Gravel-capped benches above northern tributaries of the Escalante River, south-central Utah

David W. Marchetti1,*, Scott A. Hynek2, and Thure E. Cerling2
1Geology Program, Western State College of Colorado, 600 N. Adams Street, Gunnison, Colorado 81230, USA
2Department of Geology and Geophysics, University of Utah, 115 South 1400 East, Salt Lake City, Utah 84112, USA

ABSTRACT

Andesitic boulder deposits mantle straths cut in sedimentary bedrock high above the northern tributaries of the Escalante River in south-central Utah. The andesitic gravel deposits are derived from the southern escarpments of Boulder Mountain and Aquarius Plateau. The sedimentology and geomorphic expression of these deposits suggest they are from slurry-flow mass movements that have been reworked by fluvial processes. The andesitic boulders are significantly tougher than the local sedimentary bedrock and cause boulder armoring and topographic inversion. The andesitic boulders are also effective tools for fluvial incision when transported across weaker bedrock. Cosmogenic 3He exposure-age dating of some of the largest boulders exposed on the treads of four different deposits range from 303 ± 48 to 1395 ± 241 ka. The tallest boulders exposed on the deposit surfaces tend to yield the oldest exposure ages, suggesting that boulder erosion and deposit erosion are controlling the exposure-age populations and indicating that even the oldest exposure ages from a given deposit are likely minimum age estimates. Using the oldest exposure age from each surface, we estimate maximum Escalante River northern tributary incision rates of 151–323 m Ma⁻¹ for the period since 0.6–1.4 Ma.

INTRODUCTION

There is recent controversy over the age, and perhaps definition of, the Grand Canyon (e.g., Flowers et al., 2008; Polya et al., 2008; Wernicke, 2011); however, there is a strong consensus that prior to ~6 Ma there was no clearly identifiable through-flowing river system integrating and draining the majority of the Colorado Plateau to the Gulf of California (Spencer et al., 2002; Dorsey et al., 2007; Pederson, 2008; Dorsey, 2010; Lucchitta et al., 2011). Thus, at ~5–6 Ma, a dramatic base-level fall was imposed upon the main-stem Colorado River system, likely causing a significant increase in the bedrock incision rates of the Colorado River and its tributaries. The mechanics and timing of how this incision was transferred upstream, and its relationship to rock strength, major tectonic structures, and mantle dynamics are areas of active research (Aslan et al., 2008; Cook et al., 2009; Crow et al., 2011; Karlstrom et al., 2011, 2012). An essential component of this research is determining the rate of vertical bedrock river incision at multiple spatial and temporal scales in numerous Colorado Plateau drainages (e.g., Repka et al., 1997; Pederson et al., 2002; Wolkowinsky and Granger, 2004; Marchetti and Cerling, 2005; Darling et al., 2009; Hanks et al., 2011). With quantitative data constraining the temporal interval and rates of river incision for different segments of the Colorado River system, we can test hypotheses about the nature and timing of incision and the processes that affected incision.

In this paper, we present geomorphic, sedimentologic, and geochronologic data on four different boulder-rich gravel deposits along tributaries of the Escalante River. These deposits represent the former active channels of streams that were inundated with mass movements and presently sit high above the modern tributary drainages, demonstrating considerable bedrock incision since deposition. The predominant lithology of these deposits (trachyandesites) is well characterized with respect to cosmogenic 3He exposure-age dating (Marchetti and Cerling, 2005; Marchetti et al., 2005a, 2011). Following on that framework, we also present cosmogenic exposure-age estimates for the largest boulders from each of the four surfaces we investigated. Finally, we use the age estimates and paleostrath to modern-strath distances to estimate the average incision rates of these tributary drainages over the time since deposition and address the significance of our incision rates with regard to regional landscape evolution.

GEOLOGY AND GEOMORPHOLOGY OF THE ESCALANTE RIVER DRAINAGE

The Escalante River heads on the southwesternmost tip of Aquarius Plateau in south-central Utah (Fig. 1) and is a first-order tributary of the Colorado River. The Escalante joins the Colorado 20 river miles upstream of the confluence between the Colorado and San Juan Rivers. The river presently sits in a deep canyon, which has been cut into a broad valley between the Circle Cliffs uplift to the east and the Kaiparowits Plateau to the west (Fig. 1). The northern tributaries to the Escalante drain Aquarius Plateau and southern slopes of Boulder Mountain (Fig. 2). From west to east the largest of these tributaries include: Pine Creek, Mamie Creek, Sand Creek, Calf Creek, West and East Boulder Creeks (which merge to form a singular Boulder Creek), and Deer Creek.

The bedrock geology of the Escalante River drainage basin includes more than 3 km of Permian to Tertiary sedimentary rocks common to the central Colorado Plateau (Doelling et al., 2003). Along the northern tributaries of the Escalante River, only strata from the Early Jurassic Kayenta Formation through Late Cretaceous Tropic Shale are exposed (Weir and Beard, 1990a, 1990b; Weir et al., 1990). Most of the geology around the northern tributaries includes vast expanses of nearly bare Early Jurassic Navajo Sandstone. The Navajo Sandstone in these areas includes a wide variety of topographic forms and highly varying iron mineralization (e.g., Beitler et al., 2003; Loope et al., 2011) that has caused observable differences in weathering. Additionally, the Navajo Sandstone acts as a shallow aquifer in the area.
Figure 1. Satellite image of the Escalante River drainage basin. The pink square is the location of a convexity in the Escalante River longitudinal profile (Cook et al., 2009) and is discussed in the text.
Figure 2. Digital elevation model (DEM) of the upper Escalante River drainage basin showing the northern tributaries. Initials refer to different boulder deposits that we investigated: BMB—Black Mesa Bench; NHB—New Home Bench; DM—Durffey Mesa; DCB—Deer Creek Bench. Cross section lines A to A' and B to B' refer to Figure 12 and are discussed in the text.
and interactions between the Navajo Sandstone aquifer and the surface drainage system of the Escalante River and its tributaries are potentially important for understanding long-term drainage development (e.g., Wililams and Hackman, 1971; Billingsley et al., 1987; Mattox, 1991). The main volcanic unit that makes up the steep cliffs ringing southern Boulder Mountain and Aquarius Plateau is a porphyritic basaltic-andesite to trachyandesite (herein andesite). Recent work on this rock unit on the nearby Fish Lake Plateau indicates this widespread volcanic deposit is a densely welded ash-flow tuff emplaced ~26 Ma (Bailey et al., 2007; Ball et al., 2009). A mixture of clast- and, in places glacial, surficial deposits composed primarily of andesitic boulders mantles the southern slopes of Boulder Mountain and Aquarius Plateau. Although covered by surficial deposits in the uppermost part of the Escalante drainage basin, a weak unit of thinly bedded ashes, siltstones, chert pebble conglomerates, and sandstones underlie the andesites. This unit has long been thought to be part of the Paleocene Flagstaff Formation (Smith et al., 1963; Williams and Hackman, 1971); however, recent work on the nearby Thousand Lakes Mountain suggests that the unit is, in fact, much younger and may be part of the Eocene Crazy Hollow Formation (Deblieux et al., 2011).

Regardless of the age of this unit, its weakness and position immediately below the resistant andesites leads to a variety of large-scale mass movements around Boulder Mountain and Aquarius Plateau (Fuller et al., 1981; Williams, 1984; Marchetti et al., 2007). These mass movements, and fluvial reworking of mass movement deposits, have transported and deposited extremely coarse volcanic (andesitic) boulder gravels onto the upper drainage basin of the Escalante River.

During the Last Glacial Maximum (LGM; ~21 ± 2 ka, ~MIS [marine isotope stage] 2), Boulder Mountain had an ice cap with outlet glaciers that flowed radially from the center of the ice mass (Flint and Denny, 1958; Marchetti et al., 2005a, 2007). It is still unclear whether or not Boulder Mountain was glaciated during the penultimate glaciation (~MIS 6). Flint and Denny (1958) argue that there was a Bull Lake–age (what they meant by “Bull Lake” age is also unclear, likely either ~MIS 4 or ~MIS 6) glaciation around Boulder Mountain. However, Waits (1997) and Marchetti et al. (2005a, 2007) found no evidence of Bull Lake–age glacial deposits and reinterpret the Bull Lake–age glacial deposits of Flint and Denny (1958) as mass movement deposits. The lowest elevation of definitive glacial deposits in the upper reaches of the Escalante drainage basin is between 2600 and 2700 m along both East and West Boulder Creeks (Fig. 2). On the Aquarius Plateau, there is some evidence of periglacial activity in the form of nivation hollows, but there is no evidence of glaciation.

### GRAVEL DEPOSITS

The investigated gravel deposits sit high above northern tributaries of the Escalante River (Fig. 2). All of the deposits are dominated by boulder-sized clasts of andesite derived from the southern slopes of Boulder Mountain and Aquarius Plateau. The andesites range in color from light to dark gray with occasional reddish-brown clasts that have an oxidized groundmass. When exposed subaerially, the andesite clasts typically acquire very dark desert varnish and appear black. Overall, boulder clasts in the gravel deposits range from rounded to angular, with many areas dominated by rounded to subrounded clasts. Where exposed, the gravel deposits can display cut-and-fill stratigraphy, mild imbrication, and weak inverse grading. Although the deposits are dominated by andesitic clasts (~99%), they have occasional pebble- to cobble-sized clasts of chert. The chert clasts can be any one of a variety of colors, but yellow-brown and brick-red are the most common. The cherts are likely derived from the Tertiary unit that underlies the andesites. The matrix of the gravel deposits is a light- to dark-gray mixture of andesitic sand and silts.

In the following sections, we describe the location, sedimentology, and geomorphology of the particular gravel deposits we studied. For each deposit, we also report boulder-size measurements and pebble lithology counts from various locations on each deposit’s tread. The largest boulders for each deposit were determined by walking each deposit tread and margins and measuring the dimensions of the largest clasts. We measured between 35 and 70 boulders to determine the five largest for each deposit. The dimensions of the five largest boulders from each surface are given in Table 1. The pebble counts were done by identifying the lithology (andesite, chert, pedogenic carbonate, or sandstone) of all the pebble-sized clasts in a 0.4 m² circular area. The pebble-count data and composite lithologic percentages are given in Table 2.

### Black Mesa Bench

The Black Mesa Bench deposit is located ~9 km NNW of Escalante, Utah (Fig. 2). The deposit is 2 to possibly 8 m thick and is deposited on a strath of beveled Tropic Shale. Pine Creek has incised ~228 m below the level of the Black Mesa Bench strath (Fig. 3). The tread of the deposit is covered by large areas of Pinyon-Juniper woodland with two large sections that were recently drag-chained to remove trees and improve pasture (Fig. 4). Large expanses of the Black Mesa Bench tread have thin Av soil horizons composed of local eolian-derived silts and sands. In many areas, especially where there are overturned boulders, there are large pieces of intact or broken pedogenic carbonate rings (alternatively crusts, coatings, or pendants) at the surface or partly buried in the surface soil. Maximum pedogenic carbonate ring thicknesses

<table>
<thead>
<tr>
<th>TABLE 1. MEASURED BOULDER SIZES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Black Mesa Bench</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>New Home Bench</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Durffy Mesa</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Deer Creek Bench</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
The tread of the New Home Bench deposit is incised ~142 m on the E side (Figs. 5 and 6). The New Home Bench strath, and Dry Gulch has incised ~206 m below the W side of the Durffey Mesa deposit is cut into Navajo Sandstone in the lower reaches and Carmel Formation in the upper reaches (Figs. 5 and 6) and 12 is atop part of the ~7-km-long deposit. The location of the deposit just downstream of where Pine Creek emerges from a narrow canyon cut into the westward-dipping limb of the Escalante monocline suggests the deposit may be in part structurally controlled. Clasts in the deposit range from rounded to angular, and surface clasts range from slightly to heavily weathered. The composite pebble-sized fraction of the Black Mesa Bench surface is dominated by chert and pedogenic carbonate clasts. Only a single clast of sandstone was found in the total of 518 clasts identified.

New Home Bench

The New Home Bench deposit is located just west of the W-dipping Escalante monocline, which is the steep western limb of the Escalante anticline (Lidke and Sargent, 1983). The location of the deposit just downstream of where Pine Creek emerges from a narrow canyon cut into the westward-dipping limb of the Escalante monocline suggests the deposit may be in part structurally controlled. Clasts in the deposit range from rounded to angular, and surface clasts range from slightly to heavily weathered. The composite pebble-sized fraction of the Black Mesa Bench surface is dominated by chert and pedogenic carbonate clasts. Only a single clast of sandstone was found in the total of 518 clasts identified.

Deer Creek Bench

The Deer Creek Bench is located ~6 km SE of Boulder, Utah, and is ~2 km ESE of Durffey Mesa. The Deer Creek Bench deposit is cut into Navajo Sandstone and ranges from 2 to possibly 8 m thick (Figs. 9 and 10). Deer Creek has incised ~210 m below the level of the Deer Creek Bench strath on the E side of the deposit, while on the W side of the deposit, the drainage is full of andesite colluvium and sandy alluvium, and the elevation of the modern strath is unclear. The tread of the Deer Creek Bench deposit is covered with areas of Pinyon-Juniper woodland and has large areas and thick accumulations of locally derived eolian sands and silts, including small dune fields (Fig. 10). Smaller areas of the tread have thin, silty Av soil horizons and areas of intact or broken pedogenic carbonate rinds. Maximum pedogenic carbonate rind thicknesses are 7–8 cm. Exposures into the New Home Bench deposit show stage II–III soil carbonate development (determined using criterion of Machette, 1985). Clasts in the deposit range from rounded to angular but are dominated by subangular to subrounded, and surface clasts range from slightly to heavily weathered. The composite pebble-sized fraction of the New Home Bench surface is dominated by chert and pedogenic carbonate clasts. Only a single clast of sandstone was found in the total of 868 pebble-sized clasts identified.

Durffey Mesa

Durffey Mesa is located ~4 km SSE of Boulder, Utah, and is just to the W of the Burr Trail. The Durffey Mesa deposit is cut into Page Sandstone and ranges from 1 to possibly 4 m in thickness (Figs. 7 and 8). The drainages on either side of the Durffey Mesa deposit are choked with a mixture of andesitic colluvium and sandy alluvium, and so it is difficult to determine where the modern bedrock straths are. However, there is ~140–200 m of relief on either side of the deposit (deposit strath to top of alluvium). The tread of the Durffey Mesa deposit is covered with areas of Pinyon-Juniper woodland and has areas of locally derived eolian sand and silt deposition and thin, silty Av horizons. The surface of the deposit also has large areas of thick pieces of intact or broken and overturned pedogenic carbonate rinds and laminar plates (Fig. 8). Maximum pedogenic carbonate-rind thicknesses are 8–9 cm. Clasts in the deposit range from rounded to angular but are dominated by rounded to subrounded clasts, and surface clasts range from slightly to extremely weathered. The composite pebble-sized fraction of the Durffey Mesa surface is completely dominated by pedogenic carbonate clasts. No sandstone was found in the total of 1543 pebble-sized clasts identified.

Deer Creek Bench

The Deer Creek Bench is located ~6 km SE of Boulder, Utah, and is ~2 km ESE of Durffey Mesa. The Deer Creek Bench deposit is cut into Navajo Sandstone and ranges from 2 to possibly 8 m thick (Figs. 9 and 10). Deer Creek has incised ~210 m below the level of the Deer Creek Bench strath on the E side of the deposit, while on the W side of the deposit, the drainage is full of andesite colluvium and sandy alluvium, and the elevation of the modern strath is unclear. The tread of the Deer Creek Bench deposit is covered with areas of Pinyon-Juniper woodland and has large areas and thick accumulations of locally derived eolian sands and silts, including small dune fields (Fig. 10). Smaller areas of the tread have thin, silty Av soil horizons and areas of intact or broken pedogenic carbonate rinds. Maximum pedogenic carbonate rind thicknesses are 6–7 cm. Clasts in the deposit range from rounded to angular, and surface clasts range from slightly to heavily weathered. The composite pebble-sized fraction of the Deer Creek Bench is mostly pedogenic carbonate clasts with slightly fewer andesitic pebbles. No sandstone clasts were found in the total of 492 pebble-sized clasts identified. Around the margins of the Deer Creek Bench deposit are numerous “pedestal boulders,” where andesite clasts sit atop small pedestals of Navajo Sandstone preserved underneath the andesite clasts because they were protected from weathering (Fig. 10C). These pedestal boulders demonstrate the very different weathering rates between the Navajo Sandstone and the Oligocene-age andesites, and are good examples of meter-scale boulder armoring. These precariously balanced rocks also provide some constraints on the seismic history of the region (cf. Balco et al., 2011).
Marchetti et al.

Our observations of the four gravel deposits described above allow us to make some conclusions about the mechanisms and paleoenvironments of deposition. Several observations argue for the deposits being from mass movements. These include: the extremely large boulder sizes (Table 1); the thickness of the gravel-rich deposits; the nearly monolithologic nature of the deposits in outcrop, surface exposure, and pebble counts (Table 2); occasional inverse grading in some exposures; and finally, the sharp contact between the underlying bedrock and the deposits (e.g., Fig. 6C) shows no significant weathering or alteration (soil formation) and so suggests rapid deposition. However, several observations argue for some fluvial component to the deposits. These include: the predominant rounding of clasts in some of the deposits or areas of deposits, imbrication in some exposures, and occasional cut-and-fill stratigraphy in some exposures. Taken together, these observations suggest that most of the deposits are likely fluvially reworked debris-flow or hyperconcentrated flow run-out deposits. The deposits are clearly composite and likely the result of multiple episodes of mass movement deposition and fluvial reworking.

The treads of all four of the deposits are covered with locally sourced eolian silts and sands and large areas of intact, broken, and sometimes overturned pedogenic carbonate rinds and parts of carbonate laminar horizons. These two observations suggest that the absolute elevation of the deposit treads have been both eroding and aggrading through time. The pedogenic carbonate littering the surfaces suggests a previously thicker mantle of deposit in which the carbonate precipitated that has since been eroded away. The sometimes thick accumulations of eolian-derived silts and sands suggest that at least recently, the deposits may have been increasing in thickness in some areas. Exposures in the New Home Bench deposits showed stage II–III pedogenic carbonate morphology; however, pedogenic carbonate rind thicknesses suggest that perhaps a higher stage was achieved in most of the deposits. The Durffey Mesa deposits in particular have extremely thick pedogenic carbonate rinds (commonly 8–9 cm) and large, thick (sometimes 11–12 cm) plates of blocky laminar pedogenic carbonate. These platy-laminar carbonate clasts may have been the upper laminar part of a former K horizon, suggesting possible stage IV carbonate development sometime in the past.

Boulder Armoring

The geomorphic process of topographic inversion, or inversion of relief, has been recognized for some time, and can be important in understanding the long-term evolution of many landscapes (Brunsden, 1993; Pain and Ollier, 1995). Typically, the most common processes that cause the armoring essential for topographic inversion are lava flow deposition (e.g., Wahrhaftig, 1965; Ollier, 1988; Aslan et al., 2008) or in situ duricrust (extreme silica, iron, aluminum, or carbonate accumulations) formation in soil profiles (e.g., Twidale, 1984; Ollier, 1991; Eppe et al., 2002). Only a few studies have looked at boulder armoring as a possible mechanism for topographic inversion (Bryan, 1940; Mills, 1981, 1990). Granger et al. (2001) demonstrated that both boulder armoring and soil cover are important components of

Synthesis

Our observations of the four gravel deposits described above allow us to make some conclusions about the mechanisms and paleoenvironments of deposition. Several observations argue for the deposits being from mass movements. These include: the extremely large boulder sizes (Table 1); the thickness of the gravel-rich deposits; the nearly monolithologic nature of the deposits in outcrop, surface exposure, and pebble counts (Table 2); occasional inverse grading in some exposures; and finally, the sharp contact between the underlying bedrock and the deposits (e.g., Fig. 6C) shows no significant weathering or alteration (soil formation) and so suggests rapid deposition. However, several observations argue for some fluvial component to the deposits. These include: the predominant rounding of clasts in some of the deposits or areas of deposits, imbrication in some exposures, and occasional cut-and-fill stratigraphy in some exposures. Taken together, these observations suggest that most of the deposits are likely fluvially reworked debris-flow or hyperconcentrated flow run-out deposits. The deposits are clearly composite and likely the result of multiple episodes of mass movement deposition and fluvial reworking.

The treads of all four of the deposits are covered with locally sourced eolian silts and sands and large areas of intact, broken, and sometimes overturned pedogenic carbonate rinds and parts of carbonate laminar horizons. These two observations suggest that the absolute elevation of the deposit treads have been both eroding and aggrading through time. The pedogenic carbonate littering the surfaces suggests a previously thicker mantle of deposit in which the carbonate precipitated that has since been eroded away. The sometimes thick accumulations of eolian-derived silts and sands suggest that at least recently, the deposits may have been increasing in thickness in some areas. Exposures in the New Home Bench deposits showed stage II–III pedogenic carbonate morphology; however, pedogenic carbonate rind thicknesses suggest that perhaps a higher stage was achieved in most of the deposits. The Durffey Mesa deposits in particular have extremely thick pedogenic carbonate rinds (commonly 8–9 cm) and large, thick (sometimes 11–12 cm) plates of blocky laminar pedogenic carbonate. These platy-laminar carbonate clasts may have been the upper laminar part of a former K horizon, suggesting possible stage IV carbonate development sometime in the past.

Boulder Armoring

The geomorphic process of topographic inversion, or inversion of relief, has been recognized for some time, and can be important in understanding the long-term evolution of many landscapes (Brunsden, 1993; Pain and Ollier, 1995). Typically, the most common processes that cause the armoring essential for topographic inversion are lava flow deposition (e.g., Wahrhaftig, 1965; Ollier, 1988; Aslan et al., 2008) or in situ duricrust (extreme silica, iron, aluminum, or carbonate accumulations) formation in soil profiles (e.g., Twidale, 1984; Ollier, 1991; Eppe et al., 2002). Only a few studies have looked at boulder armoring as a possible mechanism for topographic inversion (Bryan, 1940; Mills, 1981, 1990). Granger et al. (2001) demonstrated that both boulder armoring and soil cover are important components of...
Gravel-capped benches above northern tributaries of the Escalante River

Mass movement deposits composed of coarse volcanic boulders are common throughout the upper Escalante River drainage basin. These deposits cover the paleovalley floors (straths) where they were deposited. Due to the large size of the clasts in these deposits, the local mainstem drainage and tributaries cannot easily remove these deposits, and so they can persist in the landscape as remnants of the former positions of valley floors and active river channels (Williams, 1984; Williams et al., 1990). Additionally, over long periods of time, the volcanic rocks are relatively more resistant to physical and chemical weathering causing them to erode more slowly than the local sedimentary bedrock (Selby, 1993; McLelland et al., 2008). Volcanic gravel deposits are resistant to weathering and occupy transport-limited geomorphic settings, and once the deposits are isolated from the active drainage, these effects magnify. Ultimately, both of these factors can lead to topographic inversion, where the former valley floors become preserved higher-elevation landscape elements because they were armored with coarse volcanic boulder deposits. This armor ing can be seen at many different spatial scales around the upper Escalante River basin ranging from the benches we studied (Figs. 1–10) to the volcanic pedestal boulders that commonly form around the margins of gravel benches cut into Navajo Sandstone (Fig. 10C).

Cosmogenic 3He Exposure-Age Dating of Boulder Clasts

Cosmogenic exposure-age dating is a relatively new age dating technique that uses the buildup of cosmic ray–derived isotopes, measured in certain mineral phases or pieces of whole rock, to determine the exposure duration of rock surfaces (Gosse and Phillips, 2001; Dunai, 2010). The “method” is actually a series of methods based on the isotope being measured (commonly 3He, 10Be, 21Ne, 26Al, and 36Cl) and the mineralogy of the rocks being investigated. The 3He method is similar to other cosmogenic methods in basic principle but has several differences that make it the most suitable choice for the andesite-rich gravel deposits in the northern Escalante drainage basin. 3He is a stable nuclide, which means its cosmogenic buildup in a mineral is not affected by radioactive decay, and so it is better for attempting to date very long exposure durations. The cosmogenic production rate of 3He is the highest of all the routinely used nuclides, and He isotopes can be measured relatively easily using conventional noble gas mass spectrometry and only require pure mineral separates. Since He has a low atomic mass, it can leak out of many mineral phases at Earth surface temperatures; however, it is fully retained in dense mineral phases such as olivine, pyroxene, garnet, Fe-Ti oxides, zircon, and apatite (e.g., Farley et al., 2006; Dunai, 2010). The andesites in the gravel deposits we investigated have abundant phenocrysts of pyroxene (~10%–30% pyroxene phenocrysts in most samples) and have had very long exposure durations; so 3He is a favorable cosmogenic method.

There can be several sources of noncosmogenic He in volcanic minerals that need to be assessed in order to determine an accurate 3He exposure age. The first of these is He from the magma (magmatic He) that becomes trapped in fluid inclusions during crystallization (Kurz, 1986; Cerling and Craig, 1994). This component of He is most commonly corrected for by crushing the minerals in vacuo, measuring the 3He/4He ratio of the released gasses and using...

Figure 4. Photographs of the Black Mesa Bench (BMB) deposit. (A) Digitally stitched photograph of the W side of the BMB deposit (deposit caps the hill) and Pine Creek; photograph looking SW. (B) Photograph of the BMB tread. (C) Photograph of the BMB tread showing cosmogenic sample BMB-03.
that ratio to correct the total He released from furnace heating (e.g., Scarsi, 2000; Blard and Farley, 2008). We crushed numerous splits of pyroxenes from Boulder Mountain andesites for this and previous studies (Marchetti and Cerling, 2005; Marchetti et al., 2005a, 2005b, 2007, 2011) and found that Boulder Mountain and Aquarius Plateau pyroxenes had little to no He released from crushing and therefore analytically unresolvable $^3$He/$^4$He ratios. Splits of several cosmogenic samples analyzed both as whole uncrushed crystals of pyroxene and as fully crushed powders yielded no statistical difference in the resulting He isotopic concentrations—again indicating little to no magmatic He in the pyroxenes. We suspect that the magmatic He in pyroxene fluid inclusions was degassed after eruption and during the high temperatures associated with the welding of the ash-flow tuffs (Ball et al., 2009).

In volcanic rocks with older crystallization ages (>1 Ma), another source of noncosmogenic He is radioactive decay of U and Th in the target mineral phase and the whole rock. $^4$He is produced directly from the decay of U and Th as alpha particles ($\alpha$) incorporate electrons; this $^4$He is known as radiogenic helium ($^4$He$_{rad}$). Noncosmogenic $^4$He can be produced through a mechanism where alpha particles from radiogenic decay interact with common light elements (Na, Mg, K, and Ca) and produce slowed or “thermalized” (thermal) neutrons via ($\alpha$,n) reactions. The thermal neutrons can then react with $^6$Li to produce tritium ($^3$H), which quickly decays ($T_{1/2} = 12.3$ a) to $^3$He via the following reaction: $^6$Li ($\alpha$,n) $^3$H$\rightarrow$ $^3$He (Andrews and Kay, 1982). This $^3$He is known as nucleogenic ($^3$He$_{nuc}$) and is a problem in rocks with high U and Th concentrations, high Li concentrations in the target mineral phase, older crystallization ages, and short exposure durations (Dunai, 2010). In two previous studies, we successfully used two different suites of completely shielded andesite samples, where cosmogenic $^3$He production is assumed to be nil, to correct for both radiogenic $^4$He and nucleogenic $^3$He in cosmogenic exposure-age samples (Marchetti and Cerling, 2005; Marchetti et al., 2005a). The shielded sample pyroxenes from those studies yielded $^3$He concentrations ranging from $3.7 \times 10^6$ to $10.9 \times 10^6$ atoms g$^{-1}$, $^4$He concentrations ranging from $18.25 \times 10^{12}$ to $46.54 \times 10^{12}$ atoms g$^{-1}$, and a very consistent $^3$He/$^4$He ratio of 2.08 $\times 10^{-7}$. In this study, concentrations of cosmogenic $^3$He ($^3$He$_c$) were determined from the total measured $^3$He and $^4$He concentrations ($^3$He$_{tot}$ and $^4$He$_{tot}$) using the following relationship:

$$^3$$He$_c$ = $^3$He$_{tot}$ – [$^4$He$_{tot}$ $\times$ ($^3$He/$^4$He)$_s$],

where the shielded ($^3$He/$^4$He)$_s$ ratio is 2.08 $\times$ 10$^{-7}$ (Marchetti et al., 2005a). The 1σ uncertainty associated with the shielded correction is $\sim$14% and is propagated through the determinations of the $^3$He concentrations. This shielded correction fully accounts for radiogenic $^4$He, nucleogenic $^3$He, and any possible magmatic $^3$He or $^4$He missed during crushes or split measurements of crushed powders and whole crystals.

**Sampling**

In sampling the boulders for surface-exposure dating, we chose boulders that had the best combination of height above the deposit surface, relative lack of weathering of the boulder crown, and position within the surface. Higher and larger boulders are less likely to have been buried and then exposed, and to have been significantly eroded. Clasts that sit higher above the surface are also less likely to have their tops affected by fire-induced spalling or diffusional losses of He from wildfire heating (e.g., Bierman and Gillespie, 1991). Many of the deposit
Gravel-capped benches above northern tributaries of the Escalante River

treads we sampled had patches of eolian sand and silt deposits. Sampling the highest boulders would also insure against the possibility of transient boulder burial due to surface inflation. Boulders that had heavily spalled, flaking, or chipped crowns were avoided. Good samples were slightly polished, likely by wind, and were often coated with rock varnish. Where possible, we tried to sample clasts away from the edges of gravel deposits. Boulders near the edges could be affected by creep and are more likely to have been buried and subsequently exposed by erosion that is concentrated near the edges of the deposits. Samples were removed using a hammer and chisel or airless jackhammer. Topographic shielding at all sites was negligible. Sample locations and elevations were determined using hand-held global positioning system (GPS) units with the North American Datum of 1983 (NAD 83 datum) (Table 3).

Analytical

Andesite samples were crushed to a uniform grain size, and 1–2 mm pyroxenes were separated using standard magnetic and heavy liquid techniques. The pyroxene separates were etched in dilute (~5%) HNO₃/HF multiple times to remove the outer few tens of microns of the grains. This etching should effectively remove any areas of implanted or recoil-loss He on the surface of the grains (Blard and Farley, 2008). Pyroxene separates were completely degassed in a modified Turner furnace at ~1400 °C. Helium isotope concentrations and isotopic ratios were determined using a MAP-251 mass spectrometer with electron multiplier (³He) and Faraday cup detectors (⁴He) at the Noble Gas Laboratory of the University of Utah. Reactive gasses were removed using SAES getters, while Ar and Ne were trapped and removed cryogenically using a cold head held at 10K. Measured counts of ³He and ⁴He were furnace blank corrected and then standardized against multiple analyses of purified Yellowstone Park gas (MM; ³He/⁴He ratio of 16.5 Rₐ, where Rₐ is the ³He/⁴He ratio in air ~1.384 × 10⁻⁶) or purified local Wasatch Mountain atmosphere (Little Mountain air). Proce-

Figure 6. Photographs of the New Home Bench (NHB) deposit. (A) Photograph of cosmogenic sample NHB-02. (B) Photograph of the W edge of the NHB deposit; photograph looking N–NW. Calf Creek in valley to W, Boulder Mountain–Aquarius Plateau in background. (C) Photograph of the contact between the NHB deposit and underlying Carmel Formation; photograph taken in the NW part of the NHB deposit. Hammer for scale. (D) Photograph of the NHB tread.
dural furnace and crusher blanks in this system range from 0 to $2 \times 10^5$ atoms for $^3$He and 1–5 $\times 10^9$ atoms for $^4$He. The helium isotopic data and $^3$He concentrations determined using Equation 1 above are given in Table 4.

$^3$He Exposure Ages

$^3$He exposure ages were determined using the $^3$He concentrations from Table 4 and the sample and site data from Table 3 with the CRONUS online $^3$He exposure-age calculator (Goehring et al., 2010; http://www.cronuscalculators.nmt.edu/he/he_age.xhtml). This online exposure-age calculator determines $^3$He exposure ages and age uncertainties for five different scaling routines and different boulder surface erosion rates (Table 5). The sea-level, high-latitude (SLHL) production rates used in the CRONUS online calculator depend upon the scaling routine and range from 119 to 136 atoms g$^{-1}$ yr$^{-1}$ (Table 4 in Goehring et al., 2010). The resulting exposure ages vary based on which scaling routine is applied and whether or not boulder surface erosion is taken into account. Since the boulders almost certainly experienced some erosion, we prefer the exposure ages determined with the 0.00001 cm yr$^{-1}$ erosion rate. We use the exposure ages determined with the Lal (1991) and Stone (2000) time varying production rate for discussion and arguments in the rest of the paper because the ages ± uncertainty of that scaling routine capture the full range of the rest of the exposure ages determined with other scaling routines (Table 5).

Several geomorphic factors can affect boulder exposure ages from allochthonous deposits. The first of these is pre-exposure or “inheritance,” where the sampled rock surfaces were exposed to cosmic rays prior to being incorporated in the deposit that was sampled. In this scenario the exposure-age estimate of deposition would be “too old” because some of the cosmogenic $^3$He was acquired before deposition. Several factors argue against this possibility for the gravel deposits we investigated. First, the large boulders in the deposits we sampled are likely from mass movements, which suggest geologically rapid excavation, transport, and deposition. Secondly, the gravel deposits are extremely close to their source. All of the deposits are less than ~20 km from the modern andesitic outcrops along the southern cliffs of Aquarius Plateau and Boulder Mountain. Given a modest rate of cliff retreat, the deposits were likely even closer to the volcanic escarpment during deposition ~0.6–1.4 Ma (Table 5). Finally, several studies have directly measured the amount of cosmogenic inheritance in fluvial systems and found that it is typically quite low (~5–60 ka) and considerably less of an effect than deposit erosion for surfaces older than a few 100 ka (Anderson et al., 1996; Repka et al., 1997; Hancock et al., 1999; Hidy et al., 2010; Heyman et al., 2011; Schmidt et al., 2011). Previous work by us in the nearby Fremont River drainage (Marchetti and Cerling, 2005) showed that most shielded boulders in a debris-flow deposit had no pre-exposure, and two boulders that were possibly pre-exposed had only ~8 ka of exposure age at the site of deposition. Since the boulders were likely pre-exposed up drainage, at a higher elevation with a higher $^3$He production rate, the actual pre-exposure duration of those clasts was less than ~8 ka. Ultimately, we argue that pre-exposure is unlikely for the deposits we investigated given that they are from mass movements and are close to source. Most importantly, if
there is some inheritance, it should be negligible when compared to the exposure durations and uncertainties that we determined (Table 5).

Allochthonous geomorphic deposits that are quite old (~100 ka and older) are difficult to date with cosmogenic techniques because of boulder and deposit erosion (Gosse and Phillips, 2001). This is especially true for boulders in glacial moraines older than LGM in age because of moraine crest erosion exposing previously buried clasts (Putkonen and Swanson, 2003; Heyman et al., 2011). Easterbrook et al. (2003; p. 49–56) demonstrated that the highest boulders above a Sacagawea Ridge–age (pre–Bull Lake–age; ~350–610 ka) moraine yielded the oldest cosmogenic exposure ages and the closest age estimate to the time of moraine emplacement. The fluville reworked mass movement deposits we sampled have a slight advantage over glacial moraines in that they do not start with sharp relief and the resulting concentrated erosion that a steep-sided glacial moraine would. However, deposit and boulder erosion are by far the most significant limiting factors in establishing an accurate cosmogenic age of our deposits. Here, we assume a slow rate of boulder erosion (0.000001 cm yr⁻¹) in the CRONUS cosmogenic age calculations to correct for slow boulder surface erosion (Table 5). To estimate the effects of deposit erosion, we collected multiple boulder samples from each surface and recorded the height of each sample relative to the modern deposit surface (tread) (Table 3). By plotting the exposure age of each clast versus its height above the deposit tread, we can qualitatively assess the effect of deposit erosion (Fig. 11). Figure 11 demonstrates that the New Home Bench, Durffey Mesa, and Deer Creek Bench deposits have moderate to strong positive correlations (r = 0.73–0.98) between exposure age and boulder height, and for each surface the oldest exposure ages are associated with the highest boulders. The Black Mesa Bench surface shows no correlation (r = –0.07) between exposure age and boulder height likely because the range of heights for sampled boulders from that deposit is small (0.5 to 0.7 m). Taken together, these data suggest that in most cases the higher boulders above a deposit surface will yield the oldest exposure ages, and therefore, either extreme boulder erosion (of select boulders) or deposit erosion and boulder exhumation are the most strongly controlling factors of the exposure-age populations. We, therefore, interpret the oldest exposure ages from each deposit as the best estimate of the age of deposition. Furthermore, since the boulders and boulder deposits are

Figure 8. Photographs of the Durffey Mesa (DM) deposit. (A) Photograph of cosmogenic sample DM-03. (B) Photograph of the DM deposit tread; the white material is either pedogenic carbonate rind or plate. (C) Photograph of the DM deposit (treed ridge on skyline) taken from the SE of the DM deposit and looking NW. (D) Photograph of a thick plate of pedogenic carbonate from the DM deposit.
clearly eroded, the oldest exposure ages provide a minimum age estimate for deposition and surface abandonment.

INCISION RATE ESTIMATES

We use the depth of incision around each deposit and the exposure age of the oldest boulder from each deposit to estimate the long-term incision rate of the drainages surrounding each deposit (Table 6). We subtract an estimate of each deposit’s thickness and make depth of incision measurements in areas where we have observed the modern floodplain sediment to be thin or negligible (~2 m or less). This allows us to determine a paleostrath to modern-strath estimate of bedrock incision over the time duration since deposition. The depth of incision around the deposits is quite large, and so small errors (few m) in estimating deposit thicknesses or in measuring incision depths would only slightly affect the resulting incision rates. We did not determine incision rates around the Durffey Mesa surface because both drainages around the deposit are filled with an unknown amount of sediment, and we could not identify the modern straths. Since the oldest exposure ages are likely minimum age estimates of the depositional age of each deposit, the incision rates we determine are maximum rates. The incision rates we estimate for northern tributary drainages of the Escalante River range from 151 to 323 m Ma⁻¹ and are determined over a time interval of 0.6–1.4 Ma (Table 6). Comparing the rates of geologic process, such as river incision, may not be appropriate when the time interval over which the rates are determined varies significantly (Gardner et al., 1987; Mills, 2000). With that caveat in mind, we compare our rate data with previously published incision rate data using ages in the ~0.5–1.5 Ma timeframe to avoid some of the complications of making such comparisons.

DISCUSSION

Accuracy of Our Dating Attempts

The largest uncertainty associated with our exposure ages is deposit and boulder surface erosion—which makes our exposure ages minimum age estimates. How much of a minimum estimate they may be is unknown but could be constrained. Employing additional independent dating techniques such as U-series disequilibrium or U-Pb on pedogenic carbonate rinds (e.g., Sharp et al., 2003; Woodhead et al., 2006; Rasbury and Cole, 2009; Cliff et al., 2010) or cosmogenic burial techniques (Wolkowinsky and Granger, 2004; Granger, 2006; Darling et al., 2011) could provide further temporal constraints on the age of the deposits. A recently published isochron-based cosmogenic burial age of a gravel deposit on top of a strath near Bullfrog Marina (1.5 ± 0.1 Ma; Darling et al., 2011) is significantly older than previously published cosmogenic ¹⁰Be exposure ages of surface clasts exposed on the deposit tread (0.48 ± 0.01 Ma; Davis et al., 2001). If robust and repeatable, these new burial ages give us pause, and reinforce the argument that we demonstrate above, namely that exposure ages of surface boulders in older deposits (likely >300 ka from our experience elsewhere; Marchetti et al., 2005b) are minimum age estimates of deposition. These two data sets suggest that for the Bullfrog deposit, the difference between surface boulder exposure ages and burial ages is a factor of 3. However, given the
extremely thick nature of the Bullfrog Marina deposits, we are uncertain that the surface boulder exposure ages are necessarily as severe of underestimates of the terrace depositional age as Darling et al. (2011) suggest. Hanks and Finkel (2005) make a similar argument regarding the cosmogenic burial results of Wolkowinsky and Granger (2004) at a site along the San Juan River. In aggrading deposits, the burial age of sediments deeper in a fill terrace should be older than those near the surface. Whether the difference is a short or long period of time depends upon whether the deposits are from single or multiple events, and the length of time of each depositional event. Regardless of the length of time of aggradation, the surface, and not the base of the deposit, is the best record of the last time that the deposit and its underlying bedrock strath were active parts of the fluvial system and since incised below. In that sense, cosmogenic burial ages might be best thought of as maximum age estimates of the abandonment of fluvial deposits and straths due to fluvial incision. Similarly, when cosmogenic burial ages are used to determine incision rates, those rates could be considered minimum rates because the burial ages represent the longest period of time over which the rates could be determined. This is especially the case when the burial ages are determined on sediments deep in the deposit near the deposit and/or strath contact. Ideally, the best age dating attempts would obtain cosmogenic burial ages deep in a deposit and multiple, independent surface or tread age estimates.

**Geomorphic Evolution of the Northern Tributaries of the Escalante River—Ideas and Speculations**

In this section, we discuss some ideas regarding the long-term landscape evolution of our field area with regard to the exposure ages and incision rates that we determined. It is important to remember that even our oldest exposure ages are likely minimum age estimates, and so our incision rates are maximum rate estimates. Therefore, some of the following discussion is speculative in nature because we make arguments that assume our incision rates are indeed 151–323 m Ma⁻¹ and not slower. Our goal is to explore ideas about possible controls on the deep incision seen in our field area and by exten-
An important observation regarding the boulder deposits we studied is their relationship to the Navajo Sandstone. The Black Mesa Bench deposit is just 1.5 km to the west of a deeply westward-dipping outcrop of Navajo Sandstone in the western limb of the Escalante anticline (Fig. 4A). It is also located at the downstream end of a deeply incised reach of Pine Creek, known as The Box, which is cut into Navajo Sandstone (Figs. 1 and 2). The New Home Bench, Durffey Mesa, and Deer Creek Bench deposit straths are all cut close to the upper stratigraphic boundary of the Navajo Sandstone. The very northernmost part of the New Home Bench deposit is actually cut into Carmel Formation (Fig. 6C), while most of the deposit is cut on the uppermost Navajo Sandstone. The Durffey Mesa deposit is cut into Carmel Formation (which interfingers with Page Sandstone, which is sedimentologically similar to Navajo Sandstone) just above the top of the Navajo Sandstone (Fig. 12). The Deer Creek Bench deposit is clearly cut onto Navajo Sandstone just above the top of the unit. Other field- and image-based observations made by us indicate that many of the other high-level, volcanic boulder-rich deposits in the area are cut near the stratigraphic top of the Navajo Sandstone.

Although the andesitic boulder deposits sit at a variety of elevations, the relief between different boulder deposit treads (and straths) is relatively small when compared to the variable but extreme incision of many of the northern tributaries (Fig. 12). This suggests a possible change in overall landscape morphology since deposition and abandonment of most of the high-level gravel deposit along the northern tributaries of the Escalante River in the past ~0.6–1.4 Ma. We hypothesize that prior to deep canyon incision, the overall relief of the distal Aquarius Plateau–Boulder Mountain piedmont was more subtle and the geomorphology was dominated by scarp retreat of the Aquarius Plateau–Boulder Mountain margin, colluviation and fluvial reworking, and effective lateral plantain. Since abandonment of the high-level gravel deposits, the geomorphology has been dominated by fluvial incision and deep canyon cutting. At some point, presumably after significant exposure of the Navajo Sandstone, the landscape morphology of the northern tributaries area changed and deep incision started and is currently still going on.

Our maximum incision rates of 151–323 m Ma⁻¹ demonstrate that this incision may have been proceeding at a faster rate than other longer-term (since 0.6–1.4 Ma) rates from around the Colorado Plateau (~40–150 m Ma⁻¹: Wolkovinsky and Granger, 2004; Darling et al., 2009, 2011) and the regional background incision rate of 100 m Ma⁻¹ assumed by Cook et al. (2009).

In a broad sense, both our incision rate estimates (from surface-exposure ages, likely maximum rates) and the other Colorado Plateau rates since the time period of 0.6–1.4 Ma (Wolkovinsky and Granger, 2004; Darling et al., 2009, 2011) (from cosmogenic burial ages, perhaps minimum rates) may be approaching the same value, especially given the large uncertainties associated with both dating techniques. In a more narrow sense, our rates do exceed the other regional estimates by 2–8 times and warrant some discussion. We suggest several possible explanations for the potentially faster rates of incision and deep overall landscape dissection seen in our field area since deposition of the high-level andesite gravels at 0.6–1.4 Ma:

(1) Retreat of the Aquarius Plateau–Boulder Mountain escarpment effectively shut off colluviation to the distal piedmont allowing more stream power to go into incision rather than sediment transport, deposition, and reworking. Effectively cutting off significant deposition of coarse...
TABLE 5. EXPOSURE AGES FOR DIFFERENT SCALING ROUTINES WITH 1 mm BOULDER SURFACE EROSION PER 10 ka (0.00001 cm yr⁻¹) AND ³He, FROM TABLE 4 (AGES IN ka)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Mesa Bench</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BMB-01</td>
<td>781 ± 114</td>
<td>679 ± 101</td>
<td>667 ± 99</td>
<td>673 ± 100</td>
</tr>
<tr>
<td>BMB-02</td>
<td>548 ± 78</td>
<td>480 ± 70</td>
<td>471 ± 68</td>
<td>476 ± 69</td>
</tr>
<tr>
<td>BMB-03</td>
<td>656 ± 95</td>
<td>568 ± 83</td>
<td>558 ± 82</td>
<td>562 ± 82</td>
</tr>
<tr>
<td>BMB-04</td>
<td>550 ± 78</td>
<td>482 ± 70</td>
<td>473 ± 69</td>
<td>478 ± 69</td>
</tr>
<tr>
<td>New Home Bench</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NHB-02</td>
<td>739 ± 112</td>
<td>645 ± 99</td>
<td>632 ± 97</td>
<td>638 ± 98</td>
</tr>
<tr>
<td>NHB-03</td>
<td>488 ± 72</td>
<td>430 ± 65</td>
<td>422 ± 63</td>
<td>426 ± 64</td>
</tr>
<tr>
<td>NHB-04</td>
<td>532 ± 77</td>
<td>469 ± 69</td>
<td>460 ± 68</td>
<td>465 ± 69</td>
</tr>
<tr>
<td>NHB-05</td>
<td>417 ± 66</td>
<td>364 ± 59</td>
<td>357 ± 57</td>
<td>360 ± 58</td>
</tr>
<tr>
<td>NHB-06</td>
<td>529 ± 76</td>
<td>468 ± 69</td>
<td>459 ± 67</td>
<td>464 ± 68</td>
</tr>
<tr>
<td>NHB-07</td>
<td>572 ± 82</td>
<td>502 ± 74</td>
<td>493 ± 72</td>
<td>498 ± 73</td>
</tr>
<tr>
<td>Durffey Mesa</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM-01</td>
<td>883 ± 131</td>
<td>777 ± 117</td>
<td>764 ± 115</td>
<td>771 ± 116</td>
</tr>
<tr>
<td>DM-02</td>
<td>384 ± 57</td>
<td>333 ± 50</td>
<td>327 ± 49</td>
<td>329 ± 49</td>
</tr>
<tr>
<td>DM-03</td>
<td>1087 ± 163</td>
<td>949 ± 144</td>
<td>932 ± 141</td>
<td>940 ± 143</td>
</tr>
<tr>
<td>DM-04</td>
<td>875 ± 131</td>
<td>770 ± 116</td>
<td>758 ± 114</td>
<td>764 ± 115</td>
</tr>
<tr>
<td>Deer Creek Bench</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DCB-01</td>
<td>408 ± 63</td>
<td>358 ± 56</td>
<td>351 ± 55</td>
<td>354 ± 56</td>
</tr>
<tr>
<td>DCB-02</td>
<td>337 ± 52</td>
<td>294 ± 46</td>
<td>289 ± 45</td>
<td>291 ± 46</td>
</tr>
<tr>
<td>DCB-03</td>
<td>10547 ± 265</td>
<td>1350 ± 232</td>
<td>1334 ± 227</td>
<td>1339 ± 230</td>
</tr>
<tr>
<td>DCB-04</td>
<td>862 ± 127</td>
<td>763 ± 114</td>
<td>748 ± 112</td>
<td>756 ± 113</td>
</tr>
</tbody>
</table>

Figure 11. Relationship between cosmogenic ³He exposure ages and boulder height for the deposits we sampled. The r values are the correlation coefficients between exposure age and boulder height determined for each surface. BMB—Black Mesa Bench; NHB—New Home Bench; DM—Durffey Mesa; DCB—Deer Creek Bench.
TABLE 6. INCISION RATE ESTIMATES

<table>
<thead>
<tr>
<th>Surface</th>
<th>Drainage</th>
<th>Depth of incision (m)</th>
<th>Oldest exposure age (ka)</th>
<th>Maximum incision rate (m Ma⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Mesa Bench</td>
<td>Pine Creek</td>
<td>228</td>
<td>706 ± 105</td>
<td>323</td>
</tr>
<tr>
<td>New Home Bench</td>
<td>Calf Creek</td>
<td>206</td>
<td>671 ± 104</td>
<td>307</td>
</tr>
<tr>
<td></td>
<td>Dry Gulch</td>
<td>142</td>
<td>671 ± 104</td>
<td>212</td>
</tr>
<tr>
<td>Durrfee Mesa</td>
<td>W side, unnamed</td>
<td>n/d</td>
<td>983 ± 150</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>E side, unnamed</td>
<td>n/d</td>
<td>983 ± 150</td>
<td>—</td>
</tr>
<tr>
<td>Deer Creek Bench</td>
<td>Deer Creek</td>
<td>210</td>
<td>1395 ± 241</td>
<td>151</td>
</tr>
</tbody>
</table>

Note: n/d—not determined.

Figure 12. Topographic profiles from A to A' and B to B' in Figure 2. The stratigraphic top of the Navajo Sandstone is shown with a dashed line as estimated from the structure contours in Weir and Beard (1990a, 1900b) and Williams et al. (1990). Ss—Sandstone; V.E.—vertical exaggeration.
Gravel-capped benches above northern tributaries of the Escalante River

gravels would still allow the northern tributaries to transport smaller, reworked andesitic clasts across the underlying bedrock. Since the andesitic clasts are significantly tougher than the local sedimentary bedrock (McLelland et al., 2008), this would lead to increased or easier incision. This “tool” effect is the opposite of the boulder armoring or “cover” effect previously mentioned, and demonstrates the interesting dichotomy in landscape response of areas with resistant lithologies that dominate the sediment load and weaker lithologies that make up the local bedrock when the amount and size of the resistant lithology in the sediment system varies (Sklar and Dietrich, 2001; Johnson et al., 2009).

(2) Exposure of the Navajo Sandstone allowed the northern Escalante tributaries to tap into a major source of water. The Navajo Sandstone exposed along the northern tributaries has relatively high porosity and hydraulic conductivity, and as demonstrated by the incredible iron mineralization in the area, has considerable fluid flow in the past (e.g., Beitrug et al., 2003; Loope et al., 2011). Several of the most deeply incised tributaries in the area start out as springs (e.g., Calf Creek), and most tributaries gain significant discharge from groundwater (Wilberg and Stolp, 2005). The Navajo Sandstone is also heavily fractured and jointed (e.g., Weir and Beard, 1990a, 1990b), and many of the northern tributaries are strongly controlled by the joint or fracture trends. Extreme fracturing and jointing, like that seen in the Navajo near the Escalante monocline, significantly weakens the overall rock unit, thus making fluvial incision easier (Molnar et al., 2007).

(3) Increased discharge due to melting of the Boulder Mountain ice cap at the end of the last two glacial cycles may have impacted the incision history of the Escalante River northern tributaries during the late Quaternary. Boulder Mountain had an ice cap with outlet glaciers during the LGM; however, it is unclear if it had an ice cap during the penultimate glacialiation (~150 ka; ~MIS 6) even though the nearby Fish Lake Plateau was glaciated at that time (Marchetti et al., 2011). Increased discharge to the northern tributaries of the Escalante River due to glacier melt could have increased incision rates for a short duration of time during deglaciation. Short periods of increased incision would, in turn, increase long-term rates.

(4) A fragmented knickzone may have propagated up the Escalante drainage from the main-stem Colorado River since drainage integration of the entire plateau at ~6 Ma. Cook et al. (2009) demonstrate that there is a significant profile convexity, or step, on the main-stem Escalante River system well downstream of the northern tributaries area (pink box in Fig. 1). They further suggest that if that knickzone is part of a transient incision signal propagating up the Escalante River from the main-stem Colorado system, then incision rates upstream of the knickzone should be slower than those measured at several sites downstream of the knickzones. Our incision rates of 151–353 m Ma⁻¹ are faster than the background incision rate of Cook et al. (2009) of ~100 m Ma⁻¹; however, they are maximum estimates. This may indicate that a fragment of the knickzone from Colorado River integration may have already passed up the Escalante and its northern tributaries. In this hypothetical scenario, the majority of the knickzone is still actively incising and likely hung up on the Escalante River convexity (Cook et al., 2009).

(5) Regional-scale mantle or epeirogenic based uplift may have caused faster incision. Studies of Colorado Plateau mantle dynamics have shown that faster incision rates are often associated with areas of lower-velocity mantle (Karlstrom et al., 2008, 2011, 2012; Crow et al., 2011). Since the upper Escalante drainage basin is near a marked transition in mantle P-wave velocities (fig. 1 in Crow et al., 2011), the potentially faster incision rates that we determine may be attributable to a more buoyant mantle at our site, which is near the western edge of the Colorado Plateau. Pederson et al. (2007) argue that the deep exhumation in the central Canyonlands region over the past ~6 Ma has led to >1 km of epeirogenic uplift of the central plateau. Our research site is near the western margin of that uplift and may have higher than expected incision rates in the past 0.6–1.5 Ma because of it.

CONCLUSIONS

The gravel deposits located high above the northern tributaries of the Escalante River are composed of andesitic boulders that were derived from the southern margins of Aquarius Plateau and Boulder Mountain. The stratigraphy and sedimentology of the deposits suggest that transport and deposition were predominantly by mass movement, with the deposits reworked by fluvial processes after deposition. Exposures into the deposits indicate that they are composite and likely represent multiple episodes of deposition and reworking before final abandonment. The deposits cover bedrock straths and represent former valley floors that were inundated by coarse volcanic debris and subsequently incised around by local drainages. Since the volcanic boulders are more physically and chemically resistant to erosion than the local sedimentary bedrock, the volcanic boulders erode more slowly, and deposits of the volcanic boulders help to armor and preserve the bedrock straths they were deposited on. This leads to topographic inversion or inversion of relief on a variety of scales. Cosmogenic ³⁷Cl exposure-age dating of some of the largest boulders exposed on the treads of four different deposits range from 303 ± 48 to 1395 ± 241 ka. The tallest boulders exposed on the deposit surfaces tend to yield the oldest exposure ages, suggesting that boulder erosion and deposit erosion are controlling the exposure-age populations and indicating that even the oldest exposure ages from a given deposit are likely minimum age estimates. Using the oldest exposure age from each surface, we estimate maximum tributary incision rates of 151–323 m Ma⁻¹. Our incision rates are the same order of magnitude as other regional incision rate estimates determined over the same time interval. However, if our incision rate estimates are not an overestimate, then the northern tributaries of the Escalante River may be incising faster than other regional sites over the past 0.6–1.4 Ma.

ACKNOWLEDGMENTS

We thank Alan Rigby, Suzanne Bthers, Will Gallin, and Elsie Denton for help with fieldwork. The 2010 Western State College of Colorado Research in Quaternary Geology class made most of the boulder and pebble count measurements. Kip Solomon and Alan Rigby assisted with Al analyses at the University of Utah Dissolved and Noble Gas Laboratory, Doug Powell of the Grand Staircase Escalante National Monument helped with fieldwork, logistics, and securing funding. The Grand Staircase Escalante National Monument, University of Utah, Colgate University, and Western State College of Colorado provided funding. Conversations with Bob Webb, Cassie Fenton, Brenda Beitrug Bowen, and John Dohrenwend influenced our thoughts on the incredible landscapes of the Grand Staircase Escalante National Monument (GSENM). Two anonymous reviewers and an Associate Editor of the Colorado River evolution themed issue provided very helpful reviews and comments.

REFERENCES CITED


William, V.S., Weir, G.W., and Beard, L.S., 1990b, Geologic Map of the King Bench Quadrangle, Garfield County, Utah: Utah Geological and Mineral Survey Map 119, scale 1:24,000, 2 sheets, p. 5 text.


