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Reconstructing the timing of flash floods using ^{10}Be surface exposure dating at Leidy Creek alluvial fan and valley, White Mountains, California–Nevada, USA

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ABSTRACT

Large alluvial fans characterize the piedmonts of the White Mountains, California–Nevada, USA, with large boulders strewn across their surfaces. The boulders are interpreted as flash floods deposits with an unclear trigger for the transport process. Several triggers are possible, including glacial lake outburst floods (GLOFs), thunderstorms or rainfall on snow cover. From a paleoenvironmental perspective, the origin of the flash floods is of fundamental importance. The alluvial fans that flank the White Mountains at Leidy Creek display particularly impressive examples of these deposits. The boulder deposits and the source catchment at Leidy Creek were examined using ^{10}Be terrestrial cosmogenic nuclide (TCN) surface exposure dating to help elucidate their age and origin. All boulders dated on the alluvial fans date to the Holocene. This is in accordance with the geomorphic analyses of the Leidy Creek catchment and its terraces and sediment ridges, which were also dated to the Holocene using optically stimulated luminescence (OSL) and ^{10}Be surface exposure. The results suggest that the boulders on the alluvial fan were deposited by flash floods during thunderstorm events affecting the catchment of the Leidy Creek valley. Paleomonsoonal-induced mid-Holocene flash floods are the most plausible explanation for the discharges needed for these boulder aggradations, but a regional dataset is needed to confirm this explanation.

Introduction

Alluvial fans are distinct landforms that are ubiquitous in the forelands of many mountain ranges, particularly in semiarid environments (Bull, 1977; Harvey, 1997). Most alluvial fans form where a stream exits the mountains through a narrow valley, resulting in a change in the hydrologic geometry of the flow, leading to a decrease in transport capacity and the deposition of sediment to form a fan-shaped landform (Bull, 1977). Alluvial fans store the material eroded and transported from the mountainous source area, and therefore reflect the physiogeography (e.g., morphology, lithology, aspect, vegetation) of the source region. The main factors controlling the sediment delivery to alluvial fan surfaces and characterizing the shape and sedimentary architecture of alluvial fans include the morphology, lithology, climate and its associated hydrology, and tectonics of the catchment (Harvey et al., 2005; Miall, 2006; Bridge and Demicco, 2008). Thus, alluvial fans potentially represent valuable sedimentary archives of past environmental conditions (Dorn, 1996; Reheis et al., 1996; Harvey et al., 1999; Harvey, 2005; Sohn et al., 2007; Sancho et al., 2008).

In semiarid environments, where alluvial fans are common, high surface runoff responsible for the formation of alluvial fans is dominantly generated by intensive rainfall, resulting in episodic flash floods with high sediment loads (Harvey, 1997). These high-energy flows produce debris-flow, sheetflood and channel deposits that comprise various clast sizes, which may be up to several meters in diameter. These clasts may armor the surface of the alluvial fans. Deposits and surfaces with meter-size boulders reflect high-energy transport processes often associated with flash floods events during temporally and spatially variable thunderstorms or, in mountain regions, with rainfall on a preexisting snow cover. Catastrophic glacial lake outburst floods (GLOFs) can generate high-energy transport processes in glaciated mountain regions. GLOFs are particularly common when glacial retreat causes ponding of the glacial meltwater behind frontal moraines or as supraglacial lakes (Clague and Evans, 2000; Benn, 2004; Korup and Tweed, 2007).

Flash floods events triggered by thunderstorms, rainfall on snow cover or GLOFs, transport the sediment and its meter-size boulders from the mountainous catchment to alluvial fan surfaces. The dominant

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factor controlling the sediment supply within the catchment is the weathering rate, which is in turn dependent on the geological configuration of the source area, its topography and climate. In tectonically active regions, earthquake-triggered landslides and rock falls can additionally contribute to the sediment supply. The ratio of sediment supply within the catchment and removal of the sediment to the fan surface by fluvial transport defines the geomorphic alluvial fan system as supply or transport limited (Goudie, 2004). This ratio needs to be considered, when alluvial fan deposits are used as environmental sediment archive representative of the alluvial fan catchment.

Along the eastern Sierra Nevada of California in Owens Valley, clusters of boulders are present on many of the alluvial fans (Blair, 2001; Benn et al., 2006). Blair (2001) and Benn et al. (2006) interpreted the boulders on alluvial fans and their associated sediments near Lone Pine in Owens Valley to be GLOF deposits. Benn et al. (2006) determined using ^{10}Be terrestrial cosmogenic nuclide (TCN) surface exposure dating that the alluvial fan surface boulders were deposited during the late Pleistocene and were likely coincident with times of deglaciation in the Sierra Nevada. The western margin of the White Mountains in Owens Valley, to the east of the Sierra Nevada, is also flanked by large alluvial fans (Beaty, 1989; Blair and McPherson, 1998). In contrast, the boulders on some of these alluvial fans were interpreted, based on geomorphic mapping, to have been deposited during thunderstorm-driven debris-flow events (Beaty, 1989; Hubert and Filipov, 1989). However, Beaty (1989) and Hubert and Filipov (1989) did not directly examine the boulders, and they only considered the last few hundreds of years of alluvial-fan formation. It is plausible that older generations of boulders could have been transported by GLOF-driven debris-flows. In this case, the boulders should be Pleistocene in age because the White Mountains are currently unglaciated, were not glaciated during the Holocene, and experienced only localized glaciation during the Pleistocene (Osborn and Bevis, 2001).

Large alluvial fans are also present along the eastern side of the White Mountains around Leidy Creek in Fish Lake Valley. To provide more insights on the nature of alluvial fan formation around Leidy Creek, specifically the origin of large surface boulders, we chose to undertake a Quaternary geochronological study of the alluvial fans and their source area. The late Quaternary sedimentation on the Leidy Creek alluvial fan and other fans of Fish Lake Valley was investigated by Reheis et al. (1996) and Slate (1992). These studies provided an excellent framework for our geomorphic and geochronological work. Slate (1992) concluded that climate is the dominant factor controlling alluvial-fan deposition in Fish Lake Valley on the eastern side of the White Mountains, as geomorphically similar fans were observed regardless of the presence or absence of an active fault along the mountain front. Based on paleopedological and sedimentological evidence, supported by radiocarbon dating, she proposed that alluvial-fan deposition occurs during warm and dry climates of interglacial times, whereas the alluvial fans were stable or incised during glacial time. Debate exists, however, regarding the origin of some of the landforms within the source area for the Leidy Creek fan, specifically whether some of the landforms are of glacial or fluvial origin (Krauskopf, 1971; Elliott-Fisk, 1987).

In our study, we examine the landforms within the source area of the Leidy Creek alluvial fan as well as the nature of the large surface boulders on the Leidy Creek alluvial fan. We analyze the landforms and apply ^{10}Be TCN surface exposure dating to determine the age of deposition of the boulders on both the alluvial-fan surface and associated landforms within the source region. In addition, we date terraces in the source valley using optically stimulated luminescence (OSL) methods. Determining the timing of deposition, especially the timing of these extreme events, has important implications for the paleoclimatological significance of these events. We highlight the potential and the challenges associated with using boulder aggradation on alluvial fans as paleoenvironmental proxies and discuss the need for a more regional approach.

Study area

The White Mountains stand between two broad valleys, Owens and Fish Lake, trending NW and traversing the California–Nevada state line. They rise from between ~1500–2000 m above sea level (asl) at the valley floor to 4344 m asl, at White Mountain Peak and are not currently glaciated (Fig. 1). The mountains are the westernmost range of the central Basin and Range province, and they formed as a result of uplift and eastward tilting of a crustal block (Stewart, 1988; Lueddecke et al., 1998; Stockli et al., 2003), which is bounded on its eastern and western flanks by active right-lateral strike-slip faults (Reheis and Dixon, 1996; Reheis and Sawyer, 1997; Frankel et al., 2007). Alluvial fans flank both the eastern and western margins of the White Mountains to form extensive bajadas.

The Leidy Creek alluvial fan extends over a distance of ~9 km from ~1850 m asl at its apex at the range front to ~1460 m asl at its toe in Fish Lake Valley (Fig. 2). Based on surface characteristics and age determinations of the sediments, the late Quaternary fan deposits were mapped and morphochronologically classified by Slate (1992) and Reheis et al. (1996). The bedrock in the catchment of the Leidy Creek alluvial fan is diverse but is dominated by Jurassic and Cretaceous granites, and Mesozoic metavolcanic and metasedimentary rocks (Krauskopf, 1971). Steep V-shaped valley slopes characterize the geomorphology of the source valley, which are generally covered by a thin veneer of colluvium and regolith. Alluvial deposits fill the source valley bottom, with isolated patches of poorly sorted diamict and gravel up to 20 m thick that form distinct longitudinal ridges along the valley floor (Fig. 3). Krauskopf (1971) interpreted these sediments in the uppermost 3 km of the valley to be Pleistocene glacial deposits, and in the middle and lower 7 km of the valley to be Pleistocene alluvial deposits. In contrast, Elliott-Fisk (1987) argued, that all the deposits were glacial in origin and that they formed in a more extensive glaciation than proposed by Krauskopf (1971).

The eastern White Mountains have a semiarid to arid climate. Annual precipitation in Fish Lake Valley at 1500 m asl, where the Leidy Creek alluvial fan is located, is ~130 mm and at the crest of the mountain range it is ~460 mm. In late summer, the White Mountains are affected by warm and moist air masses from the Gulf of California, known as the North American monsoon, leading to convective small-scale thunderstorm events (Hall, 1991). As a consequence and typical for drylands, these rainfall events are highly variable, frequently triggering flash floods. Nevertheless, heavy fall and winter rainfall events are also possible, even though they are less frequent and their magnitude is less pronounced than thunderstorms in summertime (Kattelmann, 1992).

Desert scrub is the dominant vegetation on the alluvial fan, while juniper and pine trees are pervasive throughout the source valley up to ~1900 m asl, where bristlecone pines are common up to an altitude of 3050 m asl (Hall, 1991).

Methods

Geomorphic mapping and sampling

We used the mapping of Slate (1992), Reheis (1995) and Reheis et al. (1996) as a framework for our work on the Leidy Creek alluvial fan, and the studies of Krauskopf (1971) and Elliott-Fisk (1987) in the source valley for the Leidy Creek alluvial fan. Boulders for ^{10}Be TCN dating were located on surfaces of different ages as mapped by Slate (1992), Reheis (1995) and Reheis et al. (1996). Within the valley, the landforms and sediments were examined, measured and described using standard geomorphic and sedimentological methods.

^{10}Be TCN surface exposure dating

^{10}Be TCN surface exposure dating determines the time elapsed since a rock surface was exposed at the surface (Gosse and Phillips, 2001;

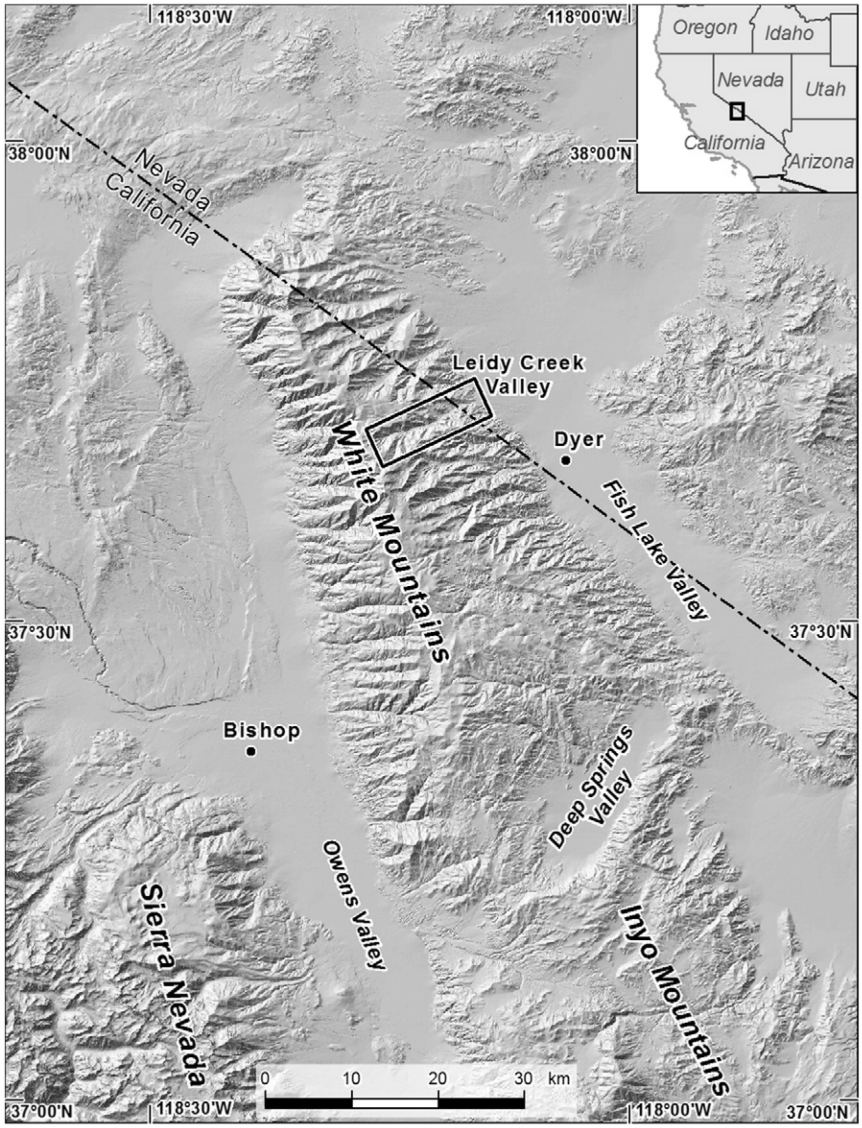

Figure. 1. The study area in the White Mountains at the California–Nevada state line. The black box indicates the catchment of the Leidy Creek valley.

Figure. 2. View of the Leidy Creek alluvial fan looking towards its apex and into the Leidy Creek valley. The massive boulder on the fan surface, ca. 2.5 m diameter, represents high-energy flash-flood deposits. Note the white cars in the middle ground for scale.

Ivy-Ochs and Kober, 2008). Many studies have already demonstrated the successful application of ^{10}Be surface exposure dating, and also for dating boulders transported by flash floods (Barnard et al., 2006; Benn et al., 2006; Seong et al., 2009). Sixteen boulders were sampled for dating. Boulders ranged in size from 2 to 7 m in length and those that exhibited little evidence of weathering were preferentially chosen (Fig. 4). For every sampled boulder, the location and geomorphic setting, size, shape and weathering characteristics were documented. No correction for topographic shielding was needed because the inclination to all the surrounding topography was <20° (Gosse and Phillips, 2001).

Approximately 250 g of rock was chiseled off the upper surface of each boulder to a depth of <5 cm. Sample preparation was undertaken at the Geochronology Laboratories at the University of Cincinnati. To extract the quartz from the rock samples, the material was first crushed and sieved to obtain the 250–500 μm particle size fraction. This fraction was processed using four acid leaches: aqua regia for 9 h, two 5% HF/HNO_3 leaches for 24 h, and one 1% HF/HNO_3 leach for 24 h. Heavy-liquid separation using lithium heteropolytungstate was applied after the first 5% HF/HNO_3 leach. Be carrier was added to the pure quartz extracts. The quartz was dissolved in 49% HF and HNO_3, fumed with perchloric acid, and passed through anion and cation exchange columns along with chemical blanks to extract $Be(OH)_2$. The $Be(OH)_2$ was

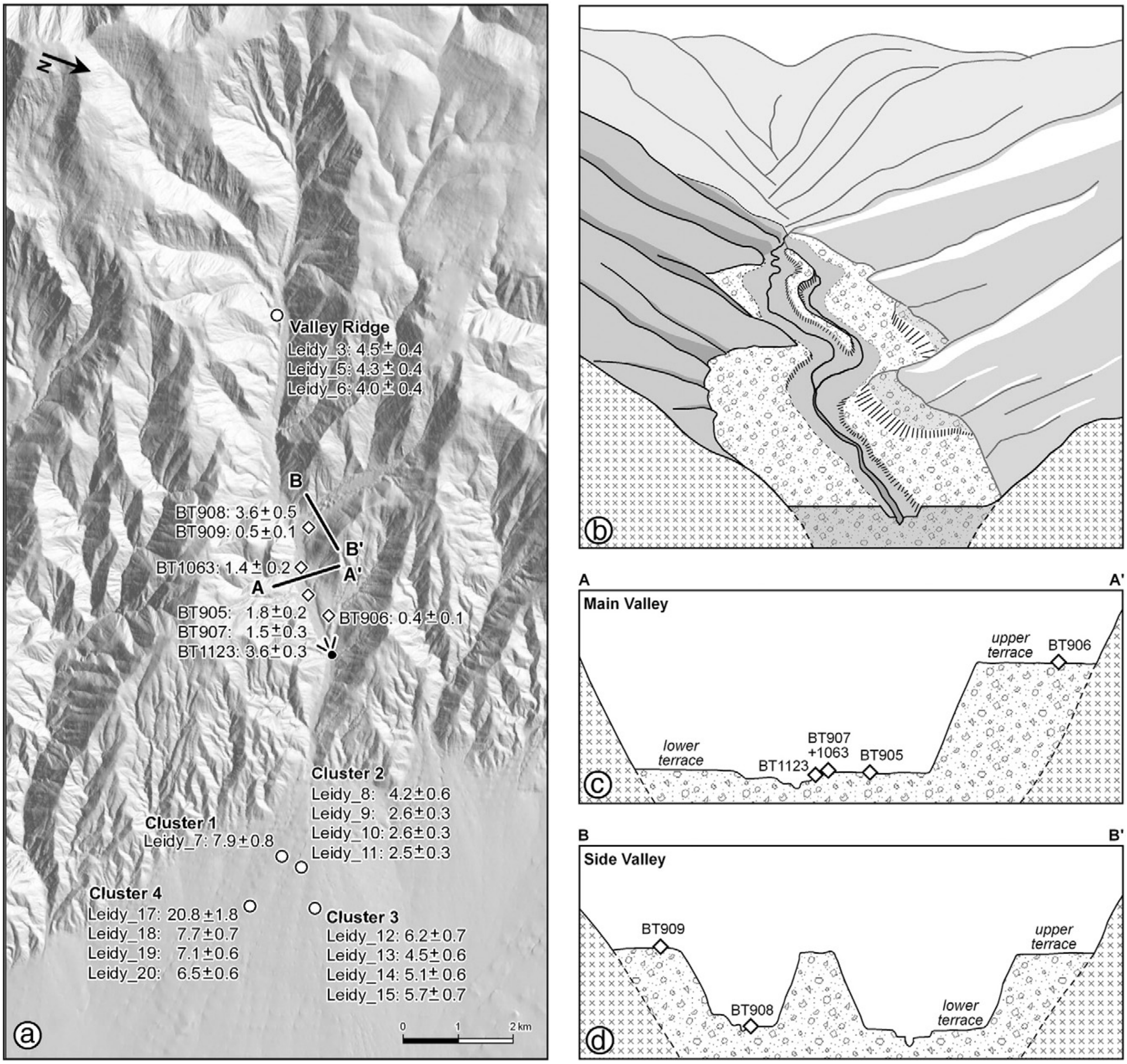

Figure. 3. Leidy Creek valley and its alluvial fan: a) Overview of the valley and its alluvial fan with sampling position for ^{10}Be TCN and OSL dating, including sample ID and ages in ka (uncertainty = 1σ). In addition, the viewpoint into the Leidy Creek valley given in part b is indicated (black dot) as well as the cross-section positions given in parts c and d. b) View into the V-shaped Leidy Creek valley with an upper and lower terrace and sediment bodies within the valley of up to 20 m height in places. The viewpoint is given in part a. c) Cross-section of the main valley with OSL sample positions. d) Cross-section of the side-valley with OSL sample positions.

combusted at 750°C to produce BeO, which was then dried and mixed with Nb powder and loaded in stainless steel targets. The targets were sent to the PRIME laboratory at Purdue University where the $^{10}Be/^{9}Be$ ratios were determined by accelerator mass spectrometry (AMS). Ages were computed with the CRONUS-Earth online calculator (http://hess.ess.washington.edu, Version 2.2.) using a time-varying production model based on Lal (1991) and Stone (2000). We recognize that the use of different models will result in different ^{10}Be ages by up to 8% for Holocene samples at this location. However, this difference does not affect the conclusions reached in our study.

Optically stimulated luminescence (OSL) dating

Optically stimulated luminescence (OSL) dating determines the last process of sediment reworking and therefore enables the direct age determination of depositional age for sediment (Rhodes, 2011). The successful application of OSL dating on fluvial sediments has been demonstrated in many studies and in a diverse range of environments (Chen et al., 2008; Rittenour, 2008; Fuchs et al., 2010). However, due to the flow characteristics and the turbidity of debris-flows, these sediments are prone to insufficient bleaching, which can result in age overestimations. To deal with this problem, there are several approaches (Agersnap Larsen et al., 2000; Fuchs and Wagner, 2003; Olley et al., 2004; Murray et al., 2012), with one approach analyzing dose distributions generated from small aliquot or single-grain measurements. Following this approach, it is argued that the part of the dose distribution showing low equivalent doses represents the best-bleached part of the distribution and therefore best OSL age estimates (Galbraith et al., 1999; Fuchs and Lang, 2001; Lepper and McKeever, 2002).

OSL samples were collected from natural exposures, five samples from the lower and two samples from the upper part of the Leidy Creek river terrace (Fig. 3). Sampling was undertaken at night, after the light-exposed outer ~10 cm sediment layer was removed.

Figure. 4. Typical boulder (Leidy_14) on the Leidy Creek alluvial fan surface being examined by Kurt Frankel. For location of the boulder see Figure 3.

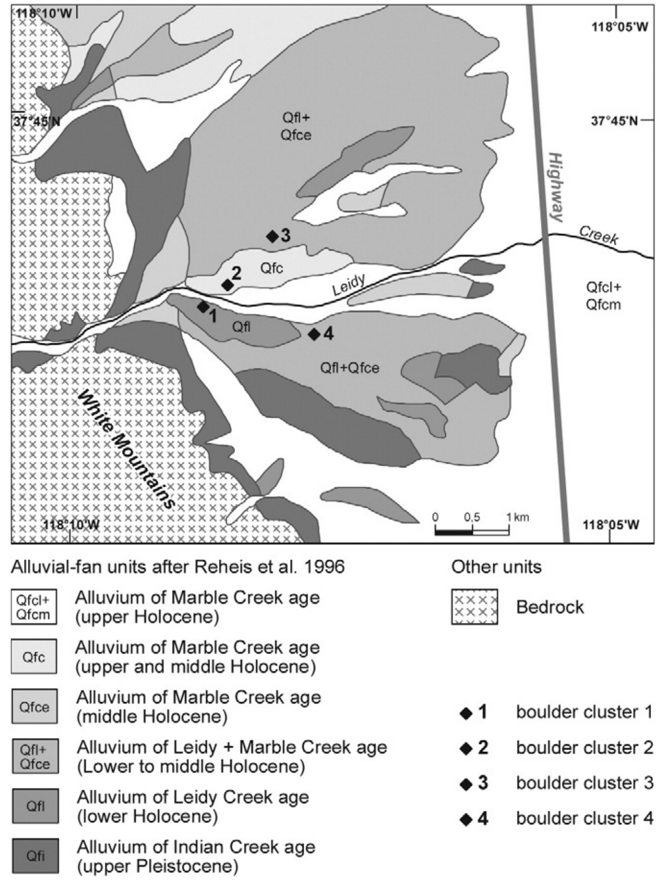

Figure. 5. Late Pleistocene Leidy Creek alluvial fan with alluvial fan units after Reheis (1995) and Reheis et al. (1996). The four boulder clusters that were sampled for ^{10}Be TCN dating are highlighted.

Sample preparation and measurement were undertaken at the Luminescence Laboratory in Bayreuth University under subdued red light (640 ± 20 nm) conditions. Sampled sediment was sieved and treated with HCl and H_2O_2 to remove any carbonates and organics. Density separation using lithium-heteropolytungstate was used to help separate quartz from heavy minerals (>2.75 g/cm^3) and feldspars (<2.62 g/cm^3). The quartz separate was etched in 40% HF for 60 min to remove any potential feldspar contamination and also the alpha-irradiated outer layer of the grains.

OSL equivalent dose determination was undertaken on the coarse-grained quartz fraction (90–200 μm) applying the single aliquot regenerative-dose (SAR) protocol of Murray and Wintle (2000). Small aliquots were used to help detect possible incomplete resetting of the luminescence signal during the last process of erosion, transportation and deposition, which would result in an age overestimation (Fuchs and Wagner, 2003). In addition, the technique of Fuchs and Lang (2001) was applied to help determine equivalent doses from insufficiently bleached samples, where the lower end of the dose distribution is thought to represent the correct equivalent dose.

Dose rates were determined by thick source α-counting and ICP-MS, calculating the cosmic-ray dose rates after Prescott and Hutton (1994). The water content of the samples was determined using the average value of the possible water content range, based on the estimated porosity of the samples.

Results

Alluvial fan

Four distinct areas with boulder clusters were identified and sampled on the alluvial fan surface in the upper- and mid-fan position (boulder clusters 1–4; Figs. 3 and 5). Each cluster consists of several surface boulders, which was associated with the late Quaternary alluvial fan sediment units of Slate (1992) and Reheis et al. (1996), who used the criteria surface form, desert varnish and soil development in combination with numerical dating to map the different alluvial fan units. Thereafter, cluster 1 is associated with the Leidy Creek alluvium unit (Qfl) of early Holocene age, whereas cluster 2 is situated on the upper to middle Holocene Marble Creek unit (Qfc). Clusters 3 and 4 are associated with the lower to middle Holocene Leidy Creek/Marble Creek unit (Qfl and Qfce).

Thirteen samples for ^{10}Be TCN dating were collected from four boulder clusters on the Leidy Creek alluvial fan. The geographical and analytical results of each dated boulder are listed in Table 1. No correction for topographic shielding was necessary because of the topographic position of the Leidy Creek alluvial fan in the broad Fish Lake Valley. No correction for rock weathering was applied, as all of the sampled boulders showed little signs of weathering, and we had no independent means of estimating the weathering rate for each individual boulder.

One boulder (Leidy_7) was dated from boulder cluster 1, which yielded an age of 7.9 ± 0.8 ka. Four boulders (Leidy_8 to Leidy_11) were dated from boulder cluster 2 that ranged in age from 2.5 ± 0.3 ka to 4.2 ± 0.6 ka. Three of these ages are the same within their uncertainties, resulting in a mean age of 2.6 ± 0.3 ka. The fourth boulder with an age of 4.2 ± 0.6 ka (Leidy_8) is interpreted as an outlier, likely having inherited ^{10}Be due to prior exposure. Four boulders (Leidy_12 to Leidy_15) were also dated from boulder cluster 3, with a range of ages from 4.5 ± 0.6 ka (Leidy_13) to 6.2 ± 0.7 ka (Leidy_12). Since every age overlaps within the uncertainty of at least one other sample, we calculated a mean age of 5.4 ± 0.6 ka from all four ages (Table 1). The age of boulder cluster 4 is also determined from four boulders (Leidy_17 to Leidy_20). Three boulders record similar ages with a mean age of 7.1 ± 0.6 ka, whereas the largest boulder (Leidy_17) had an age of 20.8 ± 1.8 ka and is considered an outlier, most probably also due to inherited ^{10}Be in a boulder that had prior exposure.

Leidy Creek Valley

Leidy Creek Valley is V-shaped with steep valley sides. The modern creek has incised into poorly sorted alluvial valley fills exhibiting debris-flow sediment structures with subangular to rounded particles, ranging from silt to boulder size. Two distinct levels of alluvial fill are partially preserved forming two generations of alluvial terraces, which we name the lower and upper terraces. The upper terrace has a

Table 1
^{10}Be samples and their location, analytical results and ages.

Sample	Latitude [DD]	Longitude [DD]	Elevation [m asl]	Thickness [cm][a]	Production rate[b] [atoms g^{-1} a^{-1}]		Quartz[c][g]	Be carrier [mg]	$^{10}Be/^{9}Be$[d, e] [$\times 10^{-14}$]	^{10}Be concentration[f] [10^4 atoms g^{-1} SiO_2]	Age[e, f][ka]
					Spallation	Muons					
Valley ridge											
Leidy_3	37.6981	−118.2289	2515	4.0	25.63	0.398	30.1006	0.3051	19.38 ± 0.44	11.15 ± 0.28	4.5 ± 0.4
Leidy_5	37.6981	−118.2289	2524	3.5	25.89	0.400	30.1422	0.3030	19.00 ± 0.45	10.83 ± 0.28	4.3 ± 0.4
Leidy_6	37.6981	−118.2289	2524	2.5	26.11	0.401	30.3925	0.3029	17.69 ± 0.37	9.98 ± 0.24	4.0 ± 0.4
Boulder cluster 1											
Leidy_7	37.7311	−118.1465	1757	4.0	15.43	0.317	20.2364	0.4401	6.39 ± 0.32	12.60 ± 0,63	7.9 ± 0.8
Boulder cluster 2											
Leidy_8	37.7329	−118.1457	1755	2.0	15.66	0.319	9.8070	0.4114	1.68 ± 0.19	6.37 ± 0.72	4.2 ± 0.6
Leidy_9	37.7328	−118.1452	1753	5.0	15.26	0.316	15.3625	0.4126	1.55 ± 0.09	3.76 ± 0.22	2.6 ± 0.3
Leidy_10	37.7328	−118.1449	1748	5.0	15.20	0.315	19.2334	0.4317	1.84 ± 0.13	3.73 ± 0.26	2.6 ± 0.3
Leidy_11	37.7331	−118.1447	1742	5.0	15.14	0.315	20.2350	0.4168	1.97 ± 0.13	3.67 ± 0.23	2.5 ± 0.3
Boulder cluster 3											
Leidy_12	37.7370	−118.1413	1719	2.0	15.27	0.315	6.1625	0.2059	3.21 ± 0.21	9.69 ± 0.65	6.2 ± 0.7
Leidy_13	37.7373	−118.1398	1710	4.0	14.92	0.312	15.3010	0.3914	2.84 ± 0.27	6.58 ± 0.62	4.5 ± 0.6
Leidy_14	37.7372	−118.1396	1709	2.0	15.17	0.314	23.4420	0.4077	4.84 ± 0.38	7.61 ± 0.60	5.1 ± 0.6
Leidy_15	37.7370	−118.1391	1705	2.0	15.12	0.314	2.0367	0.1921	1.01 ± 0.10	8.65 ± 0.87	5.7 ± 0.7
Boulder cluster 4											
Leidy_17	37.7271	−118.1364	1703	2.0	15.10	0.313	21.4348	0.4003	16.40 ± 0.40	32.70 ± 0.80	20.8 ± 1.8
Leidy_18	37.7272	−118.1364	1703	1.5	15.16	0.314	19.0954	0.4228	6.81 ± 0.23	12.10 ± 0.41	7.7 ± 0.7
Leidy_19	37.7272	−118.1363	1704	2.5	15.05	0.313	20.9151	0.4120	5.81 ± 0.20	11.00 ± 0.37	7.1 ± 0.6
Leidy_20	37.7271	−118.1363	1704	4.0	14.86	0.312	21.0231	0.4401	5.31 ± 0.20	9.91 ± 0.37	6.5 ± 0.6

[a] The tops of all samples were exposed at the surface. No geometric shielding correction for topography was necessary (horizon < 20° in all directions).
[b] Local production rate based on Lal (1991) and Stone (2000), using a time-dependent model.
[c] A density of 2.7 g cm^{-3} was used based on the granitic composition of the surface samples.
[d] Isotope ratios were normalized to ^{10}Be standards prepared by Nishiizumi et al. (2007).
[e] Uncertainties are reported at the 1σ confidence level.
[f] Beryllium-10 model ages were calculated with the Cosmic-Ray Produced Nuclide Systematics (CRONUS) Earth online calculator (Balco et al., 2008) version 2.2. (http://hess.ess.washington.edu).

maximum width of ~150 m and rises ~20 m above the active channel, the lower terrace has a width of ~120 m and rises ~5 m above the active channel. The relationship between the different generations of terraces is best observed within smaller side valleys near the confluence with the main valley. A schematic representation of the geomorphic context of the terraces for the main and a side valley is presented in Figure 3.

Table 2 provides the analytical results of each OSL sample from the terraces. From the main valley, four samples from the lower terrace (BT905, BT907, BT1063, BT1123) were dated (Fig. 3). Sample BT905 yielded an age of 1.8 ± 0.2 ka, which is confirmed by two OSL samples, taken ~50 m down valley (BT907) and ~400 m up valley (BT1063) from sample BT905, that yielded ages of 1.5 ± 0.3 ka and 1.4 ± 0.2 ka, respectively. All of these ages are the same within their uncertainties. At location BT907, but at 200 cm depth, sample BT1123 from the lower terrace has an age of 3.6 ± 0.3 ka, which is in accordance with sample BT908 (3.6 ± 0.5 ka) also taken from the lower terrace, but situated in the side valley (Fig. 3). All of these ages from the lower terrace indicate a late to middle Holocene terrace formation. OSL ages for samples from the upper terrace (BT906, BT909) yielded very young ages (<0.5 ka; Table 2). Since the older terrace is situated topographically above the younger one, these burial ages seem to be unrealistically young. Possible reasons for this age underestimation could be bioturbation or recent sediment reworking by overland flow, the latter indicated by recent rill erosion.

In the middle reach of the Leidy Creek Valley (Fig. 3), a dissected isolated sediment body forms an elongate ridge with its longitudinal axis parallel to the valley. The ridge is up to ~20 m in height, with a relatively flat surface and well-developed pavement, comparable to the downstream terraces (Fig. 7). The height and inclination of the ridge surface, gently dipping downstream, correlate well with several unpaired terraces found along the catchment, described previously as the lower terrace (Fig. 3). The sediment comprising the ridge consists of poorly sorted, subangular to rounded grains, with sizes ranging from silt to boulders. Large boulders up to 2 m edge length are present on top of the ridge and yield exposure ages of 4.5 ± 0.4 ka (Leidy_3),

Table 2
Sample locations, analytical data and ages for the OSL dating.

Sample	Terrace	Sample depth [cm]	Latitude [°N]	Longitude [°W]	U [ppm]	Th [ppm]	K [%]	$\dot{D}$ [Gy/ka]	D_e [Gy]	OSL age [ka]
BT905	lT	40	37.71854	118.18779	9.53 ± 0.68	18.38 ± 2.25	2.40 ± 0.12	5.65 ± 0.36	10.03 ± 0.54	1.8 ± 0.2
BT906	uT	30	37.72292	118.18552	5.55 ± 0.58	19.01 ± 1.94	2.93 ± 0.15	5.30 ± 0.34	2.60 ± 0.30	0.5 ± 0.1
BT907	lT	40	37.71866	118.18751	7.57 ± 0.56	33.89 ± 1.86	1.22 ± 0.06	5.14 ± 0.31	7.91 ± 1.34	1.5 ± 0.3
BT908	lT	140	37.71425	118.19796	3.87 ± 0.27	10.83 ± 0.91	2.91 ± 0.15	4.41 ± 0.26	15.85 ± 1.81	3.6 ± 0.5
BT909	uT	40	37.71494	118.19798	6.20 ± 0.31	11.18 ± 1.02	2.96 ± 0.15	4.98 ± 0.29	2.20 ± 0.29	0.4 ± 0.1
BT1063	lT	40	37.71596	118.19137	7.72 ± 0.75	21.00 ± 2.50	2.73 ± 0.09	5.71 ± 0.37	7.98 ± 0.69	1.4 ± 0.2
BT1123	lT	200	37.71866	118.18751	7.51 ± 0.44	16.25 ± 1.46	2.89 ± 0.09	5.49 ± 0.32	19.70 ± 1.27	3.6 ± 0.3

Note: for dose rate calculation, a water content of 15% was used. The water content was determined using the average value of the possible water content range, based on the porosity of the samples. An error for the water content value was chosen, which included the possible water content range. OSL age uncertainties were calculated, using the standard error of the D_e distribution.
Terrace: lT lower terrace; uT upper Terrace.

Figure. 6. Leidy Creek valley showing the lower terrace of the valley. The steep slope to the right is the flank of the upper terrace.

4.3 ± 0.4 ka (Leidy_5) and 4.0 ± 0.4 ka (Leidy_6), with a mean age of 4.3 ± 0.3 ka (Fig. 3; Table 1).

The exposure age of the boulders on the ridge agrees within their uncertainties with the age of sediment at depth in the lower terrace. The inclination of the ridge surface in direction to the valley outlet and the heights of the surface all suggest that these ridges are fluvially dissected remnants of a former valley fill. The sorting and roundness of the sediments, indicative of fluvially reworked debris-flow deposits, within these features further support this interpretation.

Discussion

All of the dated boulder clusters on the Leidy Creek alluvial fan have Holocene ages (Table 1). These ^{10}Be ages agree with the age assignments for the alluvial fan surfaces proposed by Slate (1992) and Reheis (1995). Given that the boulders were deposited during the Holocene, we can rule out a GLOF origin for them, assuming that Osborn and Bevis (2001) are correct in asserting that the White Mountains were not glaciated during the Holocene. The absence of Holocene glaciers in the White Mountains is also supported by the work of Zreda and Phillips (1995) and Phillips et al. (1996) who dated moraines from the Chiatovich Creek in the White Mountains, ~12 km north of Leidy Creek, that yielded Pleistocene ages using ^{36}Cl TCN methods with one minimum age of 11 ka, suggesting they formed only in the late Pleistocene.

Figure. 7. Elongated sediment ridges in the middle reach of the Leidy Creek valley. These ridges are up to 20 m high and have flat-topped ridge surfaces, which represent the former valley bottom. The inset shows the sediment composition of the ridges, with subangular small and large cobbles and boulders, typical of debris-flow deposits. The person provides the scale (1.65 m tall).

The isolated sediment ridge situated in the middle reach of the Leidy Creek valley (Fig. 3) also has a Holocene age (^{10}Be age of 4.3 ± 0.3 ka). The Holocene age and sedimentary characteristics of the ridge clearly show that the glacial interpretation of this feature by Elliott-Fisk (1987) as a glacial moraine must be rejected. Instead, with our new chronological data, we concur with the interpretation of Krauskopf (1971) that the sediment ridge in the middle reach of the valley is fluvial in origin. Therefore, the sediment ridge can be explained as a remnant of former valley fill, representing a fluvial terrace. In the lower reach of the valley, these terraces are easily identified morphologically, comprising two sets, a lower and an upper one (Fig. 6). The OSL ages indicate that the formation of the lower terrace took place during the late to middle Holocene. With a mean ^{10}Be age of 4.3 ± 0.3 ka this is also true for the sediment ridge in the middle reach of the valley, which can be age-correlated with the lower terrace. For the upper terrace, no reliable sediment ages are available, but since the older terrace has to be situated topographically above the younger one, the upper terrace with <0.5 ka for its formation seems much too young.

The potential and the interpretation of alluvial fans as sedimentary archives of past environmental change are dependent on their geomorphic controlling mechanism. In this respect, it is important to understand the Leidy Creek alluvial fan system with its boulders as transport or supply limited (Goudie, 2004). Today, unconsolidated and thick sedimentary valley fills of various particle sizes, morphologically presented as terraces and sediment ridges, characterize the Leidy Creek catchment. The steep valley slopes are indicated by sparse vegetation, which enables the transportation of the loose debris to the fluvial channel. Therefore, we interpret the Leidy Creek alluvial fan system not as supply but transport limited, in which the fluvial transport is coupling the valley system with the alluvial fan system, transporting the debris from the catchment to the alluvial fan (Harvey, 2001, 2002). In this regard, tectonic activity triggering mass movements like landslides or rock falls provides only additional material to an already existing sediment source and therefore has no direct influence on our interpretation of the Leidy Creek alluvial fan system as transport limited. This might be different for longer time scales extending back beyond the Holocene, where tectonic factors controlling the development of alluvial fans are more important (Harvey, 1997).

Given the hydrological system of the Leidy Creek valley, the average discharge and its capacity of the perennial creek of the Leidy Creek valley are insufficient to transport large boulders from the valley to the Leidy Creek alluvial fan. Therefore, flash floods with an above-average discharge are needed to transport the boulder sizes we investigated in this study. The flash floods interpretation is supported by the character of boulder deposition on the alluvial fan surface, which is not homogeneous in time and space, but follows temporal and spatial pulses and therefore corresponds to the nature of debris-flows, which also show a spatially and temporally heterogeneous occurrence (Figs. 3 and 5).

Particularly dynamic flash floods that transported large boulders are, for example, described by Beaty (1968), who recorded the movement of a marked boulder that advanced 2 km down the Jeffrey Mine Canyon on the opposite side of the drainage divide from Leidy Creek that he believes was during a thunderstorm-driven debris-flow. The large size (2–7 m in length) of the boulders suggests that the flows necessary to move the boulders must have been considerable. It is difficult to estimate velocity and discharge of the flash flood because the flow was probably hyperconcentrated, but the velocity to entrain boulders of this size in a normal flow would be on the order of 5–10 m s^{-1} applying equations of Costa (1983).

Possible triggers for flash floods in the Leidy Creek catchment can be thunderstorms or rainfall on a preexisting snow cover. As argued before, GLOFs as a possible trigger for flash floods can be excluded because of the Holocene age of all depositional material in this study. In our study area, summerlike thunderstorms generating flash floods are well known and their occurrence is much more frequent than heavy rainfall events in fall or wintertime. In addition, the magnitude of thunderstorm-triggered flash floods is higher than the ones triggered by rainfall (Hall, 1991; Kattelmann, 1992). Therefore we favor thunderstorms as the likely trigger for flash floods, even though rainfall events on a snow cover cannot be excluded as a possible cause.

The small-scale thunderstorm events are usually associated with warm and moist air masses from the Gulf of California, described as the North American monsoon, that affect the southwest United States (Adams and Comrie, 1997). For the Holocene, most studies show an enhanced monsoonal activity during the mid-Holocene (Harrison et al., 2003; Poore et al., 2005), even though differences in its Holocene activity pattern between the eastern and western regions of the southwest US demonstrate a much more complicated spatiotemporal behavior (Bird and Kirby, 2006; Barron et al., 2012). Nevertheless, all of the four boulder clusters from the Leidy Creek alluvial fan (Table 1) can be assigned to the mid-Holocene that had generally enhanced monsoonal activity (Liu et al., 2004). This link between enhanced mid-Holocene monsoon activity and depositional ages of the four boulder clusters should only be considered as a possible positive correlation.

Next to information about past monsoonal activity of the southwest United States, general paleoclimate information for the region of the western Great Basin comes from a large range of proxies including lake (Stine, 1990; Benson et al., 2002; Yuan et al., 2006), pollen analyses (Davis, 1999), tree line (LaMarche, 1973) and alluvial fan records (Reheis et al., 1996). These proxies provide information on changes to cooler and drier climates (8–6.3 ka, 3.2–2.6 ka, 1.2 ka, 0.75 ka), which Reheis et al. (1996) argue results in vegetation retreat, leading to an increased availability of sediment, thus boulder aggradation on the alluvial fan surface. Correlating the ages of our boulder clusters with the possible aggradation phases after Reheis et al. (1996), within uncertainties, the clusters are in accordance with one or the other cooler and drier period. This general information about the paleoclimate information of the western Great Basin is apparently in contradiction with the information about enhanced monsoonal activity in the mid-Holocene, possibly responsible for enhanced flash flood activity. However, due to the limited number of investigated alluvial fan systems, scarce regional paleoclimate records and their spatiotemporal uncertainties as well as the age uncertainties of the dated boulders, so far, no clear conclusion can be drawn about the correlation between monsoonal triggered flash floods, debris-flows and boulder deposition.

Thunderstorm events by nature are spatially limited features. This begs the question of whether the boulders of the Leidy Creek alluvial fan can be used as proxies for thunderstorm activity and therefore as paleoclimate proxies (Dorn, 1996). The presented study and its correlation with supposed paleomonsoonal activity and paleoclimate conditions give a first hint of possible positive correlations; but in order to be able to make a sound paleoclimate statement, a spatially comprehensive study is needed. This study design would require a detailed dating approach including a large number of alluvial fans throughout a region to test whether their formation is synchronous and represents a regional climatic signal.

Conclusion

Large clusters of huge boulders are present on the surface of the Leidy Creek alluvial fan, on the eastern side of the White Mountains in Nevada. High-energy geomorphic agents like flash floods would have been responsible for transporting these boulders. Possible triggers for these flash floods are GLOFs, thunderstorms or rainfall on snow cover. Using ^{10}Be, we show that four of the boulder clusters on the Leidy Creek alluvial fan are Holocene (7.9 $\pm$ 0.8 ka; 2.6 $\pm$ 0.3 ka; 5.4 $\pm$ 0.6 ka; 7.1 $\pm$ 0.6 ka). Furthermore, sediment ridges in the source valley yield also Holocene ages, with ^{10}Be ages of 4.3 $\pm$ 0.3 ka and OSL ages of 1.5 $\pm$ 0.3 ka to 3.6 $\pm$ 0.5 ka. We therefore argue that the Holocene landforms within the valley are not moraines as previously proposed, but are fluvial terraces. We can also rule out the possibility that the boulder clusters formed as a consequence of GLOFs. Because rainfall on a preexisting snow cover as a trigger for flash floods is less common in the study area, we argue that the boulders were most likely transported and deposited by monsoonal-influenced thunderstorms. Because all the boulder clusters can be assigned to the mid-Holocene, a positive correlation can be assumed for the timing of boulder deposition and enhanced mid-Holocene monsoonal activity of the SW United States. In order to substantiate a positive correlation between monsoonal activity and boulder aggradation, future studies should focus on building up a regional database of numerous alluvial fans throughout the Great Basin. This would allow for a robust exploration of the possible regional paleoclimate implications.

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