Landscape Evolution of the Needles Fault Zone, Utah, Investigated Through Chronostratigraphic and Terrain Analyses

Faye L. Geiger
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LANDSCAPE EVOLUTION OF THE NEEDLES FAULT ZONE, UTAH,
INVESTIGATED THROUGH CHRONOSTRATIGRAPHIC
AND TERRAIN ANALYSES

by

Faye L. Geiger

A thesis submitted in partial fulfillments of the
requirements for the degree
of
MASTER OF SCIENCE
in
Geology

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UTAH STATE UNIVERSITY
Logan, Utah
2014
Landscape evolution of the Needles fault zone, Utah
investigated through chronostratigraphic and terrain analyses

by

Faye L. Geiger, Master of Science
Utah State University, 2014

Major Professor: Dr. Joel L. Pederson
Department: Geology

Arcing eastward from the deeply incised Cataract Canyon of the Colorado River in southeastern Utah is a series of alternating horst and graben within the Needles fault zone. Despite this deforming system’s importance to structural geologists and genetic linkage to the history of the Colorado River, it has been little studied from a geomorphic perspective. This work relates results from detailed chronostratigraphic analysis of graben-fill to known climate fluctuations of the late Quaternary and also addresses patterns identified in topographic analysis that reveal where and when Colorado River incision and salt movement-related subsidence have influenced this unusual terrain.

Unusual features called swallow holes expose the top 6-14 m of sediment accumulated in graben bottoms. Facies exposed are mostly granuley sands, sand, and silt beds deposited on avulsing alluvial fans and via settling in ponded water. OSL and
radiocarbon ages indicate that most of this material accumulated at a rapid pace of up to 3 m/kyr from 9 to 5 ka during the middle Holocene, with relatively minor latest Pleistocene and late Holocene strata preserved. This pulse of mid-Holocene sedimentation is only broadly synchronous across the basins studied, suggesting that local sediment supply, autogenic fan processes, and/or halokinetic or groundwater-driven accommodation space changes may be the dominant controls on apparent sedimentation rate at the scale of these exposures.

Topographic analysis of seven watersheds within the Needles fault array resulted in spatial correlation between hypsometric integral, normalized steepness, and previously reported modern deformation. Stream longitudinal profile analysis reveals that streams transecting the Needles fault array share three distinct reaches, delimited by knickpoints. The lowermost reaches are within 7 km of the Colorado River, have deeply incised gorges and high $k_{qs}$; knickpoints are maintained by resistant carbonate beds of the Lower Cutler and Honaker Trail formation. The middle reaches traverse the salt-deformed horst and graben terrain and have low steepness and numerous small knickpoints where they cross normal faults. Their upper knickpoints separate them from the mostly-undeformed upper reaches, which were used to model paleo-profiles. Paleo-profiles projected to baselevel and scaled to assumed Colorado River incision rates constrain the initiation of the pulse of baselevel fall and tributary incision to 1.9—1.3 Ma. Tributary profile deformation due to salt movement is constrained to 700—200 ka based on scaling to InSAR measured subsidence and estimation of the depth at which deformation began. These independent temporal estimates for the Needles fault array are consistent with those from previously published modeling results.
Landscape evolution of the needles fault zone, Utah
investigated through chronostratigraphic and terrain analyses

Arcing eastward from the deep gorge of Cataract Canyon on the Colorado River is a series of aligned valleys (graben) and ridges (horst). This unusual landscape has formed as subsurface salt deforms toward the river and dissolves away, causing the overlying rocks to fault, slide, and subside. Geologists have long been interested in this actively evolving area they call the Needles fault zone, because understanding its mechanics and origin may shed light on how faults work in general and similar, yet inaccessible places like offshore rift zones or even the surface of the Moon. Despite this interest, the timing and long-term patterns of deformation here and are poorly constrained.

This study uses analysis of digital landscape models to better delineate these patterns and provide better age constraints on the development of the Needles fault zone. We find that the Colorado River incision that led to deformation here began as recently as 1 million years ago, and that faulting due to subsurface salt movement initiated between 700 and 200 thousand years ago.

The first part of this study takes advantage of how the development of graben valleys has changed the path of many of the streams in the study area, resulting in numerous captured streams terminating into a type of sinkhole, called a swallow hole, that develops above opening faults. These fissures are so named because, by ongoing
opening, they are “swallowing” material that is flushed into them by local drainages. By recording and numerically dating the exposed upper 6-14 m of basin-fill strata, we determined that sediment was deposited to an alluvial fan and to ponded water. We also compared calculated sediment yields over time to paleoclimate records for the region to test extant hypotheses about how drylands respond to changing climate of the same scale as modern climate change. Against expectations, our results suggest that the greatest sediment yield and storage in these upper basins occurred during the relatively warm and dry time from 9 to 5 thousand years ago, when overland flow to transport sediment was weak. This implies that we are actually measuring sediment storage, as the faults that form swallow holes were relatively less active, allowing sediment to accumulate, rather than be flushed out of the basins.

Faye L. Geiger
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Faye Geiger
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CHAPTER 1

INTRODUCTION

The Needles fault zone in southeastern Utah is a dynamic lateral spread that has generated some of the most unusual topography on earth. It maintains fierce whitewater rapids “more abrupt than in any of the canyons through which we have passed” in what John Wesley Powell was inspired to name Cataract Canyon. And it has been studied and used as a teaching tool by explorers, structural and petroleum geologists, tectonics researchers, and geophysicists. Despite this attention, our understanding of landscape evolution here is still developing, as research from a geomorphic perspective has been minimal.

This thesis consists of two approaches to augmenting that understanding. Optically stimulated luminescence (OSL) and radiocarbon dating are used with detailed stratigraphic analysis to reconstruct sedimentation history to the latest Pleistocene. Geographic information system analysis of digital landscape models is used to identifying patterns related to the rates, timing, and patterns of change, and to reconstruct the history of streams crossing the Needles fault zone. Together, these geomorphologic lenses provide insight to how the complex interplay of salt tectonics, Colorado river incision, and climate has shaped this fascinating landscape.

Chapter 2 details the reasoning for, methodology behind, and results of chronostratigraphic study of sediment exposures in the Needles fault zone. The closed basins that have developed due to deformation are natural laboratories where we set out to examine sediment yield over the Pleistocene-Holocene transition. We report that
sediment accumulation pulses are asynchronous between graben, which implies that climate is not the controlling influence on sedimentation over the timescales studied. This chapter is constructed as a draft manuscript, to be coauthored by Dr. Joel Pederson and me and targeted to the *Geological Society of America Bulletin*.

In Chapter 3, we describe the application of recently developed quantitative geomorphology tools to reconstruct timing of and parse relative influence of salt tectonism and Colorado River incision on the development of the Needles fault zone and the shape of tributary long profiles. We examine normalized steepness index patterns to identify where lithology and/or baselevel change exerts control on stream profile. We also use calculated concavities of relict upper reaches of tributaries to model paleo-profiles that represent pre-deformation topography. This chapter is intended to be a draft manuscript coauthored by Dr. Joel Pederson and me for submission to *Geological Society of America Bulletin*.

Chapter 4 is a summary of these two studies that also looks to the potential for future work in this study area.
CHAPTER 2

CHRONOSTRATIGRAPHY OF GRABEN-FILL EXPOSED IN SWALLOW HOLES OF CANYONLANDS NATIONAL PARK, UTAH—IMPLICATIONS FOR LATE QUATERNARY SEDIMENTATION AND SALT TECTONICS

ABSTRACT

Internally-drained basins within the graben of the actively deforming Needles fault array in Canyonlands National Park are natural laboratories where sedimentation response to climate change and/or tectonic controls can be examined. Unusual sinkhole features, locally called swallow holes, within these basins offer the opportunity to study exposed basin fill deposits that archive landscape response to climate change. Results from two primary and two secondary study exposures are presented, including optically stimulated luminescence (OSL) and radiocarbon ages and detailed stratigraphic interpretation.

Modes of sediment emplacement in these basin fill deposits range from high-energy avulsing flow across an alluvial fan to suspension settling in ponded water. Primary eolian deposition is minor. Modern analogues to these depositional environments are observable in the field: higher-energy facies correspond to where local drainages debouch into fans or mid-fan, and lower-energy facies correspond to exposures positioned at fan toes. Depth-integrated sediment accumulation rates from all four study locations are 2—3 m/ky over the Holocene—twice as high as those determined from the one exposure with a Pleistocene record. Rates calculated from 16—8 ka in this exposure are ~1 m/kyr. This temporal shift in sediment accumulation rates partially validates the
predominant hypothesis that climate disturbances associated with the Pleistocene-Holocene transition will result in higher sediment yield. However, ongoing high rates of sediment accumulation through the Holocene to ~3 ka suggest that landscape response is more complex. The overall sediment accumulation rates and depth of alluvial fill from seismic imaging reported by Grosfils et al. (2003) suggest that graben formation may have been ongoing for over 100 ka. Alternatively, sedimentation rates observed here may not be a true measure of sediment availability and transport capacity due to climate drivers, but rather artifacts of complex histories of changing accommodation space—and possibly groundwater level—unique to each graben basin. However, the nature of the stratigraphy observed supports the interpretation that the fill phase of the cycle is primarily sediment-supply-driven

The presence of many swallow holes in the modern landscape and lack of a recent record of deposition in the uppermost beds suggests that, at least in the sites studied, swallow hole activity is episodic. During the middle Holocene, these basins were accumulating sediment at a rapid rate, yet today, they are losing sediment to fissures associated with ongoing faulting. This faulting is driven by salt removal and dissolution at depth, but an additional mechanism that may be driving the opening of these features is drought-related water table drop. Scientists were able to attribute similar features in Iron County, Utah, to subsidence due to anthropogenic groundwater removal (Knudsen et al., 2014). In this case, climate may control depositional cycles by indirectly driving accommodation space changes.
INTRODUCTION

The actively deforming Needles fault zone and Grabens of Canyonlands National Park have been the focus of much study by structural geologists. Yet, this landscape also provides untapped opportunities to understand geomorphic history and processes driven by climate change and salt tectonics. Most previous work focused on the structural evolution of the Needles fault zone has assumed a Quaternary age of the fault array as well as minimal modification by erosion or deposition. This assumption was based on the observed few meters of sediment preserved atop visible hangwall tops in graben bottoms (e.g. McGill and Stromquist, 1979). Subsequent thermoluminescence (TL), radiocarbon, and optically stimulated luminescence (OSL) ages from some of these exposures suggested that these deposits ranged in age from ~65 ka to modern (Biggar and Adams, 1987; Reheis et al., 2005; Commins et al., 2005). Structural geologists have referenced these ages as a minimum constraint on the total age of the array. However, more systematic geophysical imaging revealed that hangwall topography is highly irregular and near-surface exposures do not represent the full extent of sediment preserved as graben fill—which may be up to 90 m thick (Grosfils et al., 2003) Thus, full sediment archives presumably record the initial halokinetically-driven opening, subsidence of each graben, and subsequent changes in deposition through time. Detailed study of graben fill therefore provides an opportunity to better constrain the timing and patterns of these changes. It may even be used to better define the overall age of the Needles fault zone, when coupled with information about total fill thickness from geophysical imaging.

Ongoing faulting has defeated or deranged many of the streams draining the Needles fault array, leaving dozens of small, internally-drained basins, which typically
comprise a graben and its adjacent horsts. These internally-drained graben of the study
area, especially those with discreet contributing catchments, are natural laboratories
where the other additional dominant control of graben-fill stratigraphy may be studied:
the type of surface processes and rate of transport removing material to graben, which are
in turn dependent upon climate. Given that a lack of records linking sediment sources to
sediment sinks is one reason process-response models remain relatively untested, the
unusual topography in the Needles fault array provides an opportunity to explore how
sedimentary systems in sensitive drylands have responded to changing late Pleistocene
and Holocene climate (e.g. Enzel et al., 2012). This has been a key scientific question for
decades that has pertinence in the context of modern global climate change.

Deformation in the Needles fault zone has generated an unusual type of exposure,
called “swallow holes” (McGill and Stromquist, 1974). They are a type of sinkhole,
which in this setting range from steep-sided fissures to dendritic depressions. All are
conduits where surface sediment is being lost into dilating faults by overland flow and/or
piping (Fig. 1.1). Swallow holes with fresh exposures permit detailed chronostratigraphic
study of the top several meters of alluvial fill (e.g. Biggar and Adams, 1987). Given that
some holes are fed by internally drained basins and share the same, minimal lithologic
variability, these exposures provide a research opportunity to study how late Quaternary
changes in climate affect sedimentation.

In this setting, salt-deformation may also influence sediment yield. Specifically,
ongoing displacement along faults locally increases slope in channels crossing or
draining horsts and promotes incision. This scenario has been documented to lead to
stream capture, which would increase contributing area and thus sediment delivery to a
Figure 2.1. Images of graben sedimentary systems in the Needles fault zone. A) drainage entering Red Lake Canyon and terminating in a fan within a flat-bottomed basin; B) a talus apron near Deep Canyon has been dissected by the development of a swallow hole, and modern drainage has begun to cut headward toward the modern fan; C) open normal fault with several meters of vertical and horizontal separation in Picture Canyon; and D) Bobby’s Hole has sloped sides and dendritic arms with piping as a major and obvious means of water infiltration (inset)
basin, which could be mistaken for increased sediment yield (Trudgill, 2002; Commins et al., 2005). However, these shifts in source area and diversion of drainages to holes likely precedes the deposition of fill exposed in swallow holes, and is not expected to be relevant to this study.

Even more important on the small scale of this study, the history and formation of the swallow holes themselves is not understood. In the present day, they proliferate in graben floors and reflect active sediment evacuation. Yet, the stratigraphy exposed in those same swallow holes includes no similar evidence of sediment removal (i.e. cut-fill stratigraphy). Taken together, these observations suggest that sediment accumulation may have been more considerable in the past, while swallow hole development and evacuation, vs. swallow hole quiescence and sediment accumulation, may be more prolific in the late Holocene.

In this study, we interpret the upper sedimentary record of four study holes in terms of sediment accumulation rates and sediment yield from catchments and assess the relation between any changes in these records and generalized local paleoclimate. We focus on two of the deepest and well-exposed swallow holes and their potential correlations. Results suggest that previous TL ages (Biggar and Adams, 1987) are too old and that exposed material is latest Pleistocene at the oldest. Our sedimentation results also suggest that there was good sediment preservation in graben during the dry, warm middle Holocene.
BACKGROUND

Setting

The Needles district of Canyonlands occupies the northernmost extent of the Monument Upwarp in the central Colorado Plateau. This area is dominated by a broad, NW-sloping plateau, which is traversed by a series of regional drainages flowing off the northern flank of the Abajo Mountains and plunging to the Colorado River in the deep gorge of Cataract Canyon (Fig. 2.2). An arcuate array of extensional faults, broadly oriented NE-SW and paralleling the Colorado River, has broken up the western half of this plateau into alternate horst and graben that range from 200—1000 m wide and kilometers lengthwise. Where the drainages traverse the graben and horst, they are frequently deranged, taking circuitous routes around horsts or captured entirely to graben.

The semi-arid climate in the Colorado Plateau means that much of the land surface here is bedrock. Within the study area, this is mainly the 150-275 m-thick eolian-fluvial Permian Cedar Mesa sandstone (Fig. 2.2), which weathers into the distinctive mushroom caps and hoodoos of the Needles in Canyonlands National Park. It conformably overlies the littoral-fluvial Lower Cutler beds, which are 120-300 m thick locally (Fig. 2.2; Huntoon, 1982a and 1982b; Loope, 1985; Condon, 1997). Together, the deeper Honaker Trail Formation, Lower Cutler Beds, and Cedar Mesa Sandstone constitute the “brittle plate” that is deforming by movement on/in the underlying Paradox evaporites to form the grabens (McGill and Stromquist, 1975).

Surface processes in the study area are strongly influenced by the semiarid climate in this interior continental plateau. Climate records for the past 48 years show that total annual precipitation is 20-65 cm across the study area, which is distributed by
Figure 2.2. Location of study sites within the Needles fault zone. Inset map shows study area location near center of the Colorado Plateau (green area). Faults (black) and geology from Doelling (2006). Black boxes correspond to study site locations: PC – Picture Canyon; CC – Cow Canyon; GF – Goldfish hole; BH – Bobby’s Hole
elevation and falls with bimodal timing in December-January and July-August (NCDC, 2013). Bedrock weathering occurs mainly via disintegration of intergranular cement that causes the sloughing off of outer grains, and by spallation. Material is transported via overland flow to bedrock channels after short upper reaches through the thin veneer of accumulated sediment or soil. Once they reach graben bottoms, channels commonly terminate in broad, low-gradient fans. Dozens of these fans are then cannibalized by gullies, which typically lead to swallow holes. Soil development is limited by low precipitation and is restricted to protected areas where biological soil crust communities can become established. Vegetation communities comprise pinon-juniper forest and sagebrush-blackbrush scrub (Cole, 1990). Shrubs and grasses tend to grow on stable sediment, while trees establish on bedrock. Sagebrush communities often occupy grazing-disturbed terrain, which includes parts of the broad plateau mentioned above as well as graben bottoms.

The study sites were selected based primarily on the best exposed sections of basin fill (Fig. 2.2). Outcrops are the walls of swallow holes, which are elongate, steep-sided depressions in the graben floor. Some swallow holes are clearly cut by drainages being piped into deep extensional fissures; others are flat bottomed with tendril gully arms where drainage paths have found their way to the depression where water has ponded and infiltrated—with sediment at least episodically piped to obscured fissures (Fig. 2.1). One study outcrop, Picture Canyon (PC) occurs in an opening at the foot of the western graben wall, whereas Goldfish Hole (GH) is positioned in the middle of a graben. However, it is positioned along strike with a fault expressed at the surface to the south.
Repeat visits to the field revealed that swallow hole exposures may change after a single storm event when new surfaces are exposed by sloughing of material from their subvertical walls or when removal of sediment from the hole floor via piping into buried or exposed fissures uncovers deeper beds. Examples of this are recounted below.

**Paleoclimate in the Colorado Plateau**

The Quaternary is marked by regular glacial-interglacial cycles with a dominant period of 100 kyr from ~700 ka to the present (EPICA, 2004). In the American Southwest, interglacial periods are characterized by relatively high mean annual temperature (MAT) and a decrease in mean annual precipitation (MAP) with respect to glacials, as well as greatest relative warming during the coldest months (Coats et al., 2008). Understanding of climate fluctuations in the Colorado Plateau is based on pollen records from soil cores, lake cores, and packrat middens, oxygen isotope data from lake sediment, carbon isotope data from packrat fecal pellets and bat guano, and from speleothem records. The pollen record from Potato Lake cores on the southern margin of the plateau extends to 35ka (Anderson, 1993), while packrat midden records in Canyonlands and Grand Canyon extend to nearly 50 ka (Betancourt et al., 1990; Coats et al., 2008). Cave deposits and pollen records from eastern Grand Canyon and western Grand Canyon cave and guano records provide chronologies back to the last glacial maximum (LGM) at ~24 ka (Mead and Phillips, 1981; Cole, 1990). Finer resolution is found in some of the packrat midden studies as well as carbon and oxygen isotope records from bat guano in Grand Canyon and lake sediment in Colorado, respectively (Wurster et al., 2008; Anderson, 2011).
MAT during the LGM were ~7°C cooler than today (Anderson, 1993). The transition out of the LGM has been characterized in the Colorado Plateau by several fluctuations in winter minimum temperature that leveled out at 11.6 ka, marking the start of the Holocene epoch (Cole and Arundel, 2005; Walker et al., 2012). These fluctuations are parsed into the Younger Dryas, a cooling event for which there is evidence throughout the Northern Hemisphere, including the Colorado Plateau.

For example, δ¹³C evidence from packrat middens in Grand Canyon supports cooler conditions similar to those during the LGM, constrained by a complementary analysis that used the lack of temperature-dependent Utah agave (Agave utahensis) components in higher elevation middens from 12.7 – 11.5 ka to estimate a winter minimum temperature 8°C lower than present day (Cole and Arundel, 2005). Other studies have found a persistent lack of xeric elements in packrat middens—and less overall preservation of middens—suggesting that cold and possibly wet conditions prevailed from ~15—10 ka (Poore et al., 2005; Coats et al., 2008). Depressed δ¹³C ratios (relative to Vienna Peedee belemnite) and elevated δD ratios (relative to Vienna standard mean ocean water) in bat guano from a Grand Canyon cave from c.a. 12.7 – 10.7 ka indicate cooler and possibly drier conditions (Wurster et al., 2008). Cooling during the Younger Dryas has been postulated to be linked to reduced winter insolation in the Northern Hemisphere (Cole and Arundel, 2005).

Following the close of the Younger Dryas, temperatures warmed relatively quickly, reaching their peak during the mid-Holocene Altithermal, from 9-6 ka (Dean et al., 1996; Cole and Arundel, 2005). Warming of up to 8°C drove a 600-1000 meter upward migration of vegetation zones (Anderson et al., 1999). Several lines of evidence
support that the mid-Holocene was also dry; these include dessication of local lakes
(Anderson et al., 2000), including lowstand conditions in the Great Salt Lake (Benson et
al., 1990; Oviatt, 1997), and dunefield expansion in central Colorado (Stokes and
Swinehart, 1997) and Canyonlands National Park (Reheis et al., 2005).

These dry conditions are attributed to increased summer and winter insolation
relative to the Younger Dryas, which dampened precipitation during both seasons.
(Wurster et al., 2008; Anderson, 2011) Several climate proxies suggest that an increase in
monsoonal precipitation in the Colorado Plateau happened around the end of the mid-
Holocene at ~7 ka. For example, Poore et al. (2005) showed a positive correlation
between the northerly extent of the Intertropical Convergence Zone (ITCZ)—as
determined from foraminifera populations in Gulf of Mexico sediment cores—and
monsoon frequency and intensity (proxied via packrat and tree ring data from the
southwestern US). The monsoon is believed to be related to ENSO activity, which in turn
has been tied to orbitally-induced changes in insolation (Asmerom et al., 2007; Conroy et
al., 2008). However, increased seasonality of precipitation does not necessarily imply a
wetter climate, but rather a change in the intensity and frequency of storms.

**Geomorphic process response to climate in drylands**

A general—but not well-tested—conceptual model of the response of desert
hillslopes and upper drainages to the most recent glacial-interglacial climate cycle has
been developed based on research in the deserts of the southwestern U.S. and the middle
east (Bull and Schick, 1979; Bull, 1991; Enzel et al., 2012). This model suggests that
during glacial periods, depressed temperatures and increased precipitation increase
bedrock weathering rates, resulting in regolith development. Relatively dense vegetation anchored and stored colluvium on transport-limited hillslopes. Transition out of the LGM was accompanied by warming, vegetation community reorganization, and increased runoff. These factors combined to mobilize material—previously stored on hillslopes—to stream channels, causing stream and alluvial fan aggradation. The full transition to the present-day interglacial in early-mid Holocene time was marked by the shift to stripped, weathering-limited hillslopes, flashier runoff, entrenched alluvial-fan heads, and transport-limited, ephemeral alluvial systems, which we see today.

This model is probably too generalized and was developed before absolute age control was readily available. Subsequent studies have debated the role of vegetation versus moisture regime as primary controls (Miller et al., 2010; Antinao and McDonald, 2013), and they suggest regional deviation from the timing and climate-driver patterns even across the American Southwest (Harvey et al., 1999; Anders et al., 2005; Sohn et al., 2007; Enzel et al., 2012). Specific responses in the Colorado Plateau are particularly poorly constrained (e.g. Reheis et al., 2005). Yet, a prediction constrained by both field and modeling work is that climate transitions and disturbance, rather than full glacial or especially dry interglacial conditions, are associated with high sediment yield (e.g. Bull, 1991; Tucker and Bras, 2000; Pederson et al., 2000; Anders et al., 2005). This project will test that prediction by examining sediment yield in small catchments with consistent bedrock lithology and assumed-to-be-negligible tectonic influence, where changes in sediment yield may be attributed to climate drivers.
METHODS

*Study sites, field sedimentology and stratigraphy*

A broad search of aerial imagery and internally-drained catchments identified with GIS tools was used to identify swallow-hole study locations. Study sites were selected from this population after field reconnaissance to assess: sufficient vertical exposure (>10 m); and intact stratigraphy. Two primary and two secondary study exposures were selected (Fig. 2.2), and they represent the best exposures in the region for research at the time of this study.

Stratigraphic panels and measured sections were used to record stratigraphic architecture, depositional units, hiatuses, and buried soils from each exposure. Sedimentary beds were defined as individual depositional events, and systematic unit descriptions and measured sections are found in Appendix B. Delineation of facies based on sedimentary structures and grain size permitted interpretation of depositional processes.

*OSL dating*

Luminescence dating exploits the unique properties of quartz and feldspar to trap electrons at defects in their crystal structure over time. Electrons become available for trapping through ionizing radiation from U-series and \(^{40}\)K decay within the surrounding sediment or the target crystals themselves. Cosmogenic radiation also excites and frees electrons; the effect is attenuated according to sediment density and particle energy and is
reduced to near zero below three meters depth (Murray and Wintle, 2000; Gosse and Phillips, 2001).

Sufficient exposure to energy in the form of sunlight (seconds for quartz and hours for feldspar) and heat (200—500 °C) voids the electrons measured in luminescence dating from their traps. Subsequent burial (shielding from light) or cooling allows charge to accumulate in the traps. A sample collected in the dark will, when exposed to stimulation by light or heat, release this accumulated charge in a distinctive luminescence signal. Measurement of this natural luminescence signal in the lab is followed by systematic artificial dosing and light stimulation that seeks to bracket and recreate the original signal. The lab dose of radiation (in grays, or joules absorbed/kg of matter) required to replicate the natural signal is called the equivalent dose, or De. The average dose rate, or the estimated rate of accumulation of charge, must also be determined in order to calculate an age:

\[
\text{Age (yr)} = \frac{\text{De (Gy)}}{\text{dose rate (Gy yr}^{-1})}
\]  \hspace{1cm} (1)

Short transport distance of sand grains in these small catchments means that incomplete zeroing of inherited OSL signal is likely. However, OSL dating is viable for hillslope and small stream deposits, given proper collection, single aliquot or single-grain analysis, and statistical processing techniques (Murray and Wintle, 2000; Rittenour, 2008; Fuchs and Lang, 2009). Sampling can therefore include reworked colluvial and alluvial packages as well as eolian strata. Units with sedimentary structures indicating low energy fluvial deposition were preferentially targeted, as these were expected to be better bleached (Rhodes, 2011). Approximately 500 ml of material was collected into stainless steel tubes, the ends of which were sealed after collection to ensure there was no
contamination by light. Sediment within a 30-cm radius was also collected from around the OSL sample site for submittal for ICP-MS and ICP-AES elemental analysis of U, Th, Rb, and K content. These values were then translated to a radiogenic dose rate using the conversion factors of Guérin et al. (2011). Other contributions to dose rate included calculation of cosmogenic contribution and water content (Prescott and Hutton, 1994).

Sources of systematic error arise mainly from assumptions inherent to determining dose rate. These include: abundance of U, Th, and K is an accurate proxy for radioactivity; water content and thus radiation attenuation of the life of sample is known. Instrumentation also introduces error, especially as a function of the radiation source. The two main problems with OSL dating of quartz are partial bleaching and low quality quartz crystals. The former leads to age overestimates and was expected to be a problem, given the short transport time/distance in small catchments. Sampling from low-medium energy facies was undertaken to minimize this risk (c.f. Summa-Nelson and Rittenour, 2012). The latter was not expected to be a problem, as sand comprising the source rock, the Permian Cedar Mesa sandstone, was originally weathered from igneous crystalline basement rocks before being transported hundreds of kilometers prior to reworking and deposition (Mack, 1978). Age underestimates can be a problem in sediment older than ~120 ka when issues like trap saturation and stability, dose rate, and OSL signal purity begin to manifest (Murray and Olley, 2002).

OSL samples were sieved to fractions between 90 and 212 μm, cleaned, and reduced to the pure quartz fraction via float in sodium polytungstate in USU’s Luminescence Laboratory. Samples were run on Risø TL/OSL readers using the small aliquot regenerative dose (SAR) technique (Murray and Wintle, 2000). Assessment of $D_e$
distributions to appraise the degree of skew, kurtosis, and overdispersion (which can point to partial bleaching) allowed determination of whether the central age model (CAM) or the minimum age model (MAM) (Galbraith et al., 1999) was applied to derive an age from $D_e$ (Arnold et al., 2009).

**Radiocarbon dating**

Stable isotopes $^{12}\text{C}$ and $^{13}\text{C}$ comprise nearly 99.9% of carbon on Earth (Bowman, 1990). Bombardment of the atmosphere by cosmic rays expels a proton from $^{14}\text{N}$ to form unstable and rare $^{14}\text{C}$. All isotopes of carbon are then taken up by the biosphere throughout the life of each organism. Unstable $^{14}\text{C}$ is effectively replaced in proportion to its abundance in the environment while the organism is alive, and upon its death, the decay of $^{14}\text{C}$ changes its ratio to stable carbon isotopes, relative to atmospheric concentrations. Measuring the relative proportion of $^{14}\text{C}$ to $^{12}\text{C}$ or $^{13}\text{C}$ allows for back calculation of the age of a sample:

$$\text{Radiocarbon age} = -8033 \ln \frac{A_{SN}}{A_{1950AD}}, \quad (2)$$

where -8033 is the inverse of the Libby decay constant, which equates to a half-life of 5568 yr. The $A$ values are the measured $^{14}\text{C}$ activity of the sample ($A_{SN}$) and the activity of a 1950-aged sample, called “modern” (Donahue et al. 1990).

Samples taken for radiocarbon dating were angular charcoal in beds with preserved sedimentary structures. Pieces of charcoal were collected into aluminum foil and stored under refrigeration until they were processed at the University of California-Irvine’s Keck Lab. Sample preprocessing—including acid-base-acid treatment, combustion, and graphitization—was conducted there prior to bombardment by a cesium
source and measurement in a mass spectrometer. Ages were calibrated using the IntCal13 Northern Hemisphere atmospheric radiocarbon calibration curve and the CALIB 4.0 program (Stuiver and Reimer, 1993; Reimer et al., 2009) at the 2-sigma level. Calibrated age ranges were converted to year BP$_{2010}$ and the midpoints of the calibrated age range were calculated.

Systematic sources of error in radiocarbon dating include instrumentation error, the stochastic nature of nuclear decay, and calibration curve fuzziness (Scott, 2007). More importantly for this work, random error is introduced when mixing of samples from different-aged sources via transport or geomorphic processes occurs. Given the potential for incorporation of material temporarily stored in alluvial fans and/or long-residing old wood, age overestimation is a possibility here.

**Sediment yield and accumulation rates**

Sediment accumulation rates are calculated in m/kyr for the two primary study exposures based the measured thickness of each dated package and time constraints provided by OSL and radiocarbon ages. Sediment yield, in turn, is the mass of material (volume·density) exported from a given unit area per unit time. It is conceptually interchangeable with sediment production. In the case of the internally drained study catchments, the material is removed to the graben bottoms and exposed via swallow holes. Maximum and minimum volumes were calculated by multiplying the basin area by end-member thicknesses, which bracket measured thicknesses in the exposed sections. Sediment yield can be converted to denudation rate (m/kyr) using the following calculation: the proportion of graben-basin area to catchment area is multiplied by the
ratio of sediment density ($\rho_s$) to rock density ($\rho_r$) and then multiplied by the graben-fill thickness/unit time (accumulation rate). Because the contributing catchment consists mainly of subarkosic sandstone, rock density was assumed to be 2.5 g/cc and sediment bulk density, was assumed to be 1.9 g/cc (Case et al., 1972; de Vente and Poesen, 2005). Catchment sizes and graben-basin sizes at the two main sites were delineated in ArcGIS using interpretation of air photo, topographic contours, and flow accumulation grids.

RESULTS

Geochronology

Table 2.1 provides summary results from final OSL and radiocarbon dating and full results can be found in Appendix A. The full range of ages across all study sites spans ~16 ky, with Goldfish hole (GF) boasting the oldest records and Cow Canyon (CC) having the youngest sediment. Short transport distances and relatively young samples led us to predict that OSL dating would supply maximum ages due to the potential for partial bleaching (Rittenour, 2008). For this reason, the Minimum-Age-Model (MAM) statistical tool was used to model ages in younger sediment, or those showing evidence of partial bleaching (Galbraith et al., 1999). Age underestimation, on the other hand, is typically a problem with mid-Pleistocene-aged sediment due to several factors, and was not expected to be a problem here.

Goldfish Hole locale

Goldfish hole was unofficially named because the shape of the swallow hole as viewed from above resembles a popular snack. It is situated between two overlapping
Table 2.1. Geochronology Summary

<table>
<thead>
<tr>
<th>OSL sample</th>
<th>Locale Position</th>
<th>Depth (m)</th>
<th>Dose rate (Gy/ky)</th>
<th>Aliqu. accepted (total)</th>
<th>OD (%)</th>
<th>Age model</th>
<th>Preliminary Age (ka)</th>
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<tr>
<td>USU-1557</td>
<td>GF Bed 50</td>
<td>1.9</td>
<td>1.28 ± 0.07</td>
<td>4.49 ± 1.41</td>
<td>21 (55)</td>
<td>51.8</td>
<td>3.51 ± 0.60</td>
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<td>USU-1556</td>
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<td>1.9</td>
<td>2.21 ± 0.11</td>
<td>19.23 ± 2.31</td>
<td>24 (36)</td>
<td>24.3</td>
<td>8.70 ± 1.06</td>
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<td>USU-1555</td>
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<td>1.59 ± 0.08</td>
<td>16.34 ± 3.36</td>
<td>21 (28)</td>
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<td>10.26 ± 1.26</td>
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<td>21.56 ± 4.22</td>
<td>23 (43)</td>
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<td>PC Bed 53</td>
<td>2.1</td>
<td>2.37 ± 0.12</td>
<td>7.80 ± 0.16</td>
<td>00 (00)</td>
<td>00.0</td>
<td>00.00 ± 00.00</td>
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<td>USU-1402a</td>
<td>PC Bed 14</td>
<td>2.1</td>
<td>2.37 ± 0.12</td>
<td>7.80 ± 0.16</td>
<td>00 (00)</td>
<td>00.0</td>
<td>00.00 ± 00.00</td>
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<td>USU-1403</td>
<td>CC Bed 18</td>
<td>1.5</td>
<td>2.52 ± 0.12</td>
<td>1.76 ± 0.78</td>
<td>19 (45)</td>
<td>67.9</td>
<td>1.76 ± 0.78</td>
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<td>USU-1404</td>
<td>BH Bed 4</td>
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<td>2.37 ± 0.12</td>
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<td>00 (00)</td>
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</tbody>
</table>

14C sample (and abbreviation)

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<th>Sample type</th>
<th>Probability</th>
<th>Calibrated age range (yr BP)</th>
<th>Sample type</th>
<th>Probability</th>
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<th>Sample type</th>
<th>Probability</th>
<th>Calibrated age range (yr BP)</th>
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<td>one piece ch.</td>
<td>0.32</td>
<td>2970 - 2943</td>
<td>several piece ch.</td>
<td>0.63</td>
<td>7576 - 7534</td>
<td>fibrous wood</td>
<td>0.96</td>
<td>8111 - 8036</td>
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<td>8111 - 8036</td>
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<td>0.96</td>
<td>8111 - 8036</td>
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Calibrated age range (yr BP)
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<th>Probability</th>
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<th>Age (cal kyr B2010)</th>
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<td>UCI-137300 C-00 PC Bed 6</td>
<td>8.78</td>
<td>4925 ± 30</td>
<td>several piece ch.</td>
<td>1.00</td>
<td>5780 - 5660</td>
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<td>UCI-137301 C-01 PC Bed L8</td>
<td>9.6</td>
<td>5040 ± 30</td>
<td>several piece ch.</td>
<td>0.24</td>
<td>5780 - 5660</td>
<td>5.88 ± 0.09</td>
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<tr>
<td>UCI-137307 C-07 CC Bed 18</td>
<td>1.5</td>
<td>175 ± 25</td>
<td>juniper seed</td>
<td>0.16</td>
<td>75 - 62</td>
<td>0.24 ± 0.04</td>
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<tr>
<td>UCI-137308 C-08 CC Bed L3</td>
<td>5.82</td>
<td>1045 ± 25</td>
<td>one piece ch.</td>
<td>1.00</td>
<td>1022 - 992</td>
<td>1.01 ± 0.03</td>
</tr>
<tr>
<td>UCI-137309 C-09 BH Bed T2</td>
<td>1.7</td>
<td>7395 ± 30</td>
<td>several piece ch.</td>
<td>0.49</td>
<td>8274 - 8236</td>
<td>8.30 ± 0.08</td>
</tr>
<tr>
<td>UCI-137310 C-10 BH Bed T2</td>
<td>1.7</td>
<td>1185 ± 25</td>
<td>seeds</td>
<td>0.32</td>
<td>1154 - 1127</td>
<td>1.18 ± 0.06</td>
</tr>
</tbody>
</table>

a Full OSL and radiocarbon methods, results, and sample behavior in Appendix A.
b OSL equivalent dose errors reported at 2σ
c OSL ages incorporated random and systematic errors reported at 1σ
d Dose response curve fit through regen1, regen 0, and regen 1’ due to low natural signal

segments of an eastern-dipping fault bounding a large, complex, and unnamed graben in the middle of the Needles fault array (Figs. 2.2 and 2.3). The antithetic eastern segment appears in air photo to be part of a stepover here: likely dipping SE to the north and SW to the south. The graben is bound on its SE side by a continuous and fairly straight normal fault. The terrain around GF was once part of the greater Cross Canyon drainage (Fig. 2.3) though all indications are this was well before the younger basin fill studied in the GF locality. Two former tributaries to the main stream, now beheaded by graben and marked by wind gaps, can be seen incised into Cedar Mesa sandstone just northwest of the study basin (Fig. 2.3).
Figure 2.3. Goldfish hole overview photos. A) View looking west from the horst directly east (white star in B). Rock in foreground is bedrock high corresponding with a stepover zone. B) Annotated aerial photo shows catchment in red and graben basin in green. Modern streams and now disconnected sections are noted in solid and dashed blue lines. Actual hole is red polygon.
The area of deposition, or graben basin, was delimited based on the position of two alluvial fans that dominate the near-swallow-hole terrain (Fig. 2.3). The southwestern fan is fed by material being shed from the horst to the NW via the captured upper Cross tributary. The northeastern fan results from a modest channel that has developed on a bedrock spit to the east of GF hole (Fig. 2.2). The rest of the basin fill here has presumably been delivered through non-channelized transport off the surrounding highlands. Figure 2.3 shows both the graben-basin area and contributing catchment area.

Goldfish hole itself is ~75 m longwise by 25 m wide, and approximately 13 meters deep (Fig. 2.4). It is approximately 100 m from the NW graben wall. 52 beds were delineated in two linked and measured sections from which four OSL and five charcoal samples were collected. A resistant calcareous silty sand at ~10.5 meters depth was traced around the interior of the hole to the base of the described exposure on the E-facing wall.

**Goldfish chronostratigraphy**

Figure 2.4 shows age control results and bed delimitations for GF Hole. A summary column follows in Figure 2.5, and the full measured section at GF is found in Appendix B. The lowermost half meter of the exposure contains beds of well-preserved granuley, sandy fan surface/small channel facies, which appear to have been deposited in rapid succession. These are followed by another half-meter of rippled sand beds that are interpreted as medium energy fan facies. Thus, taken as a package, the lowermost meter grades normally (fining upwards). Where observed, ripples suggest flow from south to north. A coarser channel facies event at 1.2 meters punctuates this waning flow, and it is
Figure 2.4. Overview of stratigraphy at Goldfish hole. A) Photos with bed delineations in large photo is SE-facing wall, small inset photo is lowest section on the NW-facing wall.

B) Just stratigraphy with numerical ages reported. Full measured section is found in Appendix B, summary column in Fig. 2.5.
overtopped by a massive sand, capped with silty mud. The top beds from this sequence, from 12.5—12.8 meters depth, are cut by a channel filled with very coarse sand, gravel, and silty sand rip-up clasts. This 30-60 cm-thick bed is interpreted as hyperconcentrated flow that cut into and entrained clasts of the units below. Its diffuse upper contact with a finer, well-sorted sand above is the lowest indication of bioturbation in the section, at 12.2 meters depth. OSL sample USU-1554 was taken 13.3 m from the surface in Bed 3, a cross-bedded sand that dated to 16.20 ± 2.49 ka. The dose distribution was positively skewed, suggesting partial bleaching of the sample, so the MAM was applied to isolate the population that had been fully reset upon transport.

The next several beds, from 12.2—11.5 meters depth, are cross-bedded to massive sands, interpreted as moderate to low energy alluvial fan facies. All show partially to wholly obscured sedimentary structures and mixing, indicative of bioturbation, with intensity of bioturbation increasing upwards. Some insect and/or animal burrows, were observed, but no clear evidence of rooting (e.g. rhizoliths, casts, old roots) was seen.

At 11.5 meters depth a hiatus is interpreted, as the overlying bed of granuley sand is better-preserved. However, the next meter of section above this granuley sand, to ~10 meters depth, is again quite bioturbated. Bed geometries can be made out and remnant sedimentary structures suggest these are channel or alluvial fan swale facies. A very well-sorted bed at 10.8 meters depth is interpreted as an eolian sand that caps 3-4 cycles of alluviation. It is overtopped by another granuley sand, the top of which is silty and weathers to a slightly resistant feature, which was traced around the interior of the swallow hole, along with other, similar resistant features, to link the two exposures.
Figure 2.5. Simplified sections of Goldfish and Picture Canyon. Radiocarbon ages for Picture Canyon are too old, with the possible exception of UCI-C01 and UC-C08. Facies descriptions and classifications are in Table 2.2. Facies are grouped based on complete sections (Appendix B).
The east-facing side of the hole (large photo and schematic in Fig. 2.4) exposes more bioturbated (based on lack of sedimentary structures and some burrows) beds at its base, and at ~10 meters there is an abrupt transition to beds wherein sedimentary structures are preserved, though cut by larger burrows (krotovina). This transition is interpreted as a hiatus, which is borne out by the ~1.5 ka difference in the bracketing OSL (USU-1555 and USU 1556) ages of 10.26 ± 1.26 ka and 8.70 ± 1.06 ka, respectively. USU-1555 was sampled from an eolian sand near the top of the west-facing exposure at a depth of 11 meters. The $D_e$ distribution showed multiple peaks, indicating there are more than one population of grains. This suggests mixing, which fits with the field interpretation that this sand is somewhat bioturbated. USU-1556, on the other hand, was well-behaved. It was collected from a ripple-laminated sand above the interpreted hiatus, from the east-facing exposure at 10 meters below the surface.

Pinch and swell geometry in two of the beds overlying this hiatus may be a sign of loading from above, perhaps by footsteps. At 9.8 meters depth, signs of insect and rodent burrows vanish from the section, and scant evidence of fine rooting appears. A hiatus of some sort is therefore interpreted here as well. However, it appears to be minimal, as radiocarbon sample UCI-C06, taken from a rippled sand at 9.9 meters depth (just above USU-1556, is within error of the OSL age, at 9.28 ± 0.10 ka.

Lower energy facies dominate the next meter of deposition (to 9 meters depth), suggesting that the depocenter on the fans was positioned elsewhere. Rippled sands and couplets capped by silty or mud layers up to a couple centimeters thick suggest that deposition here was by low energy flow or settling in ponded water. From 9 to 7.7 meters the section is coarser, culminating in a clast-supported gravel bed at 8.5 meters. Several
individual beds are reverse-graded, indicating repeated flow onset. Imbrication of pebble gravels indicates flow direction from N-NE to S-SW. Bed geometries are typically tabular wavy, with trough cross-bedding within. High rates of sediment accumulation would be expected based on these indicators, and indeed, UCI-C05 at 9 meters depth, and UCI-C04 at 8.2 meters depth are within error of one another, dating to 8.17 ± 0.07 ka and 8.09 ± 0.05 ka.

Alternating beds of granuley sand facies and massive, capped sand facies dominate the next ~0.8 meters. The simple interpretation of these cyclic changes in flow is that they record avulsion across the surface of the fan: higher energy facies record sheetflow across the fan surface, and lower energy facies record settling in swales.

Alternatively, the settling facies may record hyperlocal subsidence of the study location, wherein a temporary low permitted water to pond and deposition by settling to occur. This sort of situation is observed in the field today when sediment removal from below creates a small surface depression. However, the geometry of these features is small enough that the sloping sides of these depressions would be evident in an exposure the size of GF hole. All beds in this section of the exposure were observed to be of relatively uniform thickness and horizontal, and the exposure was cleared in order to investigate geometry in three dimensions, so this explanation here seems less plausible.

From 5.7—7 meters depth are several beds consisting of massive sand-silty cap couplets, which are interpreted to be very low energy events. Pan deposition is the modern analogue. Rooting and rhizoliths are common, and the silt caps are vesicular, indicating considerable influence by growing plants. Several of the silt caps are traceable
around the hole interior. Radiocarbon sample UCI-C03 was collected from this package at a depth of 6.6 m and dates to $7.56 \pm 0.06$ ka.

The next 1.2 meters of deposition consists of several beds of granuley sand, all of which except the uppermost grade normally to silt. This 25 centimeter thick bed is massive sand with floating granules: a “flurry” of sediment which could represent hyperconcentrated flow or a thoroughly bioturbated Sgx facies. Sedimentary structures in the other beds are mostly obscured by bioturbation, which manifests as rooting.

If the bed from 4.7—4.9 meters depth is interpreted as bioturbated, it becomes reasonable to assign a hiatus to the contact at 4.7 meters, as the overlying unit is a pristine bed of reverse graded pebbly gravel to sand. The base of this ~30 centimeter thick unit is clast-supported gravel, which is gently imbricated to indicate flow direction from north to south. Similar coarser facies occupy the column to 3.9 meters depth. From here to 2.3 meters depth is a “flurry” of sand with floating granules, generally finer-grained and with fewer clasts than the over- and underlying beds. This interval appears to be heavily bioturbated: no sedimentary structures were observed, but rooting and rodent burrows are common.

Age control sampling was possible near the surface however, because from 1—2 meters depth, higher energy facies are moderately well preserved. Uppermost OSL sample USU-1557 was collected from a ~25 cm-thick cross-bedded sand 2 meters from the surface and dated to $3.51 \pm 0.60$ ka. Despite well-preserved sedimentary structures and a moderate-energy transport environment, this sample did show evidence of partial bleaching in the dose distribution curve (Arnold et al., 2007; Summa-Nelson and Rittenour, 2012; Appendix A). Therefore the MAM was run to determine its age. A
radiocarbon sample was also collected just below the OSL sample, 2.2 meters below the surface in the underlying rippled, granuley sand. UCI-C02 dated to 3.00 ± 0.07 ka. The uppermost meter of the exposure is thoroughly bioturbated, similar to the interval from 2.3—3.9 meters depth.

Facies observed in Goldfish hole range from those interpreted as representing high energy fluvial or hyperconcentrated flow, to suspension settling in ponded water. Table 2.2 lists facies designations; it is of note that one of these, clast-supported, cross-bedded gravels (Gcx) only occurs in GF. This hole is positioned at the intersection of several alluvial fans, which may explain why there are more higher-energy facies here than at PC. Greater relief from the horst highs to the graben bottoms may also facilitate the transport of intact larger clasts from local bedrock to the basin. Nearly half of the beds (24 of 52) were classified as high energy facies, and another 23% were medium energy facies (12/52). A significant portion of beds (n = 9) were interpreted as suspension settled facies, indicating that the avulsing fans terminated in ponded water. Both of these types of events are observed in the field in present day. Figure 2.6 shows modern day analogues and examples from GF of the two coarsest facies, Gcx and cross-bedded, granuley sand (Sgx). Beds are mostly tabular with wavy boundaries indicating sheetflow over an undulating fan surface; a few are clearly lenticular, indicating channelized flow.

**Picture Canyon locale**

The second main fill exposure is in Picture Canyon (PC) (after Trudgill, 2002), which is located in the heart of the Needles fault array amidst a series of narrow, deep graben. It is 6 kilometers northeast of GF (Fig. 2.2). Today the graben bottom is
Table 2.2 Sediment facies

<table>
<thead>
<tr>
<th>Energy</th>
<th>Name</th>
<th>Description</th>
<th>Interpretation</th>
<th>GF # of beds</th>
<th>PC # of beds</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Gcx</td>
<td>Gravel, clast-supported, cross-bedded</td>
<td>High-energy channelized flow or hyperconcentrated flow</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Sgx</td>
<td>Sand with granules/pebbles, cross-bedded</td>
<td>High to medium-energy transport (sheetflow or channelized flow across the middle of the fan)</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>Medium</td>
<td>Srx</td>
<td>Sand, rippled and cross-bedded</td>
<td>fan</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Sr</td>
<td>Sand, rippled</td>
<td>Medium to low-energy transport across mid to toe of fan</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Low</td>
<td>Sm</td>
<td>Sand, massive</td>
<td>aeolian</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Smc</td>
<td>Sand, rippled to massive, mud cap</td>
<td>Low-energy alluvial transport along toe of fan to suspension settling in ponded water</td>
<td>5</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Smc</td>
<td>Sand, massive, mud cap</td>
<td>Very low-energy transport to suspension settling along margin of ponded water</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Settling</td>
<td>Sand and silt, massive</td>
<td>Suspension settling on margin of ponded water</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Fm</td>
<td>silt, massive</td>
<td>Suspension settling in ponded water</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GF # of beds</th>
<th>PC # of beds</th>
</tr>
</thead>
<tbody>
<tr>
<td>46.2%</td>
<td>23.5%</td>
</tr>
<tr>
<td>23.1%</td>
<td>32.4%</td>
</tr>
<tr>
<td>13.5%</td>
<td>35.3%</td>
</tr>
</tbody>
</table>
Fig. 2.6. Coarser facies and modern analogues. Present-day analogues of cross-bedded sand with granules and pebbles (A) and clast-supported gravels (C) near Deep Canyon. B) and D) taken from vertical exposures of these same facies from Goldfish hole (scale in decimeters). B) is the weathered profile and D) has been cleared and smoothed. D) shows a Gcx facies where gravel-sized and larger particles include mud rip-up clasts.
separated superficially from the Butler Wash/Red Lake Canyon drainage directly north by an alluvial fan surface (Fig. 2.7). This surface is cut by a 1—2 m-deep channel that trains directly into the PC swallow hole, which is ~10 m wide, 100 m long, and 15 m deep (Figs. 2.7 and 2.8). Bedrock of the hangwall is exposed, along with sedimentary fill, in this fissure. Structurally, the graben within which PC is situated is delineated by straight bounding structures and a hard-linked stepover that crosses a bedrock high, which separates the basin to the southwest.

The alluvial fan is delineated by the bright green polygon in Figure 2.7B, and its contributing catchment is defined by the drainage divide atop the horst to the NW. A small amount of material has likely contributed to this basin off the horst to the SE, but the catchment on this side is negligible.

Sixty-eight beds were recorded at PC in a continuous exposure (Fig. 2.8). Resistant, calcareous, silty sand marker beds allowed lateral tracing where the exposure walls were too steep to continue logging the section vertically. Nine radiocarbon and four OSL samples were collected; ages all fall between ~6—3 ka (Table 2.1).

**Picture Canyon chronostratigraphy**

The full measured section at PC is found in Appendix B and a summary column is found in Fig. 2.6 above. Ages range from 6.38 ± 0.04 ka to 3.80 ± 0.67 ka. However, the older end of that range is anchored by radiocarbon samples that appear to be reworked charcoal. This interpretation is based upon the fact that the ages are out of stratigraphic order both internally and with the OSL samples (Figs. 2.5 and 2.8). The hole is currently fed by a wash incised into channel fill (Fig. 2.7), so it is highly plausible that these
Figure 2.7. Picture Canyon overview photos. A) Gulley leading to Picture canyon hole looking NW from the horst directly east (white star in B). Gently sloping alluvial fan surface is annotated with drainage divide (green) between the graben basin and Butler Wash drainage. B) Swallow hole location (red-filled polygon) within graben-basin area (green polygon), fed by contributing catchment (red polygon). Note Butler Wash.
charcoal fragments were stored in the basin fill, then redeposited at a lower level in the swallow hole.

As noted in Table 2.2, facies observed in PC hole range from those interpreted as representing high energy fluvial to suspension settling in ponded water. Facies at PC are generally lower-energy than at GF, including a very low energy facies consisting of massive silt that was not observed in GF (Table 2.2). Its situation at the toe of a single, rather than multiple, fans may be the main explanation for this. Figure 2.10 pairs modern examples of some of those low-energy fluvial and ponded water settings with examples of those facies.

The basal 1.75 meters recorded in PC are wedge-shaped beds that onlap the hangwall and generally thicken toward the main fault (to the east) (Figure 2.9). The lowest 90 cm, from 11.5 to 10.6 meters depth, comprises pristine (i.e. not bioturbated) beds of fine to medium sand, granules, and pebbles. These are better sorted in the bottom half, suggesting ordered deposition into the crack from a moderate-energy alluvial source in the west. The sequence becomes less well-sorted near the top, suggesting flow became more disorganized as it increased in energy. Pebbles are locally-sourced Permian lithics and calcareous nodules. The next 1 meters, to 9.7 meters depth, is composed of wedge-shaped sand and granuley sand beds with internal cross-bedding parallel to the overall dip of the beds. Together, this bottom 1.9 meters of section records crack-filling deposition and co-depositional hyperlocal subsidence or rotation. This is likely due to removal of material from below, but in small enough quantity that faulting and/or soft sediment deformation is minimal.
Figure 2.8. Overview of stratigraphy at Picture Canyon swallow hole. In A), beds area delineated with black lines and hiatuses with black hachured lines. OSL sample locations indicated with black circles; black triangles show where radiocarbon samples were collected. Exposure faces ESE. B) shows just stratigraphy with age control. Note normal faults on left side of photo and schematic; offset is several centimeters. Figure 2.9 is below bottom edge of photo.
Figure 2.9. Wedge at base of PC exposure. A) Annotated photograph of wedge in basal portion of Picture Canyon swallow hole B) Annotations without photo underlay. Beds abut rock of hangwall.
The next 0.3 meters, from 9.7 to 9.4 meters depth, are silt, silty sand, and sand beds with ripple laminations and internal mud drapes that suggest low energy deposition at the tail end of alluvial flow or to ponded water. The deepest signs of bioturbation manifest at this point in the profile. This mild-moderate rooting and small burrows continues up through the next several beds of rippled sand with mud caps to 9 meters depth, where it abruptly ends. Radiocarbon sample UCI-C01, which provides the deepest age control here, was taken at a depth of 9.6 meters from a rippled to massive sand bed, just before bioturbation becomes common. This sample dated to 5.88 ± 0.09 ka, which is in stratigraphic order with the OSL samples above it.

A pristine, 20-cm thick sandy unit with mud rip-up clasts overtops this bioturbated zone and is interpreted to mark the return to channelized flow after a hiatus. Successive sand beds topped with silt caps, interpreted to be sporadic moderate energy flow events that wane, continue to 8.2 meters depth. Radiocarbon sample UCI-C00 was collected from one of these rippled-at-base to massive-at-top, cm-scale sand beds. Its age of 5.7 ± 0.06 at a depth of 8.8 meters depth, suggests that nearly a meter of sediment accumulated in 0.2 kyr—a very fast sediment accumulation rate. These deepest radiocarbon samples are valid, inasmuch as they represent a maximum age for the section. Given that the overlying OSL ages are within ~0.5 kyr (Table 2.1) of these ages, this implies a fast sedimentation rate.

OSL sample UCU-1400 was also collected from this package of rippled to massive sands at 9 meters depth. At 4.61 ± 0.59 ka, it is out of stratigraphic order with the OSL samples above it, as well as the radiocarbon samples adjacent to it in the section. Its equivalent dose distribution showed both high overdispersion and significant positive
skew. These are likely due to mixing and partial bleaching, respectively. Furthermore, this sample was problematic with respect to recycling ratios (Appendix A). Therefore, it is not included in subsequent analysis of sediment accumulation rates.

The silt caps show increasing density of rooting going upsection, which continues through the next package of beds to 7.8 meters depth. Radiocarbon sample UCI-C99 was collected at 9.5 meters depth from a rippled sand bed. Its age of $5.72 \pm 0.36$ is in stratigraphic order (except with the problematic USU-1400) but its error is higher, because the bulk of its mass was lost during acid-base-acid preprocessing, and consequently only 0.019 mg of material (approximately 1/10 of what is normally required for analysis remained after graphitization (J. Southen, pers. comm.) Between 8.2 and 7.8 meters depth is a generally coarsening upward sequence of couplets comprising two to three beds: a very fine to fine ripple laminated or cross-bedded sand bed followed by a very fine to silty sand topped with a silt cap. Charcoal collected from the top bed at 7.8 m depth was dated to $6.14 \pm 0.10$ ka; the first instance of truly problematic age reversal.

At 7 meters depth, a lenticular bed of sand with granules and trough cross-bedding records a higher-energy deposition event onto what had been a stable surface. This interpretation arises from the observation of climbing ripples and small mud/silt rip up clasts at the base of the granuley sand. The channel appears to have been oriented parallel to the graben-bounding fault, as its axis is exposed in cross-section on the eastern side of the exposure and the channel form thins to the west. Several pieces of charcoal collected from this channel form date to $6.38 \pm 0.04$ ka, suggesting that this flow even scoured basin fill above that had stored older charcoal. In contrast, OSL sample USU-1558, from the same channel form, dated to only $5.12 \pm 0.55$ ka, nearly 700 years
younger. The tight, relatively symmetrical equivalent dose distribution provides confidence in the accuracy of this OSL age.

The next half meter of sediment consists of repeated cycles of rippled and cross-bedded sands that grade to silt caps. These all show signs of moderate bioturbation in the form of rooting and some small insect burrows. From 6.5—6.3 meters depth, the sequence of a lenticular bed of granuley sand overlain by a series of low-energy flow to settling facies, similar to that seen from 7—6.5 meters, is repeated.

The next 0.4 meters, to 5.9 meters depth, consist of several tabular sand beds with ripples and low angle cross-bedding at the base, which sometimes include scattered granules. These beds grade normally to massive, cm-scale silt caps at their tops. These are interpreted to record moderate, waning flow across the fan. An abrupt transition at 5.9 meters from moderately dense rooting and insect burrows to pristine beds is interpreted as rejuvenated deposition onto a stable surface. This 1.2 meter-thick pulse of deposition consists of sand and granuley sand beds, all tabular in the orientation of the exposure. Most are normally-graded, though some are reverse graded, preserving flow onset. Centimeter-scale silt caps, indicating suspension settling, occur occasionally. OSL and radiocarbon samples USU-1559 and UCI-C96 were sampled from this depositional pulse, at 5 and 5.6 meters from the surface, respectively. USU-1559 was taken from a rippled, cross-bedded sand and was generally well-behaved, and its age of 3.89 ± 0.47 is deemed reliable. UCI-C-96 consisted of a single piece of angular charcoal collected from a rippled sand. Like the previous radiocarbon sample, its age of 5.88 ± 0.09 was deemed too old. Bioturbation decreases with depth from 4.7 meters depth, indicating there is
another stable surface at 4.7 meters. This is overlain by two nearly pristine, tabular beds of coarse sand to silt. These are interpreted as channelized flow events.

From 4.7 to 3.3 meters depth, grain size and diffuse bed boundaries are the primary tools for interpretation, because mixing due to bioturbation is profound. The lowest meter of this interval consists of granuley sand beds, tabular in shape, with abundant rooting, burrows, and little preservation of sedimentary structures. Faint cross-bedding is observed in some of the beds, and this, in part, drives their interpretation as originally channel and swale sands, deposited in medium-energy flows. Above these coarser beds are 0.4 meters, from 3.7 to 3.3 meters, of sand and silt. The uppermost 10 centimeters of this interval is a pure silt bed that is interpreted to be settled material in ponded water. A single piece of charcoal collected from this bed, UCI-C95, yielded a too-old age of 5.22 ± 0.07.

In the beds above 3.3 meters, sedimentary structures are again evident, suggesting there is another stable surface here which was buried by subsequent deposition. Tabular beds of rippled sand persist from 3.3 meters to ~3 meters, and are then followed by fining-upward beds of sand to silt. Taken as a whole, this sequence from 3.3 to 2.4 meters shows evidence of repeated alluviation, waning to suspension settling. The uppermost 0.3 meters of this interval is heavily bioturbated. Radiocarbon sample UCI-C94 was collected from a massive sand at 3.3 meters depth; its age of 5.56 ± 0.04 ka is 1.5 kyr older than the trend of OSL ages here (Fig. 2.11). Radiocarbon sample UCI-C93 was collected at 3 meters depth from the surface and was slightly older than UCI-C94 below it, supporting the interpretation that charcoal from the upper parts of the section is reworked.
Fig. 2.10. Finer facies examples and modern analogues. Present-day analogues of rippled sand (A) and sand with a thick mud or silt cap (C). B) and D) show vertical exposures of these facies from Picture Canyon hole. In B), climbing ripples were found at the base of where USU-1400 was sampled; knife is 20 cm long. D) was taken from a cleared contact which showed mud cracks in the top of a silty cap of a sand bed at approximately 6 m depth.
Figure 2.11. Age-depth plot of radiocarbon and OSL ages from Picture Canyon.

Regression line through OSL ages in stratigraphic order and best behavior has a slope of 2.8. If all OSL ages are included, the accumulation rate increases to 3.5 m/kyr. Note that three lowest radiocarbon samples are along trend with the OSL-derived sediment accumulation rate, further supporting their validity as dating depositional events.
The remaining 2.4 meters of the exposure consist of granuley sand beds. These are better preserved at depth and become increasingly disturbed by rooting (both modern and ancient), burrowing, and mixing closer to the surface. The uppermost 1 meter of exposure is a flurry of sand and granules, is calcareous, and has incipient ped development, especially in the topmost half meter. Sedimentary structures, where preserved, consist of low-angle cross beds and ripples. A few beds appear to normally grade to silt caps, similar to those interpreted to be waning alluvial events deeper in the section. OSL sample USU-1401 was collected from a rippled, granuley sand bed near the weakly bioturbated base of this package at 2.1 meters depth. Its age of $3.8 \pm 0.67$ ka agrees stratigraphically with the other OSL ages, but this sample’s behavior was poor. The De histogram suggests there are two populations of grains and shows positive skew, hinting that mixing and partial bleaching are likely problems here. Given that this sample is the youngest-aged, this is unsurprising, and the MAM was used to model an age (see Appendix A for details).

Secondary localities

Swallow holes in two secondary locations were also studied. The Cow Canyon (CC) exposure lies along a graben-bounding fault that is part of a splay on the NE branch of a complex, 150-meter deep graben named Cow Canyon on USGS maps (Fig. 2.12). It is 3 km to the SSW of the PC exposure. Bobby’s Hole (BH), the other secondary locality, is located 2 km to the SE of GF (Fig. 2.13). BH formed in the middle of a half-graben directly cross-strike to the deep graben named Bobby’s Hole on USGS maps. While CC and BH swallow holes had only six and four meters of sediment exposed, respectively,
Figure 2.12. Cow Canyon overview photos. A) Orthophoto showing swallow hole (solid red polygon) with contributing catchment in hollow red polygon. B) Arrow points to the swallow hole as viewed from the eastern horst (white star in A); note active fan surface upstream of the hole C) View of the swallow hole from a joint-controlled slot, which funnels runoff from the western horst (yellow star in A).
the sedimentology and ages derived from them can nonetheless contributed to our understanding of how deposition occurs in graben and may related to climate.

At CC, as at PC, ongoing extension in the Needles fault array continues to generate space for sediment to be “swallowed”, and a crack along the western graben wall serves as a sink from which channels have headwardly eroded, resulting in a series of incised drainages leading to the crack. The contributing catchment to Cow Canyon hole consists mainly of Cedar Mesa sandstone exposed on the surrounding horsts, as well as a relay ramp at the NE end of the graben branch. Small fan surfaces that have been recently incised by small channels define the graben bottom topography today (Fig. 2.12). The Cow Canyon exposure was logged during two visits 11 months apart; during that time the first exposure sloughed off, complicating correlation of the two logged exposures. The second exposure contains 24 beds from which two radiocarbon (UCI-C08 and UCI-C09) and one OSL sample (USU-1403) were collected. Facies range from Sgx to Smc and generally show an upward-coarsening sequence, with low-energy flow and pond-settling facies at the bottom grading to interleaved silty sands and granulely sands at the top. Bioturbation was less prominent here than at any other exposure studied, especially within the top 2 meters.

Bobby’s Hole (BH) is located in a shallow, asymmetrical graben that has developed in the horst bounding a larger, well developed graben immediately to the NE (Fig. 2.13). It is approximately 2 km SE of GF, and similarly, the horsts retain windgaps, indicating it was once part of the Cross Canyon drainage (Figs. 2.2 and 2.13). While the graben in which it occurs is the shallowest and possibly most-recently developed of all the study graben, the hole itself has less vertical exposure related to a widening fault or
Figure 2.13. Bobby’s Hole overview photos. A) Orthophoto shows swallow hole (filled red polygon) and contributing catchment (hollow red polygon). B) View looking SW (white star in A) shows the hole (white arrow) location relative to the half graben. C) sloping sides with piping.
removal of material. Its sloping walls that are covered in weakly developed biological soil crust, scrub, and bunchgrass (Fig. 2.13C). BH has two levels that were logged on separate occasions five months apart, and like Cow Canyon, the first logged face was destroyed by washout that occurred during monsoonal rains in late summer of 2013. One OSL age was collected from this lower exposure (USU-1404) and the other was collected from the upper exposure (USU-1405). Two radiocarbon samples (UCI-C09 and UCI-C-10) were also collected and dated. Facies logged here ranged from Sgx to Smc, representing medium-high energy fluvial and settling environments, though granuley sands and sands dominated the section over finer facies (see Table 2.2). The top 2-3 meters was heavily bioturbated.

**Cow Canyon and Bobby’s Hole chronostratigraphy**

Geochronologic results from Cow Canyon generally support that the 6 meters of sediment exposed here accumulated over the latest Holocene (Table 2.1, Fig. 2.14). A cross-bedded to massive sand at 1.5 meters depth was sampled for both OSL and radiocarbon dating, and the resulting ages of 0.70 ± 0.16 ka for USU-1403 and 0.24 ± 0.04 for UC-C07 are in agreement that this sample is late Holocene. Both the younger radiocarbon age (and positively skewed equivalent distribution, best fit with a MAM, support that the OSL age from USU-1403 is too old, likely due to partial bleaching. Therefore the radiocarbon age is expected to be more reliable and is used in plots (e.g. Fig. 2.14). The next deepest sample, USU-1402, was collected from a cross-bedded to massive sand at 2.3 meters depth and dated to 4.00 ± 0.47 ka. This OSL sample is likely too old, as a deeper radiocarbon sample, UCI-C08 from a silty sand at 5.8 meters depth,
Figure 2.14. Age-depth plots for the four study exposures. Regressions through trends in points yield sediment accumulation rates for discreet time periods. All OSL ages are circles and radiocarbon ages are triangles. Error bars are 1 σ. Only in-place, reliable ages are shown (e.g. not all PC results are plotted; only radiocarbon results from CC are plotted).
dated to only 1 ka. The bed from with the piece of angular charcoal dated in sample UCI-C08 is stratigraphically linked to the bed from which samples USU-1403 and UCI-C07 were taken and so it considered reliable. The OSL age is problematic because it was sampled from an exposure to the north of the full, logged section, and may therefore represent an older fan lobe not in section with the other ages. While several hiatuses (pristine beds above bioturbated beds) were observed in CC, no obvious unconformities or incipient paleosols were, which is unsurprising given its short and relatively recent timescale.

While Bobby’s Hole had a shorter exposure than Cow Canyon, it is considerably older. OSL samples USU-1405, from 1.5 meters depth, and USU-1404 from 2.4 meters depth, dated to 7.03 ± 1.01 ka and 7.55 ± 0.90 ka, respectively (Table 2.1; Fig. 2.14). They are in correct stratigraphic order. Both samples were well-behaved with respect to equivalent dose distribution.

A profound age difference and inversion between radiocarbon samples UCI-C09 and UCI-C10, both from 1.7 meters depth, suggest one of both of these ages is invalid. Both samples came from a mildly bioturbated sand 1.7 meters below the surface. The former, based on several pieces of charcoal, dated to 8.30 ± 0.08 ka and is likely reworked charcoal. The latter ate of 1.18 ±0.06 ka was based on dozens of seeds and is interpreted as out of context and perhaps introduced to the subsurface by burrowers at a later time. Taken together, these results suggest that most sediment accumulated at Bobby’s Hole in the early-middle Holocene.

**Correlation and summary of records**

While the exposed sections in Goldfish and Picture Canyon holes are similar in
total depth, they represent largely different timescales within the middle-late Holocene, and the record in GF extends to the late Pleistocene (Figs. 2.4, 2.5, and 2.8). The ten meters of sediment that accumulated in PC over two millennia during the mid-Holocene do not correlate stratigraphically with the three meters of sediment that accumulated during this timeframe in GF, but age control allows the assertion that they are time-correlative.

**Sediment accumulation and yield**

Sediment accumulation rates were determined by obtaining the slope of a line regressed through data clusters that showed a trend (Fig. 2.14). Deposition was assumed to be uniform and steady for these time intervals, with no accumulation and subsequent removal of material. Field observations suggest that this may be a fairly safe assumption, as scour is only observed in one location (the lowest 2 meters in GF) and otherwise depositional tops are preserved, with evidence that they became stable surfaces upon and underneath which flora and fauna was able to establish. Integrated accumulation rates account for these hiatuses, though Figure 2.15 demonstrates how accumulation could happen in pulses, followed by non-deposition as recorded by a hiatus. Vertical sampling location also affects accumulation rates, though we attempted to account for this by extending the interval that was interpreted to have a certain rate to a hiatus, where possible. We also assumed that ages from samples collected represent timing of deposition. However, certain OSL ages (discussed above) appear to be too old (likely due to partial bleaching). Likewise, radiocarbon ages—particularly those from PC—are likely remobilized from stored sediment in the basin floor fan and are therefore also too old.
Figure 2.15. Sediment accumulation rates determination at Goldfish Hole. A) Rates determined by regression through trends in data and integrated “background” accumulation rate from 16—3 ka. B) Observed hiatuses are used to illustrate episodic sedimentation, occurring at the same rate over short time intervals that integrate to lower rates when hiatuses are included.
Goldfish hole is the deepest, most variable, and longest-spanning stratigraphic record studied. This made it possible to separate the lower, latest Pleistocene-early Holocene sequence (16.2—8.7 ka) from the middle Holocene bulk of the section (9.3—7.6 ka), and then the later Holocene upper strata (7.6—3.0 ka), for the purposes of comparing rates of accumulation and sediment yield. These delineations were based on trends observable in the plotted points, as well as where interpreted hiatuses plot (Figs. 2.14, 2.15) Sediment accumulation rates were determined by the slope of a best-fit line through the data points comprising each time interval. Estimated rates of sediment accumulation in GF vary from 0.44 m/kyr over the lower Pleistocene-Holocene transition section to a high of 1.9 m/kyr from ~10—8 ka. Sedimentation at the GF exposure slows during the middle Holocene to 1 m/kyr.

Sedimentation at PC occurred over a shorter timespan that at GF. The approximately 8 meters of sediment bracketed by UCI-C01 and USU-1401 accumulated over 2 kyr, at an integrated rate of 2.9 m/kyr. While hiatuses were noted in Picture Canyon (Appendix C), age control points were too far sparse and in close agreement to extract hiatus-bounded trends as was done at Goldfish.

Accumulation at Bobby’s Hole occurred over the same time frame, and at nearly the same rate, as at Goldfish Hole during the middle Holocene. However, it lacks the mid-late Holocene sequence observed at GF. Having only two data points further limits the confidence with which this mid-Holocene sedimentation pulse can be attributed to a shared driver. Cow Canyon did have a late Holocene accumulation, but it was 2-3 times faster than seen elsewhere in this study. It also has few data points.
Generally speaking, accumulation rates at GF and PCE are similar during the early-middle Holocene, the intervals of highest sediment accumulation in GF and PC are out of sync: highest rates in GF occur from 8.7—~7.0 ka (assuming the hiatus at 4.6 bounds this interval), whereas the entire logged PC section accumulated between 5.9 and 3.8 ka. The records at CC and BH are nonexistent during this time interval, and therefore cannot contribute to understanding how synchronous sedimentation was then.

Rates of sediment accumulation in PC determined using radiocarbon ages (Fig. 2.16) ranged from 3.5 to 8.2 m/kyr, depending upon which samples were used for the regression. These rates are very high and are almost certainly artifacts of stored burned wood having been archived in the landscape, then remobilized in the sedimentation events dated with OSL ages.

Sedimentation rates were used to determine sediment yield for GF and PC; the latter during the three time intervals discussed above. Table 2.3 lists calculated sediment yield and denudation rates based on these accumulation rates, contributing catchment and graben-basin sizes as illustrated in Figures 2.3 and 2.7, and constants as described in the Methodology section above.

While rock and sediment properties can be assumed to be more or less constant, accumulated thickness was allowed to vary to account for spatial changes in depositional locus. Bed geometries and sedimentary structures indicate that deposition to these graben basins occurs via both channelized flow as well as sheetflow across the surface of the fan.

We attempted to capture this assumed spatial heterogeneity of interval thickness by allowing graben-basin fill thickness to vary around an average, which was based on the interval encompassed by age control.
Figure 2.16. Age-depth plot of radiocarbon and OSL ages from Picture Canyon. Bold regression is through samples in which lies the highest confidence. Grey lines demonstrate extremely high rates that would be calculated if reworked charcoal ages were used.
Table 2.3. Sediment yield and denudation rates for Picture Canyon and Goldfish hole graben

<table>
<thead>
<tr>
<th>Location</th>
<th>Catchment Area - $A_c$ (m$^2$)</th>
<th>Graben basin area - $A_{gb}$ (m$^2$)</th>
<th>$A_{gb}$ to $A_c$ ratio</th>
<th>Graben basin fill thickness (m)$^a$</th>
<th>Time (kyr)$^b$</th>
<th>Denudation rate (m/kyr)$^b$</th>
<th>Yield (tonnes/km$^2$/yr)</th>
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<tr>
<td>Picture Canyon</td>
<td>Entire</td>
<td>90385</td>
<td>0.090385</td>
<td>23261</td>
<td>0.26</td>
<td>7.7</td>
<td>2.09</td>
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<td></td>
<td>thickness x 0.5</td>
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<td></td>
<td>3.85</td>
<td>0.36</td>
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<tr>
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<td>97402</td>
<td>0.097402</td>
<td>70309</td>
<td>0.72</td>
<td>11.4</td>
<td>12.71</td>
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<td>1.675</td>
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<td>Middle Holocene</td>
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<td></td>
<td></td>
<td>1.635</td>
<td>0.79</td>
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<tr>
<td></td>
<td>Late Holocene</td>
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<td></td>
<td>7.11</td>
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<td></td>
<td></td>
<td></td>
<td>2.37</td>
<td>0.28</td>
</tr>
</tbody>
</table>

$^a$Thickness of dated section first, followed by scaled thickness values

$^b$Adjusted to reflect sediment accumulation rates plotted in Fig. 14

ρ_{sediment} \ldots \ldots \ldots 1.9

ρ_{Cedar Mesa ss} \ldots \ldots \ldots 2.5
Graben-basin geometry, on the other hand, was simplified in the assumption that each was a simple rectangular prism. This choice was based on our judgment that the degree of resolution for accumulation was not deemed sufficiently fine to warrant attempting to quantify more complex geometries. Moreover, reliably determining subsurface geometry is not feasible: while surficial components like fan surface gradient can be measured, subsurface geometry is difficult to determine. For example, in Picture Canyon, hangwall bedrock that dips southwest is exposed in the swallow hole. These beds can be correlated to the caprock of the footwall (suggesting vertical separation of ~15 m), yet they cannot be traced laterally in the graben due to sedimentary cover. 2-D seismic imaging of the subsurface of graben suggest that hangwalls are typically not a coherent block, and field observations support that multiple iterations of hangwalls may be buried in the subsurface (Grosfils et al., 2003).

DISCUSSION

Depositional environments and processes

The location of each hole in their respective graben, relative to the position of the main fan surface(s), corresponds with what is found in the subsurface. GF contains facies commonly found in the medial and medial-distal fan, and PC is dominated by medial-distal to distal-playa facies (Figure 2.17). GF hole splits open the fan feeding its graben nearer to where the fan emanates from the graben wall than PC. Furthermore, the GF graben has higher relief, which may contribute greater sediment size.
In PC, the toe of the fan is exposed in cross-section within the study swallow hole. Generally lower energy facies here relative to GF suggest that most deposition was at the distal part of the fan or into ponded water located along the SE graben wall. This relationship between active fans and flat-bottomed pan with mudcracks is observed in several locations throughout the Needles fault array in the present day, and it is part of drylands fan models (e.g. Denny, 1965). The coarsest facies in PC are found in the lowest 2 m of sediment units in Picture Canyon and abut the hangwall bedrock, where fluvial deposition to faulting which separated the now-buried hangwall from the bounding footwall preceded the development of the fan.

It is notable that very few of the beds at any site were interpreted as eolian. While dunes were recorded as being active in the area over the same timescales as this study, they are likely not a large source of sediment (c.f. Reheis et al., 2005). Dunes today are primarily situated on parks within protected areas and the largest graben.

The presence in most fluvial beds of some or many granules consisting of carbonate chips and/or bedrock suggests that there would have been mixing between the weathering rind of bedrock, loose sand, and perhaps material scoured from bedrock during fluvial transport. Weathering and exposure of sandstone on horsts was expected to sufficiently bleach grains before they are transported directly to graben. However, it appears that, at least at Picture Canyon, where OSL samples showed signs of partial bleaching and radiocarbon ages suggested reworking, sediment is temporarily stored in graben bottoms before final deposition in the distal fan. The presence of an incised channel at PC supports that older deposits may be cannibalized, even within these small systems.
Figure 2.17. Schematic cross-sections of two main study graben. Goldfish hole (top) is nearer the source of the alluvial fans filling the graben-basin, while Picture Canyon (bottom) is most distal from the main source on the west side of the graben. Figures are not to scale.
Correlations between sites

True sedimentary correlation was not possible between sites, which is unsurprising, given their dispersal and unique internally drained catchments. However, as demonstrated in Fig. 2.17, this is also at least partially a function of where exposures are located in their fan systems. Age control permits some time-based correlations. Goldfish is the only locality with preserved late Pleistocene strata, and three of the four sections are dominated by middle Holocene deposits. Cow Canyon is the only study site a latest Quaternary record. The near-pristine condition of its upper 1.5 m can be interpreted as a proxy for recent deposition, which supports Biggar and Adams’ (1987) results from Cross Canyon and another locale, which also displayed uppermost beds with little bioturbation that yielded latest Holocene radiocarbon ages.

Sediment accumulation and yield through time

Goldfish, Picture Canyon, and Bobby’s Hole exposures provide evidence for rapid sediment accumulation rates ranging from 2—3 m/kyr between 9 and 5 ka (Figs. 2.14, 2.18). Cow Canyon shows faster accumulation rates since then, while Goldfish has evidence for slow rates and hiatuses into the late Holocene, as well as in late Pleistocene time. While both Picture Canyon and Goldfish Hole quickly accumulated sediment during the mid- Holocene, they are actually asynchronous: the pulse preserved in Goldfish occurred from ~9-7 ka, while the one in Picture Canyon spanned ~6-4 ka. There are at least four plausible explanations. The first is that sediment accumulation and yield is a function of autogenic cycling within this alluvial system, and that on the time and
Figure 2.18. Age-depth plots juxtaposed with climate data/proxies. A) shows same data as Fig. 2.14. Blue rectangle shows duration of the Younger Dryas interval. White area overlays highest sedimentation rates at GF, and red rectangle roughly encapsulates the mid-Holocene Altithermal. B) Plant succession index developed from packrat pellets collected in Grand Canyon, Arizona is adapted from Cole and Arundal (2005). This proxy curve mimics fairly closely oxygen isotope data in C) and D), especially for the Younger Dryas. C) Oxygen isotope concentration from a speleothem in the Guadalupe Mountains, New Mexico, adapted from Asmerom et al. (2007). Note scale is relative to Peedee Belamnite, whereas in D), oxygen isotope data from foraminifera in a Santa Barbara ocean basin core, off the Pacific coast of California, is recorded in permil (adapted from Hendy et al., 2002). E) Great Salt Lake shoreline elevations from Benson et al. (1990) plotted against time. The precipitous drop in lake levels c.a. 17 ka was due to rapid draining of the lake to the north; levels after 11 ka have remained low compared to those during the latest Pleistocene. F) Portion of the integrated summer solar insolation curve for 30ºN, plotted from data freely available from NOAA and generated and reported by Huybers (2006).
spatial scale of these deposits, that control is dominant. For example, the apparent slowing of accumulation in GF after 7 ka may be due to the fan avulsing to a different part of the basin. A similar situation might also have occurred in PC: sediment was accumulating elsewhere than the exposure face for a while, and then fan topography became steep enough to cause flow redirection.

Secondly, salt tectonics may play a role: extension of faults and/or evacuation of material may have generated a sink that captured flow. Wedge-shaped beds at the base of the Picture Canyon exposure, which abut the hangwall, support the interpretation that accommodation space was available at the onset of the fast sediment accumulation here. No evidence of syn-depositional deformation, such as growth faulting, were observed, suggesting that, at the least, the sedimentation rate is slower than the rate of local lowering due to salt removal.

The third explanation is that sediment yield and accumulation rate values do, in fact, reflect primarily climate-driven transport process forcing. Process models for how sediment yield changes as a function of climate change would predict that vegetation disturbance, changes in seasonality and intensity of storms, and more disparate annual temperature extremes that accompanied the most recent glacial-interglacial transition would result in high sediment yield from the landscape. While the transition out of the cool, dry Younger Dryas to the warmer mid-Holocene Altithermal might be expected to not yield high sedimentation, several climate proxies suggest that the increase in insolation in part contributed to the transition to a monsoonal summer climate beginning between 9—8 ka. These changes in precipitation intensity and seasonality that would have increased sediment transport correlate with the onset of higher sedimentation at
Goldfish hole (Wurster et al., 2008; Anderson, 2011). Figure 2.16 shows that highest sediment yield in GF during the mid-Holocene—three times greater than values in the late Holocene—happened during the dry mid-Holocene Altithermal and corresponds to warmer local temperatures (16°C) as well as drier weather overall (16D). Results from Bobby’s Hole correlate well with those from GF. Fast sedimentation at Picture Canyon is only partially constrained, as the lowest material sampled here dated to only ~6 ka. Without deeper samples, it is difficult to truly compare the early to mid-Holocene sedimentation events at PC and GF.

Finally, it is worthwhile to reexamine how we have defined sediment yield. This metric was calculated under the assumption that these small graben-basins are internally drained. However, on decadal to millennial timescales these basins appear to be leaking material: flow of water and sediment continues into dilating faults, and sediment is piped as well. It would follow that what is here interpreted as high sediment yield could be reframed as more effective retention of material. Active flushing of sediment into faults is observed today, but perhaps the less frequent, lower discharge flow events expected in the Altithermal were unable to access faults like we see in the field today. Complimentarily, lower total precipitation during the warm dry period would mean lower deformation rates due to salt tectonism, which might result in a relatively quiescent landscape in which sediment could accumulate. Previous work examining how well present-day deformation patterns track with surface infiltration found a correlation (Dr. Karl Mueller, pers. comm.), which is likely due to the capacity of water to decrease the depth at which ductile deformation of salt occurs.
Climate may have played a role in another way: by influencing water table depth. Knudsen et al. (2014) found that groundwater depth correlated strongly with timing of earth fissure opening in south central Utah. These earth fissures bear a strong resemblance, both at the surface and in interpreted cross-section, to the swallow holes of the Canyonlands graben.

This last discussion point implies—by invoking accommodation space, rather than process-based, controls—that the late Pleistocene and later Holocene sediment yields reported in this study are depressed, as not all material is retained in the study basins. In this situation, sediment yields would be greater than ~5000 metric tons/km²/yr.

When sediment yield for the study basins is plotted against catchment size along with modern observed sediment yield in modern basins of differing sizes and climate regimes, the basins in the Graben plot along trend, yet have the highest rates (Fig. 2.19).

**Swallow hole and graben evolution over the Quaternary**

While modern process analogs for the sedimentary records studied exist, they are outnumbered by the number of basins in the Needles fault zone that appear to be losing sediment to swallow holes, such as the four study sites. Indeed, during seven field campaigns over two years, we found that nearly every graben visited contained at least one, and often several, swallow holes of varying size. However, 5000-9000 years ago, these basins were preserving material instead. Several explanations invoking salt tectonics have been discussed, yet it remains difficult to conclusively ascribe our results to that driver alone. One limitation is that we do not see any inset relationships between fill in the study exposures, which would be expected if there were pulses of extension and
Figure 2.19. Sediment yield comparison between study sites and US regions. PC values are for the entire exposure. Goldfish integrated values are for the logged, age-constrained exposure. Pleistocene GF is the range of yields for the Pleistocene-late Holocene interval; mid Holocene GF is the range of yields for the early-middle Holocene interval, and late Holocene GF is the range of yields for the middle-late Holocene interval (see Fig. 2.15). Regional yields from Griffiths et al. (2006).
swallow hole formation followed by basin filling. On the other hand, another indicator of past swallow hole development—faulted sediment overlain by flat-lying beds—was observed in Picture Canyon. However, the rapid accumulation rates at there mean that the interval during which there was space for faulting to occur was relatively short. Challenging access to the Graben has limited the scope of research in past studies, and it likewise limits our ability to draw clear conclusions about linkages between climate and sediment yield in small basins over centennial-millennial timescales. What is clear is that the story here is complicated: sedimentation is uneven within individual basins and asynchronous from one to the next. The fact that halokinetic-driven accommodation space changes appear to exert an influence on sediment yield tells us that the region is undergoing change at relatively short timescales. Future work needs to survey additional basins to investigate whether there are spatial or temporal patterns in sediment accumulation.

**Basin age estimates**

The modest goal of estimating the magnitude of the timescale over which these basins have been filling was pursued only for Goldfish hole, because its variable sediment accumulation rates and records extending to the late Pleistocene mean that an integrated rate is likely more representative of the entire Quaternary. Accumulation rates were integrated through time in order to estimate a long term rate, which was as the divisor in a basin age determination equation to produce first-order estimates of basin ages. The numerator—total sediment depth—was estimated based on the existing fill depth data from seismic and gravity modeling from Devil’s Lane and Cyclone Canyon.
(Grosfils et al., 2003). When the integrated rate of 0.93 m/kyr is scaled over 90 m (the maximum depth of the two graben with geophysical imaging of fill), the resulting total time of accumulation is 96.5 kyr. This places a minimum age on the development of these imaged graben. If McGill and Stromquist’s assertion that faulting initiated proximal to Cataract Canyon and proceeded to the east toward the axis of the Monument Upwarp is accepted, then this result places a minimum constraint on when this faulting began, i.e. it was well before 100 ka (McGill and Stromquist, 1979).

REFERENCES


Northern Australia: Part 1, Experimental design and statistical models*:


CHAPTER 3

DEFORMATION AND INCISION OF THE NEEDLES FAULT ZONE
OF CANYONLANDS NATIONAL PARK AND ADJACENT LANDS,
ASSESSED BY TOPOGRAPHIC ANALYSIS

ABSTRACT

The active Needles fault zone of southeastern Utah’s Canyonlands National Park has been studied as an analogue for rift basins and normal fault evolution; however this unusual landscape has seen little research from a geomorphic perspective. The numerous streams traversing the area provide an opportunity to undertake quantitative analysis of steepness and catchment attributes. This study uses these metrics to identify patterns in topography that reflect the influence of the two main actors on this landscape: salt tectonism and Colorado River incision. We also employ metrics from stream profile analysis to construct paleo-profiles of streams traversing the fault zone, in order to constrain timing of both initiation of salt deformation and tributary response to Colorado River incision.

Previously proffered constraints on the initiation of fault array development range from 0.085 to 1.5 Ma. This study proposes that tributary response to Colorado River incision began between 2.0 and 1.2 Ma and the ensuing salt-related subsidence began between 1.6 and 0.2 Ma. Spatial patterns in topographic metrics indicate that the Needles fault zone can be parsed to a river-proximal zone influenced most strongly by Colorado River incision and bedrock lithology; a salt-subsidence-dominated graben and horst zone;
and a river-distal zone that is minimally influenced by both salt tectonics and mainstem incision. This zonal interpretation is supported by long profile analysis results, which find anomalously high steepnesses in the inner gorge; depressed steepness indexes in the horst and graben zone; and similar profile concavities among the upper reaches that suggest the streams drain a shared topographic surface.

INTRODUCTION

Landscapes are shaped by the tectonic and climatic forces acting upon them, mediated by the resistance of substrates to erosion, and topography records the result. Thus, metrics from topography can provide insight into the processes that have contributed to the modern landscape. Erosion has dominated the Colorado Plateau over the last several million years, most dramatically via Colorado River incision and subsequent response in tributary drainages and hillslopes as they adjust to a new baselevel. In bedrock rivers, this adjustment typically occurs through headward erosion, which results in a knickpoint—或 waterfall—separating the adjusted portion of the stream from the unaffected portion. A key metric for quantifying the degree to which river gradient is influenced by a passing wave of incision due to rapid erosion is steepness index. This metric is highest in the anomalously steep Cataract Canyon section of the Colorado River, in the central Colorado Plateau, yet rapid incision is only a piece of the story (Pederson and Tressler, 2012). Steepness index can indicate uplift and the presence of resistant bedrock as well. Cataract Canyon’s position at the center of a “bulls-eye” of high incision rates throughout the plateau suggests that rock uplift due to isostatic
rebound contributes (Roy et al., 2009; Pederson et al., 2013). Moreover, hard Paleozoic limestones exposed in the Monument uplift likely play a role, and there is evidence from tributaries to the Colorado River above Glen Canyon that a passing wave of incision may currently be positioned—or partially pinned—in Cataract Canyon (Cook et al., 2009). Regardless, the rapid incision of Cataract Canyon has produced a major mass movement that has garnered research interest in its own right: the Needles fault zone.

This unusual landscape, composed of an arcuate array of normal faults bounding alternating horst and graben, has formed as subsurface evaporate movement to the free boundary of Cataract Canyon causes brittle deformation in the overlying sandstones, carbonates, and shales (McGill and Stromquist, 1975). Extension and subsidence is ongoing at present-day rates of 0.5 to 3 mm/yr as measured by remote sensing (Furuya et al., 2007), and streams crossing the array have been diverted, captured, and otherwise deranged by the development of normal faults (e.g. Trudgill, 2002). Just as the longitudinal profile of the Colorado River encodes information about its history, examination of the long profiles of these streams has the potential to reveal magnitude and timing of salt tectonic influence. Moreover, as Colorado River tributaries downstream contain knickpoints related to mainstem incision, these streams may also record that incision in their form.

Despite the challenges to determining relative influence on tributary long profile form in the Needles fault array—including bedrock heterogeneity and competing local baselevel fall drivers like faulting and mainstem incision signal—the recent proliferation of research using long profile analysis to parse similarly complex baselevel histories means there is hope. Long profile analysis exploits empirical relationships between
stream slope and discharge at a given point along a profile, which reveal the degree to which a stream is in equilibrium with the surrounding landscape. For example, Gallen et al. (2013) combined profile metrics with erosion rates to identify a Miocene-aged pulse of baselevel fall that previously had been missed in the southern Appalachians. Their analysis hinged on identifying two terrains within their study catchments, which had different profile metrics: a relic landscape with which streams were in equilibrium and an incising, adjusting channel system influenced by the relative baselevel fall. Another example of applied long profile analysis comes from Gani et al. (2007). The number of reaches separated by knickpoints in rivers draining the Ethiopian Plateau was used to verify three separate pulses of uplift/baselevel fall identified by relations between long term incision rates and remnant paleotopography (Gani et al., 2007). In a third example, steepness anomalies from longitudinal profiles of rivers draining the Tibetan Plateau have revealed high rates of slip along the Tibetan Fault (Clark et al., 2004). The efficacy of these geomorphic tools in diverse terrains suggests they have the potential to be effective in the Needles fault zone as well.

Derangement of many of the streams in the area notwithstanding, there are a few drainages that fully traverse the Needles fault zone, as well as two that lie beyond the area of salt influence. These qualities mean that these subparallel regional drainages offer an opportunity to extract information on competing forcing mechanisms: baselevel fall due to the passage of a wave of incision up the Colorado River and localized subsidence due to salt evacuation. The purpose of this study is to examine long profile shape and metrics in order to parse spatial and temporal patterns in salt tectonics, rapid incision of the Colorado River, and bedrock geology. Research here has implications for
understanding larger-scale landscape evolution on the Colorado Plateau. We hypothesize that the initially dominant baselevel fall due to Colorado River incision has been stalled and diffused in the now predominantly subsidence-controlled landscape of the Needles fault zone. Long profile analysis should yield consistent results between similar reaches of different drainages if these patterns are consistent through the landscape. Other topographic analyses, such as hypsometric integral determination, ratio of volume to area, and steepness index, should likewise be distributed in meaningful patterns, if these zones of influence are as well-defined as we expect.

**BACKGROUND**

*Setting*

Canyonlands National Park is located near the center of the Colorado Plateau, a physiographic province characterized by high elevation, relatively mild tectonic deformation and deeply incised drainages (Fig. 3.1). The bedrock geology is dominated by broadly contiguous subhorizontal Paleozoic and Mesozoic sedimentary rocks that are punctuated by isolated mountain ranges cored by Tertiary laccoliths, high mesas capped by Tertiary basalt, and select canyons incised to Precambrian basement. Precambrian NE-SW and NW-SE lineaments control the orientation of most structures within the central plateau (Baars, 1981), which can be very generally grouped into high-angle faults bounding the late Paleozoic Uncompahgre Uplift (Ancestral Rockies), and the broad folds and monoclines formed during the Eocene Laramide orogeny. The growth of these features exploited NE-SW and NW-SE trending basement faults generated by Proterozoic
riftiing (Marshak et al., 2000). Of particular importance for this study was the development of the Monument Upwarp, a broad zone of uplift defined by a steeply dipping east limb defined at Comb Ridge in southeast Utah, and a gently dipping west limb (Bradish, 1952).

Within the 50,000 km² composing the Pennsylvanian-Permian Paradox Basin, there are also dozens of salt-movement-related structures, including collapsed anticlines, diapirs, and the Needles fault array (Fig. 3.1). Geologists have worked in the Paradox Basin for over a century, mostly motivated by the search for oil and gas resources (e.g. Woodruff, 1910; Baker and Reeside, 1929). Outcrop of Pennsylvanian and early Permian carbonates and siliciclastics of the Paradox Basin is restricted to the deep canyons of the Colorado River and its tributaries. Near the confluence of the Green and Colorado in Canyonlands National Park, these typically-interred units are uplifted within the north-striking Monument Upwarp and Cane Creek Anticline (Hunton, 1982a, 1982b; Hintze et al., 2000). Overlying Paradox evaporites, shales, and carbonates in the study area is another 1000 m of upper Permian through lower Jurassic siltstones, mudstones, and conglomerates (Fig. 3.2; Huntoon, 1982a; Condon, 1997). Working upward, the first unit above the Paradox Formation comprises alternating, 15m-thick beds of fossiliferous limestone and sandstone (Fig. 3.2; Condon, 1997). Collectively called the Honaker Trail Formation, this sequence of shallow marine and coastal dunes is up to 300 m thick (Hunton, 1982b). The Honaker Trail Formation grades up into the overlying littoral-fluvial Lower Cutler beds, which are 120-300 m thick locally (Fig. 3.2; Huntoon, 1982b). The bedrock here is capped by the 150-275 m-thick Cedar Mesa sandstone. This eolian-fluvial unit weathers to the distinctive mushroom caps and hoodoos of the Needles in
Figure 3.1. Location map of study area (black box) and Colorado Plateau (top left inset). Intensity of coloration of Paradox salt facies indicates relative thickness. Note the Monument Upwarp terminates at the confluence of the Green and Colorado Rivers. Modified from Nuccio and Condon, 2000.
Canyonlands National Park. The lower Cutler beds and Cedar Mesa sandstone transition laterally to the Cutler Formation undivided to the northeast, where it consists of arkosic conglomerates, sandstones, siltstones, and mudstones deposited by high energy streams and debris flows evacuating material from the high elevations of the Uncompahgre uplift (Condon, 1997). Together, the Honaker Trail Formation, Lower Cutler Beds, and Cedar Mesa Sandstone constitute a brittle plate that is deforming due to underlying Paradox evaporate movement to form the grabens (McGill and Stromquist, 1975). Overlying the Cedar Mesa sandstone outside of the study area are the Organ Rock shale and White Rim sandstone, which are unconformably overlain by the Triassic Moenkopi Formation, Chinle Formation, and Jurassic Glen Canyon Group (Condon, 1997).

In the study area, bedrock is gently folded along the N-S Monument Upwarp; this structural context set the stage for Needles fault array formation. Four main physiographic mini-provinces which are traversed by parallel drainages can be defined here: rugged uplands where drainages descend from the Abajo Mountains; a broad plateau of relatively undeformed bedrock, mantled with alluvium, that we call the Beef Basin paleo-surface; the horst and graben of the Needles fault array; and deeply incised gorges of tributaries and Cataract Canyon (Fig. 3.3A). A semi-arid high desert climate means much of the land surface is bedrock with a thin veneer of eolian or alluvial sediment. Precipitation is bimodally distributed between winter storms and late summer monsoons and varies from 200 to 650 mm per year, generally correlative with elevation (PRISM, 2013). Channelized flow is ephemeral and flashy in tributaries to the Colorado River.
Figure 3.2. Stratigraphy of Paradox Basin sedimentary rocks, modified from Barbeau (2003). Study area falls at the marked interval; Cedar Mesa sandstone outcrops and overlying units (including Mesozoic rocks not shown here) have been removed within the last 6-3 Ma.
**Colorado River incision history**

Epeirogenic uplift of the Colorado Plateau beginning in the Oligocene set up conditions favorable to incision of today’s deeply cut drainage networks (Pederson et al., 2002; Humphreys et al., 2003). However, integration of these networks likely began in the late Miocene, when basin and range faulting on the southwestern margin of the plateau caused a local baselevel fall that drove rapid incision, which has since propagated upstream (Lucchitta, 1972; Young and McKee, 1978; Cook et al., 2009). Convexities in the modern-day longitudinal Colorado River profile and modeling suggest that this incision signal has been diffused and split upstream of Grand Canyon (Cook et al., 2009; Pederson and Tressler, 2012). The Cataract Canyon knickzone was likely generated by the passage of the main baselevel fall signal, caught up in and maintained by the relatively resistant carbonate bedrock as well as the localized uplift, tilting, and mass movement associated with salt movement and the Needles fault zone (Furuya et al., 2007; Pederson and Tressler, 2012).

Canyon cutting after Colorado River integration ~6 Ma is supported by thermochronologic modeling based on (U-Th)/He apatite ages from Canyonlands National Park and the Monument Upwarp, which indicate rapid unloading began sometime between 10 and 4 Ma, resulting in between 1.5 and 3 km of exhumation (Hoffman et al., 2011). This is consistent with paleosurface reconstructions and apatite fission track and apatite U/Th-He ages (Pederson et al., 2002; Lazear et al., 2013). The post-Colorado River integration unburdening is particularly important to this study because it places a maximum age < 4 Ma on the relic surface (where Cedar Mesa sandstone and Lower Cutler beds outcrop) used for paleo-profile reconstruction.
Figure 3.3. Study area physiographic classification and bedrock geology. A) Classified
elevation classes can be grouped into four terrains: rugged, high relief slopes leading to
the Abajo mountains (white and pink); low-relief Beef Basin paleo-surface (orange);
horst and graben (yellow); and deep canyons adjacent to the Colorado River (green).
Note major knickpoints separate the deep inner canyons from the horst and graben-
dominated parts of the landscape. These knickpoints also correspond with the carbonate-
rich Lower Cutler and Honaker Trail lithologies, shown in B), surface geology (adapted
from Doelling, 2006). Imperial Canyon lineament, noted in both figures, roughly
coincides with local southern extent of Paradox salt pinchout.
Salt tectonics and Needles fault zone deformation

Removal of overburden via Colorado River incision permitted the subsurface Paradox salt to move downdip on the Monument Upwarp. Salt deforms plastically when under sufficient stress and this ductile deformation is expressed as flow of the salt that can reach rates of decimeters/year in some settings. The addition of groundwater will accelerate this rate by lowering coherence within the salt; therefore areas in the Needles fault zone where surface water penetrates have been hypothesized to deform at higher rates than other areas (Dr. Karl Mueller, pers. comm.) Modern subsidence and extension occurring in the Needles fault zone is occurring at a rate of 0.5—3 mm/yr (Furuya et al., 2007). Highest rates of deformation occur on the southeast and southern end of the array, and generally support models of eastward propagation of graben away from the Colorado River through time. The details of exactly how, in what spatial pattern, and at what long-term rates this deformation has occurred continue to drive research (e.g. Alken et al., 2013; K. Mueller, pers. comm.).

Tributaries to the Colorado River in Cataract Canyon have been diverted, captured, and defeated by growing faults; however, the uppermost portions of the three main streams (Butler Wash, Cross Canyon, and Gypsum Canyon) appear to be mostly outside of the influence of salt deformation (Fig. 3.3; Huntoon, 1982b; Trudgill, 2002). This permits the use of the geometry of these upper portions for use in reconstructing paleo-profiles. The Results section of this chapter will discuss the degree to which these uppermost portions are actually insulated from baselevel fall due to mainstem incision and salt-related deformation.
**Stream longitudinal profile metrics**

The concept of a smoothly concave, equilibrium profile of elevation as a function of distance downstream for a river channel is based partly on observation but also on theory (e.g. Mackin, 1948). Continuity in the longitudinal profile is governed in part by the tendency of a stream to do the minimum amount of work in order to reach its baselevel, and to distribute work evenly along its length (Langbein and Leopold, 1964). The ability of the stream to do work, such as transport sediment or incise bedrock is expressed as stream power, $\Omega$, which is a function of discharge ($Q$) and slope ($S$) as well as the density of water ($\rho$) and acceleration due to gravity ($g$):

$$\Omega = \rho g Q S$$  \hspace{1cm} (1)

Invoking the mechanism by which streams erode their beds and transport material and substituting contributing area as a proxy for discharge yields the stream power erosion relation:

$$E = k A^m S^n$$  \hspace{1cm} (2)

where rate of erosion ($E$) is a function of contributing area ($A$), slope ($S$), a constant that accounts for numerous geometric/hydrologic characteristics and assumptions regarding expressing erodability ($k$) (set largely by bedrock strength), and exponential constants $m$ and $n$, which capture elements of channel geometry and basal shear stress. Assuming a steady-state profile or stream segment where incision ($E$) and uplift ($U$) are equal allows equation 2 to be rearranged to

$$S = k_s A^{-\Theta},$$  \hspace{1cm} (3)
known as Flint’s law (Flint, 1974), where slope at any given place in a channel is set by the steepness index, \( k_s \), as well as drainage area \( (A) \) modulated by the concavity index, \( \Theta \). \( K_s \) is equal to \( (U/k)^n \) and \( \Theta \) is equal to \( m/n \).

In practice, \( \Theta \) and \( k_s \) are determined from the slope and y-intercept, respectively, of the trend of slope against contributing area in a log-log plot calculated from a digital terrain model (Fig. 3.4 inset). Below contributing drainage area of \( 10^5 \) m\(^2\), colluvial transport occurs, and above \( 10^7 \) m\(^2\), channels tend to be alluvial (transport limited). Comparison of steepness values from different profiles is possible when they are normalized to a reference concavity, \( \Theta_{\text{ref}} \), which is typically determined by a weighted averaging of concavities across the study area (Snyder et al., 2000; Kirby et al., 2003). The resulting normalized steepness index, \( k_{\text{sn}} \), produced for each reach permits comparison between drainages of different size. Another key modification to equation (3) addresses the assumption that drainage area is a simple, linear proxy for discharge. This assumption breaks down for strong orographic situations and desert rivers like in the semiarid Colorado Plateau (Tucker and Bras, 2000; Roe et al., 2002). A more accurate normalized steepness index, \( k_{\text{qsn}} \), arises when the flow-accumulation grid used to calculate contributing area in GIS is weighted to simulate real precipitation runoff patterns in a catchment using climate data (Pederson and Tressler, 2012).

Steepness anomalies in long profiles form due to changes in climate, baselevel, sediment supply, and geology (Whipple and Tucker, 1999; Whipple, 2004; Wobus et al. 2006). These changes alter stream slope, discharge, and/or sediment size, which become manifest as anomalies in or deviations from the idealized concave-up longitudinal profile.
Fig. 3.4 – Stream longitudinal profile example showing adjustment of profile due to baselevel fall. Inset shows how concavity (θ) and steepness index (k_s) are determined by regressing through log slope and log contributing area empirical data. Note that concavity is positive at the convexity (red circle), where the adjusted channel abruptly transitions to adjusting channel. Modified from Snyder et al. (2000).
Sometimes these anomalies are transient, as when a change in discharge (due to stream capture, for example) or baselevel initiates channel adjustment. Knickpoints can also be maintained in a quasi-stable state by resistant bedrock lithology and/or by increased sediment load (where a side canyon delivers regular debris flows, for example). Different $k_s$ and/or $\Theta$ values are determined for each segment, typically separated by knickpoints (Wobus et al., 2006; Harmar and Clifford, 2007). Because steepness index varies as a function of uplift rate ($U$) and erodibility ($K$), high values may indicate relative uplift if erodability is held constant along the stream profile; alternatively they may point to changes in erodability (i.e. lithology) if uplift is assumed to be constant. Baselevel fall can be substituted for uplift. The spatial distribution of knickpoints or $k_{sn}$ values has been used to reconstruct baselevel change, uplift history, and patterns in lithology (Crosby and Whipple, 2006; Pederson and Tressler, 2012; Miller et al., 2012).

**METHODS**

Spatial analyses and extractions were conducted in ArcGIS 10.1, MATLAB, and Excel (Microsoft Excel, 2003; ArcMAP, 2012). All analyses were run on 10-m DEM grids downloaded from the National Elevation Dataset, which comprises digitized 7.5’ USGS topographic maps created in 1981 and corrected/inspected in 1999 (Gesch et al., 2002; Gesch, 2007; [http://ned.usgs.gov/usgs_gn_ned_dsi/viewer.htm](http://ned.usgs.gov/usgs_gn_ned_dsi/viewer.htm)).

Analyses were undertaken to determine $\Theta$, $\Theta_{ref}$, $k_s$, $k_{sn}$, $k_{qsnn}$, basin ratio of volume to area (RVA), and hypsometric integral (HI). A working dataframe using the UTM Grid NAD 83 Zone 12N projection was used.
Longitudinal profiles

The Stream Profiler tool, developed to examine longitudinal profile metrics (freely available on geomorphtools.org), was used to extract and calculate metrics from longitudinal profiles for seven drainages within the Needles fault zone that drain to the Colorado River (Wobus et al., 2006; Whipple, et al., 2007). Inputs to the tool were a 10-m DEM of the study area and flow accumulation (FAC) grids. DEMs were projected and mosaiced in ArcGIS prior to conversion to ASCII and use in the profiler tool. FAC grids were generated using a partially filled DEM that preserved the real sinks present in the Needles fault zone. Precipitation-scaled flow accumulation (FAC) grids were generated in ArcMap using 30-year climate data from PRISM (http://www.prism.oregonstate.edu/). Precipitation data were projected as a grid, which was resampled to the same cell size as the 10-m DEM and clipped (Appendix D). Values were then normalized to the maximum precipitation value for the study area (653 mm/yr) so the maximum precipitation value = 1 on the scaled grid. The resultant grid was input to the flow accumulation tool, resulting in an adjusted flow accumulation raster.

Profiles were smoothed using a 100-m moving average window and elevations were sampled along 10-m contour intervals. These parameters were selected after sensitivity analyses (see Appendix D for details). Channel heads were delimited by a minimum accumulation of 1000 cells (~90000 m²) for the regular FAC grid, and 300 cells (26,100 m²) for the precipitation-scaled FAC grid. Channel heads were confirmed by visual inspection of aerial photos (see Figure 3.16). A reference concavity of 0.4 was selected based on concavities of other streams in the Colorado Plateau, as well as concavities of the upper reaches of the streams. Outputs k_sn and k_qsn were overlain on
terrain and geologic maps, and knickpoints were checked against mapped faults and lithology contacts and air photos.

Longitudinal profile metrics were also calculated in Excel for the three largest drainages, both as a check against the profiler tool output and in order to model paleo-profiles. Elevation and flow accumulation values were extracted every 50 m along streamlines created from flow accumulation paths in ArcMap. Once in Excel, contributing area, distance from mouth, and slope were calculated for each point. Contributing area (A) was determined by multiplying the number of cells contributing to a point by the 86.86 m² of a 9.32 x 9.32 meter cell. Distance from the stream mouth (D) was determined by summing the 50-segments between the point and the mouth. Slope was determined at each point, n, over a 200m, interval:

\[ S_n = \frac{Z_{n+2} - Z_{n-2}}{D_{n+2} - D_{n-2}} \]  

Slope was plotted against A in log-log space and power law regressions revealed reach concavity (exponent on area) and steepness index (y-intercept) (see Eqn. 3).

**Paleo-stream projection**

Idealized paleo-stream profiles were generated based on concavity, steepness, and elevation values from the upper, relict reaches of each of the three major drainages in the study area. Concavity and steepness indices were derived from several regressions through the slope-area plot of the upper channel. Metrics were chosen based on best fit (R²) and best visual fit to the relict channel geometry. Contributing area and chosen best
fit $\Theta$ and $k_s$ values were input to Flint’s equation (Eqn. 3) to calculate slope ($S$) which was in turn input into the following relation,

$$Z_{\text{new}} = Z_p - (S \cdot d)$$

(5)

where $Z_p$ is the elevation of the point upchannel a distance of $d$. Every point in the profile, with the exception of the highest, received a “new” elevation, which is plotted against distance to the channel mouth to generate model profiles. Finally, elevation values along modern profiles were subtracted from modeled paleo-elevation values, resulting in a residual that was analyzed with respect to rates of incision and modern subsidence measured in other studies.

**Hypsometric integral and RVA**

The relationship between slope and area within a catchment is described by the hypsometric integral, HI, and it has been used to gauge the relative maturity of a basin, as well as dominant transport processes (Strahler, 1952; Willgoose and Hancock, 1998). It is the ratio of mean relief to total relief:

$$HI = \frac{(Z_{\text{mean}} - Z_{\text{min}})}{(Z_{\text{max}} - Z_{\text{min}})}$$

(6)

DEMs clipped to seven study catchment boundaries were input to a hypsometry tool, available from the ESRI website (Davis, 2010). The output of proportional area to proportional elevation was plotted in Excel to produce hypsometric curves. Mean, min, and max elevations for input to the HI equation were extracted with the Zonal Statistics tool in the Spatial Analyst toolbox in ArcGIS.

Relative tectonic activity (or baselevel drop) between basins may be expressed in the ratio between catchment volume and planimetric area, RVA, which can also be
thought of as mean erosion depth (Frankel and Pazzaglia, 2006). Catchment area was extracted with the Zonal Statistics tool, while volume was a multi-step process: first, a triangular irregular network (TIN) was generated to cap each catchment. This surface was then converted to a raster and a difference grid was calculated. Values from the differenced raster were also used to generate total relief along stream profiles.

RESULTS

_Catchment Metrics_

Seven Colorado River tributary streams and catchments, which traverse the Needles fault zone, were assessed for topographic metrics (Table 3.1; Figure 3.5). Of the catchment-wide terrain measurements, some simply scale with overall size of the drainage basin too much to be very useful. For example, area and relief track one another nearly perfectly, which is expected since the largest streams drain the highest terrain, and the baselevel of all streams varies by only 50 m. It also follows that the streams draining the highest terrain

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (km²)</th>
<th>Relief (m)</th>
<th>HI</th>
<th>RVA</th>
<th>k_sn</th>
<th>k_qsn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum</td>
<td>309</td>
<td>1704.5</td>
<td>0.55</td>
<td>153.7</td>
<td>36.1</td>
<td>31.7</td>
</tr>
<tr>
<td>Red Lake</td>
<td>147.7</td>
<td>1081.7</td>
<td>0.54</td>
<td>125.3</td>
<td>18.9</td>
<td>14.7</td>
</tr>
<tr>
<td>Cross</td>
<td>47</td>
<td>1004.0</td>
<td>0.67</td>
<td>52.6</td>
<td>31.7</td>
<td>25.2</td>
</tr>
<tr>
<td>Imperial</td>
<td>32.6</td>
<td>826.1</td>
<td>0.73</td>
<td>52.5</td>
<td>36.8</td>
<td>27</td>
</tr>
<tr>
<td>Elephant</td>
<td>27.3</td>
<td>724.5</td>
<td>0.55</td>
<td>56.4</td>
<td>12.5</td>
<td>8.7</td>
</tr>
<tr>
<td>Y</td>
<td>11.3</td>
<td>627.5</td>
<td>0.58</td>
<td>56.6</td>
<td>16.7</td>
<td>11.5</td>
</tr>
<tr>
<td>Tilted</td>
<td>9.9</td>
<td>686.0</td>
<td>0.64</td>
<td>57.3</td>
<td>45.6</td>
<td>36</td>
</tr>
</tbody>
</table>

_Table 3.1 Topographic Metrics_
Figure 3.5. Study catchments’ HI values and measured rates of deformation. A) Line of sight (LOS) change with respect to satellite position modified from Furuya et al. (2007). Positive change is subsidence and negative change is uplift. Catchment outlines are overlaid in white. B) Catchment locations color coded by hypsometric integral. Star shows location of photo in Figure 3.9. C) Hypsometric curves plotted for the seven catchments with HI values. Colors match those in B).
and having the volumetrically largest inner gorges, Gypsum and Red Lake, would have highest RVA values as well. Furthermore, low and relatively uniform RVA values for Cross, Imperial, Elephant, Y, and Tilted canyons may be because all are situated in the zone of subsidence and faulting due to salt deformation, which has decreased overall relief. This effect is most exaggerated in Cross and Imperial Canyons, which have the lowest RVA values, despite being the third and fourth largest catchments.

Hypsometric and gradient indexes, on the other hand, do seem to vary in a coherent and meaningful way. Normalized hypsometric curves, plotted in Figure 3.5C, reflect the topographic sub-provinces outlined above and in Figure 3.3A. The curves’ shapes show a broad and high plateau dominating topography (the Beef Basin paleo-surface/horst and graben zone from Fig. 3.3A) with a steep lower section leading to the Colorado River gorge (inner gorge from Fig. 3.3A). Some of the catchments have HI near 0.5, indicating they are relatively maturely developed, but three have higher values of 0.64-0.73, suggesting a “youthful” erosional state, or being in a state of adjustment. The relatively youthful, high values of HI in Imperial, Cross, and Tilted canyons may reflect active deformation, because they correspond spatially to areas of highest subsidence rates measured by Furuya et al. (2007) (Fig. 3.5A).

Overall drainage-averaged \( k_{\text{sn}} \) and \( k_{\text{qsn}} \) steepness indices likewise vary across the study area with a potentially meaningful pattern (Table 3.1, Fig. 3.6). We focus on the precipitation-adjusted \( k_{\text{qsn}} \), inasmuch as it should more accurately reflect the local hydrology. \( k_{\text{qsn}} \) values are lower than \( k_{\text{sn}} \) values, which is expected because the former utilizes a downward-adjusted FAC grid. But \( k_{\text{qsn}} \) is also more variable and results in a slightly different ranking of catchments by overall drainage steepness (Table 3.1).
Figure 3.6. Normalized steepness index ($k_{qn}$) values by reach. Inset log-log slope-area plot of Gypsum Canyon (pink outline on map) has slope and y-intercept of solution to each reach. Highest values occur within inner gorges of tributaries nearest the Colorado River and in the upper reaches of Gypsum headwaters. The former reflect resistant lithology of the Honaker Trail and Lower Cutler beds limestones. Upper Gypsum steep zones occur at the transition to the upper Cedar Mesa sandstone.
Gypsum catchment has a high steepness index, due to anomalous steepness in all reaches. Of the streams draining smaller catchments, Tilted, Imperial, and Cross Canyons have notably higher steepness, and these are the same three with high HI (Fig. 3.5B, C). All four of these high kqsn drainages are at the south end of the study region, consistent with more active deformation there.

**Long profile metrics**

Plots of channel elevation against distance from headwaters to mouth for the three largest drainages show that the three major streams have three reaches separated by two clear and large knickpoints (Fig. 3.7 A, B, C). Gypsum Canyon has a third, higher, and very prominent knickpoint not shared by the other two streams, and therefore a fourth reach. Concavity and normalized steepness indexes were calculated for each reach based on slope-area plots (based on both unscaled and precipitation-scaled contributing area grids). Reach definition was done several times for each stream, along a spectrum from broad (separated by major knickpoints) to fine (separated by ~10m knickpoints) in order to test channel metrics’ sensitivity to reach definition. It was found that results didn’t vary appreciably (Appendix D), and therefore the broad reach designation is used for ensuing discussion, as it is most conducive to comparison between channels.

Regressed values for concavity become irrationally high in lower reaches as the drainages enter the inner canyon and approach the Colorado River gorge. This is an artifact of there being only very small increases in discharge/contributing area in these unusual lower canyon reaches, and the few datapoints stack upon one another in the log-
Figure 3.7. Longitudinal profiles of A) Gypsum Canyon, B) Cross Canyon, and C) Butler Wash/Red Lake Canyon with mapped and inferred bedrock geology, structure, and mapped faults. Reaches R1, R2, and R3 in each profile are delimited with bars, which are labeled with the reach name, concavity, and normalized, discharge-scaled steepness index ($\Theta, k_{qs}$). These metrics were derived from log-log slope-area plots generated in MATLAB. Note Paradox evaporate domes at mouths of Cross and Red Lake Canyons and Monument Upwarp anticline.
A  GYPSUM

B  CROSS

C  BUTLER/RED LAKE

KEY

- Pc  Permian Cutler Fm
- Plc  Permian Lower Culter
- IPh  Pennsylvanian Honaker Trail Fm
- IpP  Permian Paradox Fm
- Quaternary alluvium
- Faults
log plots (e.g. Figs. 3.6, 3.8). Thus we focus on reach-scale steepness indexes and discuss in detail the concavity measurements of only the upper reaches here.

Reach 1 (R1), below the lowest knickpoint, is 7 km long in Gypsum Canyon, 5 km in Cross Canyon, and 4 km along lower Butler Wash in Red Lake Canyon (BW/RL). In Gypsum Canyon, the R1 knickpoint occurs in the limestone of the Honaker Trail Formation (Fig. 3.7). In Cross and BW/RL Canyons, it is held up in the conformably-overlying Lower Cutler beds, a transitional and heterogeneous unit consisting of carbonate cemented sandstone, limestones, and some shale (Figs. 3.6, 3.7, 3.9). Regardless, in all cases the knickpoints in the steep R1 relate to resistant limestone beds. The rapid, recent incision of Cataract Canyon has propagated upstream in tributaries, and appears to be influencing this reach of the tributaries, as three streams have very high normalized steepness index values in this lower reach (Table 3.1; Figs. 3.6, 3.7, 3.8).

Reach 2 (R2) is situated between two major knickpoints and is 9, 10, and 7 km long for Gypsum, Cross, and BW/RL Canyons, respectively. In Butler Wash and especially Cross Canyon, it coincides with the horst and graben terrain and has moderately high steepness index values (between those of R1 and R3 on these streams). Observations of modern deformation in the Needles fault zone from Furuya et al. (2007) show that there is subsidence across both of these streams, though not at Gypsum Canyon, because the subsurface salt pinches out just south of the Imperial Canyon lineament (see Fig. 3.5A). R2 in Gypsum is distinctive for its slight negative concavity (it is straight to slightly convex) and its very high $k_{qns}$ values, matching those from the rugged lower gorges of R1 (Fig. 3.7). This is consistent with the greater knickzone of R2
Figure 3.8. Log-log slope-area plots of Gypsum, Cross, and Butler Wash/Red Lake Canyons output by MATLAB. Concavity, $\Theta$, is the calculated slope of each regression line. Steepness index, $k_{qsn}$, is the y-intercept of each line. Longitudinal profiles on right. Note that concavity is largely dependent upon selected regression limits. Note near-vertical slopes of regression lines through largest area portion of each stream.
Figure 3.9. 120-meter Lower Red Lake Canyon knickpoint, looking upstream (northeast) from the south side of the canyon. Resistant carbonate beds of the Honaker Trail Formation form cliffs and maintain the knickzone, while interleaved shale and mudstone offers less resistance to weathering.
in Gypsum being undampened by subsidence, unlike the R2 in Cross and BW/RL, which has adjusted to a concave shape. A convex R2 in Gypsum Canyon is also likely maintained by the interbedded, resistant limestones of the Lower Cutler (Fig. 3.7). It is notable that the large knickpoint defining the upstream edge of this reach along Butler Wash in Red Lake Canyon (mile 11, Fig. 3.7C) lies downstream of the edge of salt-related deformation. Yet the faulting is clearly producing smaller knickpoints upstream, in the lower part of R3, as well. This implies that there may be salt deformation in R3 of BW/RL. If R2 were defined to include these smaller knickpoints, it would be similar in length to the other two (10 km). This distance is most likely indicative of the approximate location of the edge of salt deformation, and therefore the approximate position of the Meander Anticline axis.

In reach 3 (R3), the streams traverse a shared, correlatable topographic surface, named in this work the Beef Basin paleo-surface (Figs. 3.5B, 3.10). R3 is cut into Lower Cutler strata, has relatively low steepness indexes, and contains stretches that cross Quaternary alluvium (Fig. 3.7). Because it appears to be in equilibrium with the relict Beef Basin paleo-surface, R3 was utilized for modeling paleo-profiles. The absence of faulting in Gypsum and Cross Canyons seems to validate this approach; however, the presence of two structures in the headwaters of BW/RL Canyon suggests that more of its profile is affected by salt deformation (Figs. 3.7C, 3.10). Furthermore, the Beef Basin paleo-surface is dendritically incised in upper BW/RL Canyon, and the surface contiguous with Cross and Gypsum drainages may only encompass a small part of R3 in BW/RL Canyon (Fig. 3.10).

Finally, while there are not structures mapped in this reach of Cross Canyon, it is
Figure 3.10. Annotated orthophotograph of upper Gypsum, Cross, and BW/RL Canyons. R3 channel heads are noted with red arrows. Beef Basin paleo-surface is outlined in solid orange where clear, and dashed orange where uncertain. Drainage divides between the three catchments are marked in blue. Note the E-W trending graben of the Imperial Canyon lineament in upper BW/RL Canyon.
clear from the geologic map that R3 of this stream actually follows the Imperial Canyon lineament (which is mapped in upper BW/RL Canyon). This explains the Quaternary alluvial fill in this reach of Cross Canyon: it is actually flowing down a filled graben axis. Therefore, while R3 crosses appear to cross a shared paleo-surface and be in equilibrium in each stream with that paleo-surface, the assumption that the paleo-surface is itself wholly undeformed appears to be flawed. This will be discussed further in the Paleo-Profiles section of this chapter.

**Reach 3 metrics**

Concavity and normalized steepness values from R3 of each stream were used as a starting point for modeling paleo-profiles. R3 metrics output from MATLAB and Excel slope-area plots were used to generate paleo-profiles, which were then assessed for accuracy based on the fit of the regression ($R^2$) and visual matching (Figures 3.11, 3.12, 3.13). Discrepancies arose between the two methods because MATLAB computes reach metrics based on equal intervals of elevation drop (in this case, 10 m), while the methodology employed in Excel relied on sampling at regular channel longitudinal distance intervals (50 m). The advantage afforded by the stream profiler tool is that choosing regression limits is efficient, so reach boundaries can be fine-tuned before saving a fit. On the other hand, modeling in Excel afforded the freedom to adjust the sampling interval to capture the most data without being redundant. In Excel, a sampling distance of 500 m was used to determine concavity and steepness index for Cross and Gypsum Canyons based on these sensitivity tests (Figure 3.14). BW/RWL Canyon, however, required a tighter sampling interval to capture the uppermost reach metrics, and
Figure 3.11. Gypsum Canyon R3 metrics determination and long/paleo-profile plots. A) Regressions through slope-area data points for both precipitation-scaled and unscaled drainage areas (DA, x-axis). Best-fit equations for each population are colored to match regressed line. Each point set is complimentarily colored where lighter colors (cerulean, orange, green) correspond to points based on scaled flow accumulation values and darker colors (navy, red, forest green) identify points based on unscaled flow accumulation values. Note good agreement of solutions with data ($R^2 = 0.76—0.87$). B) Paleo-profiles calculated using concavity and steepness index metrics determined in A, as well as metrics from the MATLAB stream profiler tool. Lower plot is entire profile and upper plot shows the top of R3 from 33—15 km from the mouth. Paleo-profile with greatest fidelity to present-day profile was constructed from $\theta = 0.44$, $k_s/k_q = 32/33$ acquired in the “R3 scaled” and “R3 unscaled” delimitation (green colors). Note that for Gypsum Canyon, the difference between using scaled and unscaled drainage area data is negligible.
Figure 3.12. Cross Canyon R3 metrics determination and long/paleo-profile plots. A) Regressions through slope-area data points for both precipitation-scaled and unscaled drainage areas (DA, x-axis). Darker colors are based on raw flow accumulation data; lighter colors are from precipitation-scaled data. Best-fit equations for each population are colored to match regression line. B) Long profile plot with paleo-profiles using metrics from regressions in A and metrics extracted in the MATLAB stream profiler tool. Lower plot shows entire profile, upper shows the profile between 22 and 12 km from the stream mouth. Best-fit metrics from “R3 - scaled” ($R^2$ of 0.92) used to construct paleo-profiles were $\theta = 0.41$, $k_s = 4.8$. For the “R3” reach plotted in Excel, the paleo-profiles generated with metrics from both scaled and unscaled points are nearly identical. Note that the scaled MATLAB fit is actually convex; this is a function of the point distribution being shifted left (toward smaller drainage areas) when a scale FAC grid is used.
Figure 3.13. Butler Wash/Red Lake Canyon R3 metrics determination and long/paleo-profile plots. A) Slope-area plots for select reaches near the channel head showing effect of sampling interval and scaled vs. unscaled DA. Data populations with high slopes (blue and purple) were sampled every 50 m; those with low slopes (red and green) were sampled every 500 m. Parallel light blue and pink data populations (and regressed lines) are fit to unscaled and scaled populations, respectively. Regression equations and $R^2$ are colored to match lines and point populations. Note that agreement between plotted data and regression is moderately good, though not as good as in Gypsum and Cross Canyons. ($R^2 = 0.07—0.78$). B) Long profile plots with paleo-profiles built from metrics determined in A and metrics derived from slope-area plots in MATLAB. Lower plot is entire profile, upper plot is 37—35 km from mouth. “R3 fit-scaled” line has the best visual fit for the entirety of R3 and the best $R^2$ value. Numerous knickpoints in upper part of channel impeded finding a good fit over a long distance. The “Visual Fit” (“R3 Upper”) metrics are based on the slope and y-intercept of a line through points sampled every 50 m in the headwaters of BW/RL. “R3-unscaled” and “Visual Fit” (“R3 Upper) were used for paleo-profile projections in Figure 3.14.
Figure 3.14. Gypsum Canyon example sensitivity testing. A) Degree to which sampling interval and smoothing affect long profile resolution. Real knickpoints (confirmed in orthophoto examination) are smoothed out by averaging elevations over 500 m, but not over 200 m. B) Slope-area plot for data points from profile with elevations sampled every 500 m. C) Slope-area plot for data points from profile with elevations sampled every 250 m. Note population of points present in C), but not B) at where the contributing drainage area is between $10^7$ and $10^8$ m$^2$. This point-stacking in C), produced by oversampling of data, depresses the slope of a regression line, thereby reducing measured concavity. Note that data points based on the scaled flow accumulation grid shift left and will tend to have slightly higher concavities.
A

Gypsum Long Profile Sampling Sensitivity

Elevation (m ASL)

Distance from mouth (km)

B

Gypsum SA plot
500m sampling interval

Slope (m/m)

DA (m2)

C

Gypsum SA Plot
250m sampling interval

Slope (m/m)

DA (m2)
paleo-profile results below are based on metrics that were determined using tighter sampling interval (Fig. 3.13). See Appendix D for sensitivity test results for all channels.

Gypsum Canyon had a paleo-profile concavity of 0.44 and a steepness index of 32. The Cross Canyon paleo-profile was generated using a concavity of 0.41 and a steepness index of 4.8. Two BW/RL Canyon paleo-profiles were generated. The first was based on a best fit of the entire designated R3. Resulting metrics were a concavity of 0.35 and a steepness index of 6. Utilizing this fit to construct a paleo-profile relies on the assumption that the Beef Basin paleo-surface extends throughout R3 of BW/RL Canyon. However, visual inspection of air photos (Fig. 3.10) and an unrealistically depressed paleo-baselevel elevation for BW/RL (Fig. 3.15) suggests that this assumption is faulty. Therefore, a second paleo-profile for BW/RL was generated based on best-fit metrics for the uppermost concavity in R3, which were a concavity of 1.63 and a steepness index of $5 \times 10^7$.

*Paleo-profiles*

When projected to above the present-day Colorado River, the paleo-profiles provide estimates of the paleo-baselevel, which can be parlayed into total incision at the mouth of each tributary (Fig. 3.15). However, applying paleo-baselevels in this fashion requires accepting several assumptions. First, the stream in R3 must be assumed to be in equilibrium with the surrounding landscape, i.e. that the present-day geometry is similar to the geometry of these headwaters when baselevel fall occurred. If this is true, the concavity would be expected to be near the reference concavity value (0.4), steepness indexes should be small, and the profile should be smoothly concave-up. Second, it must
Figure 3.15. Stream long profiles with incision-rates-scaled residuals and catchment elevations. A) At Gypsum Canyon, base level fall due to Colorado River incision began between 1.5—1.0 Ma. Paleo-baselevel projects to 1728 m ASL, for total incision of 599 m. No salt deformation is expected here. R3 begins at vertical green line. B) Cross Canyon has tighter incision-based residuals, placing initiation of baselevel fall due to incision between 1.7—1.4 Ma. Paleo-baselevel project to 1867 m ASL, for total incision of 693 m. R2 paleo-baselevel projects to 1690 m ASL, for maximum interpreted subsidence of 177 m. C) At Butler Wash/Red Lake Canyon, two paleo-profiles and resulting incision residuals are plotted (based on the “R3 Fit - scaled” and “R3 Upper” regressions from Figure 3.13). Greater spaced residuals based on the “R3 Upper” profile widen the range of when incision began to 2.0—1.6 Ma. Tighter residuals result from the flat-at-mouth “R3 Fit - scaled” profile, which constrains initiation of incision to 1.0—0.83 Ma. Projected paleo-baselevel for the first metric set is 1988 m ASL, and it is 1517 m ASL from a profile constructed with the second metric set. Total subsidence of R2-R3 is predicted to range from 176—647 m.
be assumed that all three streams’ R3 traverses the same terrain, i.e. a shared paleosurface. This can be tested by comparing concavities—they should be similar—and through qualitative geomorphic appraisal of the landscape. It must also be accepted that the stream’s catchment has remained steady over time, i.e. no stream capture. This can be explored by examining topography for wind gaps. The final assumption is that the land surface through which R3 meanders has not subsided (or uplifted) relative to the modern baselevel. If subsidence has occurred, the paleo-profile would project too low, and the present-day profile might show a dampened Colorado River incision signal. The ensuing discussion will explore the validity of these assumptions based on results reported in this section, and discuss the repercussions of holding to these stated assumptions.

Paleo-profiles were modeled in R2 as well, in order to estimate maximum subsidence due to salt removal. R2 in Cross and BW/RL Canyons traverses highly deformed (faulted) terrain, and has low steepness indexes. Given these observations, and work by others modeling salt evacuation/dissolution and subsidence (Furuya et al., 2007; Allken et al., 2013), we deemed it reasonable to expect that this reach of the long profile is affected by halokinesis. Attributing the existence of R2 in Cross and BW/RL Canyons predominantly to salt-related subsidence permitted us to estimate maximum salt-related subsidence. This was accomplished by modeling and subtracting the projected R2 paleo-baselevel from the projected R3 baselevel (Figure 3.15). Results are reported in Table 3.2.

The projected baselevel elevations for Gypsum and Cross Canyons are 1728 and 1827 m above sea level (ASL), respectively, which is internally consistent, as Cross Canyon is upstream of Gypsum Canyon and would be expected to debouch at a higher
### Table 3.2. Modeled profile estimates

<table>
<thead>
<tr>
<th></th>
<th>Θ</th>
<th>$k_a$</th>
<th>Paleomouth elevation (m)</th>
<th>Mouth elevation (m)</th>
<th>Total incision (m)</th>
<th>Subsidence (m)</th>
<th>Range of timing of initiation of incision (Ma)$^d$</th>
<th>Range of timing for initiation of subsidence (Ma)$^e$</th>
<th>Total incision to HTF (m)</th>
<th>Range of timing of initiation of subsidence (Ma)$^f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum</td>
<td>0.44</td>
<td>32</td>
<td>1728</td>
<td>1129</td>
<td>599</td>
<td>0</td>
<td>1.50 - 1.20</td>
<td>N/A - N/A</td>
<td>410</td>
<td>1.03 - 0.82</td>
</tr>
<tr>
<td>Cross</td>
<td>0.41</td>
<td>4.8</td>
<td>1867</td>
<td>1174</td>
<td>693</td>
<td>178</td>
<td>1.87 - 1.50</td>
<td>0.36 - 0.18</td>
<td>737</td>
<td>1.84 - 1.47</td>
</tr>
<tr>
<td>BW/RL-R3$^a$</td>
<td>1.63</td>
<td>50000000</td>
<td>1987</td>
<td>1181</td>
<td>806</td>
<td>646</td>
<td>2.02 - 1.61</td>
<td>1.62 - 0.65$^g$</td>
<td>345</td>
<td>0.86 - 0.69</td>
</tr>
<tr>
<td>BW/RL-R3$^b$</td>
<td>0.36</td>
<td>6</td>
<td>1595</td>
<td>1181</td>
<td>414</td>
<td>254</td>
<td>1.04 - 0.83</td>
<td>0.51 - 0.25</td>
<td>617</td>
<td>1.54 - 1.23</td>
</tr>
<tr>
<td>restored BW/RL - R3$^c$</td>
<td>0.36</td>
<td>6</td>
<td>1867</td>
<td>1181</td>
<td>686</td>
<td>526</td>
<td>1.715 - 1.372</td>
<td>1.05 - 0.53</td>
<td>617</td>
<td>1.54 - 1.23</td>
</tr>
</tbody>
</table>

Honaker Trail
Fmn. Elevation (m) Cross 1457           BW/RL 1250

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$^a$ Paleoprofile modeled using metrics from fit "R3 Upper" ("Visual Fit") (see Figure 13)

$^b$ Paleoprofile modeled using metrics from fit "R3 fit-scaled" (see Figure 13)

$^c$ 272 m is added to paleo-mouth elevation, full incision, and salt subsidence values

$^d$ Incision rates minima and maxima used were 400 and 500 m/Myr and were based on interpolated incision rates from Pederson et al. (2013)

$^e$ Subsidence rates used range from 500 - 1000 m/Myr, based on lowest rates observed/calculated by Furuya et al. (2007)

$^f$ Based on overburden removal method outlined in Results.

$^g$ Assumes profile from 1595 m to R2 paleo-baselevel (1341 m ASL) is dominated by subsidence signal.
elevation (Figure 3.15). In present day, the mouth of Gypsum Canyon is 45 m lower than the mouth of Cross Canyon, which is in turn 7 m lower than the mouth of BW/RL Canyon. The BW/RL Canyon paleo-profile would therefore be expected to project to >1827 m ASL. The paleo-profile based on the “R3 Upper” metrics projects to 1988 m ASL, which is appropriate. However, paleo-baselevel from the best fit based on another regression, “R3-unscaled” is modeled at 1595 m ASL, which is ≥232 m too low (the difference between the improperly low baselevel and the Cross Canyon paleomouth elevation). This implies that at least 272 m, and up to 393 m (the difference between the two modeled paleomouth elevations for BW/RL), of subsidence has affected R3. In order to test this reasoning, 272 meters was added to total incision depth, paleo-mouth elevation and subsidence for use in calculating the scaled values in Table 3.2.

Incision rates interpolated by Pederson et al. (2013) were used to scale the total baselevel fall estimated from the R3 projected profile. Results for Gypsum Canyon indicate it began to incise the Beef Basin paleosurface between 1.5 and 1.2 Ma, while Cross Canyon began to headwardly erode from a new baselevel sometime between 1.9 and 1.5 Ma. Initiation of incision for BW/RW Canyon happened sometime between 2.0 and 0.8 Ma (Table 3.2, Fig.3.15). This range is wide because it includes total incision calculated from both the R3 fits. If only the subsidence-corrected R3 Upper and R3 fit are used, the range tightens to 2.0—1.3 Ma. These estimates are based on the major assumption that late Pleistocene incision rates can be used as a longer term average.

Timing for initiation of subsidence (i.e. deformation by salt movement) was determined using the minimum modern rates of deformation that Furuya et al. (2007) measured are over the course of a decade. However, these rates may not represent long-
term rates, so a second method was used to determine whether results converged. This method assumed that subsidence became dominant once the Colorado River incision wave had propagated up each tributary to the Honaker Trail Formation. Thus, the difference in elevation between the Honaker Trail Formation and paleo-baselevel was scaled to incision rates to produce an estimate (Table 3.2). Calculated ranges for Cross Canyon were from 0.36—0.18 Ma. The range for BW/RL based on R2 subsidence only was 0.51—0.25 Ma. If additional subsidence is added (to account for the lowering of the entire profile), the range is pushed back to 1.1—0.5 Ma. Finally, if R3 is assumed to be dominated by salt subsidence, and the same rate is assumed, that timing for initiation of subsidence ranges from 1.62—0.65 Ma. Results from this overburden stripping method agree with those just reported for the R3 Upper paleo-profile. Otherwise the ranges do not overlap (Table 3.2). Unrestored BW/RL values determined from the “R3” metrics were in agreement with results from Cross Canyon. Thus despite large assumptions on how modern rates of subsidence represent longer-term rates, or when unloading along the canyon allowed lateral spread and salt deformation, initiation of deformation can be broadly constrained to 1.6—0.2 Ma.

DISCUSSION

Patterns in topographic metrics

Patterns of topography, particularly RVA, HI, and \( k_{hr}/k_{qsh} \), reinforce interpretations of how the dominant mainstem incision and salt deformation signals are spatially distributed. Apart from the largest catchments, whose RVA values are very high for
reasons outlined above, the highest values are unevenly distributed. Two small
catchments comprising just inner gorges have high RVA values because they are
dominated by mainstem incision. Of the three medium-sized catchments, only Elephant
Canyon catchment has a high RVA, because its mainstem-influenced deepening has not
been ameliorated by subsidence, as is the case with Cross and Imperial Canyons, which
have moderate RVA values.

HI mimics patterns of modern subsidence observed by Furuya et al. (2007), and
can at first glance might be interpreted to reflect extent of subsidence and deformation.
However, subsidence (lowering of stream elevations) would be expected to dampen HI.
Butler Wash/Red Lake is an excellent example of this principle: according to long profile
analysis, it has experienced the greatest amount of subsidence over time, and has the
lowest HI value. An alternative explanation is that in catchments whose channels are
dominated by adjustment to the baselevel fall signal due to Colorado River incision, HI is
high. However, the long profile form for the main channel in all seven catchments shows
a major knickpoint just upstream of the mainstem Colorado River, meaning all are
adjusting to a disturbance and are not graded. HI following deformation is not
straightforward, however: subsidence (the main way salt deformation is expressed here)
would be expected decrease elevations in middle reaches and lower HI. Perhaps transport
processes, another feature about which HI can provide insight, are the dominant influence
on HI in smaller catchments, which are more likely to be dominated by diffusive, rather
than fluvial, processes (c.f. Willgoose and Hancock, 1998).

Steepness patterns match areas closest to the Colorado River, suggesting
baselevel fall is the main influence on steepness in this landscape. However, lithology
cannot be ignored, as those reaches with high $k_{qan}$ values also coincide with resistant carbonate-cemented and limestone units. Furthermore, the steepness of these inner gorges and flashy nature of the streams has resulted in channels choked with large boulders. The transport-limited nature of the deepest portions of these canyons may also contribute to high steepness. The highest steepness anomaly values occur in undeformed Elephant Canyon, supporting the hypothesis that bedrock exerts a strong influence on steepness patterns.

Stream long profiles and paleo-profiles

Steepness index also varied considerably between the three main drainages that underwent long profile analysis. Gypsum Canyon had the greatest steepness anomaly for its upper reaches (R4 and R3), while Red Lake and Cross Canyons are considerably lower in their upper stretches. In R4 of Gypsum Canyon, lithology is the likely driver, as this portion of the stream drains Triassic sandstone, and these clastic rocks proximal to the Abajo Mountains have undergone mild contact metamorphism (Heylmun, 1958). Because the R3 for all three drainages traverses similar geology, the depressed steepness in Cross and Red Lake Canyons is likely due to salt-related subsidence. Paleo-profile models suggest that subsidence in this reach is likely in BW/RL Canyon (Fig. 3.14C). While there is not sufficient data in Cross Canyon to determine whether R3 has subsided, there is geologic evidence that it is affected by salt-related subsidence. The upper part of Cross Canyon aligns with the Imperial Canyon lineament, which manifests in surface geology as a graben in the R3 of BW/RL canyon.

The deep concavities in the two upper reaches of Gypsum Canyon (0.78 and 0.92)
are not atypical for high elevation terrain subject to ~50 cm annual precipitation (Zaprowski et al., 2005; PRISM, 2013). The shortened R3 used for paleo-profile modeling for Gypsum Canyon ($\theta = 0.44$) is similar to concavities for BW/RL (0.36) and Cross (0.40), as well as to other streams in the Colorado Plateau.

Agreement of the R3 best-fit concavities among the three study streams bolsters the argument that this reach drains a shared topographic surface (the Beef Basin paleosurface) with which each stream is in equilibrium. Additionally, the R3s in Gypsum and Cross Canyon have smooth, concave-up profiles that fit a typical description of a graded profile. R3 in BW/RL is problematic, though, as it contains numerous knickpoints. Moreover, qualitative geomorphologic observations suggest that the Beef Basin paleosurface has been left behind entirely by this drainage, save perhaps for the uppermost part of R3. If this is the case, it becomes challenging to compare this R3 remnant (referred to above as “R3 Upper”) with the R3s in Gypsum and Cross Canyons, as it has a very high concavity (1.63) and is less than 1 km long.

Other stated assumptions that require examination are that the streams studied today have retained their general shape, length, and drainage pattern through time. An examination of the present topography suggests that Cross Canyon may be separated from its original headwaters, which are now a part of the Gypsum Canyon network (Fig. 3.16) Additional observations include the clear diversion of parts of the R2s and the R1s in Cross and BW/RL Canyons by normal faulting. However, the capture and diversion of these streams appears to have happened long enough ago that they have integrated into their main channels.
**Incision and salt deformation**

When considering dominant influences on the present-day landscape configuration, it is important to recall that most of the exhumation of this area was accomplished over the preceding ~6 Myr, during which nearly 3 km of material was removed by erosion (Hoffman et al., 2011). The existence of the Beef Basin paleo-surface suggests that this exhumation happened in pulses, between which hillslopes and streams adjusted to new baselevel. Results of paleo/long profile modeling suggest that the most recent pulse of incision and subsequent—and ongoing—adjustment likely initiated between 2—1 Ma.

Whether this pulse has proceeded past the Confluence of the Green and Colorado Rivers has been a matter of uncertainty (e.g. Cook et al., 2009). The low HI value for Elephant Canyon, just upstream of the Confluence, suggests that this channel is close to equilibrium with its catchment. Moreover, the reach of Elephant Canyon above the knickpoint appears to be graded (Appendix D). The presence of a large knickpoint midway through the profile indicates that the baselevel fall signal, initiated by Colorado River incision, has affected the channel, at least to a certain point. This knickpoint coincides with and is likely maintained by resistant limestones in the Honaker Trail Formation. Geomorphic evidence from the field further upstream of Elephant canyon suggests that the Colorado River incision signal may be stalled not far upstream of the confluence, as the mouths of tributaries upstream lack fans and/or are submerged—in contrast to the active expulsion of sediment from the tributaries to the Colorado in Cataract Canyon.
Figure 3.16. Oblique view of the Beef Basin paleosurface (orange) with chosen channel heads for the three study channels. Channels are in solid blue. Hachured blue indicates Cross Canyon paleochannel. Note that the area previously drained by this paleochannel is now part of the Gypsum Canyon catchment, due to capture by a south-running tributary to Gypsum Canyon.
A passing wave of incision that propagates up the study streams from the Colorado River would be expected to manifest similarly in each profile, as lithology is the same across all three. Rates of incision, however approximate, would likewise be similar up the three tributaries. Therefore, comparing concavities and initiation of incision timing among the three is a check on quality of results. Because the R3 metrics from Gypsum and Cross Canyons are in good agreement, and their paleo-mouths project to internally consistent elevations (Table 3.2; Fig. 3.17), confidence in their paleo-profiles’ fidelity is increased (though possible stream capture and salt deformation of uppermost Cross Canyon remain as areas of uncertainty). The good agreement between Cross and Gypsum Canyons’ paleo-profiles can be used to determine which BW/RL paleo-profile is most accurate. Ranges of timing of initiation of incision overlap at 1.5 Ma. The BW/RL canyon incision estimate that best fits with this result, 1.72—1.37 Ma, comes from a paleo-profile constructed from the “R3 Fit – scaled” metrics, and corrected for R2 and R3 subsidence. Another area of agreement is in the R3 concavities: this modeled version of the BW/RL stream most closely matches the concavities from Gypsum and Cross Canyons. This result implies that the entirety of the BW/RL profile has been affected by salt subsidence, which is further supported by the low HI here, as well as the elevational trend in the stratigraphic contacts (Fig. 3.17).

If incision rates are assumed to be similar across the three study streams (a reasonable assumption, given their shared lithology, orientation, and topographic setting), then timing for incision of BW/RL should be latest. Again, the restored BW/RL-R3 and BW/RL-R3U profiles fulfill these expectations best. However, this criteria does not permit ruling out the BW/RL-R3U profile, as its calculated initiation of incision range overlaps
Figure 3.17. Comparison of present-day and modeled paleo-profiles for the three study streams. Modern profiles are thin lines, paleo-profiles are thicker lines. Modern day Colorado River is thickest line at base of figure. X-axis, distance from mouth, is color-coded to match each stream. Note two BW/RL profiles: hachured is unrestored R3-unscaled fit, and solid is restored (salt subsidence effects removed, indicated by black arrows). Simplified geologic boundaries are noted on each profile.
with that of Cross Canyon. As BW/RC is upstream of the other two streams, it is reasonable that incision would be delayed here, as the passing wave of mainstem incision could have been stalled on resistant units in the Lower Cutler beds and Honaker Trail formation. However, modeling results are broad enough that this level of detail is not resolvable.

There are multiple lines of evidence supporting the hypothesis that the BW/RL catchment and stream has been heavily influenced by salt removal. It is reasonable that total subsidence due to salt would be greatest in the BW/RL area, as the salt is mapped as 2-4x thicker there than at Cross Canyon, and it pinches out entirely just north of Gypsum Canyon (Condon, 1997). However, low modern rates of deformation observed by Furuya et al. (2007) around BW/RL ostensibly contradict this assertion (Fig. 3.5). One explanation is that most of the salt beneath BW/RL has been expelled, and there is less accommodation space. 3-D finite element modeling by Allken et al. (2013) support this idea: their best-fit models resulted in footwall blocks grounding out at the base of salt; in this case no further subsidence would be possible.

It should be noted that modeled elevations for the mouths of Cross and Gypsum Canyons suggest the river may have had a steeper slope at c.a. 1.5 Ma, when the most recent pulse of incision began. One possible explanation for this is lithology: the Gypsum Canyon paleo-profile terminates where Lower Cutler Beds used to be, and the Cross Canyon paleo-profile would have ended in the Cedar Mesa. Thus, a lithology transition would have occurred between these two mouths, coincident with a higher slope than today. In fact, this exact lithology transition (Cedar Mesa above knickpoint, Lower Cutler beds below) occurs in every tributary in the present day: KP 1 in Cross and BW/RL
Canyons, and KP2 in Gypsum Canyon. However, because the model parameters are insufficiently precise to account for that difference, it is difficult to draw any firm conclusions about paleo-slope.

Previous estimates of the timing of when the Needles fault array began to form range from 1.5 Ma—85 kyr (Biggar and Adams, 1987; Hintz et al., 2000; Trudgill, 2002). Our results narrow down that range to 0.2—1.0 Ma, which align with estimates from other workers. For example, Allken et al. (2013) recreated graben topography with the most fidelity after allowing their 3-D finite-element model to run for the equivalent of 0.350 kyr.

In summary, our results suggest that a passing wave of incision along the Colorado River began to propagate upstream through tributaries at about 1.5 Ma. This mainstem incision has most profoundly impacted the channel form and landscape attributes of the lowest third of the major tributaries, in the form of large knickpoints where the channels and catchments are adjusting to baselevel fall. Resistant lithologies contribute to the maintenance of these knickpoints. Halokinesis-induced subsidence and faulting began north of Gypsum Canyon as early as 1 Ma, and as late as 0.2 Ma.

Many uncertainties remain that future work can address. Modeling of the Beef Basin paleosurface in its entirety would provide a second methodology by which to determine paleo-baselevels for the study streams, and could help determine where zones of subsidence have affected long profile form. Additional long profile analysis of tributaries to the Colorado River in Cataract Canyon, especially those outside the zone of salt deformation, would provide a basis for additional paleo-profile modeling (provided those streams head in a paleo-terrain similar to the Beef Basin paleosurface). More datapoints
will provide the opportunity to either increase confidence in current incision initiation
timing estimates, or highlight areas of concern/uncertainty. Finally, lithologic
heterogeneity needs to be addressed in greater detail. Detailed geologic maps that break
out individual resistant beds could be generated, based on field work and air photo
analysis, which might help parse some of the smaller knickzones, as well as address
questions about profile form in the R3 of Red Lake Canyon, specifically.

REFERENCES

Allken, V., Huismans, R.S., Fossen, H., and Thieulot, C., 2013, 3D numerical modeling
of graben interaction and linkage: a case study of the Canyonlands grabens, Utah:


Baars, D.L., 1981, Tectonic evolution of western Colorado and eastern Utah, in 32nd
Field Conference, Western Slope Colorado, New Mexico Geological Society
Guidebook.

Baker, A.A., and Reeside Jr, J.B., 1929, Correlation of the Permian of southern Utah,
northern Arizona, northwestern New Mexico, and southwestern Colorado: AAPG

Barbeau, D.L., 2003, A flexural model for the Paradox Basin: implications for the

Biggar, N.E., and Adams, J.A., 1987, Dates derived from Quaternary strata in the vicinity
of Canyonlands National Park: Field Symposium, Guidebook of the Four Corners

Bradish, B.B., 1952, Geology of the Monumnet Upwarp: Geological Symposium of the
Four Corner Region, Four Corners Geological Society.

Clark, M.K., Schoenbohm, L.M., Royden, L.H., Whipple, K.X., Burchfiel, B.C., Zhang,
of eastern Tibet from large-scale drainage patterns: Tectonics, v. 23, p. TC1006,


Microsoft Excel, 2003, Redmond, WA, Microsoft.


PRISM 30 year, 2013.


CHAPTER 4

SUMMARY

Chapters two and three of this thesis report on geomorphic research conducted in the graben of Canyonlands National Park in southeastern Utah. A summary of these two chapters follows, with suggestions for future work that will address assumptions and advance the findings reported in this thesis.

Controls on sediment accumulation rates in closed graben basins

Robust models of drylands response to changing climate are still evolving, and this study sought to take advantage of small, internally-drained basins that have developed in the Needles fault zone of southeastern Utah. These basins have formed as a result of halokinetic-driven faulting in Permian sandstones and carbonates. Small streams draining the surrounding horsts deposit material to graben floors in alluvial fans. These basin-floor deposits are exposed in unusual fissures, here called swallow holes, that have opened in the basin-floor fill along graben walls or above hidden normal faults.

Four exposures, ranging from 4 to 13 m in height, were logged. Individual deposition events, hiatuses, erosional boundaries, and paleosols were broken out and described, and are represented in Appendix A. Optically stimulated luminescence (OSL) and radiocarbon (RC) samples were collected from exposures and provided age control on the stratigraphy.

Goldfish Hole (GH), one of the primary exposures studied, had 13.5 meters of exposure and sediment archives that extended from 16 ka to 3 ka. It had three hiatus-
separated depositional pulses, which were used to determine sediment accumulation rates, which ranged from 0.44 m/kyr during the late Pleistocene to 1.9 m/kyr during the middle Holocene. Sediment yield was nearly seven times greater during the middle Holocene than during the late Pleistocene. Late Holocene sediment yield was ~2 times as great as the late Pleistocene low. This shift to higher sedimentation after the Pleistocene-Holocene transition supports the dominant model that climate disturbance is a dominant control on drylands sedimentation.

However, sediment accumulation results from the other main study hole, Picture Canyon, unexpectedly reveal a pulse of rapid sedimentation during the relatively dry mid-Holocene Altithermal, from 5.8 to 3.8 ka. These ages bracketed nearly 9 meters of sediment, implying a very fast sediment accumulation rate of 3 m/kyr. The interval over which this rapid accumulation occurred does not correlate stratigraphically with the record in GF, which implies that local controls on sedimentation may exert greater control on the sediment record in these basins—at least over the timescales studied here.

Two smaller exposures were also studied, but only two age data points per exposure were deemed reliable, so sediment accumulation rates at each location were not a true regression. However, these preliminary results suggest that rapid sedimentation (~2 m/kyr) has occurred at least two locations in the Needles fault zone during the Pleistocene-Holocene transition, specifically with the onset of higher ENSO frequency. Additional, rapid sedimentation events later in the Holocene epoch may be likewise associated with climate perturbations such as the mid-Holocene Altithermal and the onset of the strengthening of the monsoon signal at ~3 ka. These speculations can only be borne out with study of additional internally-drained basins in the Needles fault zone.
The dynamic nature of the graben basins provides an alternative explanation for changing sedimentation rates through time. Sediment accumulation occurs in basin-floor fans, and simple avulsion of the fan channel may explain hiatuses; that is, sedimentation may be controlled by autogenic cycling within the fan. Yet another possible control is that basin floor subsidence due to salt evacuation/dissolution and/or groundwater removal, focuses deposition in a specific area, which appears as high sedimentation rates when exposed in a two-dimensional swallow hole.

**Chapter 2 Future Work**

The areas of greatest uncertainty—and promise—for the use of graben basins as natural laboratories where landscape response to climate change can be studied lies in the limited dataset. A greater diversity of catchment sizes and sediment record length must be captured, if questions of autogenic alluvial fan cycles in deposition are to be addressed. Collecting data from more sediment archives across the Needles fault zone will also permit statistical analysis of shared depositional pulses. Including more basins in this type of study will also help constrain the range of sedimentation rates and yields in the study area, which will help determine whether a climate-driven explanation is plausible, by permitting comparison with other desert catchments. Finally, the link between groundwater removal, as suggested by UGS work in central Utah, and swallow-hole development, can be explored by comparison of historical photos that show the growth of swallow holes and precipitation records (Knudsen et al., 2014).
Reconstructing landscape history using morphometric and stream longitudinal profile analysis

While the Needles fault zone has been extensively studied from a structural geology perspective as a model for normal fault development and analogue for inaccessible extensional zones, it has been little-studied from a geomorphic perspective. However, it is primarily a geomorphic feature, and offers an opportunity to use quantitative morphometric tools to better constrain patterns and timing of Colorado River incision and initiation of salt deformation.

Elevational classification permits delimitation of four mini physiogeographic provinces: steep inner gorges and slopes proximal to the Colorado River, a horst and graben zone, a low-relief bench with alluvial streams, and steep slopes leading to the Abajo Mountains. Landscape metrics including hypsometry, ratio of volume to area (RVA) and steepness index \( (k_{SN}/k_{QSN}) \) were applied to seven catchments of streams within the Needles fault zone. RVA was found to highlight canyons where the steep, Colorado River incision-dominated inner gorges had been stalled from further headward erosion—either due to encountering the horst and graben zone or because they were at the uppermost extent of the wave of incision. Hypsometric integral (HI) was found to positively correlate with modern rates of subsidence as measured by INSAR, though that finding is interpreted as mostly coincidental, as subsidence of the horst and graben zone would be expected to lower overall HI, as this zone coincides with the middle reaches of most catchments. Patterns of steepness anomalies reflected the Colorado River incision influence on channels and also coincided with resistant bedrock lithologies.

Longitudinal profiles for two sub-parallel streams draining across the four provinces (Cross and Butler Wash/Red Lake (BW/RL)), and a third sub-parallel stream
just south of the salt pinchout (and therefore outsize the zone of halokinetic influence) (Gypsum) were subdivided into three main, shared reaches. Reach metrics extracted using two different methodologies were concavity ($\Theta$) and steepness index. The three streams’ reach 3 (R3) traverses a shared surface, dubbed the Beef Basin paleosurface. Concavities for R3 were similar among the three streams, suggesting that the surface is a relict graded surface that has not yet “felt” the influence of Colorado River incision. It was initially assumed that the Beef Basin paleosurface was likewise unaffected by salt-movement-driven deformation; however both Cross and BW/RL Canyons exhibit evidence that this reach is affected, either by faulting, in the case of the former, or by subsidence and faulting, as in the case of the latter.

Nonetheless, R3 metrics were used to reconstruct the graded paleo-profiles that were assumed to exist at one time, before the most recent pulse of Colorado River incision began to erode the Beef Basin paleosurface. The elevation difference between each river’s paleo-profile and current profile was scaled to published Pleistocene incision rates in order to estimate when the mouths of these streams began to respond to baselevel fall. These estimates are in agreement with one another, and extend from 1.8—1.2 Ma. Total subsidence at the mouth of BW/RL Canyon was calculated to fall between 520—650 m and ~200 m at the mouth of Cross Canyon. Initiation of timing of salt-movement related deformation was estimated to be between 1.6—0.5 Ma. This constraint is tighter than those previously published (some of which are as young as 0.1 Ma) and agree with 3-D finite element modeling results published recently (Allken et al., 2013).
Chapter 3 Future Work

Future work would address key areas of uncertainty, such as whether the Beef Basin paleosurface was truly shared by all three streams. Corroborating the contiguity of the Beef Basin paleosurface would increase confidence in the use of R3 metrics to reconstruct paleoprofiles of the three main study streams. Moreover, it could be used to determine a paleo-baselevel for the three study streams, which would provide another means of determining the amount of subsidence at each stream’s mouth.
APPENDIX A

OSL Equivalent dose (D_e) distributions are shown plotted against probability. The sample number, facies classification, and depth are noted for each sample.

Goldfish Hole

USU-1557

Figure A.1. USU-1557 from cross-bedded sand, 2 meters from surface. A) Cumulative probability curve shows strong single peak and “tail” classically associated with partial bleaching.

Table A.1. USU-1557 rejection criteria and results

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Number</th>
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</thead>
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<tr>
<td>Number of samples run</td>
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<tr>
<td>Total accepted</td>
<td>18</td>
</tr>
<tr>
<td>Total rejected</td>
<td>29</td>
</tr>
<tr>
<td>Number with recycling ration &gt; 20%</td>
<td>14</td>
</tr>
<tr>
<td>Number with recuperation &gt; 10%</td>
<td>9</td>
</tr>
<tr>
<td>Number with D_e &gt; 1.1 x highest regen dose</td>
<td>3</td>
</tr>
<tr>
<td>Number with poor dose rate curve fit</td>
<td>3</td>
</tr>
</tbody>
</table>
Figure A.2. USU-1556 from a rippled sand 10 meters below the surface. Cumulative probability curve shows double peaks, suggesting two grain populations, and “tail” classically associated with partial bleaching.

Table A.2. USU-1556 rejection criteria and results

<table>
<thead>
<tr>
<th>Number of samples run</th>
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<td>Total accepted</td>
<td>19</td>
</tr>
<tr>
<td>Total rejected</td>
<td>11</td>
</tr>
<tr>
<td>Number with recycling ration &gt; 20%</td>
<td>11</td>
</tr>
<tr>
<td>Number with recuperation &gt; 10%</td>
<td>0</td>
</tr>
<tr>
<td>Number with $D_e &gt; 1.1 \times$ highest regen dose</td>
<td>0</td>
</tr>
<tr>
<td>Number with poor dose rate curve fit</td>
<td>0</td>
</tr>
</tbody>
</table>
**USU-1555**

![Cumulative Probability Curve](image)

Figure A.3. USU-1555 from a rippled to massive sand 11 meters below the surface. Cumulative probability curve shows a single peak with wide distribution and a significant “tail”.

**Table A.3. USU-1555 rejection criteria and results**

<table>
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<th>Category</th>
<th>Value</th>
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<tr>
<td>Total accepted</td>
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</tr>
<tr>
<td>Total rejected</td>
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</tr>
<tr>
<td>Number with recycling ration &gt; 20%</td>
<td>6</td>
</tr>
<tr>
<td>Number with recuperation &gt; 10%</td>
<td>0</td>
</tr>
<tr>
<td>Number with De &gt; 1.1 x highest regen dose</td>
<td>1</td>
</tr>
<tr>
<td>Number with poor dose rate curve fit</td>
<td>0</td>
</tr>
</tbody>
</table>
**USU-1554**

Figure A.4. USU-1554 from a cross-bedded sand at 13.3 meters depth from surface. Cumulative probability curve shows double peaks suggestive of mixing and significant skew, prompting use of the MAM age model.

Table A.4. USU-1554 rejection criteria and results

- Number of samples run: 43
- Total accepted: 23
- Total rejected: 20
- Number with recycling ratio > 20%: 14
- Number with recuperation > 10%: 1
- Number with $D_e > 1.1 \times$ highest regen dose: 1
- Number with poor dose rate curve fit: 4
**Picture Canyon**

**USU-1401**

Figure A5. USU-1401 from a cross-bedded, granuley sand 2 meters from the surface. Significant skew of the equivalent doses in the cumulative probability curve prompted the application of the MAM model to isolated grain population most likely to have been fully reset by sunlight.
Figure A.6. USU-1559 from a cross-bedded, granuley sand 5 meters from the surface. Distribution is nearly normal and the partial bleaching “tail” is absent; this sample was considered well-behaved.

Table A.5 USU-1559 rejection criteria and results

Number of samples run.........................41
Total accepted......................................18
Total rejected.....................................23
Number with recycling ration > 20%...........15
Number with recuperation > 10%...............6
Number with \( D_e > 1.1 \times \) highest regen dose........0
Number with poor dose rate curve fit..........2
Figure A.7. USU-1558 sampled from a cross-bedded, granuley sand bed 7 meters below the surface. Tight, normal distribution with a non-significant skew meant this was considered a well-behaved sample.

Table A.6. USU-1558 rejection criteria and results

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<th>Criterion</th>
<th>Results</th>
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<td>Total accepted</td>
<td>19</td>
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<tr>
<td>Total rejected</td>
<td>22</td>
</tr>
<tr>
<td>Number with recycling ratio &gt; 20%</td>
<td>14</td>
</tr>
<tr>
<td>Number with recuperation &gt; 10%</td>
<td>1</td>
</tr>
<tr>
<td>Number with (D_e &gt; 1.1 \times ) highest regen dose</td>
<td>3</td>
</tr>
<tr>
<td>Number with poor dose rate curve fit</td>
<td>4</td>
</tr>
</tbody>
</table>
USU-1400

Figure A.8. USU-1400 sampled from a rippled to massive sand 9 meters below the surface. At least bimodal distribution across a wide range of equivalent doses that are positively-skewed required the application of the MAM age model. These results were considered problematic enough to warrant exclusion from sediment accumulation rate calculations.
Cow Canyon

USU-1403

Figure A.9. USU-1403 from a cross-bedded sand, 1.5 meters from surface. Cumulative probability curve shows one strong peak and “tail” classically associated with partial bleaching. Histogram on right reveals that this tail actually comprises three separate dose populations, suggesting this sample has suffered mixing (most likely due to bioturbation).

USU-1402

Figure A.10. USU-1402 from a cross-bedded sand, 2.3 meters from surface. Cumulative probability curve shows one strong peak and “tail” classically associated with partial bleaching. Normal distribution is relatively tight otherwise.
**Bobby's Hole**

**USU-1405**

Figure A.11. USU-1405 from a weakly cross-bedded, granuley sand, 1.5 meters from the surface. Beds were somewhat bioturbated; the triple peaks in this equivalent dose distribution support that mixing has occurred.

**USU-1404**

Figure A.12. USU-1404 from a weakly cross-bedded, granuley sand, 1.5 meters from the surface. Beds were somewhat bioturbated; the triple peaks in this equivalent dose distribution support that mixing has occurred.
## APPENDIX B

Table. B.1. Radiocarbon data from University of California Irvine Keck AMS laboratory.

<table>
<thead>
<tr>
<th>14C sample (and abbreviation)</th>
<th>Locale</th>
<th>Position</th>
<th>14C age</th>
<th>Calibrated age range (yr)</th>
<th>Sample type</th>
<th>Probability</th>
<th>Calibrated age range</th>
<th>Age (cal kyr B2010)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCI-137302 C-02 GF Bed 49</td>
<td>2.2</td>
<td>2835 ± 25</td>
<td>2910 - 2883</td>
<td>one piece ch.</td>
<td>0.32</td>
<td>2970 - 2943</td>
<td>3.00 ± 0.07</td>
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<tr>
<td>UCI-137303 C-03 GF Bed 42</td>
<td>6.64</td>
<td>6615 ± 30</td>
<td>7597 - 7534</td>
<td>several piece ch.</td>
<td>0.32</td>
<td>7622 - 7597</td>
<td>7.56 ± 0.06</td>
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</tr>
<tr>
<td>UCI-137304 C-04 GF Bed 35</td>
<td>8.2</td>
<td>7225 ± 30</td>
<td>8051 - 7976</td>
<td>fibrous wood</td>
<td>0.96</td>
<td>8162 - 8158</td>
<td>8.09 ± 0.05</td>
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<tr>
<td>UCI-137305 C-05 GF Bed 31</td>
<td>8.97</td>
<td>7310 ± 30</td>
<td>8051 - 7976</td>
<td>several piece ch.</td>
<td>0.96</td>
<td>8162 - 8158</td>
<td>8.09 ± 0.05</td>
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<tr>
<td>UCI-137306 C-06 GF Bed 23</td>
<td>9.91</td>
<td>8245 ± 30</td>
<td>9181 - 9136</td>
<td>one piece ch.</td>
<td>0.32</td>
<td>9241 - 9196</td>
<td>9.28 ± 0.10</td>
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<tr>
<td>UCI-137293 C-93 PC Bed 49</td>
<td>3.08</td>
<td>5060 ± 40</td>
<td>5857 - 5808</td>
<td>one piece ch.</td>
<td>0.32</td>
<td>5892 - 5862</td>
<td>5.87 ± 0.10</td>
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<td>UCI-137294 C-94 PC Bed 47</td>
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<td>4735 ± 30</td>
<td>5348 - 5393</td>
<td>three piece ch.</td>
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<td>5408 - 5393</td>
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<tr>
<td>UCI-137295 C-95 PC Bed 46</td>
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<td>5168 - 5130</td>
<td>dozens piece ch.</td>
<td>0.26</td>
<td>5610 - 5533</td>
<td>5.72 ± 0.36</td>
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</tr>
<tr>
<td>UCI-137296 C-96 PC Bed 36</td>
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<td>5030 ± 30</td>
<td>5782 - 5736</td>
<td>dozens piece ch.</td>
<td>0.26</td>
<td>5828 - 5793</td>
<td>5.88 ± 0.09</td>
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<td>UCI-137297 C-97 PC Bed 26</td>
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<td>5530 ± 30</td>
<td>6382 - 6349</td>
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<td>UCI-137298 C-98 PC Bed 17</td>
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<td>5290 ± 30</td>
<td>6382 - 6349</td>
<td>dozens piece ch.</td>
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<td>6401 - 6399</td>
<td>6.38 ± 0.04</td>
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<tr>
<td>UCI-137299 C-99 PC Bed 8</td>
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<td>4910 ± 160</td>
<td>5610 - 5533</td>
<td>dozens piece ch.</td>
<td>0.18</td>
<td>5830 - 5633</td>
<td>5.72 ± 0.36</td>
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<tr>
<td>UCI-137300 C-00 PC Bed 6</td>
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<td>4925 ± 30</td>
<td>5780 - 5660</td>
<td>dozens piece ch.</td>
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<td>5851 - 5847</td>
<td>5.88 ± 0.09</td>
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<tr>
<td>UCI-137301 C-01 PC Bed L8</td>
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<td>5040 ± 30</td>
<td>5780 - 5660</td>
<td>dozens piece ch.</td>
<td>0.20</td>
<td>5851 - 5847</td>
<td>5.88 ± 0.09</td>
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<td>UCI-137302 C-02 PC Bed L8</td>
<td>1.5</td>
<td>175 ± 25</td>
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<td>one piece ch.</td>
<td>1.00</td>
<td>1.00 - 0.99</td>
<td>1.01 ± 0.03</td>
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<tr>
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<td>2.5</td>
<td>1045 ± 25</td>
<td>2.00</td>
<td>several piece ch.</td>
<td>2.00</td>
<td>2.00 - 1.99</td>
<td>2.00 ± 0.01</td>
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<td>UCI-137304 C-04 BH Bed T2</td>
<td>1.7</td>
<td>1185 ± 25</td>
<td>1.00</td>
<td>several piece ch.</td>
<td>1.00</td>
<td>1.00 - 0.99</td>
<td>1.01 ± 0.03</td>
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</table>

*Radioactive age calibrated with InCal13 curve and reported in years before AD1950; errors reported at 2σ.*

*Radioactive age calibrated with InCal13 curve and reported in years before AD2013 to match OSL.*

*Age reported by averaging range; error is difference between median and each value.*
APPENDIX C

Figure C.1. Detailed stratigraphy of Goldfish hole.
Figure C.2. Detailed stratigraphy of Picture Canyon hole.
Table C.1. Summary of stratigraphic field observations, Cow Canyon

<table>
<thead>
<tr>
<th>Unit</th>
<th>Thickness (cm)</th>
<th>Total thickness</th>
<th>Bed shape</th>
<th>Composition</th>
<th>Grain size</th>
<th>Grading</th>
<th>Silt/mud cap?</th>
<th>Sed Structures</th>
<th>Bioturb?</th>
<th>Other structures</th>
<th>Sorting</th>
<th>Interp</th>
<th>fan location</th>
<th>OSL</th>
<th>RC</th>
<th>Facies</th>
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<td>silty sand</td>
<td>mL to silt</td>
<td>normal</td>
<td>y</td>
<td>horizontal laminations; lenses of porty sorted, coarse sand</td>
<td>none</td>
<td>moderately well-sorted</td>
<td>lower plane-bed alluvial event ending with suspension settling</td>
<td>mid</td>
<td>Slm</td>
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<td>planar laminations</td>
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<td>toe</td>
<td>Slm</td>
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<td>y</td>
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<td>y</td>
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<td>few root traces</td>
<td>voids</td>
<td>few rip-up clasts</td>
<td>toe</td>
<td>Sxmc</td>
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<td>normal</td>
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<td>few root traces</td>
<td>poorly sorted flow onset preserved followed by waning flow</td>
<td>mid</td>
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<td>low energy channel margin</td>
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<td>Sxmc</td>
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<td>y</td>
<td>plane and x-beds</td>
<td>some modern rooting and burrows</td>
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<td>toe</td>
<td>Sxmc</td>
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<td>y</td>
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<td>y</td>
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<td>USU - 1402</td>
<td>Smc</td>
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<td>well sorted</td>
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<td>well-sorted</td>
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<td>rooting</td>
<td>moderate</td>
<td>rooting, insect</td>
<td>organic material</td>
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<td>toe</td>
<td>Sxmc</td>
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<td>moderate</td>
<td>rooting</td>
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<td>rooting, insect</td>
<td>organic material</td>
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<td>rooting</td>
<td>organic material</td>
<td>rooting, insect</td>
<td>organic material</td>
<td>well sorted</td>
<td>low energy flow to suspension settling</td>
<td>toe</td>
<td>Sxmc</td>
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Table C.1. Summary of stratigraphic field observations, Cow Canyon

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<th>Unit</th>
<th>Thickness (cm)</th>
<th>Total thickness (cm)</th>
<th>Bed shape</th>
<th>Composition</th>
<th>Grain size</th>
<th>Grading</th>
<th>Silt/mud cap?</th>
<th>Sed Structures</th>
<th>Bioturb?</th>
<th>Other structures</th>
<th>Sorting</th>
<th>Interp</th>
<th>Fan location</th>
<th>OSL</th>
<th>RC</th>
<th>Facies</th>
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<td>low angle x-bedding to massive</td>
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<td>well sorted</td>
<td>low energy flow to suspension settling toe</td>
<td>Sxmc</td>
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<td>peds</td>
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<td>low energy flow to suspension settling toe</td>
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Table C.2. Summary of stratigraphic field observations, Bobby’s Hole.

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<th>Grain size</th>
<th>Grading</th>
<th>Sed Structures</th>
<th>Bioturb?</th>
<th>Other structures</th>
<th>Sorting</th>
<th>Interp</th>
<th>fan location</th>
<th>OSL</th>
<th>RC</th>
<th>Facies</th>
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<td>1</td>
<td>32</td>
<td>wedge</td>
<td>sand and silt</td>
<td>fU to vcU</td>
<td>normal and reverse</td>
<td>low angle x-bedding</td>
<td>abundant krotovina, roots, mixing larger clasts comprise mud rip ups and white carbonate chips, Truncated by fault, which dips to E moderately poorly sorted</td>
<td>high energy alluvial flow</td>
<td>mid</td>
<td>Sgx</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2</td>
<td>2</td>
<td>wedge</td>
<td>sand and silt</td>
<td>vľ to f</td>
<td>normal reverse at base,</td>
<td>low angle x-bedding, planar laminations</td>
<td>moderate mixing fractures on E side</td>
<td>moderately poorly sorted</td>
<td>low energy alluvial event</td>
<td>toe</td>
<td>Sxmc</td>
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<td>clasts are mud rip ups and calcite chips moderately poorly sorted</td>
<td>high energy alluvial flow, channel margin</td>
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<td>16.5</td>
<td>wedge</td>
<td>silty sand</td>
<td>vľU to mL</td>
<td>normal</td>
<td>low angle x-bedding</td>
<td>not evident</td>
<td>heavy; mostly obscures sed structures moderately poorly sorted</td>
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<td>silt to mL</td>
<td>normal</td>
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<td>none</td>
<td>thickens to SW, some coarse clasts</td>
<td>low energy alluvial event</td>
<td>toe</td>
<td>Smc</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>wedge</td>
<td>silty sand</td>
<td>silt to clL</td>
<td>normal</td>
<td>low angle x-bedding</td>
<td>not evident</td>
<td>thickens and coarsens to S</td>
<td>low energy alluvial event</td>
<td>Sxmc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>5.5</td>
<td>lenticular</td>
<td>sandy granular sand</td>
<td>f to c</td>
<td>graded</td>
<td>low angle x-bedding</td>
<td>mostly obscured</td>
<td>1.5 meters below surface</td>
<td>moderately poorly sorted</td>
<td>moderate energy alluvial flow</td>
<td>USU-1404</td>
<td>Sx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td>20</td>
<td>sandy granular sand</td>
<td>vľL to mL</td>
<td>ungraded</td>
<td>low angle x-bedding</td>
<td>considerably bioturbated</td>
<td>moderately sorted</td>
<td>moderate energy alluvial flow</td>
<td>USU-310</td>
<td>Sx</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>F3</td>
<td>30</td>
<td>sandy granular sand</td>
<td>vľL to mL</td>
<td>unsorted</td>
<td>low angle x-bedding</td>
<td>upper 1 cm is silt cap</td>
<td>moderately poorly sorted</td>
<td>moderate energy alluvial flow</td>
<td>UFI-308</td>
<td>Sxmc</td>
<td></td>
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</table>
APPENDIX D

Notes
The suffix “int” in a file name indicated that the raster values are integer, rather than float.

Disc 1
- DEMs **10m, from Utah AGRC**
  - 10m_clip is for display in Arc
  - 10m_clipp_hlsh is for display in arc
  - Raw contains unclipped DEM (sanj_ned10) and hillshade (10mhillsh) files for San Juan County.

- Flow Process **FG generated using 10-m DEMs.**
  - fac, fdr are raw flow accumulation and flow direction grids with no fill
  - sinks is a grid showing where sinks are located. It was generated by subtracting the unfilled DEM from the filled DEM
  - With_sinks is the important folder that contains the partially-filled FAC grids upon which long profiles were based.
    - fac_11m and fac_11m_int are the specific grids used. They are grids where sinks >11m deep were filled.

- Geology **Utah Geological Survey GIS component maps**
  - Contains shapefiles for faults and surface geology from both the entire state of Utah and the 30 x 60 La Sal quadrangle. When displaying these in Arc, it is important to fiddle with the layer file to ensure they are matched to the correct shapefile. The La Sal quadrangle files are more detailed.

- Hypsometry **FG generated**
  - Hypsometry, watershed outlines for all 7 study catchments

- LP Arc Extract **FG generated**
  - Points extract for the three streams used for long profiles, for export to Excel.

- RVA **FG generated**
  - _diff, tincap, rastcap files for all 7 study catchments. Note that “Elefm” is the main Elephant catchment, while “Elef” is a smaller catchment to the west.

- Scaled **Stream Profiler Tool outputs for ArcGIS**
  - stream shapefiles for all study streams in the Needles fault zone (NFZ). Output by the stream profiler tool (MATLAB). Attributes for each streamline include \( k_{qsm} \) values; streams were broken up into as many reaches as possible.

- SJ orthophoto **State of Utah**
  - orthophoto from 2009 of San Juan County. No altered.

- Swallow Holes
  - Outlines of the four study graben-basins and catchments (Bobby’s, Cow Canyon, Goldfish, and Picture Canyon)
  - Holes are shapefiles of the outlines of each of the study swallow holes

- Topos **UAGRC, clipped by FG**
georegistered, scanned 7.5’ USGS topo maps. If using as a base, choose the five that have “clip” in their name, as their edges have been clipped so they can seamlessly align. (daclip, bypsumclip, loopclip, sbclip, xcclip)

- Unscaled
  - Stream and knickpoint shapefiles for all study streams in the NFZ. Output by the stream profiler tool (MATLAB). Attributes for each streamline include ksn values. Knickpoints are classified in

- UT Land Ownership UAGRC
  - used to show NPS boundary

Disc 2
- PRISM data
  - Fac__wt1 and _facwt1_int were used for the scaled long profile Matlab and Excel work.
  - prism_clip is the prism grid clipped to the same outline as the clipped DEMs.
- Streams Point Extract
  - same as “LP Arc Extract on Disc 1; included here so it could be easily displayed with PRISM data
- Geology
  - duplicate of Disc 1; included so it could be displayed with other data
- BnA sample sites Drawn by FG after Biggar and Adams, 1987
- Sed exposures Drawn by FG based on topographic, air photo analysis
- Trudgill Paleostreams Drawn by FG after Trudgill, 2002, and orthophotos
- COR_GR_Utah Merged streamlines from several NHD HUC10 packages. Simple shapefile for maps/display
- StrmlinesCombo Merged streamlines from several NHD HUC10 packages
- Utah isolated from US states map. Projected in NAD 83
- Matlab modeling results