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THE UNIVERSITY OF ALBERTA

Postglacial Geomorphic Evolution and Alluvial Chronology of a Valley in the Dinosaur Badlands, Alberta

by

(C) Sarah L. O'Hara

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF Master of Science

Department of Geography

EDMONTON, ALBERTA

Fall 1986

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Supervisor

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Date Sept. 29, 1986

Abstract

The Dinosaur badlands, Alberta, have developed in the highly erodible Upper Cretaceous deposits of the Judith River Formation. Badland development was initiated in the immediate postglacial period when pro-glacial lakes to the south and west drained across the area, removing thin Pleistocene deposits, and exposing the underlying bedrock. Incision was in two phases: initial widespread scouring, with later incision cutting deep U-shaped valleys. The study valley, which is located to the south of the Red Deer River, is believed to have formed during the episode of deep incision.

After the valley was incised a period of aggradation took place. This was in response to an increase in the baselevel of the Red Deer River. Sediments fine upwards from coarse fluvial sands and gravels to fine grained alluvial fan deposits. The former were deposited in the immediate postglacial period, when a wetter and cooler climate (and possibly lake discharge in the early period of deposition) resulted in greater discharge throughout the area. A shift towards arid conditions at approximately 8 000-9 000 B.P. resulted in widespread alluvial fan deposition throughout the study area.

Incision of the valley fill occurred prior to 5 400 B.P. leaving truncated fans forming a high surface 0.3 to 2.5 m above the valley floor. This episode of erosion was triggered by downcutting in the Red Deer River, responding to a change to a more humid climate.

Accumulation of fine grained fluvial deposits has since occurred. Based on a date of 315+/-65 B.P. (S-2546) from a cottonwood log 0.6 m below the top of the fill it is possible to conclude that aggradation was still active 300 years ago. Assuming that the rate of sediment accumulation below this log was the same as above, it can be suggested that deposition of the recent fill began approximately 600-800 years ago. This leaves a period of about 5 000 years where there is no evidence of valley cutting or filling in the study area.

The most recent episode of incision has occurred in the last 100-300 years. Aerial photographs indicate that several episodes of arroyo cutting and filling have taken place. It is believed that the gradual build-up of sediment in the valley increased its gradient until it

reached a critical angle causing incision to occur. The most recent episode of arroyo cutting began after 1950. This was due to shifting of the Red Deer River towards the valley thereby reducing its length and increasing its gradient sufficiently to reactivate incision.

PREFACE

The purpose of this study is three-fold: 1) to map the geomorphology, 2) to establish the alluvial chronology, and 3) to develop a better understanding of the controls of arroyo cutting and filling of a valley in the Dinosaur badlands, Alberta.

The problem of alluvial valley cutting in the American southwest has been the focus of [illegible]ic research since the turn of the century, when many formerly well-vegetated valley [illegible]ere suddenly en[illegible]lies or arroyos. The economic effect was often catastrophic and provided a conside[illegible]entive for research (Graf, 1983). Despite extensive studies the exact cause of episodic arroyo cutting remains controversial, but a number of theories have been advanced. The main ones involve the effects of changes in land-use, climate and the longitudinal profile of the valley.

Few studies have been carried out in the northern U.S. and none have been under taken in Canada. The extensive nature of arroyo incision in the southwest has attracted considerable attention compared to areas less economically significant. This is especially true of Canada where large scale settlement and use of the western ranges was not as early or as important as the American southwest.

The area of badlands now occupied by Dinosaur Provincial Park is a particular case in point. Here, the effects of land-use on the geomorphic history of the area must be minimal. However, the area has undergone considerable climatic variation during the Holocene and historic times. Additionally, process geomorphic studies indicate that threshold conditions may be a particularly important control in badlands environments with relatively large scale alternations in phases of erosion and sedimentation accompanying minor fluctuations in external variables.

Acknowledgments

This study could not have been completed without the help and cooperation of a great number of people in the Department of Geography and Dinosaur Provincial Park.

I am indebted to my supervisor, Dr. Ian Campbell for giving me the opportunity to study in Canada, and for his encouragement, guidance and financial assistance (NSERC operating grant A-7968) throughout this entire project. I would like to thank the Department of Geography for an inter-sessional bursary for the summer of 1985. I am grateful to the members of my committee, Dr. Bruce Rains, Dr. Charlie Schweger and Dr. Emlyn Koster for their advice and comments on the final draft of this thesis.

Thanks are due to Jenny de Lugt, for being an excellent and enthusiastic field assistant, as well as being 'chief cook and bottlewasher' throughout the long field season. I would like to express my thanks to Chief Ranger Roger Benoit and his staff for their encouragement and hospitality during the three summers I spent in the Dinosaur badlands. Much of the field work involved manual labour , and many people gave up their spare time to help trench pits. I especially want to thank Dennis, David, Ken and Andrew for operating the jack-hammer, without which many of the sites could not have been excavated.

Everybody in cartography and photography in the Department of Geography have provided advice on the drafting for this thesis. Special thanks to Stephanie Kusharyshyn, who drafted Figure 3.1, and Geoff Lester who drafted Figures 2.2 and 2.3.

Finally I wish to thank the many people who have made my stay in Canada a most enjoyable and memorable one, especially Ma and Pa (show me the moraines?) Greenshirt, Don Lemmen, Tom Morris, Dirk de Boer, Jenny de Lugt, Captain Neutron and last but not least Evs. Thanks for the Memories.

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1. THE STUDY AREA

1.1 Location

Badlands fringe the Red Deer River for some 300 km between Nevis (near Red Deer) and Atlee in southeastern Alberta (Stelck, 1967), covering an area of approximately 800 km^2. The most extensive and spectacular badlands development is in the Steveville area where Dinosaur Provincial Park is located (Fig. 1.1). The park is intricately dissected by a multitude of large and small valleys which act as tributary systems to the Red Deer River. One of these major valleys forms the study area of this thesis ; it is south of the Red Deer, in the central area of the park (Fig. 1.1).

1.2 Study area

The study area covers approximately 2 km^2 and consists of an unnamed major valley and one of its upper tributaries (Fig. 1.2). The upper tributary trends WNW-ESE, forming a narrow steep-sided valley (Fig. 1.2). It is characterized by extensive bedrock exposure in the upper reaches, which becomes obscured under a thin colluvium veneer as the valley widens and the walls become less steep. The main valley has a more west-east trend and widens from 90 m to approximately 400 m where it joins the Red Deer River. Within the valley three major depositional landform units can be distinguished:

1. Old, relatively large alluvial fans which have built out into the study valley from small side valleys. Extensive removal of these deposits has left them truncated thereby forming a terrace which stands 0.3 to 2.5 m above the valley floor.
2. The valley floor which is covered by fine-grained fluvial deposits. At a number of localities this is overlain by recent, low-angle alluvial fans which have formed either by incision into the older fans or by deposition from small tributary valleys that have been able to incise to the level of the valley floor.

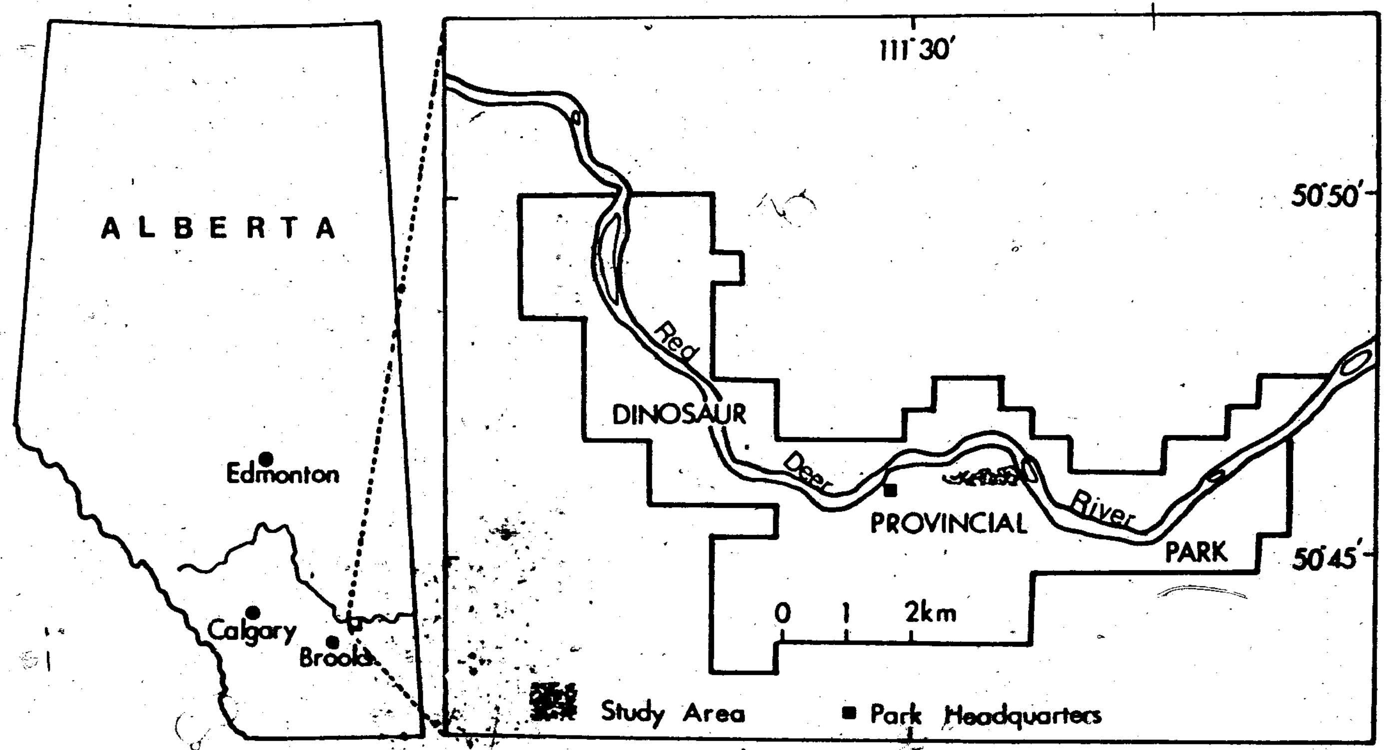

Figure 1.1 Location of the study area

Figure 1.2 Aerial photograph of the study area (scale 1:10 000)

3. A major arroyo which entrenches the valley floor throughout the main valley but is less defined in the upper tributary.

At the crest of the valley sides extensive flat areas (mesas) are found (Fig 1.2). These are particularly prominent on the north side of the valley and have formed by the removal of weaker bedrock above a thick and extensive band of resistant sandstone. This forms a major structural bench throughout the study area (Fig. 1.3).

1.3 Geology

Badlands have developed along the Red Deer River within deposits of the Upper Cretaceous. From Drumheller the Red Deer River flows south-eastwards cutting through the Horseshoe Canyon Formation, the Bearpaw Formation and into the Judith River Formation [1] (Koster, 1984). It is within the latter deposits that the Dinosaur Badlands are found.

The Judith River Formation consists of near horizontally bedded sandstones and shales which are divisible into coarse and fine members (Koster, 1984). Coarse deposits include highly indurated cross-stratified arkosic sandstones (which frequently exhibit deeply rilled surfaces, Fig. 1.4), together with friable muddy sandstones. The latter account for 60 per cent of the sandstones within the Dinosaur badlands and consist of mud/sand couplets with occasional ironstone horizons (Koster, 1984). Sandstones, except where cross-stratified, tend to be structureless and are formed of fine-grained sands (Dodson, 1971) between 0.21 mm and 0.125 mm in diameter. They are generally grey or greyish-yellow in colour with occasional red and greyish-brown units (Harty, 1984).

Finer sediments consist mainly of soft, non-fissile shales which are generally grey or olive grey in colour. These are frequently interbedded with rippled muddy sandstones, iron cemented sandstones and rare volcanic ash layers (Koster, 1984). The shales are commonly bentonitic with a high montmorillonite content which often exceeds 90 per cent (Bryan *et al.*, 1984). This causes swelling on wetting and contraction on drying resulting in a deeply

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[1] Formerly the Oldman Formation.

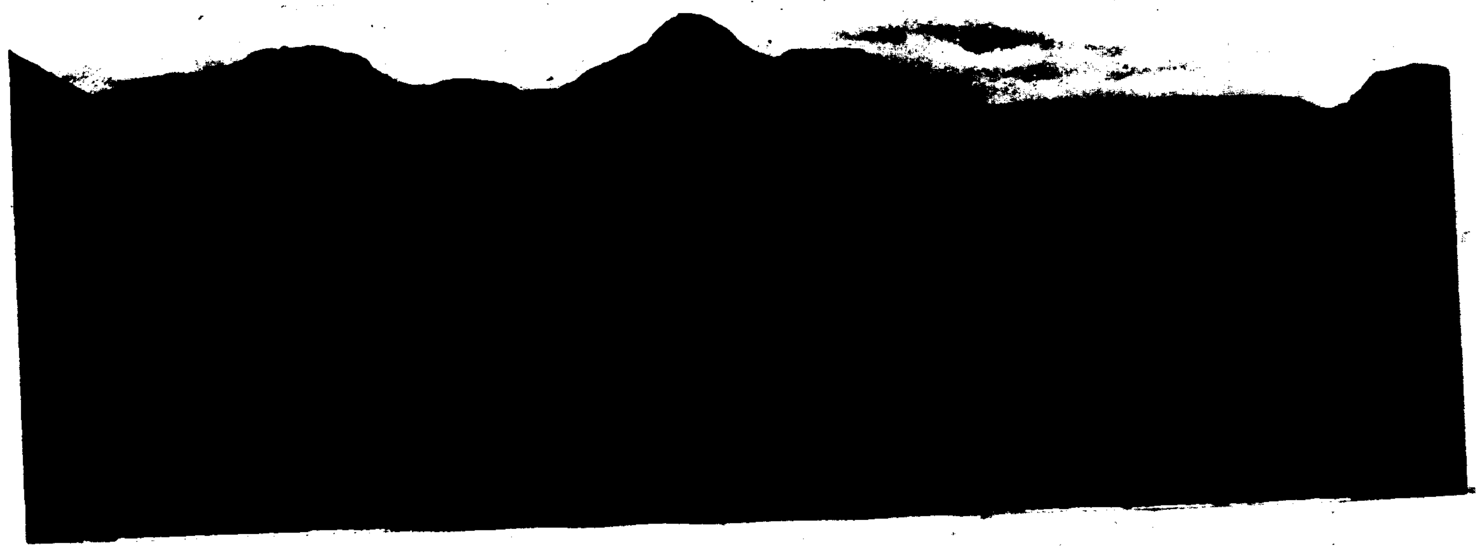


Figure 1.3 Highly resistant iron cemented sandstone band which forms a major structural bench throughout the study area. Much of the soft shale-dominated bedrock above this bench has been removed

Figure 1.4 Deeply rilled sandstones

Figure 1.5 Bentonitic shales exhibiting characteristic '*popcorn*' weathered surface

weathered '*popcorn*' character observed at the surface of many of these deposits (Fig. 1.5).

Although there is extensive bedrock exposure within Dinosaur Park, bedrock within the study area, particularly in the main valley, is largely obscured by alluvial and colluvial deposits. The most prominent bedrock outcrop is the iron-cemented sandstone that dominates the study area.

1.4 Geological history

The Judith River Formation was laid down on the distal low gradient reaches of a coastal foreland plain, adjacent to the Bearpaw Sea (Koster, 1984), some 72 to 73 million years ago (Folinsbee *et al.*, 1965). Sediments derived from the newly uplifted Rocky Mountains were deposited as channel sands and inter-channel muds and clays. Continual channel migration resulted in abrupt vertical and lateral changes in lithological units. It has been suggested that deposition was wholly within a freshwater environment (Dodson, 1971). Koster (1984), however, concluded that deposition was affected by periodic tidal influences due to fluctuations in the position of the Bearpaw Sea and with resultant changes in baselevel causing changes in the mode of deposition (Koster, 1984).

Conformably overlying the Judith River Formation are the marine deposits of the Bearpaw Formation that were laid down in the final advance of the inland sea. After it regressed continental deposits accumulated for some 30 to 35 million years until about 25 million years ago when regional uplift and tilting of the continental interior occurred and widespread denudation took place (Beaty, 1976). A thin veneer of till and various glacio-lacustrine and glacio-fluvial sediments were laid down over the area during the Pleistocene epoch. In the vicinity of Dinosaur Park, fluvial and glacial erosion has removed the Bearpaw Formation and younger deposits re-exposing the highly erodible Judith River Formation (Fig. 1.6).

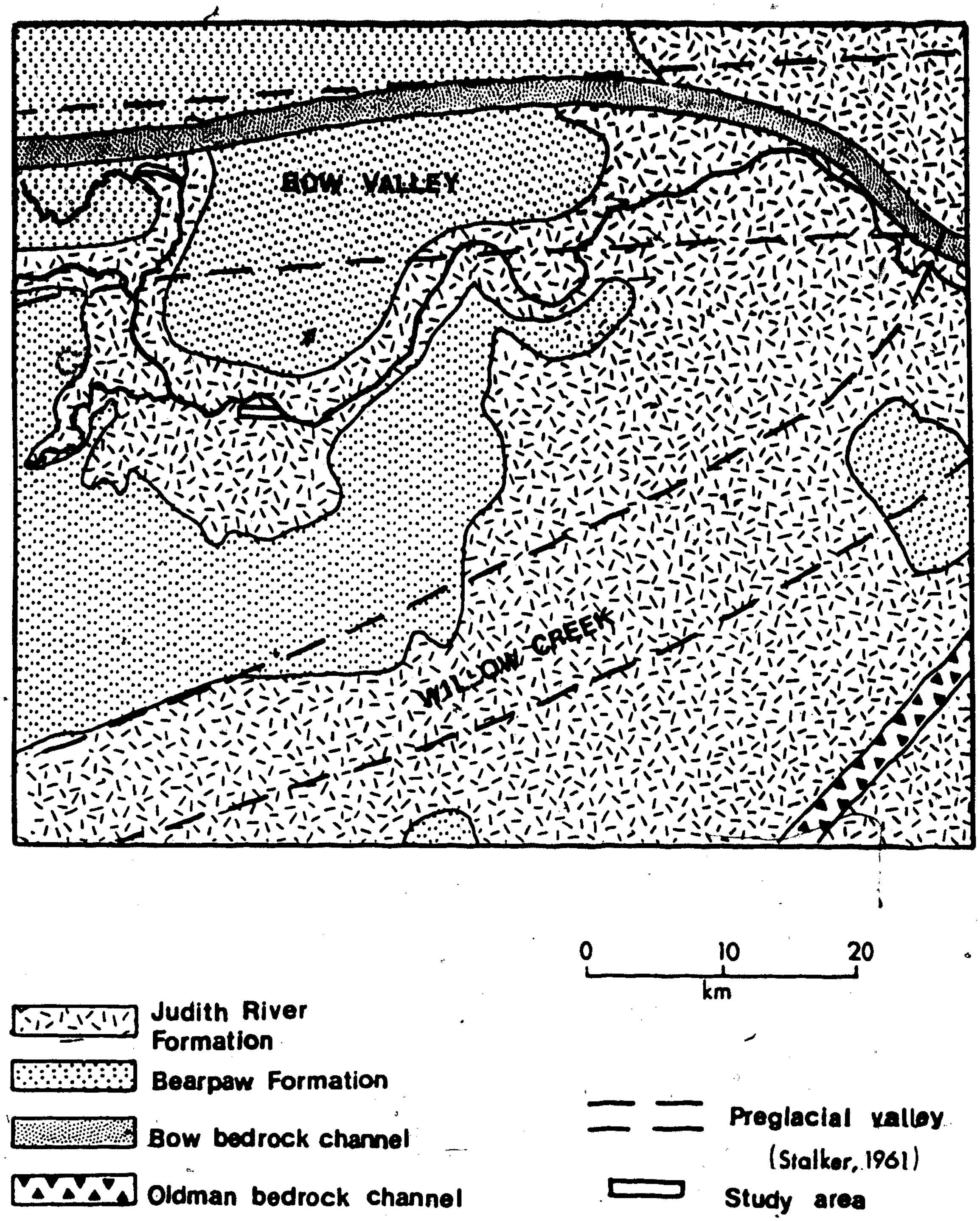


Figure 1.6 Bedrock geology in the vicinity of the study area (Adapted from McPherson, 1968)

1.5 Surficial geology.

Surficial deposits in this region consist mainly of glacial and glacio-lacustrine material (Berg and McPherson, 1973). In the vicinity of Dinosaur Provincial Park the Judith River Formation is overlain by Pleistocene deposits at the prairie surface. A distinct relationship between the thickness of the till cover and the extent of badlands development has been observed, with better development seen in those areas where only a thin till cover is found (Beaty, 1975). This relationship is well demonstrated in Dinosaur Park which is situated on a local bedrock high in relation to the pre-glacial Bow valley (Fig. 1.6). Preferential deposition in the lower valley areas resulted in them becoming plugged with till, while only a thin till veneer was deposited elsewhere. Thus, south of the Red Deer River, where the thin till cover has been stripped off exposing the underlying bedrock, extensive badlands have developed. North of the river badland development has been limited by thick till deposits in a pre-glacial tributary valley (Koster, 1984).

With the exception of scattered erratics all glacial material has been removed from the study area. Surficial deposits consist of Holocene alluvial deposits which form the valley fill (these will be discussed in greater detail in Chapter 4). A well developed prairie brown soil, 20-45 cm thick, covers the upper fan surfaces and mesa tops. Its texture and grain-size distribution is similar to that described by Bryan *et al.* (in press) for deposits which cover a number of surfaces in a small drainage basin which drains into the study area. They suggest that this material is loess which has been deposited over Cretaceous bedrock. Although it covers several terrace levels in the drainage basin Bryan *et al.* (in press) concluded that loess input had occurred during one period. Material immediately overlying bedrock gave a thermoluminescence date of 5 400+/-800 B.P.(Alpha 2074). It is believed that the soil which covers the upper terrace and mesa surfaces in the area has developed on the loess described above.

1.6 Climate

The study area is in the Prairie Province climatic region of Canada and falls into the semiarid BSk category of the Koppen Climatic Classification (Campbell, 1974). Data from Brooks, 35 km southwest of Dinosaur Provincial Park, show that the mean annual precipitation is approximately 350 mm per annum (Harty, 1984); (see Table 1.1). The majority of precipitation, approximately 70 per cent, falls between May and September as highly localized, fairly intense convectional storms of short duration (Campbell, 1970; Bryan and Campbell, 1980). Some 30 per cent falls as snow in the winter months (Harty, 1984).

The study area has a mean annual temperature of 3.9 °C (Table 1.2). However, short warm summers and long cold winters which typify such continental regions result in a mean annual temperature range of nearly 40 °C. The mean daily maximum temperature for July, the hottest month, is 26.2 °C and the mean daily temperature for January the coldest month is -19.7 °C. Extreme temperatures range from over 40°C in the summer to as low as -48 °C in the winter giving an absolute temperature range of almost 90 °C.

1.7 Vegetation

Much of the Dinosaur badlands has a limited vegetation cover because of the semiarid climate, poor soil development, steeply-angle slopes and large expanses of highly erodible bedrock. In marked contrast to this, a relatively dense vegetation cover is seen in the study area, where loess-covered surfaces and the flat valley floor reduce runoff and promote better vegetation growth.

Plant species consist of prairie grasses, xerophytic flowering plants and shrubs with some species dominating certain surface types (Fig. 1.7). On the valley floor, where there is little soil development, vegetation consists mainly of needle grass *(Stipa comata)* (see A, Fig. 1.7). On older alluvial fan surfaces a well developed prairie brown soil, between 20 and 45 cm thick, supports a dense vegetation mat consisting predominantly of blue grama *(Bouteloua gracilis)* (see B, Fig. 1.7). Blue grama and needle grass generally dominate dry sites as they are

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Mean Snow/Water Equivalent (mm)	20.9	13.6	13.5	11.3	0.9	0	0	0	0.6	3.6	12.2	20.0	96.6
Mean Rainfall (mm)	0.9	0.8	2.5	14.8	37.4	65.7	32.2	40.1	32.8	8.3	2.4	1.0	238.9
Total Precipitation (mm)	21.8	14.4	16.0	26.1	38.3	65.7	32.2	40.1	33.4	11.9	14.6	21.0	335.5

Data Source: Canadian Climate Normals: Precipitation 1951-1980, Vol. 3, Environment Canada, 1982.

Table 1.1 Precipitation data from Brooks AHRC: 1953-1980

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Mean Daily Temp. (°C)	-14.2	- 9.5	- 4.1	4.6	11.1	15.6	18.6	17.3	11.9	6.3	- 3.1	- 9.4	3.8
Mean Daily Min. Temp.	-19.7	-15.1	- 9.8	- 2.2	3.8	8.6	11.0	9.7	4.4	- 1.0	- 9.1	-15.1	- 2.9
Mean Daily Max. Temp.	- 8.6	- 3.8	1.7	11.3	18.4	22.5	26.2	24.9	19.2	13.6	2.9	- 3.7	10.4
Extreme Max. Temp.	17.8	17.2	25.0	31.1	35.6	37.2	40.0	38.9	35.6	31.1	22.2	17.2	40.0
Extreme Min. Temp.	-46.7	-43.9	-37.8	-25.0	-10.0	-2.2	1.7	0.0	-10.6	-24.4	-36.1	-47.2	-47.2

Data Source: Canadian Climate Normals: Temperature 1951-1980. Vol. 2, Environment Canada, 1982

Table 1.2 Temperature data from Brooks AHRC: 1953-1980

Figure 1.7 The main vegetational features in the study area

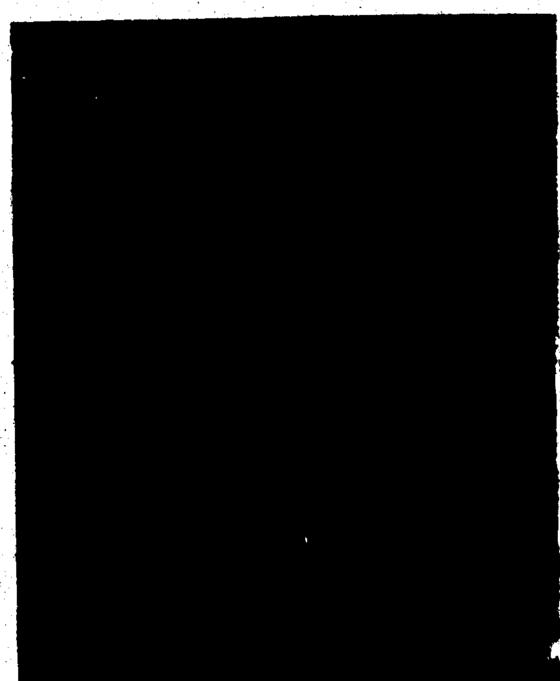


Figure 1.8 Field assistant using a powered jack-hammer to break down the highly indurated alluvial fan deposits

the most resistant to drought conditions and can grow at relatively low temperatures (North, 1976). Other less frequently observed grass species are Western wheat grass (*Agropyron smithii*), June grass (*Koeleria cristata*) and Sandberg bluegrass (*Poa secunda*).

Xerophytic flowering plants such as prickly pear (*Opuntia polyacantha*) and cushion cacti (*Mamillaria vivipara*) are commonly found in small dense clusters on alluvial fan surfaces and are only rarely found on the valley floor. Small clumps of drought resistant shrubs such as sagebrush (*Artemisia cana*) and pasture sagewort (*Artemisia frigida*) are seen, particularly in the lower part of the valley near the Red Deer River. Sage appears to be closely related to old meander scars and valley side gullies and probably reflects moister conditions at these localities (see C, Fig 1.7).

Throughout the badlands the vegetation is dominated by grasses, shrubs and cacti, with extremely rare, and isolated cottonwood trees. However, dense cottonwood and willow stands grow on the sand flats adjacent to the Red Deer River. Consequently, where the study valley joins the river the vegetation is lush and dense. The line where the riverine vegetation stops coincides with the main entrenchment of the Red Deer River and does not encroach up the main valley (Fig. 1.2).

1.8 Research methodology

1.8.1 Fieldwork.

Prior to the field survey, aerial photographs (scale 1:10 000) and selected enlargements of these (scale 1:1 660) provided the basis for detailed morphological mapping. Features identified on the air photographs were confirmed in the field and less distinct morphological features were mapped. Sites which were believed would best show the alluvial stratigraphy were chosen and trenches were excavated; these were extended down to bedrock where possible. Establishing the depth to bedrock was desirable, firstly to provide a complete section of the valley fill and, secondly, to verify the results of seismic profiling carried out in the spring of

1984 (Campbell, unpub. data). Site excavation was by hand digging, or with the use of a power jack-hammer where excessive induration of the material occurred (Fig. 1.8). The exposed sections were logged in detail, major sedimentological units distinguished and samples taken for laboratory analysis.

A detailed topographic survey of the field area, begun in 1984, was expanded in 1985. Surveying allowed the reconstruction of longitudinal profiles of the valley and the arroyo to be measured so that variations in their gradients could be determined. Valley cross-sections were also measured to show changes in the valley morphology and to help in the reconstruction of the alluvial chronology. Variations in the arroyo form were established from within-channel cross-sections. To supplement this, a general survey was carried out to determine select elevations. The elevations of logged sections were measured so that the depth to bedrock and subsequently the bedrock profile could be established, and to aid in the correlation of major sedimentary units. The gradients of some alluvial fans were also measured to help in the reconstruction of [illegible] valley configurations.

1.8.2 Aerial photographic interpretation.

As well as using the air photographs for initial geomorphic mapping they were also used to help document morphological variations in the arroyo which entrenches the main valley. The earliest air photographs available were from 1938 (1:15 800) and these together with air photographs from 1950 (1:40 000), 1961 (1:15 800), 1969 (1:12 000), 1977 (1:10 000) and 1984 (1:10 000) provided a 46 year record of changes in the valley. The photographs were enlarged between four and six times to allow a detailed study of the arroyo incision. Some difficulties were found when estimating the depth of incision because of shadows and the poor quality of many photographs.

Sections of a number of photographs containing the lower portion of the valley and the adjacent Red Deer River were enlarged to a common scale of 1:10 000. These were used to help calculate the lateral shift of the Red Deer River over this period in order to determine the possible effects this may have had on the longitudinal profile of the valley. Changes in the valley profile would effect the gradient of tributary streams and could be a possible causative factor in the recent period of arroyo incision.

1.8.3 Laboratory analysis.

Because the alluvial deposits have a similar source area, and due to similarities in the colour and texture, it is difficult to distinguish their derivation. It was believed that grain-size analysis would provide as useful a means of identifying depositional modes and sources as any other method. Samples taken from the logged sections were:

1. Air dried at room temperature for 48 hours
2. Disaggregated using a mortar and pestle
3. Colour determined using a Munsell Soil Colour Chart
4. Passed through Canadian Standard sieves from -1 phi to 4 phi at 0.5 phi intervals.

Analysis of the silt/clay fraction of the samples was prevented by the high montmorillonite concentration of the deposits which inhibited dispersion and caused the sediments to flocculate.[2]

---

[2] A sample taken from the alluvial fan deposit at location 18a, was run through the laser sedigraph at Wagner Oilfield Manufacturing Ltd.. Although flocculation was prevented by the constant agitation of the sample the results indicated that considerable swelling of the material had occurred during the process. Without extensive pre-treatment of the samples it would not be possible to obtain any accurate measurement of the silt/clay content using any of the techniques available to the researcher.

2. PAST RESEARCH ON ARROYO CUTTING AND FILLING

2.1 Introduction

Widespread valley entrenchment in the American southwest attracted significant interest amongst scientists at the turn of the century. Since then numerous studies on the causes of arroyo cutting and filling have been carried out. These have been extensively discussed and reviewed in the literature (e.g. Tuan, 1966; Cooke and Reeves, 1976; Graf, 1983), and no more than a brief outline of the pertinent studies need be made here.

2.2 Land-use changes

The coincidence of Anglo-American settlement and valley entrenchment in the American southwest led early workers (e.g. Dodge, 1902; Rich, 1911; Duce, 1918) to conclude that land-use changes were the cause of accelerated erosion. Removal of vegetation and compaction of the soil by grazing animals would reduce infiltration and increase the potential for erosion. It seems unlikely that this has been important in the Dinosaur badlands as better and more accessible grazing land is abundant on the prairie surface, and it is more likely that this would have been used in preference to the more hostile, poorly vegetated badlands.

2.3 Climatic change

The recognition of fossil cut and fill sequences (Bryan, 1925), which pre-date the introduction of livestock and possibly man into the southwestern states of America, led to the emergence of a second hypothesis: episodic erosion due to climatic change. While there is general agreement that changes in climate can result in accelerated erosion there is considerable dispute as to the effects of such changes.

Huntington (1914) concluded that a shift towards more humid conditions would result in valley incision, while infilling would occur during more arid periods. Bryan (1925;1940), however, held the opposite view, with incision taking place during dry periods. The latter theory was widely accepted for a number of reasons. Firstly, it could be extended back into the Quaternary record and, secondly, there was evidence to suggest that there had been a shift towards drier conditions in the late 19th century when the most recent period of erosion began. As the length of instrumented climatic records grew, subtle shifts in the regional climatic pattern were noticed, such as changes in rainfall intensity, and a number of workers suggested these rather than global changes were responsible for periods of valley cutting and filling (Leopold, 1951; Cooke, 1974; Hereford, 1984).

There is still disagreement as to whether erosion occurs during arid or humid periods. It has been suggested that accelerated erosion coincides with the onset of more humid conditions (after a period of drought), before vegetation has had time to re-establish and that periods of geomorphic activity are short-lived (Knox, 1972) (Fig. 2.1). This theory is borne out to some extent by Bull's (1964) observations on erosion in fan deposits of Fresno County, California. He documented two periods of fan-head entrenchment which occurred between 1900 and 1945 and found that they coincided with periods of above-normal rainfall.

2.4 Changes in the longitudinal profile of the valley

Changes in the longitudinal profile of a valley can have a considerable effect on whether it is aggrading or undergoing erosion. These changes can occur in a number of ways, including variations in the controlling baselevel. Baselevel is the downward limit of channel incision or the level below which a channel cannot erode. The term local baselevel is used to refer to a level to which a portion of a system grades (Leopold *et al.*, 1964). If it is increased the mouth of the valley is drowned and aggradation will occur, while lowering the baselevel increases the valley gradient resulting in incision (Fig. 2.2).

Where tributary streams enter meandering main streams, shifts in the meander pattern have the effect of lengthening or shortening the tributary stream profile. In this event, the profile of the tributary stream is steepened or reduced causing either incision or aggradation in an analogous fashion to a negative or positive change in baselevel (Fig. 2.3). The Red Deer

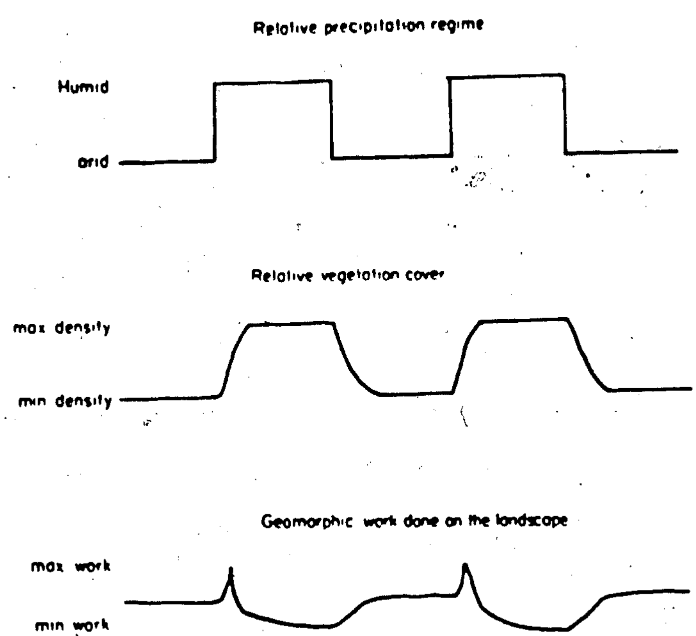


Figure 2.1 The relationship between climate and geomorphic activity (Modified from Knox, 1972)

River has undergone a 200 m shift in many of its meanders between 1880-1960 (McPherson, 1966) and evidence from topographic maps and aerial photographs shows that lateral channel migration can be extremely rapid. Such changes will have had a considerable influence on the profile and alluvial history of the study valley.

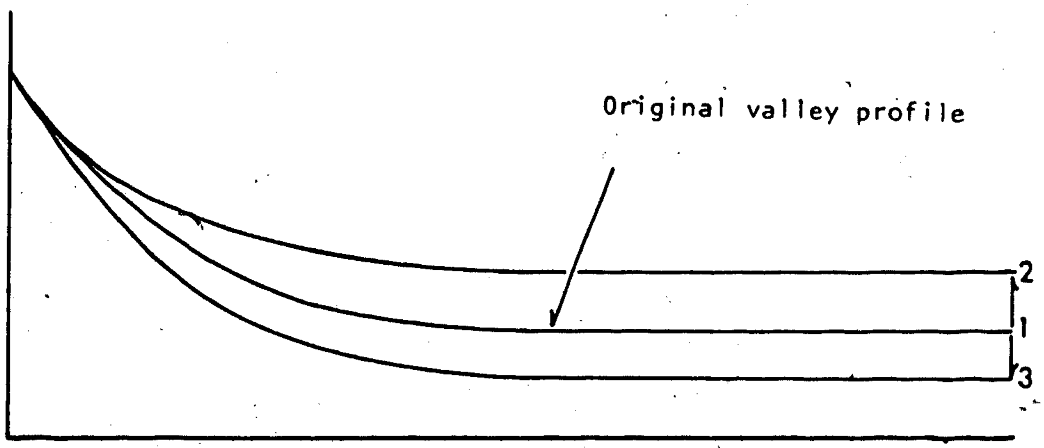
Oversteepening of a valley profile and eventual incision of the fill can occur without changes in baselevel. This occurs when continual deposition of sediment gradually increases the valley gradient until it reaches a point of instability and incision takes place. The transition from one state of operation to another marks the crossing of a threshold. Two types of threshold exist (Schumm, 1973):

1. extrinsic thresholds which are exceeded due to changes in external variables such as climate or baselevel, and;
2. intrinsic thresholds, where there is a change in the system yet no change in external variables. An example of this would be the long-term weathering of slope deposits and eventual failure due to the gradual reduction in the strength of slope material (Carson, ~~1971).~~

A special type of intrinsic threshold is a geomorphic threshold :

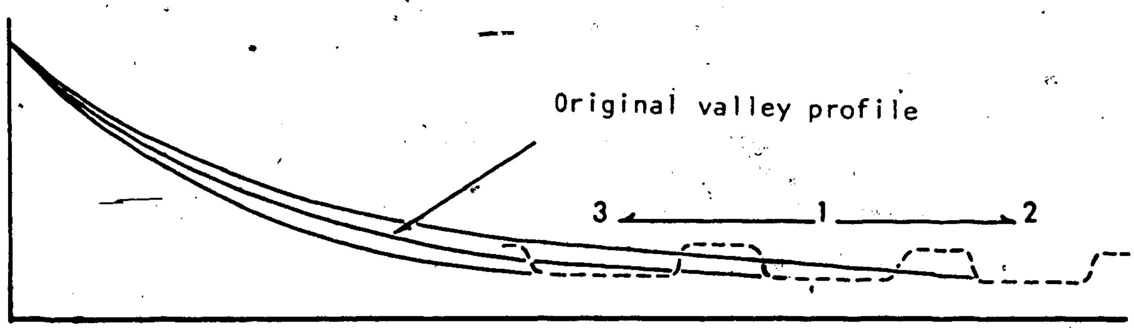
"*.... a geomorphic threshold is one which is inherent in the manner of landscape change ; it is a threshold which is developed within the landscape by changes in the morphology of the landform itself through time. It is the change in the landform itself that is most important because until it has evolved to a critical situation adjustment or failure will not occur.*" (Schumm, 1973).

The importance of thresholds in arroyo cutting and filling was first suggested by Schumm and Hadley (1957). They measured the longitudinal profile of gullied and ungullied valleys in New Mexico and Wyoming and found that gullying occurred on oversteepened reaches of the valley floor. Later studies in Colorado reported similar findings (Patton and Schumm, 1975) and the relationship has been further demonstrated under laboratory conditions (Schumm, 1977). In controlled studies of alluvial fan growth precipitation was delivered to a



1. Original baselevel position; 2. Aggradation as a result of an increase in the baselevel; 3. Incision due to a decrease in the baselevel.

Figure 2.2 The effects of baselevel change on alluvial filled valleys



1. Original position of the river; 2. Migration of the river away from the tributary valley, increasing its length and decreasing its gradient causing aggradation to occur; 3. Migration of the river towards the tributary valley, decreasing the valley's length and increasing its gradient causing incision to occur.

Figure 2.3 Effects of lateral shifting of a river on an alluvial filled valley sediment source area at a constant rate. Material was transported out of the sediment source area and deposited on the flood plain as an alluvial fan. Repeated fan-head entrenchment occurred even though the variables remained constant. Fan-head entrenchment, as a result of gradual oversteepening, leads to the crossing of a threshold inherent in the system.

Figure 2.4 (modified from Schumm, 1977) illustrates the concept of geomorphic thresholds within an alluvial filled valley. The critical angle at which failure will occur and erosion take place is shown by line 1. Line 2 represents the decreasing stability of the valley floor as sediment accumulation increases the slope angle. Superimposed on this line are vertical lines which represent the variability of valley floor stability in response to floods of different magnitude. When the valley floor is in a stable condition even high magnitude events will have little effect on the system. As the valley floor stability diminishes a major event may be sufficient enough to cause the crossing of a threshold to take place, e.g. Time A. Failure, however, would have eventually occurred at time B without any major flood event.

This theory would clearly explain many of the anomalies which have been reported in the literature (e.g. Gregory, 1917; Peterson, 1950). Gregory (1917) noted that although many valleys in the American southwest, which had been ranched, incised in the late 1880's others did not. Also, some valleys which had never been used for grazing purposes were extensively dissected. He concluded that this evidence indicated that human land-use changes were not the cause of accelerated erosion. While Gregory's (1917) conclusion is valid, it would seem more likely that this is an example of a geomorphic threshold. Many of the valleys that Gregory investigated may have been at or near a critical slope angle and incision would have occurred regardless of whether cattle were introduced or not. Those valleys where ranching was practised but did not suffer incision were probably in a more stable condition and would be unaffected by such changes.

The concept of thresholds has a considerable bearing on the study of arroyo cutting and filling and the way in which such studies are approached has changed. Rather than looking for a single causal mechanism it is now realized that arroyo cutting and filling results from many

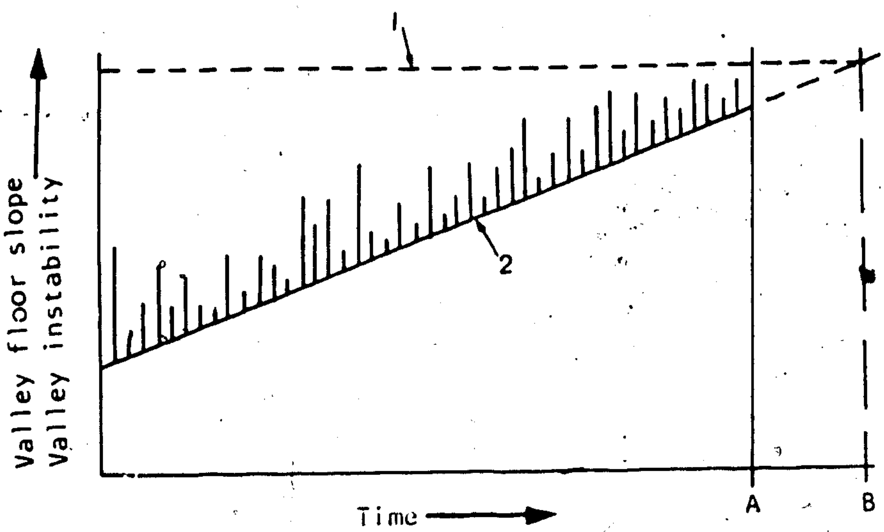


Figure 2.4 Thresholds within alluvial filled valleys (Modified from Schumm, 1977)

factors. Consequently, while valley incision may occur in response to a change in climate, it does not follow that climatic change causes incision. Furthermore, evidence suggests that more than one period of valley cutting and filling can occur during an episode of net erosion. A change in external variables is not required to trigger each event. Periods of valley cutting and filling have been a result of a complex response to the initial period of incision (e.g. Patton and Schumm, 1975; Womack and Schumm, 1979). Thus, care should be taken when interpreting the alluvial chronology of an area and all aspects of the system should be investigated before any conclusions are made.

2.5 Previous research in Dinosaur Provincial Park

Geomorphic research in Dinosaur Provincial Park has been predominantly process orientated and has only an indirect bearing on this study. Campbell (1974) measured average erosion rates of 0.4 cm per annum on nine 1 m^2 experimental plots. Recently, research has focussed on the complex relationship between lithology and precipitation patterns on geomorphic processes (Bryan *et al.*, 1978; Hodges and Bryan, 1982.). On another scale, surface and subsurface drainage of water and sediment to the Red Deer River has been investigated (Campbell, 1981; Bryan and Campbell, 1980, 1982).

Of greater relevance to this study is the research carried out by Faulkner (1970) and Bryan *et al.*(in press). Faulkner (1970) looked at gully evolution at Steveville. She investigated ten small drainage basins, two of which extended into the upper prairie surface where no head-water competition occurs, and concluded that as the larger basins expanded they restricted the growth of smaller ones. If these observations are correct it would follow that gullies which develop first, for example along structural lines of weakness, would become dominant and control the development of basins which form later. Faulkner (1970) also noted that the lithology had a significant influence on the morphology of the basin. However, as basins extended back into the prairie surface lithological controls became less pronounced and the basin profile flattened.

Although the study area is located away from the prairie surface similar findings would be expected in the development of small tributary valleys. This should be particularly true of the small valleys which have developed by headward incision into the side walls of the study valley. Side valleys which developed first would drain larger areas and would reflect the control of lithological factors less than those valleys which developed later.

The development of the Dinosaur badlands has recently been discussed by Bryan *et al.*(in press) who reconstructed major postglacial geomorphic events in the area. They suggest that at approximately 15 000 B.P. a series of interconnecting proglacial lakes were located to the south and west of the area which drained eastwards along a series of spillways as the ice retreated (Fig. 2.5). Tributary spillways drained into the main spillway, the Red Deer River, which probably formed ice marginally.

Two periods of spillway incision appear to have taken place, similar to the development of the Souris spillway (Kehew, 1982). The initial period of incision occurred over a wide area, with extensive lateral scouring removing glacial deposits and exposing the underlying Cretaceous bedrock. This is referred to as the 'broad valley stage'. Subsequent incision resulted in deep, narrow canyons been cut into the newly exposed bedrock. A series of flat topped grassy surfaces are found in the park and it is suggested that the two highest surfaces formed during these two periods of planation and incision by glacial meltwaters. Remnants of the older surface (ca. 685 m a.s.l.) are found in two groups which are over 3 km apart and it is believed that these formed during the initial 'broad valley stage', indicating that the channel at this time must have been at least 3 km wide. This spillway extended eastwards across the Park from the Little Sandhill Creek joining the Red Deer River at Deadlodge Canyon. Later drainage occurred through smaller tributary spillways, such as the Onetree Creek and the Little Sandhill Creek which drained east across the region (Fig. 2.5). It is suggested that the main valley in this study represents an abandoned spillway.

Subsequent valley development shows a strong north-south orientation and possibly reflects the regional structure. Drainage from the Little Sandhill Creek was captured by the

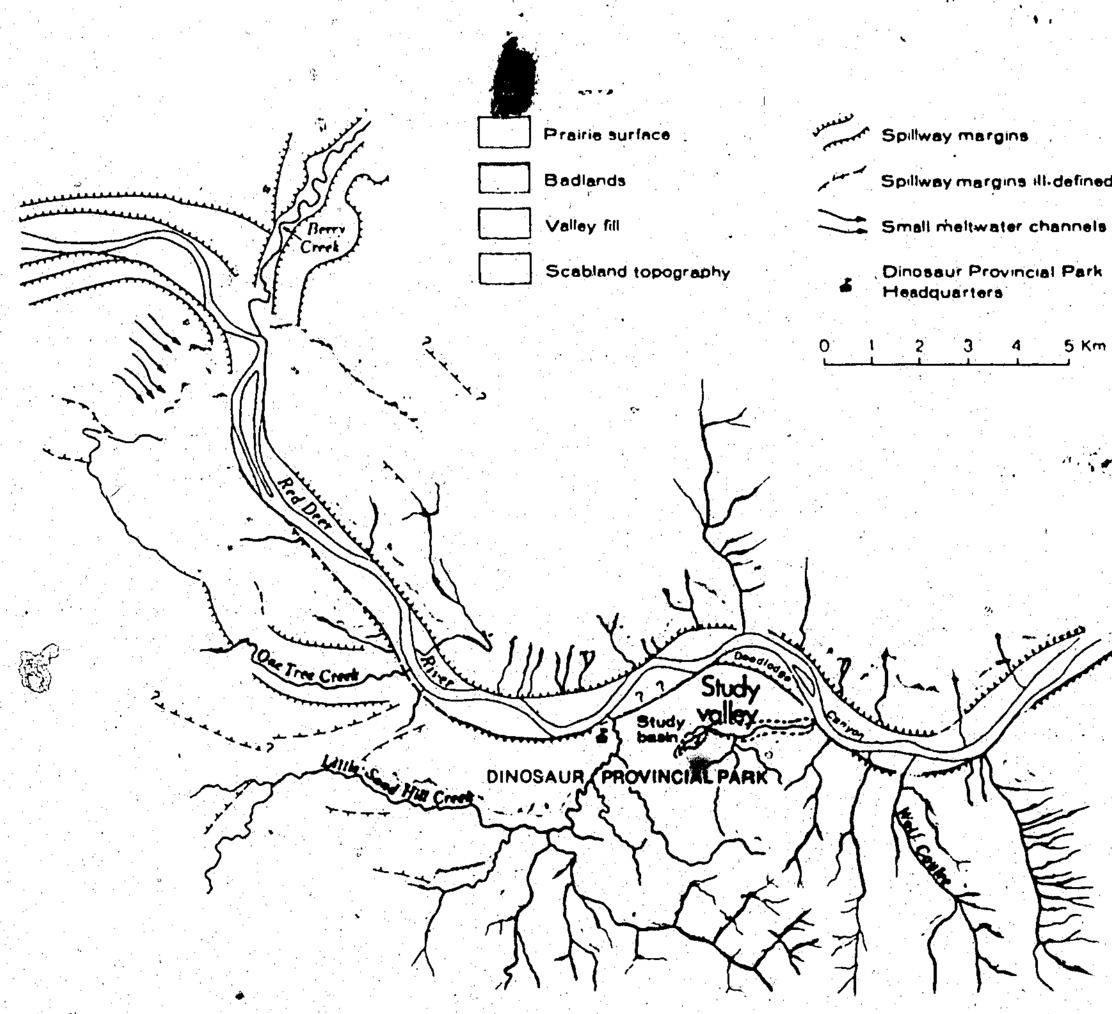


Figure 2.5 Major spillway channels in the vicinity of Dinosaur Provincial Park (modified from Bryan *et al.*, in press)

southward extension of one of these major tributaries and consequently abandoned its old channel. Further geomorphic development within the badlands has been the result of internal fluvial activity exhibiting more or less degrees of structural control.

3. THE VALLEY MORPHOLOGY

3.1 Introduction

The morphology and alluvial deposits of the study area will be discussed in Chapters 3 and 4. In order that the areas referred to can be easily located, the field area has been divided into four sections on the basis of morphological variations. These areas are the upper tributary (A-B, Fig. 3.1), the upper valley (B-C, Fig. 3.1), the central valley (C-D, Fig. 3.1) and the lower valley (D-E, Fig. 3.1).

A number of distinct morphological features are found throughout the study area. The most prominent are:

1. An older, higher surface which stands 0.3 to 2.5 m above the valley floor (Fig. 3.1);
2. A younger more extensive surface (Fig. 3.1) which forms the valley floor.

Recent incision of the valley floor has formed a major terrace in the main valley. In the upper tributary, however, the depth of incision is considerably less and here the lower surface forms part of the floodplain. To avoid confusion the lower surface will be referred to as the valley floor regardless of its form.

3.2 The upper tributary

The upper tributary trends WNW-ESE, and is approximately 900 m long. Its upstream end is characterized by steep, almost vertical side walls with extensive bedrock exposures (Fig. 3.2). As the valley widens downstream the walls become less steep and a colluvium veneer covers many slopes. The valley width ranges from 30 m near its head to nearly 90 m where it enters the main valley (see cross-sections 1 and 2, Fig. 3.3). The tributary floor ranges from 652 m a.s.l., where the first major tributary enters the valley upstream of location 1 (Fig. 3.1), to 648 m a.s.l. where it joins the main valley. This gives an average gradient of 0.78°. The valley walls rise some 15-25 m above the valley floor. A number of side valleys enter the upper tributary with those from the south generally draining small drainage basins; for example the

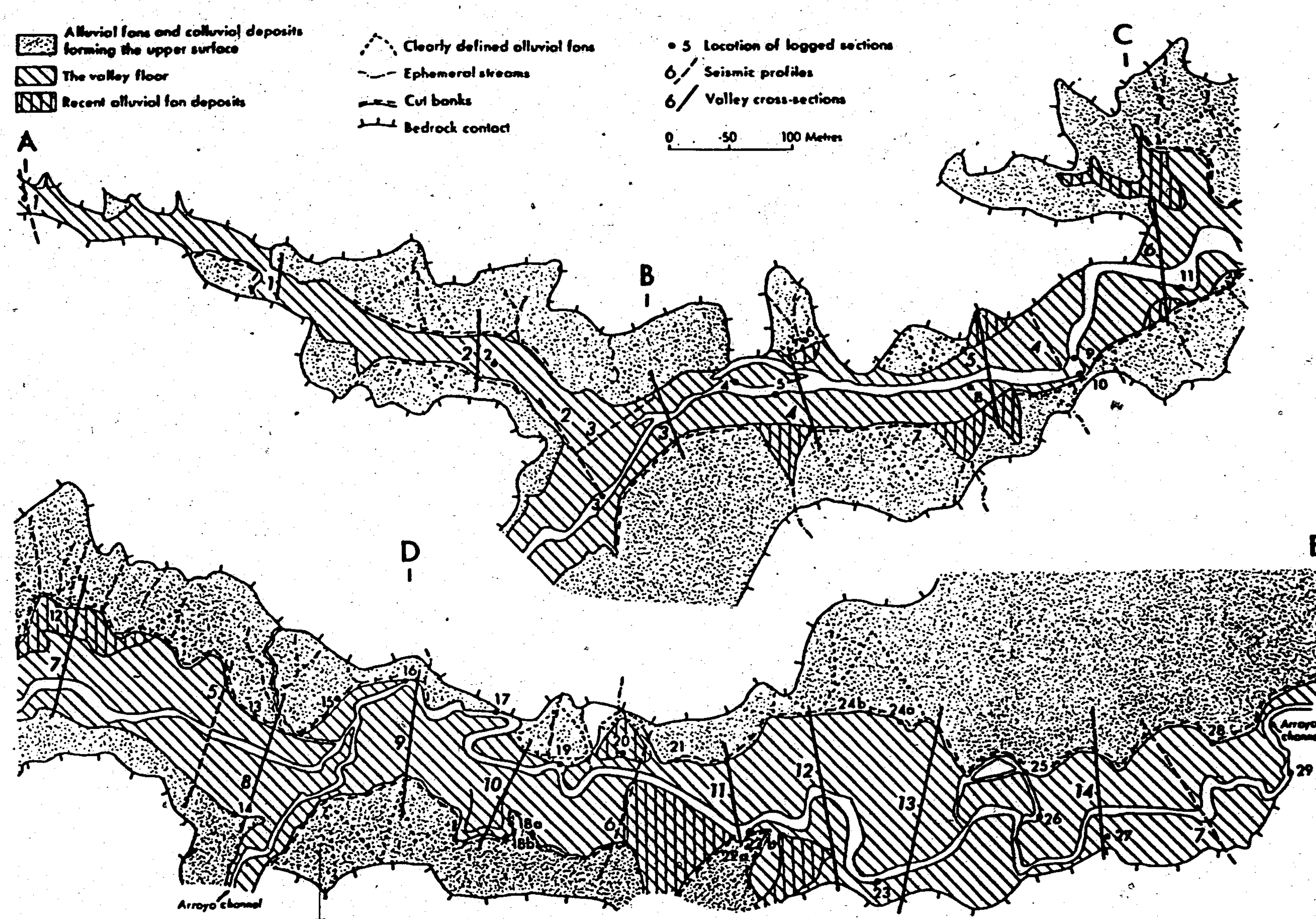


Figure 3.1 Major geomorphic features in the study area

Figure 3.2 View down the upper tributary showing the steep valley walls and extensive bedrock exposure

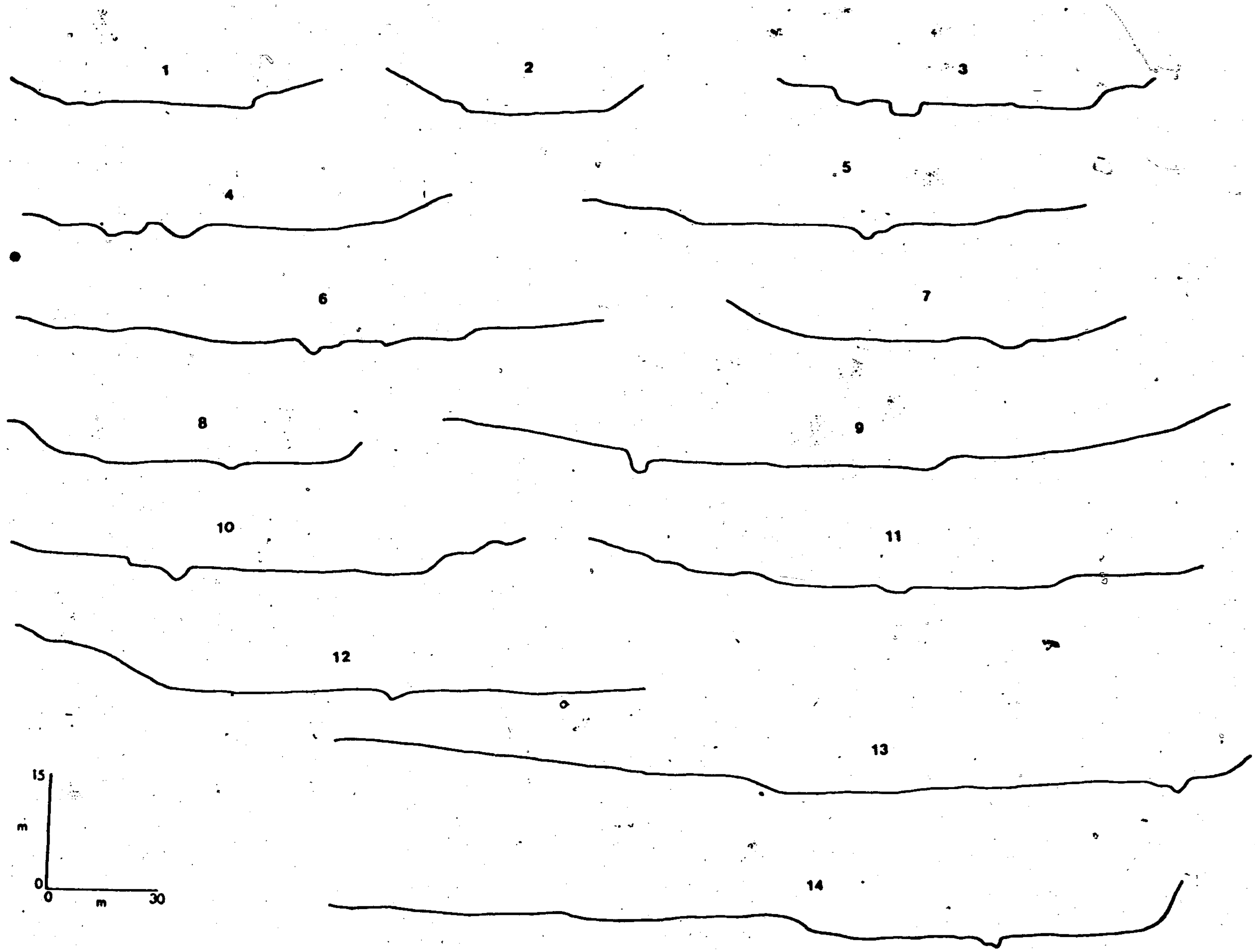


Figure 3.3 Cross-valley profiles of the study area (see Fig. 3.1 for the location of the sections)

experimental drainage basin described by Campbell (1980). Side valleys from the north are much more limited in extent. This relationship will be discussed in section 3.6.

Only small remnants of the older surface are observed in the upper tributary, there stand approximately 30-50 cm above the valley floor. These remnants are covered by a well developed prairie brown soil, 20-30 cm thick, which supports a dense grass mat. Remnants are most extensive immediately downstream of major southern tributaries, a relationship which is noted throughout the field area. Older alluvial fan deposits which form the upper surface are generally small discreet fans. In the upper reaches of the tributary many of these form steeply angled features that would best be termed taluvial cones. Where the tributary widens, more extensive less steep forms are seen. The width of the upper tributary has probably had a considerable influence over fan deposition. As it is very narrow, material tends to be removed during storm floods and this has prevented fans from accumulating. This is seen today where fan deposits are preserved only where they are protected from scouring during flooding.

The lower surface is covered by sandy fluvial deposits and has been slightly gullied. Channel entrenchment is discontinuous, being greatest downstream of major side valley tributaries but elsewhere having a poorly defined braided pattern (Fig. 3.4). Recent fan deposits overlie the lower surface, but these are not extensive as sediment tends to be removed during periods of flood.

3.3 The upper valley

The main valley cuts generally E-W across the badlands and is approximately 1900 m long. In this section the upper 450 m of the main valley will be discussed (B-C, Fig. 3.1). Two tributary valleys enter the main valley at its head; the upper tributary which has already been described, and a larger tributary which enters the valley from the south, but is not included in this study. The upper valley ranges in width from 120 to 150 m (see sections 2-5, Fig. 3.3) with side walls rising 20 to 25 m above the valley floor. Past fluvial activity has largely removed alluvial fan and colluvial deposits from the north side of this section of the main valley and as a result a greater portion of bedrock is exposed here compared to the south side. The bedrock exposures form steep valley walls on the north side of the valley, while on the south side alluvial fans have produced a more subdued profile (Fig. 3.5). Fan deposits have been extensively truncated and now stand approximately 1 m above the valley floor at an average elevation of 643.5 m.[3] The fans here do not tend to coalesce and generally form singular features. In most cases their source area is no longer evident (Fig. 3.6). Because the fans have been extensively truncated it was not possible to determine their exact gradients. However, measurements of the fan remnants indicates that their surfaces graded at an angle of approximately 4-6° (Table 3.1).

The floor of the upper valley ranges from 644-641 m a.s.l. giving a gradient of 0.34°. It is covered by fine grained fluvial deposits and is rapidly being vegetated. The main valley is incised by an arroyo channel. The arroyo is most deeply entrenched at the head of the upper valley where it is approximately 2 m deep (Fig. 3.7). The depth of incision rapidly decreases down valley and at the junction of the upper and central valley is less than a metre deep (Fig. 3.7). The arroyo has a classical form at the head of the main valley with straight-sided walls and a flat sandy bottom (Fig. 3.8). However, as the channel depth decreases and width increases the form becomes less distinct. The gradient of the arroyo floor is 0.27° which is slightly less than the gradient of the valley floor. Although the arroyo meanders elsewhere in the main valley it has a relatively straight form in this section (Fig. 3.1). At approximately 450 m from the head of the valley a major bedrock outcrop deflects the channel first 90° northwards and then 90° eastwards which results in a slight northerly shift in the arroyo channel (Fig. 3.1). This shift is also evident in the form of the valley and suggests that bedrock control was also important in the past.

Small low-angled alluvial fans have built out onto the valley floor. These are deposited either from small side valleys that have been able to incise down to the level of the main valley floor, or have been deposited as a result of entrenchment of older fan deposits and subsequent

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[3]Based on the heights measured on the lower end of the truncated fans.

Figure 3.4 Poorly defined, braided channel incising the alluvial fill in the upper tributary

Figure 3.5 Downstream view of the upper valley. Note extensive fan deposits from the south side which subdue the valley profile

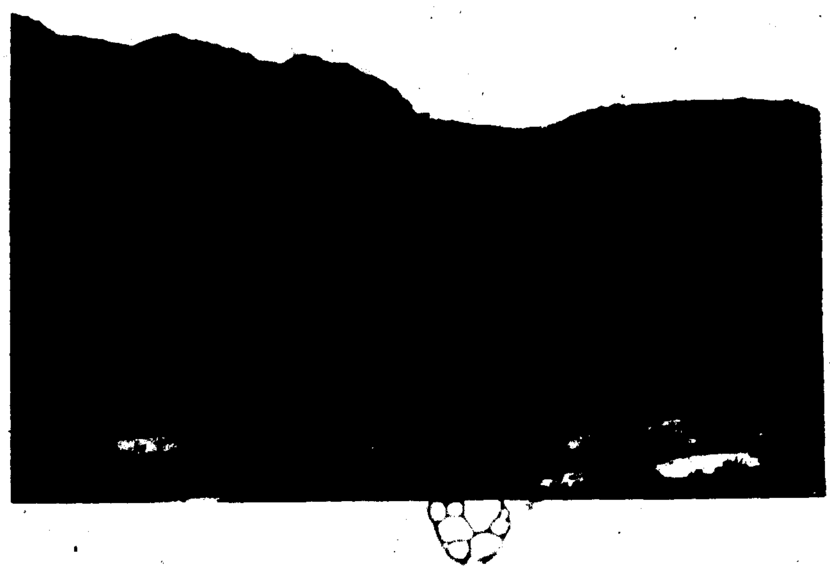

Figure 3.6 Alluvial fan which has built out into the upper valley. The sediment source area is no longer evident as it has been removed

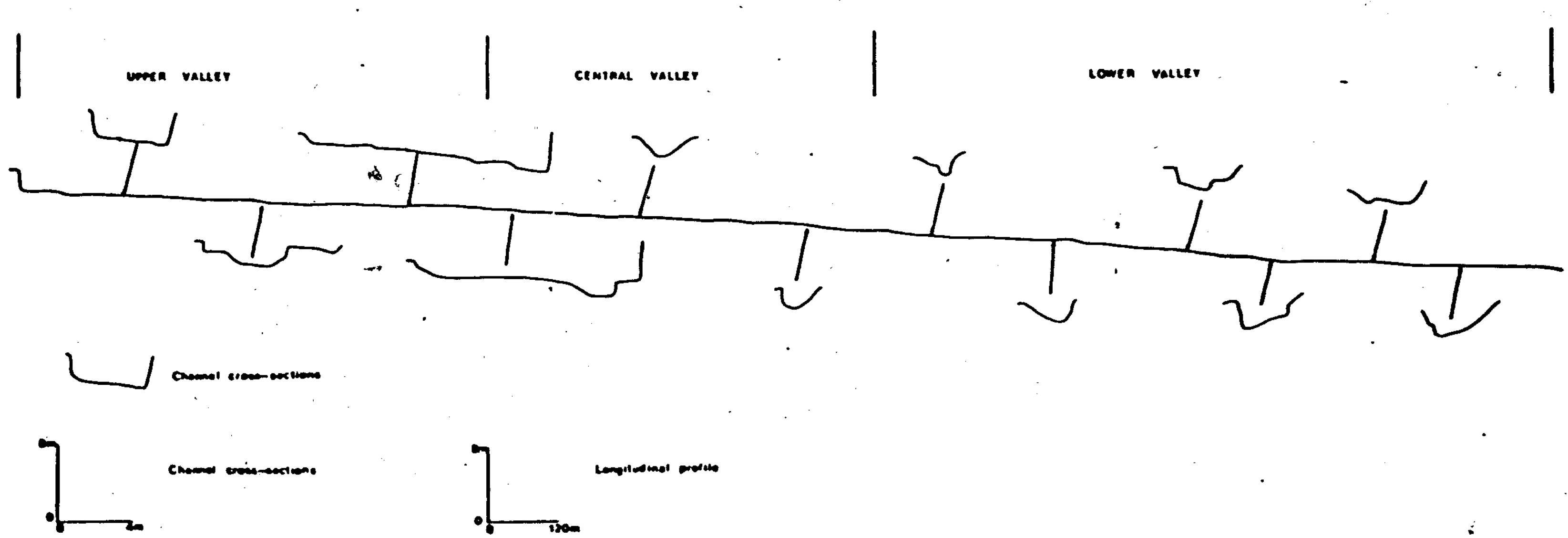

Figure 3.7 Longitudinal profile of the arroyo channel, showing within -channel cross-sections

renewed aggradation (Fig. 3.9).

3.4 The central valley

Below the shift in valley position there is a change in the overall valley morphology. The valley width increases from 200 to 270 m (see cross-sections 6-11, Fig. 3.5) and extensive fan deposition has produced a more subdued cross-valley profile than in the upper section of the valley (Fig. 3.10). The valley crest is approximately 670 m a.s.l., some 30 m above the valley floor which has a gradient here of 0.34°. Bedrock exposure is limited to the upper slopes where alluvial and colluvial deposits are thin.

Remnants of the upper surfaces are predominantly on the north side of the valley suggesting that deposition from the south was limited in the past. Larger fan deposits frequently coalesce and it is difficult to distinguish individual forms. These fans have been extensively truncated and remnants now stand between 60-120 cm above the valley floor. Only one fan profile could be measured with any degree of accuracy and this had a gradient of 3°. It is clear, however, that these fans graded to an elevation 1-2 m higher than the present valley floor. Gullying and renewed alluvial deposition has occurred with recent fan deposits covering a large area of the lower surface (Figs. 3.1 and 3.9). Unlike the rest of the lower surface these areas are poorly vegetated, which suggests that deposition is still active.

The arroyo incision in the central valley is not as deeply incised as the upper valley, being only 60-100 cm deep (Fig. 3.7). Except for a series of meanders at the top of the central valley the arroyo channel is straight. It tends towards the south side of the valley but is deflected northwards where a major tributary enters the valley from the south (C-D, Fig. 3.1).

3.5 The lower valley

The lower valley ranges in width from about 270-400 m (see cross-sections 11-14, Fig. 3.3). The average height of the valley floor is 635 m a.s.l. and the valley crest 663 m a.s.l., giving a relief of nearly 30 m. The valley is bordered by extensive flat-topped mesa surfaces

Section	Length(m)	Gradient of the valley floor (degrees)	Gradient of the arroyo (degrees)	Gradient of the older fans (degrees)
Upper tributary	900	0.78	N/A	N/A
Upper valley	450	0.34	0.27	4-6
Central valley	400	0.34	0.27	3.2*
Lower valley	900	0.43	0.32	2.3 - 3.7

* only one fan measured

Table 3.1 Variations in the gradients of the valley floor, arroyo channel and older fan surfaces in the study area

Figure 3.8 Classical arroyo channel form with steep sides and a flat sandy bottom

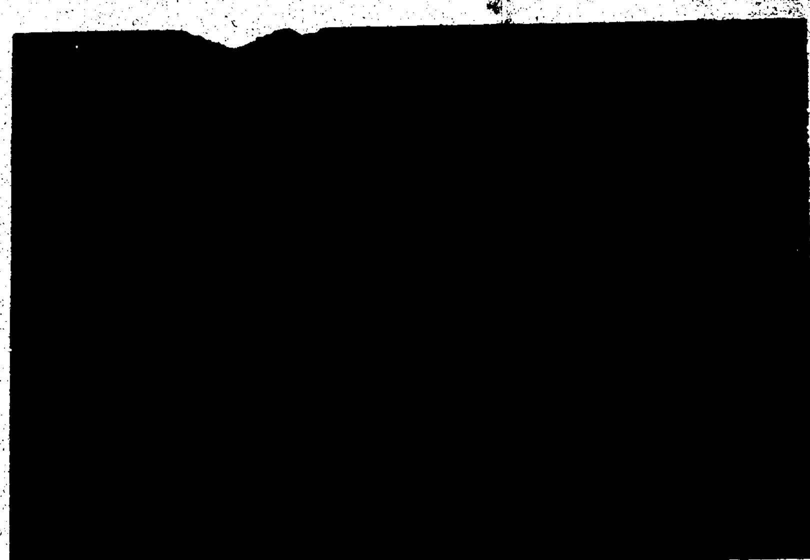

Figure 3.9 Renewed fan deposition as a result of truncation and gullying of older alluvial fans

particularly on its north side (Fig. 1.2). These have formed as a result of bedrock removal above an iron cemented sandstone bench. The removal of surficial deposits on the south side of the valley has resulted in extensive bedrock exposure in the lowest 300 to 400 m of the main valley.

Remnants of the upper surface are most extensive in this part of the valley, particularly on the north side (Fig. 3.10). They stand 1.3 to 2.5 m above the lower surface, with variations in height being a result of the extent of fan truncation and the position of the fan in the valley. Height differences increase down valley. The field survey clearly shows that a third surface, which stands about a metre below the upper surface, is present in the lowest valley (see section 15, Fig. 3.3). It is only evident on the north side of the valley and is extremely limited in extent. Like the upper surface it is covered by a well developed prairie brown soil which supports a dense vegetation mat.

Alluvial fans have been deposited from small side valleys that have a marked north-south orientation. Fans frequently coalesce and individual forms are difficult to distinguish. On the south side of the valley older fan deposits are more restricted and extensive fans only built up where southerly tributaries enter the valley and conditions were suitable for fan building. As remnants of the older fan surfaces are more extensive in this part of the study valley, it was possible to make more accurate measurements of their gradients, which range between 2.3 and 4.0° (Table 3.1). Many of the cut banks indicate that extensive erosion occurred along meanders in the past and distinct meander forms are observed in the valley (Fig. 3.1).

The valley floor is well vegetated except where fan deposition is active. It has a slightly steeper gradient here, about 0.43 °, compared to the upper and central valley sections. This increase in gradient is reflected in the greater sinuosity of the arroyo channel which has a sinuosity ratio[*] 1.56 in this section and less than 1.2 elsewhere in the valley. The arroyo is quite variable in character in this area but appears to have a greater width and depth than in the

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[*] The sinuosity ratio is the ratio between the channel length and valley length. If the ratio is greater than 1.5 the channel is said to meander.

Figure 3.10 View of the central and lower valley looking up valley from it confluence with the Red Deer River

central valley (Fig. 3.7). The gradient of the arroyo is also slightly steeper than up valley, being 0.32° compared to 0.27° upstream (Table 3.1 and Fig. 3.7).

3.6 Lithological and structural controls

The valley morphology has been considerably influenced by lithological and structural controls. The most notable feature in the study area is a 1-3 m thick band of iron cemented sandstone at 660 m a.s.l.. Its highly indurated nature makes it extremely resistant to erosion and it forms a major structural bench which dominates the valley. Much of the softer shale-dominated bedrock above this bench has been eroded and only isolated bedrock outcrops are seen (Fig. 1.3). The underlying bedrock, however, is protected by the sandstone cap rock and erosion generally occurs along north-south orientated tributaries. The marked orientation of these tributary valleys indicates development along structural lines of weakness. Babcock's (1973) study of joint orientation across the plains of southern Alberta (cited in Koster, 1984) shows a complex pattern which comprises of three orthogonal systems (Fig. 3.11):

1. The major system, striking ca. 45° and 155°, that parallels both the structural undulations of the major Phanerozoic surfaces as well as the alignment of the maximum/minimum horizontal stress with respect to the Rocky Mountain fold belt (S1/T1, Fig 3.11).
2. A less prominent system striking 005° and 95° which is parallel and perpendicular to the Sweetgrass Arch (S2/T2, Fig. 3.11).
3. A third set of unknown origin strikes at 045° and 135° (S3/T3, Fig. 3.11).

Koster (1984) demonstrated statistically that the drainage alignment in Dinosaur Park showed a pronounced parallelism to the minimum compressive stress within the Alberta syncline and the strike of the Sweetgrass Arch (see S1 and S2, Fig. 3.11). The latter is the dominant orientation in the study area.

The tributary valleys have an area no greater than 5000 m². They enlarge by erosion of the weak bedrock underlying the iron cemented sandstone which then forms an overhang (Fig. 3.12). Eventually this collapses and a renewed cycle of head-cut erosion begins. The eroded

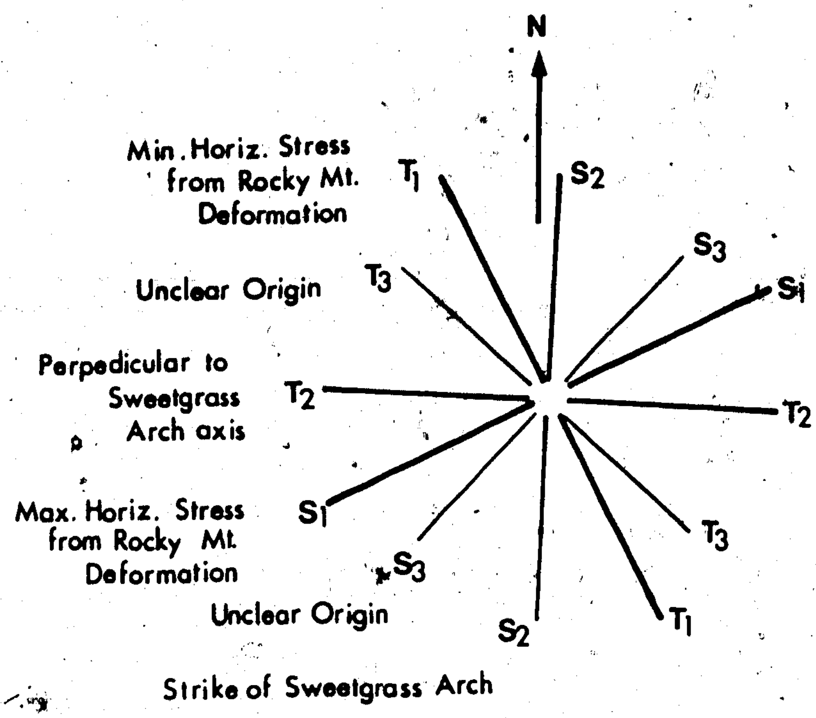


Figure 3.11 Orientations and causes of bedrock joint sets in southern Alberta (from Koster, 1984)

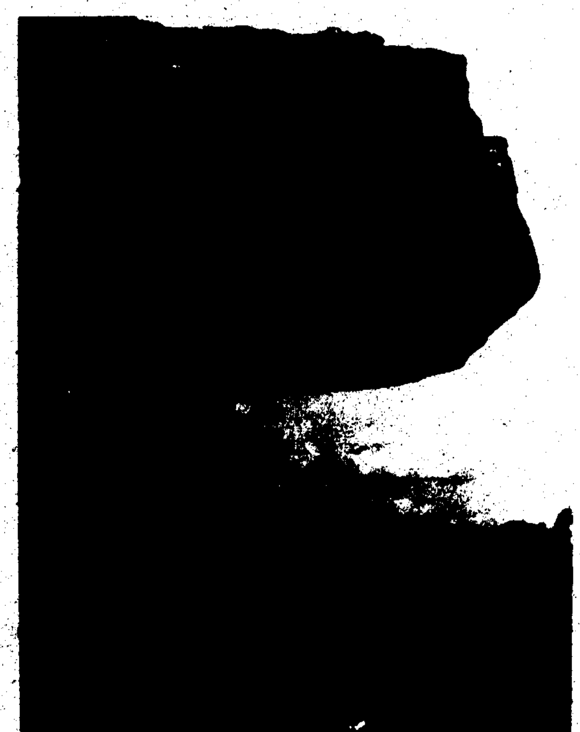


Figure 3.12 Development of an ironstone overhang as a result of erosion of the underlying weaker bedrock

material is usually deposited as small alluvial fans (Fig. 3.6). Incision of these deposits has left truncated fans standing between 0.3 and 2.5 m above the valley floor (Fig. 3.10). Because of the extensive removal of the alluvial fans it is difficult to determine the relationship between their size and the contributing area. This is further exacerbated by the fact that the sediment source area for many of the fans no longer exists (Fig 3.6).

Observations suggest that Faulkner's (1970) model of gully evolution can be applied in part to the development of the north-south orientated tributaries. A clear relationship between headward extension and the long profile of the tributaries is seen; those that had been able to extend furthest back into the the mesa surface are less influenced by local structure. This is reflected in the longitudinal profiles which, as Faulkner (1970) noted, become less steep with the elimination of structural control.

A second feature that has had a considerable influence on the valley morphology is regional slope, which trends SW-NE. This is reflected in the regional drainage pattern with nearly 90 per cent of drainage enters the study area from the south. Four major basins which range from approximately 0.3 km^2 to 1.2 km^2, drain into the area (Fig. 3.13). Unlike the smaller, north-south orientated valleys these large drainage basins have a marked SW-NE orientation. Although later headward extension has been along a north-south trend (Fig. 3.13). These major tributaries have all been able to incise down to the floor of the main valley and in all cases have been effected by the most recent period of entrenchment. The pronounced orientation of these valleys (with later headward extension along a different orientation), and the fact that they have been able to incise down to baselevel, suggest that they formed during the early stages of badlands development. Their orientation is a result of regional slope control.

Local and regional structural features have had a considerable influence on the development of the valley morphology. Most significant is the effect of varying ratios of discharge and sediment which will occur in different areas. As large drainage areas tend to have a greater potential for storage than smaller ones the sediment delivery ratio decreases as the drainage basin size increases (Carson and Kirkby, 1973). Major tributaries entering the study

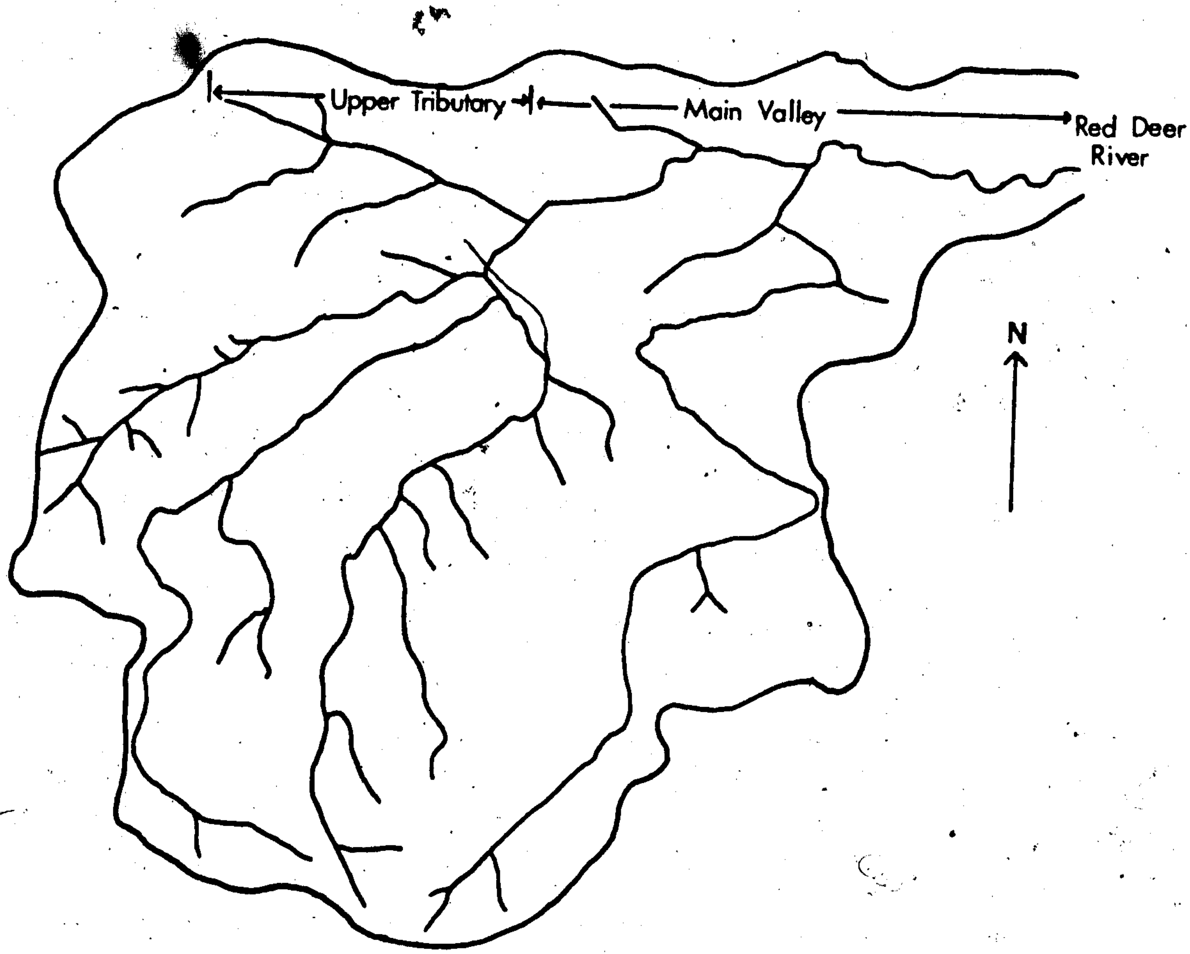


Figure 3.13 Major drainage features in the vicinity of the study area

area will tend to have a low sediment delivery ratio in comparison to small ones. Consequently the potential for erosion will be greater in the large tributaries which enter the study area from the south and these will be able to adjust to changes, for example in base level, very rapidly. Furthermore, high discharge will remove sediment out of the system and alluvial fans do not form. Smaller drainage basins such as the north-south orientated tributary valley, which have high sediment delivery ratios, have less ability to erode and transport sediment out of the system and alluvial fans build up at the mouth of the basin.

This relationship has been extremely important in the development of the valley morphology. The conditions required for fan deposition are evidently more favourable on the north side of the valley. In the past this affected fluvial activity by forcing the stream southwards across the valley thereby reducing the potential for fan deposition at such localities. Only immediately downstream of major tributaries, where the past and present arroyo is deflected to the north of the valley, have extensive fans been deposited from the south (Fig. 3.1). At these localities (e.g. locations 6 and 16, Fig. 3.1) sediment is removed from the north and fans build up from the south side of the valley. Sediment input from northern valleys dampens this effect downstream of southern tributaries, pushing the arroyo back across the valley (Fig. 3.1).

3.7 The bedrock profile

The underlying bedrock topography can be inferred from the seismic profiles. Seven profiles were measured in the main valley in 1984 and all indicate that the depth of fill is no greater than 4-5 m throughout the valley (Fig. 3.14). Most of the shots were from one upper surface to another. These indicate that the bedrock profile across the valley is quite flat with only slight undulations recorded. As bedrock generally outcrops in the valley walls it suggests that prior to fan deposition the valley walls were steep, similar to that observed in the upper tributary. From this it can be suggested that the main valley has a U-shaped profile with a flat bottom and steep valley walls. The implications of this will be discussed in Chapter 6.

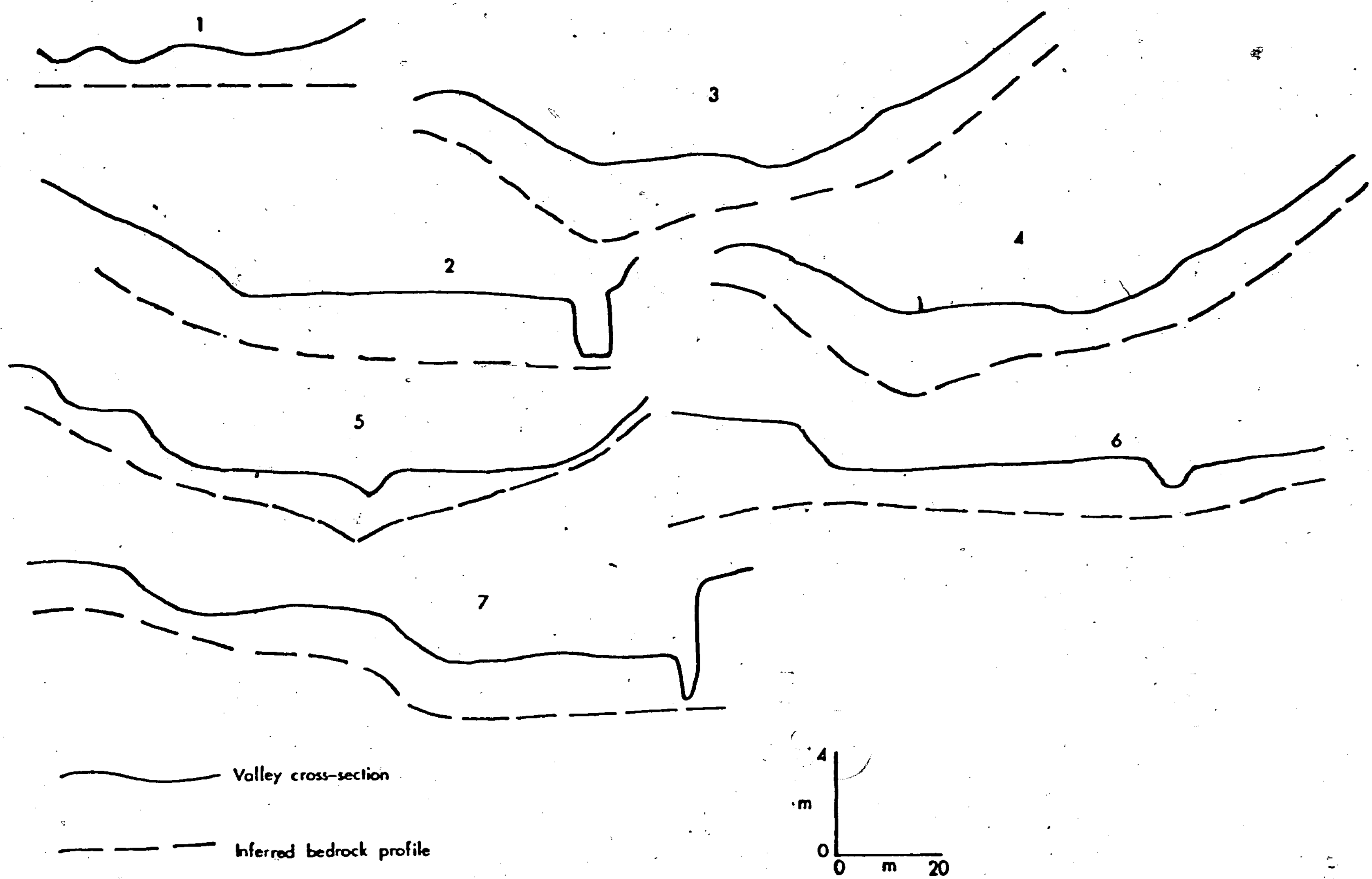


Figure 3.14 Seismic profiles from the study area (see figure 3.1 for location of the sections)

4. THE ALLUVIAL CHRONOLOGY

4.1 Introduction

Seismic profiling of the study area indicated that upto 4 m of alluvium fills the valley. Twenty-nine sites where sectioned and logged (see Appendix A), so that major sedimentological units could be identified and the alluvial chronology established. Based on the degree of cohesion, grain-size ditribution, texture and inpart colour and the morphological expression of the deposits, the valley fill can be broadly divided into two major types of alluvium: a) alluvial fan deposits, and b) fluvial deposits.

The alluvial fans are localized deposits whose shape approximates a segment of a cone. They are deposited from small side valleys and grade out into the study valley at an angle between 2.3-6° (Table 3.1). Several distinct features characterize materials deposited in this way. The most notable is the extremely cohesive nature of the deposits, which made them impossible to dig without a jack-hammer. Cohesion is believed to be a result of the high silt/clay content in these deposits which frequently exceeds 50 per cent. The silt/clay content decreases with proximity to the sediment source area and is comparable to that of the course fluvial sands at the fan apex. In such instances it was possible to distinguish the two types of alluvium by the shape of individual particles; fluvially deposited sediments having a higher degree of roundness. Most of the fan deposits are very similar in colour and fall in the 5Y 7/2 light grey to 5Y 6/2 light olive grey colour range.

Vesicular layering is a prominent feature of fan deposits. This is believed to be a result of repeated wetting and drying of the sediment, causing the rearrangment of particles and the formation of vesicles. The presence of silt/clay is believed to be an inportant factor in this phenomenon (Miller, 1971). Fan deposits are frequently layered, indicating that sheet wash deposition was inportant. Small scale ripples and cross-stratified beds were also observed within fan deposits at a number of locations and are believed to have formed during fluvial activity over the fan surface.

Fluvially deposited materials are much more varied in nature, ranging from coase bedload gravels to clayey overbank fines. The majority falling in the medium-coarse sand range. With the exception of finer grained material, fluvial deposits have little or no cohesion and consequently are easy to excavate. The sands can be divided into coarse and fine members. The former tend to be massive with occasional ripples and cross-stratification. The latter on the other hand are extensively rippled, cross-bedded and interbedded with thin layers of sheet wash deposits. Although sedimentary structures were noted in most fluvial deposits it was not possible to make any conclusions of the flow regimes under which sediments were deposited. This area is, and probably was, characterized by ephemenral flow and variations between events will have been considerable. Consequently no long term patterns of flow conditions will be recorded in The valley fill.

4.2 The upper tributary

Two sites were excavated in the upper tributary (Fig. 3.1). These exposed most of the valley fill but not deposits which form the upper surface. Deposits at both sites consist of poorly consolidated fluvial material. At location 1 the valley fill was trenched down to bedrock, exposing a complex sequence of cut and fill deposits, 2.9 m thick (Fig. 4.1). These are made up of fine to medium grained sands which vary in silt/clay content from 4.5 to 31 per cent. At the base of the section a fine lag deposit, containing ironstone clasts approximately 1 to 2 cm in diameter, overlies bedrock.

A less complex sequence of fine to medium grained sands overlying coarse bedload gravels was exposed at location 2 (Fig. 4.2). These showed a fining up sequence and, at the top of the fill, sediments with up to 50 per cent silt/clay content cover the valley floor. Although small scale ripples and cross-stratified beds are seen in the sands, these are much smaller than those observed at location 1 which suggests they were deposited under lower energy flow conditions. This may be due in part to the width of the valley. At location 1 the valley is only 35-40 m wide; this tends to restrict movement of the channel and sediments are constantly

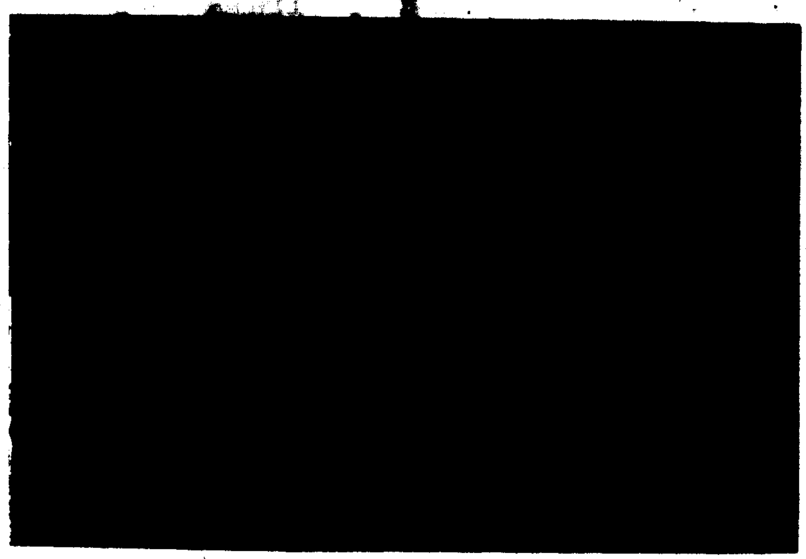


Figure 4.1 Cut and fill sequence at location 1

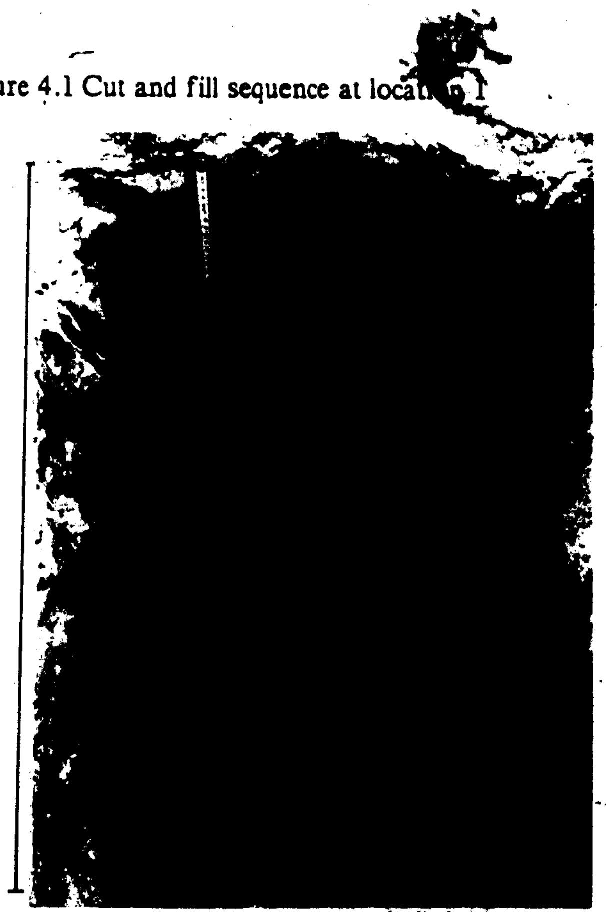


Figure 4.2 The valley fill at location 2

reworked. Furthermore, high discharge from a small tributary valley immediately upstream of location 1 will have contributed to the continual reworking of sediments, leaving a series of cut and fill deposits. As the valley widens this process becomes less important and deposition is under lower energy conditions.

Seismic profiling just upstream of location 1 indicated that the fill should be approximately 1 to 1.2 m thick (Section 1, Fig. 3.14). This is considerably less than that actually measured. The profile also inferred that the contact was horizontal. Because this is a bedrock contact it seems highly improbable that such a regular surface would be formed. It is more likely that this represents the water table at this site and not the bedrock contact. As these seismic profiles were measured early in the spring (of 1984) the water table will have been recharged by snow-melt and it would be relatively high. Furthermore,as the valley is very narrow at this point the water table would be higher than in wider parts of the valley.

4.3 The upper valley

Seven sites were investigated in the upper valley (locations 3 to 9, Fig. 3.1). Five sites within the arroyo exposing deposits which form the lower surface, while pits at locations 6 and 7 exposed deposits which form the upper surface as well. At location 6, coarse angular fan material overlies poorly consolidated fluvial sands (Fig. 4.3). A similar stratigraphy was also exposed at location 7 (Fig. 4.4). The fluvial sands at both sites are rippled and bedded (Fig. 4.5) and analysis shows they have a similar grain-size distribution, falling in to the coarse-medium sand range (Appendix B). The transistion from fluvial to fan deposition is abrupt and a distinct boundary between the two alluvium types was noted. At location 7 a thin band of overbank fines was found at the contact (Fig. 4.4), which suggests that with the onset of fan deposition fluvial activity was forced away from this site.

Although the two site showed a similar stratigraphy some differences were observed, with 3.1 m of fan deposits at location 6 compared to only 1.3 m at location 7. Furthermore, deposits at the former site are much coarser in nature. Variations in the thickness and

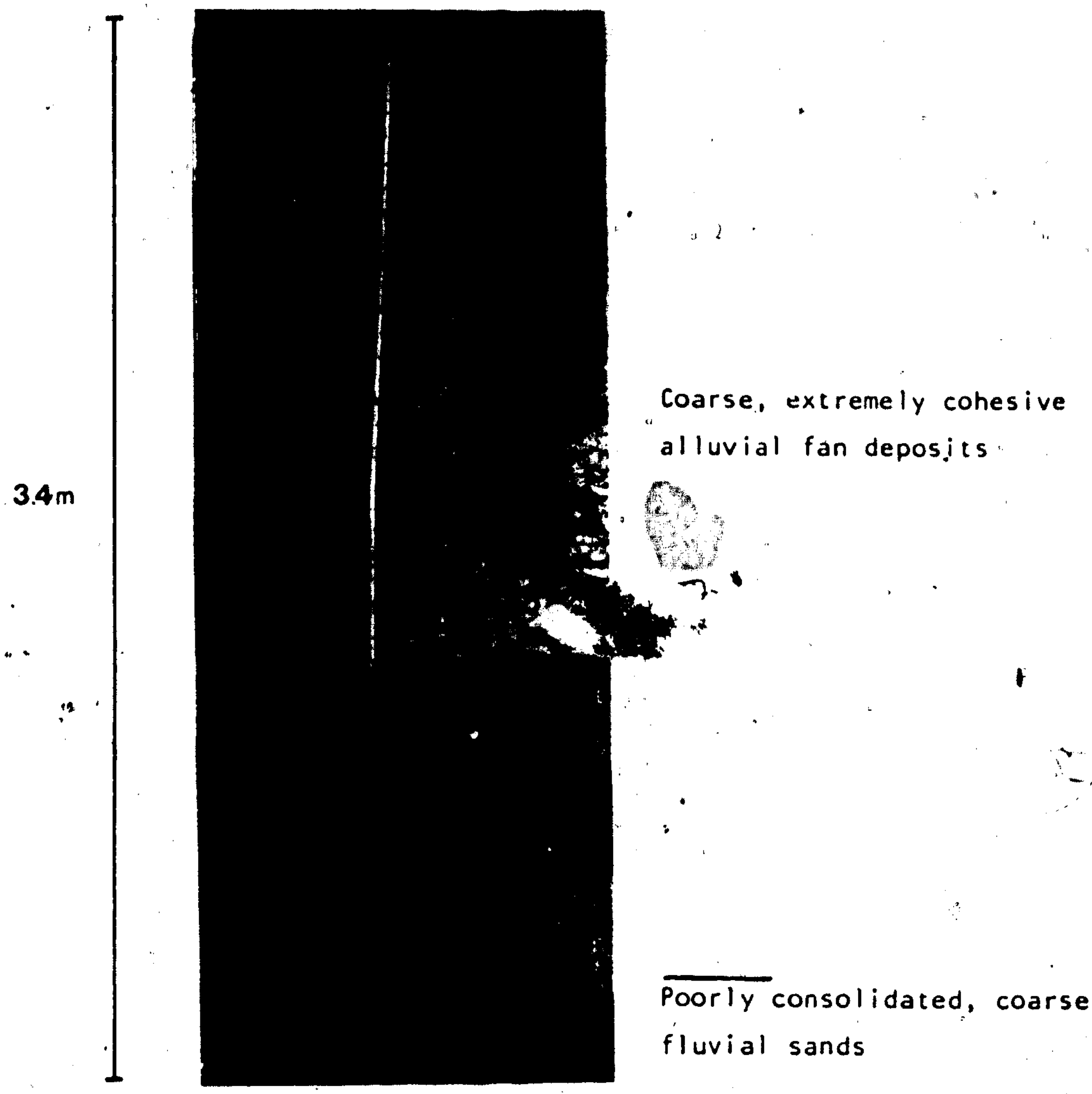


Figure 4.3 The valley fill at location 6

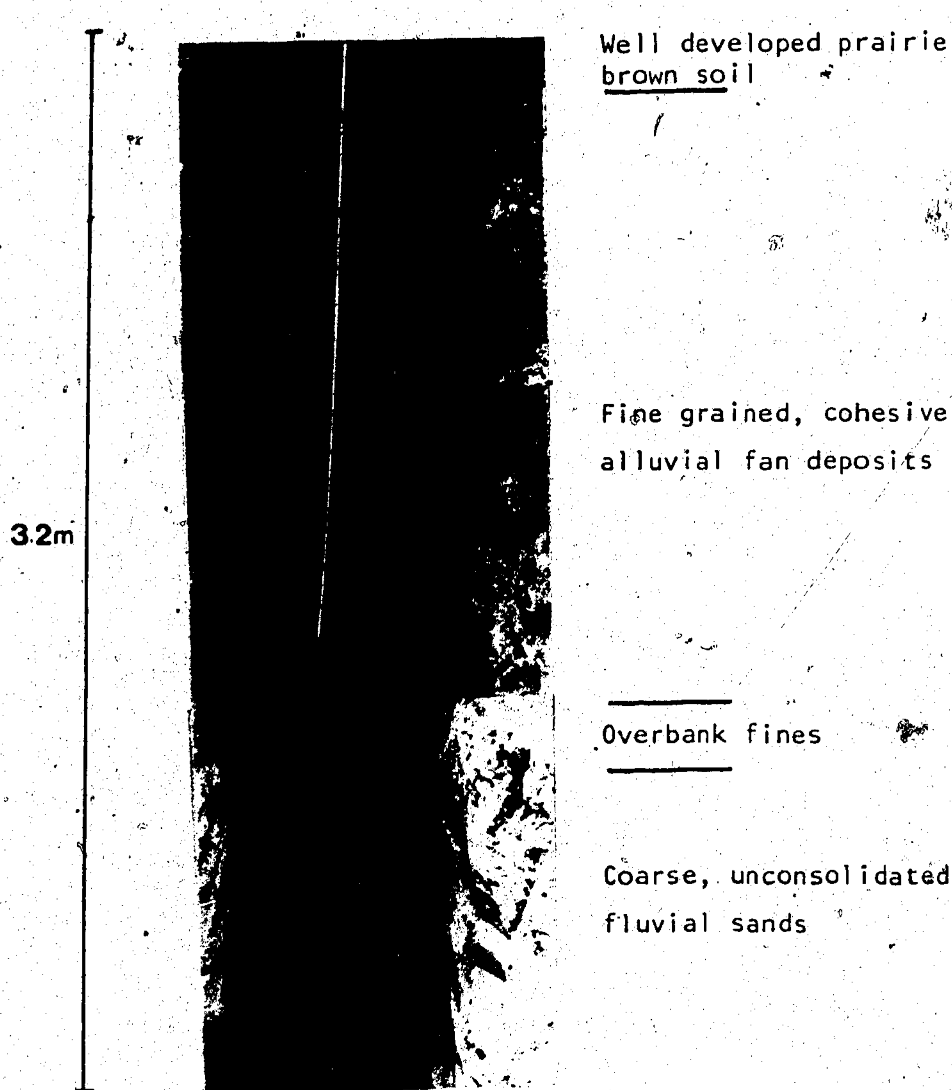


Figure 4.4 The valley fill at location 7

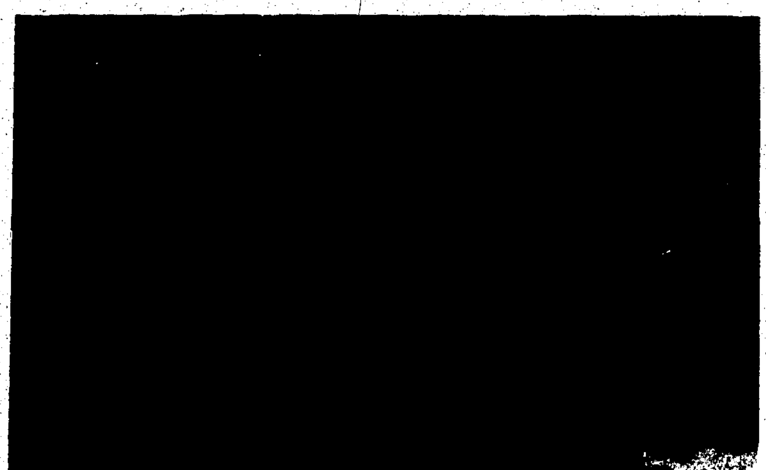


Figure 4.5 Cross-stratified fluvially deposited sands at location 7

grain-size distribution of the fan deposits are believed to be a result of the size of the sediment source area and the position downfan of the section; location 6 having a larger sediment source area and being a more proximal site. Distinct beds and small scale sedimentary structures where observed in the fan deposits which indicate that fluvial activity was important over the fan surface in the past (Figs. 4.6 and 4.7). Despite differences in the thicknesses of the deposits surveying of these sites indicates that the onset of fan deposition occurred when approximately 1 m of sands had accumulated to a height of 640.5 m a.s.l.

At both sites the valley floor is covered by recent fan material which forms a well defined inset fill. At location 6 (see A, Fig. 4.7) this is due to gullying and renewed deposition from an old fan deposit; at location 7 deposition is from a small southern tributary which has incised down to the level of the main valley floor.

The valley fill exposed at the other five localities was composed entirely of fluvial material. Fine grained vesicular sheet wash deposits were observed at the surface of all the sites and are similar in appearance to deposits exposed elsewhere in the valley. Sediments of this type also cover the floor of the upper tributary and it is believed that they were laid down when the upper tributary was in flood. Deposits in the main valley were probably laid down under similar conditions prior to valley incision.

At locations 4 and 5 the valley fill was exposed to the base of the arroyo. At both sites the fill consists of thin sheet wash deposits interbedded with fine to medium grained sands (Fig. 4.8 and 4.9). The latter are extensively rippled and cross-bedded. Micro cross-stratification occurs in distinct beds which are partially eroded by adjacent and overlying sets (Fig. 4.10). These structures are generally formed by the preservation of linguoid ripples (Harmes and Fahnestock, 1965). Ripples of this type have formed on the floor of the arroyo. Their amplitude is slightly greater than those preserved in the fill and indicates that flow conditions in the arroyo attain higher flow velocities than those reached during deposition of the upper section of the valley fill.

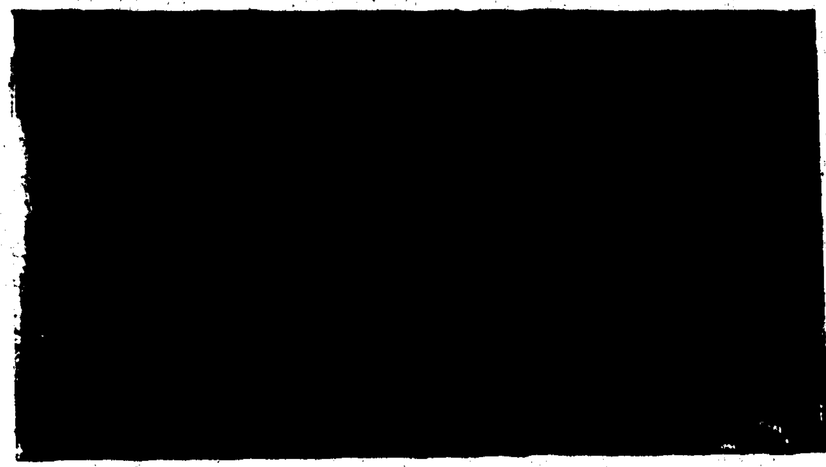


Figure 4.6 Small-scale sedimentary structures in the fan deposit at location 6

Figure 4.7 Well bedded alluvial fan material in the upper section of the fan deposit at location 6. Note recent fan material overlying the surface at A

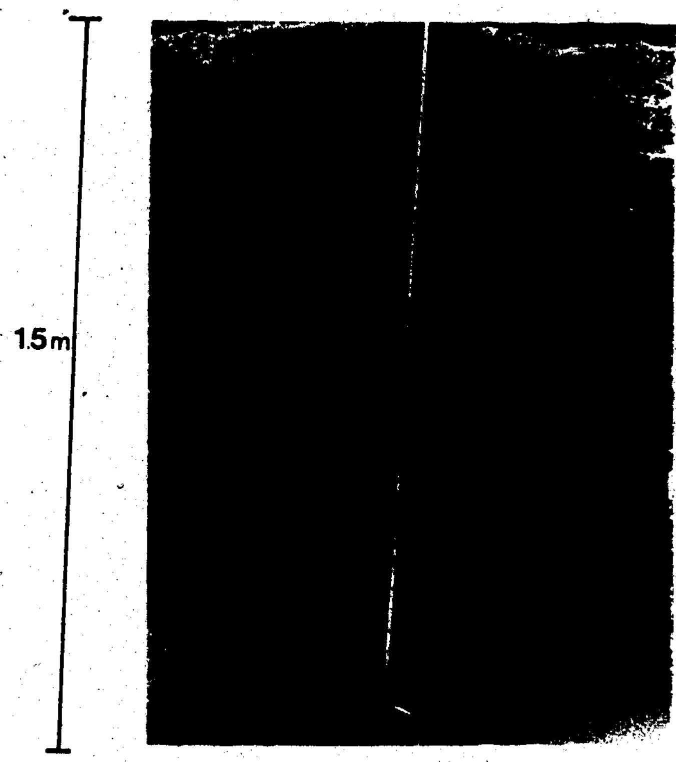


Figure 4.8 Interbedded cross-stratified fluvial sands and sheet wash deposits exposed in the arroyo wall at location 4

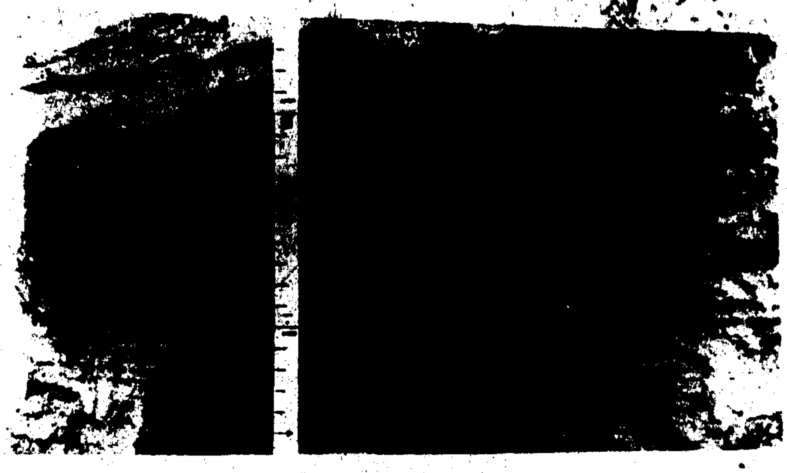
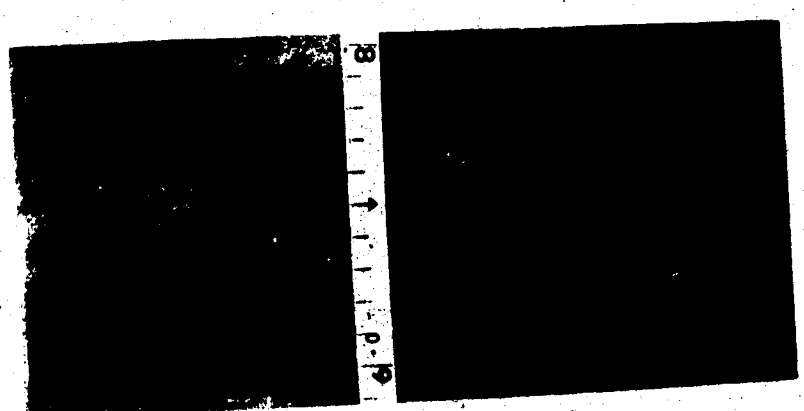


Figure 4.9 Thin sheet wash deposits exposed at location 4



Fig[illegible]grained, cross-stratified fluvial sands at location 4

The pits at locations 3, 8 and 9 were trenched down to bedrock and show that the depth of fill in this section of the valley is about 3 m. This supports the results of seismic profiling in this area (see sections 2 and 3, Fig. 3.14). Deposits consist of fluvial material with varying thicknesses of sheet wash deposits at the surface. Immediately upstream of location 3 the remains of a cottonwood tree were found 0.6 m below the surface of the fill (Fig. 4.11). This gave a date of 315+/- 65 B.P. (S-2546), and indicates that sediment accumulation was active at this time.

A distinct relationship between old and new deposits is observed at all sites and is best preserved at location 9 (Fig. 4.12). Here, fluvial sands form an inset fill approximately 50 cm thick which truncates older fluvial deposits. Deposits exposed down the arroyo wall continue below the recent fill, indicating that the depth of incision by the arroyo has not been much greater than at present. Considerable variations between the deposits exposed at locations 8 and 9 and location 3 were observed. At the latter site, 2.9 m of sediment were exposed (Fig. 4.13). The upper 2 m of the fill are similar to materials seen at locations 4 and 5 and consist of extensively rippled fine to medium grained sands interbedded with sheet wash deposits. At the base of the valley fill coarse structureless gray sands have been deposited over a thin bed of poorly sorted bedload gravels which in turn overlie bedrock (Fig. 4.13). In marked contrast the valley fill exposed at locations 8 and 9 consists of coarse fluvial sands overlying bedload gravels (Figs. 4.12 and 4.14). Fine grained sheet wash deposits are limited to the upper 20 to 30 cm of the section. Small scale sedimentary structures are found throughout the sands which indicate that deposition was under moderate flow conditions.

As discussed, sheet wash deposits are believed to have been laid down when the valley was in flood, prior to arroyo incision. Discharge into the upper valley from the upper and southern tributaries would have spread across the valley floor. The increased width of the upper valley, together with the effect o[illegible] water meeting will have reduced the velocity of the flow and deposition would [illegible]on has been greatest in the upper part of the main valley and hence a greate[illegible]ss of sheet wash deposits in this part of the valley.

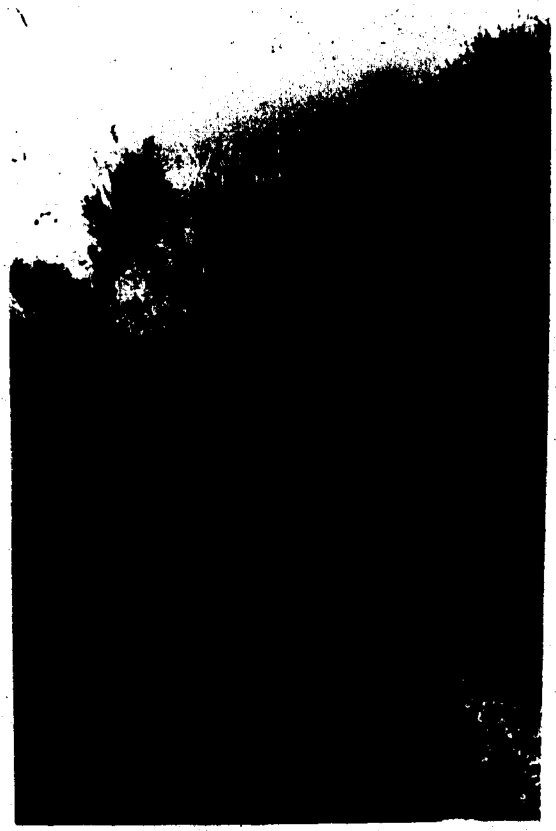


Figure 4.11 Cottonwood log which gave a date of 315+/-65 B.P.(S-2546) found immediately upstream of location 3

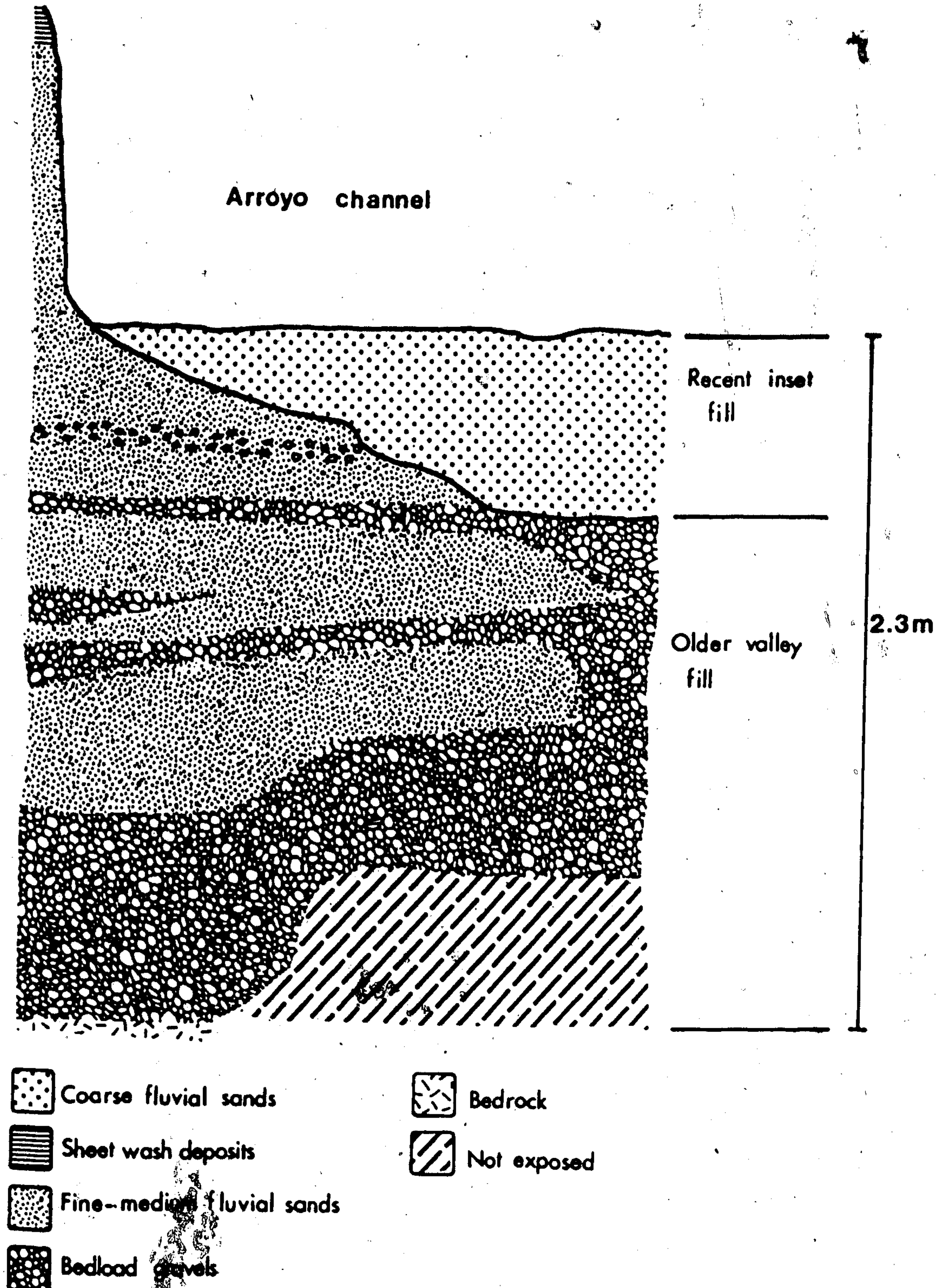


Figure 4.12 The relationship between recent and older fluvial deposits at location 9

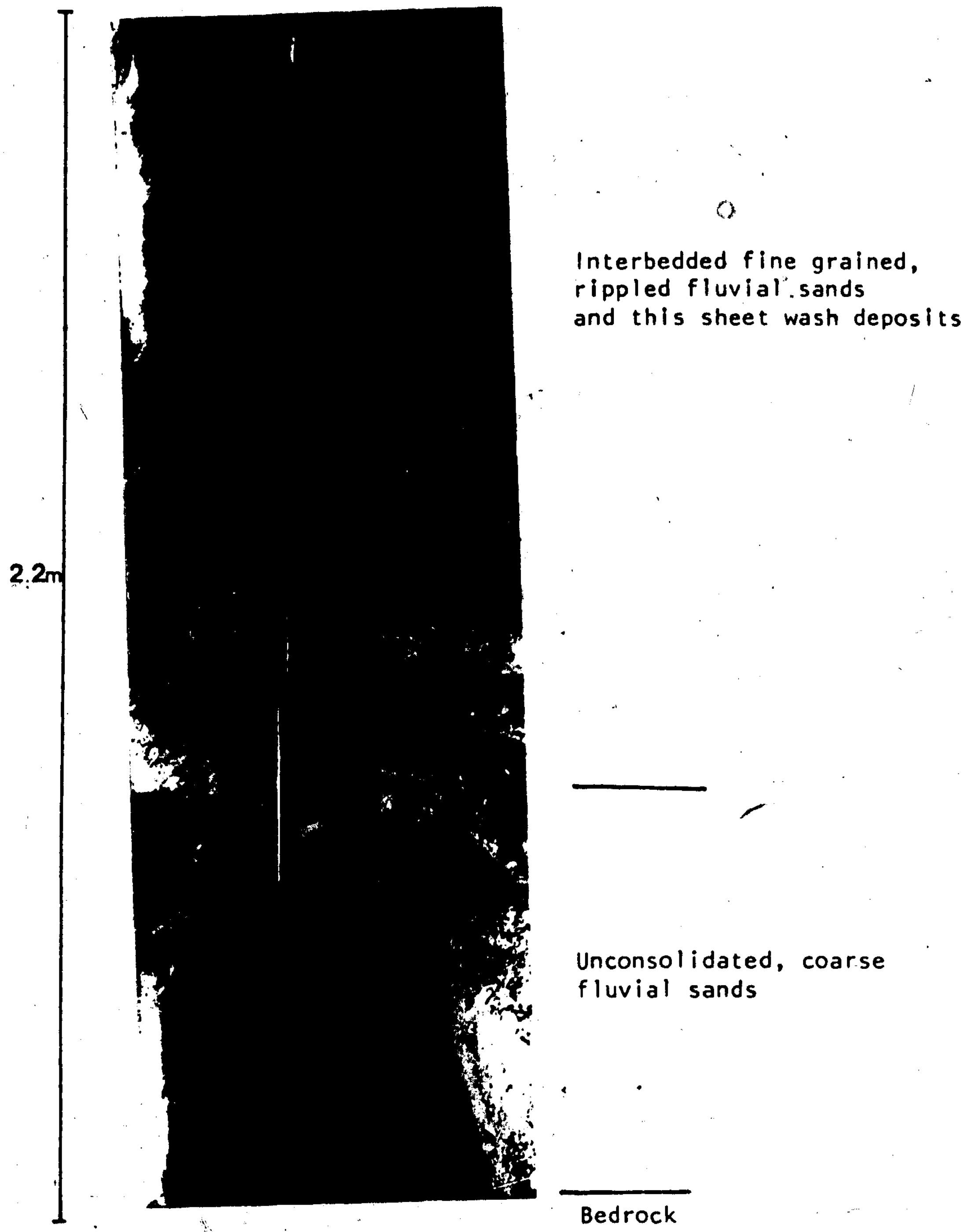


Figure 4.13 The valley fill at location 3

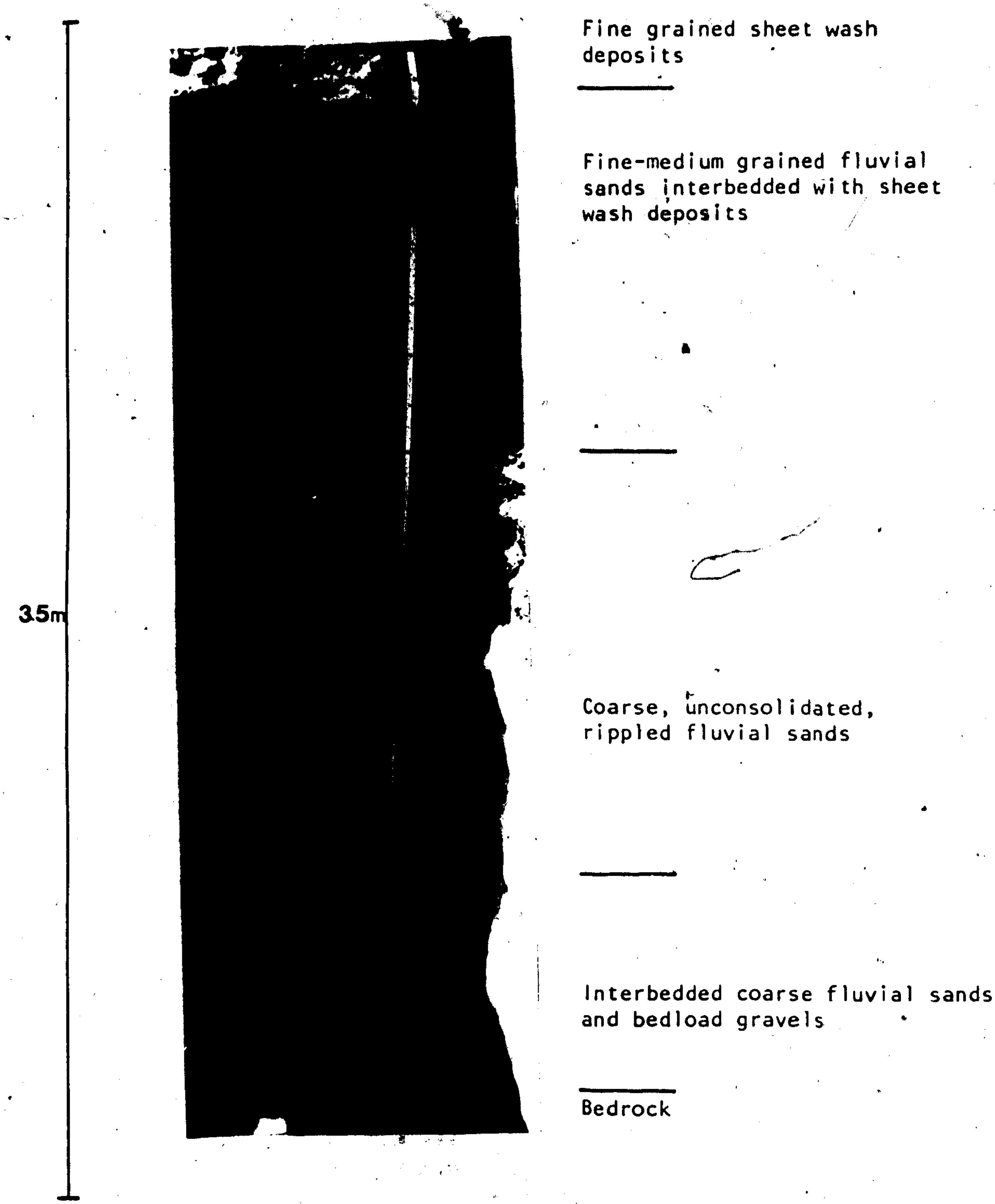


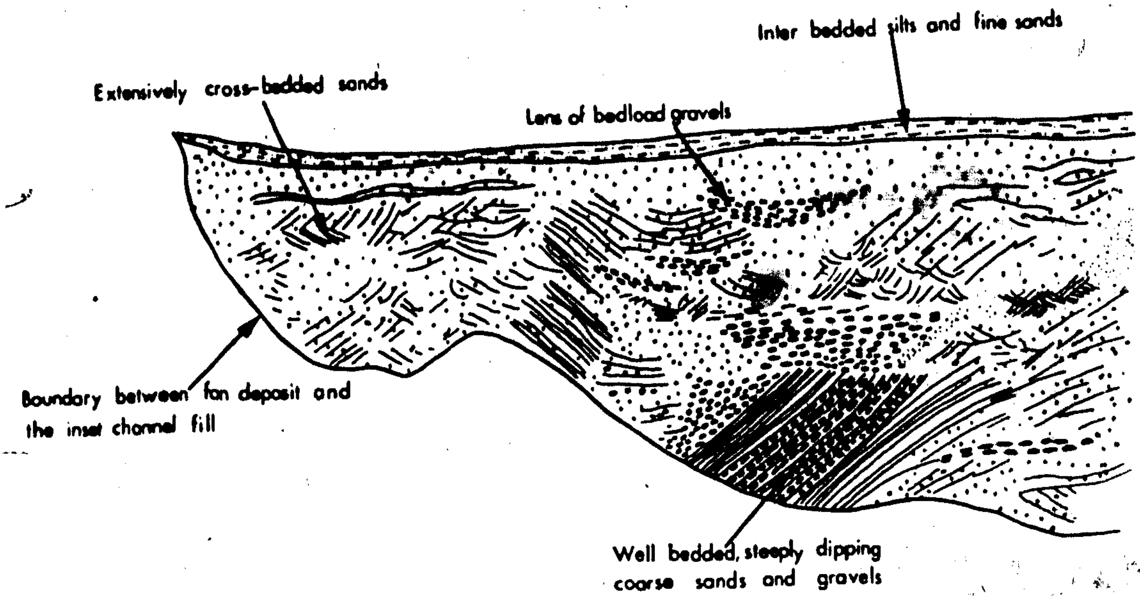
Figure 4.14 The valley fill at location 8

The depth of fill below the arroyo floor at location 3 is less than 1 m while at locations 8 and 9 it is about 2.5 m. Because the inset fill at location 9 is approximately 50 cm thick it indicates that the depth of incision at this site has been no greater than 1.3 m, compared to about 2.2 m at location 3. The reason for this is not clear but variations in slope angle and sediment type may be important. Little variation in the gradient of the fill is found in the upper valley which would suggest that in this instance slope angle is not important.

The effect of sediment type on the shape and form of alluvial channels has been discussed by Schumm (1960). He noted that channels cut into coarse alluvium tend to have a high width/depth ratio, while those entrenched into fine alluvium have a low width/ depth ratio. Grain-size analysis of the sediments which form the valley fill shows that the wash surfaces have a silt/clay content greater than 50 per cent, compared to about 4-5 per cent for the fluvially deposited coarse sands. Sheet wash deposits are found at all the sites but are far more prominent at location 3 where the upper fill of fine grained sediments is 2 m thick. Only 40-50 cm of similar fill is found at the other two locations. Because the arroyo has a low width/depth ratio in the upper valley compared to the channel shape at locations 8 and 9 (Fig. 3.7), it suggests that variations in sediment type have resulted in differences in the channel form. The relationship between sediment type and incision in the upper valley indicates that once the fill is entrenched down to the coarse sands entrenchment is effectively halted. The lack of cohesion of the sands makes them susceptible to lateral rather than vertical erosion, and consequently limits the depth of arroyo incision. It is believed that this may have been important in the past and incision of the valley fill will never have been much greater than at present.

4.4 The central valley

Deposits in the central valley were investigated at six sites, four on the north side of the valley and two on the south (Fig. 3.1). At location 11 the arroyo has exposed an older channel fill (Fig. 4.15), that is itself inset into an old fan deposit. The fill is composed of fine to



Sketch diagram of the inset channel shown in figure 4.15

Figure 4.15 The channel fill at location 11.(D. Evans is pointing to the gravels shown in the figure below).

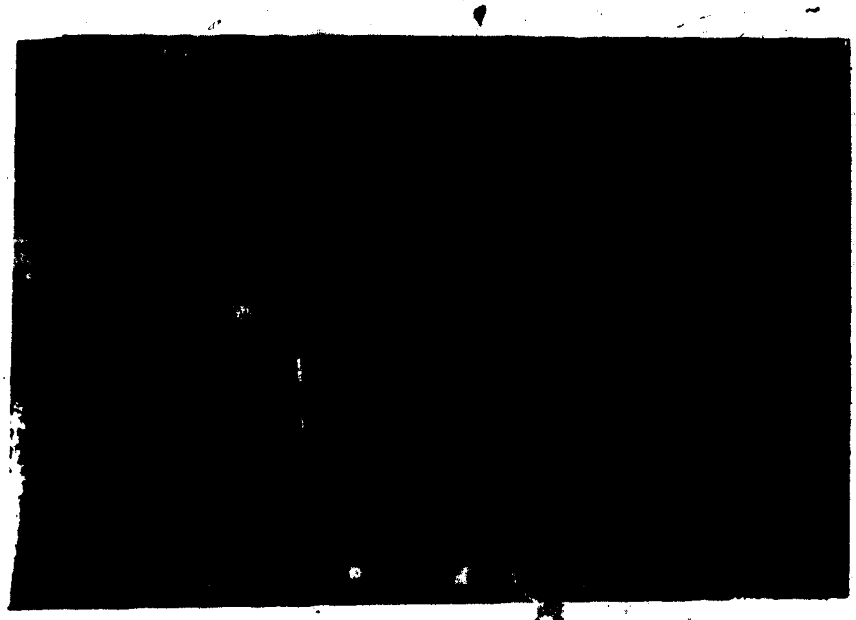


Figure 4.16 Steeply dipping bedload gravels which fill the channel thalweg

medium grained rippled and cross-stratified sands with steeply dipping coarse sands and ironstone clasts up to 3 or 4 cm in diameter which fill the channel thalweg (Fig. 4.16). Small lenses of fine bedload gravels are found throughout the section (Fig. 4.15) and record the progressive infilling of the channel. As it infilled deposits became finer, possibly in response to a decrease in the flow regime. Underlying the fill on the upstream side of the channel are coarse poorly consolidated sands. These are similar in appearance to sands found elsewhere in the valley.

The channel fill is inset against an old fan deposit and an abrupt boundary between the two deposits is seen. The surface of the truncated fan stands about 1 m above the channel. The deposit indicates that in the past fluvial activity has been along the south side of the valley and was not deflected across valley until this location. The present arroyo is deflected to the north side of the valley by bedrock outcropping at location 10 (Fig. 3.1).

All the other sites in this section entrench the upper surface as well as the valley floor. The pits at locations 12 and 14 (Fig. 3.1) were dug down to bedrock, the depth of fill being 1.5 and 2.3 m respectively. The seismic profile of this section of the valley indicates that the depth of fill is of the same order as that exposed at the two sites (see section 5, Fig. 3.14) and that in the mid-valley there is approximately 2-2.5 m of fill. The exposed valley fill varies between the two sites, deposits at location 12 being predominantly fan material while those at location 14 are fluvial.

The pit at location 12 entrenched a truncated fan exposing 1 m of coarse, cohesive fan material overlying 50-60 cm of interbedded fine grained fluvial sands and thin beds of sheet wash material (Fig. 4.17) laid down over bedrock (Fig. 4.18) The fill at this site indicates that while accumulation of fluvial deposits was predominent in the early stages of deposition, material was been deposited from side valleys. The latter been preserved as thin sheet wash deposits. Deposition from side valleys later became much more important. Gullying of the fan surface has resulted in renewed deposition. This process is still active, and a thin bed of fine grained fan material covers the valley floor (Fig. 3.1). The valley fill at location 12 is thinner

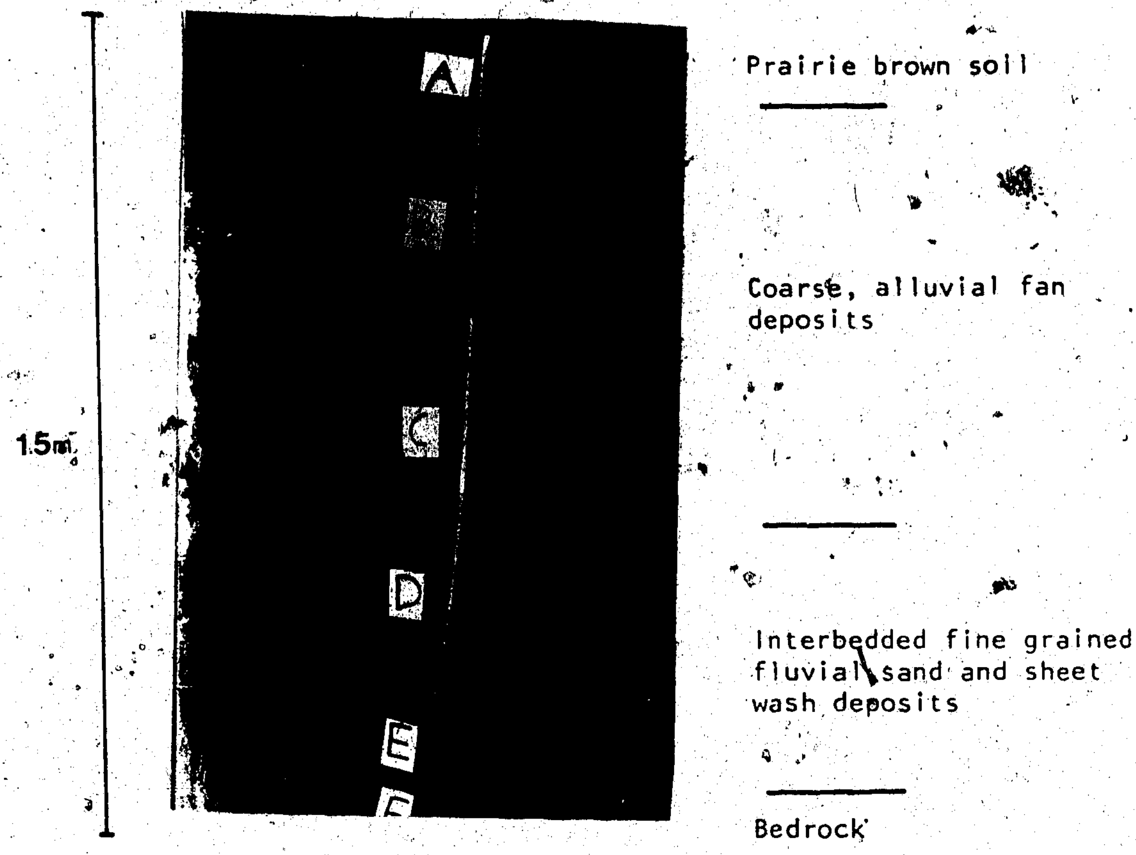


Figure 4.17 The valley fill at location 12

Figure 4.18 Close-up of the bedrock contact at location 12

than would be expected because of the close proximity of this site to the valley side.

The valley fill at location 14 (Fig. 4.19) is composed almost entirely of fluvial deposits with approximately 30 cm of fan material overlain by 20-30 cm of soil at the top of the section. Below this, is seen, 1.4 m of interbedded fluvial sands and overbank clays. These record fluctuations in the position of a past channel at this location. Migration of the channel was probably in response to fluctuations in sediment input into the valley at this site. Eventually the fluvial deposits were overtopped by the fan. At the base of the section an 80 cm of gravelly bedload overlies bedrock. In the side wall of the trench a small inset channel deposit was observed (Fig. 4.20). This cuts the upper 60-70 cm of the valley floor and is believed to have been deposited more recently than the other sediments exposed at this site. Because the deposits which underlie the channel are continuous within the trench it indicates that they are the same material. Consequently there has been little removal of the older deposits at this site. This provides some information on the depth of incision and fill at this location.

The fill at locations 13, 15, and 16 consist of fan deposits overlying unconsolidated fluvial sands. These have all been subjected to varying degrees of truncation, deposits at location 13 being the least affected. Here, the upper 2 m of fill are made up of fine grained cohesive fan deposits within which are numerous fine-grained sheet wash deposits. The latter are similar to the material which covers the surfaces of recent fans. Fan deposits are extensively rippled especially in the mid section of the fill (Fig. 4.21). Underlying the fan are rippled and laminated unconsolidated sands approximately 80 cm thick. At the base of the section coarse bedload gravels become dominant and prevented further excavations.

More than 2 m of fan material were exposed at location 15. A thin bed of sand, similar in appearance to the local bedrock, was found in the deposit and is believed to be bedrock debris, eroded from a nearby outcrop, that has become incorporated in the fan. Fluvial deposits similar to those exposed at location 13 underlie fan material here. Grain-size analysis of sediments from the two sites show that fan material is much coarser at location 15, the more proximal site, having only 21 per cent silt/clay content compared to over 50 per cent at location

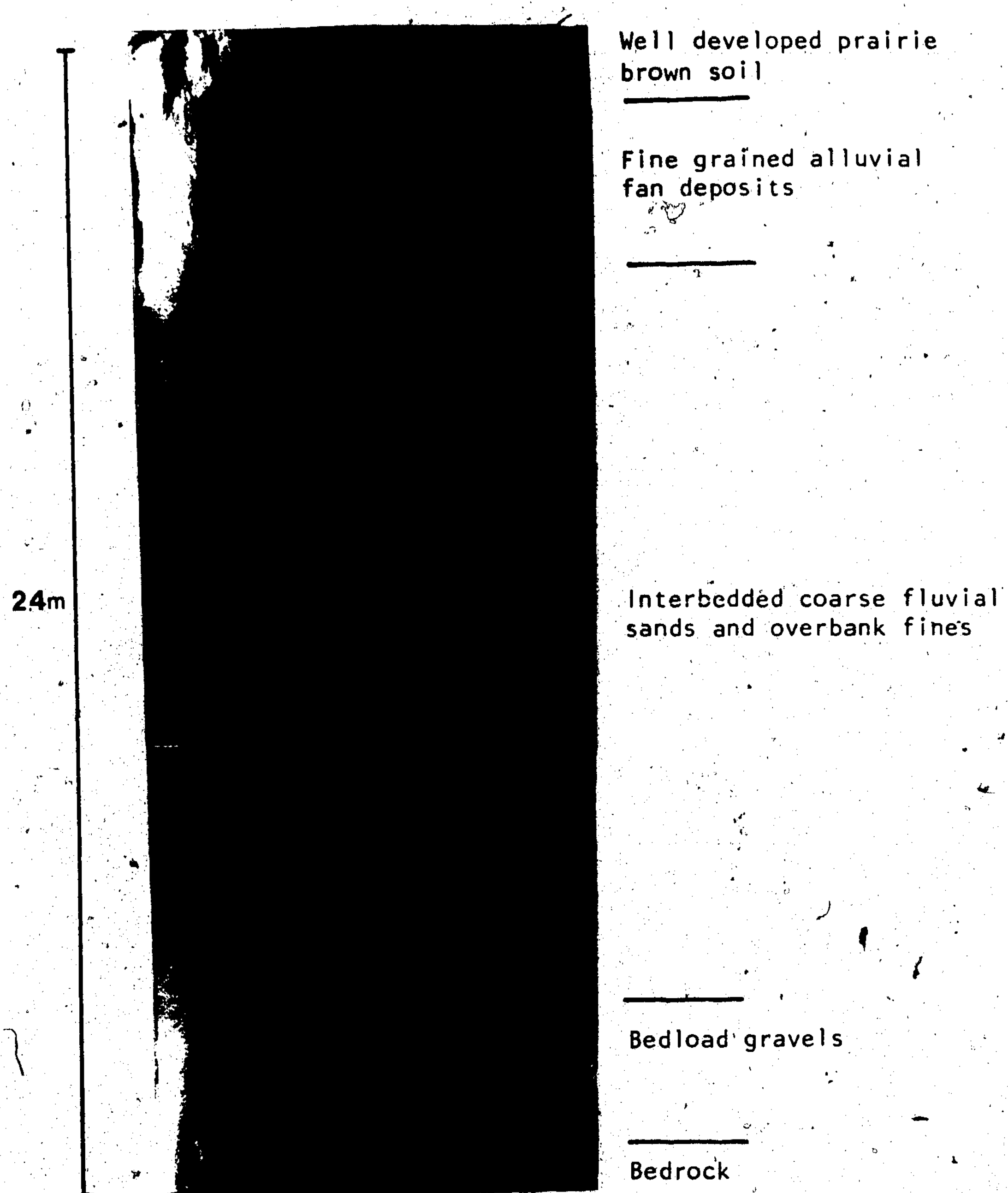


Figure 4.19 The valley fill at location 14

Figure 4.20 Close-up of the channel fill exposed in the side wall of the pit trenched at location 14

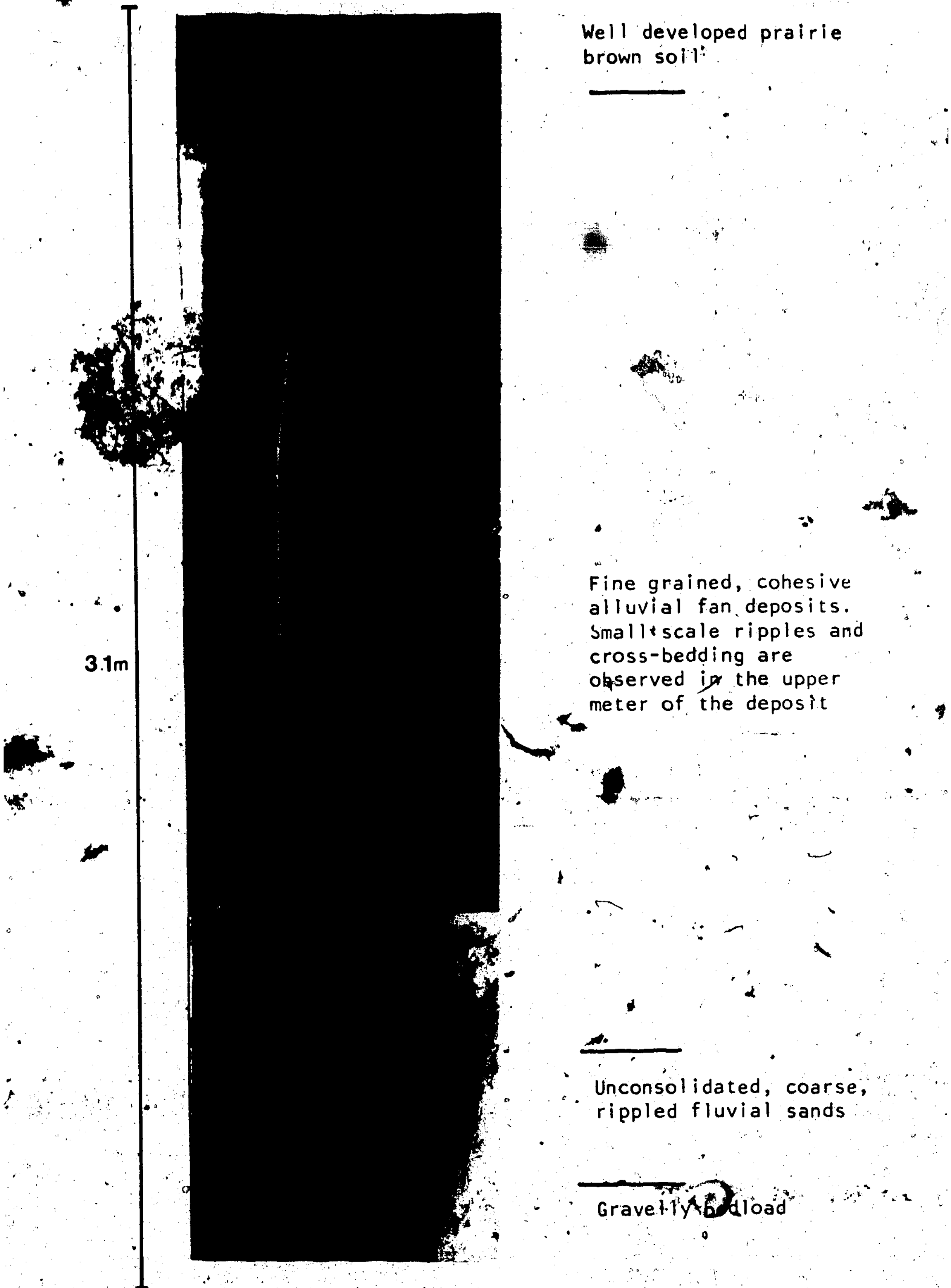


Figure 4.21 The valley fill at location 13

13 (Appendix C). Fluvial deposits, however, have a similar grain-size distribution suggesting that they are the same material (Appendix B).

Deposits at location 16 have been extensively eroded exposing the fan apex and the underlying bedrock. Because this site is adjacent to the lowest downstream tributary to enter the valley, fluvial activity has been forced over to the north side of the valley eroding deposits at location 16 (Fig. 4.22). An old meander has cut across and down the fan exposing a three-dimensional section of the deposit. At the apex fan material overlies bedrock, while downfan it is underlain by fluvial deposits. The nature of the fan varies considerably from coarse, angular material at the apex to extensively rippled fine sands and silts at more distal sites (Fig. 4.23). Underlying the fan on the upstream side is about 60 cm of fluvial sands overlying a thick deposit of clays and silts. These have extensive load structures at the base of the section and probably represent material laid down during a long period of ponding prior to the deposition of fans at this site.

With the exception of location 11 the valley fill at all the other sites in the central valley is very similar: unconsolidated medium-coarse grained fluvial sands overlain by fan deposits. Recent deposits are extremely limited and are no greater than 60-70 cm thick. This clearly indicates that incision and infilling in this section of the st[illegible]e not been significant since the main period of deposition.

4.5 The lower valley

The lower valley is the largest of the valley sections studied and provided many excellent sites for exposing the fill. Fifteen pits were entrenched in this area, the majority on the north side of the valley where deposits are best preserved (Fig. 3.1). The valley fill varied with location. Nine sites cut through the upper as well as the lower surface and exposed either fluvial deposits or fan deposits overlying fluvial sands. The sections exposed at locations 17, 19, 22, 24a, 24b, 28, and 29 fall into the latter category. A similar stratigraphy was also exposed at locations 18a and 18b, but fluvial sands have been deposited above as well as below the fan

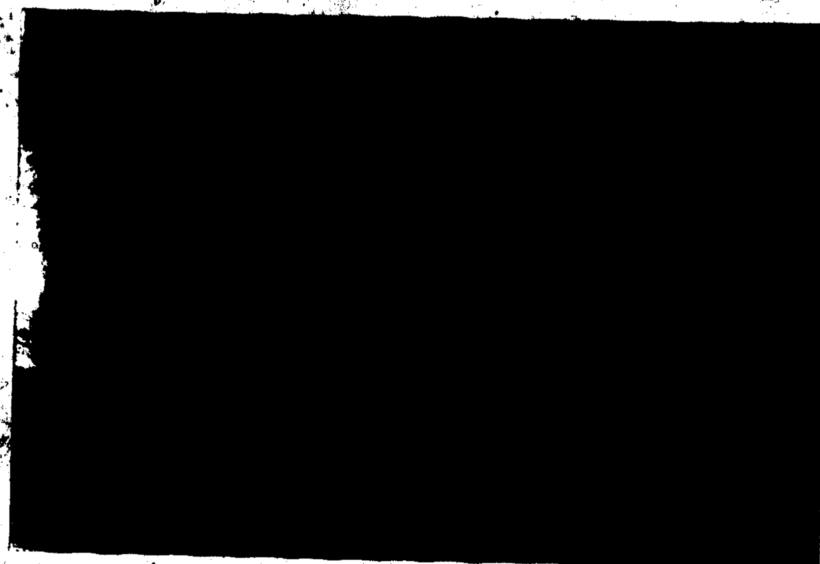


Figure 4.22 Alluvial fan deposits exposed at location 16. Grain-size decreases from A to B

Figure 4.23 Close-up of the small scale sedimentary structures from the distal section of the fan shown above

material.

A number of sites, particularly those at old meander scars, exhibited a distinct relationship between deposits forming the upper and lower surfaces. This is best seen at location 17 (Fig. 4.24). Here recent deposits form an inset fill 60 to 70 cm thick. Fluvial sands which underlie fan deposits in the upper surface continue beneath the inset fill. This indicates that the depth of incision during the last period of entrenchment did not exceed the depth of the present arroyo cut at this location. This relationship was also observed at location 22. At this site a large fan has been deposited from a southern tributary valley (Fig. 3.1). The tributary valley has been able to incise down to baselevel, eroding the middle part of the fan. Later fluvial activity has deposited fine grained fluvial sands over the lower surface. These are characterized by small scale ripples (Fig. 4.25) and sedimentary structures similar to those at location 17. Renewed fan deposition from the tributary valley has occurred in recent years (Fig. 4.26). Recent alluvial activity from the tributary valley has deposited a small low-angled fan over the area. The depth of fill at this site is similar to that at location 17, and is exposed in the wall of the present arroyo. At location 11 (in the central valley) the channel fill is underlain by coarse structureless sands similar to those beneath the fill at location 17. It is possible that the cut and fill sequence observed at locations 11, 17 and 22 were formed at the same time. This provides valuable evidence on the past configuration of the valley and gives some indication of the depth of incision during the penultimate episode of erosion.

At location 19 approximately 80 cm of fan material overlies more than 2 m of unconsolidated sands. Because of this sites proximity to the sediment source area fan material is angular and coarse grained with less than 5 per cent silt/clay content. Fluvial sands are medium to fine grained with small ripples and cross-bedded structures. Freshly cleared surfaces were rapidly covered by a white precipitate which is possibly sodium that has leached out from the bedrock.

At location 22b (Fig. 3.1) a section was cut through a fan remnant on the south side of the valley. As with other sites which trench the upper surface, alluvial fan deposits have been

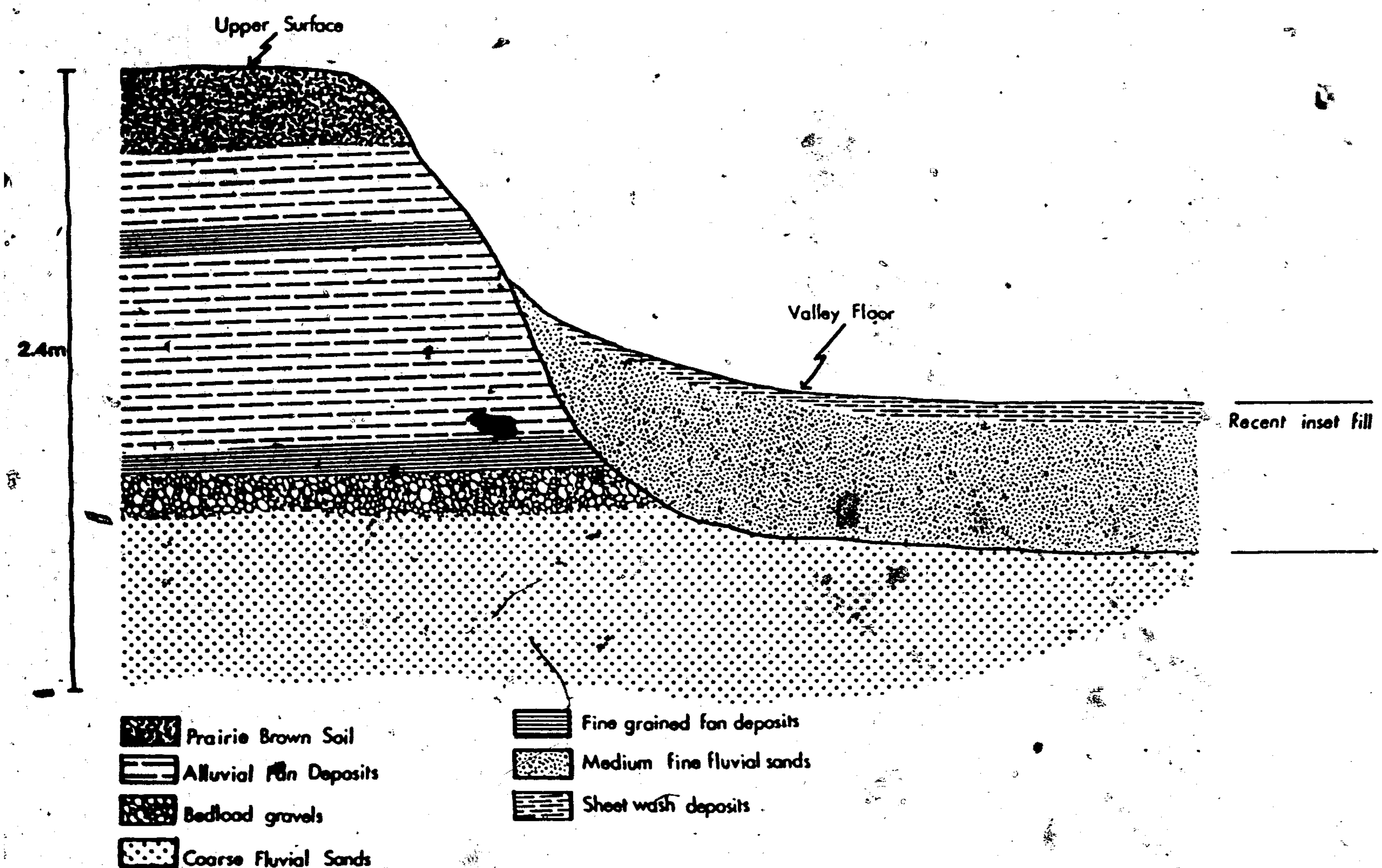


Figure 4.24 The relationship between old and more recent deposits seen at location 17

Figure 4.25 Close up of the fine grained, cross-stratified fluvial deposits at location 22

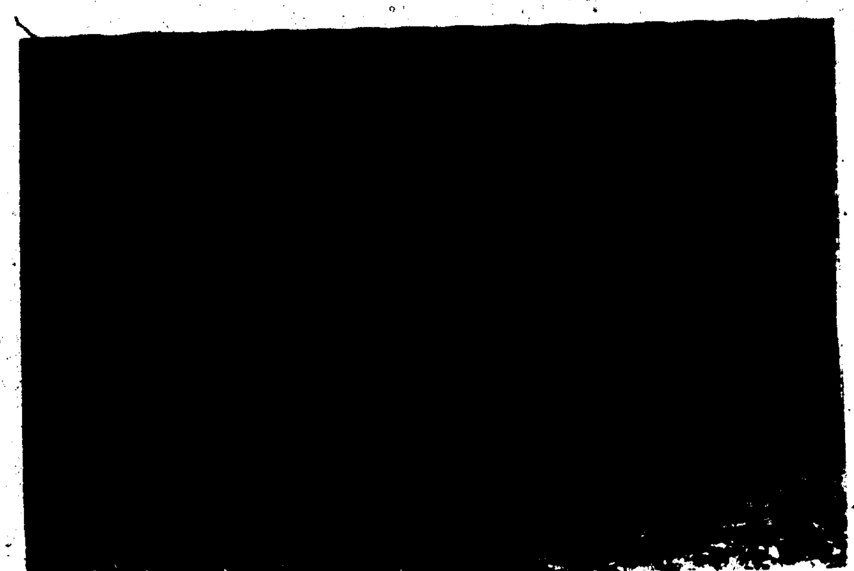


Figure 4.26 The inset fill at location 22. Note the recent fan deposits (A) overlying the fluvial sands shown above (B)

deposited over fluvial sands. At the boundary of the two depositional types is a thick bed of overbank clays. Their presence suggests that a channel was forced away from this location with the onset of fan deposition.

Deposits were exposed at two sections at location 24 and again showed that considerable variations in deposition can occur at sites located close to one another. At location 24a (Fig. 4.27) 1.4 m of fan material is overlain by a well developed prairie brown soil. Fan deposits are extremely cohesive, with small scale ripples throughout the section. Underlying the fan material are coarse, unconsolidated fluvial sands. At location 24b a greater thickness of fluvial material is observed with less fan deposits evident. In the lowest 200 m of the main valley two pits were trenched. These were adjacent to one another at location 28 and 29. Deposits at both sites are similar but were best exposed at location 29 (Fig. 4.29). Here, very fine grained alluvial fan material overlies fluvial sands. At the boundary between the two sediment types distinct dewatering structures are observed in the sands which suggests they were waterlogged when fan deposition commenced.

Two sites were trenched at location 18 (adjacent to location 19, Fig. 3.1). Although the stratigraphy is similar to other sites which trench the upper surface, fine grained fluvial sands have been deposited over the fan material, a relationship not seen elsewhere in the valley. At location 18a (Fig. 4.28) a well developed prairie brown soil about 60 cm thick is underlain by rippled fluvial sands. Thin sheet wash deposits are interbedded with the sands and these gradually become more dominant until only fan material is observed. At the base of the exposed section fluvial sands and fan material are interbedded. At location 18b a similar relationship is observed, however, a greater thickness of fluvial deposits and less fan material is observed at this site. Thus despite the proximity of the two sites considerable variations in deposits are seen.

Because of the varying sediment[illegible] in the extent of removal of deposits, considerable variation in the thickness of fan deposits was observed. Grain-size analysis of the fan deposits shows that more distal locations have a higher percentage of silt/clay material (Appendix C); for example, deposits from location 15 (which is the most

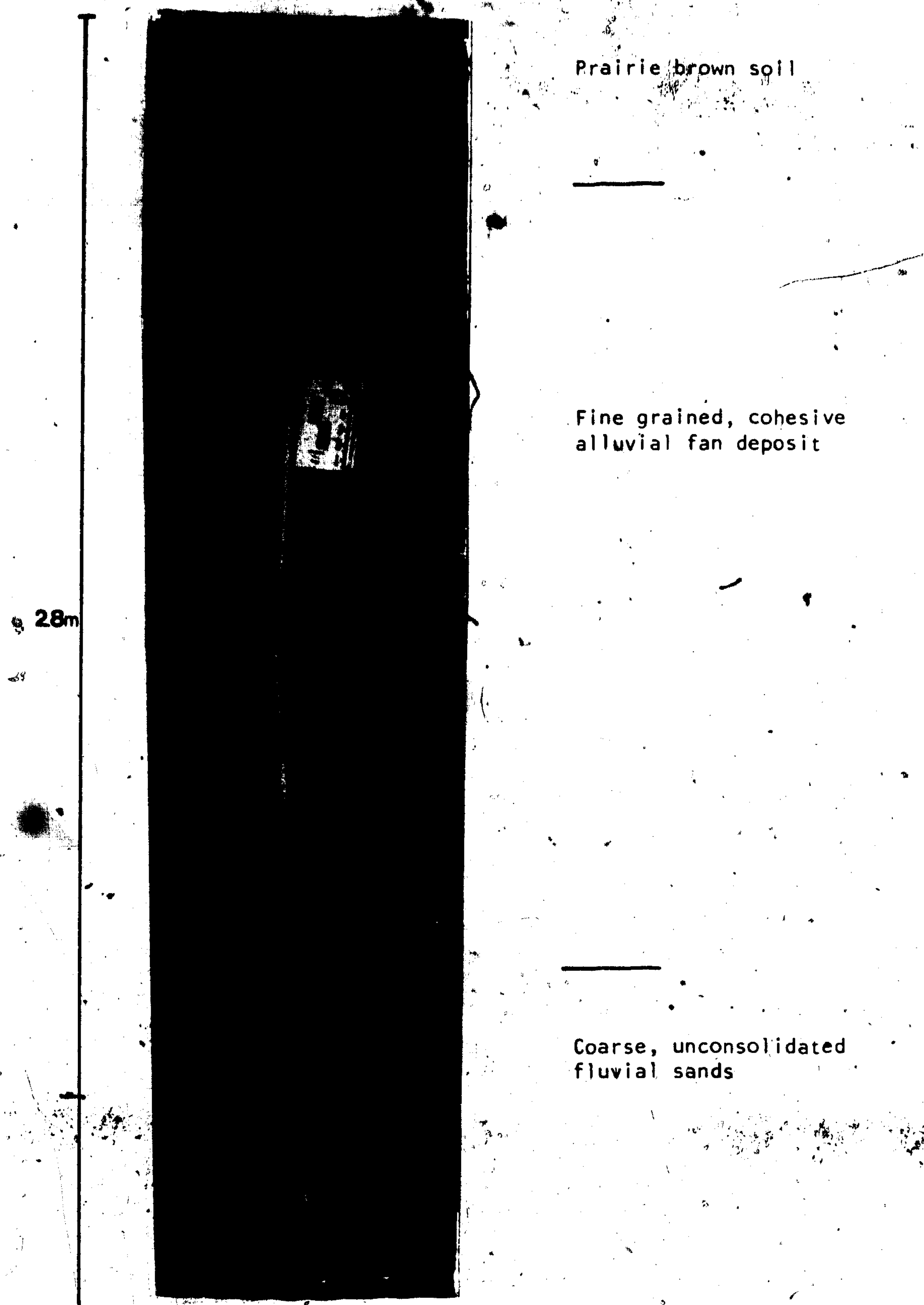


Figure 4.27 The valley fill at location 24a

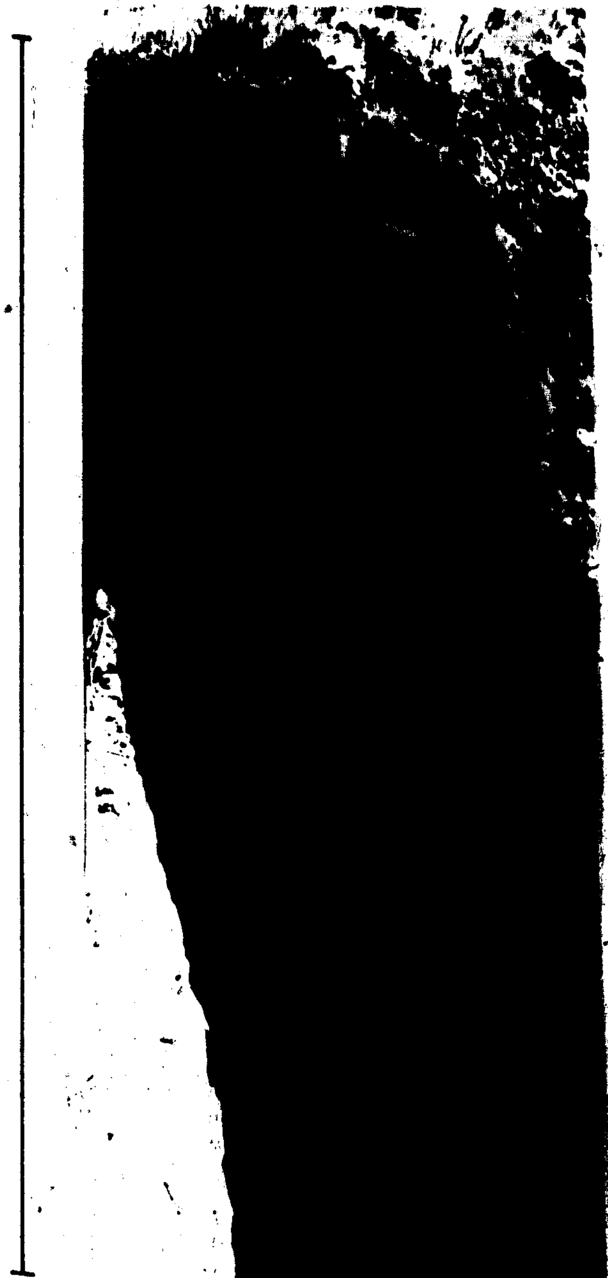


Figure 4.28 The valley fill at location 28

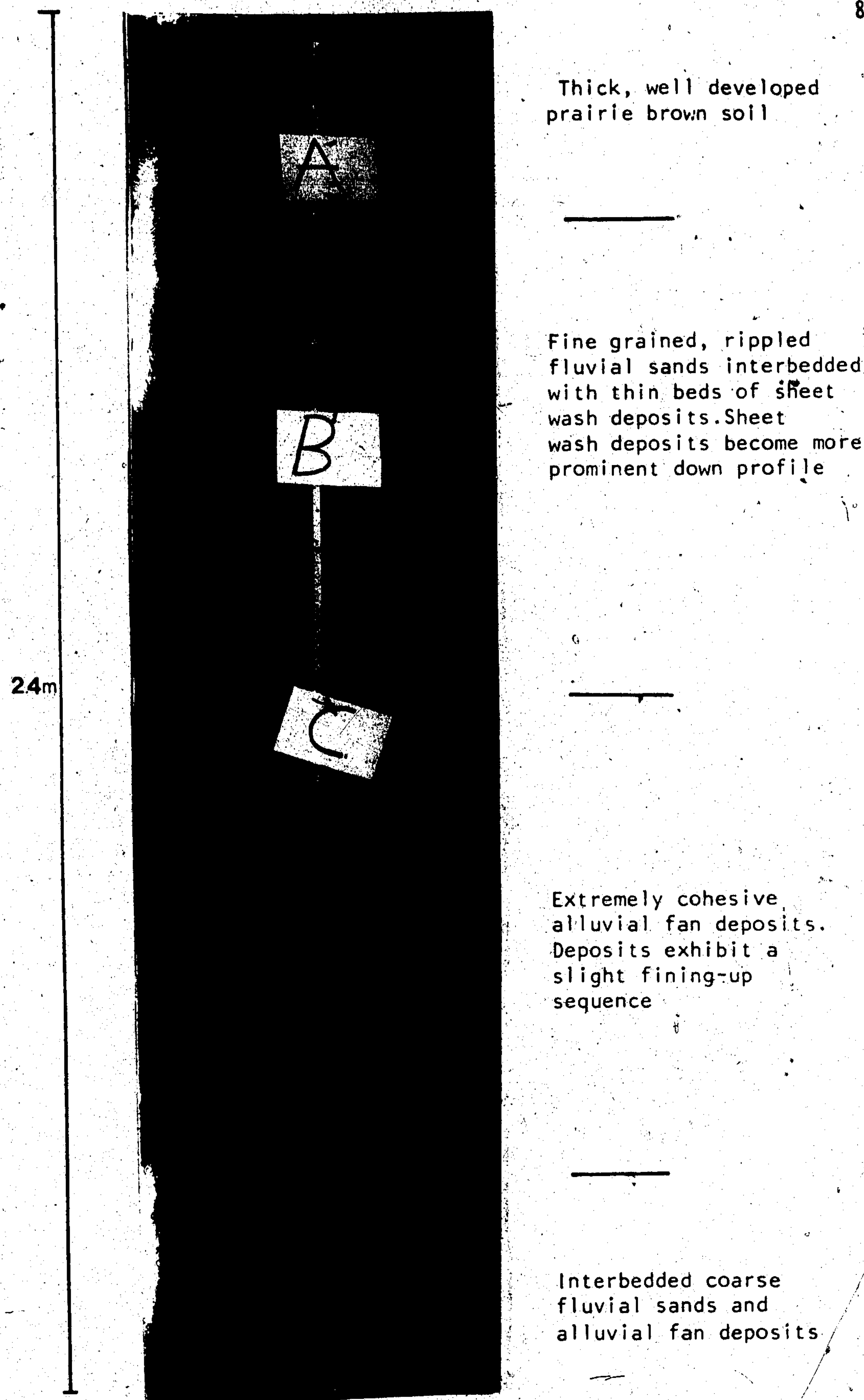


Figure 4.29 The valley fill at location 18a

proximal site) have a silt/clay content of less than 5 per cent, while deposits at location 28, the most distal site, have nearly 75 per cent silt/clay material (Appendix C). Samples taken from the older fluvial deposits (usually found underlying the alluvial fans) were also analyzed. The grain-size distribution shows considerable similarities between all sites with deposits falling in the medium to coarse sand range. The silt/clay content was less than 11 per cent in all the samples and in many cases no greater than 5 per cent. (Appendix B). Nearly all the samples fall in to the light brownish gray to light gray of the Munsell soil colour classification.

Despite the general similarities between these sites, there are quite considerable variations in the mode of deposition. However, these differences are usually due to local influences and too much importance should not be attributed to this situation. This fact is also illustrated at those sites where two pits were entrenched in close proximity to one another, as in the cases of locations 18a, 18b, 24a and 24b. At both sites the two trenches were no more than 20 m apart, yet considerable differences were seen (Appendix A). This clearly demonstrates that variations in the mode of deposition are due to local influences.

Fan deposits are generally found at a similar height in the fill at adjacent sites. At locations 17, 18 and 19, however, deposition was out of phase, with fan deposition occurring later at location 17 than at locations 18 and 19. This is believed to be a result of variations in the amount of sediment input into the valley. All these sites are immediately downstream of the last major tributary to enter the study area (Fig. 3.1). The arroyo is, and probably was, deflected across to the north side of the valley by the tributary, allowing fan deposits to accumulate on the south side. Although sediment has probably been deposited from northern tributary valleys it was insufficient to counteract the effects of sediment input from the south side of the valley. Consequently, while fan deposits accumulated on the south side, fluvial material was deposited on the north. The sediment source area for the southern fan deposits appears to have been very limited and is no longer evident. With the loss of sediment input from the south, deposition from the north was sufficient to force the arroyo southwards across the valley. This allowed fan deposits to accumulate on the north side of the valleys. Eventually the fan deposits at location 18 were overtopped by fluvial deposits. This site is the only one in the valley where this relationship is seen and clearly indicates that local factors can have a significant effect on depositional processes.

Two sections were cut through the middle terrace (found in the lower valley only) at locations 21 and 25. A well developed prairie brown soil 40-50 cm thick covers the sands at both sites. The soil is best developed at these sites and location 18 and this is probably due to the fact that it has developed on unconsolidated fluvial material rather than on the indurated alluvial fan deposits. The fill at both sites is composed entirely of fluvial deposits. Several distinct horizons can be observed in the deposits at location 21 (Fig. 4.30). However, analysis indicates that they all have a similar grain size. Small sedimentary structures are found throughout the fill but are best seen at the base of the section (Fig. 4.31). At the base of the section bedload gravels prevented further excavations.

At location 25, a 1.65 m section was exposed. This was again formed primarily of coarse fluvial deposits. The upper 1.35 m of sands are extensively rippled and cross-bedded and are slightly finer grained than the underlying sands. Throughout the upper part of the fill are thin clays which resemble deposits which form on the surface of scour pools in the present arroyo. It is suggested that these formed under similar conditions in the past. The coarse fluvial sands which are found at about 1.35 m in depth are similar to the sands which underlie the fan deposits elsewhere in the valley and their grain-size distribution suggests that they are a similar deposit. It was not possible to reach bedrock at either of these sites. However, it is possible to estimate that the depth of fill at location 25 is in the order of 3.7 m. This is based on the depth to bedrock at location 26 (not yet discussed) which was trenched immediately in front of this site.

Deposits at locations 26 and 27 (Fig.3.1) consist entirely of fluvial materials 2.2 m thick. This again agrees with the results of seismic profiling in the valley which indicated that the depth of valley fill was between 2 and 2.5 m. Both sites have small inset channel deposits in the upper part of the fill. However, it is not possible to determine whether they pertain to the

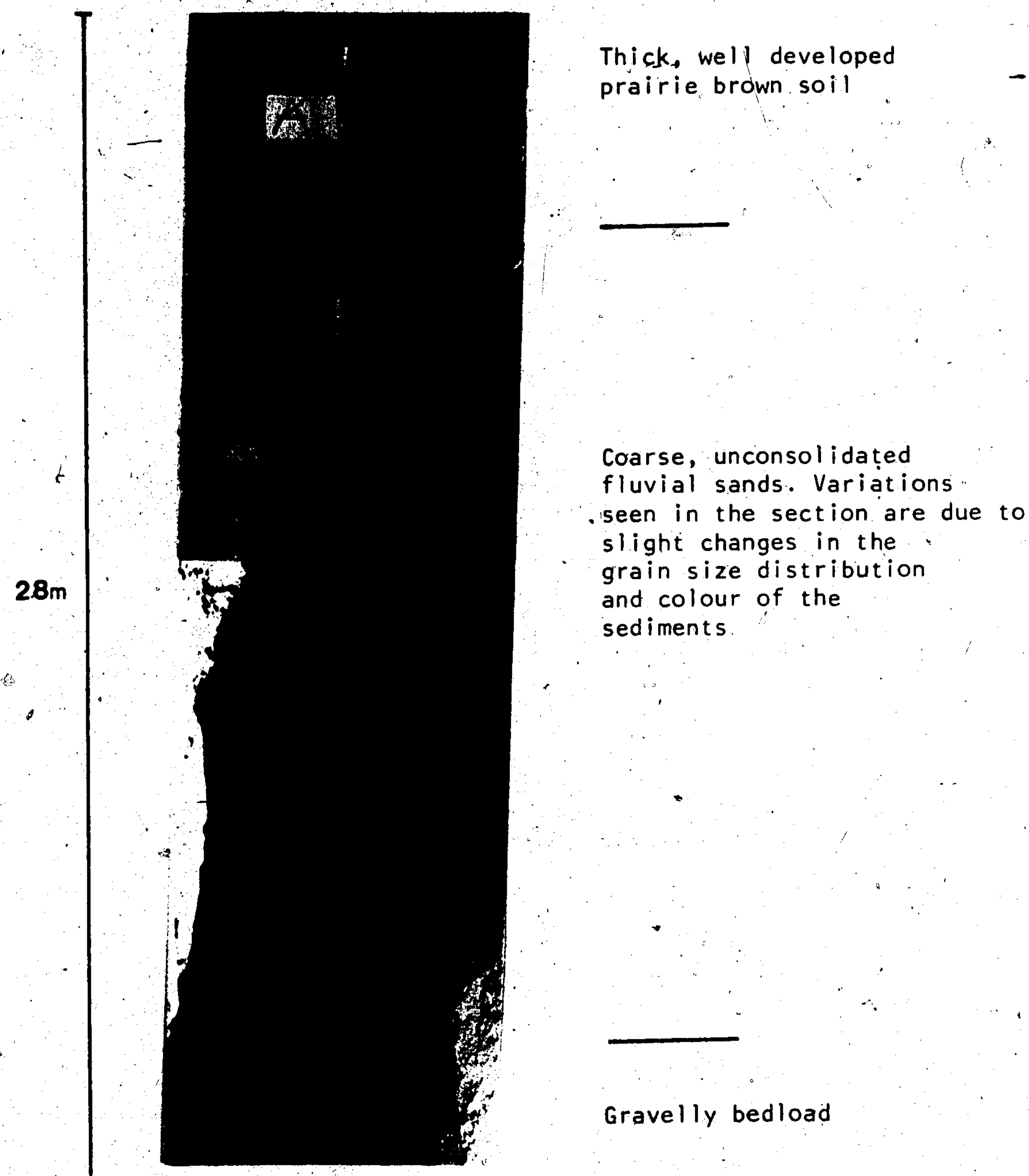


Figure 4.30 The valley fill at location 21

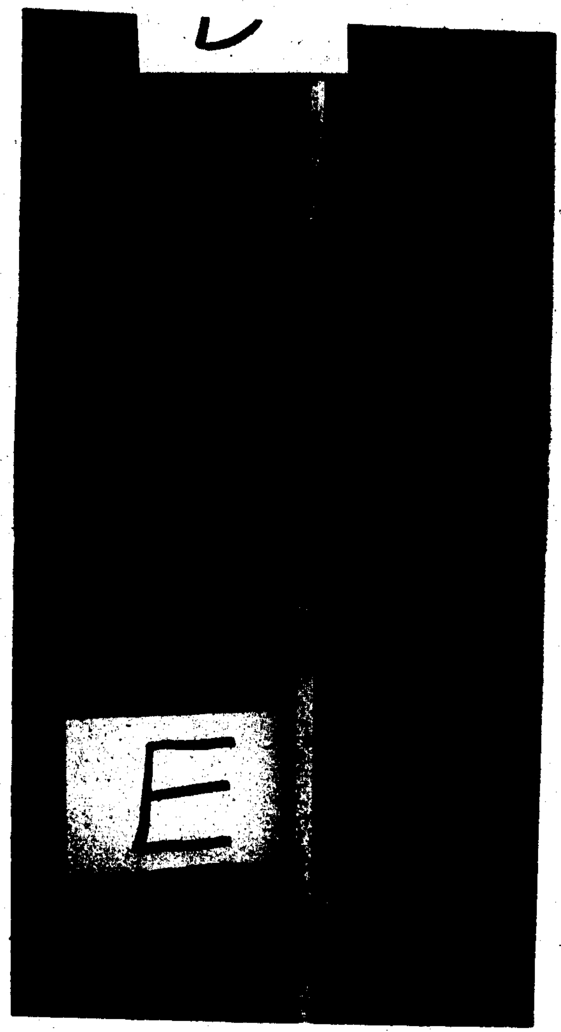


Figure 4.31 Close-up of the sedimentary structures observed at the base of the section at location 21

same period of deposition. The trench at location 26 cuts across an old abandoned meander scar. A channel, about 1.15 m deep, is clearly inset into the main valley fill. The fill material is formed of fine to medium grained sands at the base with silty/clay deposits in the upper part of the fill. The finer material dips gently towards the centre of the channel and was probably deposited under low energy conditions. The entire fill has been covered by a fine grained, poorly indurated deposit which was probably laid down after the meander was abandoned. During periods of high discharge flood waters would spill into the scar and fines would settle out of suspension. Two sections were logged in the trench, one down the front wall and the other down the side wall. The latter exposed the main valley fill which has not been truncated by the channel fill. The sediments are composed entirely of coarse sands with small beds of bedload gravels. Bedload gravels at 1.15 m down the profile are truncated by the channel fill in the front wall of the pit. At the base of the section a thin lag gravel overlies bedrock.

Coarse fluvial deposits are found at location 27, which was entrenched down an old cut-bank. Recent material has formed an inset fill at the upper surface of the pit. The sands forming the main fill are coarse grained with small ironstone clasts throughout. At the top of the section 30 cm of fine fluvial sands overlie coarse sands which are nearly 1.7 m thick. Small sedimentary structures are seen within the sands and are similar to those found elsewhere in the valley. At the base of the section a thick lag deposit of ironstone gravels overlies bedrock.

At location 20 a pit was trenched through one of the recent fan deposits. Like older fan forms the fan material is extremely cohesive below the immediate surface and a jack-hammer was required for digging (Fig. 1.8). The upper surface is covered by bedded fine grained material approximately 30 cm thick the main fan deposit; below this are fine grained sands interbedded with thin alluvial fan deposits. At about 110 cm depth are poorly sorted bedload gravels and coarse fluvial sands. The presence of thin fan deposits in the upper sands indicates that deposition from the side valley was active during the last period of valley filling. It is suggested that, with rare exceptions, these will not be preserved because of removal during storm events. Only when the valley is deeply incised will these beds be preserved and an alluvial

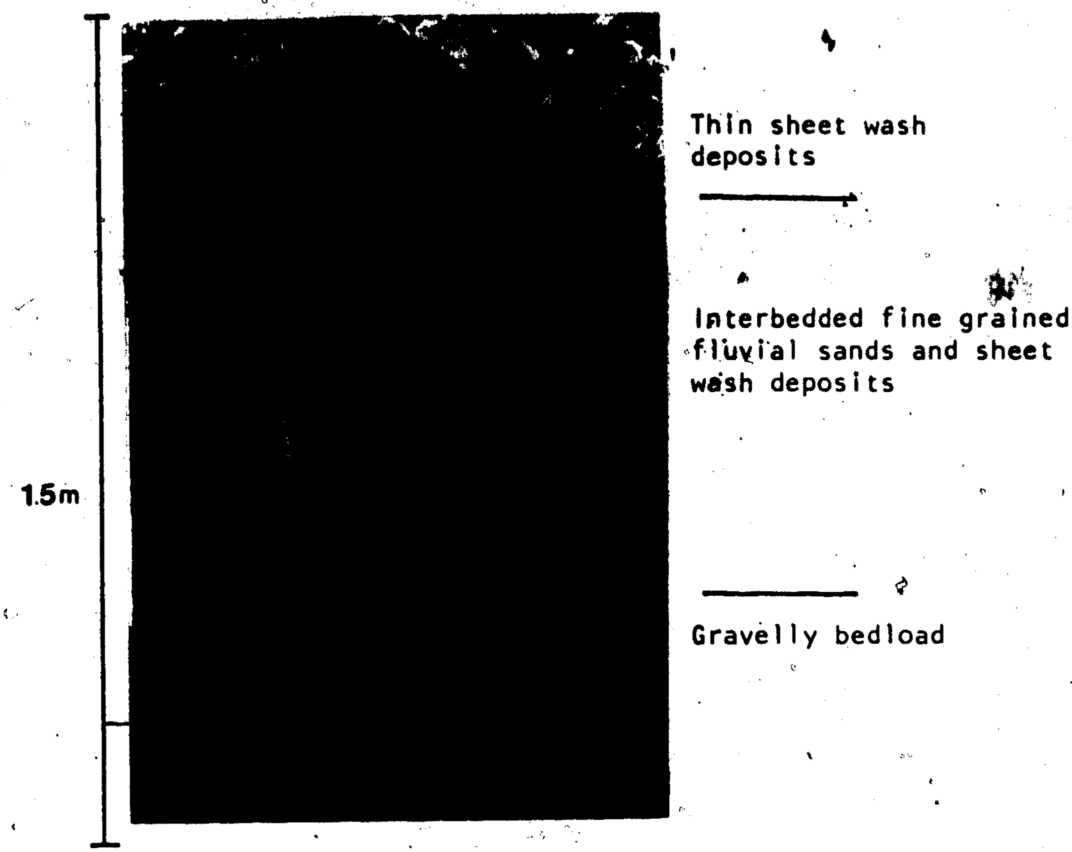


Figure 4.32 The valley fill at location 20

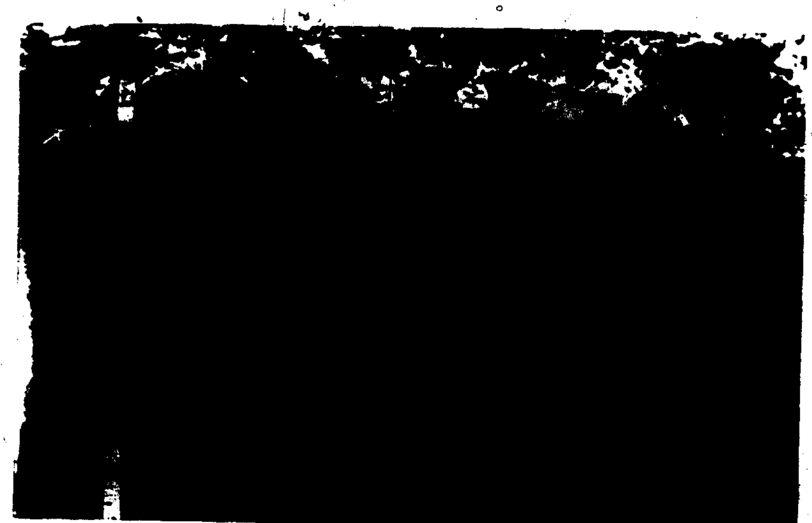


Figure 4.33 Close-up of the recent fan deposits in the upper part of the fill at location 20

fan formed. This suggests that fan accumulation at this location has occurred since the most recent period of valley entrenchment.

4.6 The valley fill

On the basis of the logged sections, seismic profiles and valley morphology, The valley [illegible]n be divided into fl[illegible]and alluvial fan deposits. In Figure 4.34, 24 of the logged sections are shown at the[illegible]ghts and positions in the main valley. This provides further information for reconstructing the alluvial chronology

The bedrock profile of the valley can be inferred from the seismic profiles (Fig. 3.14). The results of the survey were verified to some extent by the logged sections which indicated whether seismically determined depths to bedrock were correct. The depth of fill in the upper valley is about 3 m while in the lower valley it is from about 2-2.5 m. The longitudinal bedrock profile can be estimated from this and it descends from 639.5 m to 629 m with a gradient of 0.33°(Fig. 4.35). At the mouth of the valley the profile appears to be somewhat over-steepened. This may be an attempt by the system to attain grade with the Red Deer River.

Overlying bedrock are poorly consolidated fluvial deposits. These generally consist of bedload gravels and sands which exhibit a fining up sequence (Appendix A). The gravels are formed predominantly of ironstone, though occasional erratics are found. There does not appear to be a trend towards a greater thickness of gravels at any particular part of the valley. Analysis of these sediments shows that they have a similar grain-size (Appendix B), colour, and texture which suggests they are the same deposit. The fluvial deposits accumulated to approximately 1 m in the upper valley (to 640.5 m a.s.l.) and 4-5 m in the lower valley (to 634.5 m a.s.l). The considerable variation in the thickness of the deposits may be due to a number of factors. Firstly, the last major tributary to enter the study area drains a consi[illegible]able area and will have contributed a large amount of sediment to the lower valley. This may have been too great for the system to transport causing deposition. Secondly, the main valley enters the Red Deer River at an almost 90° angle, which will have considerably reduced the velocity of

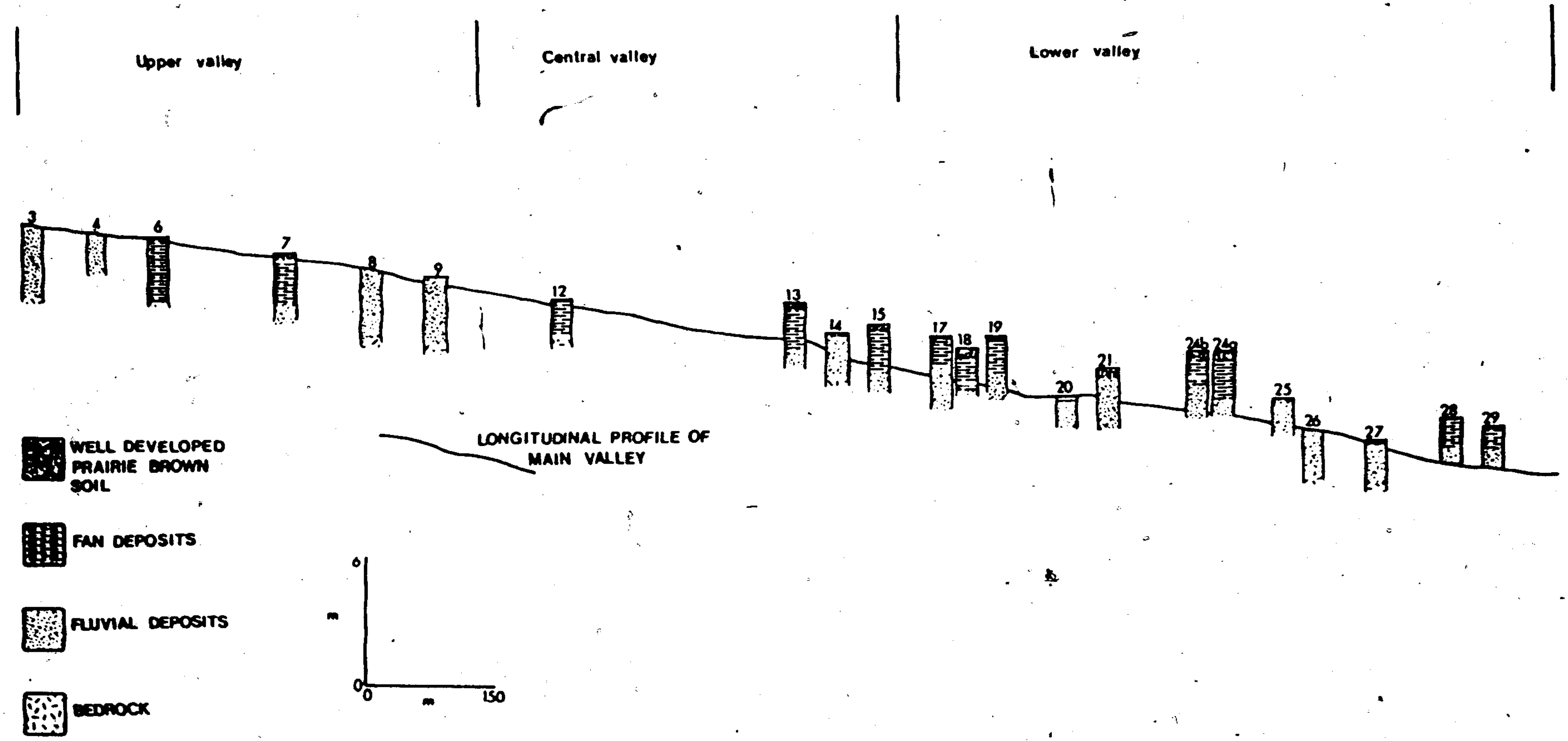


Figure 4.34 The logged sections shown in their relative heights and positions in the study area

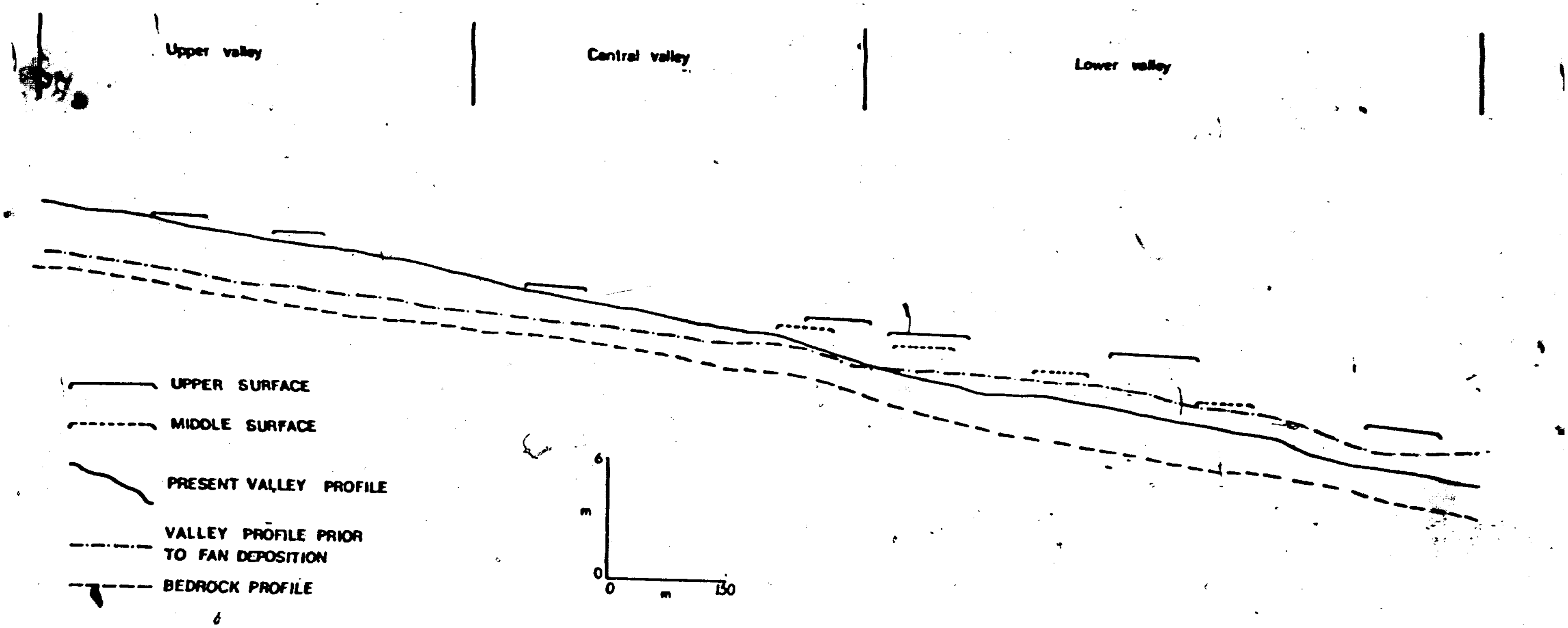


Figure 4.35 The present and past profiles of the main valley

flow through the valley, resulting in deposition. The accumulation of thick deposits in the lower valley indicates that the valley was grading to a higher level than previously. The fluvial deposits are directly overlain by alluvial fans. A distinct boundary between the two depositional types can be observed in the valley fill. From this it was possible to determined that the valley slope prior to fan deposition was approximately 0.20° (Table 3.1 and Fig. 4.35) which is considerably less than at present. It is not possible, however, to determine for how long fluvial deposits accumulated.

Overlying the fluvial deposits are fine grained, cohesive alluvial fan deposits. These deposits vary in thickness but in general are thickest in the upper valley (Fig. 4.34). This may be due to a number of factors. Firstly, the profile of the valley prior to fan deposition was very gentle compared to the present valley profile (Fig. 4.35), with the height of the fill, lower compared to the present, in the upper valley and higher in the lower valley (Fig. 4.34). As the main valley acts as the local baselevel control for the side valleys there would be a greater tendency for side valley incision in the upper reaches of the study area compared to the lower valley. Furthermore, because the valley is much narrower in the upper valley material deposited from the side valleys tends to build upwards rather than spread out over the valley floor, as seen in the lower valley.

The fan deposits have been truncated and now form the upper surface which is found throughout the study area. Establishing the height of the remnants by surveying allows som estimate of the valley profile after deposition of the fans. The upper surface ranges from 643 to 634 m to give an average gradient of 0.27°. This is considerably less than the present valley gradient (Table 3.1). As the fans are covered by loess it indicates that fan deposition had ceased at or before the time of input at 5 400+/- 800 B.P. The nature of this episode of incision is difficult to determine as a surface 1 m below the upper surface is present in the lower valley (possible reasons for this will be discussed in Chapter 6). The depth of incision, however, can be determined at a number of sites, especially at those where older materials underlie recent deposits; for example at location 17. The depth of incision is believed to be in the order of 3 to

4 m. As loess covers the upper and middle surface it indicates that incision took place before 5 400 B.P.

A further period of deposition occurred. The date of its onset is not known, but based on a date from a cottonwood log 0.6 m below the top of the fill it is possible to conclude that aggradation was still active about 300 B.P. The deposits laid down are fluvial although considerably finer grained than earlier fluvial deposits. Deposition appears to have been greater in the upper valley with up to 2 m of fine sands and sheet wash surfaces being observed here. Elsewhere the infill appears to be more in the order of 0.6-1.0 m. Overlying this surface are small, recent alluvial fans. The fill at location 20 suggests that deposition of thin, extremely fine grained alluvial fan deposits occurred during the last period of valley infill. This, together with the fine grained nature of the fluvial sediments, suggests that deposition was during less humid conditions than earlier episodes of fluvial deposition and that there were periods of little flow in the valley when thin fan deposits could build up. It was not until the most recent period of valley incision that greater thicknesses of fan material could accumulate. Recent incision has occurred since about 300 B.P. and will be discussed in greater detail in Chapter 5.

From the valley fill and morphology at least three episodes of incision and two periods of valley infilling can be documented:

1. Incision of the bedrock valley.
2. Valley infilling with deposition of coarse fluvial sands and then widespread alluvial fan build-up.
3. Re-incision of the valley fill and the formation of a high terrace (the middle terrace in the lower valley may have been formed during this erosional episode) 30-250 cm above the present valley floor.
4. Valley infilling with fine grained fluvial deposits.
5. Renewed incision in the last 100-300 years.

5. RECENT CHANGES IN THE STUDY AREA

5.1 Introduction

Aerial photographs of Dinosaur Provincial Park are available from 1938 and provide a 46 year record of events within the study area. These document a complex history of changes in the extent and configuration of the arroyo channel during this time. The poor quality of early photographs, as well as shadows on many of them, made it difficult to determine the depth of incision. However, a close relationship between vegetation and arroyo incision was observed and provided some means of determining whether a channel was present.

In the American southwest valley entrenchment usually causes a dramatic reduction in the vegetation cover due to lowering of the water table. In the Dinosaur badlands the reverse is seen. In the upper tributary a poorly braided channel traverses the valley and during major storm events the valley floor is flooded. This causes constant erosion and reworking of sediment and it is difficult for vegetation to get established. When the valley floor is incised storm runoff is channelled into the gully and does not flow over the entire valley floor, thus allowing vegetation to grow. Furthermore, as the depth of incision in the study area is no greater than 1-2 m (considerably less than that recorded in much of the American southwest) the water table is not lowered substantially during incision and conditions are more favourable for vegetation growth. Consequently during periods of arroyo incision vegetation flourishes on the valley floor.

There are several classifications used to describe stream forms and morphologies. The most suitable for this study is that outlined by Schumm (1967), who categorized streams on the basis of their degree of sinuosity, (Fig. 5.1) and Brice (1974) who defined meanders based on their form. In Schumm's (1967) classification channels range from tortuous to straight with those that have a sinuosity greater than 1.5 being termed meandering.

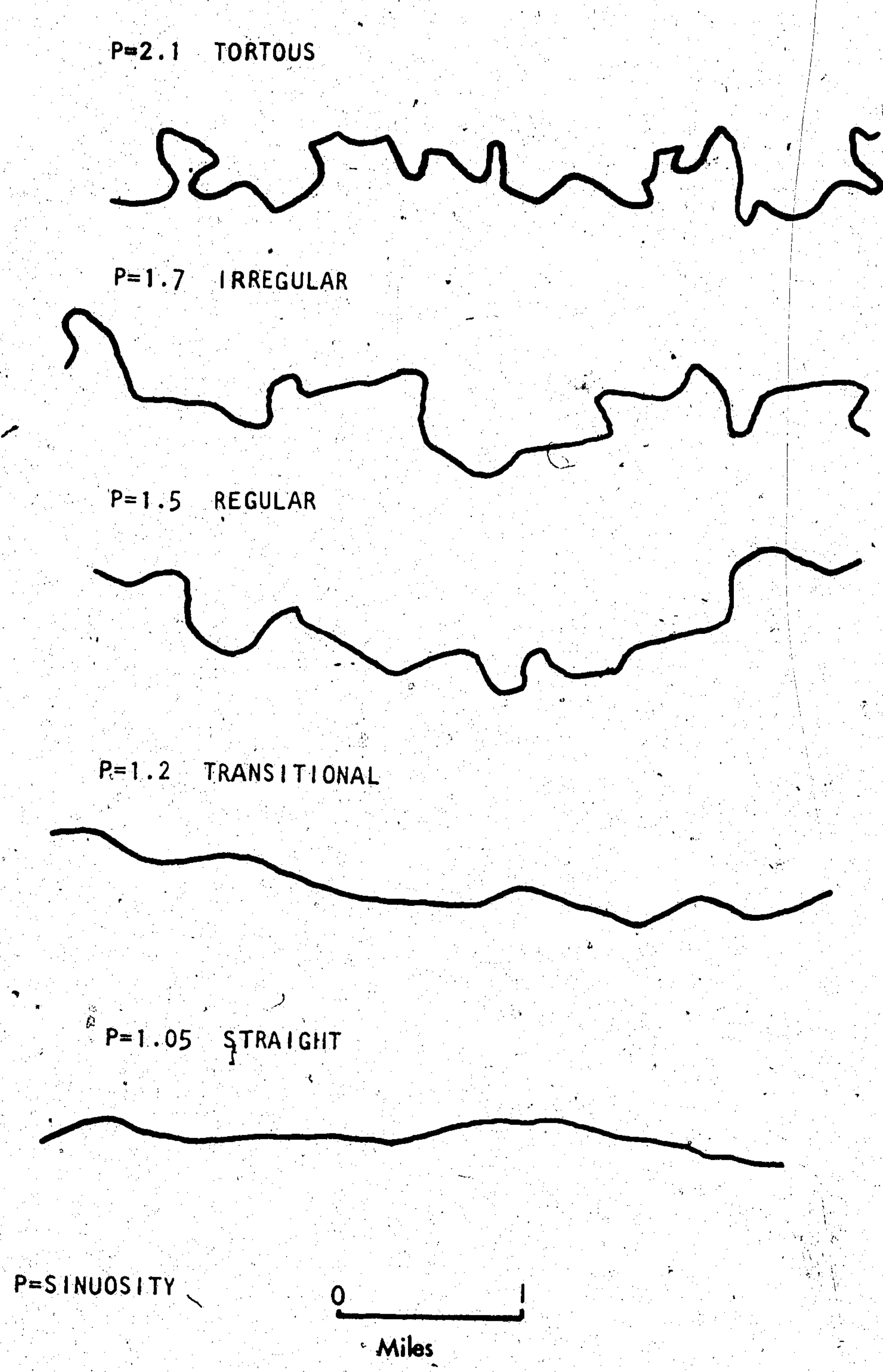


Figure 5.1 Classification of alluvial stream patterns (modified from Schumm, 1963)

5.2 The arroyo form:1938

Arroyo incision is apparent throughout the entire study area in 1938 (Figs. 5.2 and 5.3). The arroyo is highly contorted with a sinuosity of 1.87 and would be termed irregular to tortuous by Schumm's (1967) classification. A variety of meander forms are observed ranging from simple symmetrical, simple asymmetrical to compound asymmetrical (using Brice's (1974) classification of meander morphology). There is a general increase in meander size down valley which is probably due to the less restricted nature of the valley and the greater slope angle. Meander amplitudes up to 100 m and wavelengths up to 200 m are measured and in general the ratio of meander amplitude to wavelength is 1:2. The vortex of the meanders in most cases points downstream. Vegetation is observed in the lower valley and at the boundary of the upper and central valley but is scant elsewhere (Fig. 5.3). The aerial photographs indicate that the depth of arroyo incision is greatest at those locations where the vegetation cover is most dense. At other sites the arroyo is less distinct (Fig. 5.3), and suggests that some aggradation is occurring and that the arroyo does not have a continuous form.

5.3 The arroyo form:1950

No well-defined channel can be identified from the 1950 air photographs (Figs. 5.2 and 5.4), indicating that a period of arroyo filling occurred between 1938 and 1950. Only in those localities where a well-defined channel was observed on the 1938 air photographs can a faint channel scar be seen (Fig. 5.4) on the 1950 photographs. In the lower 300 to 400 m of the main valley a wide sandy (?) channel can be observed. However, it is not possible to determine the depth of incision. Vegetation is sparse and only small clumps of sage are observed in the lower valley. This suggests that there is no significant incision and discharge is washing and depositing sediment over the entire valley floor.

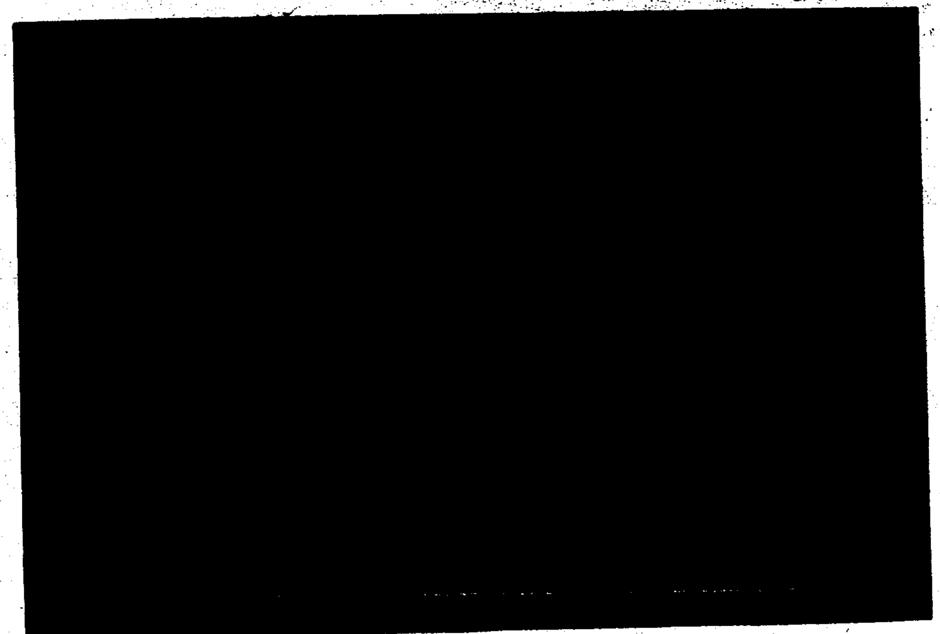


Figure 5.2 Variations in the arroyo form between 1938 and 1984

Figure 5.3 Aerial photograph of the study area: 1938 (scale 1:10 000). Note, the whole valley is incised, although the channel is not as well defined in the central valley (A), where there is little vegetation cover.

Figure 5.4 Aerial photograph of the study area: 1950 (scale 1:10 000). With the exception of the lower valley (A) no defined channel can be observed. Vegetation is scant, which suggests that runoff is washing over the entire valley floor

5.4 The arroyo form: 1961

A period of renewed incision occurred after 1950 and a well-defined channel is apparent throughout much of the valley on the 1961 air photographs (Figs. 5.2 and 5.5). The entrenchment is clear in the lower and most of the central valley and a distinct knickpoint occurred at the head of the incision (Fig. 5.5). Upstream of the knickpoint the channel was less defined (Fig. 5.5). The arroyo follows a similar path to that of 1938, but changes in the meander form are noted with a slight reduction in the amplitude and a corresponding increase in meander wavelength at several locations. Only one major change in the arroyo form is noted as a result of meander cut-off. In 1938 several highly irregular meander forms entrenched the lower valley, and the largest of these was not re-activated during re-incision. On the 1950 photographs it appears that the meander had already been cut off and discharge had been along a relatively straight path which suggests that channel abandonment occurred prior to 1950. A slight reduction in the sinuosity of the arroyo is apparent because of this and other factors. Meanders are either simple asymmetrical or compound asymmetrical, the latter being found in the central and lower valley only. Vegetation on the valley floor is restricted to areas below the arroyo knickpoint.

5.5 The arroyo form: 1969

Major changes in the arroyo configuration occurred as a result of meander cut-off between 1961 and 1969. This resulted in a considerable decrease in channel sinuosity to 1.3. (Figs. 5.2 and 5.6) and the channel would be described as transitional using Schumm's (1967) classification. The amplitude of all meander forms was considerably reduced and this is particularly noticeable for a series of meanders at location A (Fig. 5.7). These have been reduced in amplitude from approximately 80 m to 35 m. There was little increase in meander wavelength, however, and the ratio of meander wavelength to amplitude is 1:4. Meanders have generally reached a simple asymmetrical form (Fig. 5.2). Upstream migration of the knickpoint has occurred at an average rate of 50 m per annum (Fig. 5.8) with over 410 m of incision since

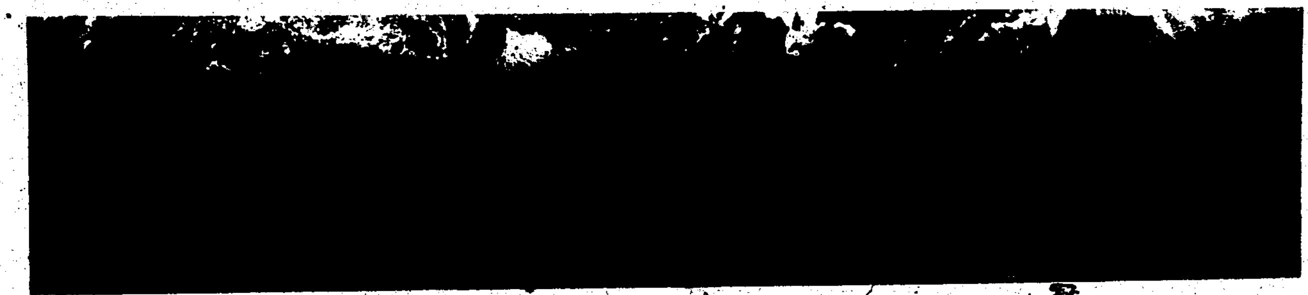


Figure 5.5 Aerial photograph of the study area:1961 (scale 1:10 000). Renewed incision of the study valley has taken place. A distinct knickpoint can be observed at A. Vegetation is well established below this point.

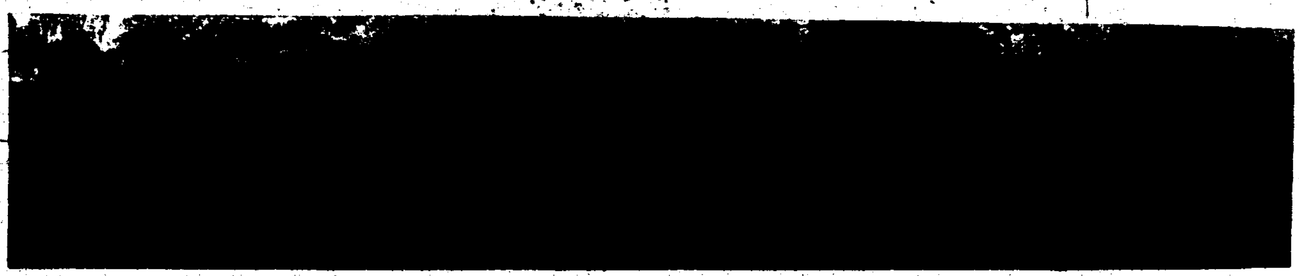


Figure 5.6 Aerial photograph of the study area:1969 (scale 1:10 000). Further knickpoint incision has occurred (A). Note cut off of meanders at B and C which has taken place since 1961

1961 to give an average rate of approximately 50 m per annum. Above the knickpoint a less defined channel is observed and approximately 100 m above the knickpoint the channel loses its definition and the system becomes braided (Fig. 5.6). Braiding continues into the upper reaches of the upper and southern tributaries where a more defined channel is observed and clearly indicates that the arroyo has a discontinuous form at this time.

5.6 The arroyo form:1977

There is little change in the arroyo between 1969 and 1977 although some slight modification of the meanders has occurred (Figs. 5.2 and 5.9), and channel sinuosity is lowest at this point. Knickpoint migration between 1969 and 1977 was at an average rate of 35 m per annum (Fig. 5.8) which is slightly less than in the period 1961 to 1969. This suggests that there was less activity in the valley during this period. The channels which incised the upper and southern tributaries in 1969 have infilled and only a poorly defined channel scar is seen. Vegetation is rapidly colonizing those areas that have been recently incised (Fig. 5.9).

5.7 The arroyo form:1984

An increase in channel sinuosity to 1.38 occurred between 1977 and 1984. This is mainly the result of meander growth, particularly in the lower valley, and the increased complexity of a number of meander forms (Figs. 5.2 and 5.10). The basic form of the channel has remained similar to that of 1977, but extensive knickpoint migration has occurred during this time with over 480 m of incision since 1977. This gives an average rate of upstream migration of nearly 80 m per annum which is considerably greater than that recorded in the previous 8 years. This would probably increase the sediment load transported by the arroyo at this time, with concomitant changes in the arroyo form. Vegetation is found throughout the valley except in those areas not incised or those that have been recently incised.

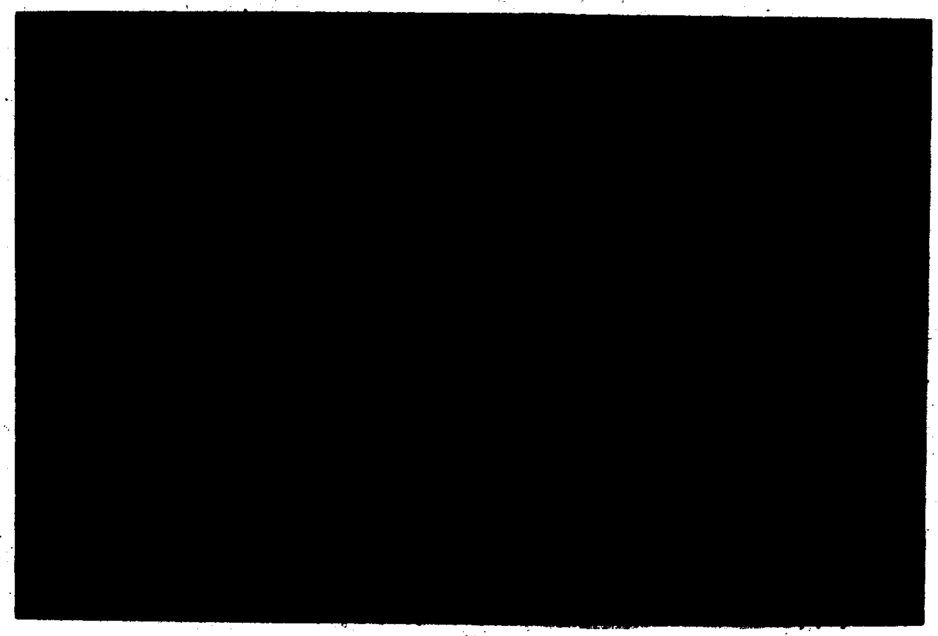


Figure 5.7 Overlay of the arroyo channel for the years discussed

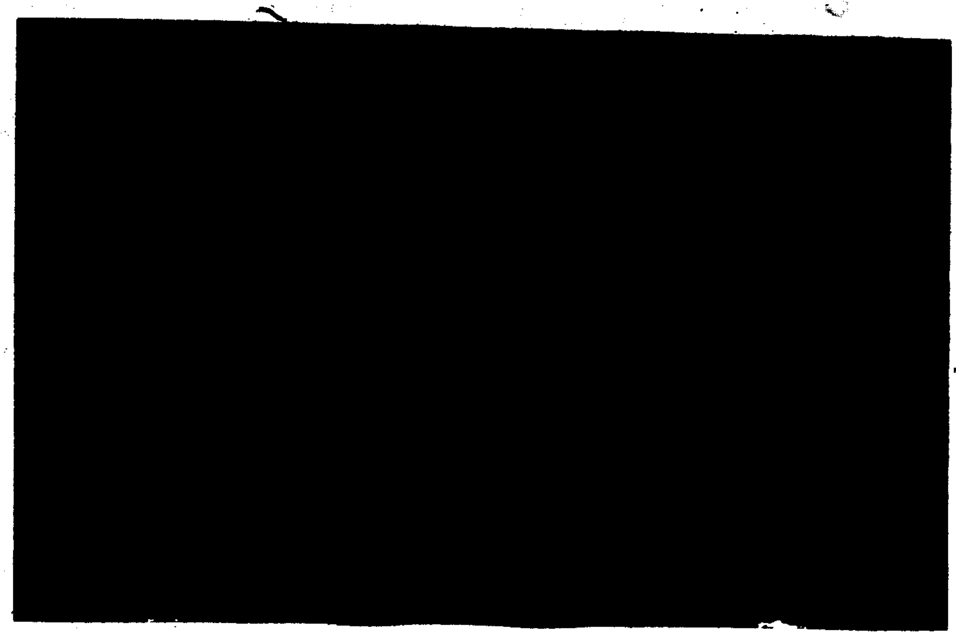


Figure 5.8 Migration of the arroyo knickpoint between 1961 and 1984

Figure 5.9 Aerial photograph of the study area: 1977 (scale 1:10 000). Continued migration of the knickpoint to (A). Vegetation on the valley floor is well established

Figure 5.10 Aerial photograph of the study area: 1984 (scale 1:10 000). The entire study area is now incised by the arroyo.

5.8 Changes in the arroyo between 1938 and 1984

In Figure 5.7 the arroyo is shown in its relative position in the valley for each of the years discussed. This clearly depicts those areas where major changes in the arroyo have occurred. The overall form of the channel has remained stable and many of the slight differences in the channel position shown in Figure 5.7 probably reflect distortions when the aerial photographs were enlarged and problems in picking out the main channel thalweg on some photographs. Nevertheless, between 1938 and 1977 there was a considerable reduction in meander amplitude with, in some instances, a corresponding increase in meander wavelength. This resulted in a decrease in sinuosity from 1.87 to 1.26 during this period . This is mainly due to meander cut-off (see B,C,and D, Fig. 5.7) and in other cases both meander cut-off and channel migration are responsible (see A, Fig. 5.7). While all the meanders have changed their form they have tended to maintain their position in the valley and no downstreamn migration has occurred (Fig. 5.7). A slight increase in the amplitude of a number of meanders occurred between 1977 and 1984 (Fig. 5.7) with a corresponding increase in channel sinuosity from 1.26 to 1.38. As discussed, this may be due to changes in the sediment load carried by the arroyo. This would be a result of increased sediment input as the arroyo migrated upstream and tributaries were rejuvenated. However, a number of other factors could be the cause of changes in the arroyo form.

The cause of changes in the size and form of meanders has been extensively discussed (e.g. Leopold and Wolman, 1957; Dury, 1964). The first person to suggest that there was a relationship between meander dimensions and hydraulic variables was Jefferson (1902). He concluded that the width of the meander belt was a function of stream width and that the greatest amount of erosion was achieved in periods of flood. Subsequent studies have developed and improved upon this model. Inglis (1949) found that meander dimensions generally seemed dependent on the square root of discharge. This was reiterated by Leopold *et al.* (1964) and Dury (1964).

Year	Sinuosity	Channel extent
1938	1.87	A well defined channel is apparent throughout the study area.
1950	N/A	Arroyo infilling has occurred since 1938 and no clearly defined channel can be observed.
1961.	1.56	Reincision of the valley has occurred since 1950 and a well defined channel is apparent in the central and lower valley.
1969	1.30	Meander cut-off in several parts of the study valley has resulted in a marked decrease in channel sinuosity. The arroyo has migrated up valley with 410 m of knickpoint migration since 1961.
1977	1.26	Channel sinuosity is at the lowest recorded in the study valley. Knickpoint migration has increased the channel length by 280 m.
1984.	1.38	The entire valley has been incised by the arroyo with 480 m of knickpoint migration since 1977. A slight increase in channel sinuosity has occurred as a result of meander growth in the lower valley.

Table 5.1 Changes in the extent and sinuosity of the arroyo channel between 1938 and 1984

Laboratory experiments by Leopold and Wolman (1957) concluded that there was a strong relationship between meander width and discharge, the width controlling wavelength. Later investigation by Carlstone (1965) showed that the dominant discharges in the modification of meander wavelength were those ranging between the highest monthly discharge for a given river and the mean annual discharge. Other studies (e.g. Friedkin, 1945) have shown that while meander wavelength increases with increased discharge there is also a relationship between meander wavelength and slope. The greater the slope angle the greater the meander wavelength.

The effect of sediment on meander forms has been discussed by Schumm (1967, 1977). He concluded that those rivers which transported a high percentage of their total sediment load as sand and gravel had a greater meander wavelength than those that had a high silt/clay per cent. This relationship has also been shown in laboratory experiments (Khan, 1971), with high percentages of coarse bedload material. With an increase in channel width and gradient meander width increases and depth decreases. With the addition of kaolinite up to a concentration of 3 per cent, and a reduction in the coarse material, there was an increase in sinuosity and the channel became narrower and deeper.

All of these studies have been carried out with respect to perennial rivers. Difficulties in the study of ephemeral rivers have led to their being neglected and only one study pertaining to arroyo meandering is found in the literature (Leighly, 1936). This study was a little more than a description of the meander forms recognized in arroyos of New Mexico. Leighly (1936), however, did conclude that there would be considerable changes in the form of the arroyo in the early stages of arroyo incision, because of rapid changes in sediment load carried. Furthermore, he noted that meander patterns in arroyo channels tended to have an irregular form.

Variations in the meander form could be due to changes in slope, discharge, and sediment input or a combination of these parameters. The channel sinuosity is greatest in the lower valley where the valley slope is steepest, which suggests that there is a relationship between the two factors.

A strong relationship between discharge and sediment input into the valley and arroyo form has been noted (see Chapter 3). At those points where major tributaries enter the study area the arroyo is deflected across the valley (Fig. 3.1). Similarly, alluvial fan deposition into the valley has been shown to influence the arroyo position, particularly in the past when large fans were deposited. Present fan deposition in the valley is limited to small fans which overlie the valley floor (Fig. 3.1). Despite their small size these fans do affect the position of the arroyo as can be clearly observed from the air photographs. From these it can be seen that periods of active alluviation have not been continual nor has deposition been synchronous throughout the valley. In 1938 a series of meanders were observed at location A (Fig. 5.7). By 1961, when renewed incision had taken place in the valley, the meanders showed some signs of migration and cut-off. This occurred in the downstream meander first and by 1969 the remaining forms had been considerably reduced in size. Sediment input, particularly from gullied alluvial fans, is evident from a number of localities on the north side of the valley. This has pushed the arroyo channel to the south side of the valley. Although there has been a recent increase in vegetation, sediment input is presently being maintained and is probably preventing the stream from returning to it southern position. In 1938 (Fig. 5.3) sediment input from the south side of the valley occurred at location C (Fig. 5.7) and a well-defined meander can be observed cutting across the valley and representing a very complex meander form (Fig. 5.3). Fan deposition was from a small side valley. By 1961 fan deposition was not as active and the meander had been abandoned. A slight increase in the amplitude of the meander is recorded between 1977 and 1984 with a corresponding increase in fan activity at this site.

While the relationship between specific locations of sediment input and meander form generally appears to be very important, at some sites there appears to be no such relationship and meander cut-off has occurred despite the lack of sediment input. Between 1961 and 196? two meander forms were abandoned. Leighly (1936) concluded that shortly after incision there would be a dramatic change in the arroyo form and meander abandonment would occur as a result of an increase in the sediment load of the channel. He concluded that this increase in sediment load would occur because of vegetation loss. In the Dinosaur badlands vegetation cover increases when incision occurs and consequently sediment yield during runoff would be reduced. However, an increase in sediment load would take place by valley incision and the incision of tributary valleys which would have a considerable effect on the arroyo form and possible result in meander cut-off.

A second factor that is of considerable importance in the valley is the effect of local bedrock controls. As discussed, the valley is very narrow and this restricts movement and migration of channels in the valley. This is demonstrated at the junction of the upper and central valley where the arroyo is deflected 90° north then 90° south by local bedrock outcrops. Down valley this influence is also noted and many of the meander forms are due to deflection at these points of more resistant character.

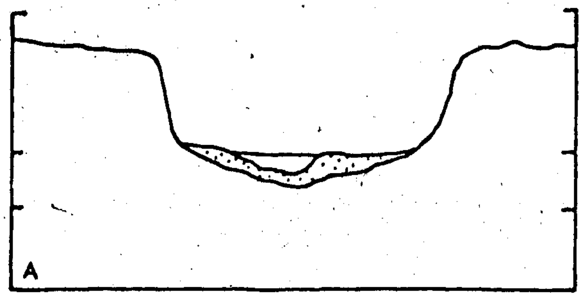
5.9 The recent arroyo history

The date of arroyo incision is not known. However, deposition was active in the valley until at least 315+/-65 B.P. based on a date from a cottonwood log buried 1 m below the lower surface, upstream of location 3 (Fig. 4.6). The dynamic nature of the valley is clearly demonstrated by the air photographs with a period of infilling and two periods of valley incision being documented. This indicates that periods of valley incision are multiple events in the study area, a finding which is duplicated by other studies which have investigated periods of recent incision in alluvial filled valleys (e.g. Born and Ritter,1970; Womack and Schumm, 1977). Schumm (1973) termed this complex response. This relationship was reported by Schumm and Parker (1973) who described the effect of baselevel lowering on valley incision in laboratory experiments They noted that after the baselevel was lowered incision of the valley occurred leaving the valley floor as a terrace (Fig. 5.11a). Erosion and channel adjustment to the increased gradient began at the mouth of the valley and moved progressively upstream eroding previously deposited alluvium (Fig. 5.11b). As the channel incised further upstream rejuvenation of tributaries occurred with a subsequent increase in sediment transport by the main channel. Ultimately aggradation takes place in the newly incised channel (Fig. 5.11c) As the tributary adjusts to the new baselevel sediment availability drops and renewed incision occurs forming a lower terrace surface (Fig. 5.11d). The decrease in sediment load is punctuated by a number of small pulses (Parker, 1976). The second stage of incision is a result of decreased sediment load and the shift from a braided to a more defined channel of low width depth ratio and higher erosive capabilities (Schumm, 1979).

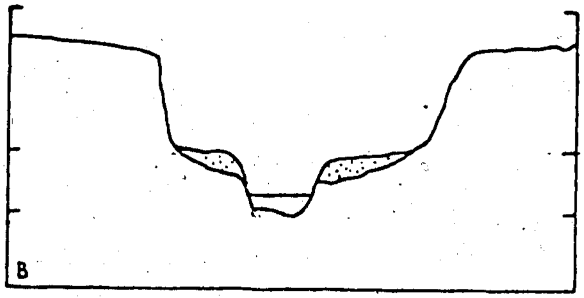
Evidence of episodic erosion in the field has been cited by Womack and Schumm (1977). They described the development of a series of unpaired and discontinuous terraces in Douglas Creek, Colorado. These formed in a major period of arroyo cutting which postdates European settlement in the area at about 1900 A.D. Entrenchment was both rapid and episodic with numerous erosional and depositional events observed. Traditionally, each of these events would be attributed to changes in external factors. However, Womack and Schumm (1977) concluded that the discontinuous and unpaired nature of the terrace would argue against this. They concluded that this was an example of episodic erosion in response to an initial period of entrenchment in the early 1900's as a result of overgrazing in the valley since the 1880's. Large quantities of sediment entered Douglas Creek from tributaries as they were rejuvenated. This would periodically overwhelm the system and aggradation would occur. Eventually oversteepening of these deposits would trigger local erosion. Similar findings were also reported by Born and Ritter (1970) who mapped 6 major flights of terraces which had formed in the lower Truckee River in response to a single drop in baselevel of Pyramid Lake, Nevada.

It is not possible to determine the cause of the recent episode of erosion in the Dinosaur badlands. Field surveying, however, indicates that the current valley gradient is higher than any that can be measured for the past valley configurations. As there have been no major climatic changes or decreases in baselevel it is believed that a gradual increase in the valley gradient by sediment accumulation resulted in the crossing of a threshold and incision.

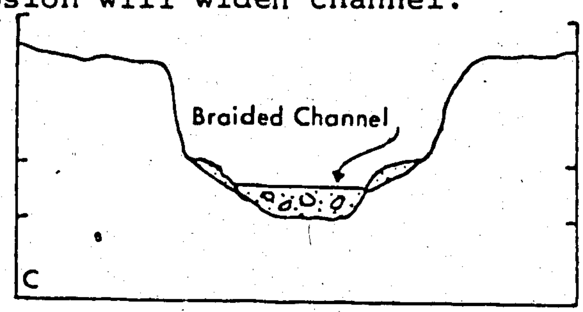
The cause of valley filling between 1938 and 1950 is also unknown. It is possible that aggradation as a result of increased sediment input into the valley by the rejuvenation of



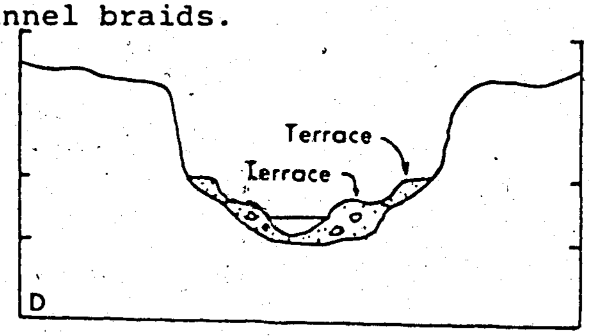
A. Valley before base level lowering.



B. After base level lowering, channel incision forms bedrock terrace. Erosion will widen channel.



C. As sediment yields increase an alluvial fill is deposited and the channel braids.



D. As sediment yields decrease the channel incises into the recently deposited alluvium forming a low alluvial terrace.

Figure 5.11 Idealized diagram of complex response in an alluvial filled valley (modified from Schumm and Parker, 1973) tributary valleys overwhelmed the system and caused aggradation to occur. The air photographs do suggest that aggradation was already taking place in the valley in 1938 and that the arroyo had infilled by 1950.

The most recent period of incision began after 1950. The rate of knickpoint migration is variable between the time periods studied. Incision may have been in response to an increase in sediment input with a gradual increase in valley gradient, similar to that seen by Womack and Schumm (1979) in Douglas Creek, Colorado. This resulted in local oversteepening and the exceedence of a threshold. A second possible cause is suggested. The air photographs show that there has been considerable lateral migration in the Red Deer River since 1938 (Fig. 5.12). This shift has been towards the valley thereby reducing its overall length. This reduction has been in the order of 70 m and occurred between 1938 and 1961 during the period of renewed incision. This shift caused a change in the valley gradient from 0.36° to 0.38° over a very short period and would be equal to a drop in baselevel of about 60 cm. Although this may not seem very significant, if the valley was in a very unstable position slight changes such as this could be sufficient to reactivate arroyo incision. At other times when the valley was more stable this would probably have no effect on the valley.

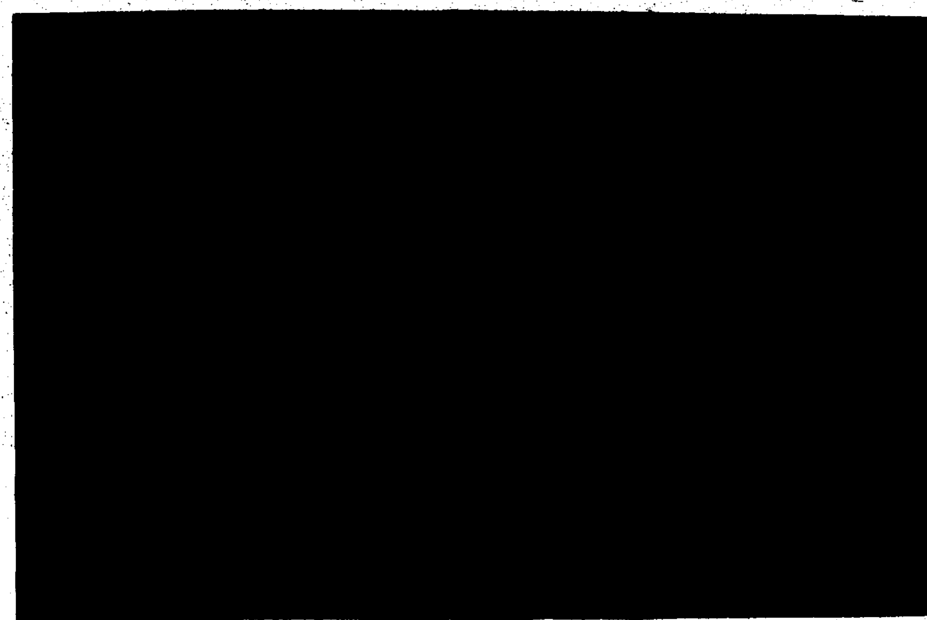


Figure 5.12 Lateral shifting in the Red Deer River between 1938 and 1977

6. DISCUSSION AND CONCLUSIONS

6.1 Discussion

The alluvial chronology of the study area has been reconstructed using the logged sections, valley morphology and seismic profiles. At least three periods of incision and two periods of valley infilling are in evidence. The cause of each episode is debatable and of the possible causes of arroyo cutting and filling discussed in the literature two may be applicable to this area: the effects of a) climatic change; b) adjustments in the longitudinal profile of the valley.

6.1.1 First episode of incision

Incision of the study valley will have been controlled by the Red Deer River, into which it flows. Air photographs indicate that the Red Deer River has a valley-in-valley form, similar to that observed by Kehew (1982) for the Souris spillway. Bryan *et al.* (in press) have suggested that this was due to an initial episode of widespread erosion in what they term the 'broad valley stage', with a later period of deep incision. Incision not only occurred in the Red Deer Valley, but in tributary spillways such as the Little Sandhill creek and Onetree Creek (Fig. 2.5). It is believed that the study valley was formed during the period of deep incision and acted as a spillway draining waters from the south of the park. This hypothesis is borne out by the U-shaped bedrock profile of the study valley (which can be inferred from the seismic profiles and bedrock outcrops), which is similar to other spillways in the region (see Stage 1, Fig. 6.1). This together with the amount of sediment which has been eroded from the valley, suggests formation under extremely high flow conditions. These conditions may have been attained during the sudden catestrophic draining of pro glacial lakes in the vicinity of the present park location.

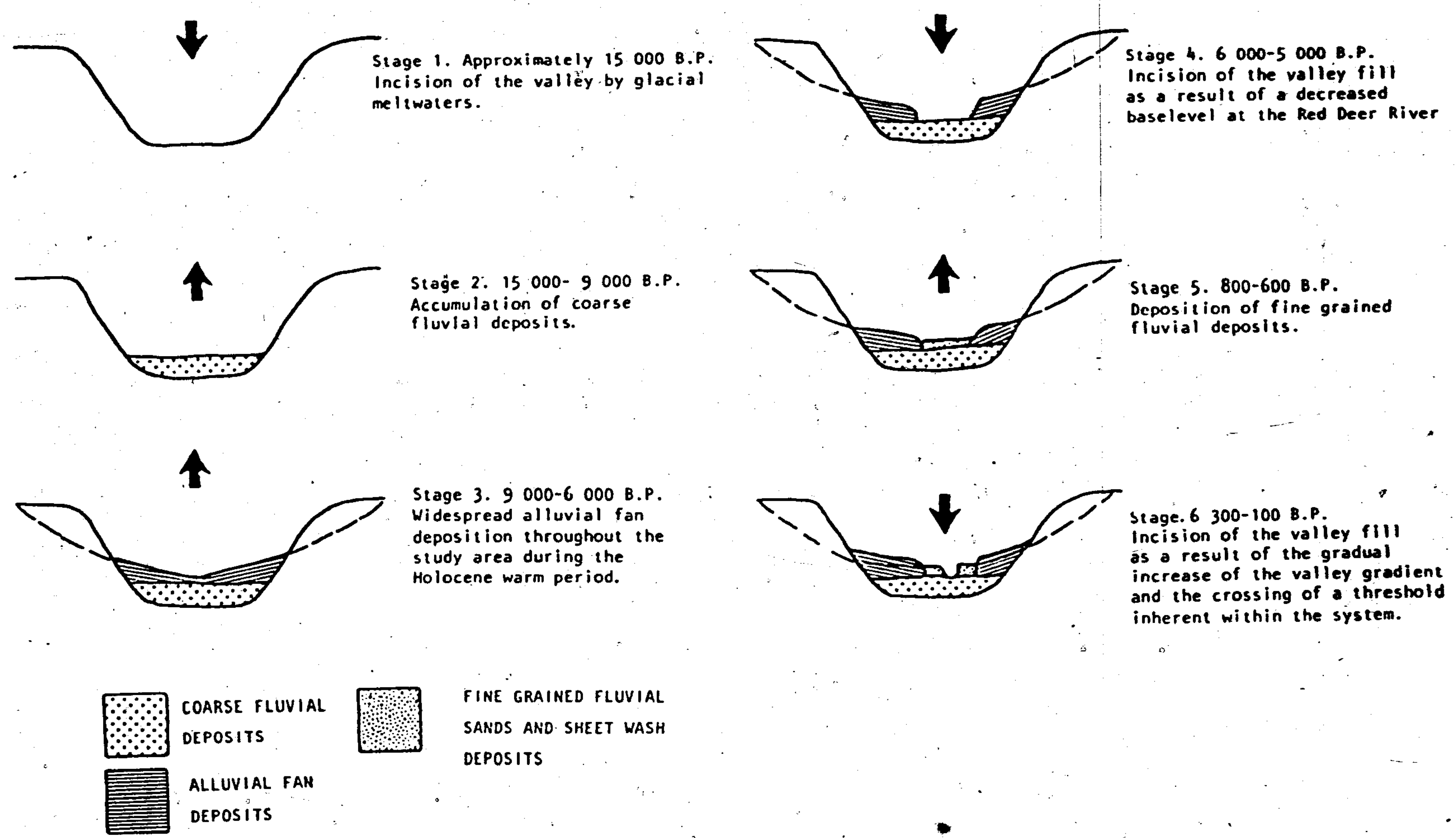


Figure 6.1 Idealized diagram of the evolution of the study valley

6.1.2 First aggradational episode

A period of aggradation took place after the valley was incised. Deposits generally show a fining-up sequence from fluvially deposited gravels and sands to fine grained fan deposits (see Stages 2 and 3, Fig. 6.1). This change in the style of sedimentation suggests that there was a considerable reduction in flow conditions during this episode of sediment accumulation. The coarse nature of the fluvial deposits indicates deposition under higher flow regimes than at present.

Several workers (e.g. Harris and Pip, 1973; Emerson, 1983; Pennock, 1984) have suggested that the immediate postglacial climate was much wetter than at present. Consequently, flow conditions in the study area would have been greater. Furthermore, the amount of runoff generated would have been considerably greater prior to loess input into the area. Measurements of the amount runoff ratio, in the experimental drainage basin, show that under present climatic conditions the badlands have a runoff coefficient of approximately 30 per cent (Campbell, 1986). This is despite the fact that over a third of the drainage basin is loess covered, which has a considerable capacity to absorb water and does not generate runoff even under the most intense rain events. Conseqently, a considerable area of the basin does not contribute runoff to the system. In the early stages of badlands development, prior to loess input (at approximately 5 400 B.P. Alpha-2074), there would have been a very high percentage of bedrock outcropping throughout the area and a higher runoff coefficient would be expected. Additionally, if the climate was wetter and possibly cooler than at present there would have been less potential for [illegible] by evaporation and a greater potential for runoff. This may have been sufficient [illegible] the flow conditions required to transport coarse sands and gravels. It is also possible that discharge from the pro-glacial lake was an additional source of fluvial input in the immediate postglacial period.

The fluvial deposits fine upwards from gravelly bedload to medium coarse fluvial sands at most of the sites studied. While this change in the grain-size distribution may be a result of deposition by a meandering stream it is believed that this was not the case in this instance.

There are several reasons for this. Firstly, the coarse nature of the fluvial deposits will have pervented channel stability, causing constant channel migration and reworking of the sediments. This will have resulted in the formation of erosional and depositional features. No such features were observed in the fill, and in fact deposits tended to be uniform within the trenches. Secondly, had there been constant channel migration a series of small fining-up sequences would be expected not just one. Thus it is concluded that the decrease in the grain-size of the fluvial deposits was due to a decrease in flow events through the study valley. This may have been due to the loss of lake discharge or a shift towards a more arid climate. In view of the fact that fine grained alluvial fan deposits overlie the sands, the latter case is the more probable. Furthermore, there is considerable evidence to suggest that extreme arid conditions prevailed in the mid-Holocene. The date of this event varies from study to study and ranges from 9 000 to 6 000 B.P. in central Alberta (Schweger *et al.*, 1981), 7 900 to 5 180 B. P. in the Highwood River basin (Pennock, 1984) and 8 500 to 5 500 B. P. in Jasper Natonal Park (Kearney and Luckman, 1981). But without better dating control only tentative conclusions can be made.

It is believed that this shift towards more arid conditions was ideal for the accumulation of alluvial fan deposits. Although material was probably deposited from valley side tributaries before the onset of arid conditions, it will have been washed away during frequent flow events. With the reduction in such events alluvial fans could accumulate. The onset of arid conditions in central Alberta is believed to be at approximately 8 000-9 000 B.P. (Schweger *et al.*, (1981), and was probably at a similar time in southern Alberta, it is possible to suggest that the onset of alluvial fan deposition in the Dinosaur badlands was around 9 000 B.P.

Alluvial fan deposits are generally fine grained and extremely cohesive. Small scale sedimentary structures were observed in many of the deposits and are believed to be the result of past fluvial activity over the fan surface. At a number of localities fan deposits are interbedded with fluvial sands while at other sites there is an abrupt contact between the two depositional types. As the former case was generally observed at a more distal site it does suggest that there was some inter-digitating of fan and fluvial sediments during the initial stages of fan deposition. The more abrupt boundary found at other sites may be a function of the position downfan of the section or an indication that at certain sites deposition was more abrupt. The presence of load structures in the the sands at the contact of alluvial and fluvial deposits at location 28 (Fig. 4.28) does suggest that the onset of fan deposition was very rapid.

Although it was not possible to measure the fan gradients accurately, it is fairly evident that they graded to a height 2-3 m above the present valley floor. This is especially true in the lower valley where truncated fan remains stand 2-3 m above the valley floor. This suggests that the valley graded to a higher baselevel in the past. Aggradation in the Red Deer River is believed to have occurred in the immediate postglacial period. The cause of aggradation is not known, but it has been suggested that it was due to isostatic rebound or an increase in the water-level to the northeast (David, 1964). A major period of aggradation has also been recorded in the South Saskatchewan River (into which the Red Deer River flows) and this probably controlled operations in the Red Deer River (McPherson, 1968), and consequently the study area.

The amount of aggradation in the Red Deer River is variable, with up to 50 m of sediment accumulation (McPherson, 1968). In the vicinity of Dinosaur Park the amount of aggradation was considerably less than this, with approximately 15 m of sediment accumulation. An extensive terrace area behind where the Park headquarters currently stands (Fig. 1.1) possibly relates to this period of aggradation. The height of this terrace is approximately 637 m a.s.l., similar to the height to which the study valley graded in the past. The available evidence suggests that the first period of aggradation in the study area was in response to an increase in the baselevel of the Red Deer River. It is not known for how long this period of aggradation continued. However, the presence of loess material on the upper fan surfaces indicated that deposition had ceased before 5 400 B. P.

6.1.3 Second episode of incision

A period of incision followed the accumulation of fan deposits (see Stage 4, Fig. 6.1). It is difficult to determine the exact nature of this erosional episode, because of the presence of a second surface approximately 1 m below the upper surface in the lower valley. The formation of this terrace is difficult to explain, but a number of possible mechanisms may be suggested.

With the onset of valley incision large amounts of sediment would be removed from the valley. This may have been too great for the Red Deer River to remove and aggradation occurred at the mouth of the valley. The resultant increase in baselevel causing valley aggradation. Experiments on the effects of increased baselevel on a valley system have shown that the effects do not tend to extend far up valley (Leopold and Bull, 1979). Therefore, if there had been an increase in baselevel the effects would probably only be seen in the lowest part of the study area.

The second terrace could also be a result of two successive periods of incision - an initial period cutting the upper terrace, with later incision forming the middle terrace. It is possible that its presence in the lower valley is a result of changes in sediment type. It is believed that coarse fluvial sands at the base of the fill in the upper valley have had a limiting effect on incision. In the lower valley similar sands are found at a much higher position in the fill, at approximately the same height as the middle terrace (Figs. 4.34 and 4.35). It is possible that these deposits had a similar effect in the past, inhibiting further downward incision when the sands were reached. This resulted in lateral rather than vertical erosion and the formation of a terrace. As the system had to reach a state grade incision of the sands eventually occurred. In the upper parts of the valley where these sands are lower in the fill, and alluvial deposits are thicker, downward incision could continue and the middle terrace would not be formed.

A third possibility is that there was an episode of incision followed by aggradation and then a further period of incision - the two erosional episodes being totally unrelated. The fact that the middle terrace is only present in the lower valley suggests that this is not the case but without more evidence on the relationship of the deposits it is not possible to make any definite conclusions. It is possible to conclude, however, that the two terrace were formed prior to loess input at 5 400 B.P.

The depth of incision can not be determined in the upper valley but, as previously discussed, it is believed that the presence of coarse fluvial sands at the base of the present arroyo has had a considerable effect by preventing vertical incision from occurring. If this is the case today it was probably the case in the past and consequently the depth of incision was probably no greater than at present. In the lower valley there is more evidence to suggest that the depth of incision was in the order of that currently found in the lower valley. At locations 14, 17, 22 and possibly location 11, older deposits are found underlying more recently deposited sediments. This sequence is particularly well preserved at location 13 and indicates that the depth of incision was similar to the present depth of incision. As the valley floor was higher at this time it is estimated that between 2.5 and 4 m of incision occurred during the second erosional episode. The cause of incision is difficult to determine. The gradient of the valley at that time was 0.27° (Fig. 4.33), which is considerably less than at present. As the arroyo which presently entrenches the valley has a gradient either the same or greater than this (Table 1.3) it suggests that the valley was in a very stable condition at this time and incision was not due to the crossing of a geomorphic threshold. Evidence suggests that there was a deterioration in the climate at about 4 000-5 000 B.P., to conditions which are wetter than at present. The onset of wetter conditions after an extended period of drought will probably have increased the potential for erosion. While it is possible that this resulted in valley cutting in the badlands it is more likely that incision in the Red Deer River (possibly as a direct result of climatic change) caused incision in the study area to take place. It is not possible to determine the date of this period of this erosional episode, but based on climatic conditions in Alberta it is suggested that incision took place at approximately 5 000-6 000 B.P.

6.1.4 Second aggradational episode

A second period of aggradation followed incision (see Stage 5, Fig. 6.1). Deposits are considerably finer with abundant sheet wash deposits in the upper surfaces. Recent deposits appear to be thickest in the upper valley where over 2 m of sediment have accumulated. In the lower valley it is more difficult to determine the amount of sedimentation but it is believed to be in the order of a metre. As discussed this is believed to be due to a rapid deceleration in flow when it leaves the confines of the tributary valleys. This results in deposition which is greatest in the upper valley. The deposits are fine grained and the sedimentary structures indicate that deposition was under lower flow regimes than are presently attained in the arroyo. It should be pointed out, however, that this does not necessarily mean there is greater water through the present system. The arroyo has the effect of channelling discharge and greater flow velocities can be reached with less actual flow. was still active in the valley at approximately 315+/-65 B. P. (S-2546) based on a date obtained on a cottonwood log 60 cm below the valley floor. The cause of this aggradational episode is not known.

6.1.5 Third episode of incision

The most recent period of incision has occurred within the last 100-300 years (see Stage 6, Fig. 6.1). At least two episodes of erosion can be documented which indicates that erosional episodes are not singular events. There have been no significant changes in baselevel over the past few hundred years which indicates that is is not the cause of this episode. The valley gradient today is at the steepest recorded and it is possible that this current erosional episode is the result of the exceedence of a threshold without any change in external variables and is an example of an intrinsic threshold. The most recent erosional episode took place between 1950 and 1961; during this time there has been no climatic change or changes in baselevel. Air photographs show that there was considerable lateral shifting in the Red Deer River at this time. The cause of the shift is not known but McPherson (1966) reported that there had been up to 200 m of lateral movement in some parts of the river valley between 1889 and 1960. In this area the shift in the river resulted in the main valley decreasing in length by about 70 m; this is equivalent to a baselevel change of about 60-70 cm. If the valley was in an unstable condition this shift could have been sufficient to cause an episode of erosion in recent years.

The available evidence indicates that no major erosional episodes occurred in the valley between the period of incision prior to 5 400 B.P. and the most recent period of erosion. Recent deposition in the valley has been very rapid with 0.6 m of sediment accumulation in the upper valley in the last 300 years. This is based on a date obtained on a cottonwood tree found upstream of location 3. The deposits above and below this log are the same and it plausable to suggest that deposition was at a similar rate. If this was the case it has taken approximately 600-800 years for the deposits to accumulate. Thus between the last episode of erosion (prior to 5 400 B.P.) and the onset of deposition there was a period of about 4 000-5 000 years where there is no evidence of valley cutting and filling in the study area. This does seem highly unlikely, especially in view of the fact that the wet period which covers much of this time was punctuated by periods of prolonged drought (Pennock, 1984). If this was the case episodes of enhanced geomorphic activity would be expected (Fig. 2.1) and indeed were seen in the Highwood basin in southeastern Alberta (Pennock, 1984). In view of this it seems highly unlikely that there has been no activity in the Dinosaur badlands and it is suggested that the evidence is either not preserved or the similarity of deposits make it impossible to distinguish these episodes.

6.2 Conclusions

The badlands formed during the final stages of deglaciation when pro-glacial lakes to the south and west drained across the area. Incision was in two phases, with initial widespread erosion removing Pleistocene deposits and later incision cutting deep U-shaped valleys into the underlying Cretaceous bedrock. The study valley is believed to have formed during the second stage of incision.

Following incision sands and gravels accumulated in the valley. Deposition was initially under a high flow regime which later decreased with a corresponding decrease in the grain-size of deposits. The transition from gravel to sand deposition was possibly a result of the loss of lake discharge. A shift towards more arid conditions at approximately 9 000 B.P. resulted in widespread alluvial fan deposition throughout the study area. Aggradation in the study valley was due to an increase in the baselevel of the Red Deer River.

Incision of the valley occurred prior to loess input at 5 400 B.P. This resulted in the formation of an upper surface which stands 0.3 to 2.5 m above the valley floor. A second surface 1 m below the upper surface, which is only present in the lower valley, is also believed to have formed during this erosional episode. Incision of the valley fill was in response to incision in the Red Deer River.

Subsequent aggradation resulted in fine grained fluvial deposits accumulating. These deposits are most are thickest in the upper valley whare over 2 m of material has accumulated. Aggradation was still active in the valley at 315+/-65 B.P. (S-2546). Using this date it is possible to suugest that the recent valley fill has been deposited over the last 600-800 years.

Recent valley incision has occurred within the last 300 years. No major changes in climate or baselevel have taken place during this time. The valley gradient is presently at the steepest recorded in the valley history and it is believed that gradually steepening of the valley has resulted in the exceedence of a geomorphic threshold causing incision to occur. The most recent period of incision has occurred since 1950. This is believed to have resulted from the rapid lateral migration of the Red Deer River towards the valley thereby shortening its length and increasing its gradient sufficiently enough to reactivate incision.

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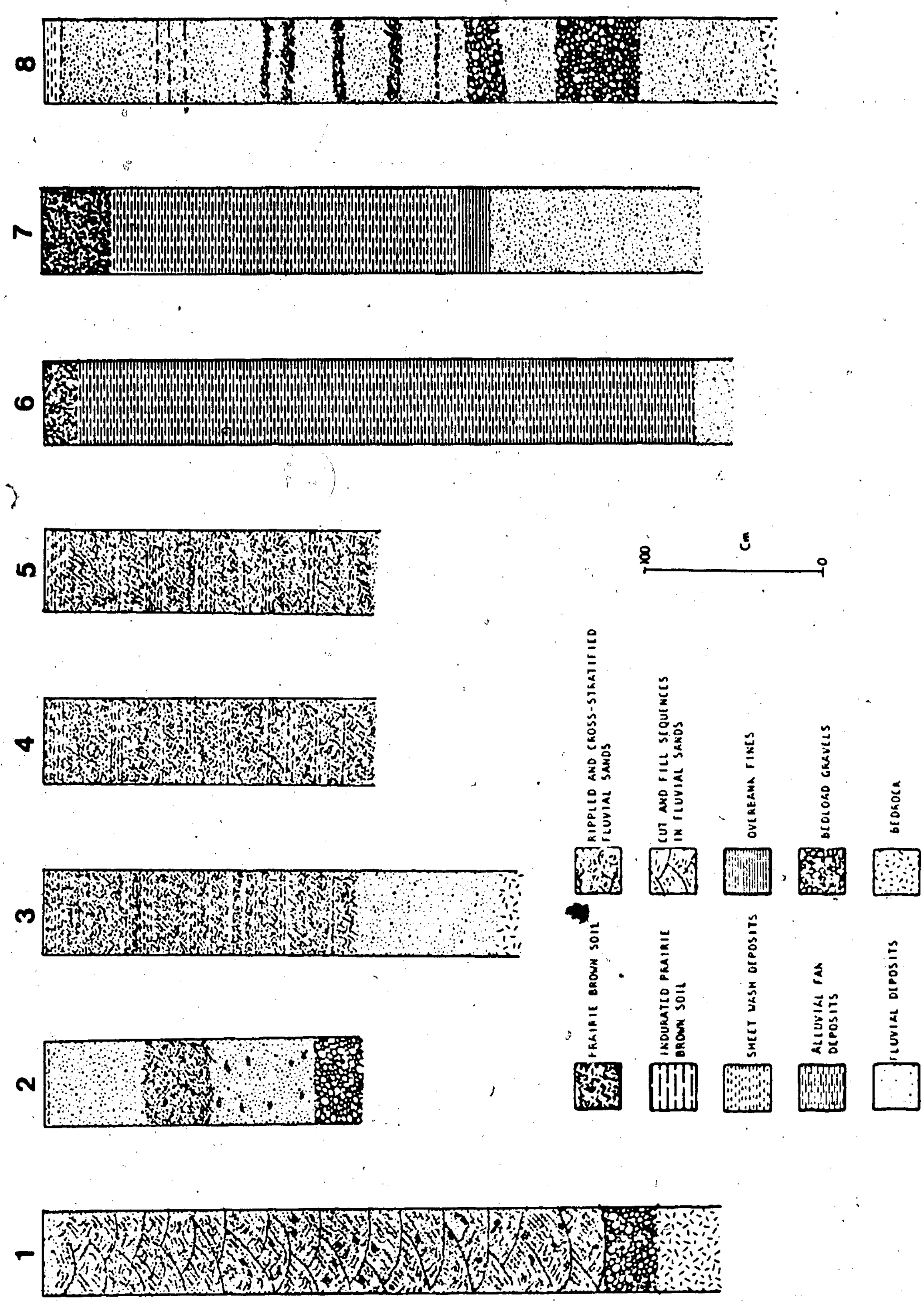
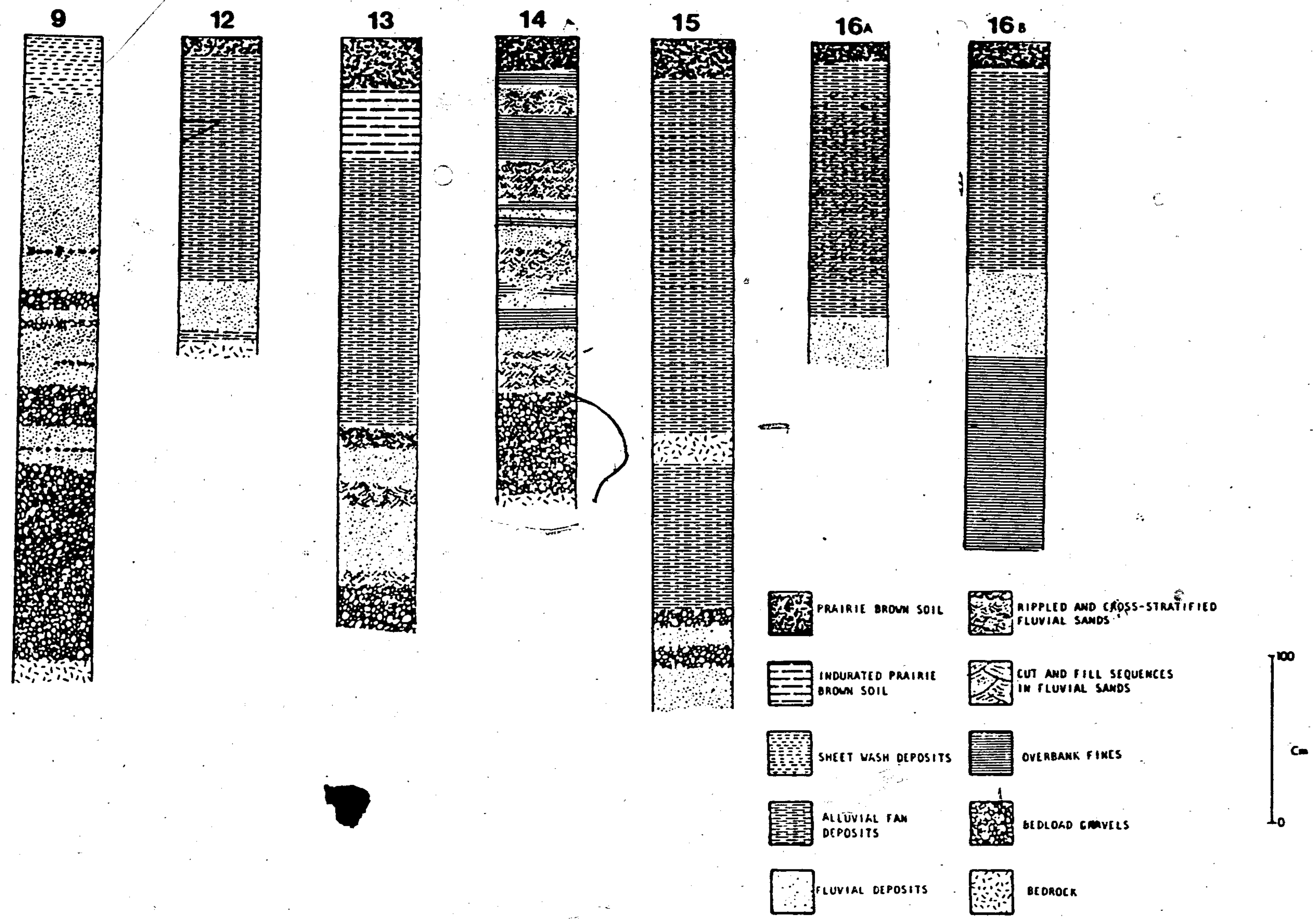
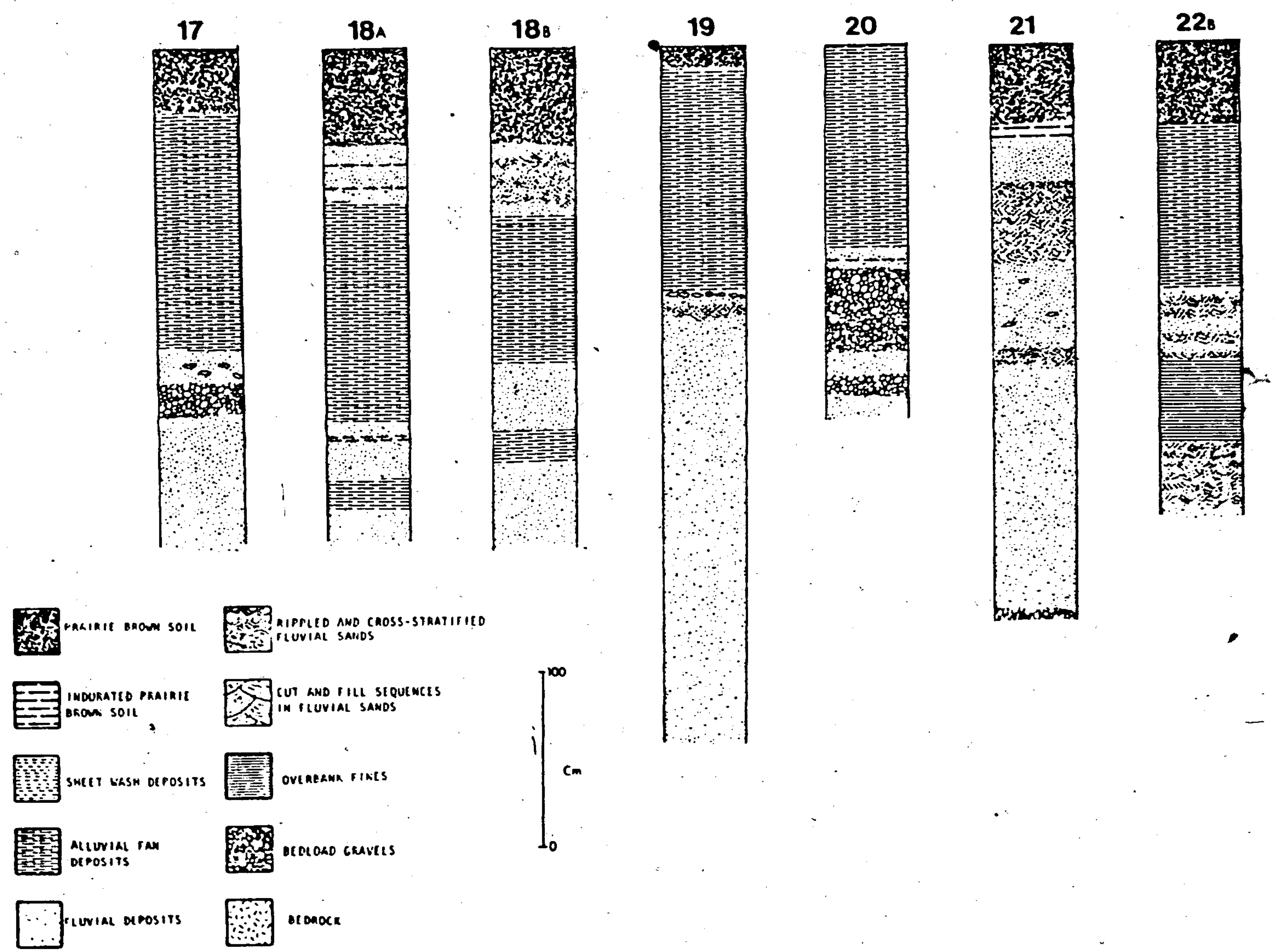
Appendix A. The logged sections from the study area



8
7
6
5
4
3
2
1
100
Cm
0
PRAIRIE BROWN SOIL
INDURATED PRAIRIE BROWN SOIL
SHEET WASH DEPOSITS
ALLUVIAL FAN DEPOSITS
FLUVIAL DEPOSITS
RIPPLED AND CROSS-STRATIFIED FLUVIAL SANDS
CUT AND FILL SEQUENCES IN FLUVIAL SANDS
OVERBANK FINES
BEDLOAD GRAVELS
BEDROCK


9
12
13
14
15
16A
16B
PRAIRIE BROWN SOIL
INDURATED PRAIRIE BROWN SOIL
SHEET WASH DEPOSITS
ALLUVIAL FAN DEPOSITS
FLUVIAL DEPOSITS
RIPPLED AND CROSS-STRATIFIED FLUVIAL SANDS
CUT AND FILL SEQUENCES IN FLUVIAL SANDS
OVERBANK FINES
BEDLOAD GRAVELS
BEDROCK
100
Cm
0


17
18A
18B
19
20
21
22B
PRAIRIE BROWN SOIL
INDURATED PRAIRIE BROWN SOIL
SHEET WASH DEPOSITS
ALLUVIAL FAN DEPOSITS
FLUVIAL DEPOSITS
RIPPLED AND CROSS-STRATIFIED FLUVIAL SANDS
CUT AND FILL SEQUENCES IN FLUVIAL SANDS
OVERBANK FINES
BEDLOAD GRAVELS
BEDROCK
100
Cm
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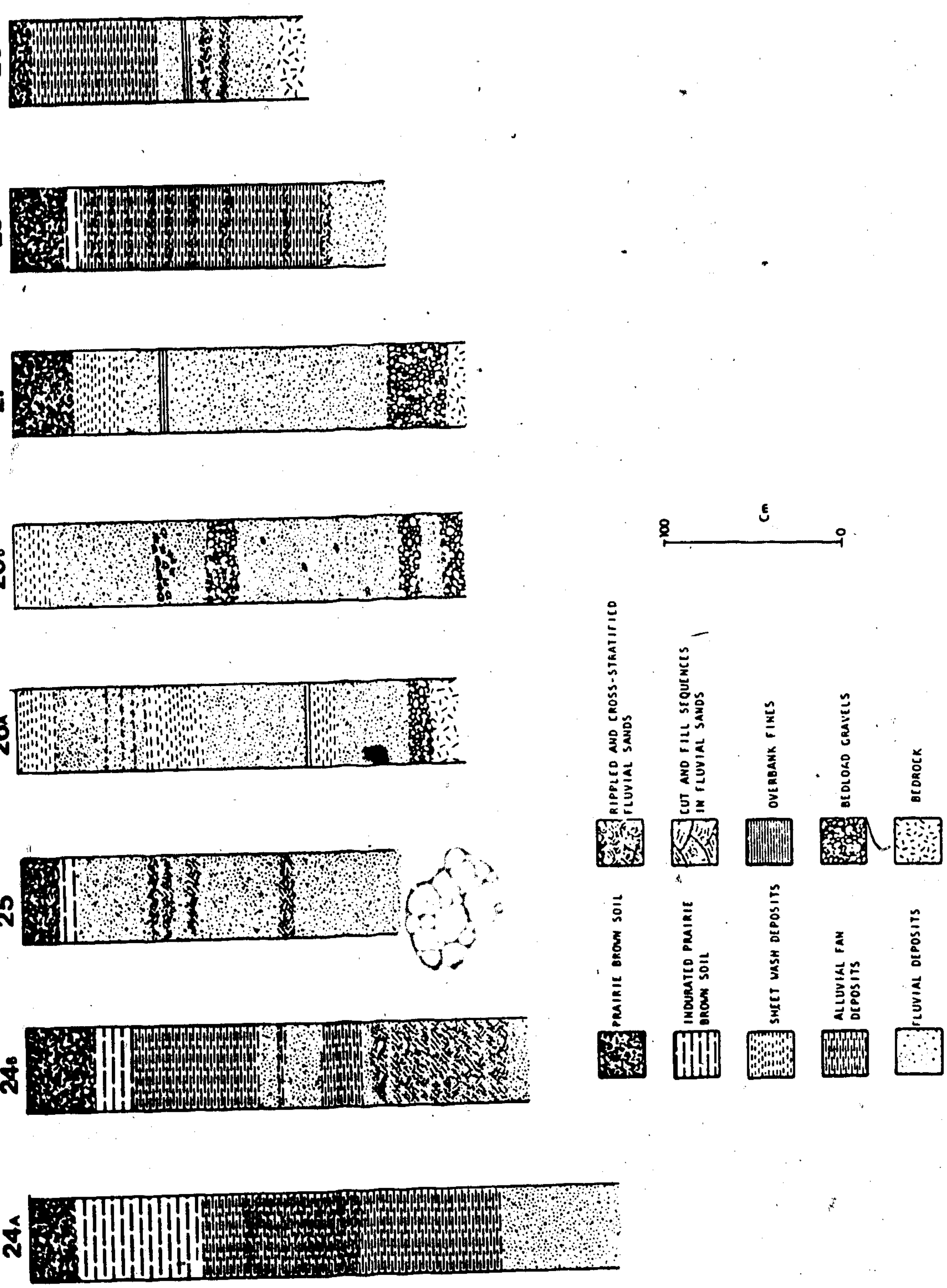
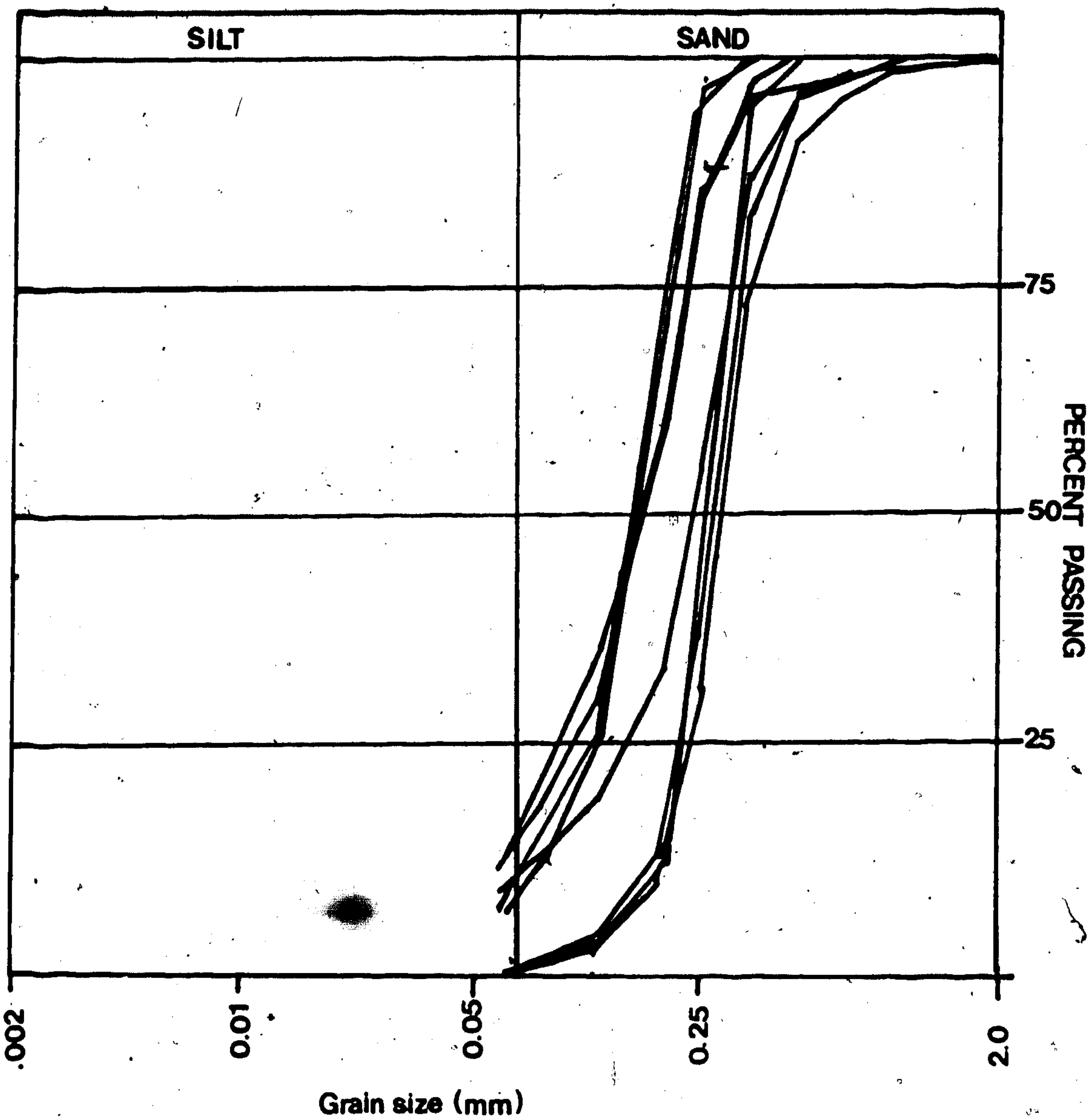
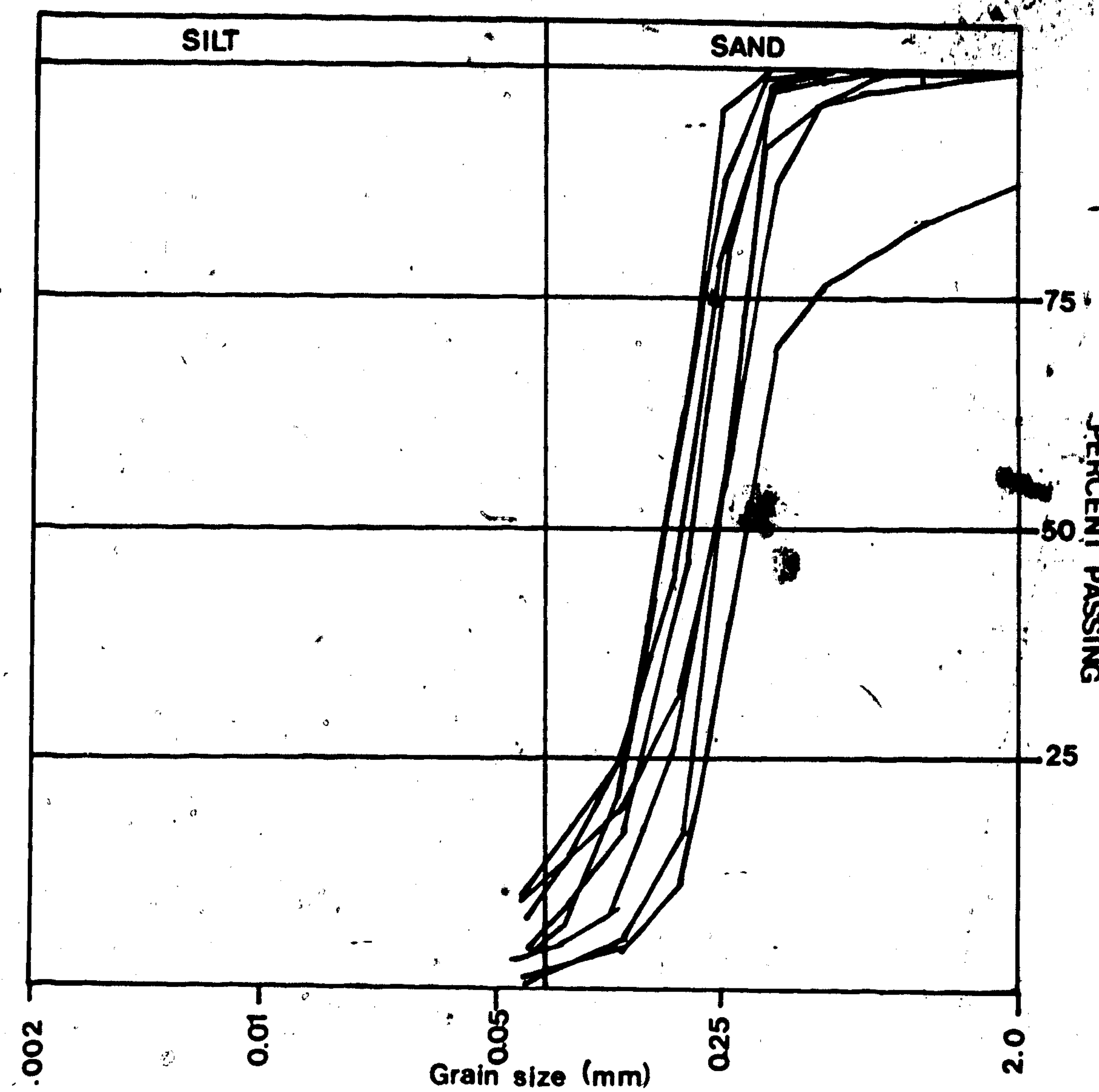
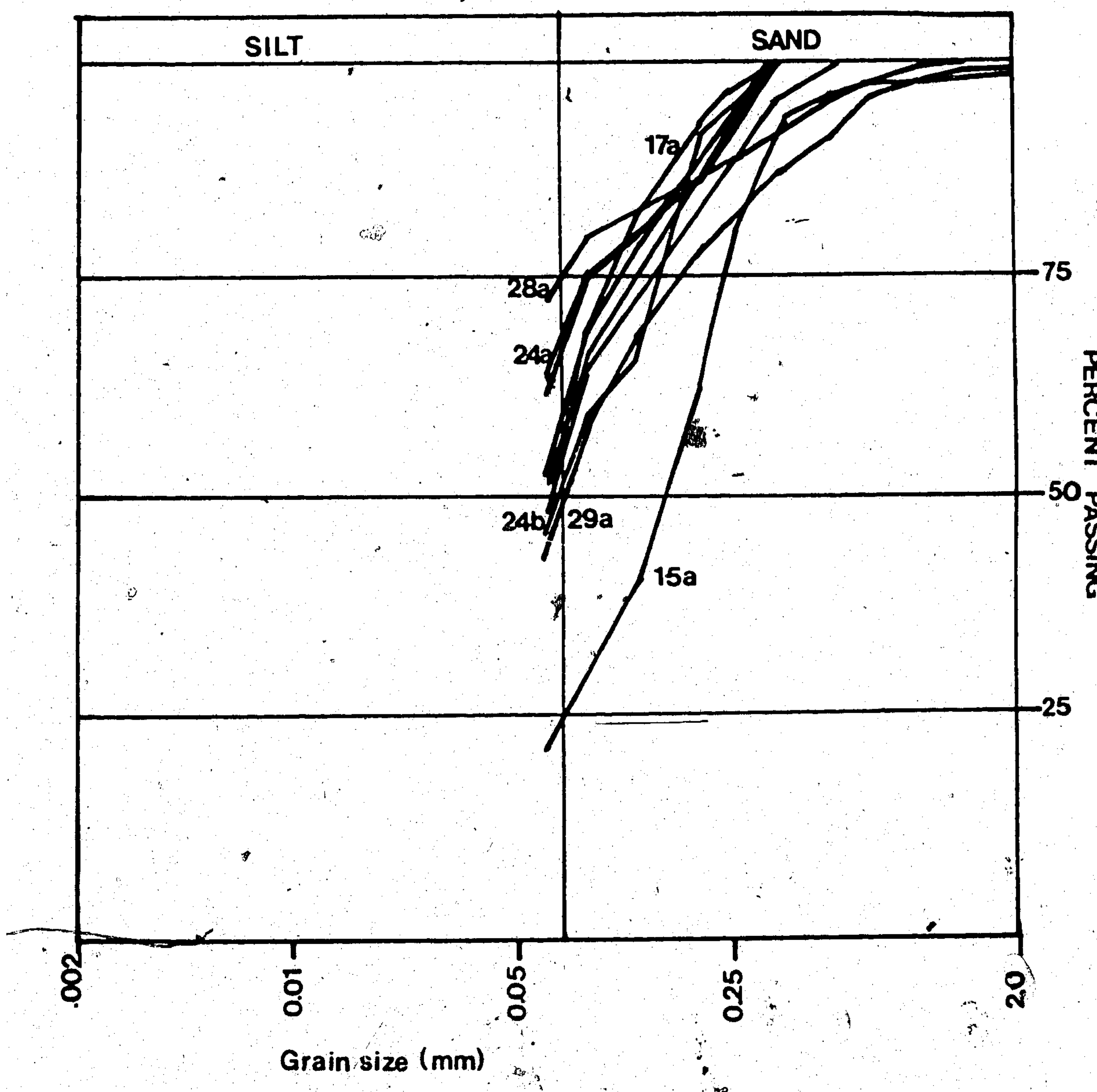

24A
24B
25
26A
26B
27
28
29
PRAIRIE BROWN SOIL
INDURATED PRAIRIE BROWN SOIL
SHEET WASH DEPOSITS
ALLUVIAL FAN DEPOSITS
FLUVIAL DEPOSITS
RIPPLED AND CROSS-STRATIFIED FLUVIAL SANDS
CUT AND FILL SEQUENCES IN FLUVIAL SANDS
OVERBANK FINES
BEDLOAD GRAVELS
BEDROCK
100
cm
0

Appendix B. Representative grain size-distribution curves from the coarse fluvial sands


SILT
SAND
75
50
25
PERCENT PASSING
.002
0.01
0.05
0.25
2.0
Grain size (mm)


SILT
SAND
75
50
25
PERCENT PASSING
.002
0.01
0.05
0.25
2.0
Grain size (mm)

Appendix C. Representative grain-size distribution curves from the alluvial fan deposits


SILT
SAND
17a
28a
24a
24b
29a
15a
75
50
25
PERCENT PASSING
.002
0.01
0.05
0.25
2.0
Grain size (mm)