GEOMORPHIC AND LITHOLOGIC CONTROLS OF DIFFUSE-SOURCE SALINITY GRAND VALLEY, WESTERN COLORADO

by

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April 1982

Completion Report No. 110

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OWRT Project No. B-203-COLO

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Submitted to
Office of Water Research and Technology
U.S. Department of the Interior
Washington, D.C. 20240

April, 1982

The work upon which this report is based was supported (in part) by funds provided by the United States Department of the Interior, Office of Water Research and Technology, as authorized by the Water Resources Research Act of 1978, and pursuant to Grant Agreement No.(s) 14-34-0001-0210 B203.

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CHAPTER I

INTRODUCTION

1.1 Statement of the Problem

Salinity is the quantity of total dissolved solids in water. The average annual salinity of the Colorado River at Imperial Dam, California, as well as in all of the major tributaries of the Upper and Lower Colorado River Basin lowlands, had nearly doubled during the century by 1965 (Iorns, et al., 1965). The most soluble and, therefore, most abundant solids in the Colorado River are sulfates and carbonates (Laronne, 1977).

The dissolved solids contribute to a concentration of about 1000 mg/l at Imperial Dam. Salinity of this magnitude is double the limit of 500 mg/l set by the U.S. Environmental Protection Agency for municipal use. Furthermore, it reduces the life and increases the maintenance cost of boilers, plumbing, and appliances used by industry and municipalities. Salinity, regardless of the types of salts involved, affects irrigated agriculture by decreasing productivity and/or increasing production costs (Bureau of Land Management, 1978). The salinity problem is an international one, as Colorado River water is used by Mexico.

More than half of the salt load in the Colorado River is thought to come from point and diffuse sources of natural origin in the upper basin (Bureau of Land Management, 1978). Point sources include saline seeps and springs, whereas diffuse sources originate from the entire drainage basin. One of the diffuse sources is runoff from Mancos Shale. This saline shale underlies large portions of the Upper Colorado River Basin in western Colorado and eastern Utah. This study addresses the geomorphic controls of salt release from the Mancos Shale that is exposed at the base of the Book Cliffs in Grand Valley, Colorado (Fig. 1.1).

1.2 Objectives

The objectives of this investigation were to:

1. Describe the geomorphology of the area.

2. Describe soluble mineral content (SMC) relationships of surficial materials in erosionally unstable landforms.

3. Relate geomorphic stability to processes of salt release from the area.

4. Recommend land use and/or salt control measures that might be employed for the purpose of reducing the salt load entering the Colorado River.

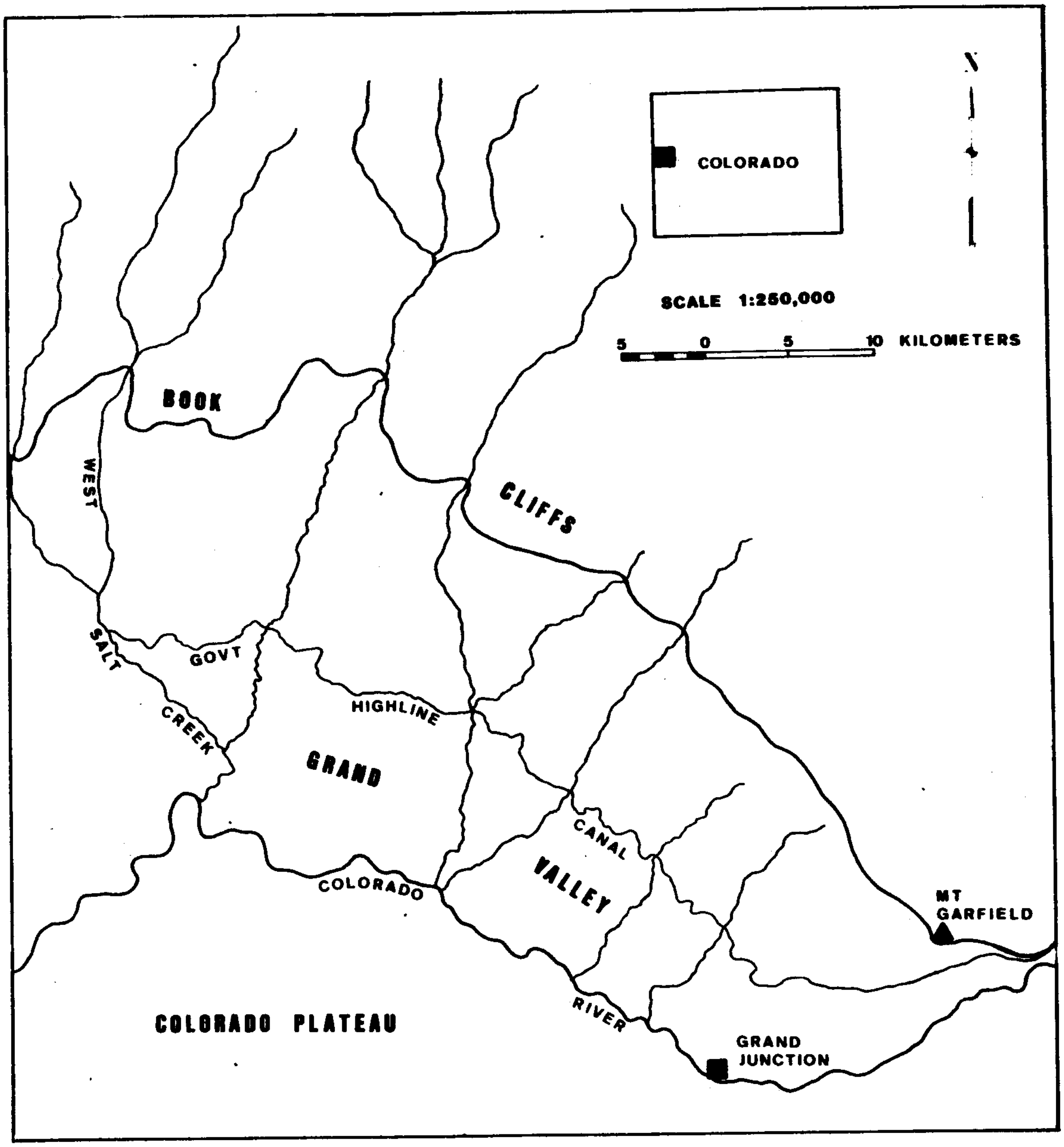


Fig. 1.1. Study area location map, Grand Valley, Western Colorado. Refer to Figure 3.1 for details.

CHAPTER II

PREVIOUS INVESTIGATIONS

Grand Valley and geologically similar regions in the Upper Colorado River Basin have been studied for various purposes for many years. Investigations have included the geomorphic description of pediments, runoff and sediment yield from hillslopes, hillslope morphology, land use, and salinity.

Studies of pediments go back to Gilberts' (1877) study of the Henry Mountains of Utah. He attributed pediment origin to lateral swinging of the streams issuing from the mountains. Rich's (1935) investigations along the Book Cliffs led to the conclusion that weathering and sheetwash are the principal pediment-forming agents, with stream capture causing the multiple surface levels. Hunt, et al. (1953), after studying the Henry Mountains, concluded that pediments are developed primarily by sheetwash and rill wash, and he also elaborated on Rich's stream capture hypothesis. Godfrey (1968) and Carter (1980) expanded on Hunt's conclusions and both observed that former interstream divides are the sites most vulnerable to dissection because the protective gravel cap is thinnest there. Carter (1980), after studying pediments south of Price, Utah, proposed sudden lowerings of the master stream's base level in order to account for multiple surfaces. Sinnock (1981) investigated pediment genesis at the base of Grand Mesa south of Grand Junction, Colorado. He concluded that the gravel deposits mantling the Mancos Shale were derived from mudflows and slurries on the basalt-capped escarpment associated with the melting of glaciers following four Pleistocene glacial episodes. Sinnock also contends that no comparable mudflows occurred in Grand Valley due to a lack of glaciation, or a resistant caprock in the Book Cliffs.

Runoff and sediment yield from hillslopes have been studied by several investigators over the past three decades. All have indicated that runoff and associated hillslope erosion occur almost wholly in response to high intensity summer thunderstorms (Schumm, 1964; Schumm, 1967; Hadley and Lusby, 1967; Lusby, et al., 1971; Bureau of Land Management, 1978). Schumm (1964) and Lusby, et al. (1971) conducted studies in Badger Wash near Mack, Colorado, and observed the importance of seasonal variations on hillslope processes. They noted the seasonal cycle of rill development and obliteration in conjunction with summer thunderstorms and winter frost heave of the surficial materials, respectively.

Based on hillslope measurements, Schumm (1964) concluded that the typical concave-convex hillslopes that have developed on the Mancos Shale are fashioned primarily by soil creep. That is, soil creep is a product of frost heave and gravity and entails the movement of soil from the convex portion over the steep portion, with soil accumulation on the concave portion. Schumm also reasoned that where creep is the dominant process, the greatest removal of material occurs on the upper part of the hillslopes, and that the fastest rates of soil movement are on the steepest portions of the slopes.

Hadley and Lusby (1967) had the opportunity to measure the erosional effects of a high intensity thunderstorm in a small basin in

Badger Wash. Their conclusions included: 1) a runoff:rainfall ratio greater than 0.50 probably is not unusual in the area; 2) much of the loose material on the hillslopes was removed; and 3) aspect played an important role in erosion in that the north facing slopes were steeper and had a greater depth of loose material due to frost heave than that of the south facing slopes, thus providing more material for erosion. According to their measurements that storm, which produced 30 minutes of runoff, resulted in the computed soil loss of 34.5 tonnes per hectare (15.4 tons per acre).

The effects of land use on the area have been studied, also. Schumm (1964) noted that in the spring following the last severe frost, the surfaces of slopes are unstable and that tracking by animals at that time of year could cause important downslope movement of soil. The Bureau of Land Management (1978) investigated the influence that grazing has on vegetative cover, infiltration and compaction of soils, runoff, and sedimentation. Their findings included the following: 1) range deterioration was halted and increase in ground cover of desirable grasses resulted when yearlong grazing was changed to a summer grazing system; 2) with more grazing, there was less infiltration due to loss of plant cover and increased compaction of soil; 3) grazing increased the compaction and the bulk density of the soil which, in turn, increased runoff and sediment yield; and 4) heavily grazed watersheds produced 30% more runoff and 45% more sediment than ungrazed watersheds. Their conclusions generally verify those reached by Lusby, et al. (1971) who, furthermore, observed that early in the year, grazed watersheds produced much more runoff than ungrazed watersheds, whereas later in the year, after the effect of summer storms, runoff was more nearly equal.

Other causes of increased runoff and erosion have been attributed to off-road vehicles and natural gas and coal exploration and extraction. The associated roads, trails, and other disturbances compact soils, reduce plant cover, and expose fresh shale. The most obvious erosion effects are rill erosion and gully headcut extension along vehicle tracks (Bureau of Land Management, 1978).

Investigations of relationships between salt release and runoff and erosion began in the last decade. Contributions have been made by Ponce (1975), Laronne (1977), and Sunday (1979). Ponce examined relationships between salinity and rainfall intensity, runoff rate, runoff duration, and suspended solids in runoff. In general, he concluded the following: 1) salt concentration in runoff is decreased when a change in rainfall intensity is not accompanied by a direct change in erosion rate; 2) salt concentration is increased when an increase in rainfall intensity is accompanied by soil erosion; 3) salt concentration is highest at the onset of runoff generation and soon decreases to a relatively constant value; and 4) salt concentration is dependent on the dissolution of mineral salts that have been exposed by erosion and that are contained in the soil matrix and on soil particles suspended in the runoff. One of Laronne's observations was that the salinity of storm runoff is influenced primarily by the availability of soluble minerals on the surface and in salt crusts derived from evaporation of soil moisture. Tests conducted by Sunday led to conclusions that the specific conductivity (EC) of runoff increases with increasing slope, increasing suspended sediment concentrations associated with rill flow, and higher SMC values. Furthermore, she observed that rill flow has a much higher rate of erosion than that of sheet flow, therefore it introduces more sediment and salt to the runoff.

Investigations on SMC of surficial materials have been conducted by Laronne (1977), the Bureau of Land Management (1978), and others. Samples tested by Laronne show: 1) the dominant mineral in Mancos Shale is gypsum, while calcite, dolomite, and gypsum are dominant in alluvium; 2) soil crust salinity increases as the permeability decreases and the SMC of the underlying material increases; 3) SMC increases with depth in shallow alluvium overlying Mancos Shale; 4) a uniform SMC with depth characterizes deep and leached bed materials and terrace deposits; and 5) Mancos Shale hillslopes contain an appreciably higher content of soluble minerals than do alluvial samples.

The Bureau of Land Management has made the following salinity classification: 1) soils developed on gravel pediment surfaces are nonsaline (EC <4000 μmho/cm) in the top 75 CM, but saline at greater depths; 2) soils developed on Mancos Shale are nonsaline in the top 30 cm, but saline at greater depths; and 3) soils on alluvial deposits are saline throughout the profile.

Carter (1980) studied pediment gravels and the gravel-bedrock interface and related his findings to salinity. Although no samples were collected, he proposed that where ground water could migrate through pediment gravel, it would become highly saline from the calcite cement in the gravels and from leached salts concentrated at the gravel-bedrock interface

Schneider (1975) also investigated the role of ground water with respect to salinity. He noted that ground water within the Mancos Shale is too meager to be considered to be a significant aquifer. However, ground water samples indicated that salts leached from Mancos Shale contribute to ground water salinity, which is in fact saturated with respect to calcite and gypsum. He also observed that, although the shale is vertically impermeable, ground water recharge can occur along laterally interconnected planes and joints. Schneider concluded that the unlined Government Highline Canal is a major contributor to ground water salinity in the Grand Valley.

CHAPTER III

DESCRIPTION OF THE FIELD AREA

3.1 Location

The study area is located in Grand Valley, Colorado. It is bounded by the Book Cliffs to the north, the Government Highline Canal to the south, Mount Garfield to the east, and West Salt Creek to the west (Fig. 1.1). The piedmont consists of an area of about 535 km^2 of exposed Mancos Shale, pediments and alluvium (Fig. 3.1).

3.2 Geology

The Mancos Shale is a marine shale of upper Cretaceous age. It is about 1200 m thick in the Grand Valley near Grand Junction, Colorado (Fisher, et al., 1960). About 300 m of the formation is exposed, and nearly all of the outcrop is north of the Highline Canal. The remainder is covered by fan deposits, alluvium that is derived from the Mancos Shale, and by Colorado River alluvium (Schneider, 1975).

Within the study area, the Mancos Shale has a structural dip of about 5°N. It is characterized by zones of thin irregular layers and overlapping lenses of calcareous sandstone, concretionary beds, and limestone interbedded in shale. The thickness of the zones range from 0.5 to 4 m and the groups are 8 to 60 m apart (Fisher, et al., 1960). The zones are much more resistant than the enclosing shale, and they crop out at times as cuestas. The shale surface is

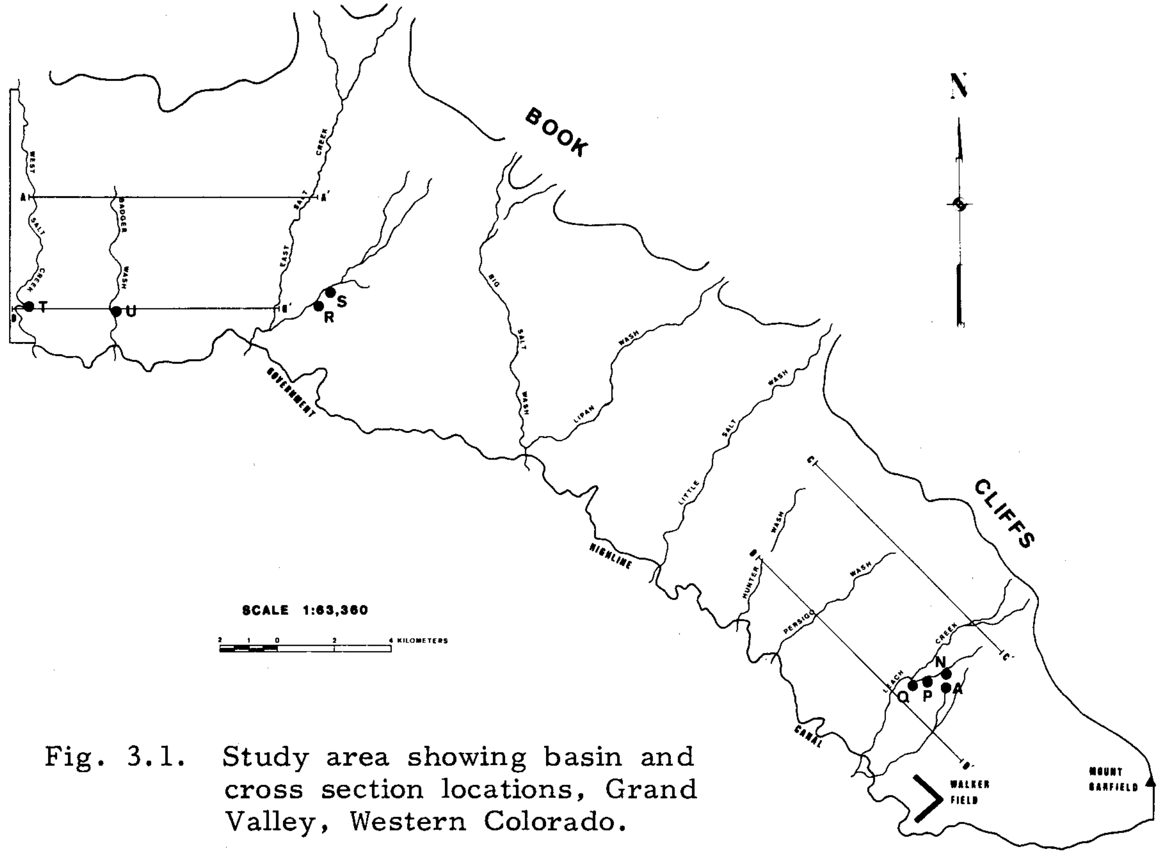


Fig. 3.1. Study area showing basin and cross section locations, Grand Valley, Western Colorado.

littered in many areas with fragments and plates of sandstone ranging up to 0.5 m in diameter and with fragments of concretions composed of hard, dense impure limestone.

Badlands dominate the area. Amid the badlands are pediments and alluvial deposits. The pediments are longitudinally concave-upward, slope away from the cliffs and occur at no fewer than three distinct elevations. Except for some of the alluvium in drainage basins extending beyond the Book Cliffs, i.e., Big Salt Wash, Little Salt Wash, East Salt Creek, and West Salt Creek, the alluvium is derived almost entirely from weathered Mancos Shale and from the pediments.

The Mancos Shale was deposited in shallow water of the Upper Cretaceous Sea (Fisher, et al., 1960). The shallow water environment was conducive to the rapid evaporation of sea water and the resultant precipitation of slightly to highly soluble minerals. The most abundant soluble mineral in the study area is gypsum ($CaSO_4 \cdot 2H_2O$), with calcite ($CaCO_3$) next in abundance. Appreciable amounts of sodium and magnesium hydrated sulfates and other carbonates are present also. Chloride salts do not occur in appreciable amounts (Laronne, 1977).

3.3 Climate and Vegetation

The climate is arid to semiarid. Annual precipitation normally is less than 250 mm per year. Precipitation mainly occurs in the form of snowfall in the winter months and as intense thunderstorms in the summer months. Runoff from the Mancos Shale badlands occurs almost exclusively as a result of high intensity thunderstorm events. Due to high daytime temperatures and low relative humidity, potential evaporation rates are very high in the summer. Consequently, most of the soil moisture is supplied by melting snow and low intensity rains in the winter.

Vegetation is of the salt-desert-shrub type (Bureau of Land Management, 1978). Black greasewood, mat saltbush, big sagebrush, and rubber rabbitbrush grow on alluvial soils and along tributaries of the abundant drainage basins. Upland sandy soils support shadscale and galleta. Gardner saltbush is the dominant plant on the shaley soils (Lusby, et al., 1963).

3.4 Land Use

Land use includes recreational use of off-road vehicles (ORVs), natural gas and coal exploration and extraction, and grazing. Trails and roads are abundant. Several watersheds in the vicinity of Grand Junction and Walker Field are popular ORV sites. Access to turn-of-the-century Mesa Verde Formation coal mines involved a network of haul roads and a railroad spur across the Mancos Shale terrain. Natural gas production in the last three decades has resulted in numerous new access roads and buried pipelines.

Despite the desert environment, the area has been grazed since the 1880's. Grazing began with cattle herds imported from Texas, and beginning around 1915, it included large flocks of migratory sheep. Heavy grazing was restricted in part by the Taylor Grazing Act in 1934 (Lusby, et al., 1963). It decreased even more in the 1950's when trucks began transporting sheep to the high country. The entire study area is still open range, however, and evidence of livestock use is present in nearly every watershed. In order to support the livestock in the desert, numerous small stock ponds were built with associated access roads.

CHAPTER IV

METHODS

4.1 Geomorphology

The geomorphology of the study area was described. This included identifying the major landforms, determining their processes of development and erosion, describing the erosional stability of each landform, and compiling geomorphic maps.

A field reconnaissance was conducted in order to identify the major landforms. The area consists of badlands, pediments, and alluvial valley floors. Badlands dominate in areal coverage, and drainage basins in them vary in size, shape, relief, rock type, and vegetative cover. The pediment surfaces and alluvial valley floor surfaces are similar in that, generally, they have smooth, gently sloping surfaces.

The processes of development and erosion of the pediments and alluvial valley floors were hypothesized from visual observation in the field and from previous investigations relating to these landforms. These two landforms were considered to be much more erosionally stable than the badlands.

Field observations supported previous investigations (Chapter II) that the badlands are characterized by rapid erosion. Consequently, they were studied quantitatively. Eight small drainage basins were chosen arbitrarily in order to investigate erosional processes. Channel profiles and valley cross sections were measured, and the size, shape, relief, rock type, and vegetative cover were described for each basin. Basins P and Q, and Basins R and S are closely spaced and both sets have similar rock type and vegetative cover, respectively. Consequently, soil depth measurements were conducted in Basins A, N, Q, S, T, and U, only. The basin characteristics were analyzed in order to determine inter- and intrabasin correlations that would be useful for describing erosional processes in the badlands.

Longitudinal profiles of the main channel and several major tributaries were measured, as well as several valley cross sections, in each of the eight basins. Channel length was measured along the center of each channel. Change in channel elevation was measured with a level alidade and a stadia rod. Where channels were incised into alluvial fill, profiles were surveyed along the channel bottom and on the surface of the alluvial fill immediately adjacent to the channel. The plane table and alidade method, as described by Compton (1962), was employed to measure the valley cross sections at roughly equally spaced locations along the basin lengths.

A hand trowel was used to dig pits for the purpose of measuring soil depth. Soil, as used in this study, is defined as the layer of material derived from underlying weathered, yet structurally distinct, bedrock. Soil depth sites included both divides, both hillslopes, and channel bottoms.

The soil depth data were analyzed for inter- and intrabasin relationships. An analysis of variance was conducted to determine the significance of difference between the soil depth means for: basin divides and basin hillslopes within each basin; and for each basin within two sets of basins according to underlying bedrock type. A

T-test was conducted to determine the significance of the difference of the means for soil depths between two sets of basins according to bedrock type. Since hillslope-facing directions were quite variable within each basin, the soil depth-hillslope aspect relationship was not tested.

Previous investigations have shown that erosion and salinity of runoff increase with increasing hillslope gradient. Since hillslope gradients increase as relief increases, a relative relief map was compiled according to the method described by Kertész (1979). The study area was divided into grids for which the relative relief in meters per square kilometer was determined. The purpose of the map was to delineate areas of high or low relative relief which would indicate areas of relatively high or low sediment and salt production, respectively. Topographic maps (1:24,000) were used to measure relative relief.

Field investigations showed that three major landforms are present in the area: 1) badlands; 2) pediments; and 3) alluvial valley floors in major drainages. The three landforms were delineated on a landforms map in order that the erosionally unstable badlands would be differentiated from the more stable pediments and alluvial valley floors. Aerial photographs (1:20,000) and topographic maps (1:24,000) were used to map the landforms.

4.2 Salinity

The surficial materials of several small basins in the badlands were examined for inter- and intrabasin SMC relationships that could be inferred for all of the badlands in the area. For the same reason mentioned above, surficial materials were studied in Basins A, N, Q, S, T, and U, only.

Soil and weathered bedrock samples were collected for SMC analysis at the same sites that soil depth measurements were recorded. For the soil samples, each sample contained a column of material from the surface to the top of the weathered bedrock. The weathered bedrock samples contained a column of the top 10-15 cm of that material. A few samples of alluvium were collected for analysis, also.

The samples were analyzed for SMC by a method very similar to that outlined by Laronne (1977). Laronne observed that many fragments of material did not break down during his procedure, so that the total SMC of his samples were not derived. Therefore, this procedure differs from Laronne's in that the samples were pulverized and sieved in order to provide silt- and clay-sized particles only.

Laronne (1977) observed 10,000 ppm solid sediment concentration in samples collected from a flash flood in the study area. He simulated the flood water in the laboratory by using a 1:99 sediment: water mixture. Consequently, the SMC in percent was calculated and used herein as follows:

$$\begin{aligned} SMC &= [(TDS_{1:99}\ mg/\ell)(g/10^3\ mg)(\ell/10^3 m)(99\ m\ell/g)]\ (100) \\ &= (TDS_{1:99})(0.0099) \qquad (4.1) \end{aligned}$$

SMC is related to the total dissolved solids (TDS) of a solution which, in turn, is related to the specific electrical conductance (EC) of a solution. The relationship between TDS and EC for Mancos Shale materials in Grand Valley, as derived by Laronne, is as follows:

$$\log (TDS) = -0.47413 + 1.1212 \log (EC) \qquad (4.2)$$

Due to the number of samples to be tested, twelve 1:99 sediment:water samples, a soil and weathered bedrock sample from each basin, were analyzed for the purpose of deriving a function describing the rate of solution of the soluble minerals. EC for the 12 samples were determined as follows: 1) the samples were air dried at room temperature; 2) the 1:99 sediment:water ratio was obtained by mixing 2 g of crushed and sieved material with 198 g of distilled water in 500 mℓ Erlenmeyer flasks; 3) the flasks were closed with stoppers to eliminate evaporation and then were shaken for eight hours on a horizontal 15-flask capacity shaker at 140-150 cycles per minute, during which time EC was recorded at 0.25, 0.5, 1, 2, 4, 6, and 8 hours; 4) at each measurement 25 mℓ of solution were poured into the EC meter cup and its temperature was recorded; and 5) EC in μmho/cm at 25°C for each solution was recorded by a 'Lecto Mho Meter' (Lab-line Instruments, Inc.) after the instrument was calibrated to the temperature of each sample.

The measurements for the 12 samples were plotted as EC versus time. Although EC values varied considerably, each sample had a similar-shaped plot. The best fitting curves for the individual plots were natural log functions and power functions, with power functions of the form $Y = bX^m$ having the best fit based on r^2 values. The exponents of the power functions, which described the curve, were averaged in order that one equation could be applied to all of the samples, regardless of initial EC values.

The power function was used to estimate the maximum EC for all of the samples by the following procedure: 1) all samples were measured for EC after two hours of shaking time; 2) intercept "b" was calculated for each sample using X = 2 hours and Y = EC at 2 hours; and 3) maximum EC (Y_{max}) was calculated by using "b" from step (2) and X = 5 hours, which was the maximum time that it took the 12 test samples to reach maximum EC values. TDS and SMC were calculated for each sample based on estimated maximum EC for each sample. Error was not determined for maximum EC or SMC.

The calculated SMC values were tested for inter- and intrabasin relationships. Analyses of variance were conducted to determine the significance of differences between SMC means for: soil and weathered bedrock samples within each basin; collective soil and weathered bedrock samples from sample transects in each basin; and collective soil and weathered bedrock samples for each basin within two sets of basins according to underlying bedrock type. A T-test was conducted to determine the significance of the difference between the SMC means for collective soil and weathered bedrock samples of the two sets of basins according to bedrock type.

CHAPTER V

GEOMORPHOLOGY

5.1 Introduction

The first objective involved the geomorphic description of the study area. This included identifying the major landforms, determining their processes of development and erosion, as well as describing the relative erosional stability of each landform. Field investigations and aerial photo interpretation indicated that badlands dominate the region, isolated pediments comprise the next largest portion of the area, and alluvial deposits make up the remaining area.

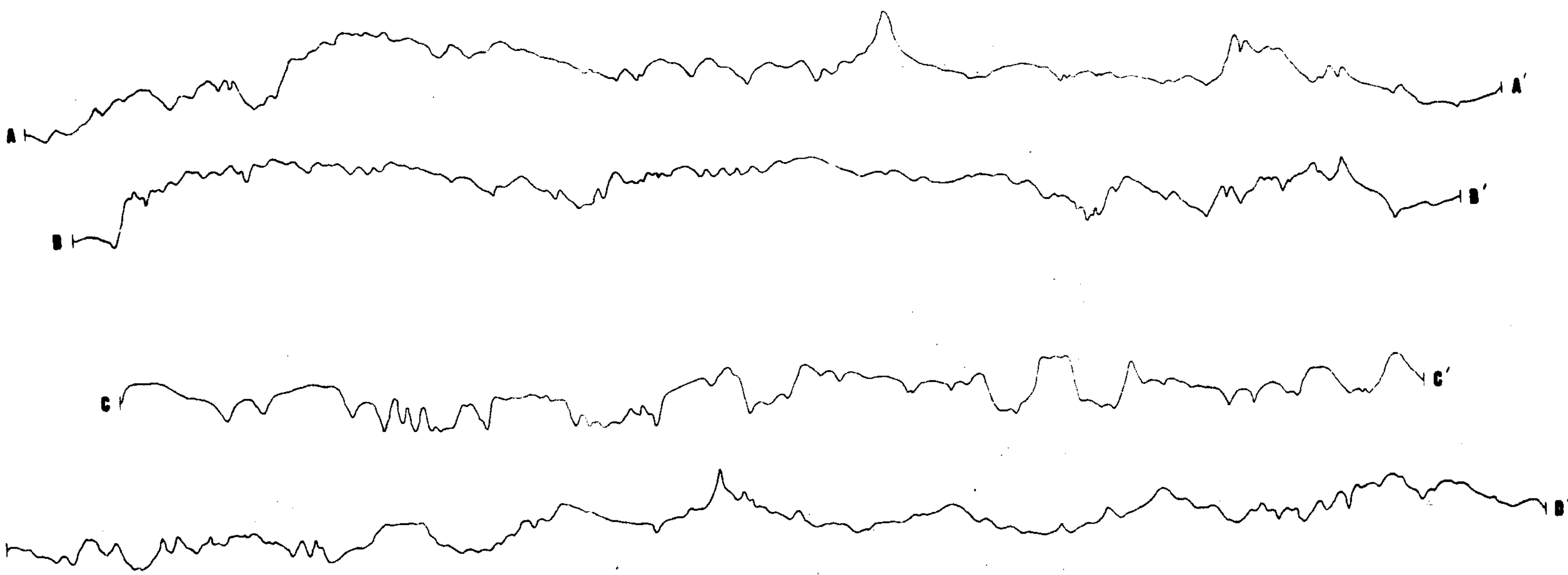
5.2 Badlands

5.2.1 Badland Topography

Badland topography is the most prominent landform in the area. The cross sections of Figure 5.1 show the characteristic appearance of the landscape. The badlands have variable relief and drainage density. Although some drainage divides are rounded, the sparsely vegetated area is characterized by an intricate maze of steep ravines.

5.2.2 Channels

Figure 5.1 gives an indication of the high density of channels in the area. In fact, six types or orders of magnitude of channels have developed in the area. From largest to smallest, they are described as follows: 1) those that extend beyond the cliffs are



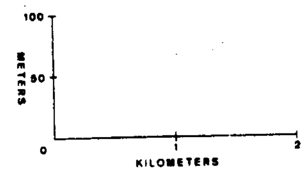


Fig. 5.1. Study area cross sections. Refer to Figure 3.1 for cross section locations.

called upland channels; 2) those that extend up to the cliffs are called cliff channels; 3) those that originate on the piedmont are called piedmont channels; 4) those that are tributaries to any of the first three types and originate on the piedmont are called tributary-basin channels; 5) those that are smaller tributaries within the tributary basins are called tributary channels; and 6) those that are formed on the hillslopes are called rills.

Channel and basin development appear to be analogous to rill formation. The similarities between these channels and the erosional development of rills were readily identified based on studies conducted by Mosley (1972). Conclusions offered by Mosley that are pertinent to this analogy are: 1) rills are formed by recession of knickpoints or headward erosion; 2) larger catchments are relatively more elongated than smaller catchments; 3) rill drainage density is lower in larger basins; and 4) rills are roughly parallel on straight slopes, and they converge on concave slopes.

Rills in the Mancos Shale badlands have been studied by several authors, including Schumm (1964), Lusby, et al. (1971), Howard (1972), and Sunday (1979). However, the analogy between rill development and the overall channel system has not been made. The analogy is important in that it indicates that the surface of the piedmont is relatively steep and that rill-type erosion is the dominant erosional process in the area.

Rills identify locations of rapid erosion. Since the area is composed of channels that appear to have the same genetic character of rills, the analogy between the channel system and rills, in terms of rapid erosion, can be inferred. Therefore, whereas rills have been targeted as primary agents of erosion in previous studies, the entire channel system is actively expanding and downcutting in the area. Consequently, efforts to reduce natural levels of erosion must be directed towards the overall channel network as opposed to only rills and tributary basins.

Twenty-three of the three largest channel types cross the Highline Canal or intersect at close proximity to it. Of them, three are upland channels, 13 are cliff channels, and seven are piedmont channels. Where they cross the piedmont, the upland channels have the lowest gradient and the piedmont channels have the highest gradient.

Due to their large size, the first three channel types were examined with the aid of topographic maps and aerial photographs, and only general characteristics were observed. The characteristics include the channel gradients and the analogies to rill development mentioned above. The main channels and several major tributaries were measured in eight tributary basins (Fig. 5.2) for the purpose of identifying inter- and intrabasin channel relationships.

Of the measured basins, Basin T is a tributary of an upland channel (West Salt Creek), Basins N, P, and Q drain into a piedmont tributary of a cliff channel (Leach Creek), and Basins A, R, S, and U are tributaries to piedmont channels (Fig. 3.1). As expected, the tributary-basin channels have greater gradients than the channels into which they drain. Consequently, where channels start on or flow over the piedmont, average channel gradients increase from Type 1 upland channels, to Type 6 rills.

The flow in nearly all channels in the area is ephemeral, flowing in response to high intensity summer thunderstorms. The only

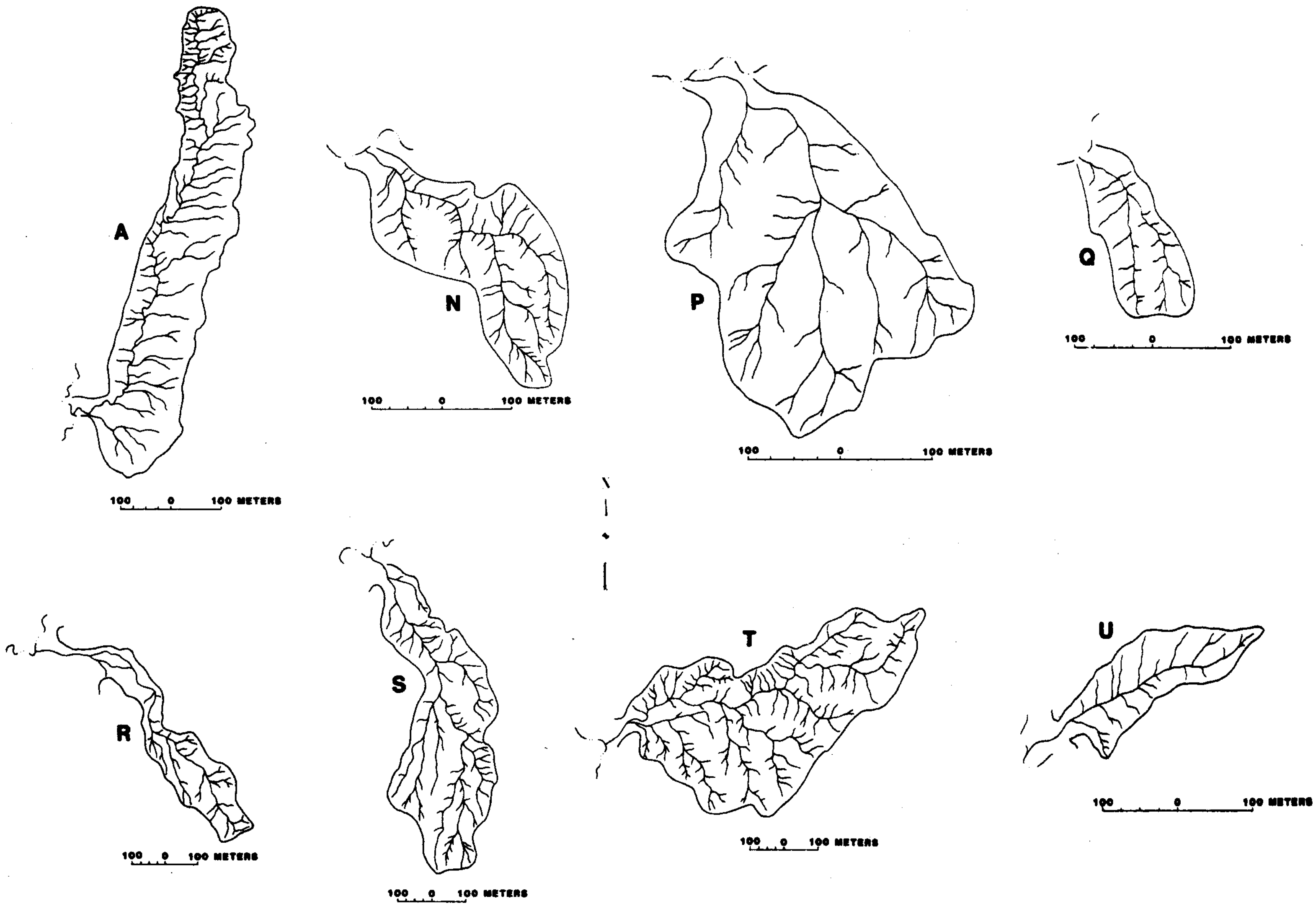


Fig. 5.2. The eight measured drainage basins in Grand Valley, Western Colorado. Refer to Figure 3.1 for drainage basin locations.

exceptions are a very few channels that have some snowmelt- and/or spring-derived flow. Two of the three upland channels, West Salt Creek and East Salt Creek, are intermittent and, at times, ephemeral streams. They flow in the spring and early summer due to snowmelt in their upland catchments, and they often flow in conjunction with intense thunderstorms. The other upland channel, Big Salt Wash, is at times a perennial stream when its flow, though very small, is supplied by ground water sources in its upland reaches.

5.2.3 Tributary-Basin Morphology

Examination of the tributary basins indicates great variability in inter- and intrabasin characteristics. In all cases, basin length is greater than basin width, but basin size, shape, and relief vary widely. Table 5.1 shows that basin area ranges from 22,000 m^2 for Basin Q to 340,000 m^2 for Basin T. Relief varies from 15.2 m to 84.7 m for Basins Q and T, respectively. The lowest relief ratio occurs for Basin S with a value of 0.052, while the highest is for Basin U with 0.097. Finally, Basin P has the smallest length:width ratio at 1.46, and Basin A has the largest at 5.45.

The only correlation found among the basin characteristics that has an r^2 value greater than 0.50 is between basin area and relief, where:

$$\text{Relief} = 20.19 + 0.0001937\ (\text{Area}) \qquad (5.1)$$

$$r^2 = .829$$

This linear relationship (Fig. 5.3) was expected, but it does not contribute to an understanding of the geomorphic processes relevant to the study.

Table 5.1. Measured drainage basin characteristics.

Basin	Area (m^2)	Relief (m)	Basin Length (m)	Maximum Basin Width (m)	Relief Ratio	Length/Width	Avg. Gradient of Main Channel (%)
A	250,000	76.2	900	165	0.085	5.45	4.11
N	44,300	32.3	420	150	0.077	2.80	6.56
P	78,000	22.6	410	280	0.055	1.46	3.64
Q	22,000	15.2	240	100	0.063	2.40	5.46
R	105,000	56.1	860	180	0.065	4.78	4.84
S	240,900	48.8	945	310	0.052	3.05	3.95
T	340,300	84.7	1000	455	0.085	2.20	5.68
U	32,000	34.1	350	90	0.097	3.87	7.38

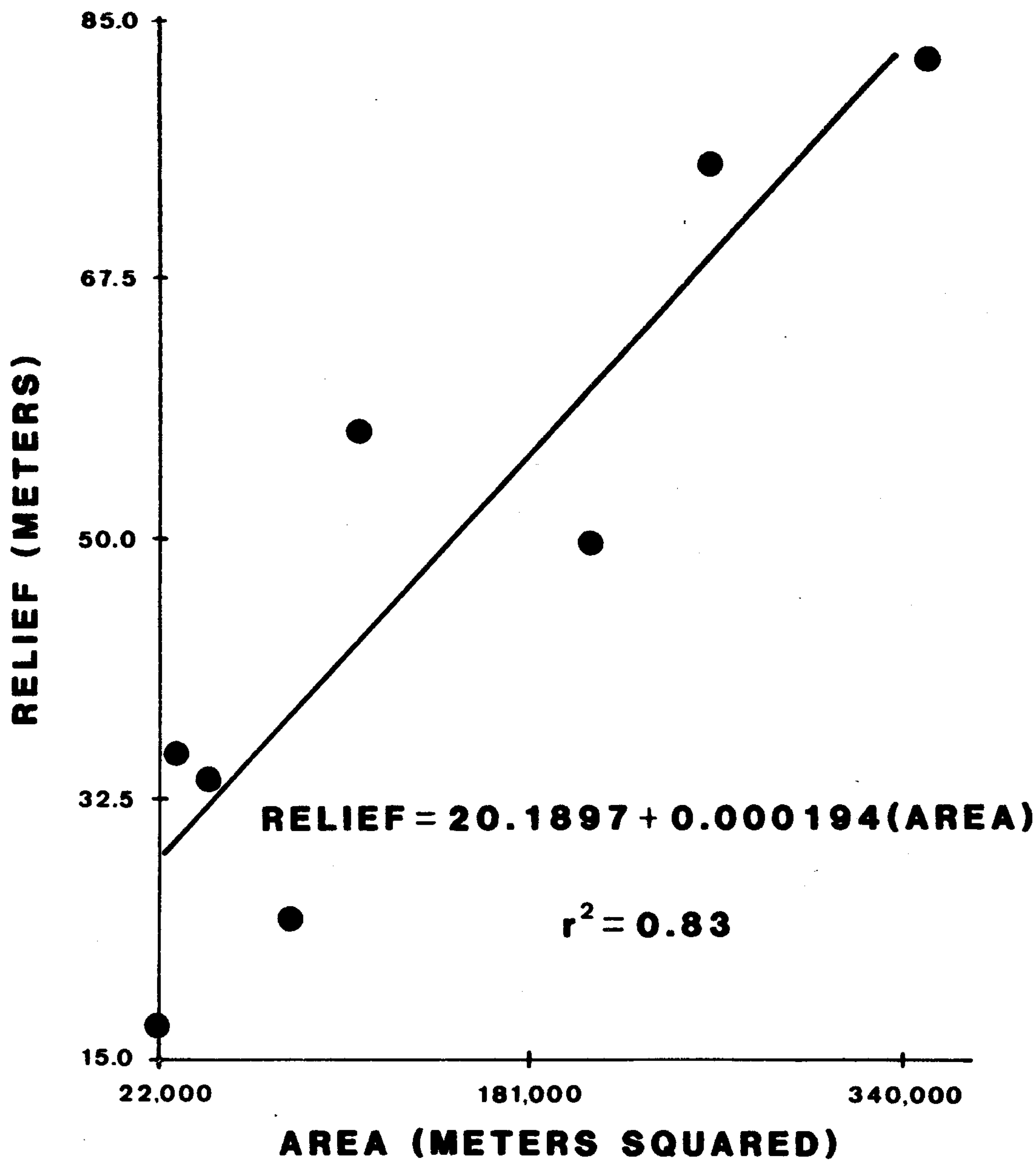


Fig. 5.3. Regression of basin area on basin relief.

Channel gradients have great variation, also. Basin P has the lowest main channel gradient (3.64%) and Basin U the highest (7.38%). In all basins, channel gradients become progressively steeper from mouth to source. Figure 5.4 shows a generalized longitudinal profile typical of the measured Type 4 tributary-basin channels. The variability of channel gradients within the basins may be due to several factors, namely the type of master channel into which they drain, the variable composition and erosional resistance of the bedrock, and/or local effects due to aspect.

All but Basins A and U have alluvium stored in their lower reaches. Gradients of alluvial valley floors, all of which are currently incised, average about 2.8%. The steepness of the alluvial valley floors gives an indication of sediment transport and depositional processes in the badlands. The Type 5 tributary channels and Type 6 rills are sufficiently steep to act as sediment conduits with no deposition. The alluvial valley floor gradient suggests that the sediment load is great enough that it can be deposited in channels with gradients generally less than 3%. At least this situation existed in the past. Field observations indicate that all channels are incising with no major sediment deposition in the study area. It appears, then, that currently a 3% gradient is much too steep for deposition to occur.

The reason that the present channel gradients are too steep for sediment storage even though they are gentler than the alluvial valley floor gradients, can be explained by the mode of sediment storage in the past. The alluvial valley floor most likely resulted from sedimentation due to backfilling. Sediment piled up, as it were,

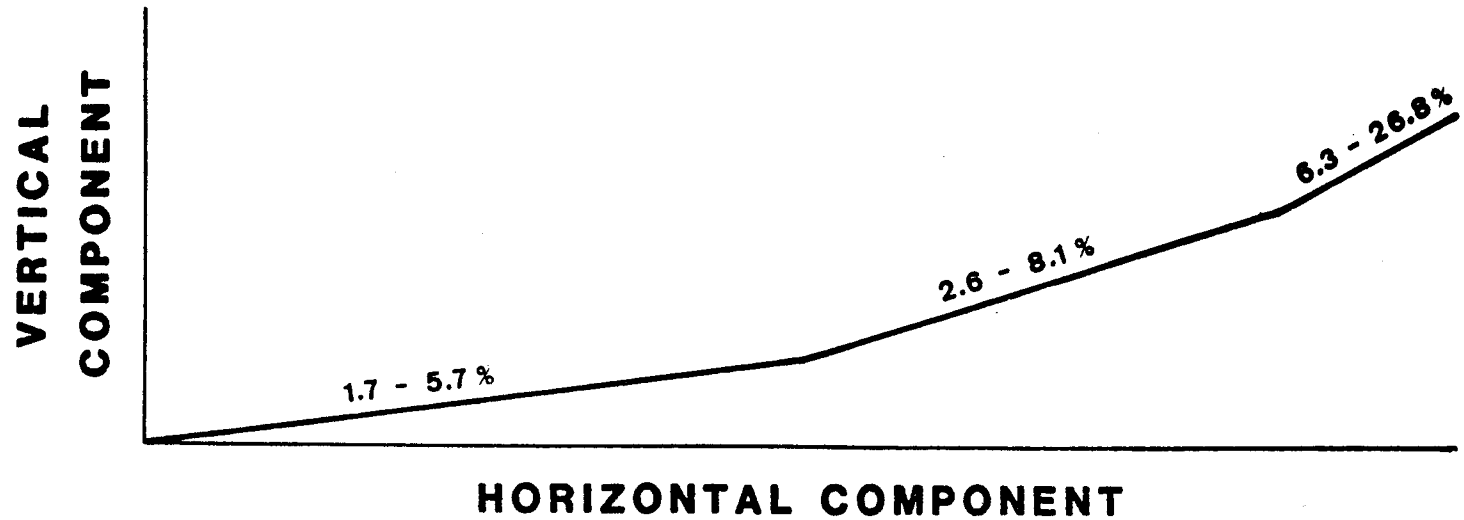


Fig. 5.4. Typical main channel longitudinal profile and ranges of channel gradients in the measured drainage basins.

instead of being carried to the Colorado River as it does now. The reasons for the change in the mode of sedimentation are explained in section 5.4.2.

5.2.4 Hillslopes

Hillslopes were studied by measuring cross sections of valleys formed by channels within the eight tributary basins. Table 5.2 reveals the wide range of hillslope gradients within basins and between basins.

Although hillslope gradients differ widely, characteristic hillslope shapes are evident (Fig. 5.5). Figure 5.5a shows a double-convex valley cross section. This type is characteristic of the upper portions of all of the basins. Figure 5.5b illustrates the convex-concave type cross section, and it occurs in the middle portions of all the basins. Within the basins, the convex and concave segments of this type alternate on opposite sides of the valleys. The alternation of segments appears to be controlled by the meandering channel configuration as opposed to control by either rock type, rock structure, or aspect. Finally, Figure 5.5c typifies the double-concave cross sections found near the mouths of all of the basins. All three types are nearly equally abundant. Of the 65 measured cross sections, 20 are double-convex, 24 are convex-concave, and 21 are double-concave.

The hillslope measurements were Type 6 rill gradient measurements. That is, the rills form directly on the hillslopes and maintain essentially the same gradient as that of hillslopes. Schumm (1964) and Lusby, et al. (1971) have studied rill development in the study area. Both investigations revealed seasonal cycles of rill development. Basically, moisture from winter snowmelt associated with freeze-thaw

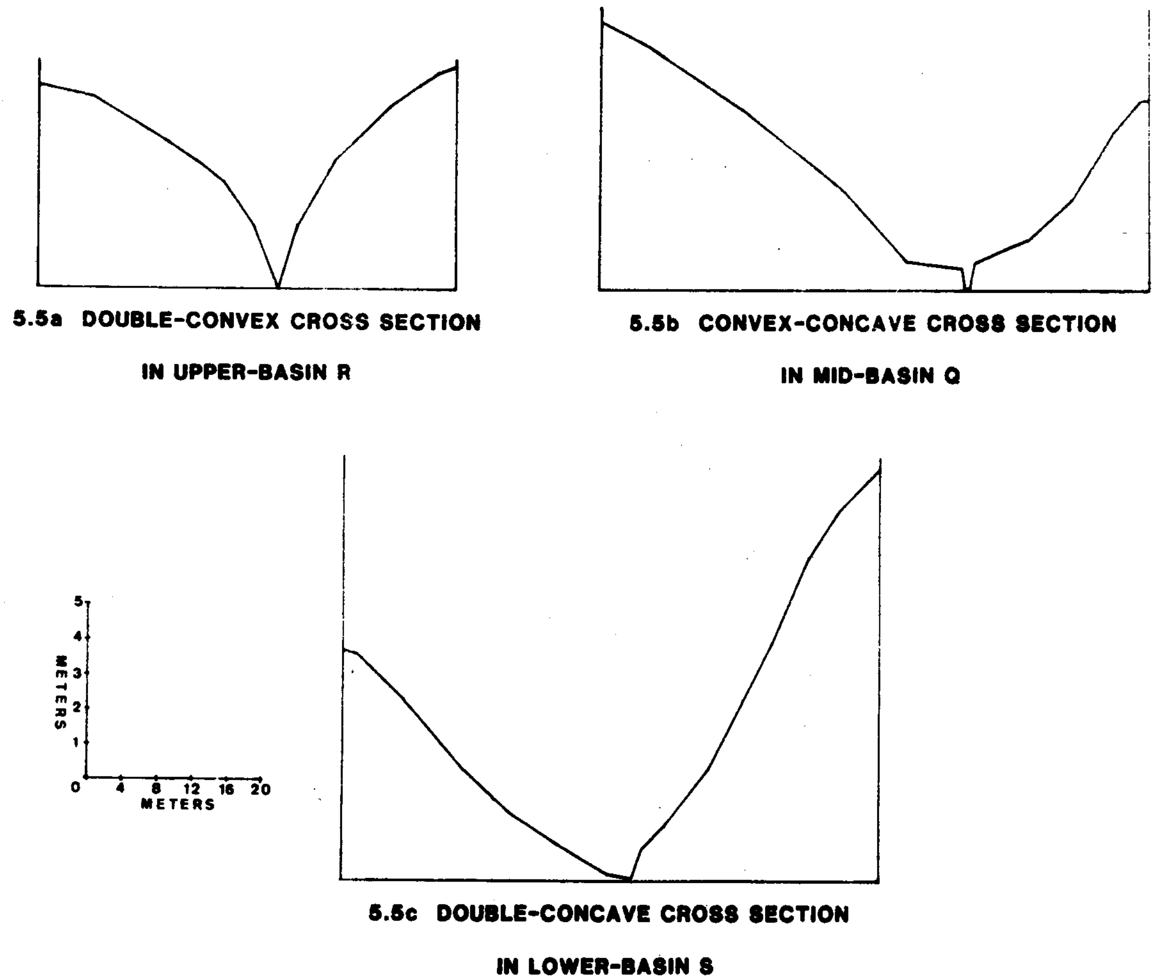


Fig. 5.5. The three types of valley cross sections present in the measured drainage basins.

action puffs up the surface materials and obliterates the rills. Concentrated runoff on hillslopes, during the first thunderstorms of the summer, erodes material softened by the winter freeze-thaw action and forms rills. During field studies in the summer of 1980, the first thunderstorm on the piedmont did not occur until August 15. Until that storm, only partially obliterated and deeply incised rills were found in the basins, whereas after the storm, the old rills were rejuvenated, and a new set of rills had developed in the affected basins.

New rills developed during the August 15 storm in Basins A, N, P, and Q. The rills were most common in the convex segments of valley cross section (Figs. 5.5a, 5.5b). It might be suggested, therefore, that erosion processes are most active in the upper portions of basins, where the convex segments occur. However, hillslope studies by Schumm (1964), hillslope gradient measurements (Table 5.2), along with field observations, suggest that all portions of basins are undergoing active erosion.

Schumm observed that soil creep, primarily related to winter freeze-thaw action, is an important erosion process in the area. His surveys indicated that soil creep is most rapid on the steepest portions of hillslopes with material accumulation occurring at the bottoms of hillslopes. The hillslope gradient measurements in the measured drainage basins indicated that all portions of basins have steep hillslopes.

Field observations indicated that the residual soil layer is very unstable after freeze-thaw activity has loosened it. On some very steep slopes, large quantities of soil had slumped into the channels

Table 5.2. Hillslope gradients.

Basin	Location	n	Avg. (%)	Min. (%)	Max. (%)
A	main channel	6	27.0	9.5	42.9
A	tributaries	14	31.4	11.1	53.6
N	main channel	7	26.5	14.0	41.9
N	tributaries	10	32.4	14.3	46.8
P	main channel	8	16.0	9.3	29.1
P	tributaries	4	16.3	13.0	21.8
Q	main channel	2	22.5	19.3	25.7
Q	tributaries	8	22.1	16.8	26.3
R	main channel	10	28.7	16.5	40.7
R	tributaries	12	27.5	20.1	40.6
S	main channel	12	24.0	15.3	44.3
S	tributaries	8	23.8	16.7	29.5
T	main channel	9	29.0	19.4	45.9
T	tributaries	12	38.3	23.9	50.0
U	main channel	6	25.8	11.9	36.2
U	tributaries*	--	--	--	--
all	main channels	60	25.2	14.4	38.3
	tributaries	68	29.2	16.6	38.4
	average		27.3	15.4	38.3

*no major tributaries

by gravity-induced slope failure (Fig. 5.6). At other localities, soil had slumped into channels as the result of disturbance by livestock, with cattle being the most destructive. After the August 15 storm, some of the steepest slopes had lost nearly all of their soil cover (Fig. 5.7).

Considering the above observations and studies, it appears that no single erosional process is dominant. In upper portions of basins, sediment is derived through the process of rill development and from removal of sediment accumulated in channels as the result of soil creep. In lower portions of basins, sediment is derived from the removal of sediment accumulated in channels due to soil creep and from bank failures of incised alluvial fill. Consequently, all portions of the basins are undergoing active erosion.

5.2.5 Soils

Soil depth studies were conducted in six of the eight basins with the goal of finding inter- and intrabasin relationships. Soil depth is the thickness of the layer of residual material derived from underlying weather, yet structurally distinct, bedrock (Appendix).

The soils are derived from two lithologies in the Mancos Shale: shale and sandstone. Field observations indicate that portions of the badlands are underlain predominantly by shale, of which Basins A, N, and Q are examples. The remainder of the badlands are underlain by interbedded shale and sandstone, of which Basins S, T, and U are examples. Soil texture analyses by Lusby, et al. (1963) show that soils derived from shales are clay-rich, while soils derived from interbedded shale and sandstone are mixtures of clay and sand.

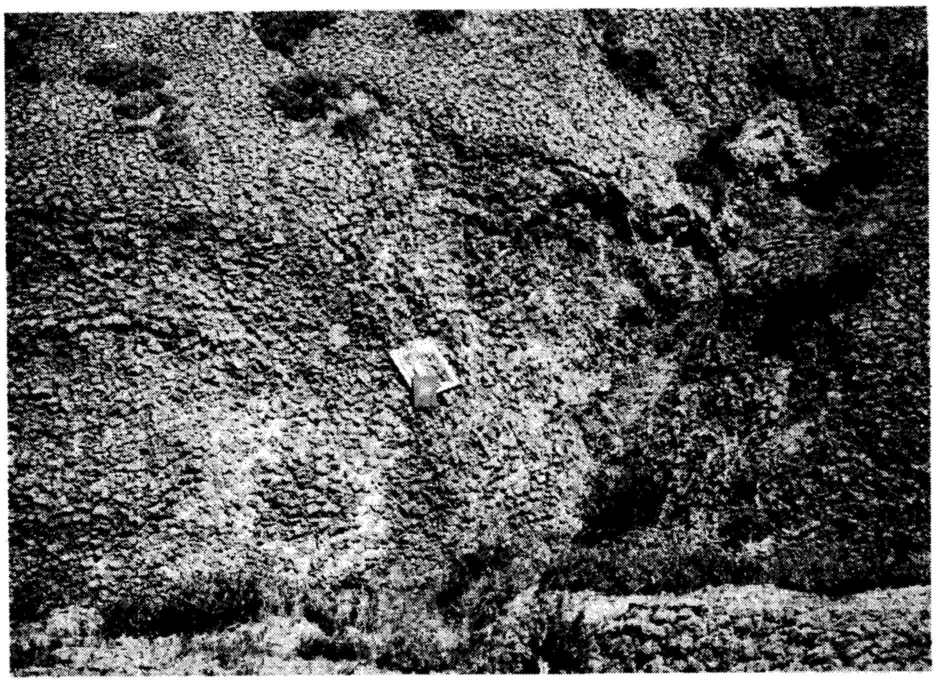


Fig. 5.6. Gravity-induced slope failure.

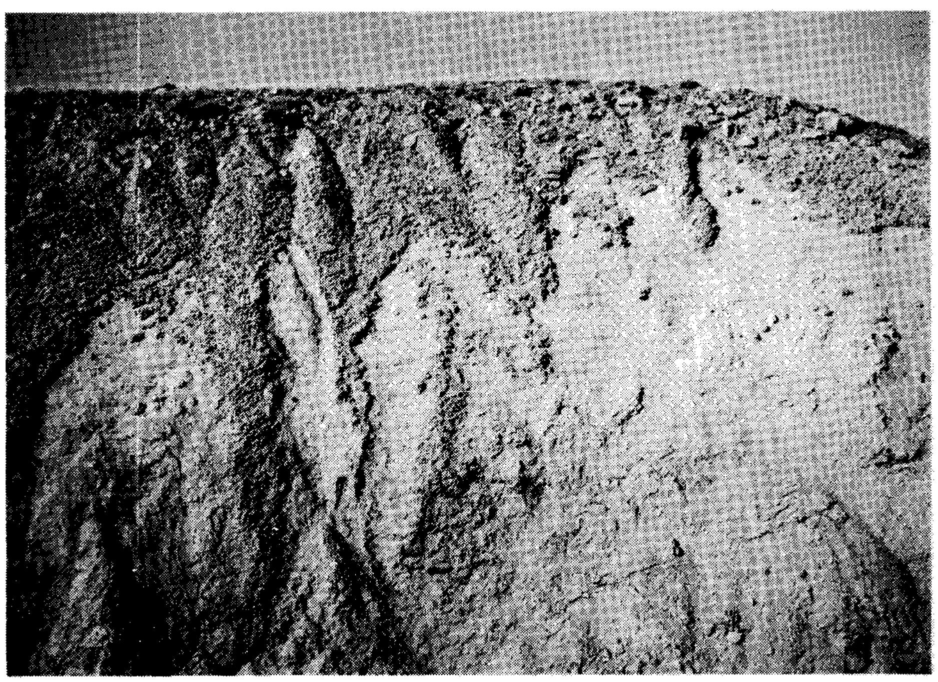


Fig. 5.7. Thunderstorm-induced slope failure.

An analysis of variance was conducted to compare the soil depth means for divides and hillslopes within each basin. Table 5.3 shows that, in five of the six basins, there is no significant difference in soil depth between divides and hillslopes at $\alpha = .05$. The implication is that the divides and hillslopes have equal rates of soil development and/or erosion. Perhaps the divides in Basin U are more erosionally stable than the divides in the other basins, thus accounting for the soil depth to be significantly greater on the divides than on the hillslopes.

Table 5.3. Analysis of variance of soil depth for basin divides and basin hillslopes.

H_0: Mean soil depth is the same for basin divides and basin hillslopes within each basin.

Basin	n	(calculated)	F-ratio (α=.05)	Accept or reject H_0
A	12	0.287	F(1,10)=4.96	accept
N	8	0.449	F(1,6)=5.99	accept
Q	12	0.0002	F(1,10)=4.96	accept
S	15	0.204	F(1,13)=4.67	accept
T	16	0.412	F(1,14)=4.60	accept
U	12	7.788	F(1,10)=4.96	reject

In order to determine if soil depths are the same in basins of the same lithology, the mean soil depths in the shale basins were compared, as were the mean soil depths in the interbedded shale and sandstone basins. An analysis of variance for each set (Table 5.4) shows that the soil depths are the same within each set at $\alpha = .05$.

Finally, the mean soil depths of the two sets of basins were compared for the purpose of checking the soil depth difference between the two sets of basins according to lithology. The two-tailed T-test in Table 5.5 indicates that the mean soil depth for basins underlain by interbedded shale and sandstone is significantly greater than the mean soil depth for basins underlain by shale at $\alpha = .05$. The explanation for this probably is due to the lower erodibility of sandy soils because of greater infiltration rates and vegetative cover than the shaley soils (Lusby, et al., 1963).

Hadley and Lusby (1967) emphasize the importance of hillslope aspect on soil depth and hillslope erosion. That is, since the north-facing slopes are colder and retain more moisture, they are expected to have deeper soil development and shorter, steeper slopes than the south-facing slopes. Effects of aspect on soil depth, however, were not studied due to the wide variation of hillslope-facing directions within each basin. Field observations of hillslope-facing directions and aerial photo interpretation suggest that aspect plays a relatively minor role in the geomorphic processes of the area.

5.2.6 Geomorphic Stability of the Badlands

Generally, the badlands of the piedmont are areas of rapid erosion. The rills and channels are steep, and they are efficient conduits for runoff and sediment transport. The hillslopes are most fragile during the spring and early summer before the first summer thunderstorm. All portions of basins are undergoing active erosion due to the combined effects of rill development, soil creep,

Table 5.4. Analysis of variance of soil depth according to lithology: A = basins underlain by shale; B = basins underlain by interbedded shale and sandstone.

A. H_0: Mean soil depth is the same for the three basins underlain by shale bedrock.

Basin	n	F-ratio (calculated)	F-ratio (α=.05)	Accept or reject H_0
A,N,Q	32	1.720	F(2,29)=3.39	accept

B. H_0: Mean soil depth is the same for the three basins underlain by interbedded shale and sandstone bedrock.

Basin	n	F-ratio (calculated)	F-ratio (α=.05)	Accept or reject H_0
S,T,U	43	0.923	F(2,40)=3.23	accept

Table 5.5. Two-tailed T-test of soil depth for the two sets of basins according to lithology.

H_0: Mean soil depth is the same for basins underlain by shale and basins underlain by interbedded shale and sandstone.

n pairs	Mean soil depth for shale basins (cm)	Mean soil depth for shale - sandstone basins (cm)	T-ratio (calculated)	T-ratio (α=.05)	Accept or reject H_0
32	4.8	9.8	T(31)=7.462	2.039	reject

and bank failure. In relative terms, badlands underlain by interbedded shale and sandstone bedrock are more stable than those underlain by shale bedrock. The former are less erodible because they have a more permeable soil layer which gives rise to deeper soils and greater, though minimal, vegetative cover than the latter.

5.3 Pediments

5.3.1 Introduction

The area has many generally smooth, sloping, gravel-capped landforms perched above the badland terrain. These features are common along other portions of the Book Cliffs as well as in other areas where Mancos Shale crops out below resistant cliffs. These landforms are referred to as pediments.

By definition, a pediment is a gently inclined planate erosion surface carved in bedrock and generally veneered with fluvial gravels (American Geological Institute, 1976). Many theories have been developed to describe the origin of pediments, but none apply to the pediments in Grand Valley. For example, there is no evidence of lateral swinging of streams issuing from mountains, as Gilbert noted (1877). Rich's (1935) conclusion that weathering and sheetwash are the principal pediment-forming agents does not apply. The theory offered by Rich (1935), Hunt, et al. (1953), Godfrey (1968), and Carter (1980) that stream capture caused the multiple surface levels does not pertain to Grand Valley, either. Sinnock's (1981) observations are more applicable than other theories, with the notable exception that Grand Valley pediments are not capped by glacial outwash and mudflows.

5.3.2 Theory of Pediment Origin

Comparison of studies of pediment origin conducted by Gilbert (1877), Rich (1935), Hunt (1953), Godfrey (1968), Carter (1980), and Sinnock (1981) suggests that landforms identified as pediments may have developed by different processes in different areas. Pediments in the study area, although similar in appearance to pediments described in other areas, appear to have developed by a series of events unlike those described elsewhere. For example: 1) the present piedmont is composed of badlands formed by headward extending drainages of ephemeral streams as opposed to being laterally planated by upland-derived streams; 2) no pediments are positionally associated with upland stream drainage basins; 3) the pediment surfaces contain numerous boulders up to 4 m in diameter which are too large to have been deposited by stream flow (note point (2)); and 4) stream capture is not an important mechanism.

Mapping directly onto topographic maps with the aid of aerial photographs proved to be a valuable tool in understanding the nature of the pediments (refer to Fig. 7.2). The lowermost pediment surfaces are the closest to the Book Cliff escarpment. Presently, the upper reaches of most of the surfaces are within 1 km of the escarpment. Such close proximity to the cliffs prevents the theory of fluvial deposition of gravels from applying to these surfaces. Also, the topographic maps indicated that all of the pediments in close proximity to the cliffs are associated with large cirque-like hollows in the cliffs. The hollows probably represent the locations of massive rock slides in the past, although the arid erosional environment has removed any physical evidence along the escarpment.

The theory of pediment formation in the study area proposed herein involves a cycle of events that has not been identified by other authors in other localities. This theory incorporates periods of massive rock slides and associated debris flows derived from the cliff escarpment contemporaneous with wet climates, separated by periods of headward expanding ephemeral stream basins in the piedmont contemporaneous with dry climates. Upland-derived streams and stream capture are not involved in this theory. Also, sudden changes in base level of the Colorado River are not required in order to give rise to the different elevations of pediments in the area.

5.3.3 Model of Pediment Origin

Figure 5.8 represents the sequence of events that are proposed as the origin of the pediments. In Figure 5.8a, the area is depicted as a region of badlands. The piedmont drainage basins are formed by headward extending ephemeral streams during a period dominated by an arid climate. The badlands persist because of the progressive incision of the Colorado River into the easily erodible Mancos Shale and because of progressive scarp retreat (Hunt, 1956; Lohman, 1965). The cliff escarpment is steep and gradually retreating, but no blocks of sandstone from the capping Mesa Verde Formation are present except at the base of the escarpment. There are no blocks or boulders beyond the escarpment base because of the low mechanical strength of the cliff-forming sandstone. The sandstones are poorly cemented with calcite cement, highly porous, and of low permeability. As blocks fall down the escarpment during the slow scarp retreat, they either disintegrate by falling and rolling, or most

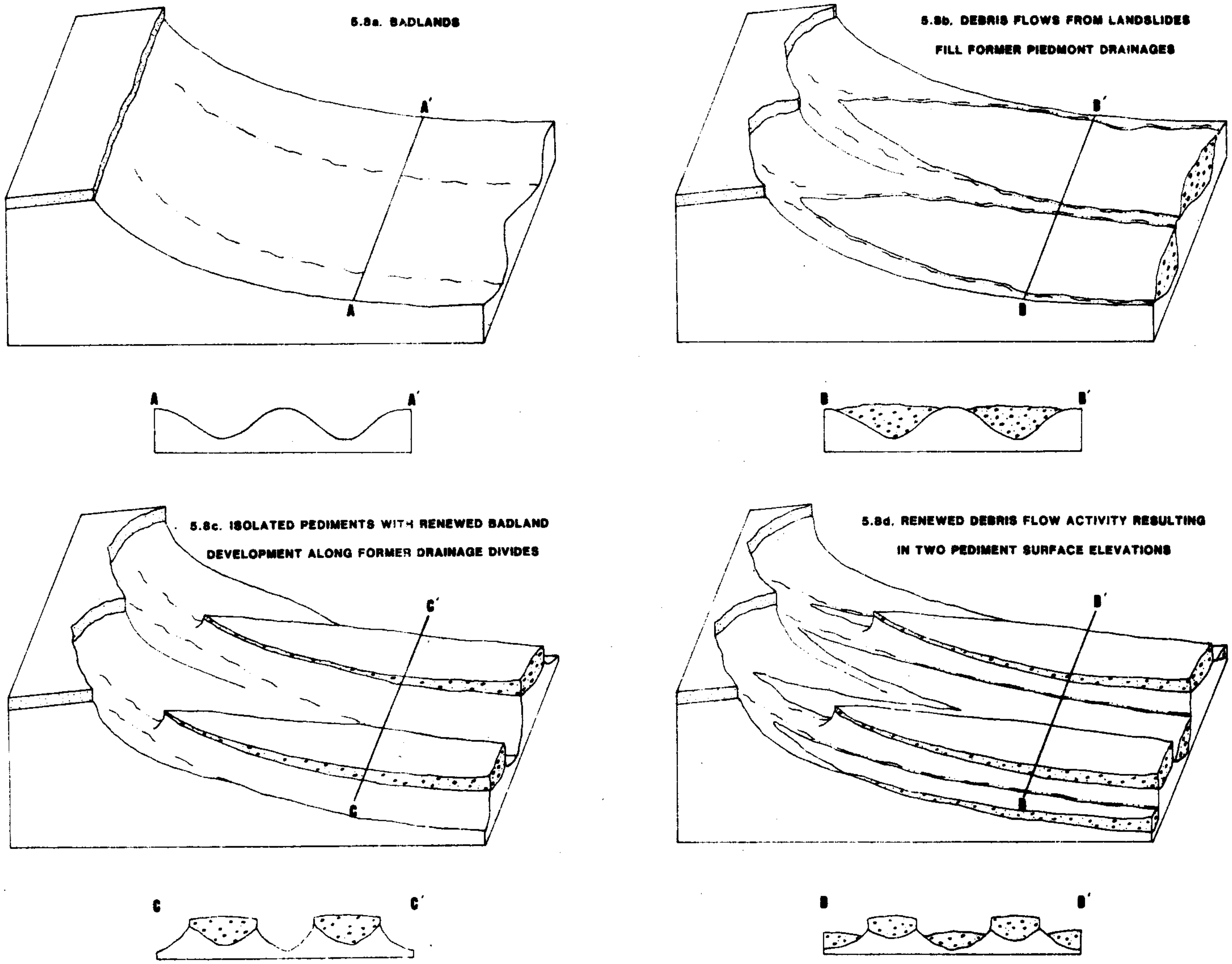


Fig. 5.8. Origin of pediments in Grand Valley, Western Colorado. See text for explanation.

commonly, they are weathered rapidly by freeze-thaw action (Schumm and Chorley, 1966).

Conditions and events associated with a wet climate are pictured in Figure 5.8b. In Figure 5.8a, the cliff scarp and the underlying steep shale slope represents oversteepened yet relatively stable conditions during the dry climate. However, the increased amounts of moisture associated with a wetter climate would quickly render the scarp unstable. Based on landslide studies in general (Varnes, 1978), instability could be due to some combination of increased seepage pressures of percolating water in the shale, solution by water from increased rainfall and snowmelt along the joints of the sandstone cap rock and in the bedding planes of the shale, and increased oversteepening of the shale slope by accelerated erosion. In order for the escarpment to regain equilibrium, one or more massive rockslides would occur. The water content and momentum associated with the slide would cause the large volumes of slide material to move down the already established piedmont drainages in the form of debris flows. Figure 5.9 shows the debris flow nature of a pediment surface north of Fruita, Colorado.

Sometimes during, or shortly after, the debris flow events, the gravel layers were cemented with calcite that was derived from the shale and sandstone on the debris flows (Carter, 1980). Because the sandstone is of low mechanical strength and because boulders up to 4 m in diameter are in the gravel deposits, fluvial processes could not have been a major factor and the boulders would have to have been buried rapidly. Debris flows occurring in relatively rapid

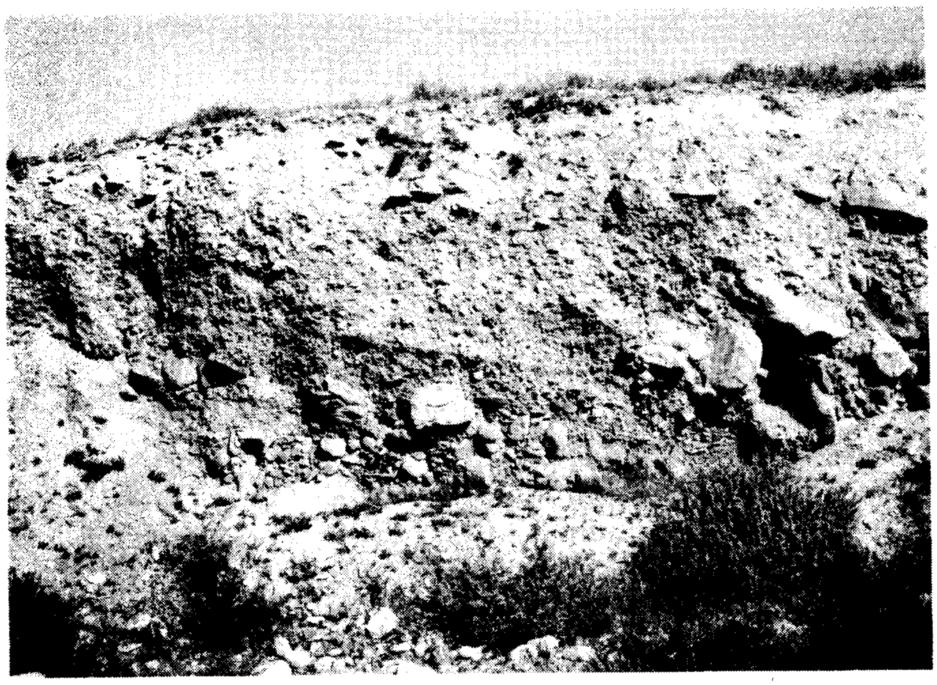


Fig. 5.9. Debris flow deposit of a pediment surface north of Fruita, Colorado.

succession, in conjunction with landslides, could transport and preserve the boulders.

Multiple debris flow events of the type mentioned above appear to have overtopped piedmont drainage divides close to the escarpment on occasion, resulting in different surface elevations. Figure 5.10a shows a situation where a set of debris flows overtopped a divide between a stream and its tributary. Consequently, the surface at the upper reaches of the pediment has two levels, a condition that becomes pronounced when the thin gravel layer over the divide is eroded away. Figure 5.10b depicts a situation where a set of debris flows overtopped a divide between two streams with different base-levels. As a result, the surfaces have two distinct levels in the lower reaches of the pediment.

Figure 5.8c represents the next period of dry climate. As in Figure 5.8a, headward expanding ephemeral piedmont streams are again the chief mode of erosion. The cemented debris flows of the previous wet climate are now more resistant than the Mancos Shale in the dry climate. The uncovered Mancos Shale drainage divides are now points of weakness and are susceptible to headward erosion, thus becoming a new set of drainages. Where headward expansion encounters cemented debris flow deposits, the debris flow deposits behave as a cap rock similar to the Mesa Verde escarpment. Also, where flows covered former shale divides, the "cap rock" is relatively thin, thus permitting more rapid headcutting than in the thicker deposits.

Eventually, over the long period of dry climate, many drainages will extend up to the base of the escarpment. The drop in

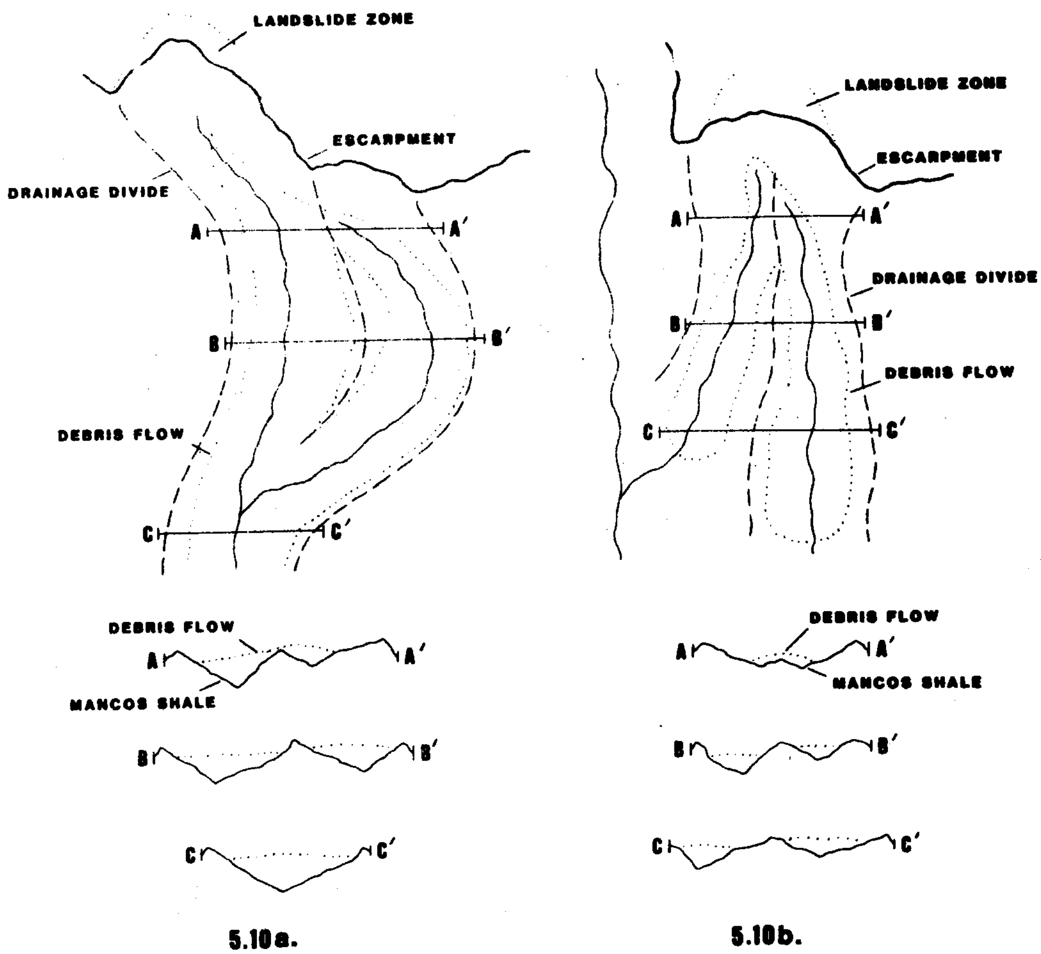


Fig. 5.10. Two geomorphic situations that produce two pediment levels by one period of debris flows.

base level by continuous downcutting of the Colorado River coupled with headcutting of the piedmont streams will leave the debris flow deposits elevated above the piedmont badlands. The result is inverted topography. The old drainages were filled by the debris flows, and the old drainage divides have become the new drainages.

In Figure 5.8d, results of the next period of wet climate are depicted. The processes are the same as those oulined in Figure 5.8b. A new episode of landslides and associated debris flows have filled the new piedmont drainage basins. During the next dry period, headward expansion of piedmont channels will start again. Points of least resistance are along uncovered shale drainage divides and at contacts between debris flow deposits and exposed Mancos Shale (Fig. 5.8d).

In one location, north of Walker Field, three distinct pediment surfaces are present (Fig. 5.11). The three surfaces indicate two or three periods of debris flow activity. The formation of the two lower surfaces could have occurred during one period of debris flow activity. This is based on the observation that the surface remnants are located the same distance from the cliffs and that their headward reaches are at about the same elevation. It is based also on the presence of different channel elevations in adjoining basins throughout the piedmont (see cross section, Fig. 5.1), and the type of pediment diagrammed in Figure 5.10b. Therefore, the two lower surfaces appear to have been caused by one period of debris flows which overtopped a piedmont divide and flowed into adjoining drainage basins of different elevations. The phenomena has been proposed by Sinnock (1981), also.

Fig. 5.11. Three pediments with different surface elevations, north of Grand Junction, Colorado.

The actual number of debris flow periods that led to the present surfaces and the age of those events is beyond the scope of this study. However, investigations in the Grand Valley area by Hunt (1956), Lohman (1965), and Sinnock (1981), were helpful in understanding past and present geomorphic processes in the study area and provide a basis for dating climatic change.

The reach of the Colorado River through Grand Valley can be considered a youthful river. Lohman's studies of Uniweep Canyon on the Uncompahgre Plateau and gravel terrace elevations and compositions along the Colorado River and Gunnison River upstream of Grand Junction led to the proposed sequence of events pictured in Figure 5.12. Both Hunt and Lohman place abandonment of Uniweep Canyon in late Pliocene or early Pleistocene at which time all the water from the Colorado and Gunnison rivers began flowing through what is now Grand Valley. Hunt calculated that the Colorado River has incised about 250 m since abandonment of Uniweep Canyon, and that half of that amount reflects late Pleistocene uplift. Therefore, most of Grand Valley was formed during the Pleistocene with its present morphology reflecting late Pleistocene uplift and erosion.

Conclusions offered by Hunt (1956) and Lohman (1965) regarding the age of Grand Valley lend support to the following hypothesis of events to explain the current landforms. The theory proposed for the cause of the debris flow deposits and inverted topography depends on changes of climate. The climatic changes could have corresponded to the glacial periods of the late Pleistocene and Holocene. Richmond (1965) divided Wisconsinan, or late Pleistocene,

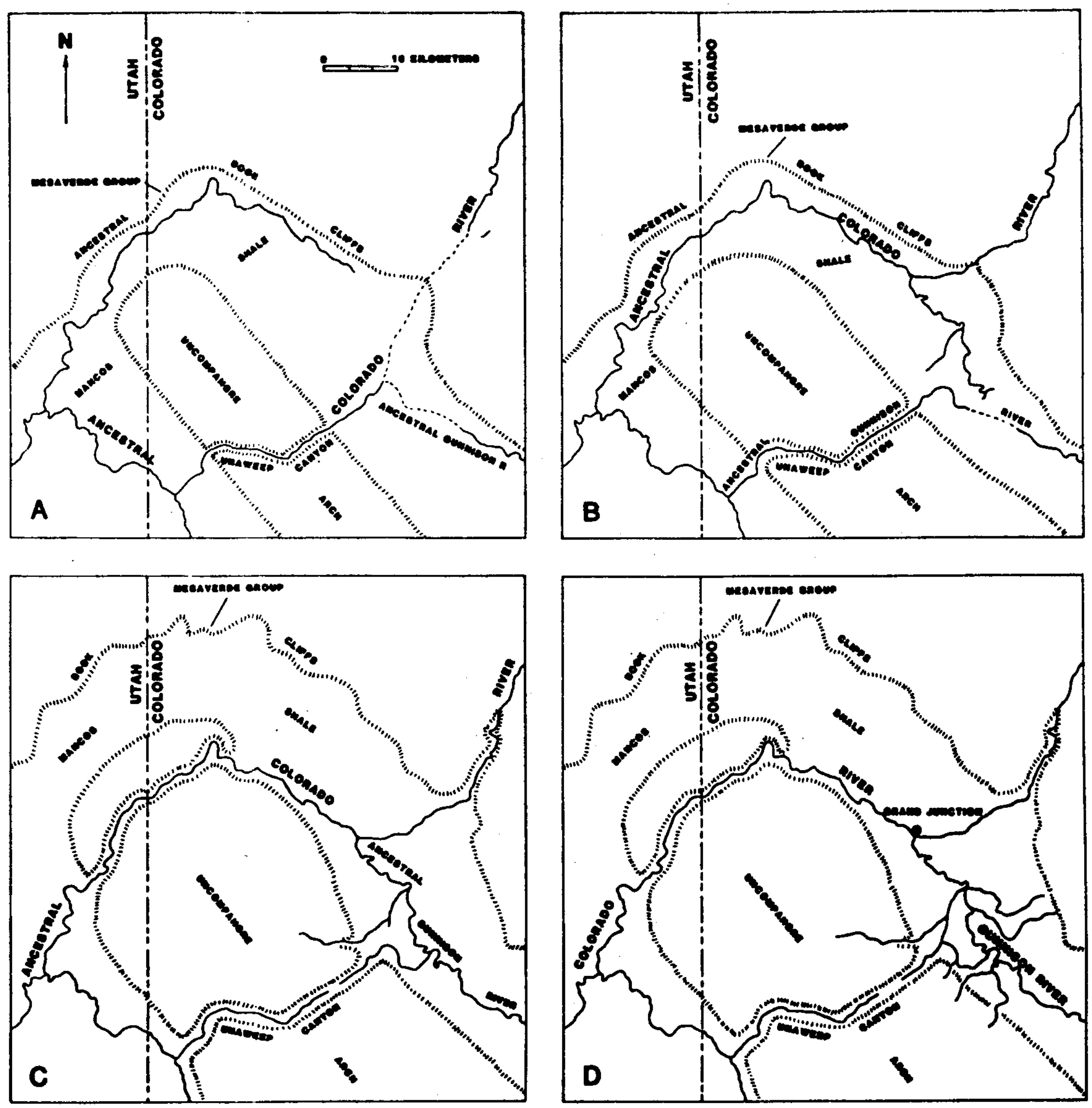


Fig. 5.12. River capture events and the development of Grand Valley during late Tertiary and early Quaternary (after Lohman, 1965).

glaciation and neoglaciation of the Rocky Mountains into seven glacial stades and episodes with associated nonglacial intervals (Fig. 5.13). Sinnock (1981) observed the effects of glaciation south of Grand Junction.

By correlating terrace deposits and pediment gravels, Sinnock concluded that the pediment gravels in his area were deposited by mudflows derived from melting glaciers in the Grand Mesa area. The difference between Sinnock's area and Grand Valley, is that the Book Cliffs were apparently too low for glaciers to occur. However, the moisture and snowmelt contemporaneous with the Grand Mesa glaciers, probably was sufficient to trigger rockslides and debris flows in Grand Valley.

As the Book Cliffs scarp retreated and Grand Valley deepened during late Pleistocene and Holocene, the piedmont topography may have undergone about seven major inversions. Each glacial stade, by this theory, could have triggered a series of rockslides and associated debris flows. Following each glacial stade the partially cemented flows would behave as cap rocks and new drainages would form by headward expansion along previous drainage divides.

The two or three levels of pediments present on the piedmont today probably reflects the number present at any one time during late Pleotocene and Holocene. That is, before a new series of debris flows begins, the previous pediment level is isolated by badland erosion, and it is eroded from most or all sides. Presently, the surface areas of the highest elevated pediments are minimal compared with those of the lower surfaces. The much smaller surface areas are due to subjection to two or three periods of arid erosional

Figure 5.13. Glaciations of the Rocky Mountains (after Richmond, 1965).

Approximate age B.P.		
800	Neoglaciation	Gannett Peak Stade
900		Interstade
4,000		Temple Lake Stade
6,500	Antithermal Interval	
10,000	Pinedale Glaciation	Late Stade
12,000		Interstade
		Middle Stade
		Interstade
25,000		Early Stade
32,000	Interglaciation	
45,000	Bull Lake Glaciation	Late Stade: Second Episode
		Late Stade: Nonglacial Interval
		Late Stade: First Episode
		Nonglacial Interval
		Early Stade

processes. It appears, then, that a pediment cannot survive more than three periods of erosion.

The purpose for describing the development and erosion of pediments relates to the long-term geomorphic process in the area. That is, during wet climates and associated debris flow events, large areas of shale outcrop are covered therefore causing less erosion of the salt-rich shales. On the other hand, during arid climates, pediments are reduced in size, thus providing an increasing area of exposed shale. Currently, the climate is arid, the pediments are decreasing in size, and a major portion of the area is underlain by exposed shale.

5.3.4 Geomorphic Stability of the Pediments

The pediments, or remnant debris flow surfaces, are relatively stable. Whether they are slightly convex upward or concave upward, their surface slopes are too gentle for rill formation. They support a much greater vegetative cover than the badlands, due in part to deeper soil development and higher infiltration rates than the badlands (Bureau of Land Management, 1978). However, all of the pediments are being encroached upon by the badlands. Also, some surfaces are partially dissected by headward cutting channels. The channels propagate headward when sheetwash from a thunderstorm cascades from the pediment into the channel.

5.4 Alluvial Valley Floors

5.4.1 Introduction

Alluvial valley floors are the least abundant landforms in the study area. All upland, cliff, and piedmont channels have alluvial deposits as do most tributary-basin channels. Presently, all channels are incised, with some piedmont and tributary-basin channels incised through the alluvium and into shale bedrock.

5.4.2 Alluviation

All of the measured channels, with the exception of Basins A and U which have no alluvium, are incised into alluvium near their mouths. Rills were not present on any of the observed alluvial valley floors. The alluvial valley floors, measured along the channels, have gradients ranging from 2.0 to 3.3 percent. The alluvium contains abundant imbricated chips of shale and/or sandstone, depending on the local bedrock. The rock chips, derived from or at the base of hillslope surfaces and from non-alluviated channel bottoms, indicate high sediment concentrations during transport. The imbrication, or upstream dip, of the flat rock chips indicate rapid flowing water. Together they represent rapid flowing and sediment laden runoff which is typical of runoff events from intense thunderstorms.

The gradients of the alluvial valley floors cannot be explained merely by the high sediment load of the runoff. For sediment to be deposited at such steep gradients, a sudden change in channel gradient and associated loss of energy are required. The alluvium can be best explained by backfilling following a decrease in channel gradient downstream.

Schneider (1975) studied the subsurface geology and Quaternary deposits of Grand Valley near Fruita, Colorado. He concluded that channels in the Mancos Shale badlands were at one time bedrock channels flowing into the Colorado River. Later, the Colorado River gradually shifted south without appreciable downcutting, thus significantly reducing the gradients of the tributary channels in that area. The lower gradients could not carry the high sediment loads from the badlands to the river. As a result, fan-like deposits formed along the present Grand Valley agricultural area with associated backfilling of the tributary channels in the badlands. The channels then became graded to the slope determined by the present position of the Colorado River.

All of the channels south of the Highline Canal have been altered by land use, including straightening to increase agricultural land area and modification by irrigation return flow. The increased erosive energy resulting from both alterations cause gully erosion. The present condition of general channel incision in the study area appears to be, at least in part, a result of agricultural practices downstream of the Highline Canal. The suggested sequence of events regarding the evolution of alluvial valley floor surfaces is that: 1) all channels were once bedrock channels; 2) the channels were alluviated over a long, continuous period of backfilling after the Colorado River shifted to the south; and 3) the channels began incising due to man-activated headward gully erosion (Fig. 5.14).

5.4.3 Geomorphic Stability of the Alluvial Valley Floors

In the larger alluvial valleys (refer to Fig. 7.2), the alluvial surfaces are stable except along the channels, which in some places have arroyos as much as 10 m deep. Therefore, the near-vertical arroyo walls are susceptible to undercutting and calving off of blocks of bank material. The surfaces not directly affected by the arroyos generally support a good cover of grasses and shrubs.

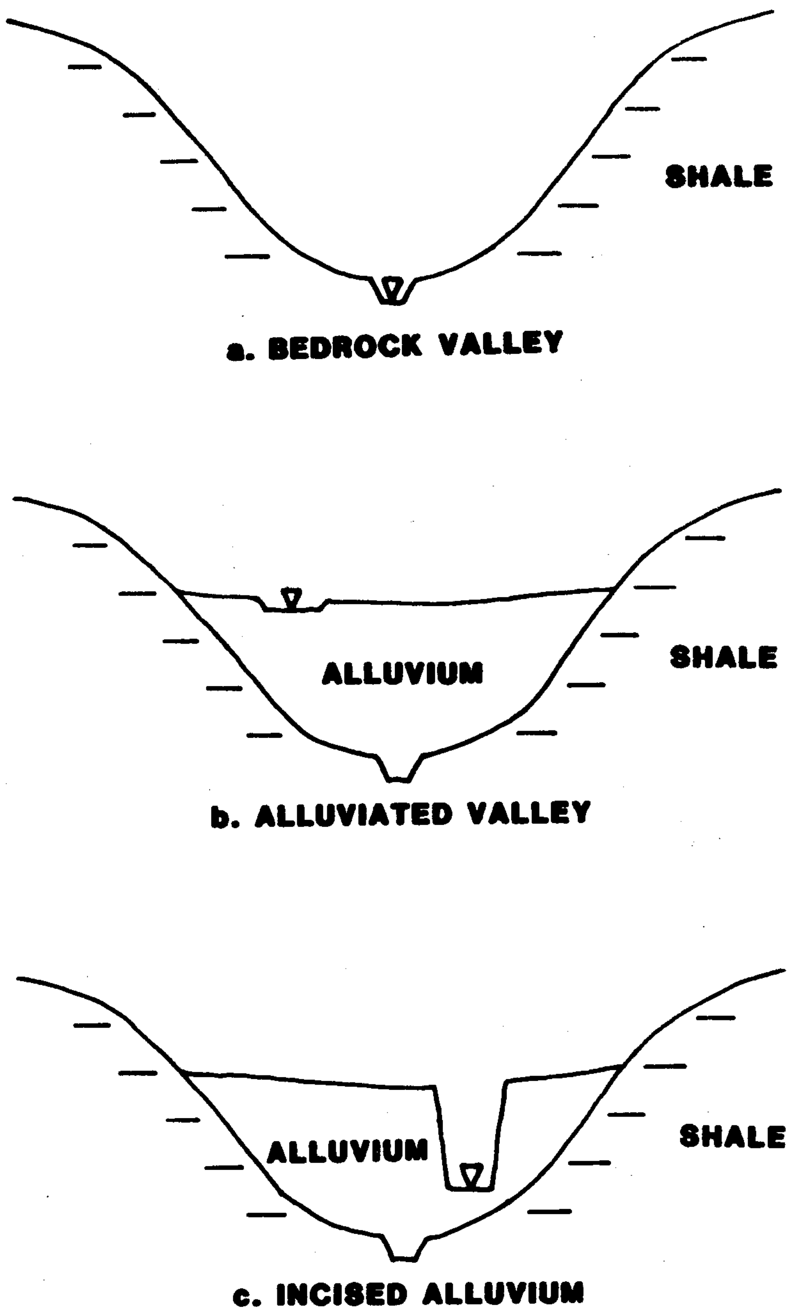


Fig. 5.14. Proposed valley evolution in the study area: a) bedrock valley before the southward shift of the Colorado River; b) alluviation of the bedrock valley by back-filling after the southward shift of the Colorado River; and c) channel incision probably due to downstream land use practices.

5.5 Conclusions

The three major landforms in the study area, from greatest to least surface extent, are badlands, pediments, and alluvial valley floors. The landforms currently are being eroded in some manner.

The badlands are eroding by the headward expansion and downcutting of numerous ephemeral drainages. Runoff from thunderstorms removes materials through rill development on hillslopes and by incorporating creep, slumped, and bank deposits along the channels. Hillslope gradients and facing directions vary widely in the drainage basins, but soils in basins underlain by interbedded shale and sandstone are significantly deeper than soils in basins underlain by shale. The badlands are the most erosionally unstable of the three landforms.

The origin and destruction of pediments in the area, as proposed herein, are due to periods of landslide and debris flow activity during glacial stades alternating with periods of arid erosion during interglacial stades. Currently, the pediment surfaces are being reduced in size as a result of badland encroachment and channel incision associated with the present arid climate. The actual surfaces, however, are gently sloping and erosionally stable.

The alluvial valley floors are currently being incised through gully and arroyo expansion, possibly triggered by land use practices south of the Highline Canal. The surfaces not directly affected by gullies or arroyos are erosionally stable.

CHAPTER VI

SALINITY

6.1 Introduction

Badlands are the most erosionally unstable of the landforms in the study area. Schumm (1964, 1967), Hadley and Lusby (1967), Lusby, et al. (1971), and The Bureau of Land Management (1978) have all indicated that runoff and associated hillslope erosion occur almost wholly in response to high intensity summer thunderstorms. Ponce (1975) and Sunday (1979) have shown that the salinity of runoff is directly proportional to sediment load in the runoff. The above conclusions suggest that the badlands are the major source of salt production from the area. Consequently, the SMC data from the six badland drainages were statistically analyzed in order to identify inter- and intrabasin relationships that could be inferred for all badlands in the area.

6.2 Salinity Analysis

The procedures for sampling and analysis for SMC of surficial materials are outlined in Chapter IV. Twelve 1:99 sediment:water mixtures were analyzed for EC over an eight hour period, each for the purpose of finding one equation that would describe the rate of solution of soluble minerals for all of the samples. This equation was then applied to the remaining samples using EC after an arbitrarily chosen time of two hours of mixing.

Table 6.1 lists the data and the best fitting regression equations for each of the 12 samples. The sample numbers ending in "a" represent soil samples, and those ending in "b" represent weathered bedrock samples. The data in Table 6.1 indicate that EC values varied considerably with a range of 33.5-1770 μmho/cm after 15 minutes of mixing and a range of 47.1-2060 μmho/cm after 8 hours of mixing.

When EC versus mixing time was graphed for the 12 samples, each sample had similar shaped plots (Fig. 6.1). The best fitting regression equations for the individual samples were natural log functions of the form:

$$Y = b + m\ln X \qquad (6.1)$$

and power functions of the form:

$$Y = bX^{m} \quad . \qquad (6.2)$$

Based on higher r^2 values, the power function was used as the equation representing dissolution of soluble minerals.

Since the 12 curves were of similar shape, the exponents, which described the curves, were averaged in order that one equation could be applied to all of the samples regardless of initial EC values. The general equation after averaging the exponents was:

$$Y = bX^{.073} \quad . \qquad (6.3)$$

Equation 6.3 was used to estimate the maximum EC, TDS, and SMC for the remaining samples according to the procedure given in Chapter IV.

A plot and summary of the SMC values (Appendix) are given in Figure 6.2 and Table 6.2, respectively. The figure and the table show the wide range of SMC within the materials in each basin. Based on averaged SMC values of soil and weathered bedrock samples, the

Table 6.1. EC of 1:99 sediment:water mixtures and associated equilibrium regression equations: "a" is soil, "b" is bedrock. See text for explanation.

Sample/ time (hr)	0.25	0.50	1	2	4	6	8	Equation, intercept @ 1 hr.	r^2
AC2a	133	136	142	150	159	159	160	$Y = 143.26\ x^{.059}$	.975
AC2b	814	817	827	835	861	878	865	$Y = 831.96\ x^{.022}$	.903
NC2a	590	594	602	604	626	635	628	$Y = 603.83\ x^{.022}$	.908
NC2b	1650	1740	1830	1900	2030	2060	2050	$Y = 1820.32\ x^{.066}$	.983
QC2a	49.4	52.8	57.8	62.5	67.6	66.5	68.0	$Y = 57.13\ x^{.096}$	.966
QC2b	1660	1760	1840	1910	2040	2040	2060	$Y = 1830.52\ x^{.063}$	.981
SD2a	46.8	50.0	52.7	56.2	60.7	61.3	62.0	$Y = 52.87\ x^{.084}$	.989
SD2b	1770	1830	1910	1940	2060	2080	2060	$Y = 1895.92\ x^{.048}$	.968
TD2a	39.0	41.9	48.7	52.7	55.8	56.8	56.1	$Y = 46.67\ x^{.11}$	.941
TD2b	43.2	45.2	48.2	51.6	56.0	56.5	56.0	$Y = 48.40\ x^{.084}$	.974
UC2a	33.5	36.0	39.9	41.9	46.6	46.8	47.1	$Y = 39.06\ x^{.10}$	.977
UC2b	34.0	36.1	39.9	43.6	49.0	49.7	49.8	$Y = 39.83\ x^{.12}$	.974

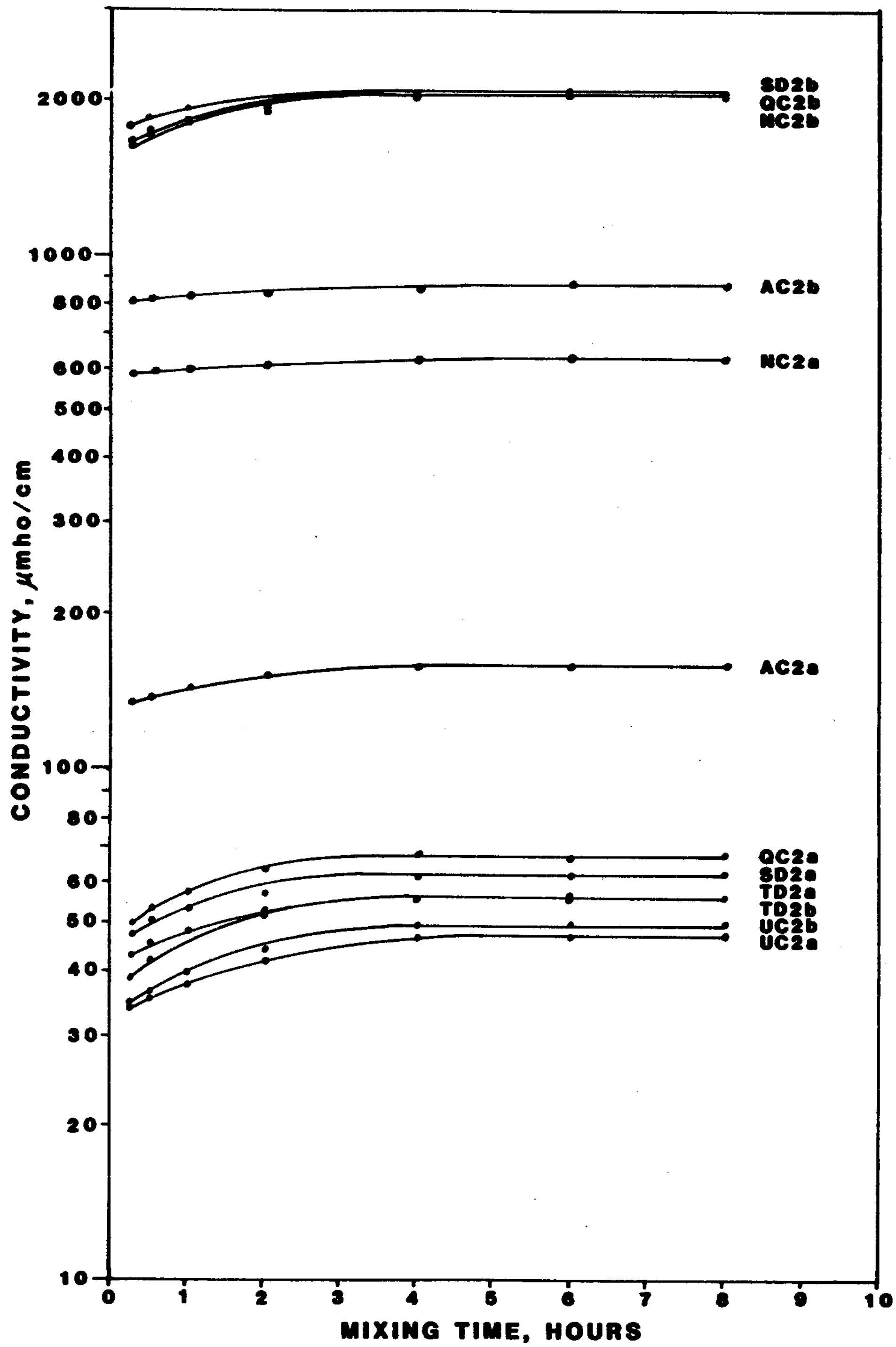


Fig. 6.1. Conductivity (EC) versus mixing time for 12 test samples to determine mixing time for solution equilibrium. Refer to Table 6.1 for data.

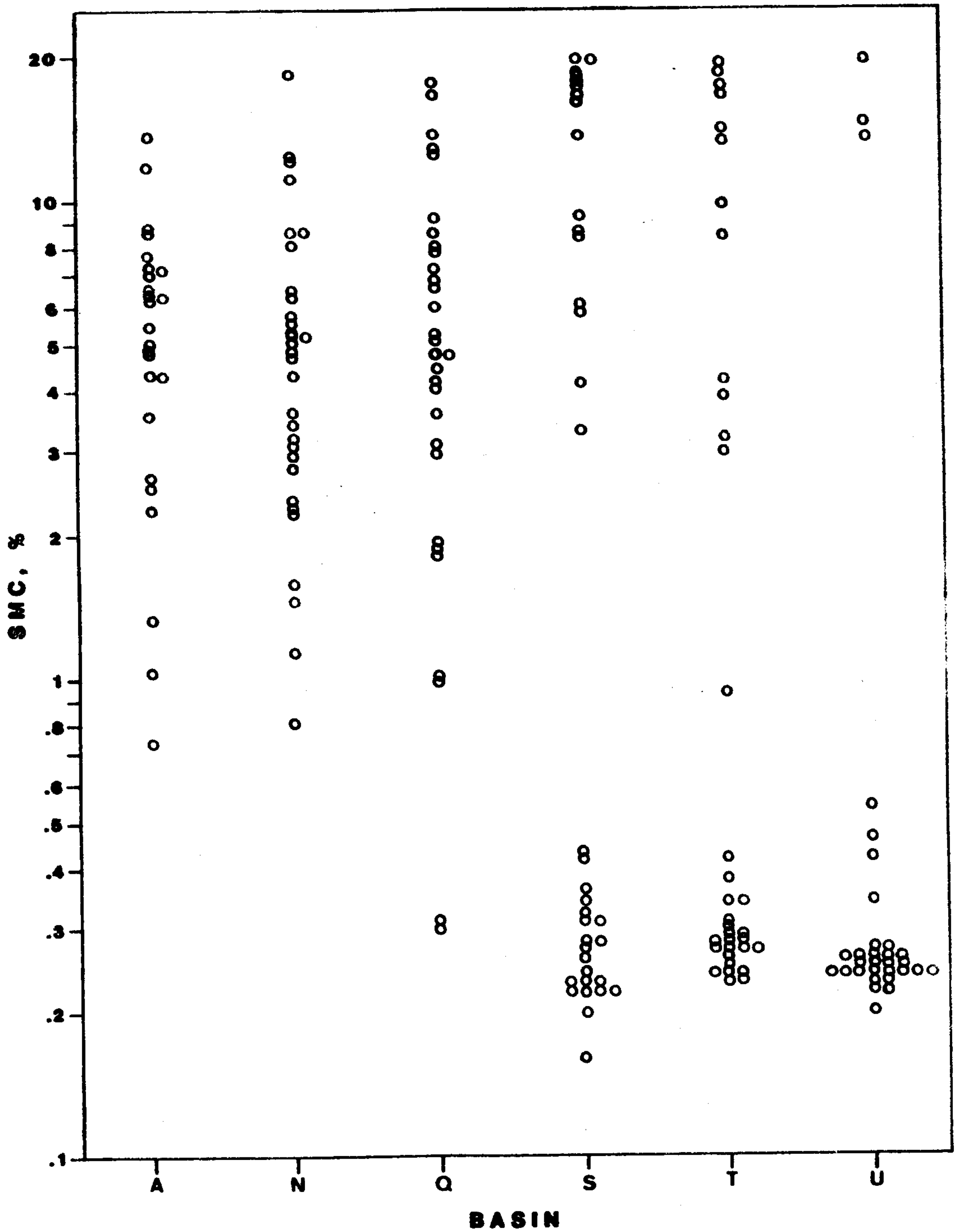


Fig. 6.2. Soluble mineral contents (SMC) of surficial materials in six badland drainage basins. Data are in Appendix.

weathered bedrock samples had a higher average SMC than the soil samples (Table 6.2).

Table 6.2. Summary of SMC analysis in percent.

Basin	Range	Soil (avg.)	Weathered bedrock (avg.)
A	0.74 - 13.81	5.10	6.12
N	0.81 - 18.40	4.82	5.90
Q	0.30 - 17.79	4.76	7.80
S	0.16 - 19.92	3.45	8.56
T	0.23 - 19.22	1.95	5.08
U	0.20 - 19.72	0.28	3.37

An analysis of variance of log SMC was conducted in order to test the significance of the difference of the soil and weathered bedrock means. Table 6.3 shows that, in five of the six basins, there is no significant difference in means of the soil and weathered bedrock samples at $\alpha = .05$.

In Chapter V it was concluded that, although erosional processes differ in various locations of basins in the badlands, surficial materials are being eroded from all portions of the basins. Consequently, an analysis of variance of log SMC was conducted to test whether or not the mean SMC of collective soil and weathered bedrock samples was the same for each transect within each basin. Table 6.4 shows that, in five of the six basins, there is no significant difference in means of the cross sections at $\alpha = .05$.

Table 6.3. Analysis of variance of log SMC for soil and weathered bedrock.

H_0: Mean SMC of soil and weathered bedrock samples is the same within each basin.

Basin	n	F-ratio (calculated)	F-ratio (α=.05)	Accept or reject H_0
A	27	1.308	F(1,25)=4.24	accept
N	28	1.294	F(1,26)=4.23	accept
Q	28	4.233	F(1,26)=4.23	reject
S	35	2.953	F(1,33)=4.44	accept
T	35	2.563	F(1,33)=4.44	accept
U	29	2.776	F(1,27)=4.21	accept

Table 6.4. Analysis of variance of log SMC for basin cross sections.

H_0: Mean SMC of collective soil and bedrock samples is the same for each cross section in a basin.

Basin	n	F-ratio (calculated)	F-ratio (α=.05)	Accept or reject H_0
A	27	1.008	F(2,24)=3.40	accept
N	24	0.464	F(2,21)=3.47	accept
Q	27	0.395	F(2,24)=3.40	accept
S	34	1.042	F(3,30)=2.92	accept
T	35	1.741	F(3,31)=3.30	accept
U	27	5.800	F(2,24)=3.40	reject

The plot of SMC data on Figure 6.2 shows that the six basins may be divided into two sets. That is, Basins A, N, and Q generally have higher SMC values than Basins S, T, and U. The basins in each set were tested to see if their means were the same, then the two sets were tested to see if their means were the same.

An analysis of variance of log SMC was conducted to test whether or not the mean SMC of collective soil and weathered bedrock samples were the same for the basins within each set. Table 6.5 shows that the means are the same for Basins A, N, and Q at $\alpha = .05$, whereas the means are not the same for Basins S, T, and U at $\alpha = .05$. However, a two-tailed T-test comparing the means of each set shows that the means of the two sets are significantly different at $\alpha = .05$ (Table 6.6).

6.3 Conclusions

Surficial materials consisting of soil and weathered bedrock have wide-ranging SMC within the individual basins. However, based on the above statistical analysis, some conclusions are drawn for the purpose of inferring SMC characteristics for the badlands in general.

In five of the six basins, there is no significant difference between the mean SMC of soil materials and weathered bedrock materials. No attempt is made here to explain why the weathered bedrock in Basin Q has a significantly greater mean SMC than the soil. In general, however, SMC of soil does not differ from SMC of weathered bedrock in the badlands.

Table 6.5. Analysis of variance of log SMC according to lithology: A = basins underlain by shale; B = basins underlain by interbedded shale and sandstone.

A. H_0: Mean SMC of collective soil and bedrock sample is the same for the three basins underlain by shale bedrock.

Basin	n	F-ratio (calculated)	F-ratio (α=.05)	Accept or reject H_0
A,N,Q	83	0.108	F(2,80)=3.12	accept

B. H_0: Mean SMC of collective soil and bedrock samples is the same for the three basins underlain by interbedded shale and sandstone bedrock.

Basin	n	F-ratio (calculated)	F-ratio (α=.05)	Accept or reject H_0
S,T,U	99	4.857	F(2,96)=3.10	reject

Table 6.6. Two-tailed T-test of log SMC for the two sets of basins according to lithology.

H_0: Mean SMC of collective soil and bedrock samples is the same for basins underlain by shale and basins underlain by interbedded shale and sandstone.

n pairs	Mean SMC for shale basins (%)	Mean SMC for shale-sandstone basins (%)	T-ratio (calculated)	T-ratio (α=.05)	Accept or reject H_0
83	4.51	0.73	T(82)=8.502	1.989	reject

In five of the six basins, there is no significant difference between the mean SMC of the sample transects. No attempt is made here to explain why the transects in Basin U are significantly different. In general, however, SMC of surficially materials is the same along the lengths of the basins in the badlands.

Finally, the SMC of surficial materials of two sets of basins have significantly different means, although in only one set do the basins have the same means. The explanation offered here for these results is based on the lithology of the basins. Basins A, N, and Q are underlain by predominantly shale bedrock, whereas Basins S, T, and U are underlain by interbedded shale and sandstone. The shales contain evaporite salts from depositional processes, whereas the sandstone lenses contain only calcite as cement (Fisher, et al., 1960). Consequently, a unit volume of shale will have a higher SMC than a unit volume of interbedded shale and sandstone. The SMC means for Basins S, T, and U differ significantly because the basins probably have different shale to sandstone ratios. Therefore, basins underlain by shale have significantly higher SMC than basins underlain by interbedded shale and sandstone.

CHAPTER VII

GEOMORPHIC STABILITY AND SALINITY

7.1 Introduction

The results concerning the erosional stability of landforms and SMC relationships given in Chapters V and VI, respectively, were used in conjunction with previous erosional and salinity studies for the purpose of relating geomorphic stability with processes of salt release from the area. Maps based on geomorphic and salinity information were desired for the purpose of describing the area according to erosional stability and salinity potential.

7.2 Geomorphic Processes and Salinity

7.2.1 Badlands

Badlands cover more surface area and are more erosionally unstable than pediments and alluvial valley floors. Erosion in the badlands occurs as rill formation during hillslope runoff, soil creep due to frost heave, and channel bank failure during runoff events. It occurs as slope failure of loose surface materials due to thunderstorm events or simply by gravitational forces, also.

Ponce (1975) and Sunday (1979) have shown that salinity of runoff is directly proportional to sediment load, and Sunday concluded that salinity of runoff is proportional to rill development on hillslopes and with hillslope gradient. The badlands are dominated by rills and hillslopes of variable gradients, and the observation by Hadley and Lusby (1967) of a soil loss of 34.5 tonnes per hectare during one storm indicates the magnitude of sediment produced in a runoff event. Since sediment is derived from all portions of basins (Chapter V), and since SMC of surficial materials is generally uniform within each basin (Chapter VI), it is concluded that all portions of basins contribute to the salinity of the runoff.

Describing the salinity potential of the badlands according to hillslope gradient would be impractical. The valley cross section measurements (Table 5.2) indicate that the hillslope gradients are variable within the individual basins. The variability prohibits a quantitative salinity analysis based on Sunday's salinity relationship. Furthermore, the vast expanse and variability of the badlands prohibits any numerical geomorphic analysis from being applied to salinity potential.

The potential for salt release from individual drainage basins in the badlands probably is most dependent on the type of underlying bedrock (Chapter VI). That is, basins underlain by mostly shale have the potential for releasing greater amounts of salts into runoff than basins underlain by interbedded shale and sandstone. This conclusion has not been verified, however, because SMC of runoff and sediment from the two types of basins have not been analyzed.

The Bureau of Land Management (1978) studied the impact of grazing on runoff and sediment yield. They found that grazing reduced soil infiltration due to loss of plant cover and increased soil compaction, and that grazed watersheds produced 30% more runoff and 45% more sediment than ungrazed watersheds. Studies conducted in Badger Wash (Lusby, et al., 1971) concluded that early in the year grazed watersheds produced much more runoff than ungrazed watersheds, whereas later in the year, after the effect of summer thunderstorms, runoff was more nearly equal. Currently, much of the area is grazed and many locations of destroyed vegetative cover, slumped hillslope materials, and sloughed channel banks due to livestock were observed during field investigations.

Sediment retention dams have been built in several badland drainages for the purpose of removing sediment from runoff and storing it. This procedure is thought to reduce the amount of salt leaving the badlands by having it retained in the stored sediment (Bureau of Land Management, 1978). However, not only has salt reduction by this method not been proven, but the salts may be stored for only a short period of time, and the dams may lead to increased erosion and salt production downstream. Laronne (1977) observed that salts were leached out of the stored sediment. Field investigations for the present study indicated that most sediment storage sites were well-vegetated, and some channels downstream of the dams were scoured into fresh bedrock and some had noticeable evaporite crusts. The effects that sediment retention devices have on reducing salt load need further study.

Apart from the detrimental effects of grazing mentioned above, ORV use and road development appear to have an adverse effect on the areas, also. Observed ORV trails were generally highly compacted and rutted, thus providing areas susceptible to increased runoff and channelization of runoff. Furthermore, many once-used trails crossed hillslopes, thus disturbing and dislodging surficial materials loosened by frost heave. Roads built across the badlands for construction of gas well sites, gas pipelines, and as access to coal mines exhibited the detrimental effect of gullying due to the channelization of runoff along ditches and below culverts, and by the presence of evaporite crusts on surfaces of freshly exposed shale in road cuts.

7.2.2 Pediments

The pediment surfaces have very gentle gradients with slightly concave to slightly convex cross sections (Carter, 1980). Runoff occurs mainly as sheetflow since the surface gradients are too shallow for rill development. The Bureau of Land Management (1978) has classified the soils that have developed on gravel pediment surfaces, the kind present in the study area, as being nonsaline at the surface. No samples were collected or analyzed, but the presence of a generally good vegetative cover reflects the assumed low SMC of the surfaces. The low SMC of the surface materials probably is due to high gravel content of the surfaces (Carter, 1980), and due to many years of leaching. Therefore, the salinity of runoff on pediment surfaces is probably insignificant.

Salt production may not be minor where channels dissect individual surfaces, however. The clean sheet flow has great erosive power where it is channelized, and if the channel is incised into a saline layer of the gravel deposit or into shale bedrock, then salt will be produced. Although it was not studied, it might be expected that the gravel deposit-bedrock contacts would have salt concentrations due to leaching of the surface materials (Carter, 1980). If so, runoff in incised pediment channels could be highly saline even though pediment surface runoff may be nonsaline. This assumption has not been verified in the field, however.

7.2.3 Alluvial Valley Floors

The alluvial valley floors are similar to the pediment surfaces, as their gradients are too shallow for rills to develop. Laronne (1977) noticed that the surface materials of alluvium have low SMC but that SMC increases with depth in shallow alluvium overlying Mancos Shale. The generally good vegetation on alluvial materials and the presence of salt crusts observed along exposed alluvium-bedrock contacts suggests that some of the salts have been leached out of the alluvium. Consequently, runoff on the alluvial valley floors probably does not acquire much sediment or salt.

The walls of incised channels, however, are steep, and field observations indicated that undercutting and sloughing of channel wall material is common. The unleached salts in the alluvium as well as salts from evaporite crusts along exposed alluvium-bedrock contacts are incorporated into the runoff during thunderstorm events. Alluvial surfaces, therefore, are insignificant producers of sediment and salt, but channel walls may deliver substantial quantities of sediment and salt to incised channel flow.

Field investigations and aerial photographs indicated that all of the alluvial valley floors are incised. The suggested reason for this is attributed to downstream agricultural practices (Chapter V). Where roadfills cross the surfaces, gullies with evaporite crusts prevail below drainage culverts. ORV and livestock trails between channel bottoms and alluvial valley floor surfaces are associated with bank failure of channel wall materials, and they probably create and increase headward expansion of some gullies. The above activities contribute to increased sediment and salt load in channel flow through the alluvial fills.

7.3 Geomorphic Maps

7.3.1 Introduction

Maps based on geomorphic and salinity studies were desired for the purpose of describing the area according to erosional stability and salinity potential. A quantitative salinity potential map was intended to be made based on the previously studied hillslope gradient-runoff salinity relationship. However, field studies indicated that hillslope gradients in the badlands are quite variable, even within the small drainage basins. Therefore, a quantitative salinity potential map was deemed impractical.

In place of a quantitative salinity potential map, two types of geomorphic maps were compiled for the purpose of delineating areas according to their relative stability in terms of geomorphic process and salt release. The two types included: 1) the portrayal of relative relief, and 2) the mapping of the three major landforms.

7.3.2 Relative Relief Map

The method describing the compilation of the relative relief map is given in Chapter IV. The theory of the map is that as relative relief increases, so does the presence of deeply incised channels, steeper channel gradients, as well as the opportunity for rill development to occur, all of which signify greater erosion and, therefore, greater salt release. The purpose of the map, then, is to visually distinguish regions according to their relative stability.

The relative relief map (Fig. 7.1) clearly indicates the great variability of relief throughout the study area. Relative relief ranges from 12 m/km^2, along a portion of Big Salt Wash and near East Salt Creek, to more than 500 m/km^2 along the Book Cliffs escarpment. The steep terrain of the escarpment is obvious and there is a 2 to 3 km wide zone along the cliffs which has a relative relief of at least 100 m/km^2. According to this map, the most stable areas are: between Badger Wash and East Salt Creek, along and to the east of East Salt Creek, the area drained by the lower portions of Big Salt Wash and Lipan Wash, along Little Salt Wash, and near Walker Field.

One major disadvantage of the relative relief map is the use of maximum relief within each square kilometer grid. For example, if a grid encloses the margin of a pediment, the measured relief will reflect the relief of the oversteeped slope even if the majority of the grid encloses a gently sloping pediment surface. Consequently, much of the land surface comprising pediment surfaces and alluvial valley floors is not identified as low relative relief because grids encompass pediment margins and arroyos, respectively.

The relative relief map, therefore, is a marginally useful tool for describing the relative stability of the area. It shows the wide variability of relative relief in the area, but it lacks precision in identifying specific areas susceptible to high sediment and salt production.

7.3.3 Landforms Map

The landforms map (Fig. 7.2) outlines the pediment surfaces and the alluvial valley floors with everything else as badlands.

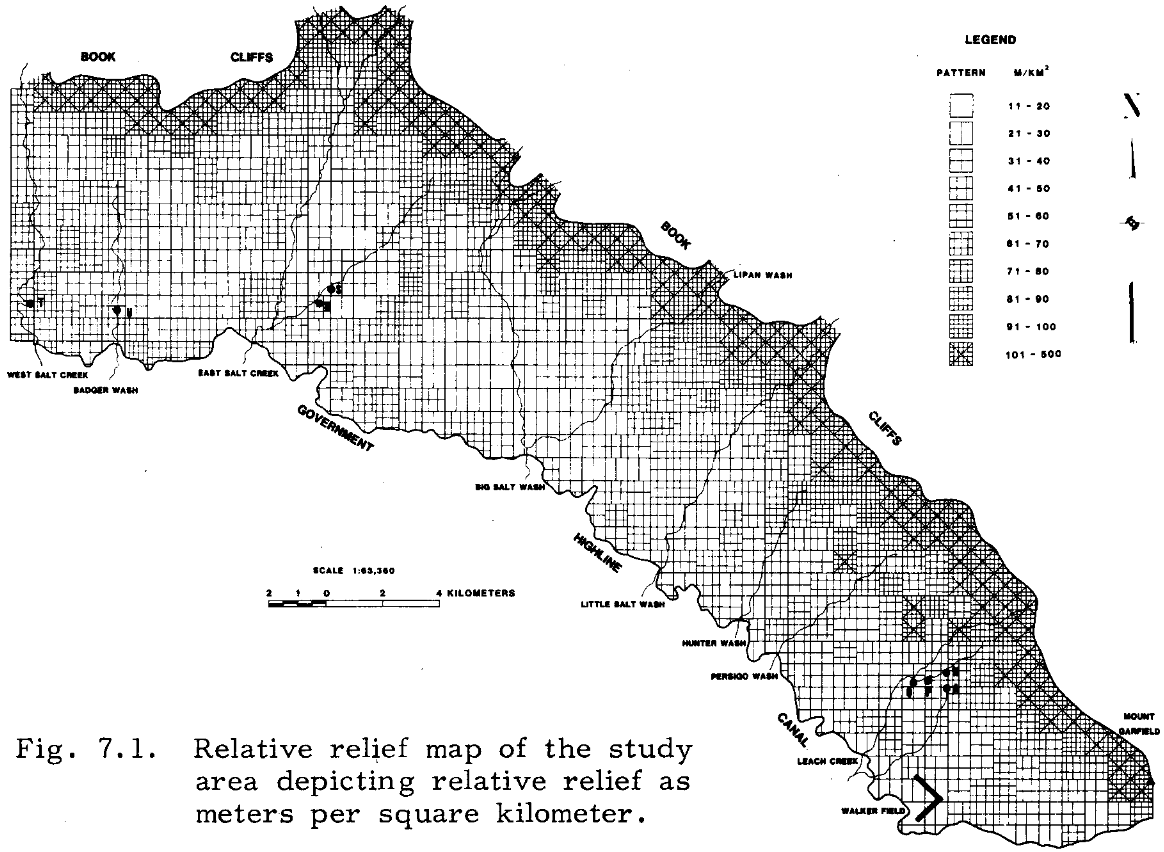


Fig. 7.1. Relative relief map of the study area depicting relative relief as meters per square kilometer.

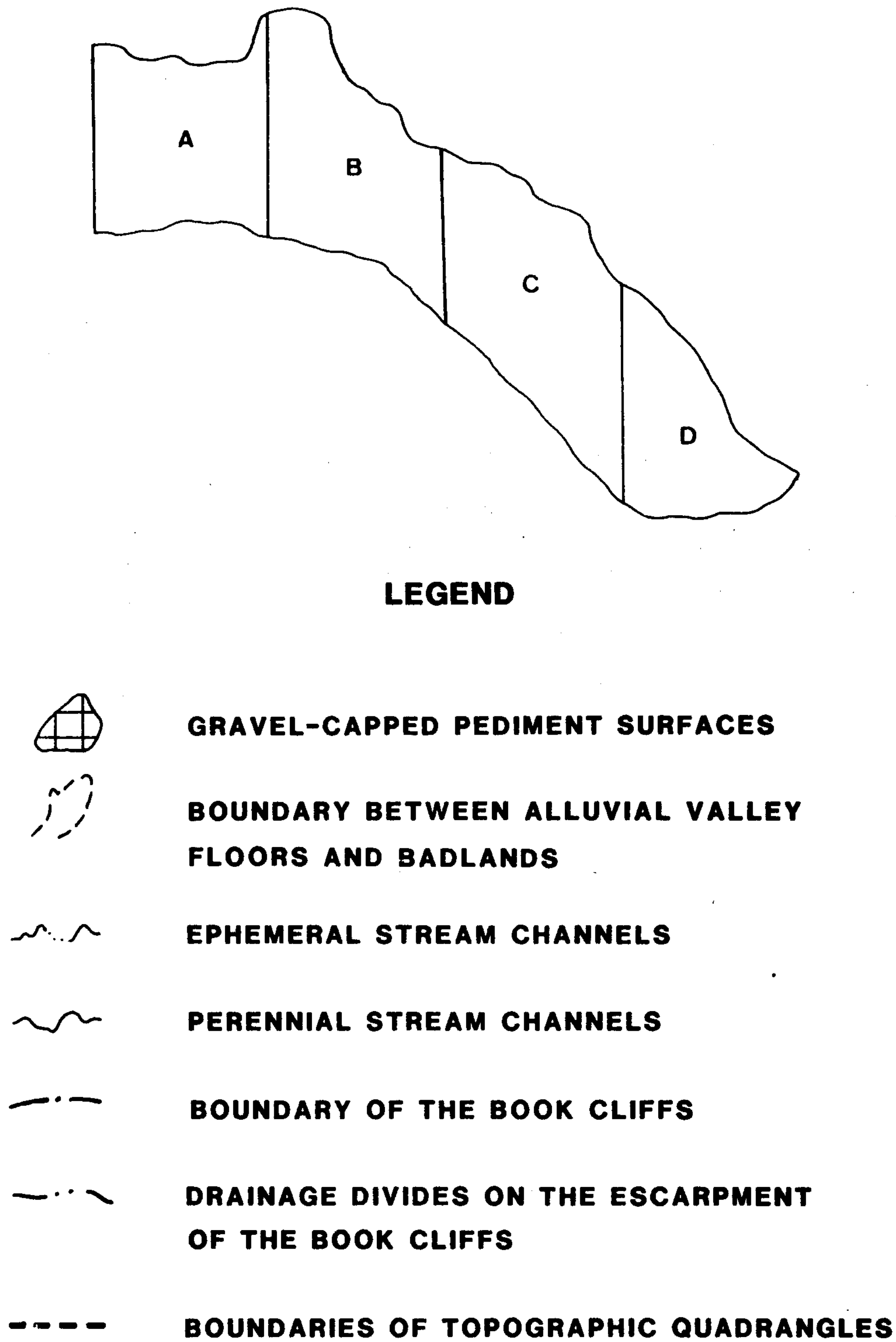
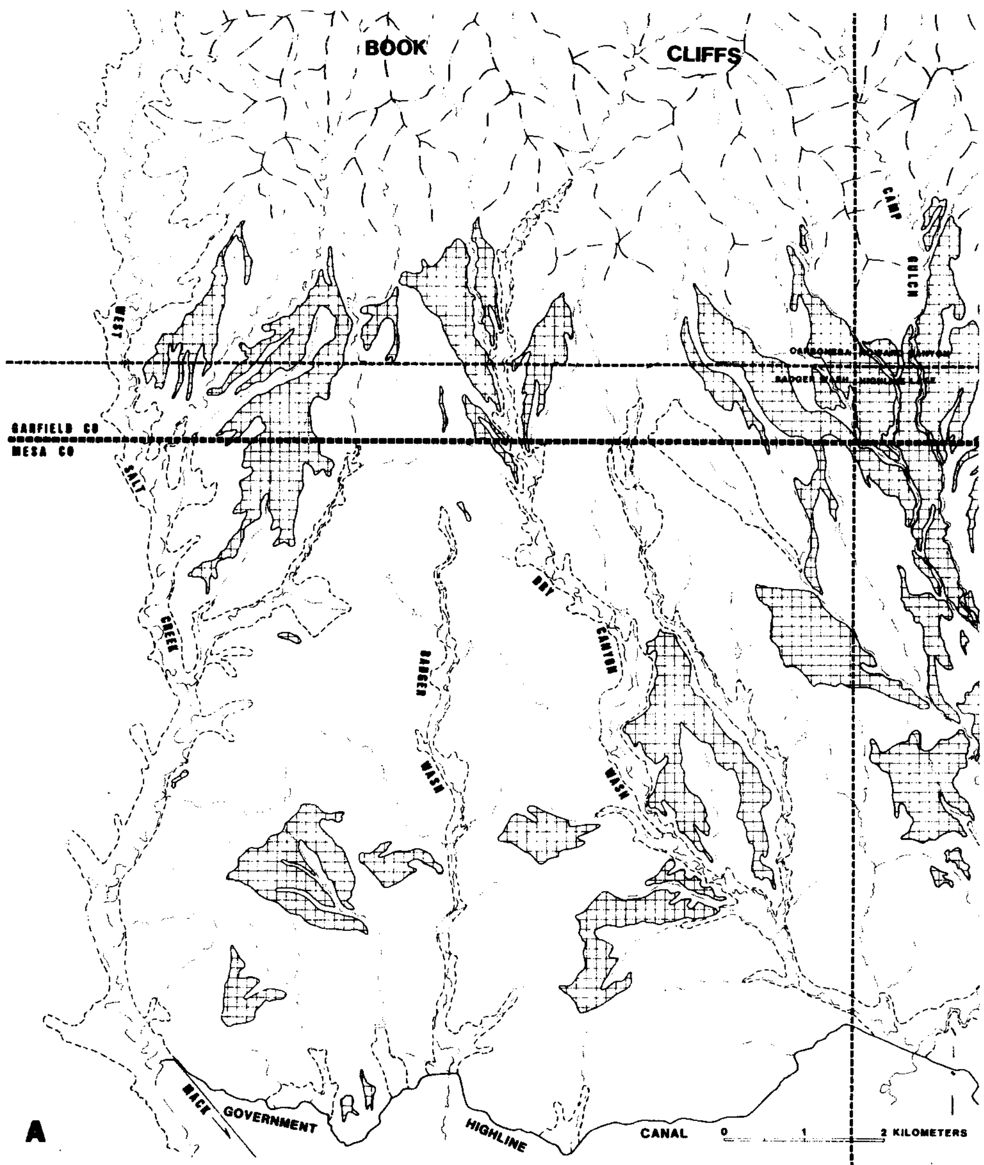


Fig. 7.2. Landforms map of the study area showing the three major landforms.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CLIFFS
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SALT
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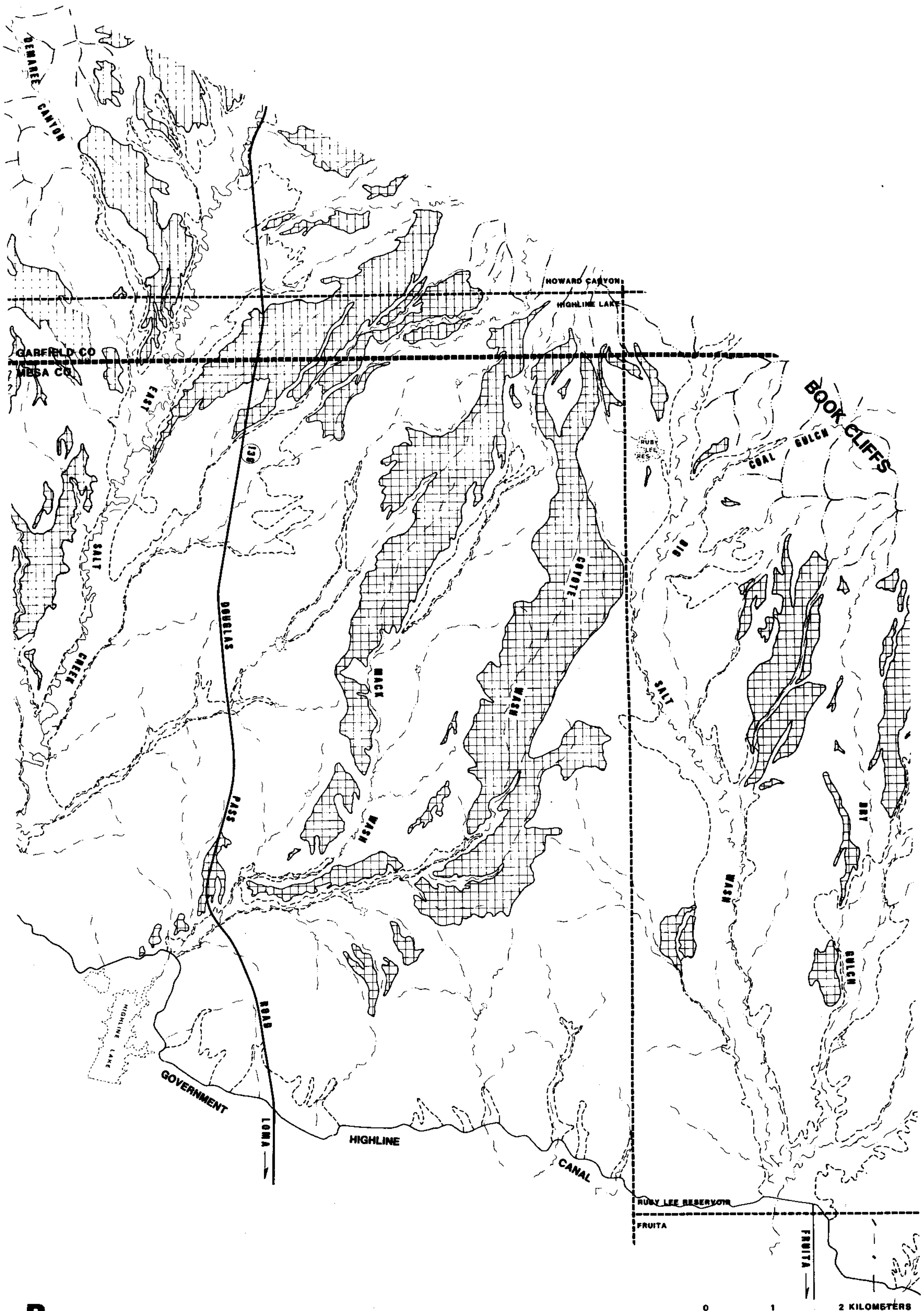
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MACK
WASH
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RUBY LEE RES
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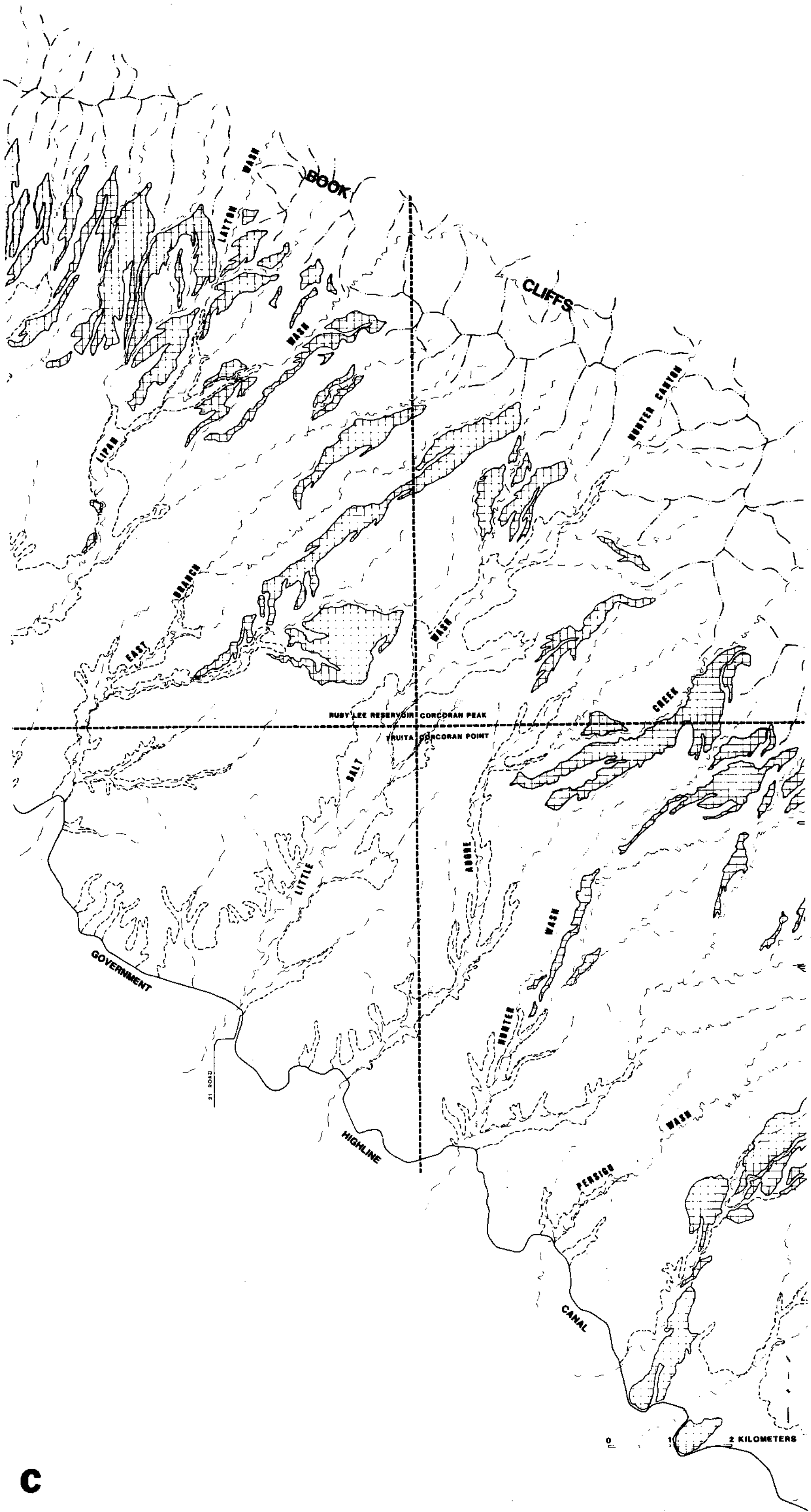
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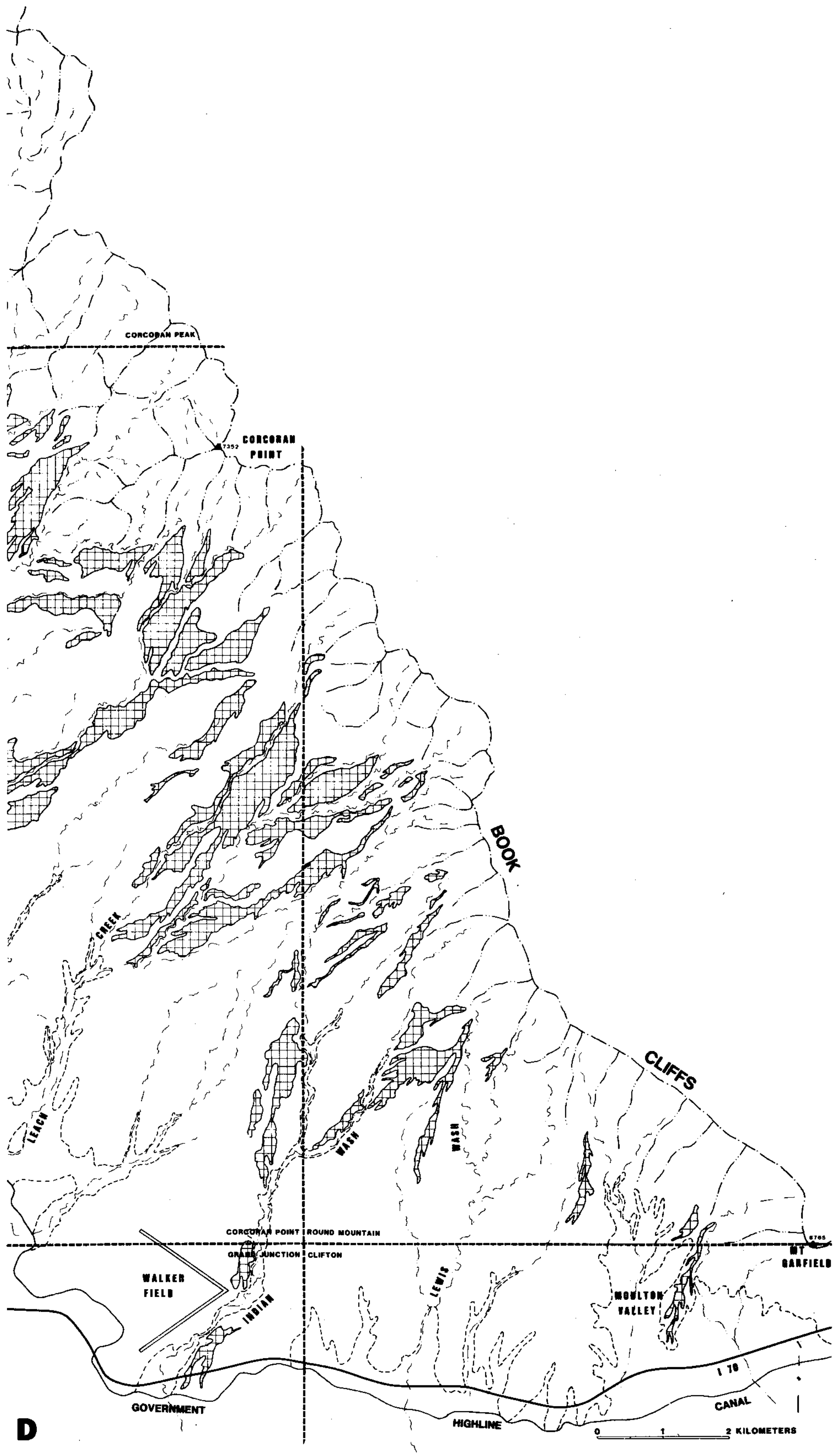
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CLIFTON
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GARFIELD
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As previously discussed, the pediment surfaces are the most stable in terms of potential erosion and salt release, and the badlands are least stable.

The alluvial valley floor surfaces outlined on the map do not indicate all of the alluvium in the study area. Most of the tributary basins in the piedmont have some alluvium in their lower reaches. The areas mapped as alluvium are those which the aerial photos showed to be well vegetated and which were in the widest portions of the valleys. Both of these criteria indicate greater stability and depth to bedrock than the unmapped alluvium.

7.4 Conclusions

The study area consists of badlands, pediment surfaces and alluvial valley floors. The pediment surfaces are erosionally stable because their surfaces are too gentle for rill development. Also, the surface materials apparently have low SMC due to material type and leaching. However, salt probably is released where channels dissect pediment surfaces.

Alluvial valley floors are erosionally stable, also. Like pediments, their surfaces are too gentle for rill development. Also, some of the salts have been leached out of the alluvium. Channels incised into alluvium, however, incorporate sediment and salt from sloughed channel wall material and salt from evaporite crusts along exposed alluvium-bedrock contacts. Road culverts, along with ORV and livestock trails, tend to increase gully erosion in the alluvium.

The badlands are erosionally unstable. Sediment and associated salt enters runoff through rill development on hillslopes and from hillslope materials that creep or slump into the channels. SMC of surficial materials is generally uniform throughout the individual basins, but basins underlain by shale have more salt available for solution than basins underlain by interbedded shale and sandstone. Sediment retention structures in the badlands may not reduce the amount of salt leaving the badlands, and they may actually increase sediment and salt production downstream of the structures. Grazing in the badlands increases runoff and sediment production. Livestock and ORV trails dislodge loose hillslope materials, ORV trails and roads increase gullying by channelizing runoff, and roadcuts expose fresh shale and associated salts to runoff.

A relative relief map was compiled for the area and, although it shows the variability of relative relief, it does not identify specific locations of erosional instability. The landforms map, on the other hand, outlines the three major landforms in the area thus differentiating the erosionally unstable and greater salt-producing badlands from the pediment surfaces and alluvial valley floors.

CHAPTER VIII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

8.1 Summary and Conclusions

The Mancos Shale, a Cretaceous marine shale, is known to be a large contributor of dissolved solids to the upper Colorado River. Tributaries of the Colorado River flow over or begin on exposures of Mancos Shale at the base of the Book Cliffs in Grand Valley, Colorado. The study area (Figs. 1.1 and 3.1) consists of three landforms: badlands, pediments, and alluvial valley floors.

8.1.1 Badlands

The badlands cover the greatest portion of the areas and produce large quantities of sediment in runoff. The badlands are formed by headward expansion of ephemeral streams. Runoff resulting from thunderstorms removes surficial materials and associated soluble minerals from hillslopes through rill development and from channels containing soil creep and slump deposits.

Two lithologies were identified, which affect soil depths and SMC of surficial materials. Drainage basins underlain by interbedded shale and sandstone have significantly deeper soils than basins underlain by shale. The sandy soils of the interbedded shale and sandstone basins have greater soil permeability and vegetative cover than the clay-rich soils of the shale basins. Also, the SMC of surficial materials, soil and weathered bedrock, are significantly lower in interbedded shale and sandstone basins than in shale basins. It has not been shown which type of basin would produce the most sediment during a runoff event, but relative SMC of surficial materials in the badlands can be differentiated on the basis of underlying lithology.

Land use practices, which accelerate erosion, increase salt production. Grazing has been shown to increase runoff and sediment yield by increasing soil compaction, reducing soil infiltration, and reducing vegetative cover. Currently, much of the area is used for grazing, and locations of destroyed vegetation cover, slumped hillslope materials, and sloughed channel banks due to livestock activity were observed. Besides grazing, ORV use and road construction appear to accelerate erosion mainly by compacting soils and channelizing runoff.

8.1.2 Pediments

Pediments comprise the next largest portion of the surface area. The origin and dissection of pediments is related to periods of landslides and debris flows alternating with periods of arid erosion associated with glacial and interglacial stades, respectively. Currently, all of the pediment surfaces are decreasing in size due to badland encroachment and incision by channels. Apart from the pediment margins and incised channels, the surfaces are erosionally stable and generally support good vegetative cover. Road construction appeared to be the only erosionally detrimental land use as it creates gullies formed by channelizing runoff into drainage ditches.

8.1.3 Alluvial Valley Floors

Alluvium is present in most of the badland drainages, and it fills wide valleys of upland and cliff channels. The evolution of the alluviated regions appears to have occurred by the following sequence: 1) all channels were once bedrock channels; 2) the bedrock channels were alluviated by backfilling after a southward shift of the Colorado River; and 3) the channels began incising probably as a result of land use practices south of the Highline Canal. Currently, all observed channels are incised and expanding.

The salts are partially leached from the alluvium and are concentrated along the alluvium-bedrock contact. Runoff in channels incised in alluvium entrain sediment and soluble minerals from sloughed channel walls and from evaporite crusts along exposed alluvium-bedrock contacts.

Except as influenced by incised channels, the alluvial valley floors are erosionally stable and generally support a good vegetative cover. However, erosionally detrimental land use practices were observed. Gullies and evaporite deposits were observed along drainage ditches and downstream of culverts as a result of channelizing runoff.

8.2 Recommendations

The fourth and final objective of this study was to recommend land use and/or salt control measures that might be employed for the purpose of reducing the salt load entering the Colorado River.

The erosionally unstable badlands must be the major focus of concern. As salinity of runoff is related to sediment load, efforts must be made to reduce sediment load. Sediment retention structures, however, have not been proven to reduce the amount of soluble minerals leaving the badlands. The stored sediment is often leached of salts, and channel scour and evaporite crusts are common below structures. Therefore, the beneficial aspects of sediment retention structures needs to be verified before any more are built in the badlands.

Applications of the soil and SMC analysis conducted for surficial materials in the badlands may be useful for land use purposes. If grazing and ORV use in the badlands is necessary for local economy and public reltations, then perhaps these uses can be restricted to regions underlain by interbedded shale and sandstone bedrock. Although the land use would probably increase sediment load from these areas, the generally low SMC of the surficial materials would most likely produce less salts than similarly used shale basins.

Road construction in the area needs tighter controls to reduce erosional effects. Roads should be constructed to avoid cutting across hillslopes, which exposes fresh shale to erosion and allows rills to develop on the oversteepened slopes. Restricting roads to alluvial valley floor surfaces, pediment surfaces, and rounded badland divides probably would result in the least amount of erosion. Also, drainage ditches and culverts need to be constructed so as to prohibit gully erosion. Perhaps water spreaders in ditches and riprap below culverts would do this.

The landforms map (Fig. 7.2) should aid land users because it delineates the erosionally unstable and salt producing badlands from the pediments and alluvial valley floors. If feasible, grazing should be restricted to available pediment and alluvial valley floors where erosional effects probably would be minimal. The landforms map could be used for preliminary road location, also.

In summary, the following recommendations are made to better understand the erosional and salinity characteristics of runoff from badlands and to reduce erosion and salinity related to current land use practices in the area:

1) Existing sediment retention structures must be examined in order to determine their effectiveness in reducing both sediment and salt production from the badlands.
2) Sediment load and salinity of runoff needs to be compared for the two basin lithologies in the badlands, i.e., basins underlain by interbedded shale and sandstone versus basins underlain by shale. The results of this study may indicate which basins would produce the least amount of sediment and salt if used for grazing or ORVs.
3) Road construction should avoid cutting across hillslopes.
4) Drainage ditches and culverts should have water spreaders and riprap, respectively, in order to reduce gully erosion.
5) The landforms map should be used to locate stable areas for grazing and road construction.

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APPENDIX

APPENDIX

SALINITY DATA FOR THE SURFICIAL MATERIAL SAMPLES

Code for Salinity Data

Sample: A A 1 a

First space:	Basin designation
Second space:	A = cross section closest to basin month; B = next closest; ect; X = samples collected downstream of cross section A.
Third space:	1 = left divide; 2 = left slope; 3 = channel; 4 = right slope; 5 = right divide; 6 = channel that basin channel flows into.
Fourth space:	a = soil sample; b = weathered bedrock sample; c = alluvium sample; d = sample taken from the alluvium contact in the channel wall.

EC: Specific conductivity of 1:99 sediment:distilled water solution measured in µmhos/cm after 2 hours of shaking.

Estimated Maximum EC: $EC = bX^{.073}$ where X = 5 hours

TDS: Total dissolved solids, where Log (TDS) = -0.47413 + 1.1212 Log (EC)

SMC: Soluble mineral content of the sample, where SMC = $(TDS_{1.99})$ (.0099)

Salinity Data

Basin A

Sample	Soil Depth (cm)	EC @ 2 hrs (μmhos/cm)	Estimated Maximum EC	TDS (mg/l)	SMC (%)
AA1a	3	619	662	488	4.83
AA1b		890	952	734	7.27
AA2a	3	1390	1486	1209	11.97
AA2b		562	601	438	4.34
AA3a	2	--	--	--	---
AA4a	3	562	601	438	4.34
AA4b		1060	1133	892	8.83
AA5a	4	632	676	500	4.95
AA5b		344	368	253	2.50
AB1a	5	767	820	621	6.15
AB1b		360	385	266	2.63
AB2a	5	642	686	508	5.03
AB2b		778	832	631	6.25
AB3a	2	195	208	133	1.32
AB3b		311	333	226	2.24
AB4a	3	792	847	644	6.38
AB4b		1040	1112	873	8.64
AB5a	1	116	124	74.6	0.74
AB5b		815	871	664	6.57
AC1a	5	867	927	712	7.05
AC1b		778	832	631	6.25
AC2a	7	155	166	104	1.03
AC2b		892	954	735	7.28
AC3a	1	--	--	--	---
AC3b		692	740	553	5.47
AC4a	5	942	1007	781	7.73
AC4b		472	505	360	3.56
AC5a	5	6.13	655	482	4.77
AC5b		1580	1689	1395	13.81

Salinity Data

Basin N

Sample	Soil Depth (cm)	EC @ 2 hrs (μmhos/cm)	Estimated Maximum EC	TDS (mg/1)	SMC (%)
NX6a	2	478	511	365	3.61
NX6b		325	347	237	2.35
NX3a	1	126	135	82.1	0.81
NX3b		394	421	294	2.91
NX3c		427	457	322	3.19
NX3d		1290	1379	1112	11.01
NA1a	--	411	439	308	3.05
NA2a	--	1400	1497	1219	12.07
NA3a	2	--	--	--	---
NA3b		449	480	340	3.37
NA3c		376	402	279	2.76
NA4a	--	1030	1101	864	8.55
NA4b		--	--	--	---
NA5a	--	306	327	221	2.19
NB1a	8	974	1041	811	8.03
NB1b		809	965	659	6.52
NB2a	9	212	227	147	1.46
NB2b		1420	1518	1238	12.26
NB3a	1	169	181	114	1.13
NB3b		314	336	228	2.26
NB4a	4	722	772	580	5.74
NB4b		555	593	432	4.28
NB5a	2	619	662	488	4.83
NB5b		639	683	506	5.01
NC1a	3	229	245	160	1.58
NC1b		781	835	633	6.27
NC2a	6	669	115	532	5.27
NC2b		2040	2181	1859	18.40
NC3a	1	1030	1101	864	8.55
NC3b	3	600	642	472	4.67
NC4b		653	698	518	5.13
NC5a	4	701	749	561	5.55
NC5b		651	696	516	5.11

Salinity Data

Basin Q

Sample	Soil Depth (cm)	EC @ 2 hrs (μmhos/cm)	Estimated Maximum EC	TDS (mg/l)	SMC (%)
QX6a	5	--	--	--	---
QX6b		398	426	298	2.95
QX3c		273	292	195	1.93
QA1a	6	841	899	688	6.81
QA1b		546	584	424	4.20
QA2a	5	666	712	530	5.25
QA2b		903	965	745	7.38
QA3a	2	--	--	--	---
QA3b		266	284	189	1.87
QA3c		153	164	102	1.01
QA4a	5	881	942	725	7.18
QA4b		1570	1679	1386	13.72
QA5a	6	256	274	182	1.80
QA5b		414	443	311	3.08
QB1a	4	830	887	678	6.71
QB1b		750	802	605	5.99
QB2a	6	149	159	98.6	0.98
QB2b		968	1035	806	7.98
QB3a	1	--	--	--	---
QB3b		473	506	361	3.57
QB4a	5	51.9	55.5	30.3	0.30
QB4b		1860	1989	1676	16.59
QB5a	7	612	654	482	4.77
QB5b		606	648	477	4.72
QC1a	4	1100	1176	930	9.21
QC1b		1460	1561	1277	12.64
QC2a	6	52.9	56.6	31.0	0.31
QC2b		1980	2117	1797	17.79
QC3a	2	--	--	--	---
QC3b		576	616	450	4.46
QC4a	5	656	701	521	4.16
QC4b		1470	1572	1287	12.74
QC5a	5	1040	1112	873	8.64
QC5b		650	695	516	5.11

Salinity Data

Basin S

Sample	Soil Depth (cm)	EC @ 2 hrs (μmhos/cm)	Estimated Maximum EC	TDS (mg/l)	SMC (%)
SX6a	1	41.7	44.6	23.7	0.23
SX3c		48.8	52.2	28.3	0.28
SA1a	5	61.5	65.8	36.7	0.36
SA1b		40.1	42.9	22.7	0.22
SA2a	18	537	574	416	4.12
SA2b		1860	1989	1676	16.59
SA3b		55.0	58.8	32.3	0.32
SA3c	1	40.0	42.8	22.6	0.22
SA4a	9	1100	1176	930	9.21
SA4b		1930	2064	1747	17.30
SA5a	10	1010	1080	845	8.37
SA5b		1950	2085	17.67	17.49
SB1a	--	2190	2341	2012	19.92
SB2a	8	69.7	74.5	42.2	0.42
SB2b		1800	1925	1616	16.00
SB3a	2	70.9	75.8	43.0	0.43
SB4a	7	438	468	331	3.28
SB4b		1040	1112	873	8.64
SB5a	7	41.7	44.6	23.7	0.23
SB5b		40.2	43.0	22.8	0.22
SC1a	6	57.8	61.8	34.2	0.34
SC1b		2050	2192	1869	18.50
SC2a	8	1560	1668	1376	13.62
SC2b		727	777	584	5.78
SC3a	1	--	--	--	---
SC4a	6	39.9	42.7	22.6	0.22
SC4b		752	804	607	6.01
SC5a	10	42.5	45.4	24.2	0.24
SC5b		36.9	39.5	20.7	0.20
SD1a	9	45.6	48.8	26.2	0.26
SD1b		1980	2117	1797	17.79
SD2a	8	53.9	57.6	31.6	0.31
SD2b		2170	2320	1992	19.72
SD3a	2	--	--	--	---
SD3b		47.8	51.1	27.6	0.27
SD4a	7	54.3	58.1	31.9	0.31
SD4b		40.8	43.6	23.1	0.23
SD5a	10	29.7	31.8	16.2	0.16
SD5b		49.2	52.6	28.5	0.28

Salinity Data

Basin T

Sample	Soil Depth (cm)	EC @ 2 hrs (μmhos/cm)	Estimated Maximum EC	TDS (mg/l)	SMC (%)
TA1a	10	431	461	325	3.22
TA1b		1010	1080	845	8.37
TA2a	25	1600	1711	1416	14.02
TA2b		1870	1999	1686	16.69
TA3a	1	47.2	50.5	27.3	0.27
TA4a	7	42.5	45.4	24.2	0.24
TA4b		47.7	51.0	27.6	0.27
TA5a	11	42.5	45.4	24.2	0.24
TA5b		63.8	68.2	38.2	0.38
TB1a	9	54.7	58.5	32.2	0.32
TB1b		50.2	53.7	29.2	0.29
TB2a	7	41.9	44.8	23.8	0.23
TB2b		1510	1614	1326	13.13
TB3a	1	43.3	46.3	24.7	0.24
TB3d		1920	2053	1737	17.20
TB4a	5	548	586	426	4.22
TB4b		510	545	393	3.89
TB5a	8	50.9	54.4	29.6	0.29
TB5b		403	431	302	2.97
TC1a	11	70.5	75.4	42.7	0.42
TC1b		142	152	93.8	0.93
TC2a	10	44.8	47.9	25.7	0.25
TC2b		45.5	48.6	26.1	0.26
TC3a	3	--	--	--	---
TC3b		57.5	61.5	34.0	0.34
TC4a	8	1160	1240	987	9.77
TC4b		2040	2181	1859	18.40
TC5a	6	53.0	56.7	31.0	0.31
TC5b		2120	2267	1941	19.22
TD1a	11	52.5	56.1	30.7	0.30
TD1b		48.1	51.4	27.8	0.27
TD2a	12	48.9	52.3	28.4	0.28
TD2b		49.8	53.2	28.9	0.28
TD3a	1	--	--	--	---
TD4a	14	42.0	44.9	23.9	0.23
TD4b		48.2	51.5	27.9	0.27
TD5a	10	49.0	52.4	28.4	0.28
TD5b		57.5	61.5	34.0	0.34

Salinity Data

Basin U

Sample	Soil Depth (cm)	EC @ 2 hrs (μmhos/cm)	Estimated Maximum EC	TDS (mg/l)	SMC (%)
UX6a	1	40.3	43.1	22.8	0.22
UX3a	2	43.7	46.7	25.0	0.25
UX3c		43.8	46.8	25.0	0.25
UA1a	11	39.8	42.6	22.5	0.22
UA1b		69.6	74.4	42.1	0.42
UA2a	10	42.7	45.7	24.4	0.24
UA2b		2170	2320	1992	19.72
UA3a	2	--	--	--	---
UA3b		41.2	44.1	23.4	0.23
UA3c		57.8	61.8	34.2	0.34
UA4a	7	76.5	81.8	46.8	0.46
UA4b		1640	1753	1455	14.40
UA5a	7	87.0	93.0	54.1	0.54
UA5b		1530	1636	1346	13.33
UB1a	14	44.3	47.4	25.4	0.25
UB1b		43.5	46.5	24.9	0.24
UB2a	7	43.1	46.1	24.6	0.24
UB2b		36.5	39.0	20.4	0.20
UB3a	1	--	--	--	---
UB3b		42.5	45.5	24.3	0.24
UB4a	6	42.7	45.7	24.4	0.24
UB4b		46.3	49.5	26.7	0.26
UB5a	10	42.6	45.5	24.2	0.24
UB5b		45.5	48.6	26.1	0.26
UC1a	11	48.3	51.6	27.9	0.27
UC1b		46.1	49.3	26.5	0.26
UC2a	8	41.9	44.8	23.8	0.23
UC2b		43.1	46.1	24.6	0.24
UC3a	3	--	--	--	---
UC3b		46.0	49.2	26.5	0.26
UC4a	8	45.6	48.8	26.2	0.26
UC4b		47.9	51.2	27.7	0.27
UC5a	11	45.0	48.1	25.8	0.25
UC5b		43.5	46.5	24.9	0.24