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AGE CONSTRAINTS ON CAVE DEVELOPMENT AND LANDSCAPE EVOLUTION IN THE BIGHORN BASIN OF WYOMING, USA

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Cosmogenic $^{26}Al/^{10}Be$ burial dating and tephrochronology of cave deposits provide minimum estimates for the timing of cave development in the Bighorn Basin of Wyoming. Spence Cave is a linear phreatic passage formed along the fold axis of the Sheep Mountain anticline and subsequently truncated by 119 m of Bighorn River incision. A fine-grained eolian (windblown) sand deposit just inside the entrance yields a $^{26}Al/^{10}Be$ burial age of 0.31 ± 0.19 million years (Ma). This represents a minimum age for the development of Spence Cave, and provides a maximum incision rate for the Bighorn River of 0.38 ± 0.19 mm/yr. Horsethief Cave is a complex phreatic cave system located 43 km north of Spence Cave on a plateau surface ~340 m above the Bighorn River. Electron microprobe analyses of white, fine-grained sediment in the Powder Mountain section of Horsethief Cave confirm that this deposit is Lava Creek B fallout ash, erupted from the Yellowstone Plateau volcanic field ca. 0.64 Ma. Assuming this as a minimum age for the development of Horsethief Cave, extrapolation of the cave profile gradient westward to the Bighorn River gorge suggests a maximum incision rate of 0.35 ± 0.19 mm/yr. Incision rates from both caves match well, and are broadly similar to other estimates of regional incision, suggesting that they record lowering of the Bighorn Basin during the late Pleistocene. However, we caution that deposition of both the Spence Cave sand and the Horsethief Cave volcanic ash may postdate the actual timing of cave development. Thus, these ages place upper limits on landscape evolution rates in the Bighorn Basin.

Introduction

Caves offer important geomorphic markers that can be used to determine rates of landscape evolution, including rates of canyon cutting (here termed river incision). Cave passages that originally formed in shallow phreatic conditions (Palmer, 1991; Ford and Williams, 1989; White, 1988), but which are now perched high above modern water-table levels can be used to reconstruct the history of base level lowering (Palmer, 1987). Because base-level lowering is usually dictated by the rate that the local river incised into bedrock, dated caves can provide a robust record of this process (e.g., Ford *et al.*, 1981; Atkinson and Rowe, 1992; Sasowsky *et al.*, 1995; Granger *et al.*, 1997, 2001; Stock *et al.*, 2004; Anthony and Granger, 2004).

Determining cave ages is difficult because caves are voids that usually cannot be directly dated. Although there are some exceptional cases where dated deposits derive from speleogenesis, such as clays resulting from sulfuric acid dissolution (Polyak *et al.*, 1998), more often only limiting estimates of cave age can be determined by dating either speleothems or sediments deposited within cave passages after the passages formed. U/Th dating of calcite speleothems or paleomagnetic or cosmogenic $^{26}Al/^{10}Be$ burial dating of clastic sediment are the primary methods of constraining cave ages. Sediment and speleothems are sometimes deposited during the waning stages of speleogenesis, but can also be deposited much later; speleothems are particularly prone to this effect. Dating coarse clastic sediment that has clearly washed into caves most directly ties the cave age to the former position of the local base-level river. Thus, coarse fluvial sediment is usually the better material for dating cave development (Stock *et al.*, 2005). Once an age has been determined, river incision rates can then be determined by dividing the height of the dated cave passage above the modern river by the age of the deposit. Because even in the best of circumstances dated deposits represent minimum estimates of cave age, rates of river incision calculated from these ages must be considered maximum rates (e.g., Ford *et al.*, 1981; Atkinson and Rowe, 1992; Stock *et al.*, 2005). Using dated deposits of uncertain relation to base level tends to reduce the estimated age of the cave, thereby increasing the estimated incision rate.

We investigated several caves in the northeast Bighorn Basin and adjacent Bighorn Mountains of Wyoming as part of a larger study of the geomorphic history of the this region (Anderson *et al.*, 2006; Riihimaki *et al.*, in press; Riihimaki, 2003). Although most of the caves we investigated did not con-

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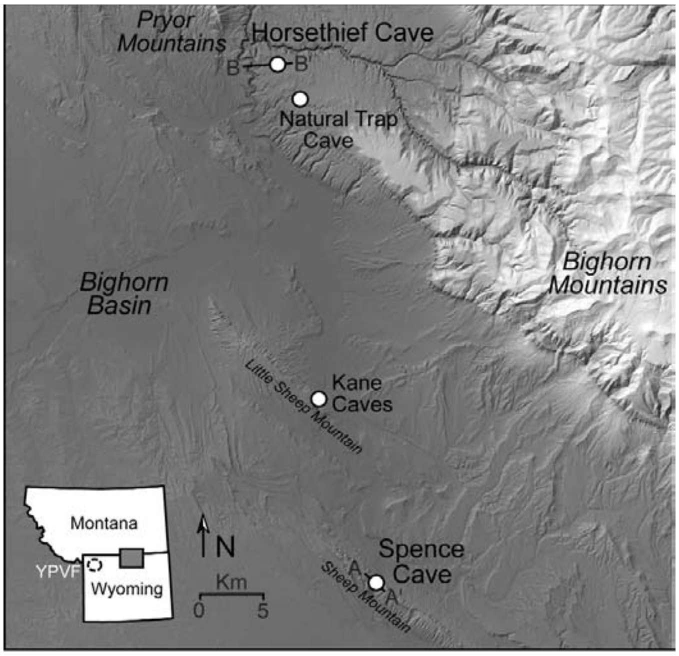

Figure 1. Map of the northeastern Bighorn Basin, Wyoming, showing locations of Spence, Kane, Horsethief, and Natural Trap caves. Cross-sections A-A′ and B-B′ are shown in Figures 2 and 4, respectively. YPVF: Yellowstone Plateau volcanic field, source of the ca. 0.64 Ma Lava Creek B ash.

tain datable fluvial sediments, we were able to obtain ages from two of the larger caves in the region, Spence Cave and Horsethief Cave (Fig. 1). In both cases, the setting and morphology of these caves suggest that they record former positions of the Bighorn River. However, they do not contain coarse clastic sediments washed in when the caves were at (or very near) river level. Rather, they contain datable sediments (windblown sand and volcanic ash, respectively) that likely entered the caves after they formed. As such, the dated sediments provide minimum estimates of the timing of cave development in the region. Combining these age data with the positions of these caves in the modern landscape yields maximum incision rates of the Bighorn River.

Setting

The Bighorn Basin is a large structural basin located in north-central Wyoming (Fig. 1). The northeast part of the basin, where the study caves are located, is flanked on the east by the Bighorn Mountains and on the north by the Pryor Mountains (Fig. 1). The Bighorn River flows northward through the basin, meandering across basin fill for much of its length, but is occasionally restricted to deep gorges incised into uplifted structures such as the Sheep Mountain and Little Sheep Mountain anticlines and the northern Bighorn Mountains (Fig. 1). The numerous caves in this region have developed primarily in the Madison Limestone of Mississippian age (360 to 325 million years ago [Ma]), but are

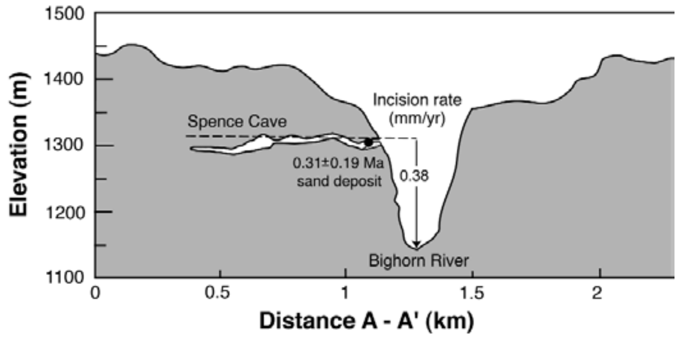

Figure 2. Topographic cross section along A-A′ (see Fig. 1) showing position of Spence Cave in relation to Bighorn River where it incises through Sheep Mountain anticline. Note vertical exaggeration. Dashed line indicates approximate water table position during cave development. Minimum cave age of 0.31 ± 0.19 Ma, based on burial age of sand deposit just inside cave entrance, suggests a maximum Bighorn River incision rate of 0.38 ± 0.19 mm/yr.

also present in the Bighorn Dolomite of Ordovician age (500 to 440 Ma). The caves discussed in this paper have formed within the Madison Limestone (Hill *et al.*, 1976).

Cave descriptions, analytical methods, and results

Spence Cave

Spence Cave is located at an elevation of 1312 m, 119 ± 2 m above the Bighorn River (Fig. 2), in the folded core of the Sheep Mountain anticline (Fig. 3). The cave consists of a single phreatic passage 728 m long, with a short constriction and 12 m drop approximately halfway through. Egemeier (1981) interpreted Spence Cave to have been dissolved by sulfuric acid upwelling along joints parallel to the core of the anticline and mixing with a shallow paleo-water table surface graded to

Figure 3. Photograph taken from Spence Cave entrance, looking across gorge cut by Bighorn River through curving strata of Sheep Mountain anticline.

Figure 4. Photograph of sand deposit just inside entrance to Spence Cave. Fine grain size, high degree of sorting, uniform lithology, and position near the entrance suggest an eolian (windblown) origin. Cosmogenic ^{26}Al/^{10}Be burial dating of the sand indicates that it was emplaced ca. 0.31 ± 0.19 Ma.

a former level of the Bighorn River. This model of cave development is analogous to ongoing sulfuric acid dissolution in lower Kane Cave (Engel *et al.*, 2004; Egemeier, 1981), located 15 km north of Spence Cave in the smaller Little Sheep Mountain anticline (Fig. 1). Lower Kane Cave is situated within a few meters of the present Bighorn River and consists of a single horizontal passage extending ~330 m into the canyon wall, parallel to the folded core of the anticline. Situated 32 m above Lower Kane Cave, 329-m-long Upper Kane Cave likely represents an earlier phase of cave development that occurred when the Bighorn River was at that level. Although we were not able to find sedimentary deposits suitable for dating in either Upper or Lower Kane Caves, they do present useful analogies for the development of Spence Cave.

The arched entrance to Spence Cave is ~5 m wide and 3 m high. The floor of the entrance area consists of an extensive deposit of well-sorted, very fine, quartz-rich sand (Fig. 4). The deposit extends ~15 m into the cave before sloping steeply down at the angle of repose into the large main passage. The deposit has faint bedding 1 mm to 1 cm thick. We observed no finer-grained sediments further inside the cave, as might be expected if the deposit were fluvially emplaced as a prograding delta into a water-filled passage, nor were there ripples or channels indicative of deposition by subaerially flowing water. Therefore, we interpret this deposit as eolian (windblown) in origin. Although this interpretation does not directly tie the deposit to a cave position near river level, we infer that this sand was in fact deposited when the cave entrance was very near the Bighorn River. This is because concentrations of eolian sand decrease rapidly with height above the ground surface (Zheng *et al.*, 2004; Anderson, 1986); even high winds usually do not mobilize sand grains of this size more than a few meters into the air. In addition, we did not identify any modern source for quartz sand close to the entrance. Thus, we consider dry sand along the banks of the Bighorn River to be the most likely source for the sand in Spence Cave, and argue that this sand entered the cave when it was within a few vertical meters of river level (*i.e.*, prior to the 119 m of incision). Constant replenishment of riverside sand banks would have provided the large source needed to produce the considerable volume of the Spence Cave deposit.

We dated sand from the top of the Spence Cave deposit using cosmogenic burial dating (*e.g.*, Granger *et al.*, 1997, 2001; Granger and Muzikar, 2001; Anthony and Granger, 2004; Stock *et al.*, 2004, 2005). This dating method exploits the fact the quartz-rich sediment at or near the Earth's surface accumulates the rare cosmogenic isotopes aluminum-26 (^{26}Al) and beryllium-10 (^{10}Be) by cosmic ray bombardment, but no longer accumulates these isotopes once the sediment enters a cave and is shielded from further bombardment. Because these isotopes decay radioactively at rates that differ by about a factor of two, the ratio of ^{26}Al to ^{10}Be in the sediment changes through time, and may be used to assess the duration of burial within the cave. We collected ~500 g of sand, purified the quartz in it by chemical dissolution (Kohl and Nishiizumi, 1992), and isolated ^{26}Al and ^{10}Be using methods described in Stock *et al.* (2005).

Table 1. Cosmogenic nuclide concentrations and burial age for Spence Cave.

Cave	Mass quartz (g)	P_{10}[a] (atm g^{-1} yr^{-1})	^{26}Al (10^5 atm g^{-1})	^{10}Be (10^5 atm g^{-1})	^{26}Al/^{10}Be	Burial age[b] (Ma)
Spence	80.08	15.0	3.754 ± 0.035	0.726 ± 0.002	5.17 ± 0.05	0.31 ± 0.19 (0.20)

[a] Local ^{10}Be production rate at Spence Cave site, scaled for altitude and latitude and assuming sea-level high latitude production rate of 5.1 atm g^{-1} yr^{-1} (Stone, 2000). Multiply by 6.1 to get local ^{26}Al production rate.

[b] Uncertainties represent one standard error measurement uncertainty. Systematic uncertainties in nuclide production rates, production rate ratio (Stone, 2000), and radioactive decay constants are added in quadrature and shown as total uncertainty in parentheses.

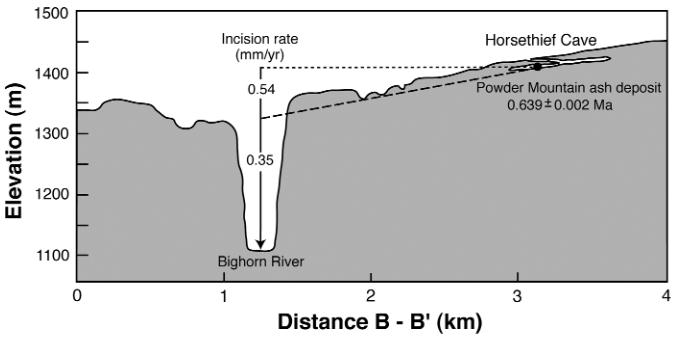

Figure 5. Topographic cross section along B-B′ (see Fig. 1) showing position of Horsethief Cave in relation to Bighorn River. Note vertical exaggeration. Assuming Bighorn River was at the same elevation as Horsethief Cave (dotted line) when Powder Mountain Passage formed, dividing this height above modern river level by the age of the Lava Creek B ash (0.639 ± 0.002 Ma) yields a maximum incision rate of 0.54 ± 0.01 mm/yr. Extrapolation of cave gradient (dashed line) suggests a river position 220 m above modern at the time Horsethief Cave formed, yielding an incision rate of 0.35 ± 0.19 mm/yr (see text).

Figure 6. Photograph of Powder Mountain Passage in Horsethief Cave. White cone-shaped deposit illuminated at far end of room is Lava Creek B fallout ash erupted from Yellowstone Plateau volcanic field 0.639 ± 0.002 Ma.

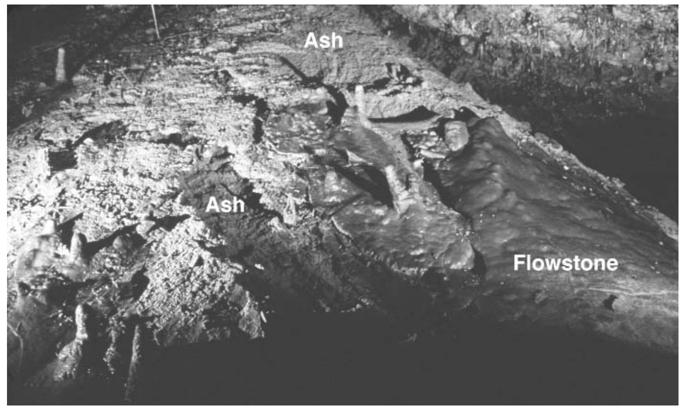

Figure 7. Close up view of Powder Mountain ash deposit. Width of view is ~2 m. Note several-cm-thick flowstone and stalagmite deposits on top of pristine white ash.

The $^{26}Al/^{10}Be$ ratio of the Spence Cave sample suggests that the top of the sand deposit was emplaced ca. 0.31 ± 0.19 Ma (Table 1). This age is close to the practical lower limit of the technique (Granger *et al.*, 1997; Granger and Muzikar, 2001), and is thus subject to relatively large uncertainty resulting both from analytical uncertainty and uncertainty in the decay constants of ^{26}Al and ^{10}Be (Norris *et al.*, 1983; Middleton *et al.*, 1993). The 0.31 ± 0.19 Ma burial age of the sand represents a minimum age for the development of Spence Cave; this is especially true because we were not able to sample the base of the deposit. This minimum age, combined with the height of the cave above the modern Bighorn River, provides a maximum incision rate of 0.38 ± 0.19 mm/yr for the Bighorn River at this location (Fig. 2). The uncertainty on the incision rate is large because of the large analytical uncertainty on the burial age.

Horsethief Cave

Horsethief Cave is located on a broad plateau surface southeast of the Bighorn River Gorge at an elevation of 1428 m (Fig. 5). Horsethief Cave is one of the longest caves in the Rocky Mountains, comprising roughly one half of the Bighorn-Horsethief Cave system. The combined length of the two caves is 23.5 km, though a natural connection between them is presently sealed (Hill *et al.*, 1976).

Horsethief Cave is an example of a network maze, with secondary spongework maze development (Palmer, 1991; Sutherland, 1976). The cave appears to have formed entirely under phreatic conditions. Although there is likely some structural control on the cave is longitudinal profile (Fig. 5), including a system of joints and a semi-impermeable layer stratigraphically below the cave (Sutherland, 1976), the fundamental control on ground-water flow through Horsethief Cave appears to have been the position of the Bighorn River. This is supported by the fact that the cave gradient trends almost due west, which represents the steepest hydraulic gradient to the Bighorn River, whereas the bedding dips southwest (Sutherland, 1976). As Horsethief Cave formed, ground-water moving through low-gradient phreatic passages likely eventually emerged as springs along the banks of the entrenched Bighorn River (e.g., Palmer, 1987). Thus, age constraints on the development of Horsethief Cave provide rates of incision for the Bighorn River due west of the cave.

The single entrance to Horsethief Cave is in a large doline, but there is evidence for additional former entrances within the cave. Some of the most striking depositional features within Horsethief Cave are the so-called "Buddhas," large conical mounds of various sedimentary materials. Most of the Buddha formations are composed of siliciclastic sediment that has been interpreted either as paleofill following an earlier period of cave development (e.g., the "Red Buddha"), or as surficial material entering the cave through now-closed fissure or doline entrances (Sutherland, 1976). In the Powder Mountain section of the cave (Fig. 6), there is a large conical deposit of white powdery material positioned below a narrow fissure extending upward into the ceiling (Fig. 7). We agree with Sutherland (1976) that this fissure was likely a former entrance, similar to the modern entrances of adjacent Bighorn Cave, and was only open for a relatively short period of time. Sutherland (1976) examined the Powder Mountain deposit and other similar deposits from the Powder Mountain area and suggested a tentative correlation with one of the Pearlette family of volcanic ashes. As subsequently shown by Izett (1981) and Izett and Wilcox (1982), the Pearlette ashes were erupted from the Yellowstone Plateau volcanic field in northwestern Wyoming and eastern Idaho (Fig. 1) and include two very widespread ash beds, the 0.64 Ma Lava Creek B ash bed and the 2.06 Ma Huckleberry Ridge ash bed.

The Powder Mountain deposit is a prime candidate for tephrochronology (chemical correlation with well-dated volcanic ashes and tuffs) because it is nearly pristine (*i.e.*, contains very few non-glass grains) and has been shielded from weathering and erosion. A sample (082201-ca) of the Powder Mountain deposit was processed and analyzed at the University of Utah tephrochronology laboratory. Analyses were performed on a Cameca SX-50 electron microprobe using methods described in Perkins *et al.* (1995) and under analytical conditions described by Nash (1992). Twenty-five glass shards were analyzed for 13 major and minor elements including oxygen. Of these 25 analyses, one shard with a Ti concentration well outside the range observed in the other 24 shards was eliminated as an outlier prior to calculating the average concentrations shown in Table 2.

Comparison of sample 082201-ca glass shard analyses with those in an extensive database of late Cenozoic tephra of the western U.S. indicates that sample 082201-ca is most likely the Lava Creek B ash bed. In particular, the glass shards of 082201-ca show the distinctive bimodal composition commonly observed in the Lava Creek B ash bed (Williams, 1994) with a dominant low Fe mode and a secondary high Fe mode (Table 2). It is worth noting that there is considerable compositional overlap between the averages of analyses for the Lava Creek B ash bed and the older Huckleberry Ridge ash bed (Table 2). However, glass shards of the Huckleberry Ridge ash bed generally display a range of compositions from lower to higher Fe rather than the discrete lower and higher Fe modes typical of Lava Creek B. Furthermore, for a given Fe concentration the concentration of Ca is lower in the glass shards of Lava Creek B ash bed relative to those of the Huckleberry Ridge ash bed. Finally, we note that other Yellowstone Plateau source ash beds, such as the 1.26 Ma Mesa Falls ash bed, the 0.64 Ma Lava Creek A ash bed, the late Pleistocene Hebgen Narrows ash bed and the 0.11 Ma Natural Trap Cave (Fig. 1) ash bed are distinctly different than either the Lava Creek B or

Table 2. Composition of glass shards from Powder Mountain, Horsethief Cave (082201-ca), and Lava Creek B and Huckleberry Ridge ash beds — Electron microprobe analyses[a].

Sample[b]	n[c]	SiO_2[d]	TiO_2	Al_2O_3	Fe_2O_3[e]	MnO	MgO	CaO	BaO	Na_2O	K_2O	Cl	F	sum	H_2O[f]	–O
082201-ca	24	75.0	0.098	11.6	1.57	0.029	0.018	0.519	0.008	3.14	4.88	0.156	0.20	97.2	5.1	0.03
082201-ca-I	17	75.0	0.086	11.6	1.45	0.028	0.017	0.497	0.006	3.16	4.83	0.171	0.24	97.1	5.3	0.04
082201-ca-II	7	74.9	0.126	11.5	1.84	0.032	0.020	0.572	0.011	3.09	5.00	0.119	0.12	97.3	4.8	0.03
LCBavg	25	73.5	0.112	11.6	1.57	0.035	0.020	0.515	0.009	3.15	4.95	0.139	0.18	95.8	4.5	0.03
LCBmax	...	75.0	0.120	11.9	1.64	0.043	0.023	0.560	0.013	3.32	5.11	0.159	0.26	...	...	...
LCBmin	...	72.0	0.098	11.5	1.50	0.030	0.015	0.470	0.006	3.07	4.78	0.120	0.07	...	...	...
HBRavg	22	74.1	0.102	11.8	1.64	0.036	0.018	0.561	0.013	3.34	4.04	0.139	0.19	96.0	4.7	0.03
HBRmax	...	75.1	0.107	11.9	1.70	0.039	0.025	0.583	0.022	3.73	5.25	0.150	0.24	...	...	...
HBRmin	...	73.4	0.092	11.7	1.59	0.032	0.015	0.532	0.008	3.03	1.51	0.126	0.11	...	...	...

[a] Analyses of Powder Mountain sample (082201-ca) by Michael E. Perkins, others by Steven W. Williams, Barbara P. Nash, and Michael E. Perkins, University of Utah.
[b] LCB = Lava Creek B ash bed with results from analyses for 8 samples. HBR = Huckleberry Ridge ash bed with results from analyses of 6 samples.
[c] Number or average number of analyzed glass shards.
[d] All oxides and elements in wt%.
[e] Total Fe reported as Fe_2O_3.
[f] H_2O content calculated from difference between measured and stoichiometric oxygen content assuming all Fe as Fe_2O_3.

Table 3. Bighorn River incision rates based on cave sediment ages.

Cave	Height Above Bighorn River (m)	Adjusted Height[a] (m)	Age (Ma)	Incision Rate (mm yr^{-1})	Adjusted Incision Rate[a] (mm yr^{-1})
Spence	119 ± 2	119 ± 2	0.31 ± 0.20	0.38 ± 0.19	0.38 ± 0.19
Horsethief	343 ± 5	221 ± 60	0.639 ± 0.002	0.54 ± 0.01	0.35 ± 0.19

[a] Adjusted heights and incision rates account for paleo-hydraulic gradient indicated by dip of cave passages.

Huckleberry Ridge ash beds. In particular, they have measurably different average glass shard compositions and show tight unimodal compositions rather than either the distinctive bimodal composition of the Lava Creek B glass shards or the range of compositions of the Huckleberry Ridge glass shards.

The Lava Creek B ash is preserved across much of the western and central United States because of its substantial volume, broad initial dispersal, and the aggrading depositional environments into which the ash fell (Izett and Wilcox, 1982; Dethier, 2001). Based on the chemical correlation, the large volume of material in the Powder Mountain deposit, and the occurrence of Lava Creek B ash elsewhere in the Bighorn Basin (Izett and Wilcox, 1982; Reheis *et al.*, 1991; Dethier, 2001), we conclude that the voluminous deposit in the Powder Mountain Passage is the Lava Creek B ash.

Precisely how old is this Lava Creek B deposit? $^{40}Ar/^{39}Ar$ dating by Lanphere *et al.* (2002) placed the age of member B of the Lava Creek Tuff at 0.639 ± 0.002 Ma and found excellent agreement between $^{40}Ar/^{39}Ar$ ages from members A and B of the Lava Creek tuff and those of the Lava Creek fallout ash. Given the pristine appearance of the Powder Mountain deposit (*i.e.*, nearly pure ash with little to no terrigenous sediment; Fig. 7), we infer that this ash entered the cave rapidly, soon after falling on the surface. That the ash fell directly into the entrance rather than being washed in is supported by (1) the steeply sloped, conical shape of Powder Mountain (Fig. 7), (2) the powdery nature of the deposit, (3) a lack of fluvial sedimentary structures, (4) the angularity of glass shards, and (5) the nearly 100% glass composition of the material. Sutherland (1976) made similar observations in the Powder Mountain area. Therefore, we argue that the 0.639 ± 0.002 Ma eruption age of the Lava Creek B member closely marks the timing of deposition within the cave. Although development of this level of Horsethief Cave could have occurred before deposition of the ash, the eruption age provides a minimum estimate of the age of the Powder Mountain passage.

Although the development of Horsethief Cave is clearly linked to former levels of the Bighorn River, the position of Horsethief Cave in the landscape creates large uncertainty in our estimates of river incision rates. Unlike Spence Cave, which is situated directly above the modern Bighorn River and is therefore a relatively unambiguous marker of the former river level, Horsethief Cave is set back ~1.75 km from the modern river (Fig. 5). As a result, the position of the Bighorn River when the Powder Mountain passage formed is harder to define. We have made two estimates of the incision rate of the Bighorn River west of Horsethief Cave. The first is determined simply by dividing the present height of the Powder Mountain passage above the modern river taken at a point due west of the cave (343 ± 5 m) by the age of the passage (here taken to be 0.639 ± 0.002 Ma). This most simple calculation yields an incision rate of 0.54 ± 0.01 mm yr^{-1}. The uncertainty in the rate is low in this case, because it is based only on how well the height of the Powder Mountain passage above the modern river is known (± 1.3%) and on the analytical precision of the $^{40}Ar/^{39}Ar$ age (± 0.3%). However, a more accurate, though less precise, method of determining the incision rate is to account for the paleo-hydraulic gradient by extrapolating the cave profile down the hydraulic gradient to the river. In most cases this will estimate a river position lower than the more simple calculation above, resulting in a slower rate of incision. We used the profile of Horsethief Cave to extrapolate west, down gradient to the Bighorn River canyon (Fig. 5). This exercise suggests that the spring outlet for the Horsethief Cave system was located ~220 m above the modern river level, rather than the 343 m used in the prior calculation, and yields a maximum incision rate of 0.35 ± 0.19 mm yr^{-1}. In this case, the uncertainty on the rate is large because of the considerable uncertainty in the reconstructed river position, which we estimate to be ~50%.

Discussion

The incision rates we calculate based on dated sediment deposits in Spence and Horsethief caves are nearly identical (0.38 ± 0.19 and 0.35 ± 0.19 mm yr^{-1}, respectively; Table 3), suggesting that they represent accurate estimates of river incision. They are also broadly similar to other estimates of incision in the region. For example, Reheis *et al.* (1991) used the presence of the Lava Creek B ash in river terraces to calculate incision rates of 0.16 mm yr^{-1} for the upper Bighorn River in Montana and Wyoming. Regionally, the depth of incision since Lava Creek B ash deposition reveals that rates of > 0.15 mm yr^{-1} are typical of Rocky Mountain rivers; these rates can be as high as 0.3 mm/yr (Dethier, 2001). Reiners *et al.* (2002) found erosion rates of ~0.15-0.4 mm yr^{-1} in the nearby Powder River Basin.

These independent incision rate estimates are within the uncertainty of our calculated incision rates from the caves. However, our best incision rate estimates are somewhat faster (0.3–0.4 vs. 0.15–0.2 mm yr^{-1}). If this discrepancy is real, and not a product of our uncertainty, then there are several possible explanations. The discrepancy may relate to geologic processes, such as isostatic uplift in response to sediment removal, that increase river incision rates preferentially in certain parts of the basin (Riihimaki, 2003). However, the discrepancy may also result from bias resulting from the various methods used to estimate incision rates. For example, incision estimates based on river terraces (*e.g.*, Reheis *et al.*, 1991) could be erroneously fast because incision below the terraces may have commenced well after deposition of the Lava Creek B ash. As mentioned at the beginning of this paper, caves are also prone to a similar bias, which can be further exacerbated depending on what type of material is dated. Unless the dated deposits can be shown to relate directly to cave development, then they represent minimum estimates of cave ages, and may underestimate the actual cave ages considerably. For example, in order to yield an incision rate of 0.15 mm yr^{-1}, the age of Spence Cave should be ~0.8 Ma, nearly 0.5 Ma older than the sand burial age we determined. Although this is outside the range of burial age uncertainty, we stress that while this age may accurately date deposition of the sand, it may not accurately date development of the cave. The same is true for the Horsethief Cave ash deposit; the Lava Creek B ash could have fallen into the Powder Mountain room well after the passage formed. The 0.11 Ma ash in Natural Trap Cave (Fig. 1; Gilbert, 1984) presents a useful example of this problem; if the age of this ash, which erupted nearly 0.5 Ma after the Lava Creek B ash, were combined with the height of Natural Trap Cave above the Bighorn River to calculate an incision rate, the resulting rate would be 3.63 mm yr^{-1}. This rate is clearly much too fast, and simply results from performing the calculation using dated material that considerably underestimates the true age of the cave. In the case of Spence and Horsethief caves, the nature of the deposits and the consistent incision rates they provide increase our confidence that the incision rates we have calculated are accurate. The important distinction between the age of a cave deposit and the actual age of the cave it resides in, noted decades ago (*e.g.*, Ford *et al.*, 1981; Atkinson and Rowe, 1992) and quantified more recently (Stock *et al.*, 2005), might explain why our calculated incision rates are higher than other regional estimates, independent of geological processes. In any case, the dated sediment deposits in Spence and Horsethief caves set important constraints on river incision rates in the Bighorn Basin since 0.31 and 0.64 Ma, respectively, and further highlight the importance of cave studies in geomorphic and tectonic research.

Conclusions

A cosmogenic $^{26}Al/^{10}Be$ burial date for fine (eolian) sand within the entrance area of Spence Cave yields a burial age of 0.31 ± 0.19 million years. Tephrochronology suggests that a fine white sediment deposit in the Powder Mountain area of Horsethief Cave is the Lava Creek B fallout ash, erupted from the Yellowstone Plateau volcanic field ca. 0.64 million years ago. These two dates provide minimum estimates for the timing of cave development in the Bighorn Basin, and yield maximum incision rates for the Bighorn River of 0.38 ± 0.19 mm yr^{-1} and 0.35 ± 0.19 mm yr^{-1}, respectively. These rates are broadly similar to independent estimates of river incision in the region. An apparent two-fold discrepancy between the rates based on the dated cave deposits and other independent estimates may be due to geologic processes, but may also result from the possibility that the dated deposits postdate the actual time of cave development. Investigation of other caves (*e.g.*, Tongue River Cave, Cliff Dwellers Cave, Spirit Mountain Caverns) may further clarify rates of landscape evolution in the region.

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