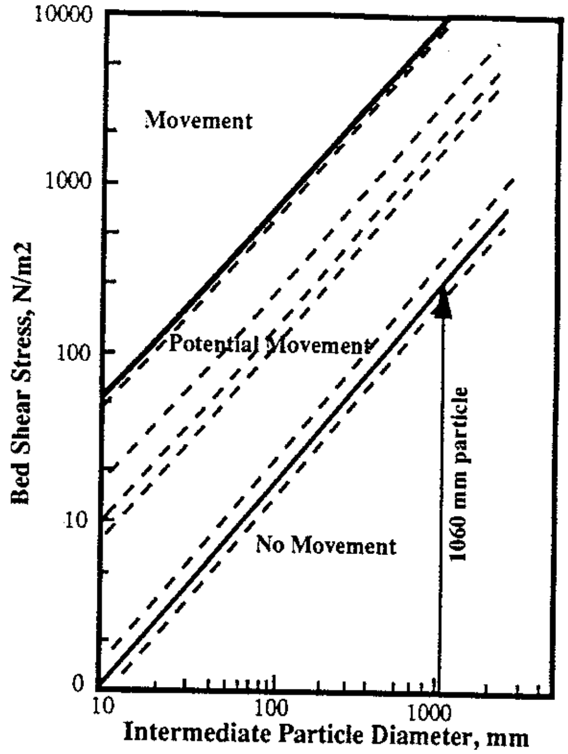

Figure 4: Approximation of the likelihood of particle movement for a given particle diameter and bed shear stress. (Source: Williams 1983).

Flow estimates:

1. Unit Stream Power, Bed Shear Stress, and Mean Flow Velocity:

Various authors have acquired data for flows that have moved particles of a given grain size. Williams compiled this data and defined the lowest unit stream power reported to transport a particular size particle. An approximate limiting line was fitted to the lower boundary of data points. This lower line represents the lowest unit stream power required to initiate transport (Williams 1983). The slope of this line was adopted for Figure 2. A given grain size remains stationary until unit stream power exceeds the value indicated by the line. A similar graphical procedure was followed for bed shear stress, τ, and mean flow velocity, V (Figures 3 and 4). As with unit stream power, there is a zone of potential movement for a given particle size. The equations for boundary lines, with d in mm, are as follows (Williams 1983):

For unit stream power, ω: (Equation 1)
$\omega = 2.9d^{1.3}$ (upper line) $\omega = 0.079d^{1.3}$ (lower line)
For bed shear stress, τ: (Equation 2)
$\tau = 3.9d^{1.0}$ (upper line) $\tau = 1.7d^{1.0}$ (lower line)
For mean flow velocity: (Equation 3)
$V = 0.046d^{0.5}$(upper line) $V = 0.065d^{0.5}$(lower line)

The lower boundary of the potential movement zone of Figures 3, 4, and 5 (Equations 1, 2, 3) presents the minimum flow strength required to transport a particle an appreciable distance. Using d= 1060mm (the largest boulder measured on the Rio Grande terraces), the approximate flows conditions are ω= 750 W/m^2, τ= 240 N/m^2 and V= 2.5 m/s. These numbers represent only the minimum flow capable of transporting the boulders present on the terraces along the Rio Grande.

2. Depth, Cross Sectional Flow Area, Water Surface Width, and Discharge:

Minimum values of other flow variables can also be estimated. Assuming that the slope of the modern channel represents the energy gradient of the transporting flow, then rearrangement of the basic definition

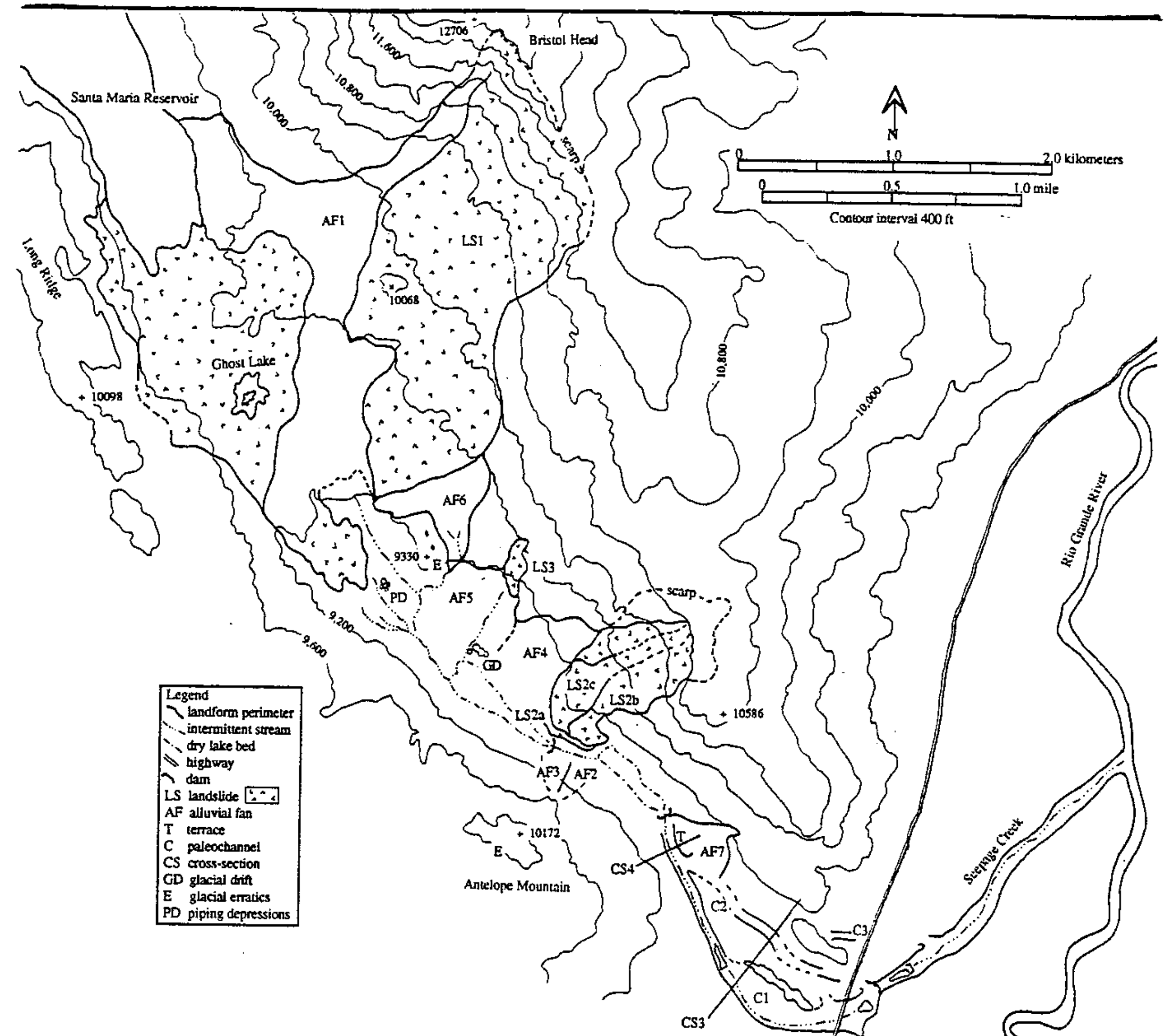

Figure 2. Geomorphic map of the Santa Maria Canyon.

Table 1. Weathering Rind thicknesses measured by Carson. Those collected on Antelope Mountain are the thickest in the set, and those collected in the Santa Maria Canyon are among the thinnest.

Site	Mean Thickness (mm)	Standard Deviation (mm)
Rio Grande Moraine, 15th oldest	0.08	0.34
T, mouth of Santa Maria Canyon	**0.11**	**0.26**
GD, Santa Maria Canyon	**0.15**	**0.38**
Moraine, 1 km W of Hogback Mountain	0.16	0.28
Ridge NW of Bennet Creek	0.25	0.63
Rio Grande Moraine, 11th oldest	0.29	0.51
Moraine, 3 km NE of Hogback Mountain	0.34	0.78
Highest Terrace, 3 km NE of Hogback Mountain	0.34	0.43
Rio Grande Moraine, 5th oldest	0.44	0.64
Antelope Mountain, upper half	**0.61**	**0.78**

They were recognized as a separate landform by their relief from surface topography, the high concentration of crystalline erratics confined to the mounds, and the abrupt change in vegetation cover between the mounds and the surrounding alluvial fans.

Weathering rinds collected on Antelope Mountain had the thickest rinds in the Carson set (0.65 mm), indicating their deposition at an earlier time than those found on the other features (Table 1). This supports Atwood and Mather's (1932) conclusion that the Rio Grande Glacier covered Antelope Mountain and Long Ridge only during the earlier glacial event (Bull Lake). However, evidence is not conclusive; standard deviations are high and the average rind thickness for Antelope Mountain Stones does not correlate with the thicknesses Kitchens (this volume) concluded represent the earlier glacial event.

Rind thicknesses from the drift deposit and the terrace (T) at the mouth of the canyon are inconsistent with the Atwood and Mather model. They are among the thinnest in the Carson set indicating a relatively short weather period; their thickness is consistent with Kitchen's younger event (Pinedale) grouping. Given the location of its end moraines, it is unlikely that the Rio Grande Glacier deposited these stones during the more recent glaciation (Pinedale). Two alternate hypotheses may explain the thin rinds. Perhaps flooding through the canyon during the more recent glaciation, eroded drift deposits left by an earlier ice flow, exposing unweathered drift and clasts. This is consistent with Colman and Pierce's (1981) conclusion that clasts in C horizons rarely develop weathering rinds. A second hypothesis is that flood waters deposited the stones and they remain in the valley only where older landforms remain uncovered by younger valley fill.

Drift and erratics suggest that the valley was glaciated at least once. Weathering rind data do not clearly constrain the timing of this event, however, they suggest that glaciation occurred first, with a later event such as a flood eroding or depositing drift.

Flooding

Atwood and Mather (1932) identified sediments from a glacial lake in Clear Creek Park (Figure 1). Glacial Lake Atwood, named and described by MacGregor (this volume), contained 6,636,447 m^3 of water at its highest level, 3094 m (10,150 ft). Paleomagnetic analysis of lake sediments indicates that the lake existed during the more recent glaciation, between 16,380 and 13,500 yr B.P. (MacGregor, this volume). McMillan (this volume) hypothesizes that the lake drained catastrophically, breaking through an ice dam and sending 6,087,090 m^3 through the Santa Maria Canyon (see Figure 1).

The strongest indication of flooding through the canyon is the arrangement of boulders into bars and on terraces at the mouth of the canyon and downstream. At least two main channels existed; they are outlined by high boulder concentrations (C1 and C2 in Figure 2). Other bars indicate that water flowed over the area between the two channels and behind the bedrock ridge below the northeast canyon wall (C3 in Figure 2). The channel where Seepage Creek now flows (C1) continues into the main valley to the confluence with the Rio Grande River. The median axes of the largest boulders average 1.41 m for the first 2.5 km away from the Canyon mouth.

The three paleohydraulic models used to predict water velocity, depth, and discharge produced different results (Table 2). The method used by Baker (1974) is based on theoretical relationships relating particle size to stream depth using the Shields' function for dimensionless shear and the Manning equation. Williams (1983) and Costa (1983) derive equations with boulder size as a function of depth, velocity, and stream power from published empirical data for bed movement.

The discharge estimated by the Baker (1974) method seems too large. The water surface level in CS 4 would be above the apex of AF7 and at an elevation of 2182 m (9160 ft) on Antelope Mountain, yet there is no evidence of flooding at this elevation. Also, Costa (1983) is critical of the use of 0.06 as the value for dimensionless shear in the Shields' calculation. The value results from experiments with smooth flow over equant sand grains, and studies since the Baker article was published suggest that the value should be smaller for turbulent flows with larger grain sizes, between 0.01 and 0.02 (Costa, 1983). When I substitute a value of 0.02 for dimensionless shear into the Baker calculations, I determined a discharge much closer to those indicated by the Williams (1983) and Costa (1983) methods (Table 2).

Costa and William's methods both produce reasonable results, though they differ by more than 5000 m^3s^{-1}. Costa (1983) found that paleohydraulic calculations he used are more accurate for small, steep-sloping channels, and overestimated a larger flow by 75%. The flow determined by the Williams (1983) method is less, however, his calculations extrapolate relationships determined from particle data with a maximum size between 1000 and 1200 mm, it is questionable whether the relationships are the same for particles of larger sizes like the ones in this study.

The range determined by these two methods provides the best estimate of discharge, between 2166 m^3s^{-1} and 7277 m^3s^{-1}. The estimate may be further constrained by cross-section and boulder information from closer to Glacial Lake Atwood and further downstream in the Rio Grande Valley.

Table 2. Results of paleohydraulic calculations.

Method	Cross-Section CS	Average Depth (m) D	Average Velocity (ms^{-1}) v	Discharge (m^3s^{-1}) Q	Average Discharge (m^3s^{-1}) of both cross-sections
Baker (1974) (dimensionless shear stress=0.06)	CS3 CS4	11.6 12.3	9.9 10.0	137,860.9 50,252.5	94,056.7
Baker (1974) (dimensionless shear stress=0.02)	CS3 CS4	3.9 4.1	3.9 4.0	6,374.0 7,535.4	6,954.7
Williams (1983)	CS3 CS4	3.0 3.2	2.6 2.6	2,480.8 1,851.9	2,166.4
Costa (1983)	CS3 CS4	4.6 4.9	5.7 5.7	9,773.0 4,781.5	7,277.3

Post-Glacial Deposition

Most of the valley is covered with post-glacial landforms formed by erosion of the northeast valley wall (Figure 2). The largest feature is the 4 km^2 landslide utilized as a dam for the Santa Maria Reservoir (LS1). It is indicated by hummocky topography with closed depressions and debris clasts up to 10 m in diameter. Other smaller slides, LS2 and LS3 also originate from the northeast canyon wall. LS2 occurred as three separate events distinguishable by differences in soil and vegetation cover. Sharp-edged rock clasts with little soil or vegetation form the youngest slide, LS2c. The middle slide, LS2b, has some soil, grass, and tree cover, and the toe of the oldest slide, LS2c, remains as a hummocky, silt-covered mound beneath the other two slides.

Alluvial fans with active debris flows are also transporting sediment to the valley floor. AF1 is the largest fan transporting sediment from the scarp of LS1 and burying parts of the slide's SE end. Gullies form the head of Seepage Creek and transport sediment and water carried by debris flows, by piping through the old slide, and by overland wash. Some are 300 cm deep and reveal a thick sequence of valley fill dominated by silt.

A radiocarbon date from the dry lake bed of Ghost Lake indicates that LS1 occurred before 7,610 +/- 90 yr B.P.. The lake lacks an outlet or inlet and was fed by seepage through the landslide. No channels cut through the slide or the deposits on the valley floor, indicating that LS1 and most of the valley's geomorphic features were deposited after the flood.

Conclusion

Evidence in the Santa Maria Canyon indicates glaciation, followed by flooding, followed by hillslope erosion. First, ice from the Rio Grande Glacier flowed into the canyon. Between 16,380 and 13,500 yr B.P. Glacial Lake Atwood drained catastrophically through the Santa Maria Canyon, with a discharge between 2166 m^3s^{-1} and 7277 m^3s^{-1} forming channels and depositing boulders. Since flooding, hillslope erosion has shaped the valley, a major event occurring before 7,610 =/-90 yr B.P., when part of Bristol Head tumbled to the canyon floor and formed the LS1 deposit.

References Cited

Atwood W.W. and Mather K.F., 1932, Physiography and Quaternary geology of the San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 166. 176p.

Baker, V.R., 1974, Paleohydraulic interpretation of Quaternary alluvium near Golden, Colorado: Quaternary Research, v.4, p.94-112.

Carson, R., personal communication, 1992.

Colman, S.M. and Pierce, K.L., 1981, Weathering rinds of basaltic and andesitic stones as Quaternary age indicator western U.S.: U.S. Geological Survey Professional Paper 1210.

Costa, J.E., 1983, Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range, Geological Society of America Bulletin, v.94, p.986-1004.

Elias, S.A., Carrara, P.E., Toolin, L.J., and Jull, J.T., 1991, Revised age of deglaciation of Lake Emma based on new radiocarbon and macrofossil analyses: Quaternary Research, v.36, p.307-321.

Kitchens, S., this volume.

MacGregor, K., this volume, Late Pleistocene history of Glacial Lake Atwood, San Juan Mountains, Colorado.

Madole, R.F., 1986, Lake Devlin and Pinedale glacial history, Front Range, Colorado: Quaternary Research, v.25, p.43-54.

McMillan, S., this volume, Late Pleistocene deglaciation of the Clear Creek Graben, San Juan Mountains, Colorado.

Porter, S.C., Pierce, K.L., Hamilton, T.D., 1983, Late Wisconsin mountain glaciation in the western United States, *in* Porter, S.C., ed., Late Quaternary Environments of the United States: Vol. 1: The Late Pleistocene: Minneapolis, University of Minnesota Press, p.71-110.

U.S. Department of Agriculture, 1985, Aerial Photographs 684-177 -179 and 684-153 -155.

U.S. Geological Survey, 1964, Workman Creek Quadrangle, Colorado: 7.5 Series (Topographic), DMA 4559 II NE-Series V877. scale 1:24,000.

U.S. Geological Survey, 1986, Bristol Head Quadrangle, Colorado: 7.5 Series (Topographic), DMA 4559 I SE-Series V877. scale 1:24,000.

Williams, G.P., 1983, Paleohydrological methods and some examples from swedish fluvial environments: I Cobble and boulder deposits: Geografiska Annaler, 65 A (3-4), p.227-243.

ICE STAGNATION IN PLEISTOCENE VALLEY GLACIERS, SAN JUAN MOUNTAINS, COLORADO: DEPOSITS AND A MODEL OF CONTROLS

Eric E. Small
Department of Geology
Williams College
Williamstown, MA 01267

INTRODUCTION

This study has two goals:

1) To describe and interpret Pleistocene valley glacier stagnant ice deposits in the San Juan Mountains, Colorado. Stagnant ice retreat and resulting deposits have not been recognized by previous workers in ancient valley glacier settings. Dead ice indicators are abundant in the San Juan Mountains and can be used to understand this process in Pleistocene valley glacier systems.

2) To determine the controls of ice stagnation in valley glacier systems. Controls of this process are not presently understood. Previous workers have suggested possible causes of stagnation for single glaciers; however, no earlier studies have determined what mix of variables is responsible for inducing this process in general. In an attempt to understand the controls of this process, a model of ice stagnation is developed in this study and tested with data from fifty valleys in the San Juans.

The San Juan Mountains are located in southwestern Colorado. Ice covered 5000km^2 of the San Juans during the most recent glacial maximum. Other than two large icefields, which formed over the high mountains and buried the continental divide, most of the Pleistocene ice in the San Juans were valley glaciers(Atwood and Mather, 1932). Detailed field work was completed in the eastern San Juans near Creede, Colorado; 107°00'W longitude and 37°40'N latitude. The middle fork of Roaring Creek, Red Mountain Creek and South Clear Creek were studied in detail. Aerial Photos from the entire San Juans range were examined.

STAGNANT ICE FEATURES

Topography

Areas of stagnant ice topography were examined using total station, plane table and alidade, and tape and inclinometer. A map of this topography in Roaring Creek valley was produced using plane table and alidade (Figure 1). This area is characterized by chaotic hummocks (kames), closed boggy depressions (kettles) and two sinuous, valley parallel ridges (eskers). This stagnant ice complex is surrounded by linear, sharp lateral, recessional and terminal moraines indicating deposition by active ice processes. Average maximum slope angle and mean slope angle of profiles across the stagnant and active ice areas demonstrate that different processes are responsible for construction of landforms (Figure 1). Previous workers have described deposits similar to these stagnant ice deposits in other areas of the San Juans.

Sedimentology

Sedimentological characteristics of ice stagnation complexes were investigated by completing measured sections, photographing outcrops, measuring fabric and analyzing sediment grain size and texture. The following sedimentological signatures of stagnant ice deposition were found: (1) extreme lateral and vertical variability in grain size, sorting and sedimentary structures indicating spatial and temporal heterogeneity in depositional processes (figure 2a); (2) patterns of esker sedimentation including interbedded fluvial gravels and quiet water deposits, and higher energy processes at the center of esker-shaped landforms (Figures 2b and 2c); and (3) faulted and tilted bedding from melting of supporting or buried ice blocks (Flint, 1971). These characteristics, along with facies associations, fabric data and spatial and temporal changes in sedimentation patterns, confirm that stagnant ice depositional processes were active in Pleistocene valley glaciers in the San Juans.

Aerial Photo Survey

Examination of aerial photos of 80 glaciated valleys in the San Juans indicates that stagnant ice topography is present throughout the entire San Juan range. Of the valleys studied, one third exhibited clear stagnant ice topography while another third were completely free of this indicator. It was not apparent whether ice stagnation occurred in the remaining valleys. Ice stagnation zones are most frequently 500m long and 200-300m wide with long axes parallel to the valley. These zones are usually limited to a single location in each valley.

ICE STAGNATION MODEL

A model was constructed, based on empirical and theoretical laws of glacier flow, to determine whether a receding valley glacier will develop a stagnant or an active margin. According to this model, ice stagnation can occur in two ways: (1) a topographic feature thins the glacier to a critical thickness, retarding internal deformation and pinching off a section of unnourished ice downstream (Figure 3a) and (2) downward melting can be slower than retreat of the active ice margin, the climatically controlled downstream limit to which ice flows, also stranding