

SEDIMENTOLOGY AND GEOMORPHOLOGY OF QUATERNARY ALLUVIAL
FANS WITH IMPLICATIONS TO GROWTH STRATA, LOST RIVER RANGE,
IDAHO

by
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A thesis submitted in partial fulfillment
of the requirements for the degree
of
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TABLE OF CONTENTS

1. INTRODUCTION.....	1
2. GEOLOGIC SETTING.....	6
3. QUESTIONS.....	11
4. METHODS.....	14
5. UPPER CEDAR CREEK ALLUVIAL FAN.....	19
Surface Descriptions.....	20
Surface A.....	21
Surface B.....	23
Surface C.....	26
Surface F.....	28
Surface O.....	28
Gravel Package Descriptions.....	30
Gravel Package I.....	30
Gravel Package II.....	44
Gravel Package III.....	52
Gravel Package IV.....	52
Age Data.....	53
Discussion.....	54
6. JONES CREEK ALLUVIAL FAN.....	67
Surface Descriptions.....	68
Surface J.....	69
Surface M.....	73
Surface N.....	74
Gravel Package Descriptions.....	74
Gravel Package X.....	75
Gravel Package XI.....	77
Age Data.....	78
Discussion.....	79
7. NORTH OF JONES CREEK ALLUVIAL FAN.....	84
Surface Descriptions.....	84
Surface H.....	86
Surface K.....	87
Surface L.....	88
Surface P.....	88
Gravel Package Description.....	89
Age Data.....	90
Discussion.....	90

TABLE OF CONTENTS CONTINUED

8. ELKHORN CREEK ALLUVIAL FAN.....	94
Surface Descriptions.....	95
Surface W.....	95
Surface X.....	97
Surface Y.....	98
Surface Z.....	100
Measured Sections.....	101
Age Data.....	104
Discussion.....	105
9. DISCUSSION.....	109
10. CONCLUSIONS.....	121
REFERENCES CITED.....	123
APPENDICES.....	130
APPENDIX A: Carbonate Coat Thickness Data by Pit.....	131
APPENDIX B: Carbonate Coat Thickness Data by Surface.....	138

LIST OF TABLES

Table	Page
1. Formations exposed in the central Lost River Range.....	10
2. List of Surface Modification Processes.....	18
3. Formations present in Upper Cedar Creek alluvial fan drainage basin.....	19
4. Age of surfaces on Upper Cedar Creek alluvial fan.....	54
5. Formations present in Jones Creek alluvial fan drainage basin.....	67
6. Age of surfaces on Jones Creek alluvial fan.....	79
7. Formations present in North of Jones Creek alluvial fan drainage basin.....	84
8. Age of surfaces on North of Jones Creek alluvial fan.....	90
9. Formations present in Elkhorn Creek alluvial fan drainage basin.....	94
10. Age of surfaces on Elkhorn Creek alluvial fan.....	105
11. Summary of surfaces and gravel packages on Upper Cedar Creek alluvial fan.....	113
12. Summary of surfaces and gravel packages on Jones Creek alluvial fan.....	113
13. Summary of surfaces and gravel packages on North of Jones Creek alluvial fan...	113
14. Summary of surfaces and gravel packages of Elkhorn Creek alluvial fan.....	114

LIST OF FIGURES

Figure	Page
1. Growth strata (progressive unconformities) from Riba (1979).....	2
2. Location map of study area.....	7
3. Fault segments and last ground rupture along Lost River fault.....	8
4. Diagram of key terms.....	12
5. Three main surfaces on Upper Cedar Creek alluvial fan.....	20
6. Surface descriptor photos of Surface A.....	22
7. Airplane photo and DOQ of Surface A.....	24
8. Surface descriptor photos of Surface B.....	25
9. Surface descriptor photos of Surface C.....	27
10. Surface descriptor photos and DOQ of Surface F.....	29
11. Sketch and photo of surfaces and gravel packages on Upper Cedar Creek alluvial fan.....	31
12. Lithofacies photos of Section 1.....	33
13. Lithofacies photos of Section 2.....	34
14. Stratigraphic column of Section 2.....	36
15. Lithofacies photos of Section 5.....	37
16. Stratigraphic column of Section 5.....	39
17. Stratigraphic column of Section 8.....	40
18. Lithofacies photos of Section 9.....	41
19. Lithofacies photos of Section 10.....	42

LIST OF FIGURES CONTINUED

Figure	Page
20. Stratigraphic column of Section 10.....	43
21. Lithofacies photos of Section 3.....	45
22. Stratigraphic column of Section 3.....	47
23. Lithofacies photos and stratigraphic column of Section 4.....	48
24. Lithofacies photo of Section 6.....	49
25. Lithofacies photos of Section 6.....	49
26. Lithofacies photo of Section 6 with board.....	50
27. Lithofacies photos of Section 7.....	51
28. Stratigraphic column of Section 7.....	51
29. Lithofacies photos of Gravel Package IV.....	53
30. Airplane photos of apex and DOQ of North of Jones Creek alluvial fan.....	68
31. Surface descriptor photos of Surface J at apex.....	71
32. Surface descriptor photos of Surface midfan J.....	72
33. DOQ and surface descriptor photos of Surface M.....	73
34. DOQ and surface descriptor photos of Surface N.....	75
35. Sketch of surfaces and gravel packages on Jones Creek alluvial fan.....	76
36. Lithofacies photo of Section 11.....	78
37. Stratigraphic column of Section 11.....	79
38. DOQ and surface photos of North of Jones Creek alluvial fan.....	85
39. Surface descriptor photos of Surface H.....	86
40. Surface descriptor photos of Surface K.....	87

LIST OF FIGURES CONTINUED

Figure	Page
41. Surface descriptor photo of Surface P.....	89
42. DOQ and airplane photos of Elkhorn Creek alluvial fan.....	96
43. Surface descriptor photos of Surface W.....	97
44. Surface descriptor photos of Surface X.....	98
45. Surface descriptor photos of Surface Y.....	99
46. Surface descriptor photos of Surface Z.....	101
47. Lithofacies photos of Section 12.....	102
48. Stratigraphic column of Section 12.....	103
49. Stratigraphic column of Section 13.....	104
50. Timeline of events on Mackay fault segment.....	119
51. New location of fault on Upper Cedar Creek alluvial fan.....	120

LIST OF PLATES

Plate	Page
1. DOQ of field area.....	inside back cover

ABSTRACT

Small-radius (<2 km), steep (8-17°), Holocene debris flow dominant alluvial fans are depositing on top of large-radius (~5 km), shallow (2-3°) inactive Pleistocene sheetflood dominant alluvial fans along the western flank of the Lost River Range, Idaho. Channel ways, with and without backfilling, have developed within the large sheetflood dominant alluvial fans. The sheetflood dominant alluvial fans are being dissected. Three wedge shaped gravel packages were identified by field mapping and measured sections in four alluvial fans along the active extensional Lost River fault. These alluvial fan deposits have all of the characteristics of growth strata (progressive unconformities) observed in extensional tectonic settings. The ages of the surfaces were calculated from carbonate coat thicknesses on clasts in the soil and are between $42,000 \pm 18,000$ yr and the present. Each of the four alluvial fans has different stratal patterns even though they are all situated on the active Mackay fault segment. This lateral variability has implications to rock record interpretations. The younger fan depositing on top of the older fan exhibits the interaction of neighboring alluvial fans, and there is a changing of the sediment transport process over time on an individual alluvial fan. Complexly interacting controls on alluvial fan development include: 1) temporal change in the locus of maximum displacement on the Mackay fault segment, and 2) changes in Pleistocene and Holocene discharge.

CHAPTER 1

INTRODUCTION

Syntectonic sediments provide important insight into tectonic problems. Growth strata are a specific variety of syntectonic sediments that have been used to identify the geometry and style of adjacent structures, determine rates of folding and faulting, and reconstruct tectonic histories. Growth strata are most commonly identified in fold and thrust belts associated with thrust faults and the resulting folds (Riba, 1976; Anadon, 1986; Nichols, 1987; Azevedo, 1993; Hessami et al., 2001; Ortner, 2001; Verges et al., 2002; Schmitt and Aschoff, 2003) but have also been observed near salt diapirs (Giles and Lawton, 2002; Millan-Garrido, 2004), and a few examples are associated with extensional structures (Horton and Schmitt, 1998; Sharp et al., 2000; Dorsey, 2002). There are also many examples of numerical models of growth strata in compressional tectonic settings (Suppe et al. 1992; Shaw and Suppe, 1994; Zapata and Allmendinger, 1996; Ford et al., 1997; Casas-Sainz et al., 2002; Salvini and Storti, 2002). Few numerical models of growth strata exist for extensional tectonic settings (Shaw et al., 1997; Gawthorpe and Hardy, 2002).

Growth strata (progressive unconformities) were first defined based on unique stratal geometries of Neogene alluvial fan deposits in the Pyrenees Mountains of Spain (Riba, 1976). The unique stratal geometries are unconformity bound wedges of sediment that exhibit a fanning of strata dips (Fig. 1A; Riba, 1976). Based on observations of these deposits, the two classic growth strata geometries (rotative offlap and onlap) were

identified (Fig. 1A and 1B). Uplift with rotation inclines the strata. Older beds have undergone more uplift and exhibit a steeper inclination.

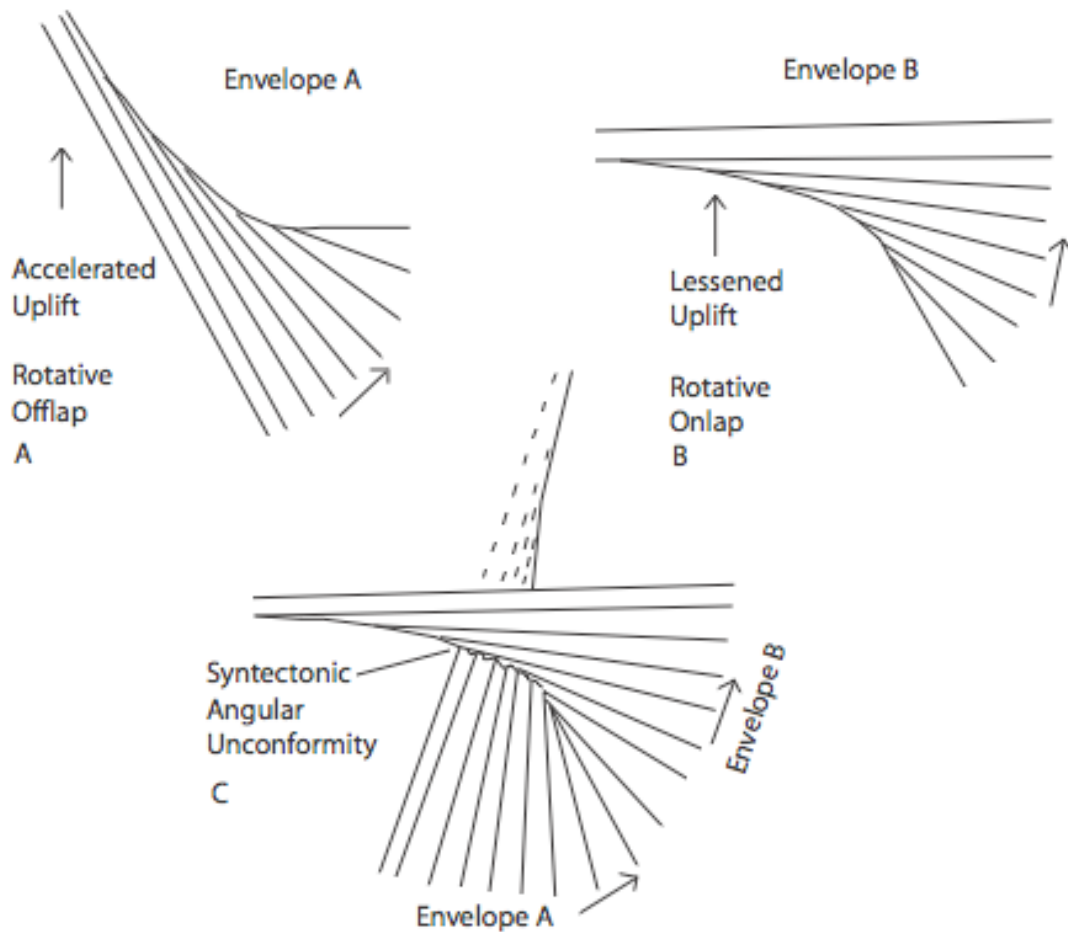


Figure 1. Progressive unconformities (growth strata) from Riba (1976). (A) A wedge (envelope) of sediment bound by unconformities with fanning stratal dips. A single progressive unconformity exhibiting rotative offlap geometry. Arrows point up section. (B) A wedge of sediment bound by unconformities exhibiting rotative onlap. (C) A cumulative progressive unconformity is composed of two single progressive unconformities. Note the angular unconformity that divides the two wedges of sediment.

Growth strata are divided into two genetic groups formed by either: progressive limb rotation or kink band migration (Riba, 1976; Suppe et al., 1992; Zapata and Allmendinger, 1996). Progressive limb rotation, first noted by Riba (1976), involves

rotation of beds over time. Kink band migration, first proposed based on numerical modeling and entails thickening of strata across axial surfaces that follow bends in the underlying fault (Suppe et al., 1992). These two groups have different stratal characteristics and geometries. Both groups demonstrate the common pattern of strata thinning toward the structure and thickening toward the basin. Because of continued rotation, the beds formed by progressive limb rotation have a fanning of dips with the oldest beds having the steepest dips. Beds developed by kink band migration do not always exhibit fanning of dips and usually have uniform bed dips. Examples of kink band migration are restricted to seismic profiles (Suppe et al., 1992; Zapata and Allmendinger, 1996) and a few field examples (Dorsey, 2002). Numerical models have scales too large for detection of the subtle bedding dips of the Lost River Range fans and hence, are not applicable to the fans studied in this project.

Growth strata formed through kink band migration have been identified in an extensional tectonic setting (Dorsey and Becker, 1995). Down dropped blocks demonstrate syndepositional rollover associated with the Whipple detachment fault, southern California. The growth strata are identified in sediments overlying the rollover. The growth strata have uniform dip through the section and thin toward the normal fault. This relationship is drastically different from most of the other growth strata examples.

The best field identified growth strata form through progressive limb rotation and are deformed during or shortly after deposition. Rotation of the sediments with progressive fault displacement results in sediment deformation. Syntectonic deposition produces thinning of the strata toward the structure and fanning of stratal dips (Fig. 1). The oldest beds have been rotated the most and have the steepest dips. The strata usually

flatten up section. Continual deformation causes angular unconformities to develop, because sedimentation cannot keep pace with deformation (Riba, 1976). This results in wedges of sediment bound by angular unconformities (Fig. 1; Riba, 1976; Anadon, 1986). Continued deformation can cause development of a syntectonic unconformity that is produced through erosion of sediment near the structure (Fig. 1C). This unconformity becomes conformable toward the basin. Several workers have identified growth strata based on fanning of dips, with an absence of intraformational angular unconformities (Horton and Schmitt, 1998; Dorsey, 2002).

Growth strata have been identified predominantly in alluvial fan deposits, which often contain incised and backfilled channel ways. Channel ways are common landforms on alluvial fans and are areas of erosion that creates a linear trough parallel to the fan radius (Azevedo, 1993; Ford et al., 1997). The composition and sedimentary style of the sediment backfilling the channel ways may enhance or inhibit observation.

Two growth strata models have been developed for extensional tectonic settings based on fault geometry. Extensional fault propagation folds (blind normal faults) produce a monocline on the surface above the fault and a hanging wall syncline (Gawthorpe et al., 1997). Strata thin toward the monocline and thicken basinward to the axis of the syncline. The strata also have a fanning of dips away from the fault (Gawthorpe et al., 1997; Sharp et al., 2000). The classic normal fault geometry is with surface offset. Growth strata associated with surface offset thicken toward the fault. Fanning of stratal dips are common and steepen down section toward the fault (Gawthorpe et al., 1997). Growth strata identified in extensional tectonic settings occur

in sediments from fluvial, lacustrine, tidal and shallow marine depositional environments (Sharp et al. 2000; Dorsey, 2002).

Growth strata identified adjacent to monoclines or anticlines in extensional and compressional tectonic settings have the same stratal geometries (Sharp et al., 2000). The strata are organized into wedges that thin toward the structure and thicken basinward. Beds exhibit fanning of dips within the wedges. Angular unconformities bounding the wedges of sediment are slight, usually less than 10 degrees. The mechanism of growth strata development is not dependent on the large stress field, but rather is related to changes of the depositional surface over time. Because anticline limbs grow in the same manner, during normal or thrust fault development, the resulting growth strata are similar.

Some workers use the term growth strata in a broad sense as a synonym for syntectonic sediments. Here, I will use a strict definition of the term growth strata, as outlined by Riba (1976): rock or sediment wedges bound by angular unconformities that were deformed during or shortly after sedimentation. This study outlines examples of alluvial fan sediments organized into wedges of gravel that were deposited adjacent to an active normal fault.

CHAPTER 2

GEOLOGIC SETTING

The Basin and Range Province is a diffuse zone of extension in the western United States that has produced multiple normal fault bound uplifted ranges and their associated down-dropped valleys. The Lost River Range of south-central Idaho is an example an uplifted range, bounded on the west by the Lost River fault and the Big Lost River Valley and to the east by the Pahsimeroi and Little Lost River Valleys (Fig. 2). The Big Lost River Valley is an example of a continental half graben with axial through drainage (Leeder and Gawthorpe, 1987). The deformation is focused on the west dipping Lost River fault, which accommodates normal displacement. The magnitude 7.3 Borah Peak earthquake formed as a result of brittle failure of the Lost River fault on October 24, 1983 (Stein and Barrientos, 1985). The mountain-bounding Lost River fault is composed of six fault segments that have unique fault rupture histories (Fig. 3; Crone and Haller, 1991). Surface faulting occurred on the Thousand Springs and Warm Spring fault segments during the Borah Peak earthquake (Crone and Machette; 1984).

This study focuses on four alluvial fans: Elkhorn Creek, North of Jones Creek, Jones Creek and Upper Cedar Creek located on the Mackay fault segment in the central Big Lost River Valley (Fig. 2). The Mackay fault segment last experienced ground rupture 4,000 years ago (Fig. 3; Crone and Haller, 1991).

The axial Big Lost River flows southward into the Snake River Plain, draining the Big Lost River Valley. The valley is sparsely populated with a few small towns. The biggest human impact on the alluvial fans today is through cattle grazing and

construction associated with irrigation ditches and roads. The Big Lost River floodplain is dominated by cropland.

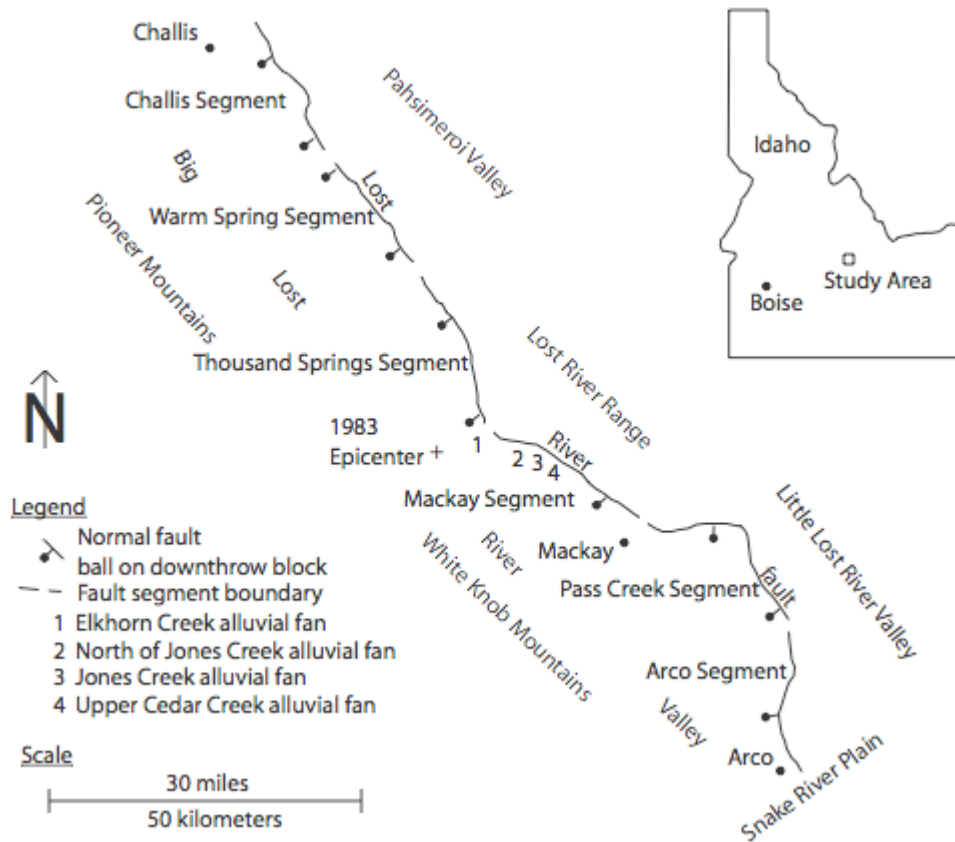


Figure 2. Location map of the study area.

Multiple mountain ranges extend west of the Lost River Range to the Pacific, the main source of moisture. This location contributes significantly to past and present climates (Meyer et al., 2004). Current climate is continental arid, with less than 25 centimeters (10 inches) of precipitation per year on the valley floor and a large yearly temperature fluctuation (-10 to 27°C) (Crosthwaite et al., 1970). The Lost River Range was weakly glaciated during the Pleistocene as evidenced by cirques and glacial moraines. The Pinedale glaciation may have been extensive ~30,000 yr (Pierce, 1979)

and the last glacial maximum was ~20,000 yr on the nearby Sawtooth Range (Sherard et al., 2004). Deglaciation occurred from ~16,000 to ~12,000 yr (Chadwick et al., 1997; Thackray et al., 2004). The modern interglacial period followed deglaciation. The glacial period is noted for colder conditions with less evaporation, longer lasting snowpack, and greater spring runoff (Pierce and Scott, 1982), whereas the interglacial period has a warmer and drier climate.

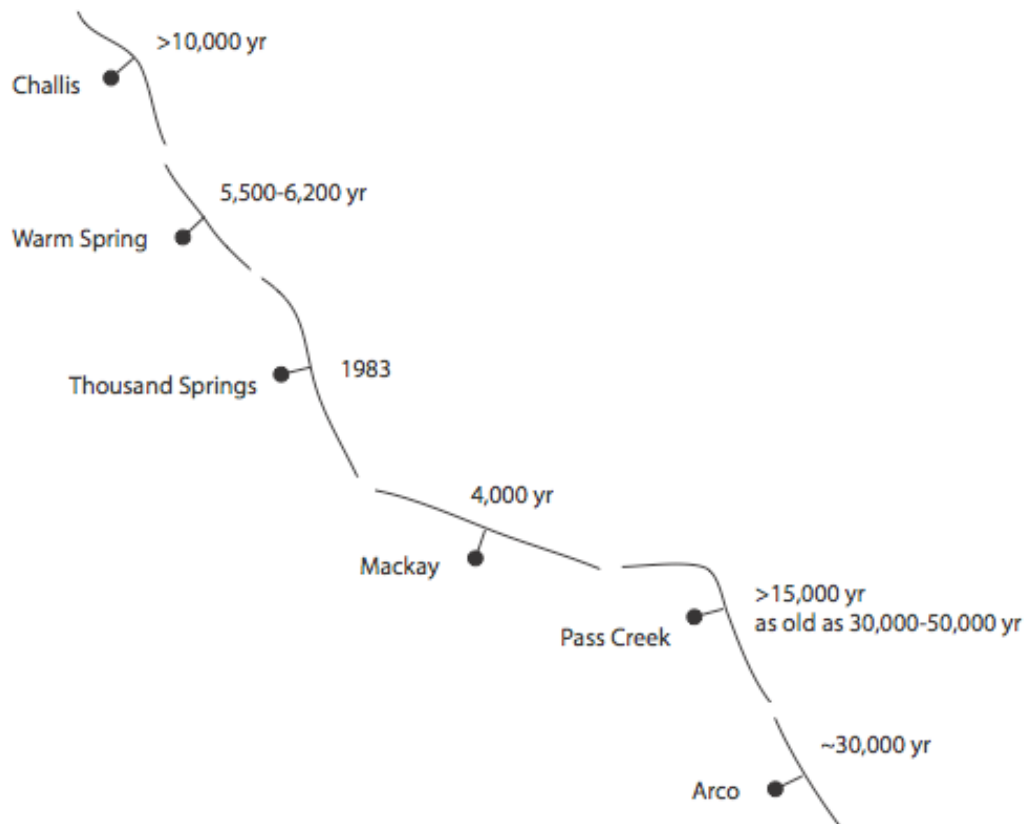


Figure 3. Fault segments along Lost River fault. Dates reflect last ground rupture from Crone and Haller (1991) and Pierce (1985).

The Lost River Range is a composite landform that developed in response to two orogenies, the Sevier and the Basin and Range. The Sevier orogeny was an active

compressive fold and thrust belt in western North American from Cretaceous to the Eocene. The Sevier orogeny transported and deformed thick successions of Paleozoic strata eastward in the Lost River-Arco Hills allochthon (Skipp and Hait, 1977). The Lost River-Arco Hills allochthon was subsequently broken up by several Basin and Range normal faults that have tilted the blocks eastward. The oldest rocks are exposed at the base of the thrust sheets on the western flanks of the mountain ranges. Orogenic collapse of the Sevier fold and thrust belt facilitated collapse and tectonic thinning of the fold and thrust belt hinterland with displacement on extensional faults (Constenius, 1996). Evidence for this mid-Eocene extension is the Pioneer Mountain metamorphic core complex, exposed in the Pioneer Mountains west of the study area (Wust et al., 1987). Between the two orogenies, there was a short period of normal faulting coeval with Challis volcanism (~55 Ma) (Janecke, 1992). These extensional faults are oriented at high angles to the current mountain front and several drainages (Elkhorn Creek, Jones Creek and Lone Cedar Creek) take advantage of the weaker rocks associated with these fault zones (Janecke and Wilson, 1992). The 1,800 m (6,000 ft) of relief between the high peaks and the valley results from mid Miocene to present displacement on the Lost River fault.

The drainage basins contributing sediment to the studied alluvial fans are composed of Paleozoic sedimentary rocks dominated by limestone and quartzarenites with minor sandstone and shale. These rocks record deposition in marine shallow water environments (Skipp and Hait, 1977). Table 1 summarizes the stratigraphy of the formations found in the Lost River Range. The Lost River Range has minor Tertiary intrusive dikes.

Table 1. Formations exposed in alluvial fan drainage basins (Ingwell, 1980; Link and Hackett, 1988; Wilson et al., 1990; Wilson and Skipp, 1994).			
Age	Name	Lithology	Thickness
Late Mississippian	Surrett Canyon	Gray, crystalline, thickly bedded limestone	260-335 m (553-1100 ft)
Late Mississippian	South Creek	Gray, crystalline, thickly bedded to massive limestone	87-140 m (285-450 ft)
Late Mississippian	Scott Peak	Gray, crystalline, thickly bedded to massive limestone	620-635 m (2034-2085 ft)
Late Mississippian	Middle Canyon	Gray, very fine- fine grained limestone	207-220 m (680-725 ft)
Early Mississippian	McGowen Creek	Gray to black, carbonaceous siltstone, mudstone and shale	146-1120 m (480-3670 ft)
Late Devonian	Three Forks	Gray, fine crystalline, fissile, platy, fossiliferous limestone	46-90 m (150-300 ft)
Devonian	Jefferson	Dark gray, finely crystalline dolomite with interbedded limestone	485 m (1590 ft)
Silurian	Laketown	Gray to black, finely crystalline, thick bedded to massive dolostone	154-396 m (505-1300 ft)
Late Ordovician to Early Silurian	Fishhaven	Light gray to black, finely crystalline, thick bedded to massive dolostone	308-407 m (1009-1335 ft)
Ordovician	Kinnikinic	Light gray, fine-medium grained, thick bedded quartzarenite	230-730 m (755-2400 ft)
Ordovician	Summerhouse	Purple to white, fine-coarse grained quartzarenite	300 m (915 ft)
Cambrian	Tyler Peak	Quartzarenite	>32 m (>105 ft)
Cambrian	unnamed phyllite	Gray to brown phyllite with interbedded sandy carbonate	100 m (330 ft)
Late Proterozoic to early Cambrian	Wilbert	Light pink, fine-coarse grained, pebbly, thickly bedded quartzarenite	418 m (1370 ft)

CHAPTER 3

QUESTIONS

Alluvial fans along the western flank of the Lost River Range do not exhibit classic alluvial fan morphology. Rather, these fans have been incised with subsequent deposition and only a few of the fans are active today. This unique aspect is the focus of this study, which attempts to explain the development of allostratigraphic packages within these alluvial fan deposits. There are three questions to be addressed in this study:

- 1) What sediment transport processes are responsible for deposition on the alluvial fans?
- 2) What is the geometric and temporal relationship between gravel packages and their bounding surfaces for each alluvial fan?
- 3) What are the similarities and differences in the geometry of the gravel packages of the four alluvial fans?

To investigate these questions, several critical terms must be defined. *Syntectonic sediments* are sedimentary deposits that were deposited as the result of active tectonic deformation. *Growth strata* are syntectonic sediments that are deformed by tectonic activity coeval with or soon after deposition. Commonly, the deformation consists of folding of strata adjacent to the active structure. A *surface* is a 2-dimensional plane that is a mappable geomorphic feature (Fig. 4). Surfaces can mantle landforms and topography, but have no overlying rock. Nondeposition and/or erosion occur on surfaces. An *unconformity* divides packages of rock and represents a period of nondeposition and/or erosion followed by deposition. A surface can become an unconformity when

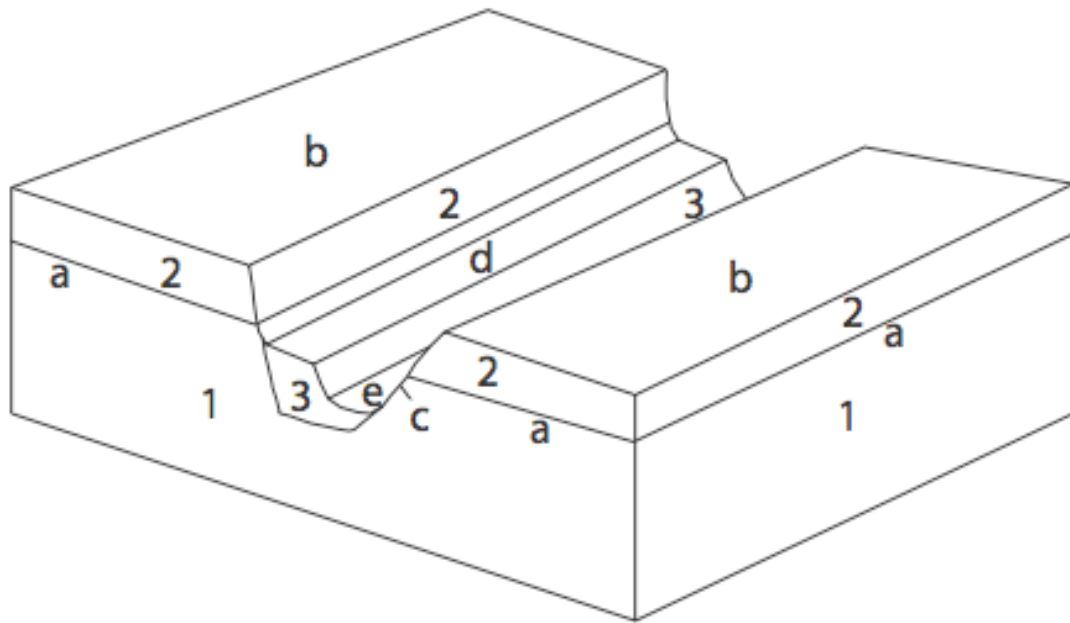


Figure 4. Schematic diagram outlining key terms. Surfaces are labeled with letters and gravel packages with numbers. The order of surface formation follows alphabetical sequence with *a* being the oldest. Gravel package ages follow numerical order with 1 being the oldest. Unit *a* is surrounded by sediment and is an unconformity while *b*, *c*, *d* and *e* are not overlain by sediment and are surfaces. Surface *c* is a U-shaped surface, which is the channel way.

buried by sediment. *Gravel packages* are 3-dimensional blocks of coarse-grained sediment bound above and below by unconformities and/or surfaces (Fig. 4). Sequences and gravel packages are similar but correlative conformities are not identified in the alluvial fan sediments. *Channel ways* are specific incised surfaces created by the removal of debris. The trough, *c*, is V- or U- shaped in cross section (Fig. 4). The surface includes the bottom of the channel way as well as the sidewalls. If the channel way is filled with sediment, as is common, then the base of the channel way will be an unconformity. Channel way is synonymous with incised channel from Blair and McPherson (1994). Water does not always flow in the channel way. Weissman et al. (2002) elected to use sequence stratigraphy terms for unconformity bound packages of

sediment on alluvial fans. Sequence stratigraphy terminology will not be used here, even though the concepts are similar. Assumptions associated with sequence stratigraphy are not appropriate for alluvial fans.

CHAPTER 4

METHODS

The proposed questions were investigated through collection of field data. The field component entailed mapping and characterization of the alluvial fan surfaces, measurement of vertical sections, and measurement of carbonate coat thicknesses on clasts from each surface. Characterization of alluvial fan surfaces was performed to distinguish the different surfaces on each alluvial fan. Each surface was described with attention given to the sediment characteristics observed at the surface including, grain size, clast lithology and matrix, microrelief of the surface, vegetation, and surface slope. The slopes of the surfaces are especially important because these data will provide evidence for amount and direction of tilting. The slopes were measured in the field with the inclinometer on a Brunton Transit. Slopes were measured and calculated from topographic maps (1:24,000 scale) in degrees and unitless ratio (ft/ft). Field measurements of surface slopes were not measured for the lowest surfaces. Vertical exposures were located at terrace scarps where measured sections were described. A tape measure and Jacob's staff were used to measure the height of sections. Sections were described on a centimeter scale. Lithologic descriptions of gravel lithofacies included, but were not limited to, grain size, roundness, grain shape, clast composition, packing, matrix, sorting, sedimentary structures, and bounding surfaces.

Pedogenic carbonate coats are common soil features found on gravel-size clasts in semiarid and arid climates with open vegetation (Pustovoytov, 2002). Growth rates of calcium carbonate coats can be used to calculate ages of soil development, which

correspond to the duration of inactivity on the alluvial fan surfaces. These ages are minimum ages because coat development does not occur immediately after the surface becomes inactive. There is a latent period during which no coat growth occurs. Coats are composed of calcium carbonate laminae precipitated on the undersides of large clasts, (Pustovoytov, 2002) with the youngest laminae on the clast and progressively older layers toward the outer surface. Parallel laminae become older toward the clast. In gravelly soils, precipitation of calcium carbonate is a result of evapotranspiration (Blisniuk and Sharp, 2003).

The best developed calcium carbonate cutans occur in the Bk horizon, generally between 0.3 and 0.5 m (1 to 1.5 feet) below the surface. Ca^{2+} ions are supplied by rainwater, eolian deposition, and locally from parent calcareous material, whereas carbonate (CO_3^-) ions are produced from decay of organic material in the soil, plant respiration, and atmospheric CO_2 (Blisniuk and Sharp, 2003). Coat thicknesses are measured on a millimeter scale and are generally less than 10 mm thick.

The thickness is dependent on clast size, soil age, and clast lithology. Coat thickness increases directly with clast size (Pustovoytov, 2002). With equal clast size and soil age, carbonate clasts have thicker coats than non-carbonate clasts. To reduce the number of variables, only carbonate clasts of the cobble (64-256 mm) size fraction were measured.

Clasts of this size fraction and lithology are very common on the alluvial fans flanking the Lost River Range. These parameters are congruent with the methods of Pierce (1985) and Pierce and Scott (1982) that established growth rates for carbonate coats on clasts in the southern part of the Big Lost River valley. An equation relating

coat thickness to numerical age was established by Pierce (1985). This study was performed near the town of Arco located in the southern part of the Big Lost River valley. Rates of carbonate coat growth on the fans deposited near Mackay are assumed to be the same as those near Arco, based on very similar climatic, topographic, and geologic settings (Pierce, 1985).

Using the average growth rate established by Pierce (1985) and thickness of coats found on the alluvial fan surfaces, a numerical age was calculated. Carbonate coats provide minimum ages of surface stability. The duration for initiation of coat growth after the establishment of a surface is unknown. About 30 coats were measured per surface. This is a large enough population to compute an average coat thickness and solve for an age of the surface that best represents each surface. Pits were dug about 0.3 to 0.5 m deep in the surface to find the thickest coats. The thickest part of the coat was measured. The coats were measured with a comparator, which has a 6x magnification [Edmund Optics NT55-148] and is accurate to 0.1 mm. Coat thickness was measured accurately to 0.1 mm. The locations of the pits were noted on digital orthophoto quadrangles (DOQ) in the field (Plate 1).

The dominance of quartzarenite clasts in the Elkhorn Creek alluvial fan deposits impedes age calculations, since the growth rate established by Pierce (1985) is based on carbonate coats developing on carbonate clasts, not quartzarenite clasts. Enough carbonate clasts were uncovered for most of the surfaces on Elkhorn Creek alluvial fan. However, on Surface Z no carbonate clasts were uncovered. A new growth rate was established for calcium carbonate growth on quartzarenite clasts. This new growth rate was only applied to clasts on Surface Z. Carbonate coats were measured on quartzarenite

and carbonate clasts on Surface X and W (Pit 21 and 22, respectively; Appendix). The coats on the limestone clasts were thicker than coats on quartzarenite clasts (on average 0.1 mm on Surface X and 0.3 mm on Surface W). Average coat thicknesses on quartzarenite clasts are 77.5% thinner than carbonate clasts on the same surface. The new growth rate was determined by multiplying the established growth rate (0.6 mm/10ka yr; Pierce, 1985) by the percent difference (77.5%), which yields a new growth rate of 0.5 mm/10ka yr. The resulting age is reasonable and consistent with other surface ages and their stage of surface modification.

The exposure of a surface to the atmosphere and the presence of a slope, no matter how shallow, makes it prone to surface modification processes. Surface modification impacts the surface morphology and sedimentology. These modifications can affect many surface dating methods, as well as the deposits observed in vertical section. Multiple processes can be occurring at the same time on the fan surface and different processes can be active on different parts of the fan at the same time (e.g. dissection at the toe and animal burrowing midfan).

Table 2 shows a list of factors that modify alluvial fan surfaces. Factors that play a significant role on the fans of this study will be explained further. Winnowing by overland flow involves mobilization of fines from primary deposits and redeposition down fan in depressions or transport beyond the alluvial fan system. This leaves a clast-supported gravel on the surface. This is especially common on the surface of an individual deposit. Rilling and gullying are small scale erosional features caused by overland flow and groundwater sapping, respectively. With further erosion and concentration of more water, large channels (meter scale) dissect the fan surface and

increase the relief of the surface. These channels exhibit a convergent drainage pattern that deepens down fan and headward erosion that lengthens the channel up fan. The excavated sediment is moved out of the alluvial fan system. The addition of windblown material (i.e. dust) will concentrate in topographic low areas and reduce surface relief. Dust can be trapped in gravels, especially matrix-poor clast-supported gravels. The origin of the dust is usually from outside the alluvial fan system. If the dust is carbonate, it may be the source for the carbonate coats. Animal burrowing can transport clasts, up to cobble size, vertically from depth to the surface. Pocket gophers selectively move pebbles from up to 0.5 m depth to the surface (K. Pierce, personal communication, 2006). Lateral erosion from rivers or lake shorelines can erode the toe of an alluvial fan. This has occurred on Upper Cedar Creek alluvial fan adjacent to the Mackay Reservoir. Colluvial collapse is gravity induced collapse of deposits and most likely occurs on steep unconsolidated deposits such as debris flow levees.

Table 2. List of surface modification processes that occur on alluvial fans. *From Blair and McPherson (1994).	
Winnowed by overland flow* Rilling and gullyng* Dissection Rainsplash erosion* Wind erosion and deposition* Plant rooting* Animal burrowing*	Weathering of clasts* Soil development* Groundwater flow* Case hardening* Lateral erosion* Tectonic faulting, folding, and tilting Colluvial collapse

CHAPTER 5

UPPER CEDAR CREEK ALLUVIAL FAN

Upper Cedar Creek alluvial fan is the second largest fan of the study (Plate 1). It has an area of 15.74 km² (6.15 sq mi) and a drainage basin of 25.50 km² (9.96 sq mi).

Upper Cedar Creek alluvial fan is the southernmost, of the four fans studied. The active channel is positioned to the south on the alluvial fan (Plate 1).

Carbonate lithologies (83%) in the Devonian Jefferson, Mississippian McGowen Creek, Middle Canyon and Scott Peak formations are the dominant rock type exposed in the drainage basin (Table 3) (Wilson and Skipp, 1994). Tertiary intrusive dikes crop out in a few small isolated areas. Dolomite and limestone are the primary clast lithologies in the alluvial fan deposits. The percents do not sum to 100 because 3% of the drainage basin is undivided Mississippian limestone.

Table 3. Formations present in Upper Cedar Creek alluvial fan drainage basin (Ingwell, 1980; Wilson et al., 1990).				
Formation	Age	Prominent Lithology	Percent of Drainage Basin	Area
Laketown Dolostone	Silurian	Dolomite	1	0.21 km ² 0.08 mi ²
Jefferson Formation	Devonian	Dolomite	31	8.01 km ² 3.13 mi ²
Three Forks Formation	Late Devonian	Limestone	4	0.94 km ² 0.37 mi ²
McGowen Creek Formation	Early Mississippian	Shale and Limestone	14	3.59 km ² 1.40 mi ²
Middle Canyon Formation	Late Mississippian	Limestone	19	4.89 km ² 1.91 mi ²
Scott Peak Formation	Late Mississippian	Limestone	23	5.96 km ² 2.33 mi ²
South Creek Formation	Late Mississippian	Limestone	2	0.52 km ² 0.20 mi ²

Surrett Canyon Formation	Late Mississippian	Limestone	3	0.65 km ² 0.25 mi ²
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Surface Descriptions

Six surfaces were mapped on Upper Cedar Creek alluvial fan: Surface A, B, C, F, C' and B'. The major surfaces are A, B, C, and F. C' and B' are minor surfaces that are lower (<10 feet) than their corresponding major surface (C and B, respectively). The minor surfaces do not have a large map area and their descriptions are lumped with the corresponding major surface. Surface C is the highest surface, B is intermediate and A is the lowest (Fig. 5). Surface F is an erosional surface located above Surface C. Each surface will be described individually starting with the lowest surface.

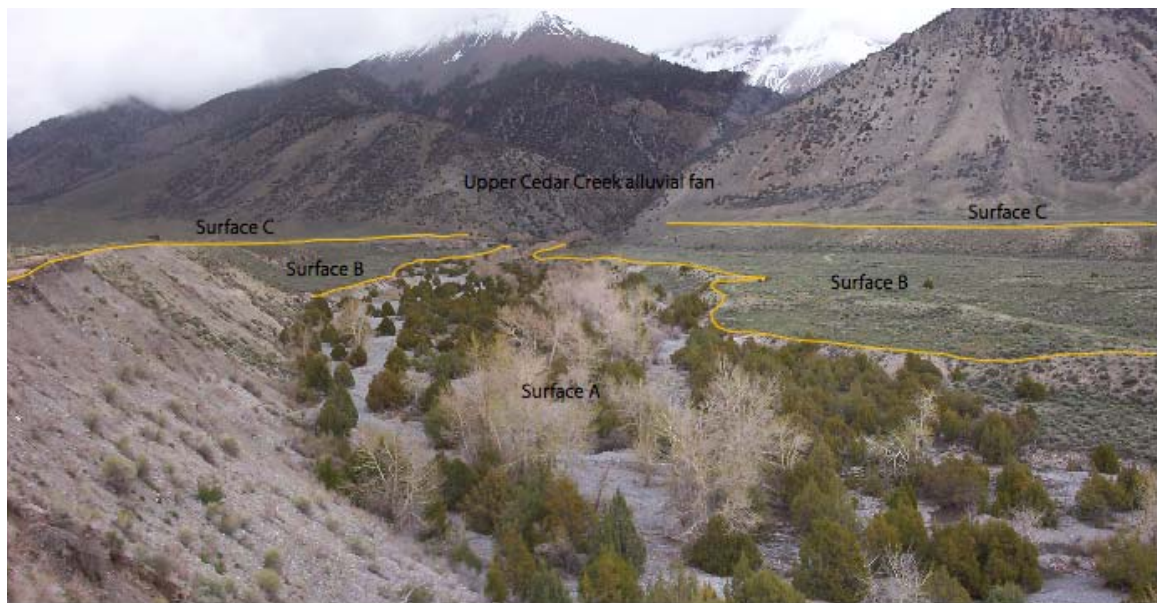


Figure 5. Photo of Upper Cedar Creek alluvial fan looking up fan at three major surfaces (A, B, and C).

Surface A

Surface A is located at the base of the channel way and is currently active. Upper Cedar Creek flows on Surface A for a few hundred meters before it infiltrates into the ground. The creek flows for a short distance because a local rancher diverts most of the flow away from Surface A to water his pasture and cattle. Surface A is ~10 m (30 ft) below Surface B near the apex and <1 m (3 ft) below Surface B near the toe. Surface A has an average slope of 2.68 degrees (0.0468 ft/ft).

The cover of Surface A is covered predominately by cobble size carbonate clasts ranging in size from pebbles to boulders. Volcanic clasts are rare. Clast shapes range from subangular to subrounded; however, a few rounded clasts were observed. No matrix is observed in gravels at the surface (Fig. 6A). However, there is matrix between buried clasts. The matrix is composed of moderately sorted sand with minor silt and clay. The amount of matrix increases with depth into the gravels. There are no carbonate coats on clasts of this surface. The few observed coated clasts are inherited from clasts from older surfaces that were incorporated into Surface A gravels.

Surface A is flat but not smooth. The surface has mounds of gravel up to ~ 1 m high that are organized into ridges and lobes. The ridges extend for several meters (<10 m) in length mostly down fan and are composed entirely of the gravel described above (Fig. 6B). The steep sided ridges are observed to be parallel or merge together at acute angles. There are places where the creek has eroded through ridges. Lobes are composed of gravel, are shorter than ridges, and have a sharp down fan contact



A



B



C



D



E



F

Figure 6. (A) Typical gravel outcrop of subangular to subrounded carbonate clasts without matrix or carbonate coats. Rock hammer is 30 cm long. (B) Three parallel ridges of different heights and slopes are several meters long; the highest ridge is 1.5 m high. The ridge side slopes starting at the top are 34, 25 and 24°. (C) Looking upfan at a gravel lobe about 1 m high with a sharp down fan contact. (D) A gravel ridge buries the base of the trees. (E) Gravel ridges bury the trunks of these trees. Note the presence of organic matter and fines on the surface. (F) An anastomosing pattern of gravels on Surface A.

such as in Figure 6C where the lobe appears to be deposited on top of the underlying gravels. Ridges and lobes bury the base of trees and bushes (Fig. 6D and 6E). Multiple channels cut through the lobes and ridges in an anastomosing pattern (Fig. 6F). Surface A has the greatest variety of vegetation of the surfaces on Upper Cedar Creek alluvial fan. Plants growing on Surface A include juniper, cottonwoods, and sagebrush. Surface A is clearly identified when seen from above because of the contrast provided by gray gravels and green trees and bushes (Fig. 7A). This distinct pattern seen from the air is exemplified in the digital orthophoto quadrangle (DOQ) and allows for easy mapping (Fig. 7B). Trunks of some of the trees are buried by gravel 10 to 30 cm deep (Fig. 6D and 6E). More fines are present in and around the tree trunks. In these areas the surface resembles Surface B. Near the toe of Upper Cedar Creek alluvial fan, Surface A is more vegetated and has a higher portion of fines, mostly silt, at the surface. The unit also widens (Fig. 7B and Plate 1).

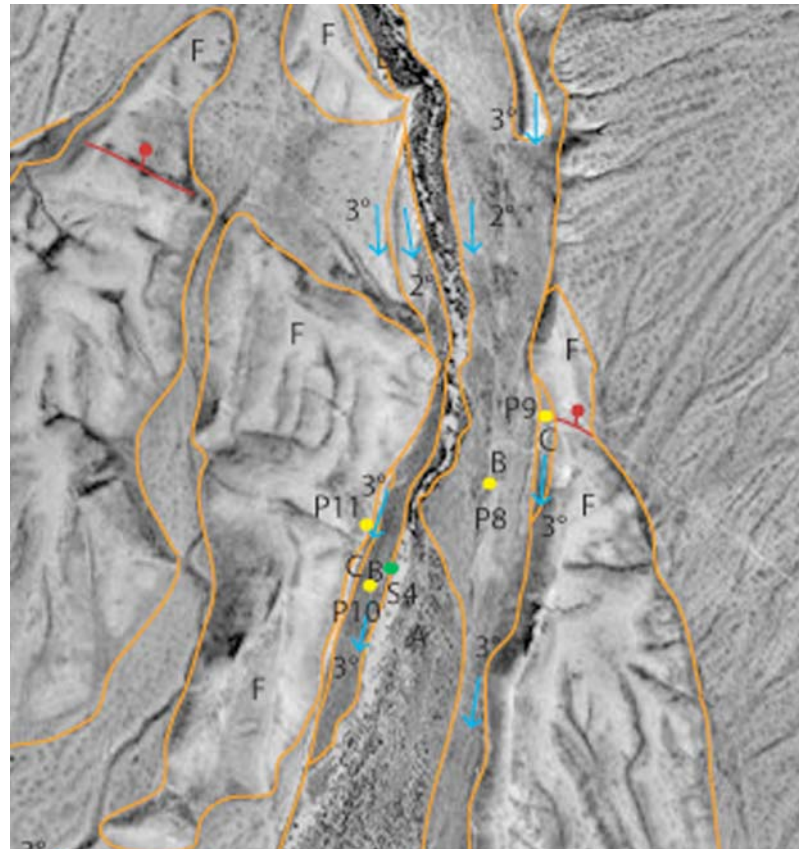
Surface B

Surface B is a well-defined intermediate age surface on Upper Cedar Creek alluvial fan (Fig. 5 and 7). The average slope of Surface B is 2.76° (0.048 ft/ft). This surface forms a relatively persistent bench that can be followed the length of the alluvial fan. Surface B is ~ 30 ft below Surface C near the fan apex. This height between the surfaces lessens to zero near the alluvial fan toe.

There are scattered subangular to subrounded carbonate pebbles and fewer cobbles on Surface B (Fig. 8A). Muddy silt fills the interstices between the clasts and makes up most of the soil at the



A



B

Figure 7. (A) The red line outlines the well vegetated map area of Surface A. North is to the left of photo. (B) Excerpt from Plate 1 demonstrating the pattern of Surface A on DOQ.

surface (Fig. 8A). The carbonate-rich soil developed on Surface B is composed mostly of silt and pebbles. The surface is soft; a 0.5 cm depression is left with each step.

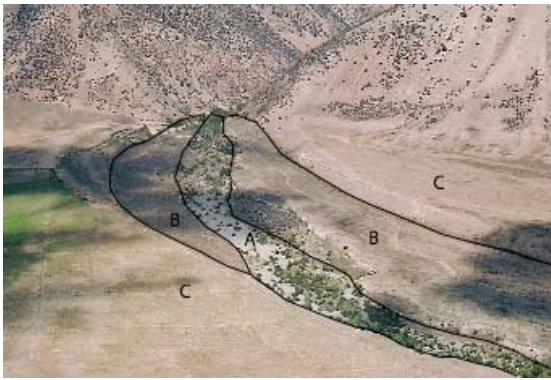
Microrelief of Surface B varies between 0.5 and 1 m. The topographic highs are linear ridges and lobes, which widen down fan. These mounds are especially clast rich, where as the topographic low areas are rich in fines at the surface. The microrelief landforms on Surface B are subdued compared to Surface A landforms. Surface B is not dissected by active drainages.



A



B



C

Figure 8. (A) Surface B with carbonate pebbles on the surface. Rock hammer is 30 cm long. (B) Surface B covered by sagebrush and with minor microrelief. Sagebrush is less than 1 m tall. (C) Black lines are contacts and surfaces are labeled with letters.

Surface B is mostly covered with sagebrush and grasses (Fig. 8B). There are no trees growing on this surface. Wild flowers low to the ground also grow on this surface. The abundance of sagebrush covering Surface B makes it appear green to brown from above depending on the season. From the air, Surface B appears to be flat and smooth (Fig. 8C). Surface B does not have a unique pattern like Surface A, when seen from above. Surface B and C look similar from the air and on the DOQ (Fig. 7B and 8C).

Surface C

The highest surface on Upper Cedar Creek alluvial fan is Surface C (Fig. 5). Ranchers have been using this surface for cattle grazing for at least hundred years. As a consequence, there are many roads and fences as well as an irrigation ditch crossing this surface. The average slope of Surface C is 3.05° (0.053 ft/ft).

There are few carbonate pebbles on the surface. The clasts are subangular to subrounded in shape. Most of the clasts have carbonate coats on them. A sandy-silt matrix dominates the ground surface (Fig. 9A and 9B). The soil is matrix-supported. The ground is soft and allows boot penetration of about 1 cm. No trees grow on Surface C. Sagebrush is the dominant plant along with grasses, wildflowers, and other short bushes (Fig. 9A, 9B and 9C). Anthills are common on this surface.

Surface C is relatively smooth with little microrelief. Topographic relief on the surface is less than 0.3 m. Surface C is inactive and undergoing degradational processes. Surface C is being buried near the fan apex and dissection occurs from midfan to the toe. The runoff channels exhibit a convergent drainage pattern (Fig. 9D and 9E). The



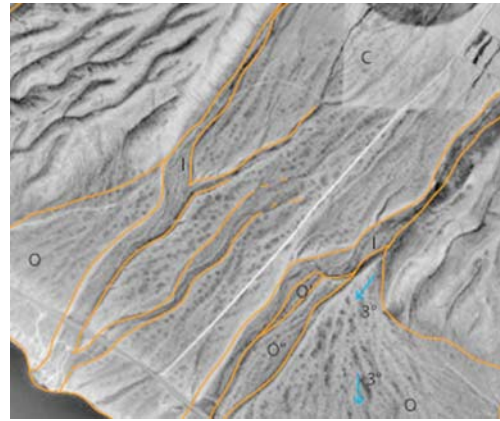
A



B



C



D



E

Figure 9. (A) Smooth morphology of Surface C with sagebrush and lack of clasts. Photo looking down fan. Person for scale. (B) Note sagebrush, a few clasts and smooth surface. Looking at oblique up fan view (C) Surface C looking downfan. Surface A is the gray gravel and green trees. Surface C is to the right of Surface A and the road. Surface F and conglomerate in foreground. (D) Excerpt from Plate 1. Convergent drainage pattern of channels on Surface C, I is incised channels and O are other surfaces. (E) Incised convergent drainage pattern of channels flowing off to left of photo. Up-fan is toward the upper right corner.

channels are incised up to 4 m. Surface C is currently being buried by newer and active alluvial fans north and south of the creek.

Surface F

The top of the bluffs near the toes of Upper Cedar, Pete and Jones Creek alluvial fans is Surface F (Plate 1). The bluffs extend farther south, out of the study area, to the town of Mackay, Idaho. Surface F lies 70 m (230 ft) above Surface C (Fig. 10A).

Surface F mantles several highly dissected bluffs. The bluffs are composed of a carbonate-cemented conglomerate. A silty top layer of poorly developed soil is enabling sagebrush and a few grasses to grow. Clasts of weathered conglomerate are common on the ground. Outcrops of the conglomerate are also common (Fig. 9C, 10B, and 10C).

Boulders of Gravel Package IV are being deposited as rock fall deposits in Gravel Package I below (Fig. 10D). The tops of the bluffs have a well defined down fan convergent drainage pattern formed by deeply eroding gullies (Fig. 10E and Plate 1). Incision of these gullies is on the order of 3 m. It is unclear if the original depositional Surface F is present today and how far it is above the current surface. In places, the flatness and accordant summits of Surface F suggest parts of the surface are locally still nearly intact.

Surface O

Surface O is used to denote other alluvial fan surfaces on the DOQ (Plate 1). Different Surface O's do not necessarily correlate or represent surfaces of the same age. These surfaces are generally, but not always, above Surface C. This surface was not a focus of the study but plays a small part in the evolution of these alluvial fans and so is



E
 Figure 10. (A) Labeled photo of the surfaces of Upper Cedar Creek alluvial fan. Looking down fan from the apex. (B) Looking down fan at bluffs showing the amount of erosion on Surface F and conglomerate outcrops of Gravel Package IV. (C) Surface F is on the left. Note uneven surface of conglomerate outcrops in distance (arrow). Looking down fan. (D) Prominent boulder is a clast of Gravel Package IV conglomerate incorporated into Gravel Package I from slope above. Person for scale. (E) Excerpt of Plate 1 showing down-fan convergent drainage pattern developed on Surface F.

mentioned here. Surface O is composed of smaller coalescing alluvial fans. Surface O has a range of slopes from 10 to 17° (0.176 to 0.306 ft/ft). The surface morphology of Surface O is angular to subangular carbonate boulders and cobbles organized into ridges and mounds. The parallel ridges are up to 1 m high and are continuous for up to ~10 of m. Trees grow on the ridges.

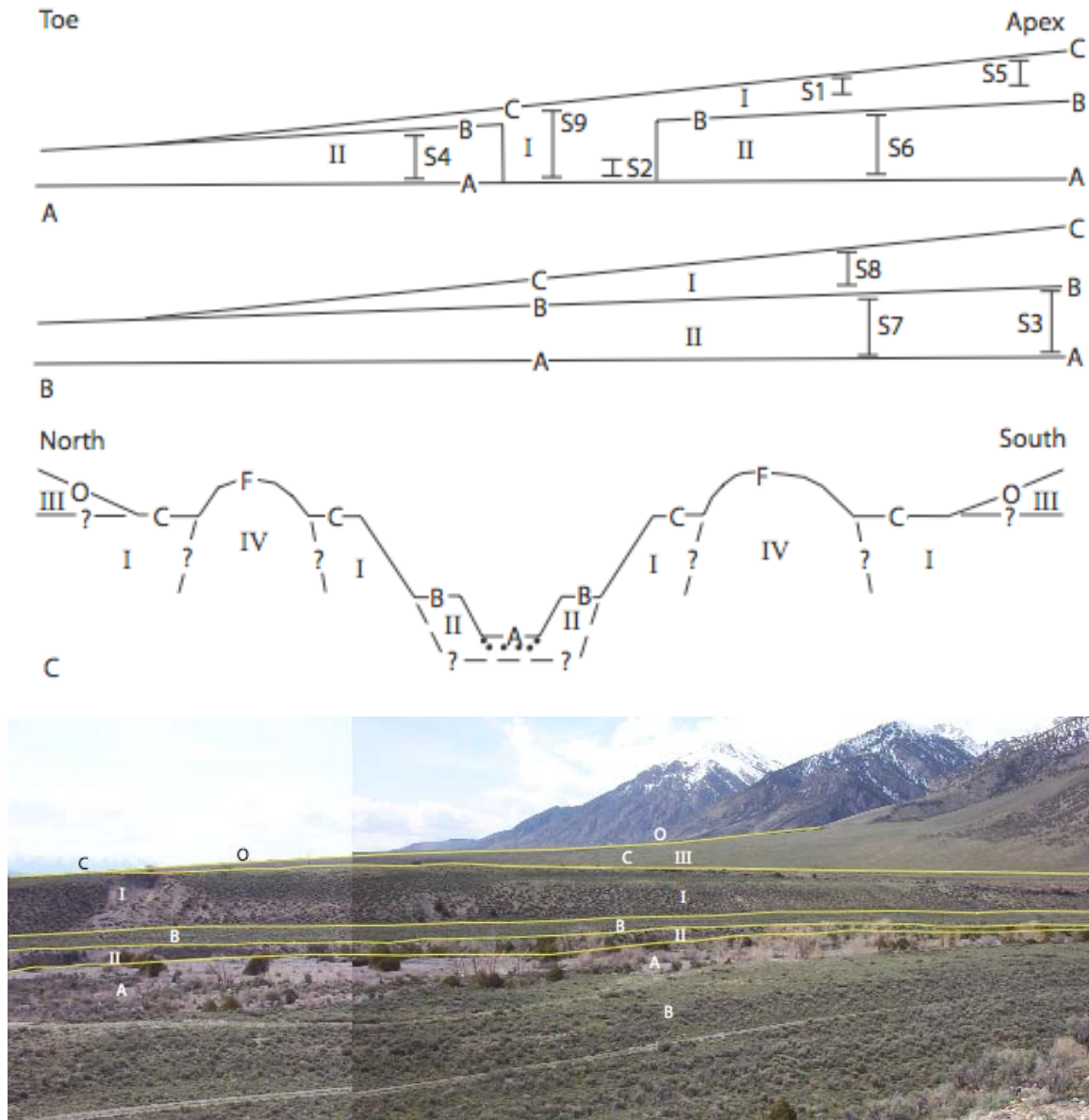
Gravel Package Descriptions

Sedimentological data was collected at ten sections on Upper Cedar Creek alluvial fan. From these sections several lithofacies were observed, including cobble gravel, pebble gravel, and silt facies. The location of each measured section is marked on Plate 1. The measured sections were used to characterize gravel packages. Upper Cedar Creek alluvial fan is composed of Gravel Packages, I, II, III, and IV (Fig. 11). Each gravel package will be discussed separately in numerical order.

Gravel Package I

Gravel Package I is composed of pebble and cobble gravels. The upper boundary of this package is Surface C (Fig. 11). The lower bounding surface is unknown because it does not crop out in the study area. Five measured sections were described through the gravel package (Sections 1, 2, 5, 8, 9, and 10). Each will be described individually in numerical order.

Section 1 was measured north of Upper Cedar Creek in Gravel Package I (Plate 1). The outcrop is 3-dimensional, caused by outbreak of an irrigation ditch, allowing the description to be made on one side and inclination of the beds to be measured on the



D

Figure 11. (A) Sketch of longitudinal exposure along the north side of Upper Cedar Creek. Surfaces are labeled with letters and Roman numerals label gravel packages. Sections are denoted with an S and a number. Section locations are denoted. Surface A does not underlie Gravel Package II and Surface B does not underlie Gravel Package I. (B) Sketch of longitudinal exposure south of the creek. (C) Cross section perpendicular to Upper Cedar Creek. No scale is implied. The dotted line is used to denote the base of the temporary stored sediment on Surface A. (D) Looking north at northern exposure of Upper Cedar Creek alluvial fan. Yellow lines divide surfaces from gravel packages. Labels correspond to line sketch. From A to the top of C is about 15 m.

other (Fig. 12E). Section 1 was described on the left hand side of the outcrop in Figure 12A. Figure 12B shows the outcrop from which the bed inclination was measured, behind the outcrop in Figure 12A. This outcrop face is oriented perpendicular to the mountain front.

Two facies are present in Section 1, cobble gravel and pebble gravel. The cobble gravel facies is massive and very poorly sorted (Fig. 12C). Clasts range in size from 3 to 200 mm. Their shape is subangular to subrounded. The poorly sorted, carbonate-rich, matrix is mostly silty sand, but grain sizes range from clay to very coarse sand. There is also an absence of matrix between some of the clasts. Clasts are carbonate and gray in color. The facies is clast supported with mostly tangential contacts and few long contacts. The cobble gravel has thicker beds than the pebble gravel.

The weakly stratified to massive pebble gravel facies is better sorted than cobble gravel facies but is otherwise similar. The pebble gravel has granule to cobble size grains with the majority being pebbles. Clast lithology is carbonate. The silty matrix is poorly sorted clay to very coarse sand that is carbonate-rich. The clast supported pebble gravel has mostly tangential contacts. Stratification is observed because of alternating facies (Fig. 12D).

Section 2 is measured through Gravel Package I. The scarp that Section 2 is exposed in is on the north side of the Upper Cedar Creek and is 30 m high but the section is 3 m high (Fig. 13A, 14). Surface B and Gravel Package II were eroded causing Surface A and C to share a map contact. To safely describe this large near-vertical outcrop a detailed stratigraphic section was described for the lower 3 meters (Section 2).



A



B



C



D



E

Figure 12. (A) The cliff exposure where Section 1 was described. (B) The cliff exposure parallel to fan radius where the dips were measured on individual beds around the corner from where the section was described. Figure 12B is the outcrop face behind the outcrop face seen in Figure 12A. (C) A close-up of the cobble gravel facies. Note coarse-grained nature of the clasts. (D) A close-up of the outcrop showing the alternating cobble and pebble gravel facies. (E) Outcrop of Section 1 viewed from a distance. Surface C is the top surface and the photo was taken standing on Surface B.

The rest of the outcrop was characterized based on observations made while scrambling up the cliff bound slopes (Section 9). The observations made on the high cliff (Section 9) are congruent with the descriptions of Section 2. The lithofacies for Section 2 are pebble and cobble gravel facies.



A



B



C

Figure 13. (A) Northern exposure of Gravel Package I. Section 2 was described at the cone shaped outcrop near the base of the cliff on the left. (B) A close up of the outcrop that Section 2 was described. Jacob staff is 1.5 m high for scale. (C) The alternating facies typical of Section 2. Jacob's staff to right with 10 cm increments marked.

The pebble gravel facies, of Section 2, contains clasts of mostly pebbles with some granules and cobbles. All of the clasts are subangular to subrounded and composed of carbonate rock. The weakly stratified, poorly sorted, clast supported gravel has tangential contacts and occasional long contacts. The moderately sorted matrix is sand-rich and has clay to sand size grains. Lobate shape clasts are flat lying to imbricated, but most of the pebbles are near equidimensional.

The massive, moderately sorted, clast-supported cobble gravel in Section 2 is similar to the pebble gravel but with a greater range of clast size. Cobbles are the dominant clast size, but pebbles and granules are present. The carbonate clasts are subangular to subrounded. The clast-supported facies has tangential contacts, but long contacts exist. Most of the long contacts are contacts between imbricated clasts. The sand rich matrix includes some clay and silt. Openwork textures are observed as well. Weak stratification is observed at Section 2 and is defined by an alternating succession of the two facies (Fig. 14).

The pebble gravel facies, in Section 2, alternates with and overlies the cobble gravel facies. The cobble gravel facies (0.9 to 0.15 m) generally has thicker beds than the pebble gravel facies (0.2 to 0.1 m). The lower contact of the cobble gravel and the upper contact of the pebble gravel are abrupt and planar. The upper contact of the cobble gravel and lower contact of the pebble gravel is gradational and wavy. Pebble clasts are on top of and between the cobble clasts at the facies boundary. The gradational contact between the facies and well-defined boundaries around the facies indicates a genetically related couplet. Dips were measured on some of the gravel beds, to be 2°S, 0, 0, 1°S, 3°S, going down section (Fig. 14).

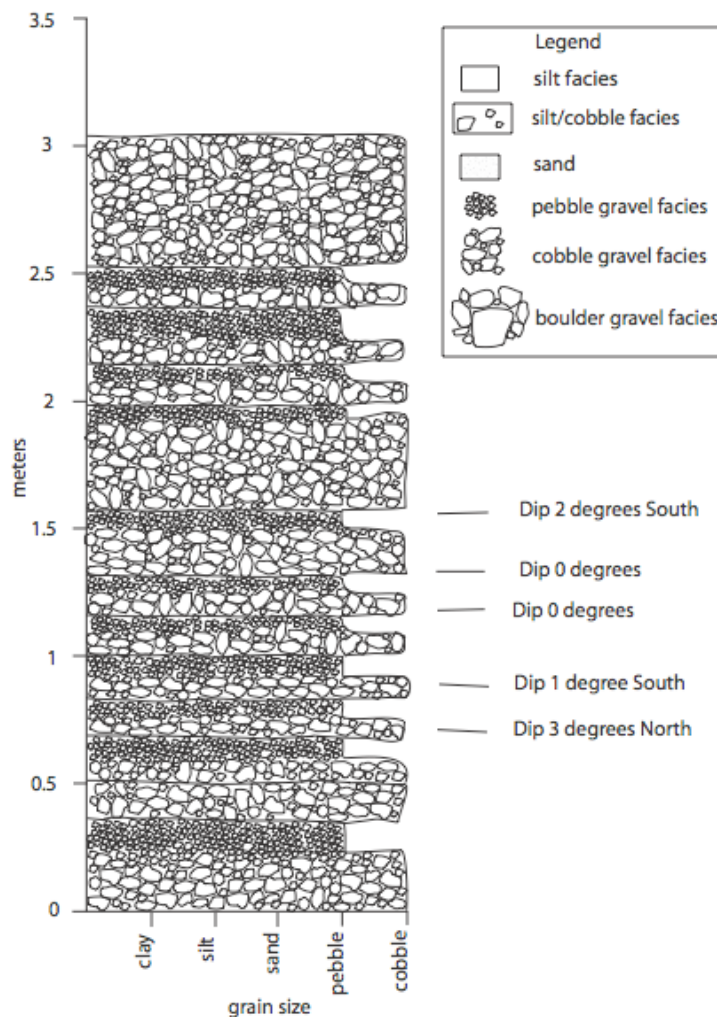


Figure 14. Stratigraphic column for Section 2 in Gravel Package I on Upper Cedar Creek alluvial fan. Note the alternating beds of cobble gravel and pebble gravel facies. The high cliff (Section 9) is similar to this section.

Section 5 was described through Gravel Package I, north of Upper Cedar Creek at the fan apex where the creek has been diverted. This exposure is man made and occurs directly above an irrigation ditch (Fig. 15A). The near-vertical Section 5 is almost 3.5 m high. The top of section 5 is Surface C; the bottom of the section is 8 to 9 m above Surface B. One inclination of 1° down fan was measured on a bed exposed in this section at the gray/tan color contrast (Fig. 15A and 15B). The silt rich beds in this



A



B



C



D



E



F

Figure 15. (A) Outcrop where Section 5 was described. People for scale. Photo taken by Jen Pierce, 2005. (B) Outcrop with color contrast enhancing the stratification, gray is the gravel and tan is silt with dark brown being current soil. (C) Close up of cobble gravel facies. Jacob staff for scale. (D) Silt facies (tan) overlying the cobble gravel facies (grey). (E) Close up of cobble gravel facies. Note range of clast sizes. Rock hammer for scale is 30 cm long. (F) Close up of silt facies with the few clasts of pebble size. Rock hammer for scale 30 cm long.

section make it different than other sections on Upper Cedar Creek alluvial fan. There are 4 different lithofacies observed in this measured section.

The massive, very poorly sorted, boulder gravel facies, in Section 5, has granule to boulder size clasts (Fig. 15C and 15D). The largest boulders are up to ~45 cm long. The carbonate clasts are subangular to subrounded. This clast-supported facies has mostly tangential contacts and rare long contacts. The sand rich matrix has some clay and silt.

The massive, poorly sorted, cobble gravel facies exposed in Section 5 is similar to the boulder gravel facies but is better sorted. Clasts range in size from granule to cobble and the largest clasts are ~25 cm long, but most of the clasts are pebbles (Fig. 15C and 15F). The carbonate clasts are subangular to subrounded. This facies is clast-supported with mostly tangential contacts and occasional long contacts. The moderately sorted silty sand matrix has a grain size range from clay to sand. There are lenses of predominantly clast supported pebble clasts that are ~1m wide and 5 to 10 cm thick (Fig. 15).

The massive silt facies is dominantly silt with floating pebble grains (Fig. 15F). The well-sorted silt matrix has minor clay. The carbonate cobbles are subrounded to subangular. This facies is matrix-supported except for the rare tangential contacts. The modern soil is developed in this facies. The silt is apparently reworked loess.

The massive silt/cobble facies has more gravel clasts than the clay/silt facies. The largest grain is 15 cm long with most clasts being cobble in size. Cobbles are composed of carbonate rocks. The poorly sorted facies is clast to matrix-supported with tangential

clast contacts. The matrix is silt-rich with minor clay. Lobate cobble clasts are flat lying. Section 5 is fining upward (Fig. 16).

Section 8 was measured through Gravel Package I, south of Upper Cedar Creek near the fan apex (Fig. 11B). This section is 2.8 m high. The lithofacies in Section 8 are identical to the lithofacies of Gravel Package I (Sections 1, 2, 5 and 9), consisting of cobble gravel and pebble gravel facies (Fig. 17). Surface C is the top of Section 8 and Surface B is several meters farther below the base of Section 8.

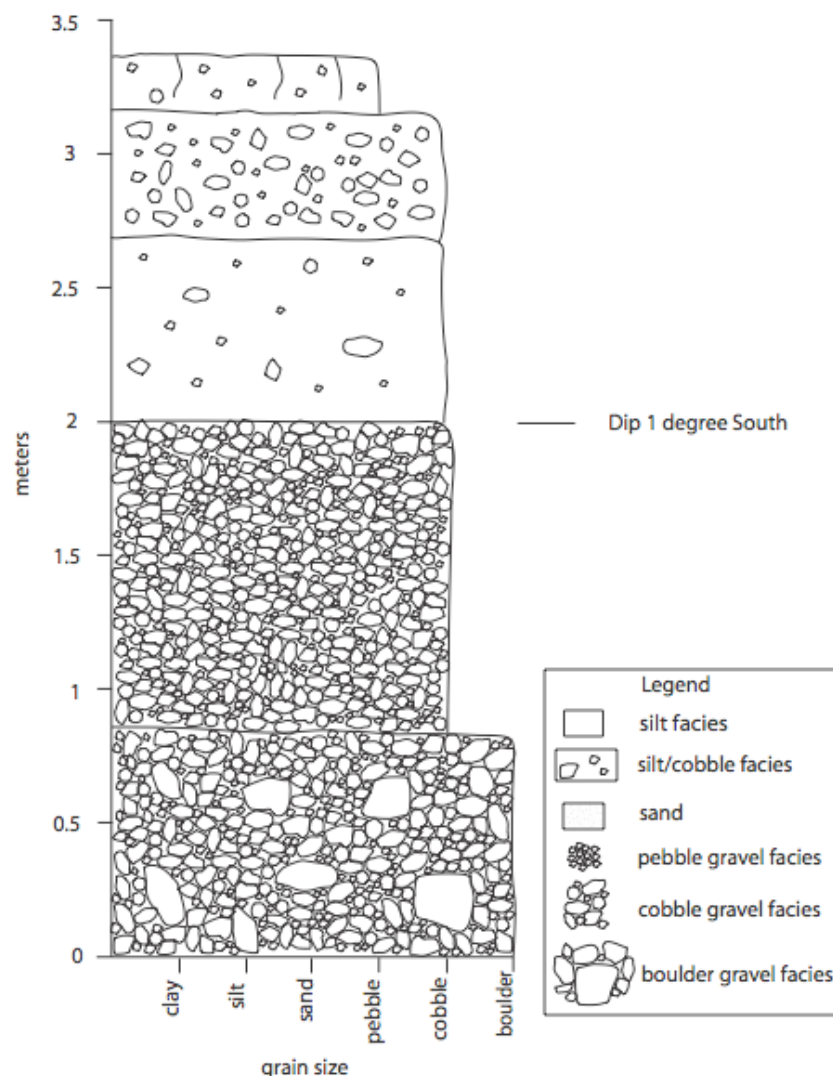


Figure 16. Stratigraphic column for Section 5 in Gravel Package I on Upper Cedar Creek alluvial fan. This section fines upward.

Section 9 was described through Gravel Package I. It is not a traditional measured section but is rather a characterization of sediment exposed in a 30 m high cliff. Precise height information was forgone for safety reasons (Fig. 18A). As in the

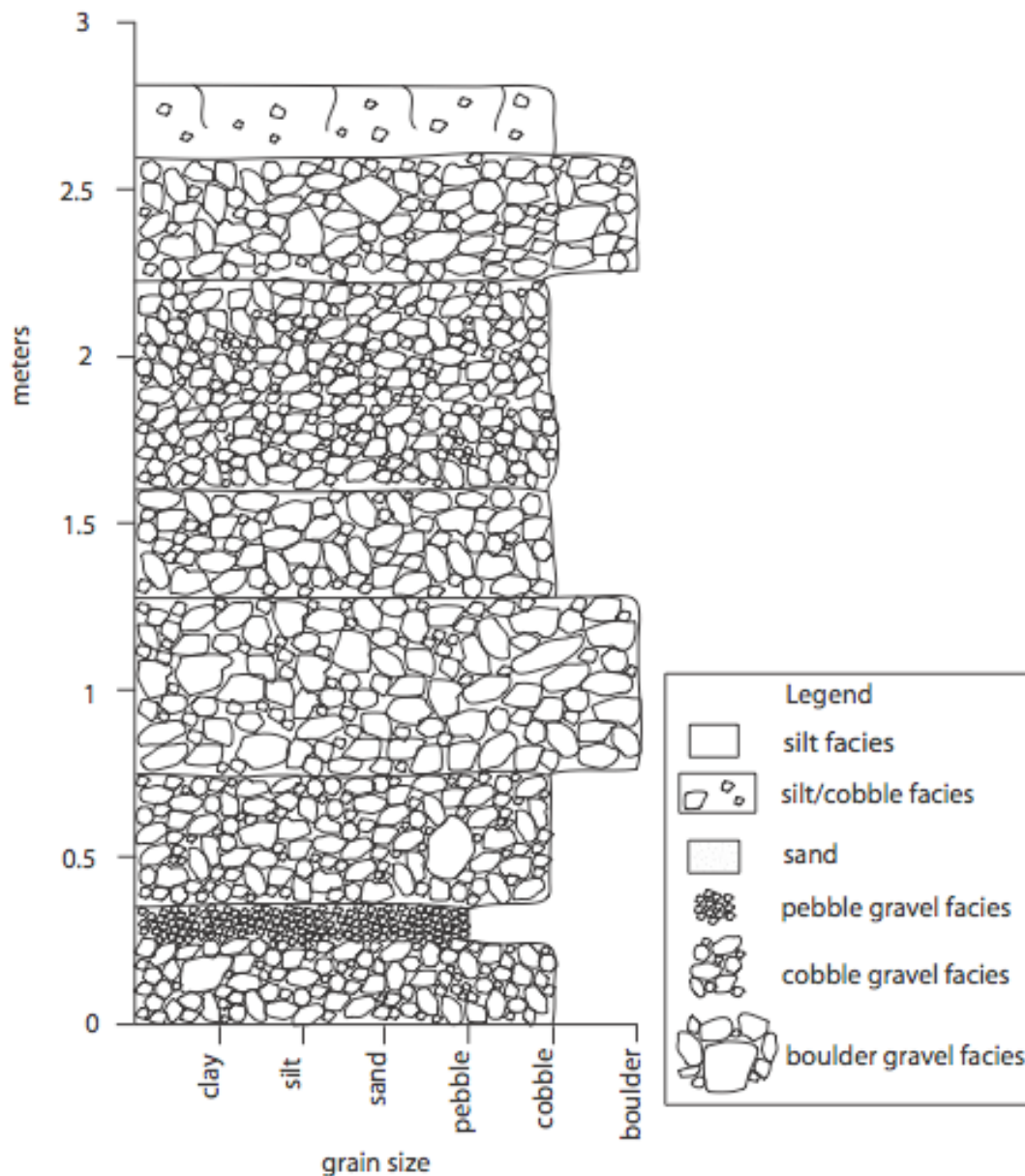


Figure 17. Stratigraphic column for Section 8 in Gravel Package I on Upper Cedar Creek alluvial fan. This section is composed mostly of cobble gravel facies.

description of Section 2, two facies were observed, pebble gravel and cobble gravel facies (Fig. 18B). The massive, poorly sorted cobble gravel is composed of subangular to subrounded carbonate clasts (Fig. 18B). The weakly stratified, poorly sorted pebble gravel is also composed of subangular to subrounded carbonate clasts. Both facies are clast-supported with tangential contacts and a few long contacts. The matrix for both facies is moderately sorted clay to sand, but mostly silty sand. An openwork texture especially in the cobble gravel facies was observed. The outcrop is weakly stratified with an alternating succession of the facies (Fig. 18B).



A



B

Figure 18. (A) Outcrop of Section 9, about 30 m high. Note horizontal stratification. (B) Close up photo of alternating facies. Cobble gravel facies appears gray and pebble gravel facies is tan. Marks on Jacob's staff are 10 cm.

Section 10 was described at a vertical scarp in Gravel Package II adjacent to Mackay Reservoir. The section is 4.4 m high (Fig. 19A and 20). Surface C is the top of the section. The outcrop is oriented perpendicular to the fan radius, thus no bed inclination data were collected. Two facies are identified in Section 10, cobble gravel and pebble gravel facies.

The massive, poorly sorted cobble gravel facies of Section 10 has clasts composed of carbonate rocks (Fig. 19B). Clast size ranges from granules to cobbles with a large majority of cobbles. The largest clasts are ~15 cm long. The clasts are subangular to subrounded (Fig. 19C). The facies is clast-supported with mostly tangential contacts and occasional long contacts (Fig. 19D). The poorly sorted matrix contains clay to sand size grains. The matrix is rich in sand.



A



B



C



D

Figure 19. (A) Outcrop of Section 10. (B) View of massive to crudely bedded coarse grained gravel. (C) Close up of cobble gravels next to rock hammer. Pebble gravel above rock hammer, which is 30 cm long. (D) Close up of cobble gravel. Tape measure with decimeter increments for scale.

The poorly sorted pebble gravel facies of Section 10 is pebble-rich but contains granule to cobble size clasts (Fig. 19C). Most of the clasts are between 0.5 and 2 cm long. The carbonate clasts are subangular to subrounded. The poorly sorted matrix consists of clay to sand sized grains and is sand-rich. The weak stratification of the pebble gravel facies is defined by flat lying clasts.

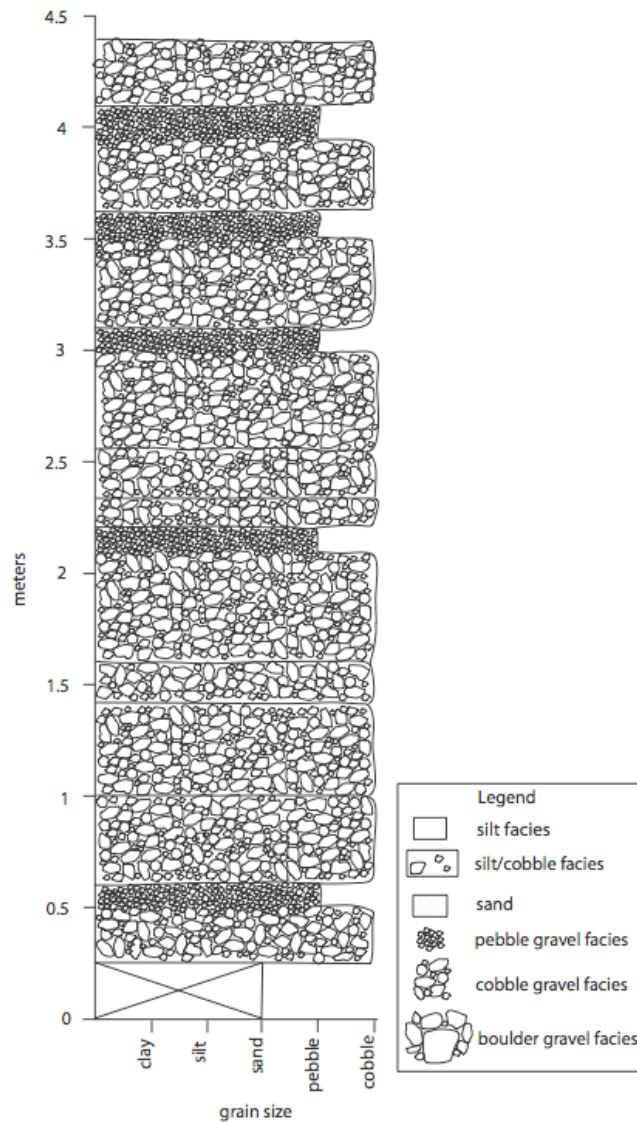


Figure 20. Stratigraphic column for Section 10 in Gravel Package I on Upper Cedar Creek alluvial fan. The upper portion of this section exhibits classic pebble and cobble gravel couplets.

Seventeen stratigraphic units are present in the moderately stratified section. The beds are laterally continuous for several meters. The cobble gravel facies usually composes the thicker beds (0.5 m) whereas the thinner beds are composed of pebble gravel facies (0.2 to 0.5 m) (Fig. 20).

Gravel Package II

Gravel Package II is composed of gravels described in 4 measured sections (Sections 3, 4, 6, and 7) (Fig. 11). Gravel Package II is bound above by Surface B and extends at least as deep as the channel way (Fig. 11D). The lower boundary of Gravel Package II is not exposed. Each measured section will be described in numerical order.

Section 3 was measured in Gravel Package II at the mountain front south of Upper Cedar creek. I rappelled to safely describe the 7 meters (23 feet) of this section (Fig. 21B and 22). Section 3 has the same facies, pebble gravel and cobble gravel, as in Section 2 (Fig. 20D). The gravel facies is organized into thick (0.3 to 0.9 m) beds. The pebble facies is observed in beds with thicknesses between 0.2 to 0.8 m (Fig. 21B and 22). The thick multiple beds of pebble gravel facies have internal stratification unlike the cobble gravel facies. Dips measured from strata are 2°S, 2°S, 2°S, 0°, and 5°S, going down section (Fig. 21 and 22). A sand bed that is 1-2 cm thick composed predominately of coarse sand and laterally continuous for ~1 m is also present (Fig. 23C). This is the best sorted bed in the section.

Section 4 was described in Gravel Package II north of Upper Cedar Creek. Section 4 is a short section (1.5 m high) because it was measured near the toe, closer to where the surfaces merge (Fig. 11 and 23A). In this short section, there are 4 beds



Figure 21. (A) Outcrop of Section 3 showing weak stratification. Boot for scale. (B) The pebble gravel facies bound above and below by cobble gravel facies. Pencil is in the stratified pebble gravel facies. The cobble gravel facies lacks matrix, exhibiting openwork. (C) Pebble and cobble gravel facies along with the stratified sand bed. Pencil for scale. (D) Stratification is easily seen with alternating facies. (E) Looking down section at the coarse and weakly gravels. Person for scale.

composed of alternating pebble and cobble gravel facies (Fig. 23B and 23C). Both facies are massive, poorly sorted gravels containing subangular to subrounded carbonate clasts (Fig. 23B, 23C and 23D). The beds are not as laterally continuous as the beds in vertical sections near the apex and are generally less than 1 m thick.

Section 6 was described through Gravel Package II north of the creek (Fig. 11A and Plate 1). The section is a vertical cliff that is ~3.5 m high (Fig. 24A). The top of the section is Surface B and the base of the section is level with Surface A. There are 7 depositional units defined by clast orientation and average clast size. Both imbricated and flat lying clasts are present. Lenses of sandy silt also contribute to stratification. The massive, poorly sorted pebble gravel facies is clast-supported. The clasts are pebbles and granules that are subangular to subrounded (Fig. 24B and 24C). The largest clasts are ~2.5 cm long and are of carbonate rock. Lobate clasts are flat lying, thereby creating stratification. The matrix is silt-rich to openwork (Fig. 24B). The pebble gravel is continuous for ~1 m laterally. A board is exposed 1.5 m in or deposited against cobble gravel facies deposits, left of Section 6 (Fig. 25). The board is a milled piece of lumber that has nail holes. Section 6 is displayed as a stratigraphic column in Figure 26.

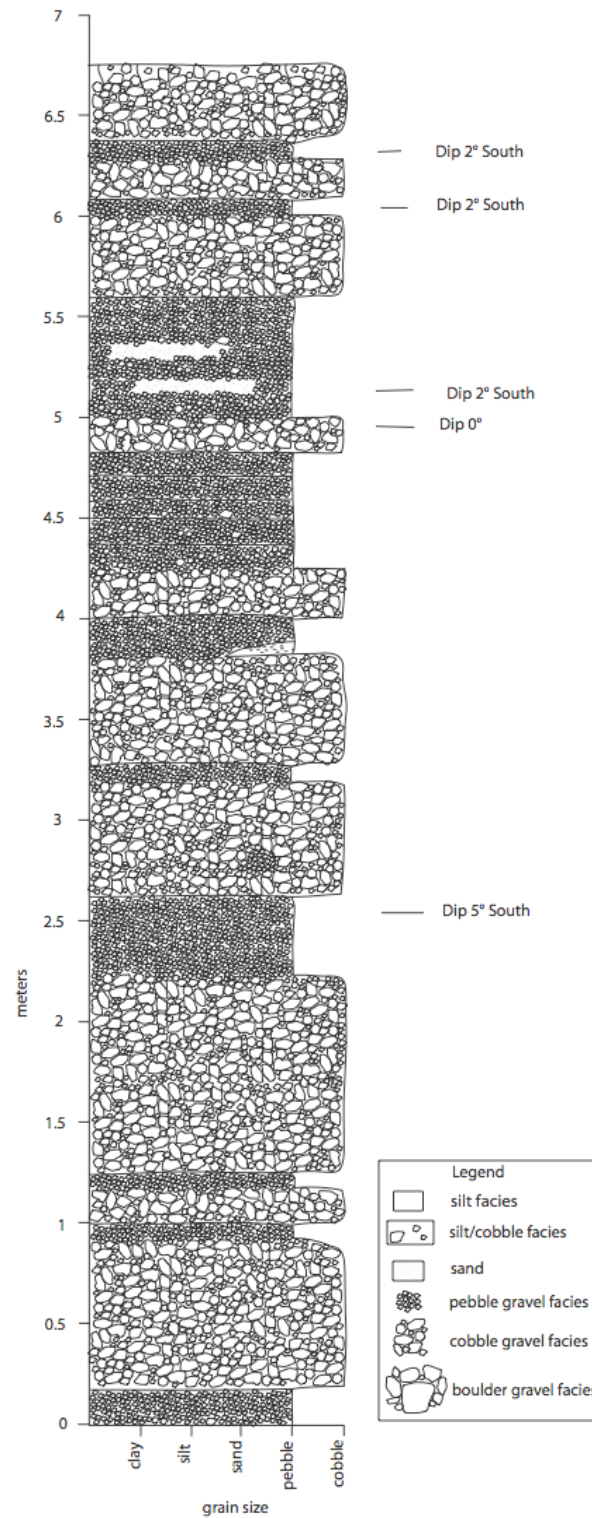


Figure 22. Stratigraphic column for Section 3 in Gravel Package II on Upper Cedar Creek alluvial fan. Note the alternating pebble and cobble gravel facies. Sand beds are interbedded with pebble gravel in upper portion of section.

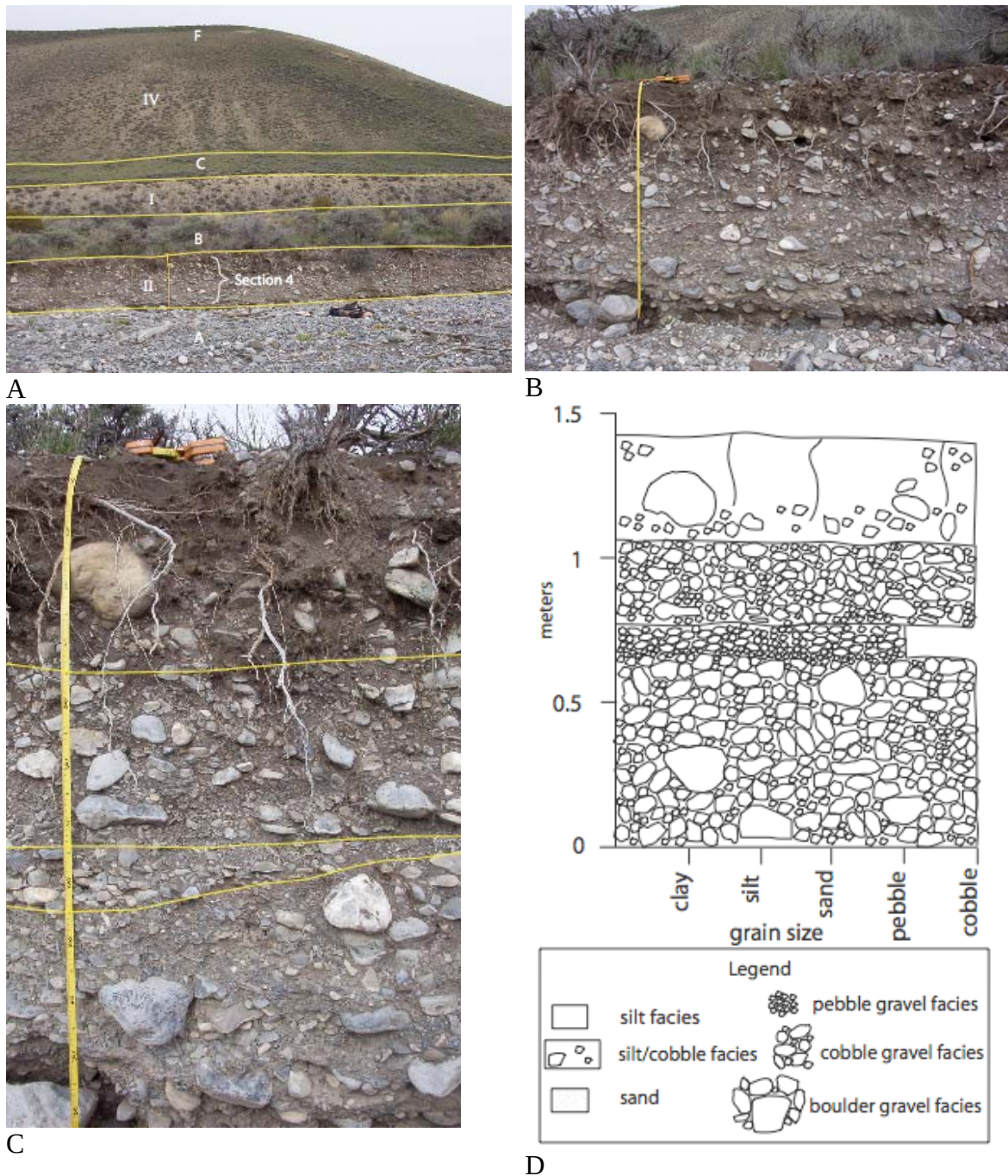


Figure 23. (A) Location of Section 4 in Gravel Package II. Yellow lines are contacts between surfaces and gravel packages. Letters are surfaces and Roman Numerals are gravel packages. Tape measure for reference left of backpack. (B) Upper dark brown layer is the silty modern soil and gray clasts are carbonate. (C) Close-up photo of facies. Yellow lines denote bed contacts that correspond to the sketch of Section 4 (Fig. 21D). (D) Stratigraphic column of Section 4 in Gravel Package II on Upper Cedar Creek alluvial fan.

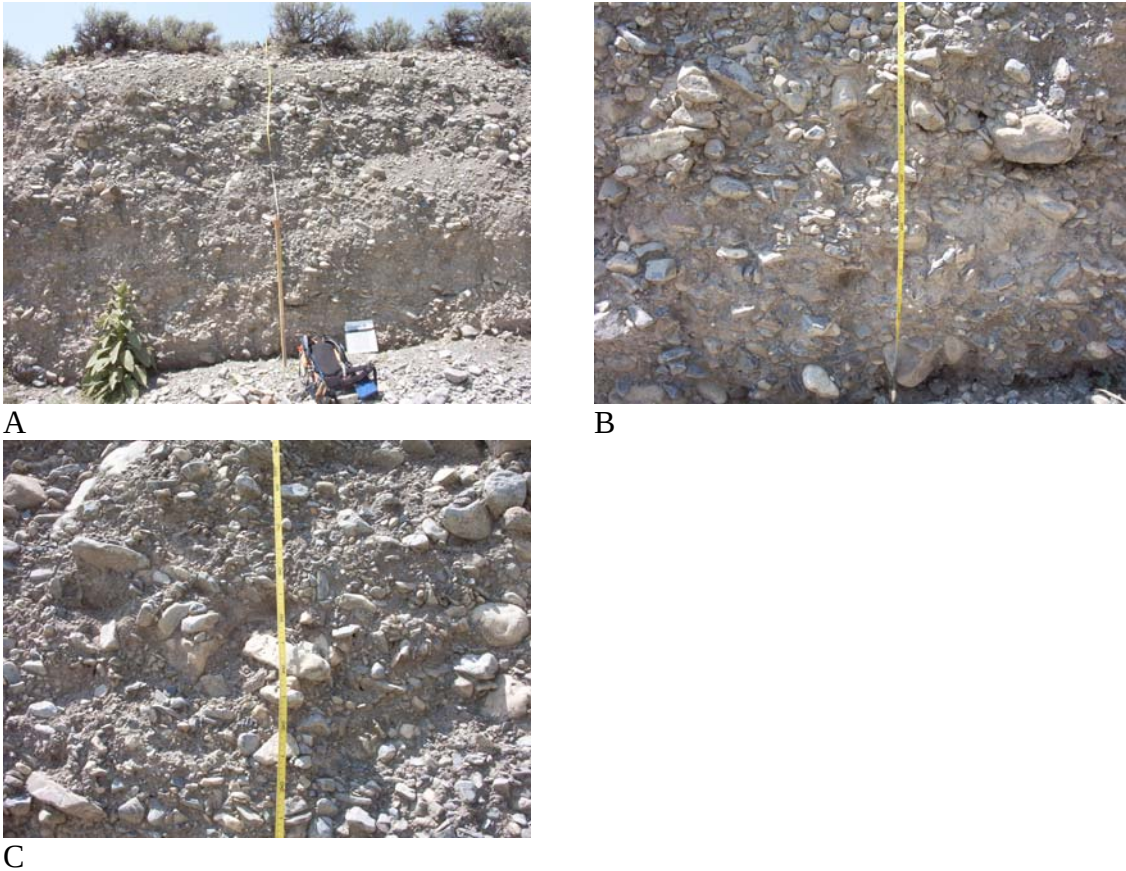


Figure 24. (A) Section 6 outcrop. Backpack for scale. (B) Close up of Section 6. The prominent clast on the right is the same one above the backpack near the base in Figure 24A. Openwork is exhibited to left of large clast. Weak stratification is present. (C) Poorly sorted character of cobble gravel facies.



Figure 25. Outcrop of Section 6 in Gravel Package II on Upper Cedar Creek alluvial with the exposed board, people for scale. Photographer Jen Pierce 2005

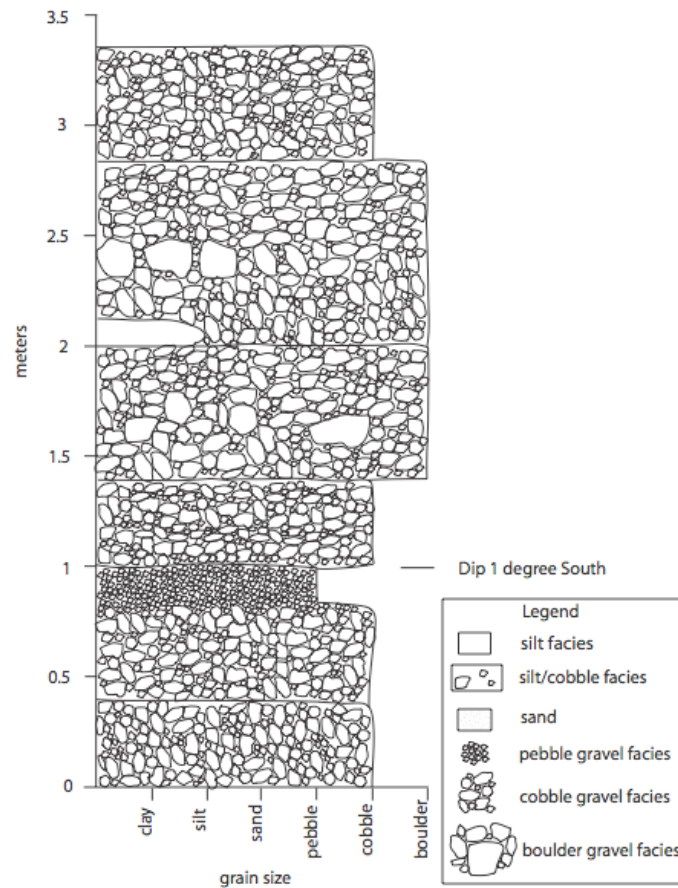


Figure 26. Stratigraphic column for Section 6 in Gravel Package II on Upper Cedar Creek alluvial fan.

Section 7 was measured in Gravel Package II, south of the creek near the fan apex (Fig. 11B). The section is 3 m high (Fig. 27A). The top of the section is Surface B and the base is level with Surface A. The lithofacies in Section 7 are the same as other sections on Upper Cedar Creek alluvial fan and include pebble gravel and cobble gravel facies (Fig. 27B). There are six beds in Section 7 (Fig. 28). Three slope measurements were made with values of 2°S, 2°S, and 3°S going down section (Fig. 28). The sediments

are weakly stratified due to clast size and clast orientation. Clast orientation includes flat lying and inclined clasts.



Figure 27. (A) Outcrop photo of Section 7. Jacob staff is 1.5 m high. (B) Close up photo showing the cobble gravel facies and the better sorted pebble gravel facies.

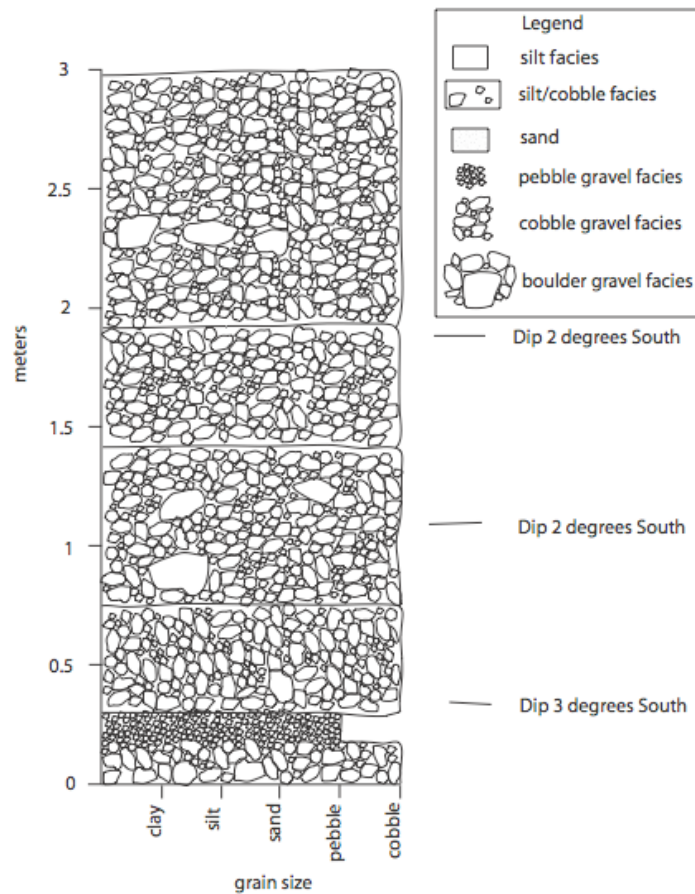


Figure 28. Stratigraphic column for Section 7 in Gravel Package II on Upper Cedar Creek alluvial fan. This section is composed mostly of cobble gravel facies.

Gravel Package III

Gravel Package III is defined as the package of sediment that is bound above by Surface O and below by Surface C (Fig. 11C). No sections were described through this gravel package, as no exposures were found. The sediment forming Gravel Package III did not originate in the Upper Cedar Creek drainage basin. Gravel Package III is composed of gravels originating from adjacent alluvial fans. The inactive nature of Surface C enabled more active adjacent alluvial fans to deposit on Upper Cedar Creek alluvial fan.

Gravel Package IV

Gravel Package IV is the only package composed of cemented sediment. This gravel package is composed of calcium carbonate-cemented cobble and pebble conglomerate. The upper bounding surface for Gravel Package IV is Surface F (Fig. 11). The lower bounding surface is unknown, as the lower succession of rock is not exposed in the study area. A detailed measured section was not described through the conglomerate. The same facies, cobble gravel and pebble gravel, as described in Gravel Package I and II are observed in Gravel Package IV, with the addition of cement. The massive, poorly sorted gravels are clast-supported with tangential contacts (Fig. 29A, 29B, 29C and 29D). Clasts are composed of carbonate rock (Fig. 29B). The conglomerates of Gravel Package IV onlap the White Knob Limestone near the Mackay Dam and farther south (Plate 1).

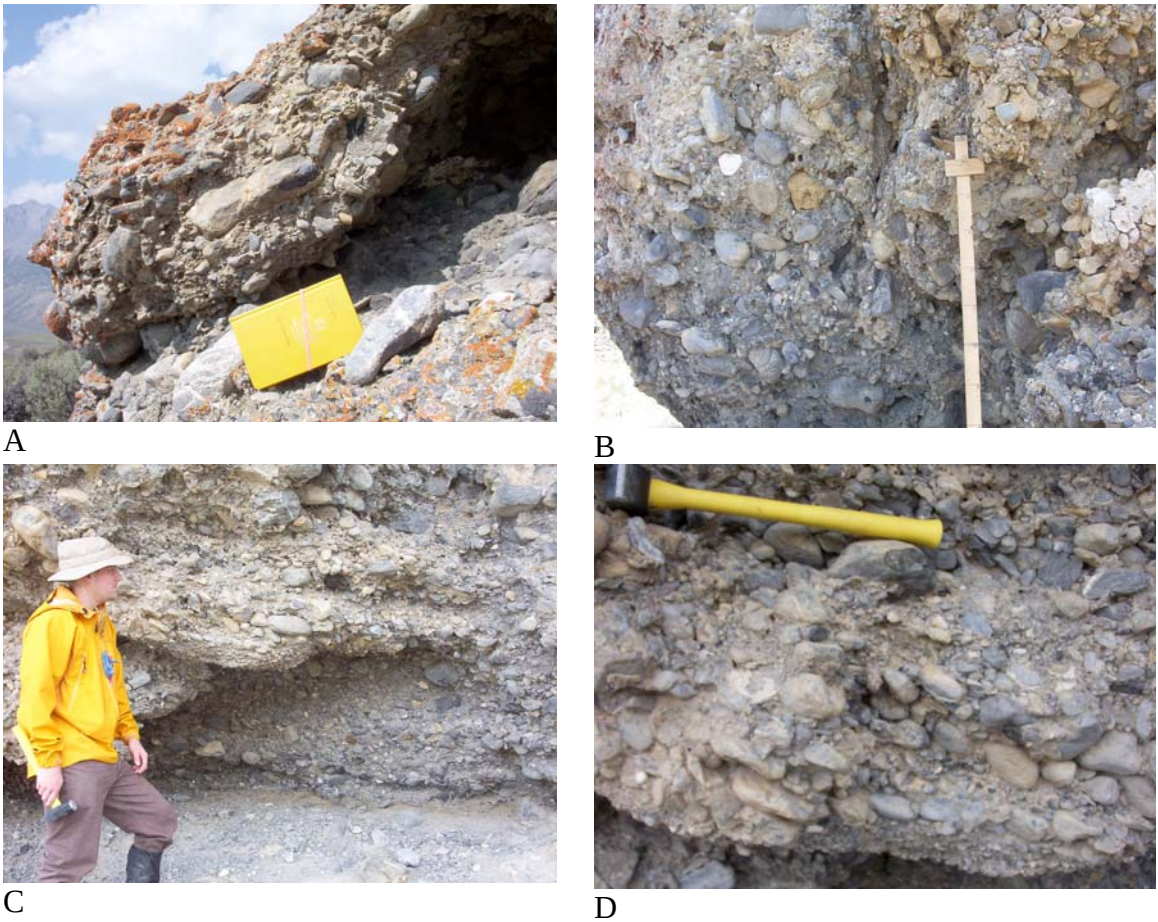


Figure 29. (A) Outcrop of Gravel Package IV. Carbonate clasts are grey to white and orange lichen commonly grows on outcrops. 17 cm long field book for scale. (B) Outcrop photo showing clasts of conglomerate. Top of Jacob staff for scale. (C) Conglomerate outcrop with weak stratification. Person for scale. (D) Close up of clast supported conglomerate showing clast imbrication. Rock hammer for scale.

Age Data

Twelve pits were dug on the two surfaces containing carbonate coats on Upper Cedar Creek alluvial fan. One hundred twelve coats on Surface B and 37 coats on Surface C were measured. No pits were dug on Surface A because there are no coated clasts on this surface. Ages were calculated using the 0.00006 mm/yr rate of carbonate growth from Pierce (1985), ages were calculated. The age of a surface represents the

period of time of inactivity. Surfaces mantle deposits of different ages that contribute to the large variance of the age of a surface. Table 4 shows the ages of each surface based on the carbonate coat thickness and the number of clasts of each surface.

Table 4. Age of Surfaces on Upper Cedar Creek Alluvial Fan. North and south in surface column are in relation to Upper Cedar Creek.			
Surface	Coat t (mm)	Number of clasts	Age (yr)
C North	2.1 +/- 1.5	15	35,000 +/- 25,000
C South	1.4 +/- 0.8	22	23,000 +/- 13,000
C total	1.7 +/-1.2	37	28,000 +/- 20,000
B North	0.3 +/- 0.2	54	5,000 +/- 3,000
B South	0.6 +/- 0.3	58	10,000 +/- 5,000
B total	0.4 +/- 0.3	112	7,000 +/- 5,000
A	0	0	Modern

Discussion

Upper Cedar Creek alluvial fan is comprised of four main surfaces, A, B, C, and F, and four gravel packages, I, II, III, and IV. The geometry of the alluvial fan deposits is defined using these surfaces and gravel packages in conjunction with their ages.

Numerical ages were calculated for surfaces, providing a bracket for the age of the gravel packages.

Surface A is the active depositional lobe and channel way for Upper Cedar Creek alluvial fan. Primary processes dominate Surface A, whereas secondary processes dominate the other surfaces (terminology from Blair and McPherson, 1994). The creek flows over this surface.

Deposition on Surface A occurred as sheetfloods and possibly debris flows. Sheetfloods are unconfined (unchannelized), turbulent, supercritical, upper flow regime flows that can be rich in sediment (Hogg, 1982; Blair, 1987; Blair and McPherson, 1994;

Blair, 2000). Sediment is transported as bedload and suspended load. Historic gravel-rich sheetflood deposits form flow-parallel elongate mounds (Blair, 1987). These mounds are 4 to 5 m long, 1 to 3 m wide and up to 0.2 m high (Blair, 1987). The mounds and ridges observed on Surface A have similar landform shape, clast size and roundness to the sheetflood deposits on Roaring River alluvial fan in Rocky Mountain National Park, Colorado (Fig. 6E) (Blair, 1987). The larger ridges and mounds are interpreted as debris flow deposits. Both sheetflood and debris flow deposits bury the bases of trees (Fig. 6D and 6E).

There has been significant reworking of the deposits on Surface A. Fluvial reworking of sheetflood and debris flow deposits is evidenced by abrupt stream cuts of the ridges, the anastomosing pattern of the gravels, and the lack of fines on the surface of deposits. The edges of the discontinuous and unpaired ridges end in erosional cut scarps at the edge of stream channels. The anastomosing pattern in the gravels is present on reworked sheetflood deposits similar to other alluvial fans. The Roaring River alluvial fan of Rocky Mountain National Park, Colorado, was formed July of 1982 by a series of debris flows and sheetfloods (Blair, 1987). Over the following three years, “normal” flow of the river carved out a braided stream pattern in the gravels (Blair, 1987). It is believed the same process occurred on Surface A based on the similar surface morphology. There is a lack of fines on the surface of the deposits. Fines were deposited coeval with the gravels and have been subsequently removed by rain splash, wind erosion and/or stream reworking into small bars. Stream flow redeposited the fines from the sheetflood and debris flow mounds into well sorted, sand-rich, small (<1 m) bars within the channels.

Surface B is the intermediate age ($7,000 \pm 5,000$ yr) surface on Upper Cedar Creek alluvial fan. The features on Surface B are similar to those on Surface A, but they are older, more weathered and vegetated. The microrelief on Surface B is more subdued than Surface A with less relief landforms that have shallower slopes. Surface A and B exhibit the same clast sizes, shapes and lithologies, however each surface has unique characteristics. There is more soil development, including an abundance of silt, on Surface B. The silt is wind derived loess. Clasts on Surface B have carbonate coats, whereas no coats exist on Surface A clasts. The vegetation on Surface B is mostly sagebrush and grasses, common species for semiarid regions of western US.

Surface C, $28,000 \pm 20,000$ yr, is the oldest datable surface on Upper Cedar Creek alluvial fan. Surface C is extensive, covering most of the alluvial fan (Plate 1). Surface C is older, more weathered, and has less microrelief than Surface B. More specifically, the microrelief on Surface B is between 1 and 0.5 m, whereas the microrelief is less than 0.3 m on Surface C. The surface is relatively smooth with no well defined landforms. The clasts on Surface C have the same shape, size and lithology as Surface B clasts. The subrounded to subangular, pebble to cobble carbonate clasts of Surface B are present on Surface C. There is more soil development on Surface C with the accumulation of windblown silt. Additionally, the carbonate coats on the clasts are thicker on Surface C than they are on Surface B. The development of a convergent drainage pattern, on Surface C, with incision up to 4 m is a strong indication of an old, inactive surface that is undergoing degradation.

Surface O is not part of Upper Cedar Creek alluvial fan. Rather, it is comprised of coalescing alluvial fans that are adjacent to Upper Cedar Creek alluvial fan. The

debris on Surface O did not originate from Upper Cedar Creek drainage basin. The distinct surface morphology is indicative of debris flow deposits. The parallel ridges are debris flow levees and the mounds are debris flow lobes (Hubert and Filipov, 1987; Blair and McPherson, 1994). The angularity of the large clasts is common of debris flow deposits (Blair and McPherson, 1994; Blair, 2003).

Gravel Package I is mainly composed of weakly stratified, alternating cobble gravel and pebble gravel facies. These couplets are observed for the entire 30 m thick Gravel Package I outcrop at Section 9 (Fig. 18A). The massive, very poorly to poorly sorted, clast-supported cobble gravel facies has subangular to subrounded carbonate clasts and a poorly sorted to moderately sorted sandy silt matrix and openwork. The pebble gravel is a massive, poorly sorted, clast supported gravel with subangular to subrounded carbonate clasts and a poorly to moderately sorted silty-sand to sandy-silt matrix. The cobble beds are generally thicker (0.2-0.7 m) than pebble gravel beds (0.1-0.2 m) (Fig. 14). A majority of the beds are thinner than 0.5 m. The pebble gravel overlies and is depositionally linked to the cobble gravel.

These couplets are deposited by sheetfloods. Sheetfloods are rare, episodic, unconfined, fluid gravity flows that are common on alluvial fans (Hogg, 1982; Blair and McPherson, 1994; Blair, 2000). Sheetfloods are supercritical fluids that have a high deposition rate. A sheetflood on the Roaring River fan has calculated values of 3-6 m/s and Froude numbers of 1.4-2.8 with an average depth of 0.5 m (Blair and McPherson, 1994). The supercritical nature of these flows enables antidune and standing wave formation (Blair and McPherson, 1994; Blair, 2000). The antidunes migrate upslope with accumulation of debris on the stoss up flow side. Most of the debris is deposited with

washout and collapse of an antidune as sheets of coarse sediment (Blair and McPherson, 1994, Blair, 2000).

The coarsest fraction, bedload, is deposited first followed by the finer fraction, suspended load (Blair and McPherson, 1994; Blair, 2000). The cobble gravel was transported as bedload in a supercritical water flow and was deposited with collapse of an antidune. The pebble gravel was transported as suspended load in the same supercritical water flow and was deposited after the bedload (Blair, 2000). The lack of matrix (openwork) observed in the cobble gravel facies is a clear indication that the cobbles were rapidly deposited together. Each couplet represents a depositional event, but multiple depositional events can occur in one flooding event (Blair, 1987; Blair and McPherson, 1994, Blair, 2000). The presence of fines, clay and silt in the cobble and especially pebble gravel rules out channelized water flow as a depositional origin because the clay and silt would have been carried out of the system (Pierson, 1987; Costa, 1988; Blair and McPherson, 1994). The silt and clay of sheetflood deposits may be secondary additions to the deposits through eolian processes as was predicted by Blair (2000). Other workers have interpreted similar sediments to have been deposited by sheetfloods (Ballance, 1984): Facies B of Kostaschuk et al. (1986), facies S3 in Wells and Harvey (1987), Hell's Gate alluvial fan (Blair, 2000), Anvil Springs fan (Blair, 1999), Facies A of Furnace Creek Formation (Blair and Reynolds, 1999), and alluvial fans on the flanks of Sierra Nevada, Spain (Calvache, et al., 1997). Two studies of historic sheetfloods (Blair, 1987; Gutierrez et al., 1998) describe deposits and landforms similar to those on Upper Cedar Creek alluvial fan.

The other facies of Gravel Package I are composed of boulder gravel, silt, and silt/cobble facies. They were identified in Section 5, which is the section described closest to the apex. These facies constitute a volumetrically small amount of Gravel Package I. The massive, very poorly sorted boulder gravel is similar to the cobble gravel above, but is coarser. The boulder gravel is overlain by the cobble gravel facies at Section 5. Traveling from the feeder channel to the channel way there is a dramatic decrease in slope. Water flows will have their maximum discharge at this change in slope, providing energy to transport material. The channel way is wider than the feeder channel; at this point the flow spreads outward and its energy decreases. The coarsest sediment transport in the flows will most likely be deposited near the apex. The boulder gravel facies is probably a result of this situation; the boulder gravel could have been deposited as the coarser bed in a sheetflood couplet, with the overlying finer-grained suspended load deposit not preserved. The overlying cobble gravel is too coarse to be transported as suspended load in a sheetflood. The boulder gravel facies may have alternatively originated as a debris flow deposit. The presence of fines and lack of openwork are more characteristic of debris flow deposits than sheetfloods. Debris flow initiation would occur under conditions with less water than sheetfloods (Blair and McPherson, 1994; Costa, 1988). If this is a debris flow deposit, then either more sediment or less water was available for transport (Blair and McPherson, 1994).

The massive silt facies is matrix-supported with few carbonate cobble clasts. The silt facies has an overwhelming abundance of silt and only minor clay and sand. This facies is massive, lacks sedimentary structures and resembles loess. Loess deposits are prevalent in the region (Pierce et al., 1982). The origin of the silt is probably eolian. The

cobble clasts may have been incorporated into the loess by animal burrowing. Burrowing animals can move cobble size clasts up to 0.5 m vertically (K. Pierce, 2006, personal communication). An alternative mechanism for incorporating the cobble clasts in the silt is through a common transport and deposition history. Sheetfloods or hyperconcentrated flows may have entrained silt from a loess deposit and integrated the silt into the flow, mixing the cobbles with the silt and depositing all of the sediment together.

A similar origin is interpreted for the silt/cobble facies. The silt was most likely originally deposited as loess. Incorporation of the silt in a sheetflood would rework the silt but, more importantly, mix the pebble and cobble clasts in the silt matrix. The water flow may have become a hyperconcentrated flow at times with the addition of a large volume of silt. Subsequent animal burrowing and/or frost heave could have moved clasts vertically.

Cobble gravel and pebble gravel facies are observed in Gravel Package II, found beneath Surface B. The pebble gravel facies is a stratified, poorly sorted pebble gravel with subangular to subrounded carbonate clasts and a silt-rich matrix. The cobble gravel facies is a massive, poorly sorted cobble gravel with subangular to subrounded carbonate clasts and openwork and silty sand matrix. The pebble gravel overlays the cobble gravel and alternates with it for the extent of the outcrop as seen in Section 3 (Figure 21 and 22). These deposits are sheetflood couplets. Clasts of the cobble gravel facies were transported as bedload in supercritical water flows. These clasts were rapidly deposited together with collapse of antidunes (Blair, 1987; Blair and McPherson, 1994; Blair, 2000). The lack of fines and the presence of openwork demonstrate that only the bedload was deposited initially. The pebbles, granules, sand, silt and clay of the pebble gravel

facies were transported as suspended load in the same fluid and were deposited immediately after the bedload (Blair, 1987; Blair and McPherson, 1994). Weak stratification is a result of deposition from water flow. The stratified, moderately sorted sand bed observed in Section 3 (Figure 19B) is located above pebble gravel facies. It was most likely transported as suspended load in a sheetflood because of internal stratification. Because it is thin (<10 cm) and laterally discontinuous (<1 m), the sand bed could be a sheetflow deposit (Hogg, 1982). A spectrum exists between sheetfloods and sheetflows, with sheetflows being on the low energy side (Hogg, 1982). They tend to be thinner flows as well (Hogg, 1982). Another possible explanation for the sand bed is reworking by stream flow. Winnowing of sheetflood deposits by overland flow could concentrate the fines in a depression farther down fan. The pebble gravel/cobble gravel couplets were deposited by sheetfloods.

Beds near the toe are not as laterally continuous as beds near the apex. This could be explained by a longer duration between depositional events, which would allow greater time for surface modification processes to occur.

Gravel Package III was not described in vertical section. Its composition is inferred from the surface morphology of Surface O. Surface morphology can provide insight into the style of deposition, which can in turn provide evidence for the type of deposits underlying the surface. Debris flow deposits cover surface O. It is hypothesized that Gravel Package III is composed primarily of debris flow deposits. This would include stacked, very poorly to poorly sorted, boulder to cobble gravel beds that are separated by planar bounding surfaces (Blair and McPherson, 1994). The debris of Gravel Package III would have come from drainages adjacent to Upper Cedar Creek.

Based on field relationships, especially south of Upper Cedar Creek alluvial fan, it is inferred that debris flow alluvial fans of Gravel Package III are prograding on top of Surface C (Plate 1). The lack of vertical exposure precludes knowing the absolute nature of the contact. If debris flow alluvial fans are prograding on top of Surface C, then Gravel Package III rests unconformably on top of Gravel Package I (Fig. 11D). The debris flow deposits of Gravel Package III contrast with the sheetflood deposits of Gravel Package I and II.

Gravel Package IV is composed of lithified sediment. The facies, pebble gravel and cobble gravel facies, that appear in Gravel Package I and II are also observed in Gravel Package IV. Based on the presence of the same facies, a similar depositional history is inferred: sheetfloods deposited the sediment of Gravel Package IV with subsequent carbonate cementation.

The age of Gravel Package IV is poorly constrained. Previous workers have mapped the bluffs as Tertiary in age (Wilson and Skipp, 1994). Gravel Package IV is older than 28,000 yr based on the presence of boulders from Gravel Package IV that are incorporated within in Gravel Package I (Figure 10E). It is hypothesized that the age of Gravel Package IV falls between Cretaceous and Pleistocene based on the degree of cementation and relative location to dated landforms. It is unclear where the clasts of Gravel Package IV originated, as the southern half of the Lost River Range as well as the White Knob Mountains are composed predominately of carbonate lithology. The slope of Surface F has a conical pattern that slopes away from the Lost River Range suggesting a westward transport direction. Deposits similar to Gravel Package IV are the Eocene Smiley Creek Conglomerate and the Upper Cretaceous-Paleogene Beaverhead Group.

The Smiley Creek Conglomerate is a poorly sorted conglomerate that was deposited in an alluvial fan environment (Aschoff and Schmitt, 2000). The Smiley Creek Conglomerate is almost exclusively sandstone and quartzite clasts and is located in the valley to the west of the Big Lost River Valley. The Smiley Creek conglomerate is interpreted as older conglomeratic bed rock. The highly dissected nature of the map areas suggests an old age (Plate 1). The presumed old (> 1 Ma) age of Gravel Package IV and the onlap relationship with the White Knob Limestone indicates that Gravel Package IV can be considered bedrock in relation to the alluvial fan gravels. There was significant erosion of Gravel Package IV prior to deposition of the Pleistocene and Holocene fan deposits.

Poorly-sorted bimodal facies that are moderately stratified are the deposits from sheetfloods thus cataloging Upper Cedar Creek alluvial fan as a sheetflood dominant alluvial fan or Type II of Blair and McPherson (1994). Gravel Package I and II as well as the active depositional lobe (Surface A) all exhibit classic characteristics of sheetflood deposits. The sediment transport process for Upper Cedar Creek alluvial fan has been the same for last $28,000 \pm 20,000$ years (age of Surface C). Surfaces B and C represent different stages of surface modification of sheetflood deposits. Sheetflood deposits, and Gravel Packages II and I underlie both Surfaces B and C. The surface morphology of Surface B is similar to that observed on Surface A. The surface morphology and weathering of surface landforms is consistent with surface ages determined from carbonate coat thicknesses.

The dates of surfaces are internally consistent. Gravel Package I is bound above by Surface C which has been dated at $28,000 \pm 20,000$ yr. Gravel Package I is older than $28,000 \pm 20,000$ yr. No older age limit for Gravel Package I can be determined from the

data. Gravel Package II is bound above by Surface B, $7,000 \pm 5,000$ yr, and the lower boundary is not determined. Gravel Package II is older than $7,000 \pm 5,000$ yr. The channel way cuts Surface C, and Surface B is the oldest surface within the channel way, thus the channel way was formed between $28,000 \pm 20,000$ (age of Surface C) and $7,000 \pm 5,000$ yr (age of Surface B) (Fig. 11D). Gravel Package II is dated at between $7,000 \pm 5,000$ and $28,000 \pm 20,000$ yr. Gravel Package III is bound above by the modern Surface O and below by Surface C, $28,000 \pm$ yr. Gravel Package III is dated between the present and $28,000 \pm 20,000$ yr. As stated above, the age of Gravel Package IV, below Surface F, is unknown, but it is likely that it represents bedrock of a significantly older age (Upper Cretaceous-Eocene).

Although Gravel Package I and II contain the same facies, they are two distinct depositional units. Surface A and B do not represent strath terraces. There is no evidence to suggest that Surface B extends into Gravel Package I as an unconformity or that beds continue from Gravel Package I to Gravel Package II. The only exposure of the contact between Gravel Package I and II contact is seen just north of Section 2, where Surface B and the underlying Gravel Package II gravels have been eroded to expose ~30 m of Gravel Package I (Plate 1). The exposure is partially obscured by colluvium, but beds do not appear to match up across the contact. Therefore, Gravel Package II does not underlie Gravel Package I nor are Surface B and A strath terraces.

The upper bounding surfaces for Gravel Package I and II are well defined with Surface B and C, respectively. However, the lower bounding surfaces are neither exposed nor observed. The longitudinal geometry of the gravel packages is inferred from normal fault behavior. Strata thicken toward normal faults because the greatest

accommodation space is located adjacent to the fault. The interpreted wedge shape for Gravel Packages I and II that thicken toward the Lost River fault are based on a model for normal faults and surface observations. The surface expression of Gravel Package I pinches out toward the alluvial fan toe where Surfaces B and C merge (Fig. 11). It is unknown if Surface C extends as an unconformity in the subsurface. The steeper slope of Surface C (3.05°) relative to Surface B (2.76°) causes their merging down fan. The surface expression of Gravel Package II thins toward the basin with a decreasing height between Surface B and A from 7 m at the apex (Section 3) to 1.5 m near the toe (Section 4). This thinning of Gravel Package II surface expression is a result of Surface B (2.76°) having a steeper slope than Surface A (2.68°) (Fig. 11). Between these three surfaces (A, B and C) the oldest surface has the steepest slope. The older surfaces are steeper and higher than younger surfaces, which is not consistent with down dropping and tilting of the hangingwall. The thickening of strata toward the fault is consistent with normal fault behavior and is called a growth fault.

There were two stages of incision and at least one stage of backfilling on Upper Cedar Creek alluvial fan. A channel way was created through erosion of Gravel Package I. Based on what is observed today the channel way is at least 30 m deep, 70 m wide, and 4 km long. Surface C was an inactive surface with incision of the channel way because sediment coming out of the mountain would bypass Surface C and travel down fan within the channel way. The channel way could be almost as old as Surface C ($28,000 \pm 20,000$ yr). The backfilling stage deposited Gravel Package II, however it was not enough to completely fill the channel way. A second channel way (5 m deep) was created with partial removal of Gravel Package II. This made Surface B inactive as the

active depositional lobe was confined to the channel way below. The second channel way is smaller than the first, with only 4 m of incision. It is not known if Surface A is the base of the channel way or if Surface A is on top of a newly deposited thin gravel package. Except for the few buried tree trunks near the apex, Upper Cedar Creek alluvial fan is an inactive landform experiencing degradational processes including dissection of Surface C. Given the trend of inactivity on Upper Cedar Creek alluvial fan, the most logical explanation is that Surface A is the base of the channel way and incision is taking place today.

CHAPTER 6

JONES CREEK ALLUVIAL FAN

The largest fan studied is Jones Creek alluvial fan. It is 19.75 km² (7.71 sq mi) in size and its drainage basin is 8.71 km² (3.40 sq mi). The active depositional lobe of Jones Creek alluvial fan is on the northern portion of the fan. Since the active depositional lobe of North of Jones Creek alluvial fan flows on the southern portion of the fan, the two channels converge down fan (Plate 1).

The drainage basin is underlain by carbonates of the Devonian Jefferson, Three Forks, Mississippian Middle Canyon, Scott Peak, South Creek and Surrett Canyon formations (Table 5). Like Upper Cedar Creek alluvial fan, limestone and dolomite (81%) are the dominant lithologies contributing clasts to Jones Creek alluvial fan. The Mount Breitenbach fault cuts across the drainage basin (Janecke, 1992). The percents do not sum to 100, because 4% of the basin was undivided Mississippian limestone.

Formation	Age	Prominent Lithology	Percent of Drainage Basin	Area
Jefferson Formation	Devonian	Dolomite	30	2.59 km ² 1.01 mi ²
Three Forks Formation	Late Devonian	Limestone	2	0.20 km ² 0.08 mi ²
McGowen Creek Formation	Early Mississippian	Shale and limestone	19	1.65 km ² 0.65 mi ²
Middle Canyon Formation	Late Mississippian	Limestone	9	0.78 km ² 0.30 mi ²
Scott Peak Formation	Late Mississippian	Limestone	25	2.21 km ² 0.86 mi ²
South Creek Formation	Late Mississippian	Limestone	4	0.37 km ² 0.14 mi ²
Surrett Canyon Formation	Late Mississippian	Limestone	7	0.62 km ² 0.24 mi ²

Surface Descriptions

There are three surfaces on Jones Creek alluvial fan: Surfaces M, N and J (Fig. 30 and Plate 1). Surface M is the extensive upper surface and Surface J is the lowest surface. Surface N covers a small map area but is above Surface M (Fig. 30C).

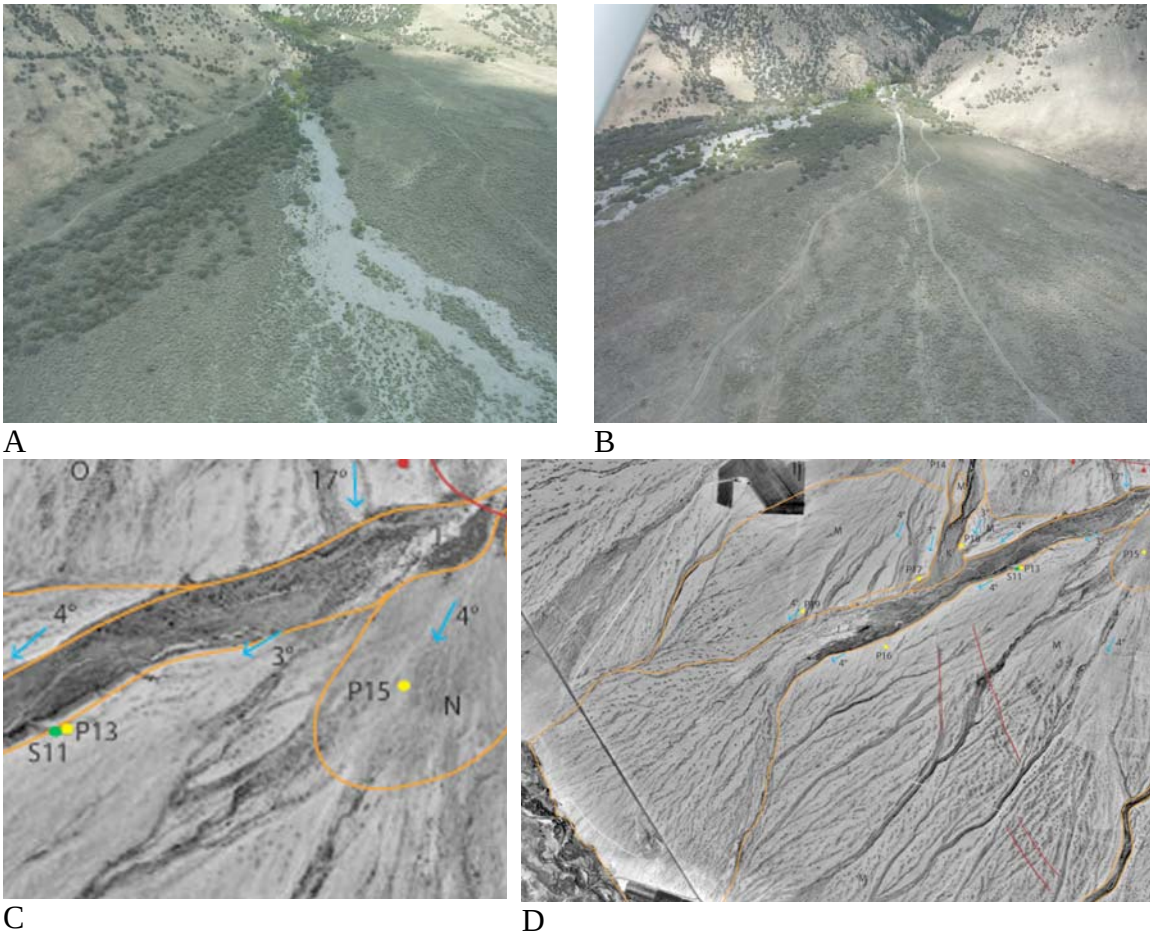


Figure 30. (A) The apex of Jones Creek alluvial fan. Surface J extends from the left of the trees to right of the gray gravels. Sagebrush-covered Surface N is on the right of the gray gravels. (B) The apex of Jones Creek alluvial fan looking from the south. The trees and gray gravels on the left are Surface J and the sagebrush cover on the left is Surface N. (C) Excerpt from Plate 1 showing the apex of Jones Creek alluvial fan. Notice the distinct map pattern of Surface J. (D) Excerpt from Plate 1 showing Surface J. The map expression of Surface J changes from the apex to the toe.

Surface J

Surface J is the active depositional lobe that encompasses the active channel way on Jones Creek alluvial fan (Fig. 30D and Plate 1). The average slope of Surface J is 3.81° (0.053 ft/ft). This surface has a varied expression along its length. Near the apex, there is a cover of gravel with a flowing creek that eventually infiltrates into the ground a few hundred meters down fan (Fig. 31A). From midfan, extending to the toe, Surface J is silt-rich with a covering of sagebrush and grasses. Map expression of Surface J widens from the apex to the toe and at the toe a distributary drainage pattern radiates from the channel way (Fig. 30D). The surface descriptions will start near the apex and move towards the toe.

From the apex to midfan, a blanket of gravel covers Surface J (Fig. 31A). The gravel is poorly sorted with grain sizes from boulder to clay (Fig. 31B). The clasts are mostly cobble to pebble in size and of carbonate rocks. There are no carbonate coats on clasts of this surface. The matrix is predominantly sand with minor clay and silt. Matrix is not observed in the surface gravels, but is present in gravel several centimeters below. The gravel is organized into mounds and ridges that are 1-10 m long with microrelief up to 1.5 m high (Fig. 31A and 31C). The sides of the gravel mounds can be steep, from $\sim 20^{\circ}$ to almost vertical. The gravels bury the bases of trees and bushes (Fig. 31D and 31E). The amount of silt increases with distance down fan.

Surface J has the thickest and most varied vegetation of any surface on Jones Creek alluvial fan. The kinds of vegetation on Surface J include junipers, cottonwoods, sagebrush, bushes and grasses. Most of the trees have buried trunks (Fig. 31D and 32E). There is an abundance of dead dried wood on the surface, with some incorporated into

the gravel (Fig. 31A). A piece of sheet metal is incorporated into the gravel as well. The tree cover is thicker on the sides of Surface J where the ground is blanketed with organic debris, forming an incipient soil. Going down fan, the density of trees decreases and sagebrush and grass density increases (Fig. 31F). The pattern of sagebrush growth, size and density looks the same as Surface M where Surface J and M merge.

Moving down fan, the amount of gravel decreases with an increase in the amount of silt on Surface J. The microrelief on Surface J decreases down fan from 1.5 m to 0.5 m. Sagebrush covers this silt-rich surface. Abundant dead sagebrush is also present. There are few clasts on the surface and no coats on the clasts. There is orange lichen growing on most of the carbonate clasts. Small mounds of cobbles, one of which contained a chunk of sawed wood, indicating an age less than 100 years are present. Grass grows better than sagebrush on silt-rich substrates, and sagebrush grows better than grass on gravel-rich substrates.

The amount of silt increases down fan until there are 2 m high walls composed entirely of silt (Fig. 32A). These outcrops are located at the junction of Surface J and Surface K (Plate 1). At this junction, Surface K is cobble-rich whereas Surface J is covered by silt with occasional cobble and pebble clasts. There are occasional cobble beds interbedded within the massive silt (Fig. 32B). The massive, poorly sorted, cobble and pebble gravel beds are 0.2 to 1 m in thickness (Fig. 32B and 32C). The carbonate clasts are subangular to subrounded. The gravels are matrix to clast supported with tangential contacts and silt matrix (Fig. 32D). The silt makes near vertical walls, but has slumped recently in a few places that have been undercut. Within these walls are holes that range in size from 0.02 to 1 m in diameter. There is a 0.3 m silt layer just



A



B



C



D



E



F

Figure 31. (A) View looking up fan at Jones Creek of gravel covered Surface J near the apex and an eroded gravel ridge on the right. (B) Vertical exposure of the gravel cover on Surface J. Rock hammer is 30 cm long. (C) Gravel ridge that is parallel to fan radius. Jacob's staff for scale. (D) Gravel mounds and ridges burying the bases of the bushes. (E) The bases of these trees are buried by a gravel mound. Rock hammer for scale. (F) View up fan from midfan at the sagebrush-covered Surface J.

below the present soil horizon. A dry channel cuts through the silt. This shallow channel (< 0.5 m) has silt-rich banks but a cobble- and pebble-rich bed. The gravel origin is most likely from up fan or the walls.

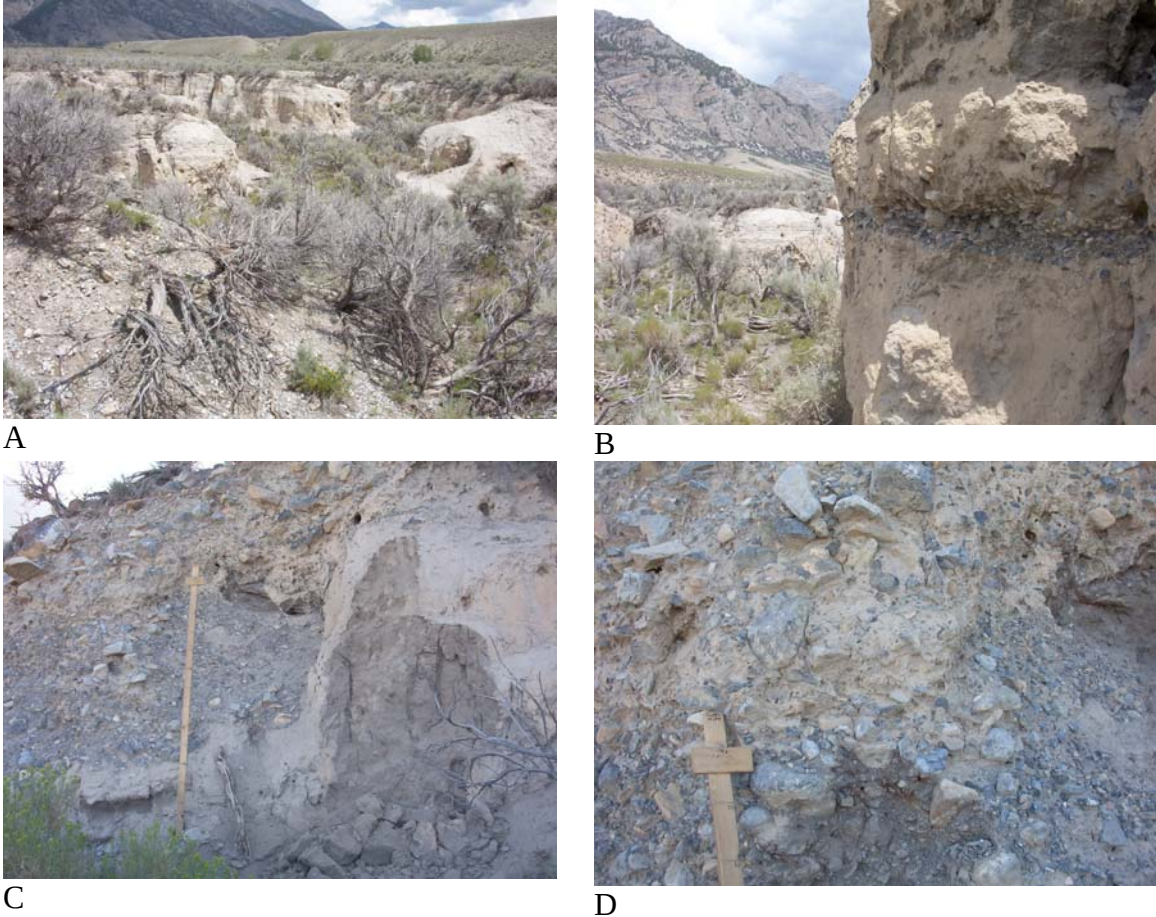


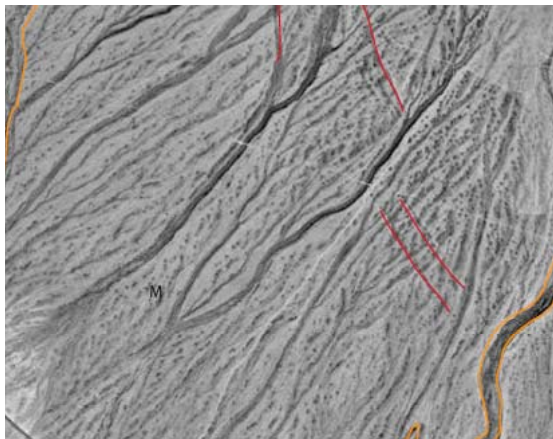
Figure 32. (A) Two meter high cliffs of silt facies on Surface J. Note horizontal stratification. (B) Silt facies is interbedded with pebble cobble gravel bed. Pebble cobble gravel is ~10 cm thick. (C) Juxtaposition of silt and cobble gravel facies. Jacob's staff is 1.5 m high. (D) Close-up of cobble gravel interbedded with silt. Jacob's staff has 10 cm marks.

The contact between Surface J and K is seen in the field as a break in slope.

Surface K is fresher looking with less weathered gravel mounds. The sagebrush is shorter, smaller, and less dense on Surface K than Surface J.

Surface M

Surface M is the highest surface on Jones Creek alluvial fan. This expansive surface extends from the toe to just below the apex (Fig. 33A and 33B). Surface M has a slope of 4.05° (0.071 ft/ft). Surface M is a smooth surface with microrelief <0.5 m (Fig. 33B and 33C). Topography on this surface is comprised of mounds that are ~ 10 m long and a few meters wide. Subangular to subrounded carbonate pebbles and cobbles scatter the ground. Silt is the most prevalent surface covering. The ground is soft to walk on



A



B



C

Figure 33. (A) Excerpt of Plate 1 showing the highly dissected Surface M. Note the convergent drainage pattern. (B) Looking south across the smooth Surface M with sagebrush. Note low relief. (C) Smooth surface with unvegetated spot ~ 3 m in diameter.

and depresses 1 cm with a boot step. Inferred unvegetated spots seen from an airplane and on a DOQ are places lacking sagebrush (Fig. 33C). Sagebrush and grasses are the dominant vegetation. Streams eroding this surface exhibit convergent dissection patterns (Fig. 33A and Plate 1).

Surface N

The map expression of Surface N is more distinct than the ground expression (Fig. 34A). The average slope of Surface N is 4.11° (0.072 ft/ft). The surface is covered mostly with carbonate pebbles, but carbonate cobbles also exist within the silty matrix. Mounds and ridges produce microrelief up to 1 m but are restricted to the apex. The rest of the surface is smooth with microrelief less than 0.3 m (Fig. 34B). There is some soil development. Trees are only present near the apex where the surface has multiple ridges and mounds. Sagebrush and ground hugging plants vegetate the surface. Streams dissecting this surface form small rills < 0.5 m deep. This surface is only 1 m above Surface J.

Gravel Packages

Two Gravel Packages X and XI are defined beneath Surface M and N, respectively, on Jones Creek alluvial fan (Fig. 35). Only one measured section was able to be described because of lack of exposure. The gravel packages will be described separately.

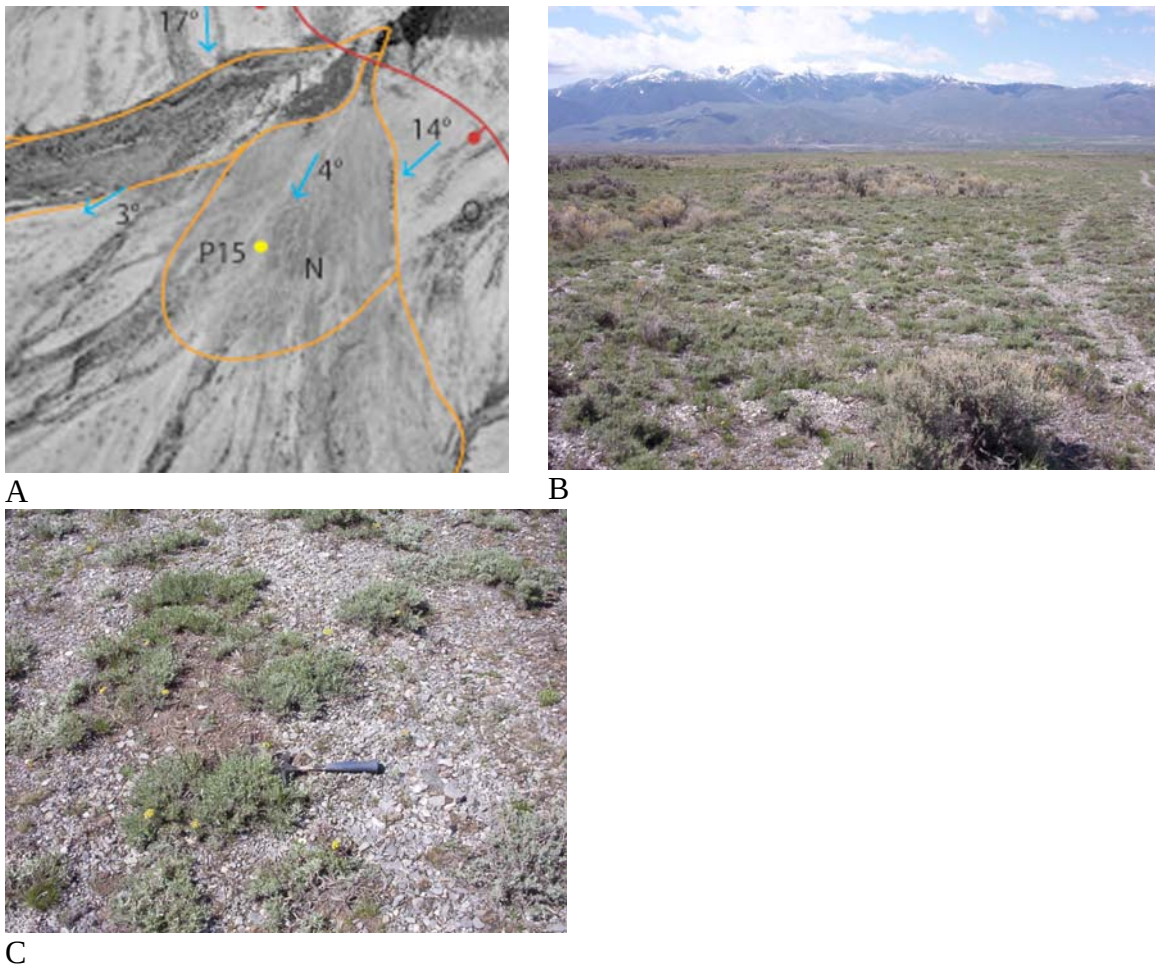


Figure 34. (A) Excerpt from Plate 1 showing the map expression of Surface N. Note distributary pattern that radiates from the fan apex. (B) Note sagebrush and carbonate pebble clasts on smooth, low relief surface. (C) Sagebrush and grasses growing on clast-rich Surface N. Rock hammer is 30 cm long.

Gravel Package X

Gravel Package X is bound above by Surface M (Fig. 35C). The lower bounding surface is unknown, as it is not exposed. Section 11 is the only vertical section measured in Gravel Package X because of poor exposure.

Section 11 was described in Gravel Package X (Fig. 35). The section was described at a near vertical erosional scarp located south of the creek (Plate 1). The section is 2.3 m high and the top of the section is Surface M (Fig. 35B and 37A). Weak

stratification is observed in the gravels based on different clast sizes (Fig. 36C). Three facies, cobble gravel, pebble gravel and silt, are identified in Section 11.

The massive, poorly sorted, clast supported cobble gravel is the volumetrically most important facies in Section 11 (Fig. 36 and 37). This facies has clasts that range in size from granule to boulder, but most are cobble and pebble. These carbonate clasts are subangular to subrounded. The clast supported cobble gravel facies has tangential

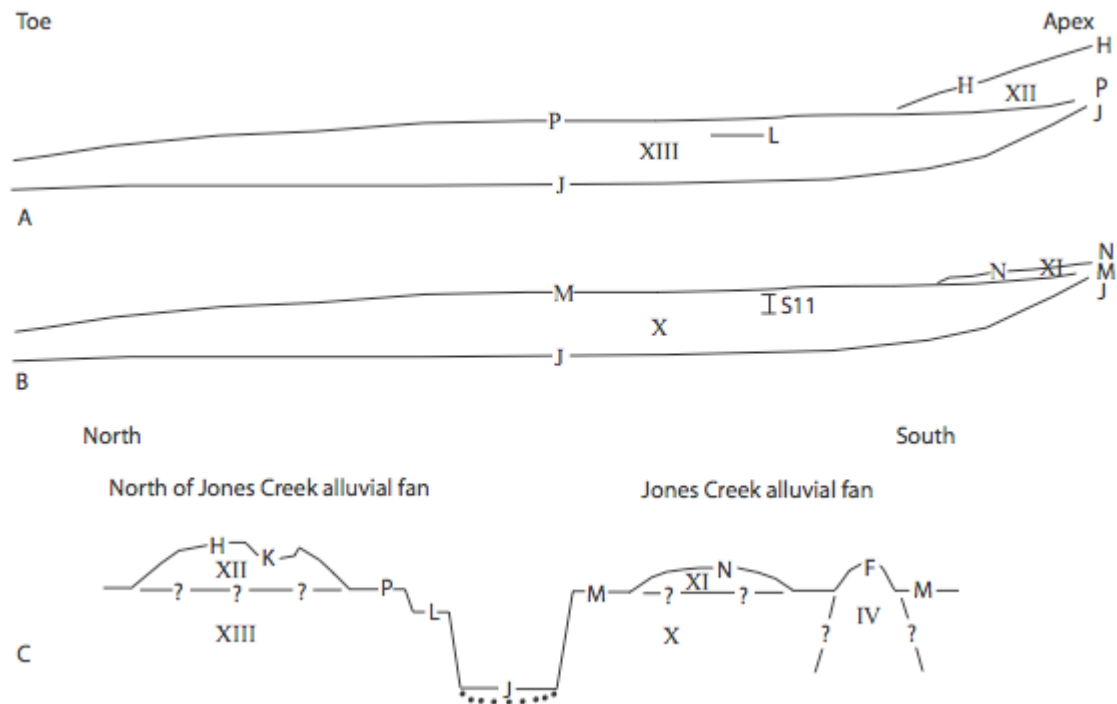


Figure 35. Sketch of surfaces and gravel packages on Jones Creek and North of Jones Creek alluvial fans. Letters are surfaces, Roman Numerals are gravel packages and S followed by a number are sections. (A) Longitudinal cross section north of Jones creek. Gravel Package XIII is inferred. Surface J is not the lower boundary for Gravel Package XIII. (B) Longitudinal cross section south of the creek. Surface J is not the lower boundary for Gravel Package X. (C) Cross section perpendicular to Jones creek. No scale. Lower boundary for Gravel Package XII and XI are inferred. The dotted line represents the lower edge of temporary storage of sediments on Surface J.

contacts with occasional long contacts. The matrix is poorly sorted clay to sand. Weak carbonate cement is present.

The pebble gravel facies is poorly sorted, clast supported and is similar to the cobble gravel facies but has smaller clasts. Clast sizes range from granule to cobble in the pebble gravel facies, but most are pebbles. The carbonate clasts are subangular to subrounded. The clast supported pebble gravel facies has tangential contacts. The poorly sorted matrix has clay to sand size grains. The pebble gravel facies is weakly stratified.

The massive, well sorted, matrix supported silt facies is composed mostly of silt, with minor pebble clasts (Fig. 36D). There is an absence of clay and sand. The pebbles and occasional cobble clasts are subangular to subrounded and are carbonate lithologies.

Gravel Package XI

The upper bounding surface of Gravel Package XI is Surface N and the lower bounding surface is probably Surface M. It is located south of the creek near the apex. No sections were exposed nor described. Based on surface expression this gravel package is very thin, probably less than ~3 m thick. The surface morphology of Surface N will be used to interpret the composition of Gravel Package XI.



A



B



C



D

Figure 36. Outcrop photos of Section 11 on Jones Creek alluvial fan. (A) Soil horizon exhibiting a strong stratigraphic contact. Note the coarseness of the outcrop. (B) Outcrop view. (C) Note weak stratification in gravels and silty interbeds. (D) Close up of silt-rich soil horizon with pebbles and cobbles. Clasts have carbonate coats on undersides. Jacob's staff for scale.

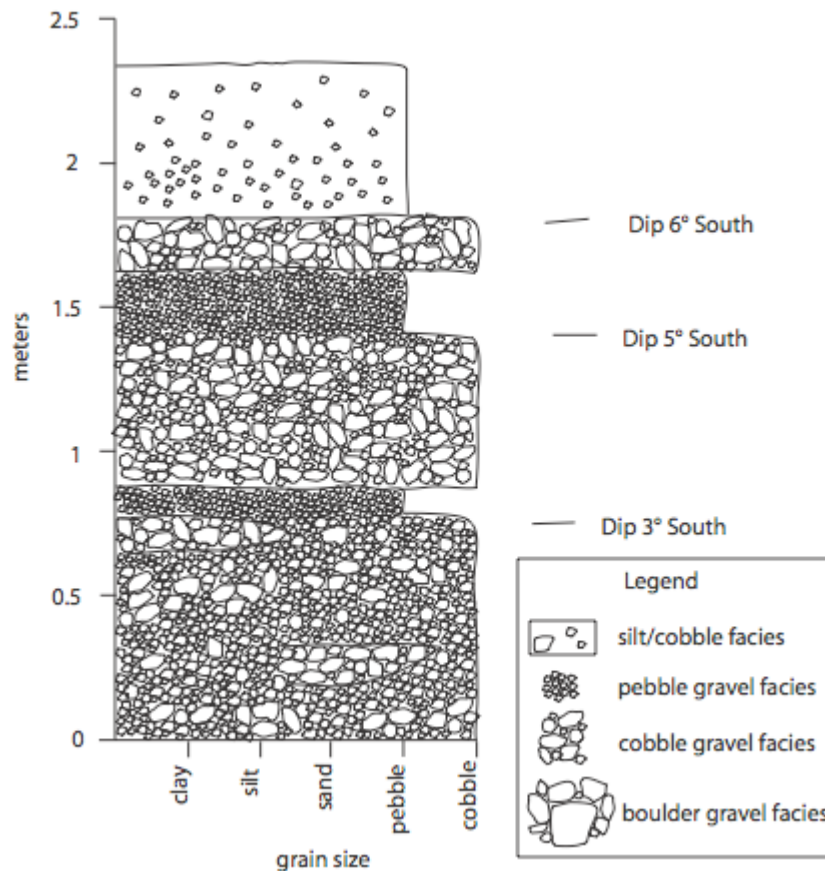


Figure 37. Stratigraphic column for Section 11 in Gravel Package X on Jones Creek alluvial fan.

Age Data

Four pits were dug and 47 clasts were measured to determine the ages of the 3 surfaces on the Jones Creek alluvial fan. Carbonate coats are not present on clasts of Surface J therefore no pits were dug. Table 6 summarizes the age data for Jones Creek alluvial fan. North and south refer to location with respect to the creek.

Surface	Coat t (mm)	Number of clasts	Age (yr)
N	0.1 +/- 0.1	20	2,000 +/- 2,000
M	2.5 +/- 1.1	27	42,000 +/- 18,000
J	0	0	Modern

Discussion

Surface M is a high inactive surface on Jones Creek alluvial fan and is $42,000 \pm 18,000$ yr old. Small microrelief, lack of gravel and extensive erosion are indicative of an inactive landform. Winnowing of fines, colluvial collapse and the addition of eolian dust have contributed to the low microrelief (< 0.5 m) and obscured the original morphology. There is little gravel exposed at the surface with accumulation of silt on the surface. Surface M has been a stable surface for a while, which allowed silt accumulation. Streams dissect almost all of Surface M (Plate 1). The streams have a convergent drainage pattern, which is a classic erosion pattern. A distributary pattern is common for depositional landforms like Surface N (Fig. 34A and Plate 1).

Surface J is the lowest surface and represents the active depositional lobe. There is a transition in its map expression down fan. The transition from gravels near the apex to silt at midfan extending to the toe is a direct result of the frequency and magnitude of recent depositional events. There have been no recent high magnitude depositional events that have deposited sediment far beyond the apex. The lack of recent deposition has allowed secondary processes to alter the surface so that Surface J and M look similar at the toe (Fig. 30D and Plate 1). Trees and other vegetation are present near the apex because of the creek. Sagebrush and grass increase down fan away from the water source because these species are better suited in dry environments. Landforms at the apex are clast supported, subangular to subrounded carbonate cobble and pebble gravel mounds and ridges. These are reworked sheetflood deposits. Sheetfloods deposit sheets of gravel that can be 4 to 5 m long, 1 to 2 m wide, and generally less than 0.5 m thick (Blair, 1987).

Gravel mounds and some of the ridges on Surface J represent such sheetflood deposits. Some of the thicker ridges may be debris flow deposits. Fluvial reworking by the creek has dissected the mounds and ridges and redeposited some of the fines down fan in small ($< 1\text{ m}$) well-sorted bars. The burial of tree trunks and bushes indicates that there has been active deposition during the last 100 years. The deposits do not cover a large area.

Silt is present down fan. The silt facies is texturally similar to loess. The presence of silt is a strong indicator of weak transport processes. Eolian processes have a slow rate of accumulation, which are also a strong indicator of an inactive landscape. Sheetfloods have not recently traveled to midfan or beyond. The silt outcrop has 2 m high scarps and is being eroded today.

Surface N has a map expression that is limited to the apex of Jones Creek alluvial fan and is $2,000 \pm 2,000$ yr old (Fig. 34A and Plate 1). The expression from the DOQ shows a distributary pattern radiating from the apex. At the apex, microrelief is up to 1 m, but the majority of the surface is smooth with little relief (< 0.3 m) (Fig. 34B and 34C). The ridges and mounds with 1 m of microrelief could be deposited by sheetfloods or debris flows. The smooth surface most closely resembles sheetflood deposits. Historic sheetflood deposits form mounds of gravel that are elongate in the direction of flow for < 10 m, and are several meters wide and less than 0.5 m tall (Blair, 1987). Debris flow deposits tend to have lateral lobes and/or levees with steep sides (near vertical) and relief up to 1.5 m (Blair and McPherson, 1998). The young age ($2,000 \pm 2,000$ yr) of Surface N does not provide much time for surface modification processes to have altered the original deposits. Lower relief (< 0.5 m) sheetflood deposits are more likely to exhibit a smooth surface faster than the higher relief (< 1.5 m) debris flow

deposits. More time is needed to smooth out higher landforms by either degrading the landform (e.g. colluvial collapse) or by filling in the depressions (e.g. addition of windblown dust) relative to smaller, shorter landforms. In addition, a mechanism to change the sediment transport process from sheetflood (Gravel Package X) to debris flow (Gravel Package XI) would need to be considered. The sediment transport process dominant on an alluvial fan is attributed to the underlying bedrock in the drainage basin (Blair and McPherson, 1994). Modified sheetflood deposits most likely cover surface N.

The numerical ages are internally consistent and correspond with the surface modification stage of each surface. The ages are comparable to those of Upper Cedar Creek alluvial fan. Surface M has the most developed soil and is the oldest surface.

Gravel Package X is bound above by Surface M and the lower boundary is unknown. Carbonate coat thicknesses provides a minimum age of $42,000 \pm 18,000$ yr for the gravel package. The dominant facies observed in Gravel Package X are cobble gravel and pebble gravel facies. The massive, poorly sorted, clast-supported cobble gravel has subangular to subrounded carbonate clasts set in a poorly sorted matrix of clay to sand. The pebble gravel facies is poorly sorted, clast supported gravel with subangular to subrounded carbonate clasts and a poorly sorted clay to sand matrix. These facies alternate in the section with the coarser facies on the bottom of the couplet (Fig. 37). One cycle of these facies represents a sheetflood couplet. The coarser cobble gravel facies was transported as bedload in a sheetflood and deposited without matrix as a gravel sheet upon collapse of an antidune (Blair and McPherson, 1994; Blair, 2000). The overlying pebble gravel facies was transported as suspended load in a sheetflood and deposited after the bedload (Blair and McPherson, 1994; Blair 2000). The matrix for the gravels

was added later through infiltration during recessional flood flow, fall out of eolian dust or mechanical transfer of sediment with descending rainfall (Blair and McPherson, 1994; Blair, 2000). The massive well-sorted, matrix-supported silt facies is only observed at the top of Section 11. There are clasts of floating carbonate cobbles. This layer was formed by the addition of silt through eolian processes to the sheetflood deposits and mixing of silt and gravel by animal burrowing and frost processes.

Gravel Package XI is bound above by Surface N, and possibly below by Surface M (Fig. 35C). These surfaces provide an age bracket of $2,000 \pm 2,000$ to $42,000 \pm 18,000$ yr for the age of Gravel Package XI. There are no vertical exposures of the deposits of the gravel package. Based on the surface morphology of Surface N, Gravel Package XI is composed of sheetflood deposits. This is similar to the sediment transport process of Gravel Package X. Because Surface N is 1 m above Surface J, Gravel Package XI is a minimum of 1 m thick and is probably a thin gravel package that thins down fan.

Three surfaces and two gravel packages are recognized on Jones Creek alluvial fan. Surface M is the oldest and largest surface. It is inferred that the steeper Surface N overlays Surface M at the apex. Gravel Package X probably thickens toward the fault, based on the model of normal fault development creating the greatest accommodation space adjacent to the fault. The active depositional lobe of Jones Creek alluvial fan is Surface J and extends from the apex to the toe (Plate 1). Surface J has the shallowest slope and is the youngest surface. Surface M is a deposition surface whereas Surface J mantles an erosional longitudinal profile. The recent deposits that bury the base of trees are interpreted to be thin, covering the base of the incised channel way. The longitudinal

profile of Surface J is a composite feature resulting from opposite processes. The first process is degradational with the removal of Gravel Package I while the second involves aggradation of recent deposits. Surface M and Surface J merge near the toe and the apex (Fig. 35). Gravel Package X was excavated to create the channel way (40 m deep, 80 m wide and 5 km long). It is unlikely that another significant gravel package is located below Surface J based on the presence of 1 to 2 m high silt cliffs, which indicate that down cutting is ongoing. With development of the channel way, sediment would bypass Surface M making it inactive. Surface N was active $2,000 \pm 2,000$ yr ago but the most recent deposits are on Surface J. There is no stage of backfilling. Jones Creek alluvial fan is a sheetflood dominant alluvial fan (Type II of Blair and McPherson, 1994). Trees do not live farther down fan on Surface J because the creek does not flow the whole distance to the toe. The three surfaces on Jones Creek alluvial fan each represent different periods of deposition.

CHAPTER 7

NORTH OF JONES CREEK ALLUVIAL FAN

The North of Jones Creek alluvial fan is the smallest (3.49 km² (1.35 sq mi)) and steepest fan (7-9°) of the study. It is located directly north of Jones Creek alluvial fan and the active depositional lobe for both converge down fan. The active depositional lobe is on the southern portion of the alluvial fan.

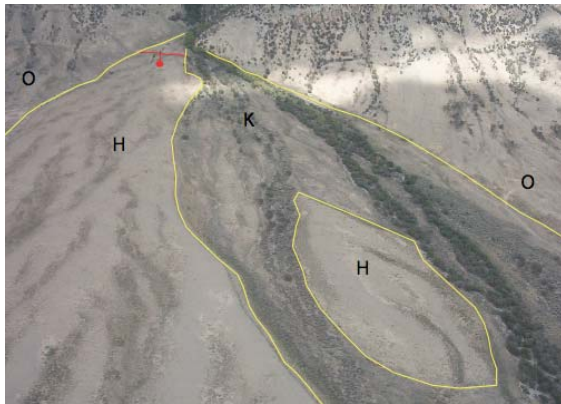
The drainage basin is small (3.83 km² (1.48 sq mi)). Lithologies exposed in the drainage basin are carbonates (79%) with interbedded fine-grained clastic rocks (Table 7). The rock units that compose the drainage basin are Devonian Jefferson, Three Forks, Mississippian McGowen Creek and Scott Peak Formations. The dolomitic Jefferson Formation composes over half of the drainage basin.

Table 7. Formations present in North of Jones Creek alluvial fan drainage basin (				
Formations	Age	Dominant Lithology	Percent of Drainage Basin	Area
Jefferson Formation	Devonian	Dolostone	55	2.10 km ² 0.82 mi ²
Three Forks Formation	Late Devonian	Limestone	4	0.16 km ² 0.06 mi ²
McGowen Creek Fm	Early Mississippian	Mudstone and shale	21	0.80 km ² 0.31 mi ²
Middle Canyon Formation	Late Mississippian	Limestone	9	0.34 km ² 0.13 mi ²
Scott Peak Formation	Late Mississippian	Limestone	11	0.43 km ² 0.17 mi ²

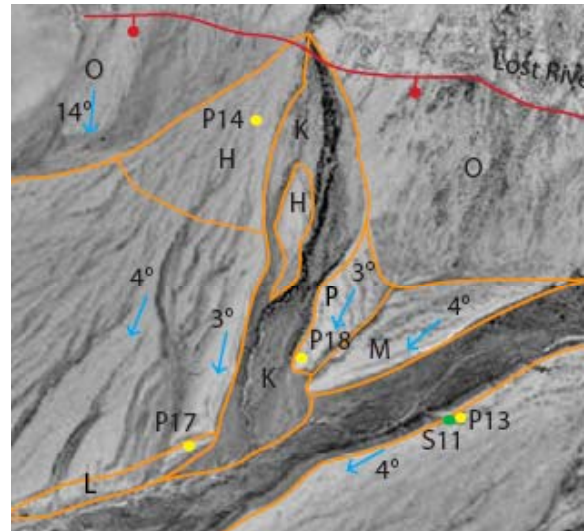
Surface Descriptions

The lack of incision into North of Jones Creek alluvial fan has preserved the original alluvial fan surface morphology, on which two surfaces are mapped, Surfaces H

and K. The active depositional lobe is Surface K while Surface H is inactive (Fig. 38A and 38B). The lack of exposure leads to no vertical sections being described. The presence of junipers was used to distinguish the two surfaces, as junipers are present on Surface K but not on Surface H (Fig. 38C). The Lost River fault has a fault scarp near the apex of North of Jones Creek alluvial fan (Fig. 38D).



A



B



C



D

Figure 38 (A) Apex of North of Jones Creek alluvial fan with surfaces. The red line is the Lost River fault and yellow lines are contacts. (B) Excerpt from Plate 1 showing the different map expressions of Surface H and K. (C) Looking down fan with Surface K to the left of the junipers and Surface H to the right. Note contrast of surface morphology between surfaces. (D) Looking up fan at fault scarp.

Surface H

Surface H is the inactive surface on North of Jones Creek alluvial fan. The average slope for Surface H is 7.20° (0.126 ft/ft). There are large angular carbonate boulders on the surface (Fig. 39A). Orange lichen are well established on the boulders (Fig. 39A). Surface H has carbonate pebbles and cobbles, and silt and clay matrix on the surface. There are linear mounds oriented parallel to the radius of the fan. The mounds are 1-2 m wide and can be up to 10 m long. Boulders are best exposed at the tops of these mounds and ridges. Sagebrush and grasses dominate vegetation of this surface. There are small (<1 m deep) incised channels dissecting Surface H. The photo in Figure 39A was taken on the side of one of these channels. The fault scarp offsets Surface H. Enough time has passed for junipers to die and all woody debris to disappear, and the mounds to be subdued and accumulate fines. Surface H has been inactive for a long time.



A



B

Figure 39. (A) Angular boulder (~1.5 m) on Surface H. Orange lichen grows on the top of the clast while carbonate coat (white) grows on the underside. (B) Looking down fan at surface morphology littered with carbonate boulders and cobbles.

Surface K

Surface K is the active depositional lobe of North of Jones Creek alluvial fan. The average slope of Surface K is 9.36° (0.165 ft/ft). The active gully is the one lined with the greenest trees in Figure 38A. Moving across the fan from Surface H to K and to the active gully, it is easy to see the progression of landforms and their surface modification states. There are parallel ridges composed of gravel that align with the radius of the alluvial fan. The ridges are 1.5 m high, 2 m wide and up to 10 m long.



A



B



C



D

Figure 40. (A) View up fan at two parallel ridges on Surface K. (B) View up fan at a clast-rich mound. Jacob's staff is 1.5 m high. (C) Gravel mound with abundant fines, especially organic material. Jacob's staff for scale. (D) A clast supported gravel mound that is fines-poor. Notice orange lichen growing on boulders and cobbles. Jacob's staff for scale.

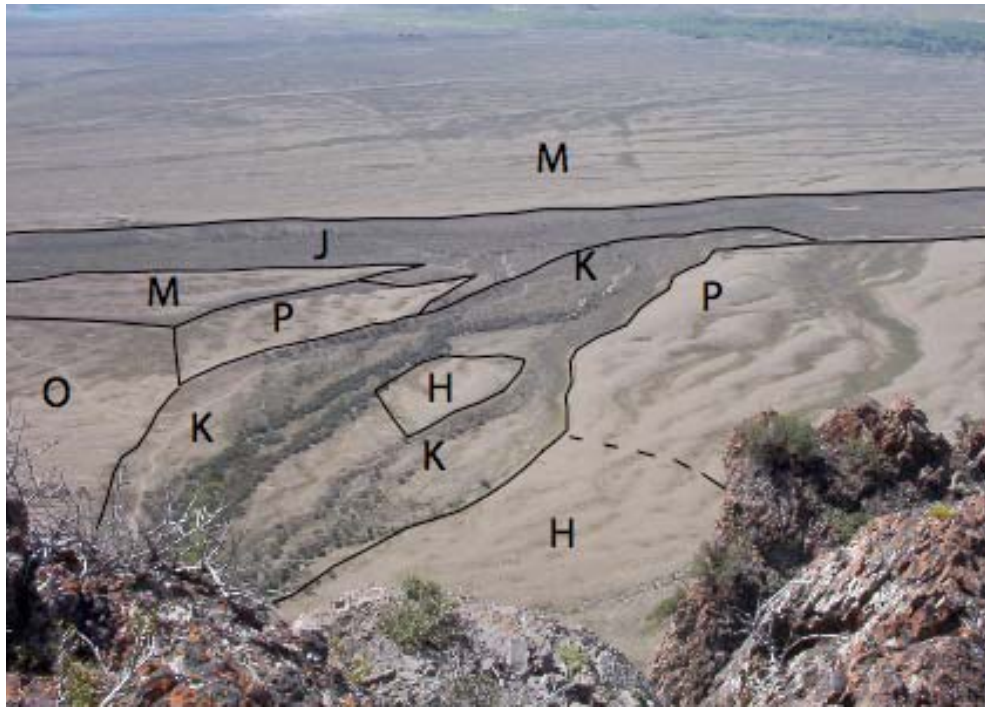
Angular and subangular carbonate boulders and cobbles cover this surface. The gravels are clast supported with a varying amount of fines. Some mounds and ridges are fines-poor while others have abundant fines, including a significant amount of organic matter, mostly pine needles (Fig. 40B, 40C and 40D). Orange lichen grows on all of the clasts. Junipers are growing on the gravel ridges. Sagebrush and grasses grow on the rest of Surface K. The fault scarp does not offset Surface K, but the creek does not flow beyond the fault down fan.

Surface L

Surface L is an intermediate surface between Surface J and P. It is only located on the north side of the creek and has a small map area (Plate 1). There is bench ~2m above Surface L that is another surface. This bench was too small to draw on the DOQ. The surface morphology of Surface L is smooth, just like Surface P. The ground on Surface L is firmer than Surface P, as my boot did not depress in the soil more than 0.5 cm.

Surface P

Surface P covers most of North of Jones Creek alluvial fan. It has an average slope of 4.40° and is smooth with microrelief less than 0.5 m. Subangular to subrounded carbonate pebbles litter the surface. The surface is silt rich. The surface is soft, and a boot depresses 1 cm in the ground with each step. This surface is being eroded as evidenced by convergent drainage patterns that dissect the surface creating 15 m deep channel ways (Fig. 38C and 41A).



A

Figure 41. (A) View south showing confluence of North of Jones of Creek alluvial fan with Jones Creek alluvial fan. Surface P has incised channel ways (to right of label P) exhibiting convergent drainage patterns.

Gravel Package Description

Gravel Package XII is the only gravel package on North of Jones Creek alluvial fan. Surface H and K are the upper bounding surfaces for Gravel Package XII. The lower bounding surface is unknown, but may be Surface P. There are no exposures to describe the sediment. The surface deposits and morphology will be used to describe the sediment that composes Gravel Package XII.

Age Data

Four pits were dug on the four surfaces of North of Jones Creek alluvial fan to determine an age of the surfaces (Table 8). One pit was dug and 18 carbonate coats were measured on Surface H on North of Jones Creek alluvial fan. This age is congruent with a 4,000 yr old fault that created the observed fault scarp (Crone and Haller, 1991). Two pits and 15 coats were measured on Surface P and one pit was dug on Surface L.

Table 8. Age of surfaces on North of Jones Creek alluvial fan			
Surface	Coat t (mm)	Number of clasts	Age (yr)
H	0.5 ± 0.2	18	$8,000 \pm 3,000$
K	0	0	Modern
P	1.7 ± 0.9	15	$28,000 \pm 15,000$
L	2.1 ± 1.0	23	$35,000 \pm 17,000$

Discussion

Surface K is the active depositional lobe of North of Jones Creek alluvial fan. The creek flows over this surface for a short distance. Angular boulder-lined gravel ridges and gravel mounds cover Surface K. They are parallel for up to 10 m and have steep sides. Similar deposits have been interpreted as debris flow levees, lobes and plugs (Hubert and Filipov, 1987; Cechovic, 1990; Blair and McPherson, 1994; Blair and McPherson, 1998). Debris flow levees are deposited as viscous flow traveling down fan. As most of the flow continues down fan, some of the debris is deposited on the flanks of channel ways as levees. These levees are boulder-rich because buoyancy forces push the boulders to the sides and front (Hubert and Filipov, 1987; Blair and McPherson, 1994). The gravel mounds found between the ridges are interpreted as debris flow plugs. Debris flow plugs are composed of the same poorly sorted coarse gravel of the levees and tend to

have a concentration of boulders at the snout (Hubert and Filipov, 1987; Blair and McPherson, 1994; Blair and McPherson, 1998). Debris flow plugs occur because the flow stops before leaving the confines of previously deposited levees. Lateral lobes are formed by debris flow deposits that occur when the debris flow leaves the confines of the levees and the flow spreads out. The lateral lobe deposits are usually shorter and wider than levee deposits with boulders concentrated around the edges of the lobe. These deposits are present on Surface K but are not as easy to identify as levees and plugs.

The lack of matrix in the gravels is a result of reworking of the debris flow deposits by channelized water flows (Blair and McPherson, 1994; Blair and McPherson, 1998). The creek is only competent enough to transport the finest grain fraction so the gravel is left matrix-poor. The debris flow plugs are especially matrix-poor, probably as a result of being in the flow path of the creek.

Surface H is the inactive portion of North of Jones Creek alluvial fan. Boulderly ridges and mounds cover Surface H. These deposits are interpreted as weathered debris flow levees, lateral and terminal lobes, and plugs. The boulder-lined, parallel ridges are debris flow levees deposited at the flanks of the flow during transport. The plugs are the gravel deposits between the ridges. Lateral and terminal lobes are interpreted as the gravel mounds that are shorter and wider than the ridges. The gravels on Surface H have a greater amount of matrix than those of Surface K. The matrix was deposited by eolian processes and has worked into the gravel. Surface H has older more weathered debris flow deposits than Surface K. Based on the deposits of Surface H and K, North of Jones Creek alluvial fan is a debris flow dominant alluvial fan or Type I of Blair and McPherson (1994).

Surface K is the active depositional lobe and hence is modern in age. Surface H is inactive and is dated at $8,000 \pm 3,000$ yr. This date is corroborated by dates of last fault rupture. The Lost River fault in this area last produced ground offset 4,000 years ago (Crone and Haller, 1991). This fault scarp offsets Surface H at the apex, but not Surface K. The creek flows on Surface K to the fault. At the fault, the creek completely infiltrates into the ground.

Surface L is an intermediate surface between Surface J and P and is $35,000 \pm 17,000$ yrs old. This surface resembles Surface P and is inactive as well. The small map area and lack of vertical exposures make the origin of Surface L difficult to interpret. Surface L could be an erosional bench created by the removal of Gravel Package XIII. Conversely, Surface L could be depositional, in which case it is the upper boundary for another gravel package. The origin of Surface L is not resolvable with the available data.

Surface P is the large surface on North of Jones Creek alluvial fan and is $28,000 \pm 15,000$ yrs old. The short microrelief (< 0.5 m) and local erosion indicate an inactive surface. The channel ways exhibit a convergent drainage pattern, which is interpreted to be an erosional pattern. The surface morphology and slope of Surface P is very similar to that of Surface M. Surface P is interpreted to be modified sheetflood deposits. Surface P is an inactive surface of modified sheetflood deposits, based on surface morphology.

Gravel Package XII is bound above by Surface H and K. As no vertical exposures of Gravel Package XII exist, the surface morphology of Surfaces H and K is used to determine the types of deposits that compose this gravel package. Both Surface H and K are covered with debris flow deposits, at different surface modification stages. Since North of Jones Creek alluvial fan has been producing debris flows for the last 8,000

yr, it is reasonable to assume that it has always produced dominantly debris flow deposits. Gravel Package XII is composed of debris flow deposits. It is interpreted that Surface P is the lower bounding surface for Gravel Package XII.

North of Jones Creek alluvial fan is a composite landform that has multiple surfaces, which represent different periods of activity. The debris flow dominant Surface K and H represent the most recent fan development. Gravel Package XII is thought to be composed predominantly of debris flow deposits. Surface H merges with Surface P down fan (Plate 1). Surface P represents an older ($28,000 \pm 15,000$ yr) surface when sheetfloods were transporting sediment from the catchment. The modified sheetflood deposits on Surface P suggest that sheetflood deposits underlie the surface. Gravel Package XIII is inferred to underlie Surface P and be composed of sheetflood deposits. There are no vertical exposures of this gravel package. Following the surface and gravel package patterns seen on the other studied fans (e.g. Surface N on Surface M of Jones Creek alluvial fan), it is inferred that Gravel Package XII overlies Gravel Package XIII (Fig. 35C). A contrast of the style of deposits would occur across this inferred unconformity with debris flow deposits above it and sheetflood deposits below. Deposition of the North of Jones Creek alluvial fan as debris flows on top of Surface P between $28,000 \pm 15,000$ and $8,000 \pm 3,000$ years ago. The multiple surfaces on North of Jones Creek alluvial fan demonstrate the different stages of alluvial fan development including a possible change in sediment transport process.

CHAPTER 8

ELKHORN CREEK ALLUVIAL FAN

Elkhorn Creek alluvial fan is a classic map-view fan cone that is 2.75 km² (1.08 sq mi) in size. The drainage basin covers 7.38 km² (2.88 sq mi) in size. It is located north of the other fans near the boundary of the Mackay and Thousand Springs fault segments (Fig. 3). The active depositional lobe is on the southern portion of the alluvial fan (Plate 1).

The drainage basin of Elkhorn Creek alluvial fan is underlain by two major lithologies, quartzarenite (81%) and carbonate (12%) (Table 9). Consequently, quartzarenite dominates the clasts on the fan. The Proterozoic Wilbert, Cambrian Tyler

Table 9. Formations present in Elkhorn Creek alluvial fan drainage basin				
Formation	Age	Dominant Lithology	Percent of Drainage Basin	Area
Wilbert Formation	Late Proterozoic to Early Cambrian	Quartzarenite	11	0.80 km ² 0.32 mi ²
Tyler Peak Formation	Cambrian	Quartzarenite	3	0.20 km ² 0.08 mi ²
unnamed	Cambrian	Phyllite	7	0.55 km ² 0.22 mi ²
Summerhouse Formation	Ordovician	Quartzarenite	54	4.02 km ² 1.57 mi ²
Kinnikinic Quartzite	Ordovician	Quartzarenite	11	0.80 km ² 0.31 mi ²
Fishhaven Dolostone	Late Ordovician to Early Silurian	Dolostone	8	0.62 km ² 0.24 mi ²
Laketown Dolostone	Silurian	Dolostone	4	0.28 km ² 0.11 mi ²

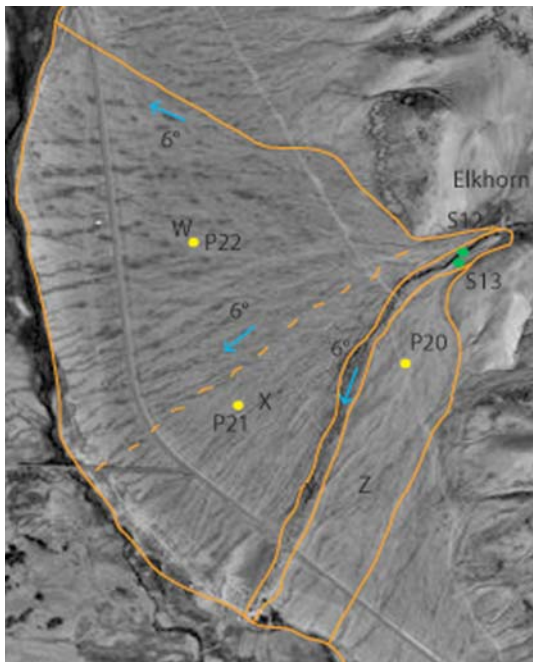
Peak and phyllite, Ordovician Summerhouse Formation, Kinnikinic Quartzite, and Fishhaven Dolostone, and Silurian Laketown Dolostone are the rock units that underlie the drainage basin. The percentages do not sum to 100 because 2% of the drainage basin is mapped as undifferentiated quartzite. The Elkhorn Creek fault is located in the drainage basin.

Surface Descriptions

Four surfaces are identified on Elkhorn Creek alluvial fan, Surfaces W, X, Y, and Z (Plate 1). The surfaces are easiest distinguished based on surface morphology. The boundary of each surface was mapped based on a change of surface characteristics (Fig. 42).

Surface W

Surface W was mapped on the far northern flank of Elkhorn Creek alluvial fan (Fig. 42A). The average slope of Surface W is 7.42° (0.130 ft/ft). The subdued microrelief on Surface W is less than 0.5 m. Cobble and pebble ridges are discontinuous and difficult to trace up or down fan (Fig. 43A). The ridges are ~2 m wide with gradual side slopes. The few boulders present are not larger than 1 m. There are cobbles and pebbles with some fines on the surface (Fig. 43B). Quartzite clasts are the most common with minor carbonate lithology. Green and orange lichen are growing on clasts. The boundary between Surface W and X is well defined on the DOQ as two different patterns, but is gradational on the ground (Fig. 42A). Surface W has more convergent drainage pattern areas, especially near the toe toward the road than Surface X. Surface X has longer ridges that are more continuous. Surface W is a more subdued than Surface X.



A



B



C



D

Figure 42. (A) Excerpt from DOQ of Elkhorn Creek alluvial fan. Note the distributary pattern that radiates from the apex. (B) The southern aspect of the fan apex. Surface Y shows up dark colored because of the presence of trees. (C) The northern aspect of the fan apex. Note the fan surface showing down fan divergent patterns. (D) Looking down fan at the southern portion of alluvial fan. Surface Y, the active depositional lobe is lined with trees.

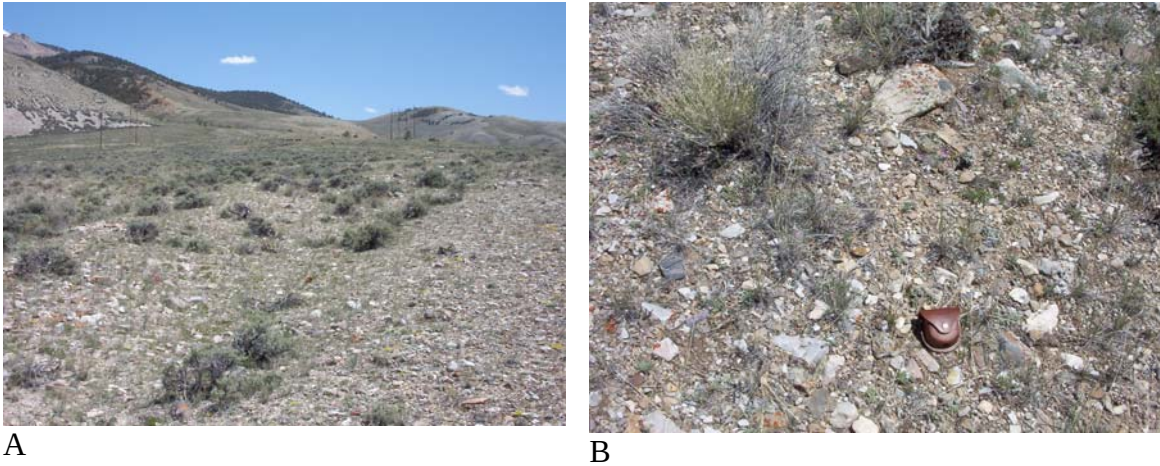


Figure 43. (A) View up fan on Surface W of the discontinuous ridges that have microrelief less than 0.5 m. (B) Pebble and cobble clasts on the surface with abundant fines. Brunton transit for scale.

Surface X

Surface X is a boulder rich surface with an average slope of 7.14° (0.126 ft/ft). The surface is littered with angular to subangular quartzarenite (~80%) and carbonate (~20%) boulders 1 to 3 meters (Fig. 44A). Carbonate composition is the other clast lithology. The ground is covered with silt and clay and minor sand matrix. Ridges of boulders and cobbles extend for ~10 m and are up to 2 m high (Fig. 44B). Some ridges are parallel with a few meeting at acute angles and all are discontinuous. Between the ridges are mounds of clast supported gravel (Fig. 44A). The clasts are covered by thriving orange lichen. Sagebrush and grasses grow on this surface, but no trees. The distributary pattern on the DOQ is narrower than Surface W (Fig. 42A).

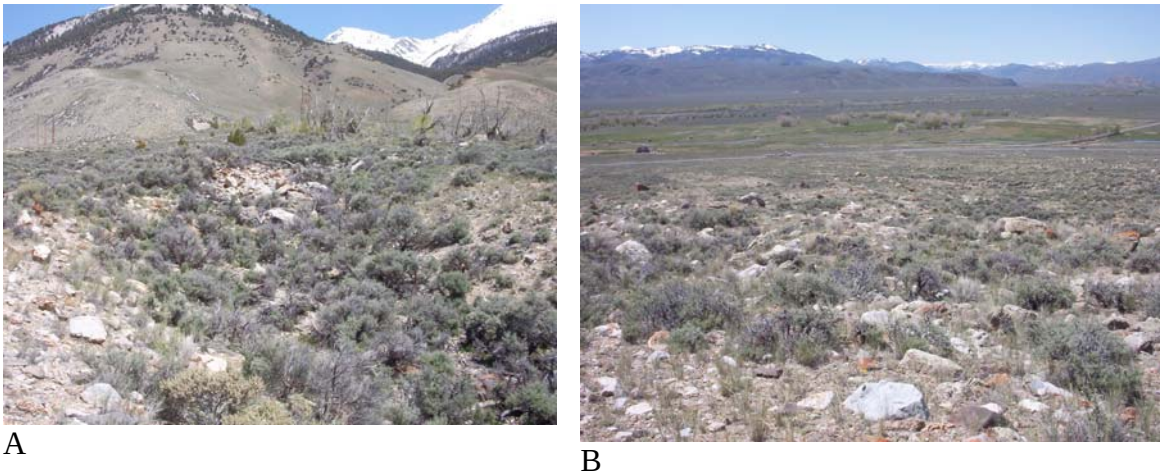


Figure 44. (A) View up fan on Surface X at two parallel ridges with a clast supported gravel mound in middle. Relief is ~1m. (B) Looking down fan at gravel ridge. Gray quartzite boulder in the foreground is ~1m long.

Surface Y

The active depositional lobe for Elkhorn Creek alluvial fan is mapped as Surface Y. This surface has a narrow map shape and extends from the apex to the toe (Fig. 42A). The average slope of Surface Y is 6.97° (0.122 ft/ft). A boulder-lined gully stretches the entire radius of the fan. This channel way is incised 7 m (Section 12) at the apex and decreases to ~1 m near the toe. The channel way is rocky with pebbles to boulders up to 1.5 m (Fig. 45A). The rocky channel way bottom stair-steps up to the apex. Cottonwood, pine, bushes and algae grow in and around the channel way. Tree growth is limited to close proximity of the channel way but extends the length of the fan. Water only flows in the gully for 10s of meters near the apex. The water is then piped to a ranch at the toe of the fan.

Adjacent to the active channel way, surface Y is boulder rich (Fig. 45B). The angular to subangular boulders are composed mostly of quartzite and limestone with



A



B



C



D



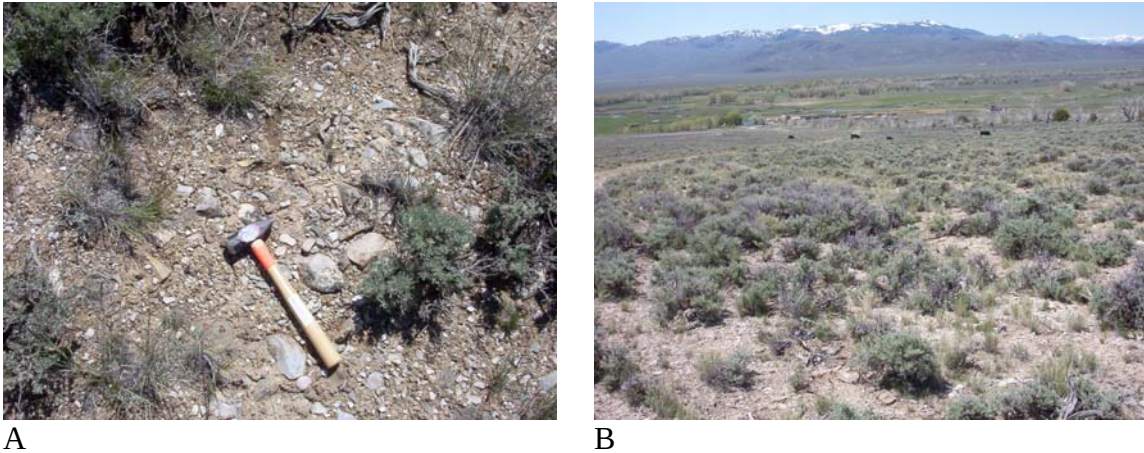
E

Figure 45. (A) View looking down fan at the boulder and tree rich channel way. (B) View looking down fan at Surface Y adjacent to incised channel. Notice the quartzite and limestone boulders along with dead trees. Jeep for scale. (C) Fresh gravel deposit. Rock hammer for scale. (D) Fines-poor fresh gravel deposits incorporated with dead logs. Rock hammer for scale. (E) Logs separate fines-rich, clast-rich gravel mound from fines-rich, clast-poor older fan surface. The logs are part of the gravel mound. Rock hammer for scale.

occasional igneous clasts (Fig. 45B). The boulders are up 1.5 m in diameter. The matrix on the ground is silt and clay, and deficient in sand. Sagebrush and grasses dominate the surface outside the channel way. Logs of about 0.3 m diameter are also on the surface (Fig. 45B). Two-meter high ridges composed mostly of boulders run parallel to the fan radius. These ridges are 3 to 10 m long and are 2 m wide. Clast supported boulder and cobble rich gravel are sometimes present between ridges. Contacts between the fresh deposits adjacent to the channel way and older alluvial fan deposits are sharp (Fig. 45E). These fresh deposits range from fines-rich to fines-poor gravel lobes and are lying on top of the weathered gravels of Surface Z and X that are fines rich (Fig. 45C and 45D). There is an abundance of dead wood and some pieces have saw cuts. Some are partially buried. Orange lichen and carbonate coats are absent from clasts on Surface Y. There have been minor human disturbances in the channel to allow a hose to pump water down fan for livestock. There is a dirt road across the channel way.

Surface Z

Surface Z is south of the active depositional lobe on Elkhorn Creek alluvial fan (Fig. 42A). Surface Z has a slope of 6.52°. It is unclear if it correlates with Surface W. The surface is covered with cobbles and pebbles of mostly angular to subrounded quartzite and a few limestone, schist, and igneous clasts (Fig. 46A). The matrix is composed mostly of silt with some clay and trace sand. There is very little microrelief on the surface (< 0.5 m) (Fig. 46B). Gravel lobes are 3 meters wide and ~10 m long oriented parallel to fan radius. Sagebrush and grass are the dominant plants. Relief on Surface Z is more subdued than on Surface W.

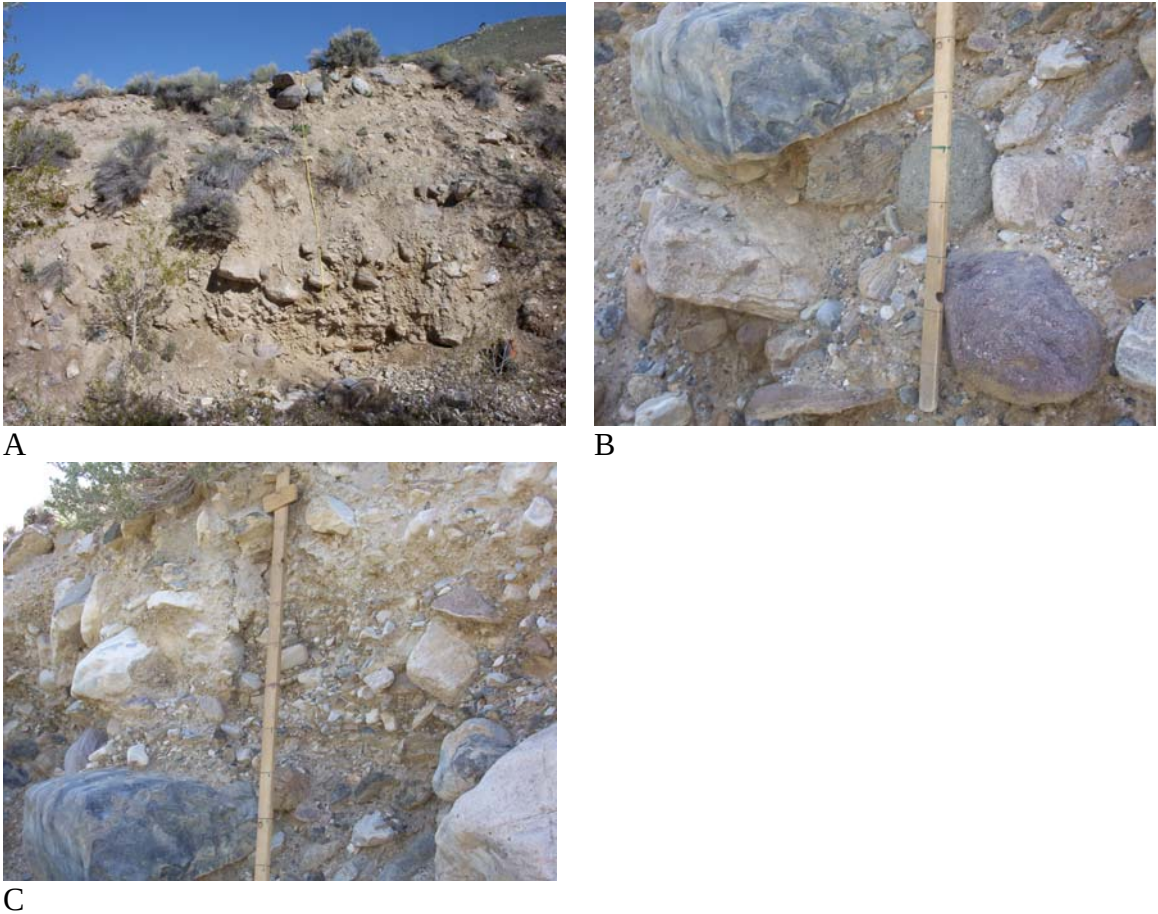


A
B
Figure 46. (A) Surface quartzite cobbles and pebbles. Rock hammer for scale. (B) View looking down fan on Surface Z. Notice lack of microrelief and sagebrush. Cows for scale.

Measured Sections

Two measured sections were described on Elkhorn Creek alluvial fan. Both were described on the wall of the channel way near the apex (Fig. 42A and Plate 1). Surface Y is the top of both sections.

Section 12 was described in a vertical wall of the channel way near the apex of Elkhorn Creek alluvial fan on the north side of the channel way (Fig. 47A). There are 9 stratigraphic units that range from 0.3 to 2.2 m thick in the 7 m high exposure (Fig. 48). The presence or absence of boulders defines bedding and identifies the facies contacts (Fig. 47C). The massive, clast supported, very poorly sorted boulder gravel facies has clasts ranging in size from granule to boulder (Fig. 47B and 47C). The boulders are up to 1.5 m. The quartzite and limestone clasts are subangular to subrounded. The boulder gravel facies has tangential to occasional long contacts. The moderately sorted matrix has silt and clay with minor sand. The massive, poorly sorted cobble gravel facies has the same moderately sorted matrix as the boulder gravel facies.



C
Figure 47. (A) Section 12 outcrop on northern wall of channel way. Note the boulder rich beds. The cliff is 7 m high. (B) Boulder rich bed of quartzarenite and carbonate clasts with silt and clay rich matrix. Marks on Jacob's staff are 10 cm. (C) Cobble gravel facies on top of boulder rich bed. Jacob's staff for scale.

Section 13 was also described near the apex but down fan ~20 m from Section 12 on the south side of the channel way wall. This section was not as well exposed with only the top 2.2 m of the incised wall being described (Fig. 49). The facies are similar to those of Section 12, boulder/cobble gravel and pebble gravel facies. There are four stratigraphic units that range in thickness from 0.3 to 0.9 m.

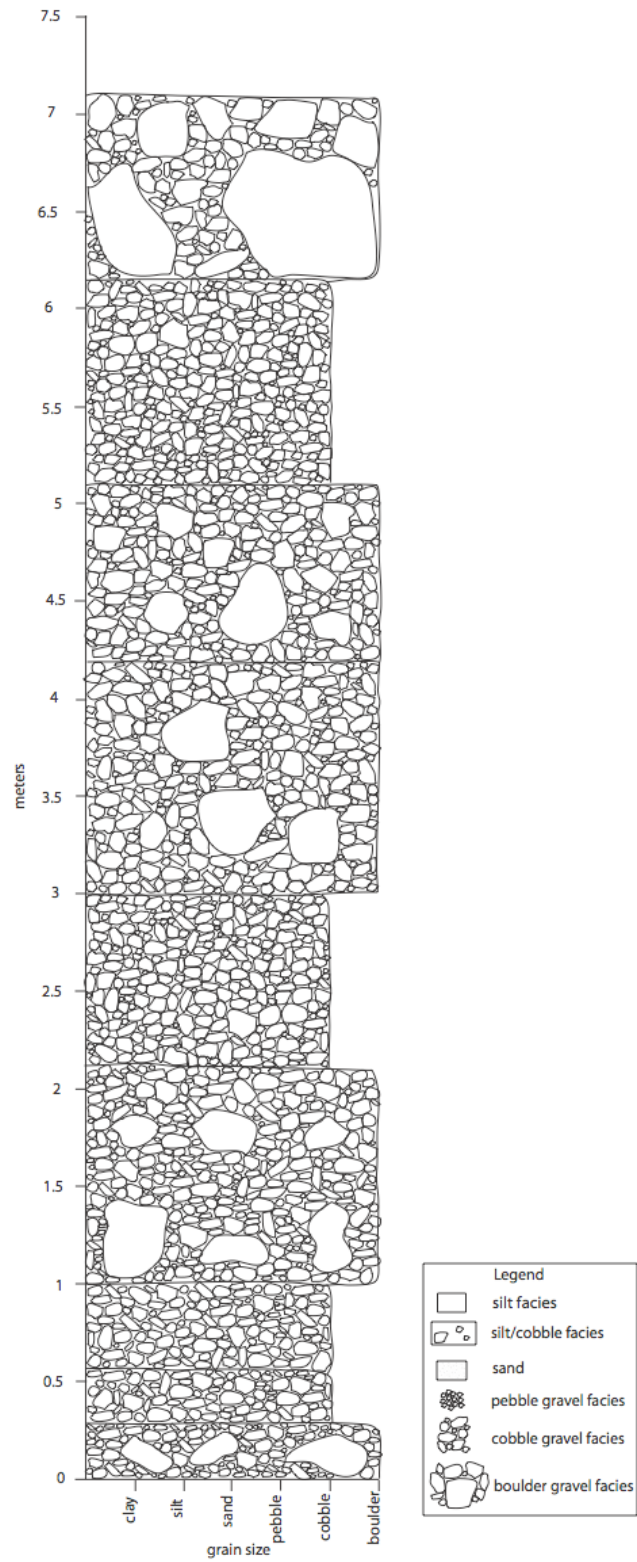


Figure 48. Stratigraphic column for Section 12 on Elkhorn Creek alluvial fan.

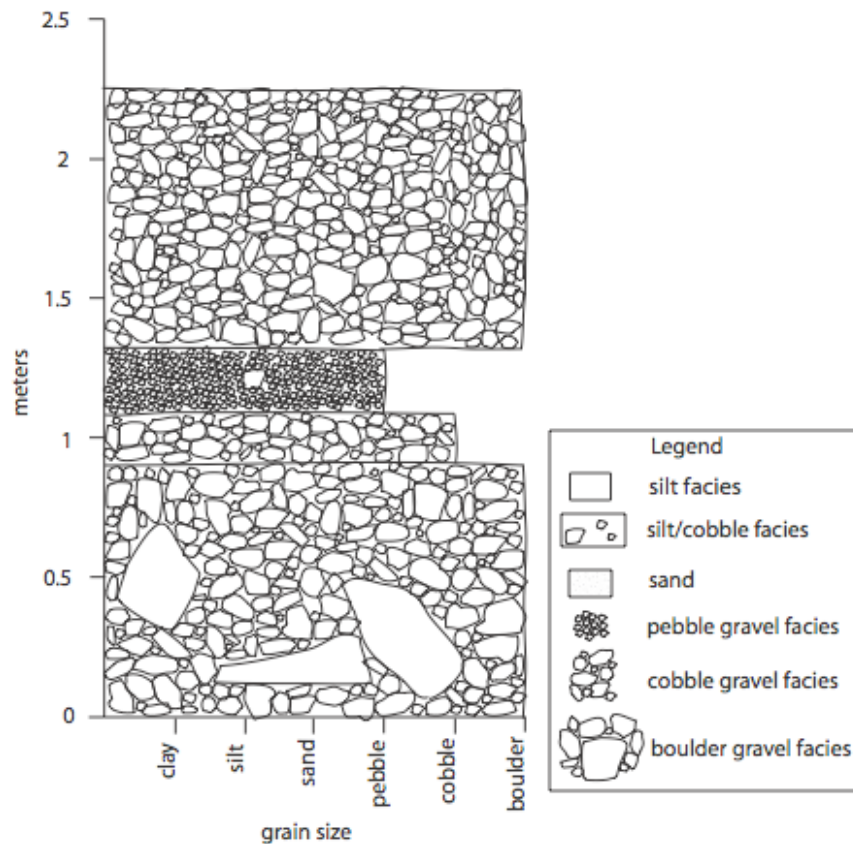


Figure 49. Stratigraphic column for Section 13 on Elkhorn Creek alluvial fan.

Age Data

Three pits and 35 limestone clasts were measured on 3 of the 4 surfaces of Elkhorn Creek alluvial fan. No pits were dug and hence no clasts were measured on Surface Y, the active surface. Table 10 shows the ages of the different surfaces on Elkhorn Creek alluvial fan. Only quartzite clasts are present on Surface Z. There were fewer carbonate clasts uncovered in pits on Elkhorn Creek alluvial fan (Appendix). This can be attributed to the drainage basin lithology. The most abundant lithology is quartzite with only minor amounts of carbonate. The standard deviation is smaller for these samples.

Table 10. Ages of Surfaces on Elkhorn Creek Alluvial Fan			
Surface	Coat t (mm)	Number of clasts	Age (yr)
W	1.2 ± 0.2	11	$20,000 \pm 3,000$
X	0.5 ± 0.2	7	$8,000 \pm 3,000$
Y	0	0	Modern
Z	1.5 ± 0.6	17	$26,000 \pm 16,000$

Discussion

Both measured sections and surface descriptions will be used to understand the deposits and sediment transport processes active on Elkhorn Creek alluvial fan. The surfaces are covered by boulders, cobbles, pebbles and parallel ridges. The deposits are massive, clast supported boulder gravels with angular to subrounded granule to boulder size clasts surrounded by a silt- and clay- rich, and sand-poor matrix.

Debris flow deposits are generally poorly sorted gravels with angular to subangular clasts organized into parallel levees and lobes on the surface and seen in vertical section as discontinuous massive beds. These characteristics are common to the sediments of Elkhorn Creek alluvial fan. The massive boulder gravel beds lack internal stratification, which implies that the beds were deposited as a single depositional event. The presence of a variety of clast sizes from boulders to clay incorporated in the same bed strongly suggests that the matrix and framework grains were deposited simultaneously by a viscous flow. Debris flows are competent, viscous flows that are able to transport boulders to clay (Costa, 1988; Blair and McPherson, 1994). All of the sediment, water and air move and stop together in debris flows (Costa, 1988). The viscous nature of debris flows enables simultaneous deposition of all grains in the flow producing poorly sorted to very poorly sorted deposits, similar to the boulder gravel and

cobble gravel facies seen in Section 12 and 13. This is observed in recent deposits (Hubert and Filipov, 1989; Blair and McPherson, 1998; Blair, 2003). Channelized water flows do not deposit fines contemporaneous with coarse grain fractions, because the fines are usually transported as suspended sediment and are deposited after the bedload. The presence of wood incorporated in the gravels is a strong indication of a debris flow origin because the less dense wood usually would be washed away in water flows (Fig. 45D and 45E) (Costa, 1988).

Angular to subrounded clasts are found in deposits of Elkhorn Creek alluvial fan. The presence of high angularity clasts implies that the clasts did not travel far and more importantly that there were few grain-to-grain collisions during transport. Since clasts are not transported in suspension but rather are supporting the load of the flow, they have limited mobility within the flow. This reduces the number and velocity of the grain-to-grain contacts preserving the angularity of clasts.

Paired parallel boulder lined ridges are common topographic features on Surface Y and Surface X. These ridges are interpreted as debris flow levees and the high boulder concentration results from buoyancy forces. The levees are the flanks of the debris flow that were deposited as the majority of the debris flow continued down fan. During a debris flow, buoyancy forces push the boulders to the edges of the flow where they are deposited on the flanks of the flow as boulder rich levees (Blair and McPherson, 1994; Blair, 2003). Boulders have a tendency to be concentrated at the tops, sides, and fronts of debris flow deposits because of the buoyancy force exerted on the lower density clasts (Blair and McPherson, 1994). This interpretation is not unique, as multiple landforms with similar features have been deposited during recent and historic debris flows (Hubert

and Filipov, 1989; Cechovic, 1990; Blair and McPherson, 1998; Blair, 2003). The coarse gravel mounds observed between the levees are debris flow plugs (Fig. 43A). Plugs form when debris flows stopped flowing before exiting the confines of the levees. Boulders concentrate at the snout because of buoyancy forces. The gravel mounds present on Surfaces W, X and Y are interpreted as modified debris flow lobes. Debris flow lobes result from debris flows exiting the confines of the levees and their subsequent spread out on to the fan surface (Blair and McPherson, 1994, 1998). As a result of their formation, their deposits tend to be thinner and wider than levees. Both of the surface descriptions and measured sections add considerable strength that Elkhorn Creek alluvial fan is a debris flow dominant alluvial fan, Type I alluvial fan of Blair and McPherson (1994).

Elkhorn Creek alluvial fan is an active depositional landform. There are no very fresh (less than a few years old) deposits on the alluvial fan. There are deposits with young trees growing on them, which are probably less than 40 yrs old. This lack of recent deposits does not prevent Elkhorn Creek alluvial fan from being cataloged as an active geomorphic landform. It is likely that debris flows will occur on Elkhorn Creek alluvial fan in the near future.

The ages based on carbonate coat thicknesses are internally consistent. These ages correlate well with the surface modification stage of each surface. The surfaces represent a progression of degradation on a debris flow dominant alluvial fan. Surface Y is the active depositional lobe with the youngest deposits and is modern. Surface X is the next youngest surface and has modified debris flow levees, plugs and lobes and is $8,000 \pm 3,000$ yr. The landforms are still recognizable but are not recent. Surface W has swalely topography that represents weathered debris flow deposits and is $20,000 \pm 3,000$

yr. Surface X has a smooth surface with subdued landforms and is $25,000 \pm 15,000$ yr.

There is a direct correlation between the numerical ages and surface modification stage, from youngest to oldest, the landforms on Surfaces Y, X, W, and Z.

The surfaces represent different depositional lobes active at different times. A simple calculation can be made by dividing the oldest age, 25,000 yr by the number of surfaces, 4, providing a rough estimate for the average time between switching of depositional lobes. An age of 6,000 is calculated as the average amount of time between depositional lobe avulsion.

The limited vertical exposure prohibits the identification of gravel packages on Elkhorn Creek alluvial fan. Assuming that the modern deposits and the measured sections are representative of the deposits for the alluvial fan than Elkhorn Creek alluvial fan is composed almost exclusively of debris flow deposits.

The older surfaces have more subdued landforms. In addition, the older surfaces have progressively steeper slopes. Surface Y is the youngest and has a slope of 7° , Surface X the next oldest surface has a slope of 7.1° and Surface W has a slope of 7.4° . Surface Z is the oldest surface and has a slope of 6.5° , which does not follow the pattern.

CHAPTER 9

DISCUSSION

Growth strata are identified in extensional tectonic settings have two stages of development along normal faults that affect the geomorphology and sedimentary facies in extensional fault bound basins (Gawthorpe et al., 1997). The first stage is termed the growth fold stage whereas the second is known as the surface faulting stage. The growth fold stage occurs when the normal fault is blind. The extensional fault propagation fold produces a monocline and topographic relief. The surface faulting stage occurs with surface offset produced by the normal fault. These concepts were developed from excellent Paleogene rocks exposures in the Suez Rift, Egypt (Gawthorpe et al., 1997; Sharp et al., 2000). Complex faulting occurs in the Suez Rift with multiple normal faults accommodating extension and local thrust and reverse faults (Sharp et al., 2000). This complexity directly affects the sediments. A newly-forming normal fault may have both stages observed at different places along strike (Gawthorpe et al., 1997).

The structural geology of the two stages is different, which contributes to contrasting geomorphology and basin fill geometries. During stage one a monocline is produced over the blind normal fault and a syncline over the hanging wall (Gawthorpe et al., 1997). The greatest amount of accommodation space is in the syncline, which is some distance away from the fault. The amount of accommodation space is reflected in the stratal thickness, which thickens from the monocline to the axis of the syncline (Gawthorpe et al., 1997). Strata onlap and truncate toward the monocline (Gawthorpe, et al., 1997). A progressive steepening of the dips down section and a fanning of the dips

results from tilting of the strata. Strata tilting is caused by fault movement and fold growth, which steepened the basinward limb of the monocline. Angular unconformities become correlative conformities parallel to bedding in the syncline (Sharp et al., 2000). This stratal geometry is growth strata. The stratal characteristics of stage one are different from stage two sediments.

Surface faulting begins with surface penetration of the normal fault. The greatest amount of accommodation space is located adjacent to the fault. Stratal thickness mirrors the accommodation space. A wedge-shaped profile of sediments is created by thickening of the strata towards the fault and thinning toward the basin. This is opposite of strata geometries from growth folding. Fanning of dips can be present with decreasing dip values up section. The wedge of sediment with a fanning of dips constitute growth strata. The degree of rotation of the hangingwall block will control tilting of overlying sediments. The listric shape of the normal fault and the role of synthetic and antithetic faults in the basin control the rotation of the hangingwall block. There are inherited differences between syntectonic sediments deposited adjacent to a monocline and those deposits next to a fault scarp.

The Lost River Range presently is part of the surface faulting stage of normal fault development outlined by Gawthorpe et al. (1997). The Lost River fault breaches the surface and has for at least 30,000 yr based on fault trench studies (Crone and Haller, 1991). There is no known evidence suggesting that the Lost River fault originated as a blind fault. Strata patterns of stage two do predict, quite well, the stratal geometry of the Big Lost River Valley sediments. The alluvial fans along the western flank of the Lost River Range exhibit some of the same features as growth strata seen in extensional

settings, including wedges of sediment and fanning of dips. Gravel Packages I, II and possibly X are wedge-shaped gravel packages that thicken toward the fault. All of these gravel packages are composed of sheetflood deposits. Bounding these gravel packages are surfaces that have a fanning of dips. Surfaces A, B and C on Upper Cedar Creek alluvial fan and Surfaces W, X, Y, and Z on Elkhorn Creek alluvial fan have increasing slope steepness with increasing age.

Differences between the studied alluvial fans and growth strata observed in extensional settings include: a lack of angular unconformities, different orientation of the fanning dips and absence of channel ways. No angular unconformities have been identified between the gravel packages on any of the four alluvial fans; however, limited exposure impeded observation. The fanning of the dips diverging toward the fault are organized differently on Upper Cedar Creek and Elkhorn Creek alluvial fans from the dipping strata in the Suez Rift. In the Suez Rift, the wedges of sediment have increasing dips of older sediments going down section (Gawthorpe et al., 1997; Sharp et al., 2000). The dips on Upper Cedar Creek alluvial fan are measured on surfaces and the oldest surface (C) is the steepest but is also the highest (Fig. 11). The next oldest surface (B) is below Surface C and has a shallower dip. The youngest surface (A) is the lowest and has the shallowest slope. The surfaces are not buried like those of the Suez rift. On Elkhorn Creek alluvial fan all of the surfaces are exposed and not buried as well. Each surface has a different slope that generally increases directly with age. The oldest surface (Z) does not follow this trend. Down dropping and tilting of sediments on the hangingwall block does not explain these surface orientations. Channel ways play an important role in the stratal geometry observed on the studied alluvial fans, but are not observed in

sediments in the Suez Rift. This difference could be attributed to the different depositional environments of the two examples. Alluvial fans are flanking the Lost River Range, whereas fluvial, tidal and shallow marine environments characterize the Suez Rift deposit (Sharp et al., 2000).

Upper Cedar Creek alluvial fan is a large sheetflood dominant Type II alluvial fan. The significant erosion, dissection, and lack of recent deposits make it an inactive landform. There are two channel ways on this fan. The oldest channel way was formed by removal of Gravel Package I. The channel way was partially backfilled with Gravel Package II (Fig. 11). The youngest channel way was created by partial removal of Gravel Package II. No ancient channel way systems were identified in the gravel package sediments. It appears that the young channel way is still incising and thus not backfilled. The surface and cross sectional views of Gravel Package I die out and pinch out at the alluvial fan toe. In cross section, the wedge shaped Gravel Package I thickens toward the fault and thins basinward. Gravel Package II also appears to be wedge shaped in cross section and thicken toward the fault and thin basinward. Gravel Package II is located completely within the channel way (Fig. 11). Thickening of strata toward the normal fault most resembles a growth fault. The surfaces that bound these gravel packages become steeper with older surfaces up section (Fig. 11). Debris flow deposits of Gravel Package III are burying Surface C. Table 11 summarizes the surface and gravel package data of Upper Cedar Creek alluvial fan.

Table 11. Summary of surfaces and gravel packages on Upper Cedar Creek alluvial fan (UUCAF)				
Surface	Slope (°)	Age (ka yr)	Underlying Gravel Package	Sediment transport process
A	2.68	Modern	II	Sheetflood
B	2.76	7 ± 5	II	Sheetflood
C	3.05	28 ± 20	I	Sheetflood
O	10-17	Modern	III	Debris flow
F	N/A	?	IV	Sheetflood

Jones Creek alluvial fan is a sheetflood dominant Type II alluvial fan that is currently inactive. The channel way has not been backfilled and may be incising today. Gravel Package XI was deposited on top of Surface M as recently as 2,000 yr ago (Table 12). Debris flow deposits of Gravel Package III are being deposited on top of Surface M.

Table 12. Summary of surfaces and gravel packages on Jones Creek alluvial fan (JCAF)				
Surface	Slope (°)	Age (ka yr)	Underlying Gravel Package	Sediment transport process
M	4.05	42 ± 18	X	Sheetflood
N	4.11	2 ± 2	XI	Sheetflood?
J	3.81	Modern	X	Sheetflood

Currently, North of Jones Creek alluvial fan is a debris flow dominant Type I alluvial fan. Deposition for the last 8,000 yr has been by debris flow processes (Table 13). Surface P evidences the previous stage of fan development and may overlie sheetflood deposits.

Table 13. Summary of surfaces and gravel packages on North of Jones Creek alluvial fan (NJCAF)				
Surface	Slope (°)	Age (ka yr)	Underlying Gravel Packages	Sediment transport process
H	7.20	8 ± 3	XII	Debris flow
K	9.36	Modern	XII	Debris flow
P	4.40	28 ± 15	XIII?	Sheetflood

Elkhorn Creek alluvial fan is a classic debris flow dominant Type I alluvial fan. The different ages of the surfaces are attributed to channel avulsion. Besides the channel way at the apex, there has been no major incision. This alluvial fan is active today and has been so for at least the last 25,000 yr (Table 14).

Table 14. Summary of surfaces on Elkhorn Creek alluvial fan (ECAAF)			
Surface	Slope (°)	Age (ka yr)	Sediment transport process
W	7.42	20 ± 3	Debris flow
X	7.14	8 ± 3	Debris flow
Y	6.97	Modern	Debris flow
Z	6.52	25 ± 15	Debris flow

The western flank of the Lost River Range is skirted by several alluvial fans that have many surfaces. These surfaces have different slopes, ages and formation histories. A surface slope is the result of many factors including: depositional or erosional development, sediment transport process, and subsequent deformation. Depositional surfaces can have straight or concave up longitudinal profiles. Erosional surfaces have almost exclusively concave up longitudinal profiles (). Different erosive processes including ice, water or wind, create surfaces with different slopes (). The slope of depositional surfaces depends on the sediment transport process. Sediment gravity flows tend to produce steeper surfaces than water flows. Debris flows, which are competent, viscous flows that have a high shear stress produce the steepest slopes. Surfaces on debris flow deposits are generally steeper than surfaces on sheetflood deposits (e.g. Surface O is steeper than Surface C). Forces acting on the surface after it has formed can change its slope. Faulting and folding along with isostatic rebound can change the primary surface slope.

All four alluvial fans are located on the same fault segment of the extensional Lost River fault. There is significant lateral variability along this fault segment from a classic debris flow fan (ECAAF) with no incision to a sheetflood fan that has two stages of incision and one stage of backfilling (UCCAF). As a result, there are multiple mappable surfaces that formed as a result of different factors. Surfaces J and A are the result of erosion. Most of the surfaces are depositional, either by debris flow or sheetflood processes. The surfaces overlying debris flow deposits are always steeper than those of sheetflood deposits. The modern erosional surfaces have the shallowest slopes. These surface slopes are inherited from an erosional time period because there is active deposition burying trees. The modern depositional surfaces are the steepest as a result of the being deposited by debris flows. Surfaces A, B and C increase in steepness with increasing age as do Surfaces W, X and Y. These data suggest that there has been tilting of the alluvial fan sediments over time. The most common pattern observed is for large inactive sheetflood alluvial fans to be dissected and buried by small young debris flow alluvial fans. This relationship is well-demonstrated by Surface O and Gravel Package III situated on top of Upper Cedar Creek and Jones Creek alluvial fans. Two alluvial fans (JCAF and UCCAF) exhibit periods of incision and one fan had a period of further deposition (UCCAF). Upper Cedar Creek alluvial fan has a period of channel way formation followed by partial backfilling. Currently, another channel way is forming. Jones Creek alluvial fan has a channel way that has not been backfilled. A complexity of deposition from two different sediment transport processes, erosion, inherited geology, climate, and tectonic factors that influence the observed geologic relationships are well exemplified along this short stretch of the mountain front. It is difficult to unravel the

complex interplay between all of the factors and their products on this landscape. It would be even more difficult to decipher the products of these interacting processes in the rock record.

Drainage basins of North of Jones Creek, Jones Creek and Upper Cedar Creek alluvial fans are dominated by carbonate bedrock of the same formations (Table 1). Debris flow and sheetflood-dominant alluvial fans result from this source rock. This contradicts the suggestion that bedrock lithology is the dominant control on sediment transport processes for alluvial fans (Blair and McPherson, 1994). Drainage basin size may play an important role in the amount of water available to transport debris.

There are two stratigraphic relationships that have implications to the rock record. One is the relationship of contrasting sediment transport processes on North of Jones Creek alluvial fan. Gravel Package XII is composed of debris flow deposits and is inferred to rest unconformably on sheetflood deposits of Gravel Package XIII. The other scenario is Gravel Package III resting unconformably on Surface M of Jones Creek alluvial fan and Surface C on Upper Cedar Creek alluvial fan. Both of these examples have debris flow deposits overlying sheetflood deposits. If provided with only a vertical section, deciphering the relationships would be difficult, if not impossible. One possible interpretation would be that a single alluvial fan experienced a change in sediment transport process over time, perhaps due to climatic controls. Another potential interpretation would be that the deposits were from two different alluvial fans with different drainage basins. In this case, clast count data would not allow distinguishing multiple alluvial fans because the same formations underlie both drainage basins.

Angular unconformities within modern deposits from Hell's Gate alluvial fan, Death Valley, California, were interpreted as progressive unconformities (growth strata) (Blair, 2000). They are not growth strata, but rather produced by a small fault block that was deformed by a strike slip fault localized mid fan. There are no wedges of sediment with fanning dips bound by unconformities. Not all intraformational angular unconformities in alluvial fan deposits adjacent to active structures are growth strata.

Two conflicting factors that control alluvial fan morphology are climate and tectonics. Many geomorphologists have approached studying modern alluvial fans by attempting to understand the multiple surfaces commonly found on them (Bull, 1964; Hooke, 1967; Harvey, 1988, 1990; Ritter et al., 1993). Based on age constraints, correlation is usually made with fan progradation during glacial periods and reduced deposition during interglacial periods. In this view it is concluded that tectonic activity is only needed to create topographic relief (Harvey, 1990). On the contrary, many sedimentologists have interpreted alluvial fan deposits in association with deformation and uplift (e.g. Christophoul et al., 2003). Growth strata were identified in this way. Growth strata are identified in alluvial fan deposits, which record tectonic deformation of fan deposits being rotated during deposition. Sedimentologists have not identified surfaces in the rock record, nor have geomorphologists identified growth strata on modern alluvial fans. Hence, a disconnect is present. One of the problems contributing to this discrepancy may be temporal. Growth strata develop over ~ 1 Ma, whereas most geomorphic studies rarely exceed 0.1 Ma (Holl and Anastasio, 1993). There may be relationships in this temporal gap that may relate climate and tectonics to deposition on alluvial fans. The other problem is that geomorphologists are not looking for growth

strata and sedimentologists are not looking for surfaces in alluvial fan deposits. One exception is the work of Williams (1982) who attributed tectonic uplift as the cause of fanning of surfaces on mountain front alluvial fans in Nepal.

This study does not resolve the temporal gap but will propose two possible explanations for the origin of the Lost River alluvial fan deposits. These possibilities will follow the current paradigm in thinking: 1) climatic cause and 2) tectonic cause. It is unclear which cause has more merit. The climatic cause is predicted upon a change in available water to transport debris across time. Conversely, the tectonic cause involves a change in the location of fault displacement.

The last glaciation (Pinedale) occurred from ~45,000 to ~10,000 yr (Figure 50) (Chadwick et al., 1997). The current interglacial period started ~10,000 yr. Dates from the high surfaces on the sheetflood alluvial fans (Surface C, M, and P), suggest activity until 28,000, 42,000, and 28,000 yr, respectively. The sheetflood dominant alluvial fans were active landforms during much of the last glaciation (Fig. 50). Effective moisture availability is greater during glacial periods, which would allow for more debris to be transported and result in creation of larger depositional landforms (sheetflood fans). At the end of glaciation, there is a transition from wetter to dryer climate. This transition period of the climatic cycle is thought to have the most available water to do geomorphic work. It seems likely that channel ways would be created during this period. They may be backfilled or not, depending on available debris. With onset of the dryer climate, the sheetflood alluvial fans are no longer active and begin being dissected and eroded. Debris flow deposits become abundant in the dryer climate and are deposited on top of the sheetflood deposits. The recent debris flow deposits may be a testament to this dryer

climate. This cause does not account for the continuous development of debris flow deposits on Elkhorn Creek alluvial fan.

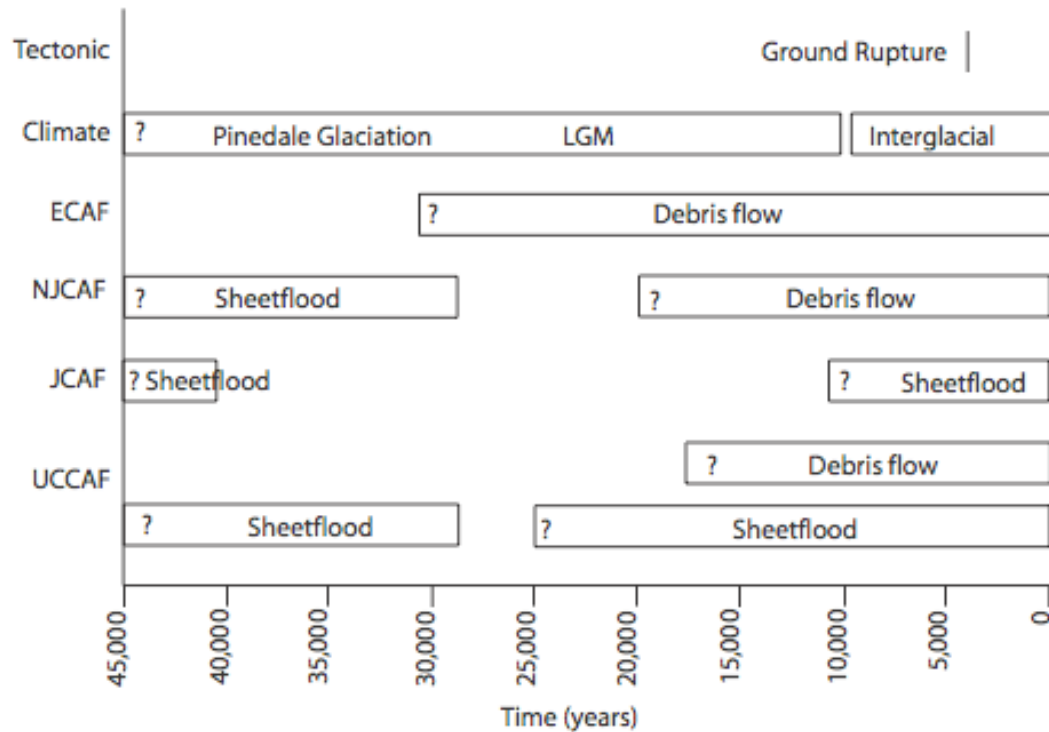


Figure 50. Timeline of events occurring on the Mackay fault segment. LGM = Last Glacial Maximum, ECAF = Elkhorn Creek alluvial fan, NJCAF = North of Jones Creek alluvial fan, JCAF = Jones Creek alluvial fan, UCCAF = Upper Cedar Creek alluvial fan.

The older surfaces, on Upper Cedar Creek alluvial fan, are steeper than the younger surfaces. This is not congruent with their close proximity to an active normal fault. One way to explain this geometry involves a basinward step in the location of fault displacement that would transfer hanging-wall sediment to the footwall. The transferred sediment (the apex of Upper Cedar Creek alluvial fan) would be uplifted instead of down dropped (Fig. 51). With movement on both faults there will be clockwise rotation of the small fault block. This would result in flattening of the surface slopes. The placement of

the new fault would be where Gravel Package I pinches out in cross-section (Fig. 51). As a result, the entirety of Gravel Package IV would be in the footwall and being uplifted. This scenario accounts for the geometries of Upper Cedar Creek and Elkhorn Creek alluvial fans.

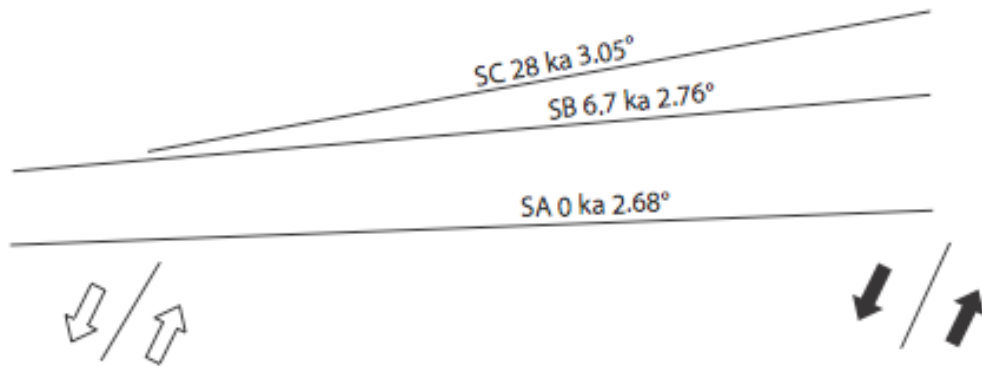


Figure 51. Cross section of Upper Cedar Creek alluvial fan with old fault position (solid arrows) and new location (open arrows). Surfaces are labeled with “S” followed by corresponding letter. Ages are in thousands of years (ka). No scale intended.

CHAPTER 10

CONCLUSIONS

- 1) Upper Cedar Creek alluvial fan is a sheetflood dominant (Type II) alluvial fan that is presently inactive. Jones Creek alluvial fan is an inactive sheetflood dominant (Type II) alluvial fan. North of Jones Creek alluvial fan is a debris flow dominant (Type I) alluvial fan. A previous stage of sheetflood deposition on North of Jones Creek alluvial fan is possible. Elkhorn Creek alluvial fan is a classic debris flow dominant (Type I) alluvial fan.
- 2) The gravel packages in the alluvial fans along the Lost River Range have well-defined upper bounding surfaces that provide a minimum age of deposition. Lower bounding surfaces were rarely identified. Gravel Packages I ($28,000 \pm 20,000$ to ?) and II ($7,000 \pm 5,000$ to $28,000 \pm 20,000$) on Upper Cedar Creek alluvial fan thicken toward the Lost River fault and thin toward the basin, and its surfaces steepen with age. Two channel ways were created through incision and the oldest was partially backfilled (Gravel Package II). Gravel Package X ($42,000 \pm 18,000$ to ?), on Jones Creek alluvial fan also thickens toward the Lost River fault. One channel way was created with removal of Gravel Package X. Gravel Package XII ($8,000 \pm 3,000$ to $28,000 \pm 20,000$) is bound above by steep surfaces and was deposited on top of Surface P, on North of Jones Creek alluvial fan. No gravel packages were identified in the deposits of the Elkhorn Creek alluvial fan but the surfaces steepen with age. Alluvial fans along the Mackay fault segment of the Lost River fault demonstrate some attributes similar to growth strata in extensional settings. The alluvial fan

sediments are organized in wedge-shaped gravel packages that thicken toward the fault and the strata have fanning dips. The older surfaces have steeper dips than younger surfaces. Conversely, these deposits differ from classic growth strata by lacking angular unconformities and having the oldest surfaces steeper and higher than the younger shallower surfaces. A complex of factors including sediment transport process, erosion, climate and tectonics contribute varied characteristics of the fan sediments and surfaces observed along the mountain front.

- 3) The commonality between the four alluvial fans include young, small debris flow fans that were deposited on top of old inactive sheetflood alluvial fans (e.g. Gravel Package III deposited on top of Upper Cedar Creek and Jones Creek alluvial fan). Upper Cedar Creek and Jones Creek alluvial fans are large inactive sheetflood fans that are currently being dissected. The wedge-shaped gravel packages that thicken toward the Lost River fault are identified in the large inactive sheetflood fans and not in the active debris flow alluvial fan sediments. Two channel ways developed on Upper Cedar Creek alluvial fan with one stage of backfilling and only one stage of incision occurred on Jones Creek alluvial fan, whereas no incision occurred on North of Jones Creek and Elkhorn Creek alluvial fans. The different stratal geometries indicate great lateral variability of fan deposits along fault segments.

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APPENDICES

APPENDIX A

CARBONATE COAT THICKNESS DATA ORGANIZED BY PIT

UCCAF = Upper Cedar Creek alluvial fan

JCAF = Jones Creek alluvial fan

NJCAF = North of Jones Creek alluvial fan

ECAF = Elkhorn Creek alluvial fan

Pit 1	Surface C	UCCAF	North of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	1.7	5	1.1
2	1.5	6	1.8
3	1.4	7	2.0
4	0.9	n = 7	All Carbonate

Pit 2	Surface B	UCCAF	North of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	0.4	11	0.6
2	0.7	12	0.6
3	0.8	13	0.4
4	0.7	14	0.2
5	0.4	15	0.6
6	0.8	16	0.3
7	0.5	17	0.1
8	0.5	18	0.1
9	0.7	19	0.3
10	0.4	n = 19	All Carbonate

Pit 3	Surface B	UCCAF	North of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
20	0.1	30	0.2
21	0.2	31	0.4
22	0.2	32	0.1
23	0.1	33	0.1
24	0.3	34	0.1
25	0.2	35	0.3
26	0.2	36	0.2
27	0.3	37	0.3
28	0.3	38	0.1
29	0.2	39	0.2
		n = 20	All carbonate

Pit 4	Surface B	UCCAF	South of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	0.5	11	0.7
2	0.7	12	0.2

3	0.4	13	0.8
4	0.4	14	0.9
5	0.5	15	0.7
6	0.5	16	0.5
7	0.4	17	0.7
8	0.7	18	0.7
9	0.9	19	0.4
10	0.9	20	0.6
		n = 20	All carbonate

Pit 5	Surface C	UCCAF	South of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	0.7	3	1.4
2	0.4	4	2.0
		n = 4	All carbonate

Pit 6	Surface B	UCCAF	South of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
21	0.6	30	1.3
22	1.4	31	0.4
23	1.1	32	0.7
24	1.0	33	1.1
25	0.5	34	1.0
26	0.5	35	0.5
27	0.7	36	0.3
28	0.7	37	0.9
29	1.5	n = 17	All carbonate

Pit 7	Surface C	UCCAF	South of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
5	1.9	9	0.7
6	2.2	10	1.6
7	2.6	11	1.3
8	0.8	12	2.6
		n = 8	All carbonate

Pit 8	Surface B	UCCAF	South of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	0.7	10	0.2
2	0.1	11	0.9
3	0.1	12	0.1
4	0.7	13	0.1
5	0.3	14	0.5

6	0.2	15	0.2
7	0.4	16	0.2
8	0.2	17	0.3
9	0.2	n = 17	All carbonate

Pit 9	Surface C	UCCAF	South of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	3.0	6	1.6
2	2.3	7	1.8
3	0.8	8	0.1
4	0.6	9	1.5
5	0.2	10	0.2
		n = 10	All carbonate

Pit 10	Surface B	UCCAF	North of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	0.1	11	0.1
2	0.2	12	0.1
3	0.4	13	0.1
4	0.1	14	0.1
5	0.5	15	0.2
6	0.2	16	0.2
7	0.1	17	0.2
8	0.2	18	0.2
9	0.1	19	0.1
10	0.1	n = 19	All carbonate

Pit 11	Surface C	UCCAF	North of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	4.5	4	1.4
2	2.3	5	1.0
3	0.5	6	0.6
		n = 6	All carbonate

Pit 12	Surface C	UCCAF	North of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	5.7	2	4.7
		n = 2	All carbonate

Pit 13	Surface M	JCAF	South of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	2.1	9	4.6
2	2.6	10	1.0

3	2.0	11	1.9
4	1.9	12	3.1
5	4.0	13	2.5
6	0.9	14	5.0
7	0.3	15	2.0
8	0.7	n = 15	All carbonate

Pit 14	Surface H	NJCAF	
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	0.7	9	0.4
2	0.9	10	0.1
3	0.6	11	0.7
4	0.5	12	0.6
5	0.2	13	0.2
6	0.3	14	0.1
7	0.4	15	0.4
8	0.4	16	0.7
		n = 16	All carbonate

Pit 15	Surface N	JCAF	South of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	0.1	11	0.1
2	0.1	12	0.3
3	0.1	13	0.1
4	0.2	14	0.1
5	0.1	15	0.1
6	0.1	16	0.1
7	0.1	17	0.1
8	0.2	18	0.1
9	0.2	19	0.1
10	0.1	20	0.1
		n = 20	All carbonate

Pit 16	Surface M	JCAF	South of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	1.5	7	3.0
2	3.3	8	2.0
3	2.6	9	2.2
4	2.5	10	3.0
5	1.8	11	3.5
6	3.6	12	3.6
		n = 12	All carbonate

Pit 17	Surface L	NJCAF	North of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	3.7	13	3.0
2	2.9	14	0.6
3	1.0	15	1.4
4	2.7	16	1.7
5	3.0	17	1.0
6	1.0	18	1.6
7	2.1	19	2.6
8	3.0	20	2.4
9	4.0	21	2.6
10	0.1	22	1.2
11	2.1	23	1.9
12	3.1	n = 23	All carbonate

Pit 18	Surface P	NJCAF	North of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	1.0	5	1.2
2	1.0	6	1.5
3	2.6	7	0.2
4	2.7	8	1.7
		n = 8	All carbonate

Pit 19	Surface P	NJCAF	North of creek
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	1.5	5	2.6
2	1.5	6	3.7
3	1.0	7	2.1
4	0.9	n = 7	All carbonate

Pit 20	Surface Z	ECAF	
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	0.6	10	1.8
2	1.0	11	2.1
3	0.6	12	1.9
4	1.9	13	2.7
5	1.6	14	1.0
6	0.9	15	0.2
7	1.5	16	0.5
8	0.7	17	0.5
9	2.2	n = 17	All quartzarenite

Pit 21	Surface X	ECAF	
Sample #	Coat t (mm)	Sample #	Coat t (mm)
1	0.3	8	0.3
2	0.4	12	0.7
3	0.1	13	0.4
4	0.4	14	0.3
5	0.4	16	0.5
7	0.3	n = 11	All quartzarenite
6	0.7	15	0.5
9	0.5	17	0.2
10	0.2	18	1.0
11	0.6	n = 7	All carbonate

Pit 22	Surface W	ECAF	
Sample #	Coat t (mm)	Sample #	Coat t (mm)
2	0.7	7	1.0
3	0.7	10	1.6
4	1.6	11	0.3
5	1.0	12	0.7
6	0.2	13	1.1
		n = 10	All quartzarenite
1	1.1	17	1.3
8	1.0	18	1.0
14	1.7	19	1.3
15	1.2	20	0.8
16	1.4	21	1.2
		n = 10	All carbonate

APPENDIX B

CARBONATE COAT THICKNESS DATA ORGANIZED BY SURFACE

Upper Cedar Creek Alluvial Fan		Surface C	North of creek	Carbonate
Sample #	Coat t (mm)		Sample #	Coat t (mm)
1	1.7		9	2.3
2	1.5		10	0.5
3	1.4		11	1.4
4	0.9		12	1.0
5	1.1		13	0.6
6	1.8		14	5.7
7	2.0		15	4.7
8	4.5		n = 15	
Average t (mm)	2.1		Age (yr)	35000
Standard deviation	1.5		Age range +/- (yr)	25000
Growth rate (mm/yr)	0.00006		Rounded age (yr)	35,000 ± 25,000

Upper Cedar Creek Alluvial Fan		Surface C	South of creek	Carbonate
Sample #	Coat t (mm)		Sample #	Coat t (mm)
1	0.7		12	2.6
2	0.4		13	3.0
3	1.4		14	2.3
4	2.0		15	0.8
5	1.9		16	0.6
6	2.2		17	0.2
7	2.6		18	1.6
8	0.8		19	1.8
9	0.7		20	0.1
10	1.6		21	1.5
11	1.3		22	0.2
			n = 22	
Average t (mm)	1.4		Age (yr)	23333
Standard deviation	0.9		Age range +/- (yr)	15000
Growth rate (mm/yr)	0.00006		Usable date (yr)	23,000 ± 15,000

Upper Cedar Creek Alluvial Fan		Surface C	Both	Carbonate
Sample #	Coat t (mm)		Sample #	Coat t (mm)
1	1.7		19	2.6
2	1.5		20	3.0
3	1.4		21	2.3
4	0.9		22	0.8
5	1.1		23	0.6
6	1.8		24	0.2
7	2.0		25	1.6
8	0.7		26	1.8
9	0.4		27	0.1

10	1.4	28	1.5
11	2.0	29	0.2
12	1.9	30	4.5
13	2.2	31	2.3
14	2.6	32	0.5
15	0.8	33	1.4
16	0.7	34	1.0
17	1.6	35	0.6
18	1.3	36	5.7
		n = 36	
Average t (mm)	1.7	Age (yr)	28333
Standard deviation	1.2	Age range +/- (yr)	20000
Growth rate (mm/yr)	0.00006	Usable date (yr)	28,000 ± 20,000

Upper Cedar Creek Alluvial Fan		Surface B	North of creek	Carbonate
Sample #	Coat t (mm)	Sample #	Coat t (mm)	
1	0.4	31	0.4	
2	0.7	32	0.1	
3	0.8	33	0.1	
4	0.7	34	0.1	
5	0.4	35	0.3	
6	0.8	36	0.2	
7	0.5	37	0.3	
8	0.5	38	0.1	
9	0.7	39	0.2	
10	0.4	40	0.1	
11	0.6	41	0.2	
12	0.6	42	0.4	
13	0.4	43	0.1	
14	0.2	44	0.5	
15	0.6	45	0.2	
16	0.3	46	0.1	
17	0.1	47	0.2	
18	0.1	48	0.1	
19	0.3	49	0.1	
20	0.1	50	0.1	
21	0.2	51	0.1	
22	0.2	52	0.1	
23	0.1	53	0.1	
24	0.3	54	0.2	
25	0.2	55	0.2	
26	0.2	56	0.2	
27	0.3	57	0.2	

28	0.3	58	0.1
29	0.2		
30	0.2	n = 58	
Average t (mm)	0.3	Age (yr)	5000
Standard deviation	0.2	Age range +/- (yr)	3333
Growth rate (mm/yr)	0.00006	Usable date (yr)	5,000 ± 3,000

Upper Cedar Creek Alluvial Fan		Surface B	South of creek	Carbonate
Sample #	Coat t (mm)	Sample #	Coat t (mm)	
1	0.5	29	1.5	
2	0.7	30	1.3	
3	0.4	31	0.4	
4	0.4	32	0.7	
5	0.5	33	1.1	
6	0.5	34	1.0	
7	0.4	35	0.5	
8	0.7	36	0.3	
9	0.9	37	0.9	
10	0.9	38	0.7	
11	0.7	39	0.1	
12	0.2	40	0.1	
13	0.8	41	0.7	
14	0.9	42	0.3	
15	0.7	43	0.2	
16	0.5	44	0.4	
17	0.7	45	0.2	
18	0.7	46	0.2	
19	0.4	47	0.2	
20	0.6	48	0.9	
21	0.6	49	0.1	
22	1.4	50	0.1	
23	1.1	51	0.5	
24	1.0	52	0.2	
25	0.5	53	0.2	
26	0.5	54	0.3	
27	0.7			
28	0.7	n = 54		
Average t (mm)	0.6	Age (yr)	10000	
Standard deviation	0.3	Age range +/- (yr)	5000	
Growth rate (mm/yr)	0.00006	Usable date (yr)	10,000 ± 5,000	

Upper Cedar Creek Alluvial Fan		Surface B	Both	Carbonate
Sample #	Coat t (mm)	Sample #	Coat t (mm)	
1	0.4	57	0.2	
2	0.7	58	0.1	
3	0.8	59	0.5	
4	0.7	60	0.7	
5	0.4	61	0.4	
6	0.8	62	0.4	
7	0.5	63	0.5	
8	0.5	64	0.5	
9	0.7	65	0.4	
10	0.4	66	0.7	
11	0.6	67	0.9	
12	0.6	68	0.9	
13	0.4	69	0.7	
14	0.2	70	0.2	
15	0.6	71	0.8	
16	0.3	72	0.9	
17	0.1	73	0.7	
18	0.1	74	0.5	
19	0.3	75	0.7	
20	0.1	76	0.7	
21	0.2	77	0.4	
22	0.2	78	0.6	
23	0.1	79	0.6	
24	0.3	80	1.4	
25	0.2	81	1.1	
26	0.2	82	1.0	
27	0.3	83	0.5	
28	0.3	84	0.5	
29	0.2	85	0.7	
30	0.2	86	0.7	
31	0.4	87	1.5	
32	0.1	88	1.3	
33	0.1	89	0.4	
34	0.1	90	0.7	
35	0.3	91	1.1	
36	0.2	92	1.0	
37	0.3	93	0.5	
38	0.1	94	0.3	
39	0.2	95	0.9	
40	0.1	96	0.7	
41	0.2	97	0.1	

42	0.4	98	0.1
43	0.1	99	0.7
44	0.5	100	0.3
45	0.2	101	0.2
46	0.1	102	0.4
47	0.2	103	0.2
48	0.1	104	0.2
49	0.1	105	0.2
50	0.1	106	0.9
51	0.1	107	0.1
52	0.1	108	0.1
53	0.1	109	0.5
54	0.2	110	0.2
55	0.3	111	0.2
56	0.2	112	0.3
		n = 112	
Average t (mm)	0.4	Age (yr)	6667
Standard deviation	0.3	Age range +/- (yr)	5000
Growth rate (mm/yr)	0.00006	Usable date (yr)	7,000 ± 5,000

Jones Creek Alluvial Fan		Surface N	South of creek	Carbonate
Sample #	Coat t (mm)	Sample #	Coat t (mm)	
1	0.1	11	0.1	
2	0.1	12	0.3	
3	0.1	13	0.1	
4	0.2	14	0.1	
5	0.1	15	0.1	
6	0.1	16	0.1	
7	0.1	17	0.1	
8	0.2	18	0.1	
9	0.2	19	0.1	
10	0.1	20	0.1	
		n = 20		
Average t (mm)	0.1	Age (yr)	1667	
Standard deviation	0.1	Age range +/- (yr)	1667	
Growth rate (mm/yr)	0.00006	Usable date (yr)	2,000 ± 2,000	

Jones Creek Alluvial Fan		Surface M	South of creek	Carbonate
Sample #	Coat t (mm)	Sample #	Coat t (mm)	
1	0.3	15	2.5	
2	0.7	16	2.6	
3	0.9	17	2.6	
4	1.0	18	3.0	

5	1.5	19	3.0
6	1.8	20	3.1
7	1.9	21	3.3
8	1.9	22	3.5
9	2.0	23	3.6
10	2.0	24	3.6
11	2.0	25	4.0
12	2.1	26	4.6
13	2.2	27	5.0
14	2.5	n = 27	
Average t (mm)	2.5	Age (yr)	41667
Standard deviation	1.1	Age range +/- (yr)	18333
Growth rate (mm/yr)	0.00006	Usable date (yr)	42,000 ± 18,000

North of Jones Creek Alluvial Fan		Surface P	North of creek	Carbonate
Sample #	Coat t (mm)		Sample #	Coat t (mm)
1	0.2		9	1.5
2	0.9		10	1.7
3	1.0		11	2.1
4	1.0		12	2.6
5	1.0		13	2.6
6	1.2		14	2.7
7	1.5		15	3.7
8	1.5		n = 15	
Average t (mm)	1.7		Age (yr)	28333
Standard deviation	0.9		Age range +/- (yr)	15000
Growth rate (mm/yr)	0.00006		Usable date (yr)	28,000 ± 15,000

North of Jones Creek Alluvial Fan		Surface L	North of creek	Carbonate
Sample #	Coat t (mm)		Sample #	Coat t (mm)
1	0.1		13	2.4
2	0.6		14	2.6
3	1.0		15	2.6
4	1.0		16	2.7
5	1.0		17	2.9
6	1.2		18	3.0
7	1.4		19	3.0
8	1.6		20	3.0
9	1.7		21	3.1
10	1.9		22	3.7
11	2.1		23	4.0
12	2.1		n = 23	
Average t (mm)	2.1		Age (yr)	35000

Standard deviation	1.0	Age range +/- (yr)	16667
Growth rate (mm/yr)	0.00006	Usable date (yr)	35,000 $\pm$ 17,000

North of Jones Creek Alluvial Fan		Surface H		Carbonate
Sample #	Coat t (mm)	Sample #	Coat t (mm)	
1	0.7	9	0.4	
2	0.9	10	0.1	
3	0.6	11	0.7	
4	0.5	12	0.6	
5	0.2	13	0.2	
6	0.3	14	0.1	
7	0.4	15	0.4	
8	0.4	16	0.7	
		n = 16		
Average t (mm)	0.5	Age (yr)	8333	
Standard deviation	0.2	Age range +/- (yr)	3333	
Growth rate (mm/yr)	0.00006	Usable date (yr)	8,000 $\pm$ 3,000	

Elkhorn Creek Alluvial Fan		Surface W		Carbonate
Sample #	Coat t (mm)	Sample #	Coat t (mm)	
1	0.8	7	1.2	
2	1.0	8	1.3	
3	1.0	9	1.3	
4	1.0	10	1.4	
5	1.1	11	1.7	
6	1.2	n = 11		
Average t (mm)	1.2	Age (yr)	20000	
Standard deviation	0.2	Age range +/- (yr)	3333	
Growth rate (mm/yr)	0.00006	Usable date (yr)	20,000 $\pm$ 3,000	

Elkhorn Creek Alluvial Fan		Surface W		Quartzarenite
Sample #	Coat t (mm)	Sample #	Coat t (mm)	
1	0.3	7	0.3	
2	0.4	8	0.7	
3	0.1	9	0.4	
4	0.4	10	0.3	
5	0.4	11	0.5	
6	0.3	n = 11		
Average t (mm)	0.9	Age (yr)		
Standard deviation	0.4	Age range +/- (yr)		
Growth rate (mm/yr)		Usable date (yr)	Use carbonate age	

Elkhorn Creek Alluvial Fan		Surface X		Carbonate
Sample #	Coat t (mm)	Sample #	Coat t (mm)	
1	0.7	5	0.5	
2	0.5	6	0.2	
3	0.2	7	1.0	
4	0.6	n = 7		
Average t (mm)	0.5	Age (yr)	8333	
Standard deviation	0.3	Age range +/- (yr)	5000	
Growth rate (mm/yr)	0.00006	Usable date (yr)	8,000 ± 5,000	

Elkhorn Creek Alluvial Fan		Surface X		Quartzarenite
Sample #	Coat t (mm)	Sample #	Coat t (mm)	
1	0.3	7	0.3	
2	0.4	8	0.7	
3	0.1	9	0.4	
4	0.4	10	0.3	
5	0.4	11	0.5	
6	0.3	n = 11		
Average t (mm)	0.4	Age (yr)		
Standard deviation	0.1	Age range +/- (yr)		
Growth rate (mm/yr)		Usable date (yr)	Use carbonate age	

Elkhorn Creek Alluvial Fan		Surface Z		Quartzarenite
Sample #	Coat t (mm)	Sample #	Coat t (mm)	
1	0.6	10	1.8	
2	1.0	11	2.1	
3	0.6	12	1.9	
4	1.9	13	2.7	
5	1.6	14	1.0	
6	0.9	15	0.2	
7	1.5	16	0.5	
8	0.7	17	0.5	
9	2.2	n = 17		
Average t (mm)	1.3	Age (yr)	26000	
Standard deviation	0.7	Age range +/- (yr)	14000	
Growth rate (mm/yr)	0.00005	Usable date (yr)	26,000 ± 14,000	

Plate 1. Digital Orthophoto Quadrangles (DOQ) of central Big Lost River Valley showing field data. Orange lines are contacts, surfaces are labeled with letters (I are areas that are incised), green dots are measured section locations, yellow dots are where pits were dug, blue arrows show direction of field measured dips, red lines are faults with ball and stick on downdropped block, black arrows show onlap relationships.

