Dating Stone Alignments by Luminescence

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Tipi rings, alias stone circles, stone rings, or rings, have been the subject of intermittent interest and disdain to regional archaeologists for more than five decades [Les Davis, *Plains Anthropologist*, 1983].

INTRODUCTION

Stone archaeological features are common in the Rocky Mountains and adjoining High Plains. They occur in four general forms: isolated cairns (occurring either singularly or as a group), linear aligned cairns, stone effigies, and stone circles (rings). While ranging from Alaska to Texas and common in other parts of the world, they are particularly abundant on the northern plains. For example, Phillips County, an area of 5,200 km^2 in northeastern Montana, contains more than 800 known sites with stone circles (Gragson 1983).

Stone circles are typically 3–7 m in diameter (Dooley 2004; Zedeño et al. 2008) and most have been inferred to represent anchoring support for perishable superstructures used for residency, hence the term "tipi rings" (Davis 1983; Finnigan 1982; Kehoe 1960; Smith et al. 1995; Späth 1989; Wolf 2007). Figure 1 depicts a late-nineteenth-century photo from southern Alberta showing stones around the perimeter of a tipi. Some rings, called "medicine wheels," are considerably larger in diameter and are assumed to have some communal function. Stone effigies are also assumed to reflect some non-domestic concern. Cairn lines

ABSTRACT

Stone alignments, including tipi rings and drive lines, are abundant on the northern Plains and adjacent Rocky Mountains, but they have been notoriously difficult to date. This paper applies luminescence dating to sediments directly underneath the rocks to estimate the age of placement of the rock. This is based on the assumption that before the rock was emplaced, turbation processes brought sufficient grains to the surface, where sunlight reset the signal. Single-grain dating of potassium feldspars allowed isolation of these original well-bleached grains, which by now have built up a signal because the rock prevents transfer to the surface. Plotting the number of original well-bleached grains with depth showed that these grains were concentrated just under the rock and decreased with depth. This is what would be predicted if the assumption is true. Dates were derived from several samples from Kutoyis in north central Montana, from Whitewater in eastern Montana, and from several sites in northwestern Wyoming. Many samples from Kutoyis and Wyoming dated to the last 600 years, but some samples from both places were more than 2,000 years old. The Whitewater features also dated to around 2,000 years ago. The ages are consistent with the cultural history of the areas.

Alineamientos de piedra, incluyendo círculos domésticos y estructuras de cacería, abundan en los Grandes Llanos septentrionales y las Montañas Rocallosas, pero son muy difíciles de fechar. Este artículo aplica el fechamiento de luminiscencia a los sedimentos encontrados directamente debajo de las rockas para estimar la fecha en que las rocas de estos rasgos fueron emplazadas en la superficie. Esta técnica se basa en la suposición de que antes de que la rocka fue emplazada, procesos de turbación mobilice suficientes granos hacia la superficie donde la luz del sol modifico la señal original. La datación de granos de feldespato potásico permiten la identificación de estos granos asoleados, los cuales han desarrollado una señal especial debido a que estuvieron cubiertos por una roca durante mucho tiempo. La comparación del número y profundidad de granos asoleados originales reveló que estos granos se concentraron en la superficie cubierta por las rocas y decreceron a major profundidad, así como se explicó en la suposición original. Las fechas se derivaron de varias muestras del sitio Kutoyis en el centro-norte de Montana, del sitio Whitewater en Montana oriental, y de varios otros sitios en el noroeste de Wyoming. Muchas muestras de Kutoyis and Wyoming datan de los últimos 600 años pero algunas muestras provenientes de estos sitios son anteriores a 2000 años de edad. Los rasgos del sitio Whitewater también datan de aproximadamente 2000 años atrás. Las edades son consistentes con la historia cultural regional.

Advances in Archaeological Practice 3(4), 2015, pp. 378–396

DOI: 10.7183/2326-3768.3.4.378

FIGURE 1. Tipis in southern Alberta ca. 1895. Note the stones around the perimeter of the tipi just behind the empty frame. Courtesy of Glenbow Museum, Calgary, Alberta.

are often spatially associated with rings and appear to have a number of functions, most presumably associated with hunting, such as serving as blinds or drive lines. Single cairns are less easily interpretable, but may have served as markers of territory or directional posts.

Despite this remarkable evidence for settlement and subsistence, archaeologists have marveled at the lack of productive information these features have yielded, leading to the "disdain" mentioned in the lead quote. Well-known Plains archaeologist George Frison (1978:53) once predicted that "whatever their true function, stone circles will plague archaeologists on the High Plains for some time to come" (Frison 1978:53), a comment that still rings true 37 years later. Of course, the reason for Frison's concern is the complete inability to place them in a chronology. Consequently, their ages are largely unknown, with a potential range from as young as 300 years to as old as 5,000 years or more (Dooley 2004). Complicating matters is that adjacent stone features may not be the same age. Campsites may contain several hundred stone circles, representing repeated occupations over unknown time spans. Linear alignments may extend for several kilometers and have been reused and repaired over centuries.

Dooley (2004) has summarized the dating problems that have prevented any semblance of settlement pattern history. Most dating methods have relied on association with diagnostic artifacts or radiocarbon-datable materials, but whether the artifacts were deposited at the same time as the rocks, or whether the radiocarbon date addresses the same event as construction, is difficult to know. Associated artifacts, moreover, are relatively rare (Davis 1983). Perhaps greatest confidence has been placed in radiocarbon dates from hearths inside the circles. But these too are rare. Most known features occur on the present surface where organic materials are poorly preserved or are dispersed by aeolian and other processes. Such difficulties have led archaeologists to explore a number of relative dating techniques (Dooley 2004). One is "siltation," or the degree to which a rock has become buried, a method based on the assumption that embedded rocks are older than those without sediment build-up (Deaver 1989). Sediment build-up is from sod that grows around the rock and acts as a trap for wind-blown particles. The rock may also sink by compression to some degree (Davis 1983:350). Because sedimentation rates are highly localized, this is most useful in distinguishing ages of features from the same depositional environment. Another method is lichenometry, based on the degree of lichen accumulation, which under some conditions can grow at a predictable rate (Benedict 1985, 2009; Broadbent 1987). The method is highly dependent on localized ecological variables, but again can be useful for distinguishing ages of rocks from similar environments. Lichen build-up has not been studied in the study area. An added problem is that prehistoric use of a rock does not necessarily entail destruction of the lichen on the rock, so the lichen age may not have cultural significance, although statistical techniques on a large number of measurements have been proposed to circumvent this problem to some degree (Benedict 2009). Finally, reuse of rocks from older features may provide a kind of stratigraphic order (Deaver 1989). Older stone circles may be incomplete because rocks have been drawn from them for more modern features, or younger stone features may overlap older circles from which rocks have been later removed. However, such chronological ordering requires assumptions that may not hold in all situations.

While clever combinations of these various techniques have been used to provide rough chronologies within sites and small regions (e.g., Dooley 2004), less problematic and less relative chronological means are in high demand. We argue in this paper that dating of rock features should be achievable using luminescence dating. Minerals such as quartz and feldspar, which are present in many rocks and sediments, store energy from the absorption of natural radioactivity. This energy is released upon exposure to sufficient sunlight (or heat), resulting in the emission of light called luminescence. By measuring the sensitivity of the luminescence signal and the natural radioactivity, rocks and sediments can be dated to their last exposure to light (or heat). Luminescence dating subsumes several related methods distinguished by the source of stimulation of the luminescence signal: thermoluminescence (TL), which is stimulation by heat; optically stimulated luminescence (OSL), which is stimulation by visible light; and infrared stimulated luminescence (IRSL), which is stimulation by infrared light. IRSL is the method employed in this study.

Luminescence dating of the bottom surface of a rock, assuming that prior to emplacement it got bleached, or exposed to sufficient sunlight to reset the signal, has been the subject of a number of studies in the last seven to eight years. This has been recently reviewed by Sohbati et al. (2011), who have developed a fairly simple method for dating using IRSL. As an alternative, we apply luminescence dating to sediments beneath the rocks. There have been attempts to date soils beneath rocks on an ordinal scale based on degree of weathering (White 1998), but luminescence can achieve ratio-scale calendar estimates and has been applied in similar contexts in the Near East (Holzer et al. 2010; Porat et al. 2006), Europe (Outram et al. 2010; Vafiadou et al. 2007), and South America (Rink and Bartoll 2005). Luminescence dating of the underside of rocks and dating sediments underneath the rocks both have their own sets of problems and should be considered complementary approaches, rather than one being better than the other. The senior author is currently investigating both methods on some other tipi ring sites. It should also be mentioned that dating the sediments is less destructive, given that it does not involve taking the rock away, something that might not be allowed in the case of culturally important features.

Preliminary luminescence dating of the sediments discussed here has been published in a technical report (Feathers 2012), and readers will be referred to that report for many details in technique. For interested readers, other technical details of the sample-taking process are included in the supplemental materials accompanying this article. Here we will concentrate on the main methodological issues, while updating the results of the earlier report and discussing their archaeological significance. We hope that the paper will demonstrate a viable method for dating rock alignments that will be useful to archaeologists. General strategies for collecting luminescence dating samples have recently been published in this journal (Nelson et al. 2015).

METHOD

Stable surfaces over some length of time can contain within the top few centimeters of sediment many grains that have been exposed to sunlight, the zeroing mechanism in luminescence. Grains are brought to the surface by natural turbation processes and most likely exposed during erosion of micro-relief created by the turbation, as shown in Figure 2 (Bush 2007). If the sediment now under a rock was formerly part of a stable surface during which time many grains got fully exposed and if emplacement of the rock ended the process of grains coming to the surface, then luminescence dating of those grains should date the time of emplacement. Because some grains may not have been sufficiently bleached at the time of interest, or may have been bleached at a much earlier time, single-grain dating is necessary to help isolate those grains that were well-bleached.

Samples

Samples were collected from five localities, currently undergoing other research. The collection procedures are detailed in the Supplementary Text.

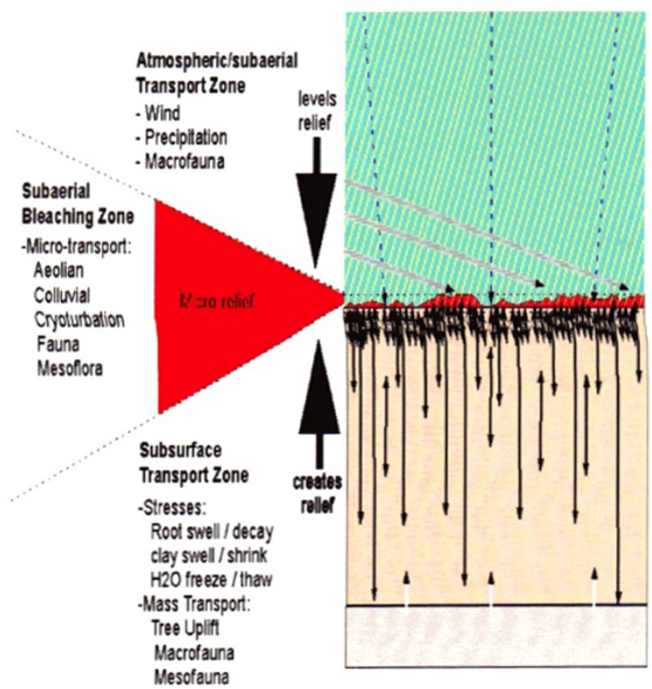


FIGURE 2. Model of turbation processes on a stable surface. Subsurface processes bring grains to the surface, usually forming some kind of relief. Subaerial processes erode the relief as the grains are exposed to sunshine (from Bush 2007).

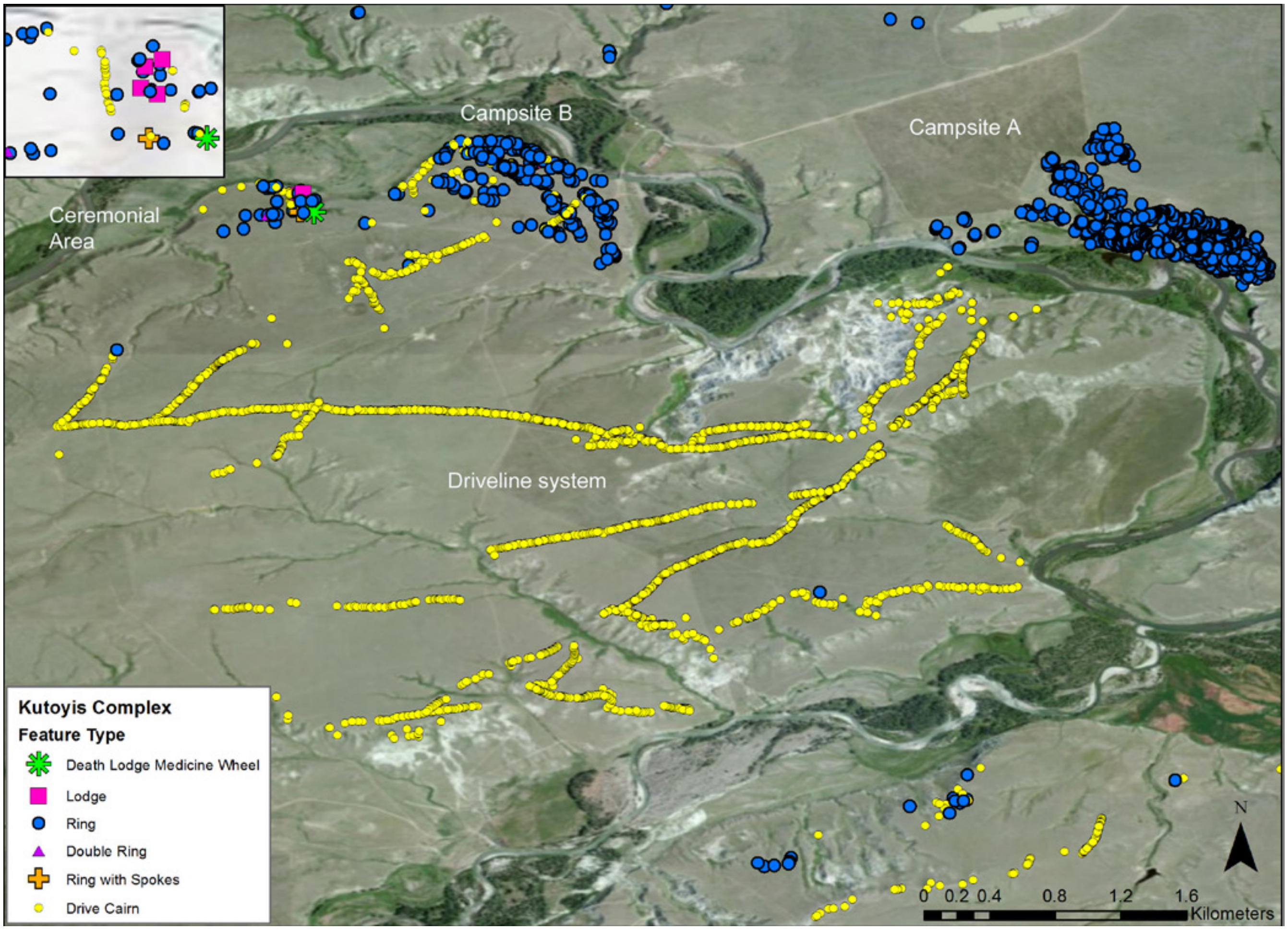


FIGURE 3. Map of Kutoyis complex. The two main drive lines lead to a jump in the upper right. Also shown are the two main campsites and Memorial Monument.

1. Kutoyis. Twenty samples were obtained from the Kutoyis bison hunting complex east of Glacier National Park on the Blackfeet Reservation, north central Montana. The locality straddles the Two Medicine River and contains 3,600 well-preserved rock features and bone scatters. The stone architecture on the reservation is being analyzed by the Kutoyis Archaeological Project (KAP) (Zedeño et al. 2014) to study landscape engineering and its impact on the harvest of bisons well as the temporal relationship of domestic and non-domestic sites to hunting facilities (Ballenger et al. 2008; Jones et al. 2010; Zedeño et al. 2010; Zedeño et al. 2008).

The Kutoyis bison hunting complex extends across 16 km^2 on the plateau overlooking the river and in its floodplain (Figure 3). The river cuts into Upper Cretaceous rocks, but the site is located on overlying glacial till or a post-Pleistocene terrace formation by the river. The kill site, located at the foot of a cliff-face below the terminus of two connected drive lines, contains stratified evidence of multiple hunting episodes, a primary butchering area, and a processing area. Across the river are a large number of tipi rings, the contemporaneity of which is not known. Eighteen calibrated radiocarbon dates from stratified contexts range between ca. A.D. 1210 and A.D. 1886, 10 of them clustering in the mid-A.D. 1500s (Zedeño et al. 2014:Table 1). The network of rock alignments at Kutoyis (Figure 3) includes two major drive lines, each 4.5 and 2.5 km long, called the north and south drive lines respectively, forming a funnel and leading to the cliff (Zedeño et al. 2014). Two minor alignments are associated with a secondary kill site. The alignments consist of rock cairns of 1 to 40 rocks, varying in size from 10–60 cm in diameter. Two clusters of tightly packed single- and double-course rock rings are located within 1 to 4 km of the drive lines. Campsite A (Lower Kutoyis), which contains 651 structures, including 421 rings, is located on the terrace directly across from the drive lines. Campsite B (Upper Kutoyis), with 258 rings, is located 4 km west of the drive lines and covers two river terraces. Adjacent to Campsite B is a cluster of rings, called Memorial Monument. It consists of a circular structure with two concentric rings and a linear alignment, often referred to as a death lodge medicine wheel (Brumley 1988; Vickers and Peck 2009). It is flanked by two large-diameter rings, and 24 smaller rings are arranged in a circular pattern, reminiscent of historical Blackfoot ceremonial encampments (Banks and Snortland 1995; Kehoe 1960).

Normal-sized ring diameters vary from 3–9 m, while the larger ones vary from 10–12 m. Most rocks are well-embedded in sod

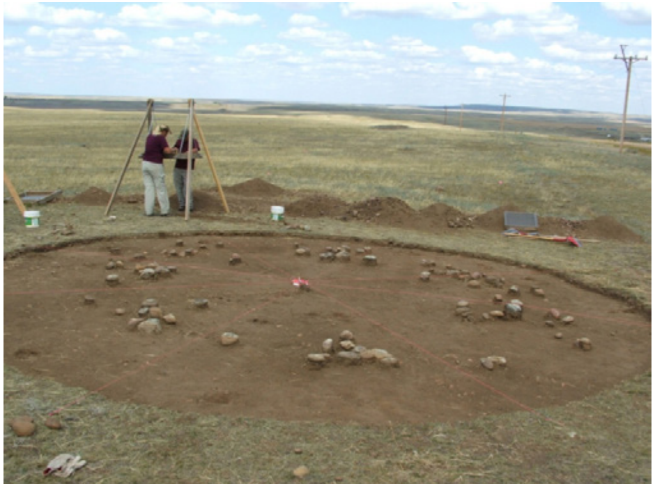


FIGURE 4. Photo of a tipi ring at one of the Whitewater sites, Phillips County, Montana (24PH762, Ring 1); photo by Stephen Aaberg.

with little evidence of displacement. Five samples for luminescence dating were collected from the south drive line, three from the north drive line, five from Campsite A, three from Memorial Monument, and four from Campsite B. Two of the samples from Campsite A were from the same ring.

2. Whitewater. Six samples from under rocks of tipi rings were collected from three closely located sites in northern Phillips County, near the community of Whitewater, Montana, close to the Canadian border and about 400 km east of Kutoyis onto the Plains (Figure 4). The sites, 24PH762, 24PH3773, and 24PH3775, were investigated in 2009 when the IRSL samples were collected, as part of a mitigation project (Junction U.S. 191, Whitewater) funded by the Montana Department of Transportation. All three sites occur in complex glacial terrain within prairie grasslands. All three sites are situated on landforms that appear to be of glaciofluvial origin based on the frequency of glacial cobbles that exhibit fluvial percussion scars.

Site 24PH762 contains 66 tipi rings and 14 non-aligned cairns. Morphological, dimensional and spatial variability of the features suggests multiple occupations. Artifacts recovered include cores, choppers, flake tools, flakes, and heat-altered rocks. Formally finished tools and time-sensitive artifacts are not apparent. One complete tipi ring (R-1) was excavated along with a 6-m^2 area outside the ring. A small cairn was also excavated about 7 m from R-1. Beneath the cairn was a small basin-shaped hearth with charcoal and butchered bison bone. The charcoal yielded a conventional radiocarbon age of 1040 ±5 0 BP (calibrated 1020

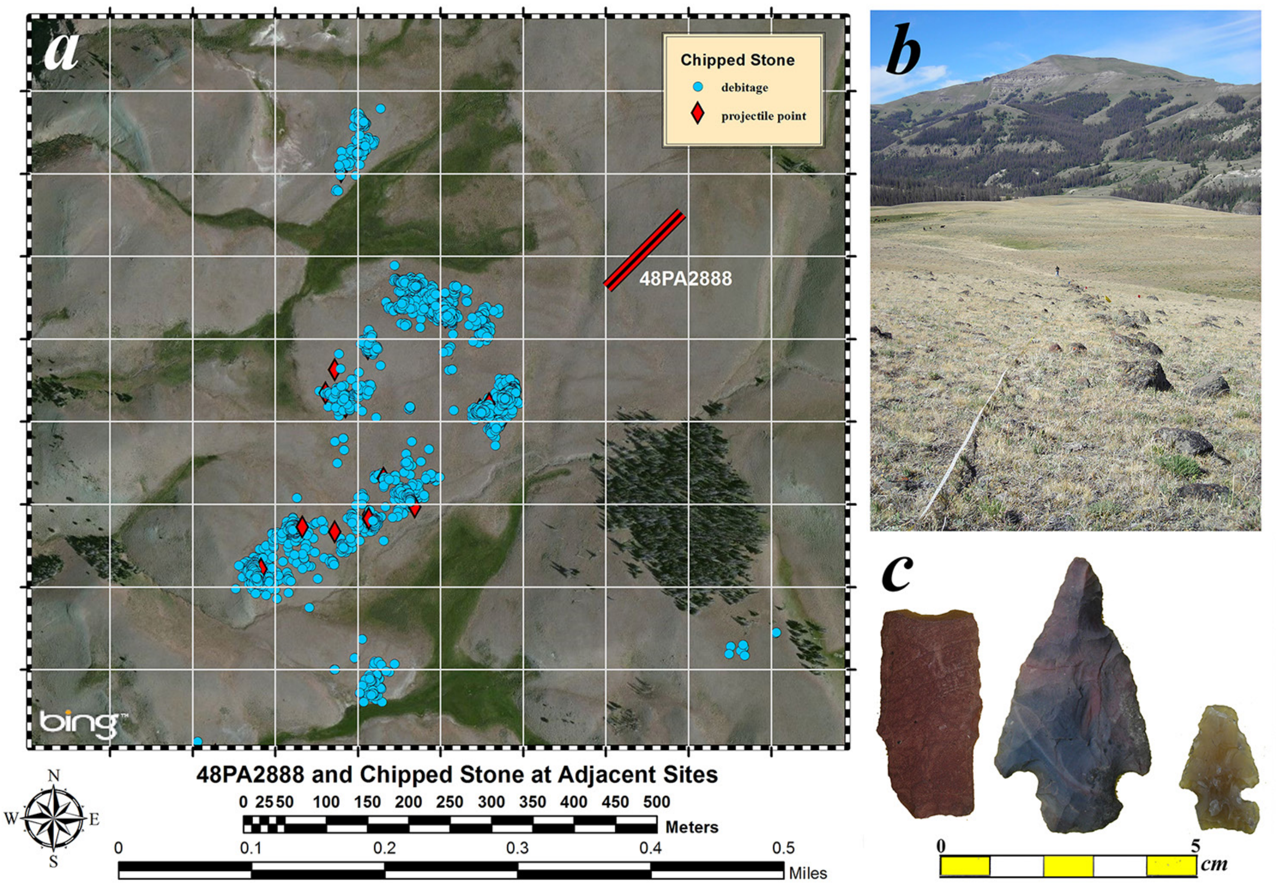


FIGURE 5. Stone alignment at 48PA2888 and documented chipped stone: (a) relation of alignment to chipped stone (circles, debitage and stone tools; triangles, projectile points); (b) overview of alignment (view from northeast to southwest); and (c) examples of projectile points from 48PA2888 area (left to right: Paleoindian, Archaic, and Late Prehistoric).

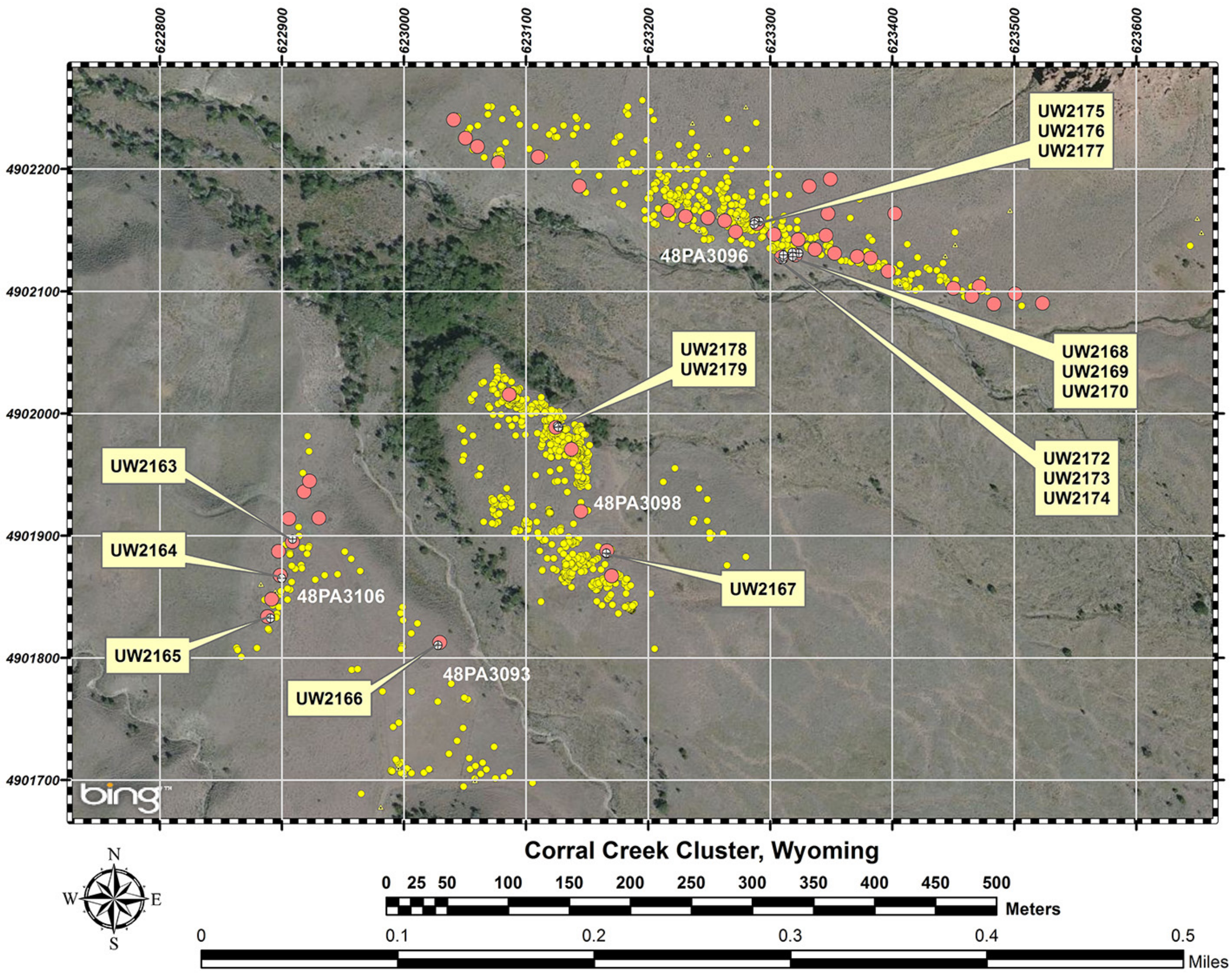


FIGURE 6. Distribution of stone circle (large red circles), surface chipped stone (smaller yellow circles), and OSL sample locations at Corral Creek site complex, Park County, Wyoming.

± 50 BP, Beta 279637). Two IRSL samples were obtained from R-1.

Site 24PH3773 contains 12 tipi rings and two boulder effigies of unclear form (Crofutt and Aaberg 2003). The configuration of the rings, like 24PH762, suggests multiple occupations, and the same kinds of artifacts were recovered. Neither time-diagnostic artifacts nor radiocarbon datable materials were encountered. Two IRSL samples were collected from one ring, R-11.

Site 24PH3775 contains a single tipi ring and a light scatter of quartzite artifacts and heat-altered rocks. The small amount of material remains suggests a single-occupation. Two IRSL samples were collected from the ring.

The last three localities are situated in northwestern Wyoming, just east of Yellowstone National Park.

3. Jack Creek. Site 48PA288 is a linear rock alignment extending about 50 m down a slope at 2,900 m in the volcanic Absaroka Mountains (Kinneer 2007). Although no chipped stone or temporally diagnostic artifacts were found in direct association with the alignment, over 6,000 stone tools and debitage, including 26 projectile points, were found on nearby surfaces (Figure 5). Age estimates based on point morphology range from a Paleoindian Cody Complex base similar to some of those recovered from the Horner site (Frison and Todd 1987) to typical Late Prehistoric arrow points (Figure 5). While the alignment is in an area where Late Prehistoric sheep traps would not be unexpected, no evidence of wooden components associated with many of these traps (Frison 2004; Kornfeld et al. 2010) has been documented, possibly because of fires in the Jack Creek area during the late A.D. 1400s to 1600s (Reiser 2010:103–104) that left much of the area open grassland (Figure 5). Four IRSL samples were collected, but only three were processed.

4. Corral Creek. Corral Creek is a group of four stone-ring sites, also in the Absarokas, at an elevation of 2,100 m (Figure 6). Although these localities have been assigned individual site numbers based on spatial breaks in artifact density and geomorphology, they are best considered as a single stone circle complex that represents a variety of occupational and formational

FIGURE 7. Photo of stone circles at 48PA1151 near Cody, Wyoming. Pictured are Jim Feathers (left) and Larry Todd (photo by Barbara Hay).

histories. At one of the sites (48PA3096), 32 stone circles, with an average diameter of 6.3 m, have been identified along a 500 m stretch of the north bank of the creek. More than 400 pieces of chipped stone have been recovered, including 11 projectile points, two apparently of Paleoindian age, six of Archaic age, and three of indeterminate age. The relationship between the chipped lithic artifacts and the stone circles is not clear but demonstrates the long, and probably complex, occupational history of the Corral Creek land surfaces. A second site (48PA3098) contains six rings of about the same size as those in the first site. No temporally diagnostic stone tools have been found, but a cluster of 33 glass beads averaging 2.4 mm in diameter was recovered, of unknown association with the rings. Based on a bead diameter-age formula developed in Colorado (von Wedell 2011), they have an estimated manufacture date of 1837. The third site (48PA3106) consists of nine slightly smaller rings, with no diagnostic artifacts. The last site in the Corral Creek group (48PA3093) contains only a single stone circle, but it is likely that other circles were present prior to construction related to oil exploration. Sixteen IRSL samples were collected, representing all four sites.

5. Cody. The final locality is site 48PA1151 (Figure 7) in the western margins of Big Horn Basin, near Cody (elevation 1,600 m). The site, situated on a terrace above limestone bedrock, contains several rings, two of which were sampled. Few stone tools, and no temporally diagnostic items, are reported from this site.

Luminescence Analysis

Samples were collected vertically in plastic tubes without exposure to light (see Supplemental Text for more details). The tubes were cut into five 4-cm segments, labeled A through E, with segment A directly under the rock, and E 16-20 cm below the rock. The sediment from each segment was processed separately. Because each segment is relatively small, isolating the best bleached grains requires single-grain analysis of a sensitive dosimeter. Quartz and potassium feldspar are the common alternatives used in luminescence dating. Quartz in the region has low sensitivity, as confirmed by several assays on these materials and by other samples from the northern Rockies processed by the University of Washington laboratory (mostly unpublished, but see Munyikwa et al. 2011). That left K-feldspars as the best candidate, although for some of the samples, particularly from the volcanic Absarokas, even the feldspar is relatively insensitive, requiring a large amount of machine time to get a statistically appropriate number of responsive grains. As a result, the Absaroka samples suffer from small sample size. For feldspar single grains, luminescence was measured using an infrared (IR) laser for stimulation and the equivalent dose— the amount of radiation dose necessary to produce the natural signal—was determined by the single-aliquot regenerative proposal (SAR) (Wintle and Murray 2006), as adopted for feldspars by Auclair et al. (2003). See Feathers (2012) for further details on the luminescence characteristics of these samples.

Feldspars have one significant disadvantage: anomalous fading, the athermal loss of signal through time, which if not taken into account will result in age underestimation. Fading was measured on individual grains, and the ages for each were corrected following Huntley and Lamothe (2001). Elevated-temperature IRSL stimulation was also used to see if fading could be reduced to negligible amounts (Buylaert et al. 2012; Buylaert et al. 2009). Fading issues are described in more detail in the Supplemental Text. Once an age was determined for individual grains, a minimum age model (Galbraith and Roberts 2012) was applied to isolate statistically the youngest mode, those grains most likely to have been fully bleached prior to rock emplacement. The minimum age model assumes that the logs of the true ages are drawn from a truncated normal distribution, where the lower truncation point represents the log average of the fully bleached grains (Galbraith and Roberts 2012).

Dose Rate

Dose rate was measured on bulk samples using thick source alpha counting, beta counting, and flame photometry, as well as from field dosimeters. Two complications affect dose rate assessment. The first is the heterogeneous radioactive environment surrounding the sample. The overlying rock, which will supply a good portion of the gamma dose rate, has different radioactivity from the underlying sediment. The sediment itself, glacial till for the Kutoyis and Whitewater samples and colluvium for the Absaroka samples, is not likely to be homogeneous. To check the uniformity of the sediment radioactivity, the dose rate was measured on both sections A and E, as well as the rock. External dose rates for the different sections were calculated in the laboratory using gradient calculations (Aitken 1985:Appendix H) to estimate the proportional contribution from the air, the rock, and the two end sections. The result from section A was compared with the results from $CaSO_4$:Dy dosimeters. The $CaSO_4$ signals were calibrated against a beta source, used with the shutter closed to obtain a low dose, which in turn was calibrated against quartz with a known gamma dose. The second complication is the internal dose rate in K-feldspars from ^{40}K. While pure K-feldspar (orthoclase) contains stoichiometrically about 14 percent K, individual grains isolated by the preparation procedure are apt to contain a range. This could result in different dose rates for different grains, which will result in different age estimates for grains that would in reality be the same age if differential K were taken into account. We measured K content from individual grains also used for equivalent dose measurements by using tape to transfer grains from the measurement disks to scanning electron microscope (SEM) stubs. An energy-dispersive X-ray (EDS) attachment to the SEM was used to determine K on each grain. Because of time and financial constraints, only a small number of grains could be measured (Supplemental Table 2). Additional dose rate methods are described in the Supplemental Text.

Accuracy

No independent age assessments are available for any of the samples. This prevents a true test of accuracy. Radiocarbon dates and associated artifacts are available for some sites but their relationships to any of the rings or alignments are tenuous. We can test, however, if the data are consistent with the proposed model, which will provide some confidence in the results. The vertical age profile should show an increase in age with depth up to the geological age of the deposit (which for those samples on glacial till should be, if well-bleached, Late Pleistocene). Samples collected directly from the current surface with no rock present should yield a modern age. Three such samples were collected at Kutoyis, Whitewater, and Corral Creek. The method will fail if turbation continued after rock emplacement. While we avoided sampling where there was visible evidence of such horizontal turbation (e.g., ant infestation or shallow embedded rocks), we also tested for this possibility from one sample from Kutoyis. We took one sample from under the center of the rock and another from under the edge of the rock. If any post-placement turbation occurred it would be more prevalent near the edge of the rock than at the center.

The rings may provide a further test of accuracy. If the rings functioned as inferred, as anchors for residential structures, then different samples from the same ring should be the same age. A full ring is necessary for anchoring to be effective, and duration of use should be short, given the mobility the structures imply, so that long-term repair was not necessary. There is, however, clearly some potential for post-abandonment displacement of stones by a variety of biological processes (e.g., trampling by large herbivores such as bison) and cultural processes (e.g., repositioning or moving stones during subsequent occupations). Several pairs of samples from individual rings were collected from Kutoyis, Whitewater, and Corral Creek to begin assessing these aspects of ring positional stability. Same ages are not expected for the drive lines, which may have been reused over long periods of time and repaired.

RESULTS

Dose Rate

Supplemental Table 1 provides concentrations of major contributors to the dose rate from Segments A and E and from the overlying rock. This shows the range of variability observed among the two segments and the rock. Also given in Supplemental Table 1 are the total dose rates for Segment A, both as calculated from the laboratory measurements and as calculated using the dosimeter for the external dose rate. These are plotted against each other in Figure 8, which shows that the dosimeters yield slightly higher dose rate estimates than do the lab measurements for Kutoyis, but lower dose rate estimates than the lab for the Wyoming samples. One possible reason for the

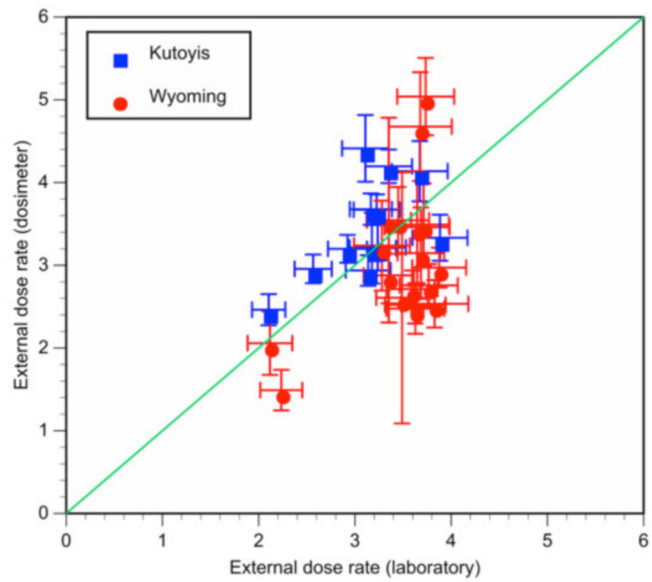


FIGURE 8. External dose rates (Gy/ka) determined by laboratory and field determinations plotted against each other. Where the two are equal is represented by the straight line.

discrepancy with the Wyoming samples is the higher moisture content in the Absaroka Mountains during the winter compared to the summer, due to substantial snow accumulation. As a more direct measure, the external dose rate determined from the dosimeters was used in age calculation with two kinds of exceptions. One is for samples where the dosimeter measurement was very imprecise, because of aliquot-to-aliquot scatter, but still statistically agreed with the lab measurement (UW2165, UW2170, UW2173, UW2177, and UW2180). The other was for samples where the dosimeter measurement was much higher than the lab measurement and also higher than other dosimeter measurements from the same site (UW2169 and UW2445). The dosimeter results were considered overestimated in these two cases. In other cases, where the two measurements differed, the dosimeter measurement seemed reasonable for the site. Finally, no dosimeter information was available for Whitewater.

Acceptance Rates

Not every grain has a suitable luminescence signal for determining an equivalent dose. Criteria were established to accept or reject grains for analysis (see Feathers 2012 for a detailed discussion). Some had to do with meeting technical requirements of the SAR protocol and will not be discussed here because few grains (less than 4 percent) were rejected for such reasons. The main reason for rejection was lack of a measurable signal above background, which was the case for 84 percent of all grains. One other criterion that was not too important for A segments (less than 2 percent) but was increasingly important for deeper segments was failure of the natural signal to intersect the regeneration curve. This was mainly because high regeneration doses were not applied in the interest of saving machine time. This affects only grains much older than the time period under consideration here.

TABLE 1. Dose Recovery.

Temperature/Power	N	Recovered Dose/Administered Dose	Over-dispersion (%)
50°C/30%	292	1.06 ± .01	12.8 ± 1.1
50°C/70–90%	162	1.13 ± .03	23.4 ± 2.2
225°C/30%	188	1.30 ± .03	24.6 ± 1.7
290°C/30%	43	1.33 ± .06	24.1 ± 4.1

Note: N is the number of grains used in the analysis. The values represent combination of grains from 17 different samples.

Supplemental Table 3 gives the acceptance rates for all samples. They are relatively high for Whitewater, 48PA1151, and some Kutoyis samples, but quite low for other Kutoyis samples and especially so for Corral Creek samples. The variation at Kutoyis may depend to some degree on the derivation of the sediments, given that till from the Canadian plains has higher acceptance rates than alluvium from the Rocky Mountain front. The low acceptance rate for Corral Creek samples probably stems from the low alkali feldspar concentrations in the andesitic Absarokas. Low acceptance rates correlate with low internal K contents, which is not surprising given the correlation of low sensitivity with low K contents that has been observed (Prescott and Fox 1993; Reimann et al. 2012).

Low acceptance rates also mean a limitation on sample size. For example, we measured 875 grains for UW1914 at Kutoyis but accepted only 14 for equivalent dose determination. The 875 exhausted the 180–212μm fraction of the sample, so it is not possible to increase this sample size.

Anomalous Fading and Dose Recovery

Measured fading rates are given in Supplemental Table 4 for different stimulation temperatures and laser power. The elevated temperature stimulations did reduce fading rates, but not always to negligible amounts. Some grains still faded significantly more than the 1–1.5 percent considered to be a lower limit because of measurement error (Buylaert et al. 2012). Although they were not measured directly in this study, residual signals from elevated temperature stimulation can also be a problem (Reimann et al. 2012). Minimum age calculations from high temperature stimulations for the Kutoyis samples tended to be older than those from the low temperature stimulations, suggesting a residual, but the situation with the Whitewater samples was less clear. See the Supplemental Text for a more detailed discussion of fading.

Dose recovery tests among different stimulations are given in Table 1. Dose recovery is a method of evaluating the procedures used for determining equivalent dose. The luminescence signal is reduced to zero by exposure to light and then a known dose is applied. The SAR protocol is carried out using the known dose as a proxy for the natural dose. The derived equivalent dose is then compared with the known dose. The ratio between them should be close to one for appropriate procedures. Results reported in Table 1 show that increasing the stimulation temperature increasingly overestimates the given dose. The high temperature stimulation results are therefore problematic to some degree, and reliance should be placed on the low temperature stimulations. This means accepting the poorer precision that results from fading corrections (Feathers 2012).

Age Distributions

If the turbation model described earlier holds, then the longer the duration and the more intense the turbation, the deeper should well-bleached grains be found. The intensity of turbation will depend on the agents of turbation, but these can only be a matter of speculation for the areas under investigation. Burrowing small mammals and insects are common, and large herds of bison capable of kicking up sediment once roamed the prairie areas. Roots from grasses and bushes such as sage may also contribute, but trees, which are responsible for intense turbation in forested areas, are not present except perhaps at Jack Creek. Freeze-thaw processes, present in all these areas, will also play a role.

To see whether the samples are behaving like the turbation model, age distributions were determined for each of the five segments from several samples. Figure 9 illustrates radial graphs for two samples, UW1912 from Kutoyis and UW2156 from Whitewater. These graphs plot age against precision, with the age normalized on the y-axis by the number of standard errors away from some reference value, in this case the minimum age for segment A. The shaded area encompasses all grains within two standard errors of the reference. Lines drawn from the origin through any point intersect the right-hand scale at the estimated age. For UW1912, from Kutoyis, most young grains are bunched into the first 4 cm, mixed with a large number of old grains. Young grains are depleted by segment B and nearly disappear by segment E, when all grains seem to cluster around 25 ka. For UW2156, from Whitewater, young grains are found much deeper, but old grains still dominate each segment, where they seem to center around 12 ka for segment E. These distributions match the expectations of the turbation model: most younger grains concentrated near the top of the profile, with a steady decrease with depth. All segments have a backdrop of older grains of roughly the same age, probably the original depositional age during the Pleistocene. This is not what would be expected if the sediment was only partially bleached at the time of deposition. In that case, the younger grains would be distributed more evenly. Other samples tested, from all sites, have similar patterns, although the ones from Wyoming are harder to interpret due to small sample size.

For the younger grains to represent the age of rock placement, they should have been at zero age at the time of placement. Looking at modern surface samples should inform on that probability. Three samples were collected in the same way, except with no rock present, at Kutoyis, Whitewater, and Corral Creek. Minimum age values used an unlogged version of the model (Arnold et al. 2009), ignoring all negative values, which can occur

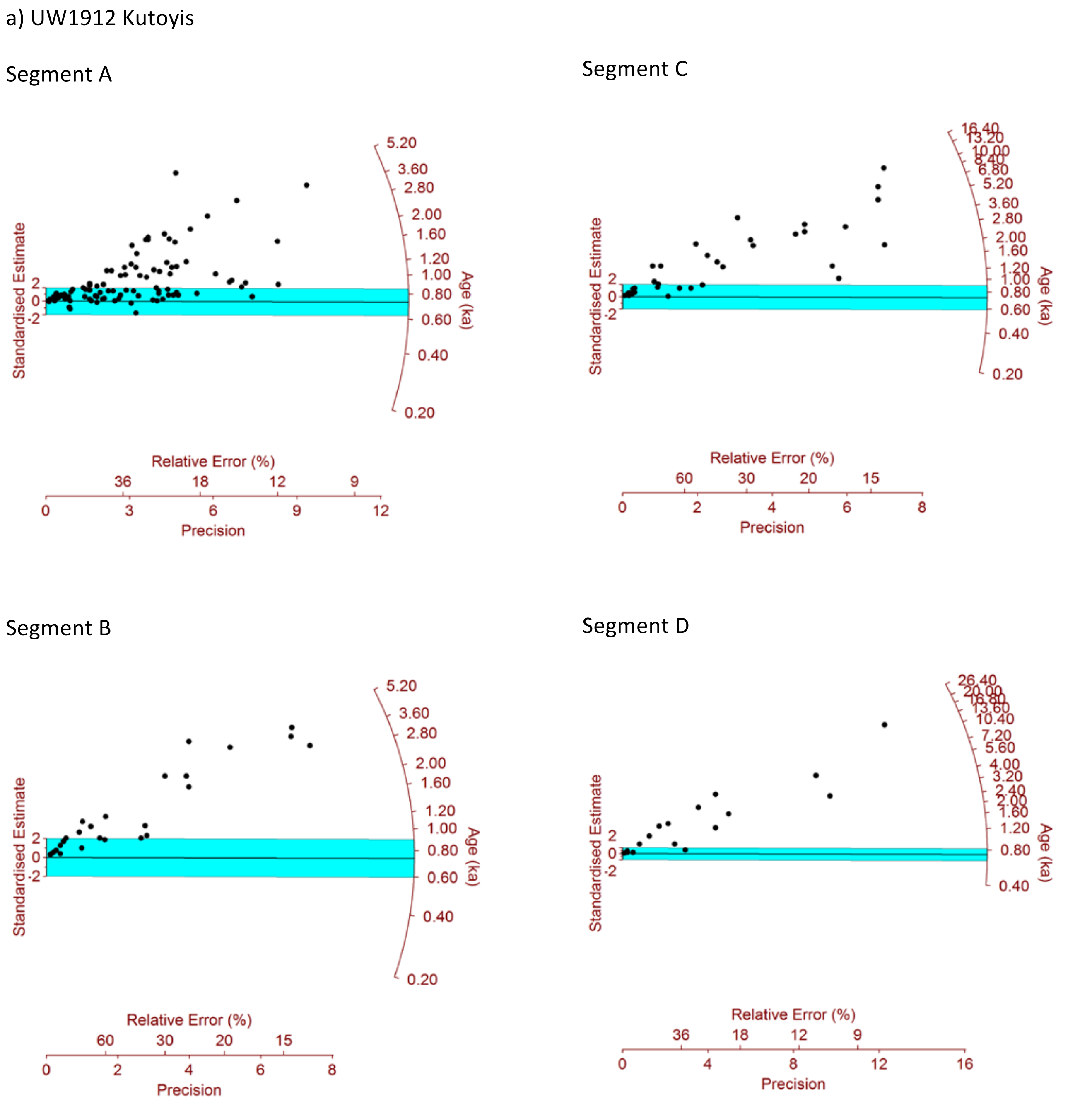


FIGURE 9. Radial graphs of different sampling segments from (a) UW1912, Kutoyis, and (b) UW2156, Whitewater. Segment A is the segment just under rock, and B through E are progressively deeper. Radial graphs plot precision on the x-axis against the age on the y-axis. The age is normalized by the number of standard errors the error is from the reference, which in this case is the minimum age calculated for Segment A. A line drawn from the origin through any point intersects the right axis at the estimated age for that grain. Younger grains are found much further down for the Whitewater samples, suggesting more intense turbation processes. Grains seem to maximize around 25 ka for UW1912 and 12 ka for UW2156, which may represent the original age of deposition.

due to their statistical nature. The resulting minimum ages are .08 ± .02 ka for UW1910 (Kutoyis), .04 ± .02 for UW2154 (Whitewater), and .05 ± .02 for UW2171 (Corral Creek). These are near zero but suggest a residual value of 40–80 years, not significant for older samples, but of some importance for samples less than 1,000 years old. One can expect that the ages at Kutoyis may be overestimated by about 80 years, and those at Whitewater and Corral Creek by about 50 years.

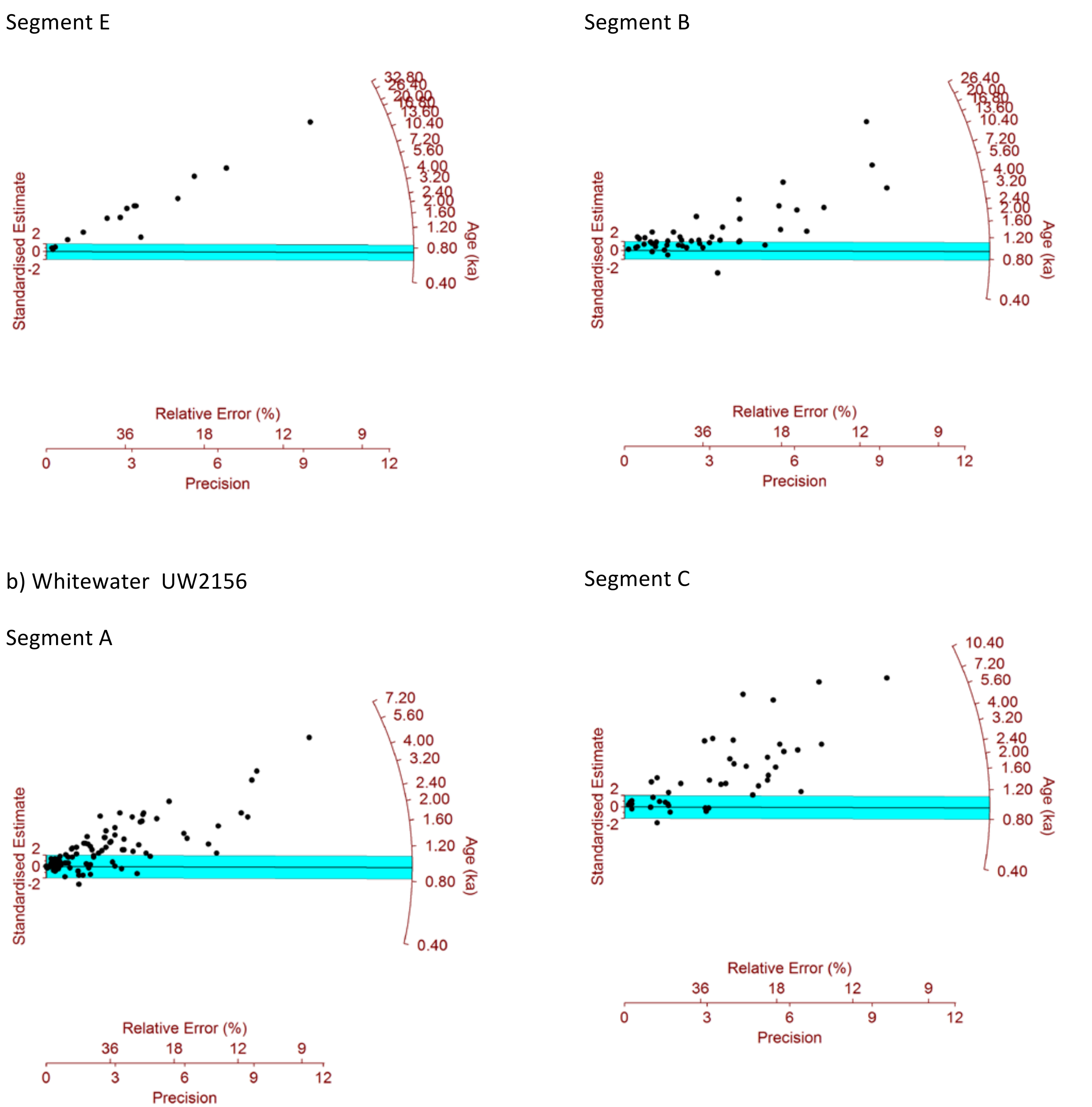
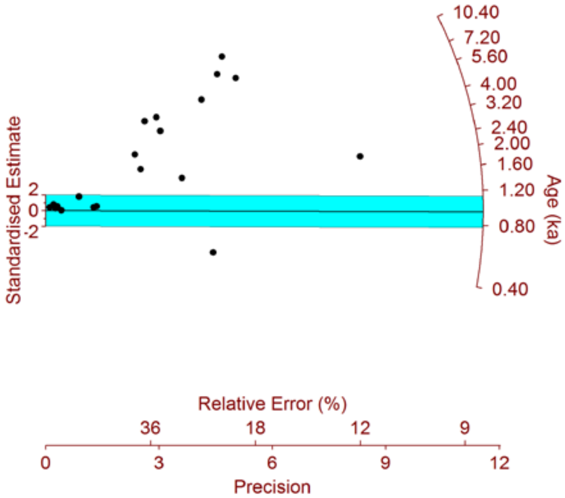


FIGURE 9 (continued).

Even with a rock in place, there still could be horizontal turbation from the sides, so that placement of the rock does not end the turbation process. If this occurs, the derived age will be underestimated. To test the possibility, we took two samples for UW2446 at Kutoyis. One came from the center of the rock, which was 38 by 24 cm in the horizontal dimensions, 7 cm thick, and embedded 10 cm, and one came from the side. If any horizontal turbation has taken place, one would expect the age of the sample near the side to be younger than the one from the center. In fact, they were statistically indistinguishable: .58 ± .12 from the side and .45 ± .09 from the center. If horizontal turbation were common, one might also expect all ages to be about the same, but the derived ages range up to 2,000 years. Of course, this does not mean that horizontal turbation never happens; it just means that it does not appear to be a general phenomenon.

Another indicator that horizontal turbation may not be a significant factor is the presence of equivalent ages for rocks from the same ring—a gauge, as mentioned, of accuracy. Turbation might not be expected to affect all rocks to the same extent, so

Segment D



Segment E

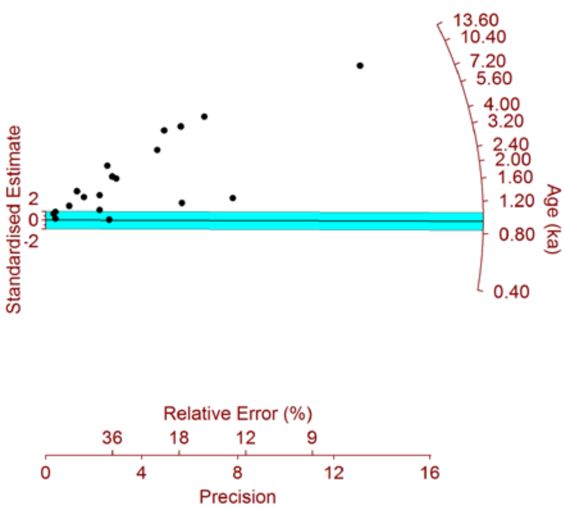


FIGURE 9 (continued).

equivalence in age suggests that horizontal turbation is of no great consequence. Rocks from the same ring were sampled at Kutoyis, Whitewater, and Corral Creek. UW1914 and UW1915, from the same ring at Kutoyis, gave respective ages of .48 ± .18 ka and .48 ± .12, practically identical. UW2152 and UW2153 from the same ring at 24PH762, Whitewater, gave respective ages of 1.52 ± .28 and 1.28 ± .18. UW2157 and UW2158, from the only ring at 24PH3375, Whitewater, gave respective ages of 1.99 ± .61 and 1.41 ± .21. Systematic uncertainties were not discounted in these comparisons, but random uncertainties in fading corrections and minimum age calculations swamped any systematic errors. One attempt to discount systematic errors showed this to be the case. The samples from the same rings at Corral Creek will be discussed later, as will be one further pair from Whitewater, where there was disagreement.

DISCUSSION OF AGES

Kutoyis

Minimum ages for all samples from Kutoyis are reported in Table 2. Most are based on low temperature stimulations, but in a few cases the high temperature stimulations resulted in ages that did not differ from low temperature stimulations.

Most ages range between A.D. 1500 and A.D. 1800. These agree with the bulk of the radiocarbon ages obtained mostly on charcoal and bone from the bison bone bed under the cliff at the terminus of the main drive line but also from some other areas. Some earlier radiocarbon dates from deeper in the bone bed dates correspond well with the OSL ages of UW1912, UW1918, and UW2445. The range of ages for the South Drive Line indicate that the drive line was constructed to perform the earliest kills and was reused and expanded through time until it reached 4 km in length by the historic period. The tipi rings cover the same age range. All these ages fall within the defined temporal range of the Old Woman's Phase, a period of intensified bison hunting (Peck 2011; Zedeño et al. 2014).

More surprising are the much older dates from two large rings from Memorial Monument as well as one of the smaller tipi rings at the upper campsite (the other large ring sampled, UW2440, has an age more like others at Kutoyis). These give a weighted average age of A.D. 10 ± 240. Zedeño et al. (2014) consider these ages too old for the archaeology, but there is nothing technically wrong with them. An alternative explanation, suggested by the surface finding of a projectile point known as Besant (100 B.C.–A.D. 500), is that the locale had an earlier occupation of a somewhat different nature than what came later, perhaps an earlier variant of the ceremonial structures.

Whitewater

The ages derived from the Whitewater samples (Table 3) are in general much older than those at Kutoyis. Five of them give a weighted average of A.D. 370 ± 140. The most significant outlier is UW2156, which is much younger. The error bars are less for these samples than those at Kutoyis due to the larger sample size achievable from more sensitive grains.

The radiocarbon date from the external hearth at UW24PH762, A.D. 1020, is younger, but it does fall in the range of the Avonlea Phase in northern Montana (900–1100 B.P.; Davis 1988), including two sites just south of Austin Basin, Henry Smith site (24PH794) and Fantasy Kill site (24PH1324), which range in age from 1200 to 940 B.P. Avonlea sites in southern Alberta and southern Saskatchewan tend to include earlier dates that extend to about 1800 B.P., with dates between 1200 and 1500 B.P. being relatively common (Morlan 1988). The Avonlea Phase predates the Old Woman's phase. The paired OSL dates from 24PH762, although older than the radiocarbon date (which was drawn from a feature outside the rings), match these older dates for the Avonlea Phase. However, there is considerable overlap between dates from the Besant Phase of the Middle Precontact period and the earlier dates for Avonlea. Radiocarbon dates for Besant

TABLE 2. Kutoyis Minimum Ages.

Sample	N of Grains	Age (ka)	% Error	Calendar Date
South Drive Line				
UW1911	58	.33 ± .12	35.5	A.D. 1680 ± 120
UW1912	76	.74 ± .07	9.2	A.D. 1270 ± 70
UW2437	80	.43 ± .09	20.2	A.D. 1580 ± 90
UW2438	84	.50 ± .10	20.0	A.D. 1510 ± 100
UW2439	50	.34 ± .10	30.0	A.D. 1670 ± 100
North Drive Line				
UW1913	55	.34 ± .06	19.3	A.D. 1670 ± 70
UW2443	37	.20 ± .06	31.0	A.D. 1810 ± 60
UW2444	55	.41±.12	29.6	A.D. 1600 ± 120
Lower Kutoyis Camp Site				
UW1914	12	.48 ± .18	37.7	A.D. 1530 ± 180
UW1915	24	.48 ± .12	24.9	A.D. 1530 ± 120
UW1916	33	.22 ± .06	28.8	A.D. 1800 ± 60
UW1917	35	.26 ± .07	27.5	A.D. 1760 ± 70
UW1918	70	.63 ± .13	20.2	A.D. 1380 ± 130
Memorial Monument				
UW2440	45	.42 ± .14	32.0	A.D. 1590 ± 140
UW2441	53	2.18 ± .44	20.3	170 ± 440 B.C.
UW2442	58	1.66 ± .33	20.1	A.D. 340 ± 330
Upper Kutoyis Camp Site				
UW2445	46	.80 ± .28	35.2	A.D. 1210 ± 280
UW2446	100	.45 ± .09	20.3	A.D. 1560 ± 90
UW2447	47	2.24 ± .50	22.0	240 ± 500 B.C.
UW2448	34	.25 ± .07	29.5	A.D. 1760 ± 70

Note: There is a possible age overestimate of 80 years based on the modern sample. All ages are based on low-temperature stimulations, except for UW1914, UW1915, UW2438, UW2442, and UW2447, where both high and low temperature stimulations were accepted. UW1914 and UW1915 are also from the same ring.

TABLE 3. Whitewater Minimum Ages.

Sample	N of Grains	Age (ka)	% Error	Calendar Date
24PH762				
UW2152	79	1.52 ± .28	18.5	A.D. 490 ± 280
UW2153	132	1.32 ± .21	15.9	A.D. 690 ± 210
24PH3773				
UW2155	88	1.58 ± .36	22.9	A.D. 430 ± 360
UW2156	110	.95 ± .09	9.3	A.D. 1060 ± 90
24PH3775				
UW2157	58	2.48 ± .63	25.3	470 ± 630 B.C.
UW2158	114	1.90 ± .34	17.7	A.D. 110 ± 340

Note: There is a possible 40-year age overestimate based on the modern sample. UW2152, UW2156, and UW2157 used both high and low temperature stimulations. The others just used low temperature. UW2152 and UW2153 are both from the same ring. UW2157 and UW2158 are from the only ring at the site.

Phase sites in Montana, Alberta, North Dakota, and Wyoming range from 2090 to 1039 B.P., although 75 percent of them fall between 1500 and 2100 B.P. (Aaberg et al. 2006). The R-1 OSL dates, therefore, could indicate either an Avonlea or a Besant occupation, although the phases are not well-defined and their age range could vary from place to place.

The two ages from R-11 at 24PH3773 did not produce statistically overlapping dates. But they do fall within the same temporal range of both the OSL dates (UW2155) and the radiocarbon date (UW2156) from R-1 at 24PH762. Although temporary displacement of the rock by turbation processes could account for the discrepancy of the two ages, reuse of ring stones may also be a possibility.

The paired OSL dates from 24PH3775 are consistent with single use of the ring. The dates currently represent one of the two oldest dates for tipi ring sites in Montana, excluding sites aged through relative dating of time-sensitive artifacts. A conventional radiocarbon age of 3940 ± 20 B.P. (Beta-24985) obtained from a tipi ring at 24BH2317 in southeastern Montana currently represents the oldest chronometric date for a tipi ring in Montana (Brumley and Dickerson 2000). The early date at 24BH2317 was attributed to the Middle Precontact period McKean Complex, which has a temporal range from 5000 to 3000 B.P. The Oxbow Phase is generally thought to have preceded McKean, persisting from 6000 to 2500 B.P., with more recent dates coming from northern locations in Canadian Prairie provinces (Aaberg et al. 2006). Both McKean and Oxbow points and sites are reported from the glaciated prairies of northern Montana, southern Alberta and southern Saskatchewan. The Cree Crossing site (24PH3396) located on the Milk River about 9 km south-southeast of Whitewater contains Oxbow artifacts radiocarbon-dated to 3410 ± 40 B.P. and 3570 ± 40 B.P. (Aaberg et al. 2003). Nine kilometers east of Whitewater, site 24PH8 contains a mixed assemblage in and among tipi rings, including points attributed to both McKean and Oxbow. The site also yielded radiocarbon dates from 3230 to 3930 B.P., but were obtained outside and between tipi rings (Deaver 1983). This evidence indicates prehistoric activity in the area during the time that the tipi ring at 24PH3775 was apparently constructed.

Wyoming

The samples from Corral Creek and Jack Creek suffered from poor sensitivity, so the sample size is small. The ages reported in Table 4 for Corral Creek exhibit wide variation, ranging in age from 5.9 ka to .27 ka. Even samples from the same rings show high variation. Much of this variation can be attributed to small sample size, because some samples may not show younger grains because none happened to be present among the ones measured. Increasing sample size adequately would be extremely time consuming, expensive, and impractical. As an alternative, we have combined samples either from the same site or from the same ring for the Wyoming samples, assuming contemporaneity. This, of course, reduces the resolution. To combine samples, grains from each sample involved are pooled and treated as one sample.

Combined ages are reported in Table 5. All three rings give close to the same age at 48PA3106, and the combined age is 10 ± 240 B.C., strong evidence that this is a relatively old site. Two of the samples from 48PA3098 also appear to be old, but one, from the same ring as one of the others, is quite a bit younger, which could be a result of this rock having been repositioned after the ring was originally abandoned. The combined age of A.D. 1220 ± 280 is largely driven by the data from UW2179. It is possible that Ring 2 is substantially older than Ring 5, but the data are too poor to resolve this. The three rings measured at 48PA3096 each give a combined age within error terms of each other. Combining all samples from all rings produces an age of A.D. 1430 ± 110. While individually there are a few samples that are much older, this is likely a small-sample size effect, and the best estimate for the whole site is the fifteenth century date. The two samples from the linear arrangement at Jack Creek give a combined age of A.D. 1680 ± 50. The older age for one of the samples is probably due to small sample size.

We also combined the data for the two samples from separate rings at 48PA1151, the site near Cody. The combined age of A.D. 1300 ± 250 is mainly the effect of UW2180, which has a relatively large sample size on its own. The measured grains for UW2180 also included 19 that gave negative equivalent dose values, much more than any other samples. The next highest were 6 for UW2179 and 6 for UW2181, the latter also from 48PA1151. Either horizontal turbation was prevalent at this site, or both samples are really quite young, the very old age for UW2181 just being a function of small sample size. The data are not sufficient to distinguish these alternatives.

The Wyoming data also led us to consider a sampling issue and the degree to which individual stones within a feature are positionally stable, which, aside from sample size effects, may influence date variation. Figure 10 illustrates several of the stone circles from the Corral Creek complex, with six of the sampled stones indicated. When faced with the task of sampling rocks from the stone circles, one could argue that the appropriate population should be the total number of individual stones, rather than the number of complete features. In Figure 10 the sampling problem could be viewed as collecting samples from a population of seven rings, of which three were sampled, or as an exercise of sampling over 500 individual stones, of which we sampled only six in the group illustrated in this Figure. If the circles are the sample population, we've sampled 42 percent of those illustrated in Figure 10. If the stones are the sample population, our sample drops to only about 1 percent. The number and range of stone sizes (Table 4) in a single ring produces a complicated sampling problem. While the age disparity in ages from individual rings at Corral Creek may indeed be a sample size problem, the possibility cannot be ruled out that it may also be a function of post-abandonment movements. We expect that the older the ring and the smaller the stones, the greater the likelihood that some of the stones have been repositioned, but we have not yet implemented investigations to evaluate possible stone repositioning impacts on dating circles. These issues await further field investigation.

Sampling issues notwithstanding, several trends are apparent in the Wyoming samples (Figure 11). First, as might be expected for stone circles, most have ages that fall within the Late Prehistoric period (Kornfeld et al. 2010). Second, all rings sampled in the stone circle cluster at 48PA3106 (see Figure 6) have dates falling into the Late Plains Archaic period (3000–2000 years ago), which is consistent with a projectile point documented within

TABLE 4. Minimum Ages from Wyoming Sample.

Sample	Feature	Stone Surface Area (cm^2)	N of Grains	Age (ka)	% Error	Calendar Date
Corral Creek—48PA3106						
UW2163	10	1178	21	2.54 ± .34	13.4	530 ± 340 B.C.
UW2164	3	510	16	2.23 ± .56	25.1	220 ± 560 B.C.
UW2165	1	875	22	1.65 ± .32	19.4	A.D. 360 ± 320
Corral Creek—48PA3093						
UW2166	9	775	20	.27 ± .09	33.3	A.D. 1740 ± 90
Corral Creek—48PA3098						
UW2167	2	682	13	5.87 ± 1.54	26.2	3860 ± 1540 B.C.
UW2178	5	961	16	2.40 ± 1.18	49.2	390 ± 1180 B.C.
UW2179	5	1230	12	.6 7± .28	41.8	A.D. 1340 ± 280
Corral Creek—48PA3096						
UW2168	12	598	19	.31 ± .20	64.5	A.D. 1700 ± 200
UW2169	12	779	10	4.03 ± .79	19.6	2020 ± 790 B.C.
UW2170	12	1035	15	.77 ± .35	45.4	A.D. 1240 ± 350
UW2172	14	896	14	.61 ± .37	60.6	A.D. 1400 ± 370
UW2173	14	1536	12	1.93 ± .51	26.4	A.D. 80 ± 510
UW2174	14	646	18	.93 ± .32	34.4	A.D. 1080 ± 320
UW2175	16	448	14	1.07 ± .36	33.6	A.D. 940 ± 360
UW2176	16	570	14	.50 ± .20	40	A.D. 1510 ± 200
UW2177	16	630	13	1.85 ± .47	25.4	A.D. 160 ± 470
Cody—48PA1151						
UW2180	3	754	14	.47 ± .18	38.3	A.D. 1540 ± 180
UW2181	6	836	16	4.29 ± 2.06	48	2280 ± 2060 B.C.
Jack Creek—48PA2888						
UW1670	102		48	.31 ± .05	16.1	A.D. 1700 ± 50
UW1671	103		18	.85 ± .31	35.6	A.D. 1160 ± 310

Note: All ages are possibly overestimated by 50 years based on the modern sample.

TABLE 5. Combined Ages for Wyoming Samples.

Site	Ring #s	N of Grains	Age (ka)	% Error	Calendar Age
48PA3106	1,3,10	59	2.02 ± .24	11.9	10 ± 240 B.C.
48PA3098	2,5	51	.81 ± .28	34.2	A.D. 1200 ± 280
48PA3096	12	44	.48 ± .20	41.7	A.D. 1530 ± 200
48PA3096	14	44	.68 ± .23	33.8	A.D. 1330 ± 230
48PA3096	16	41	.59 ± .16	27.1	A.D. 1420 ± 160
48PA3096	12,14,16	129	.58 ± .11	19.0	A.D. 1430 ± 110
48PA2888	Same line	66	.33 ± .05	15.2	A.D. 1680 ± 50
48PA1511	3,6	30	.71 ± .25	35.2	A.D. 1300 ± 250

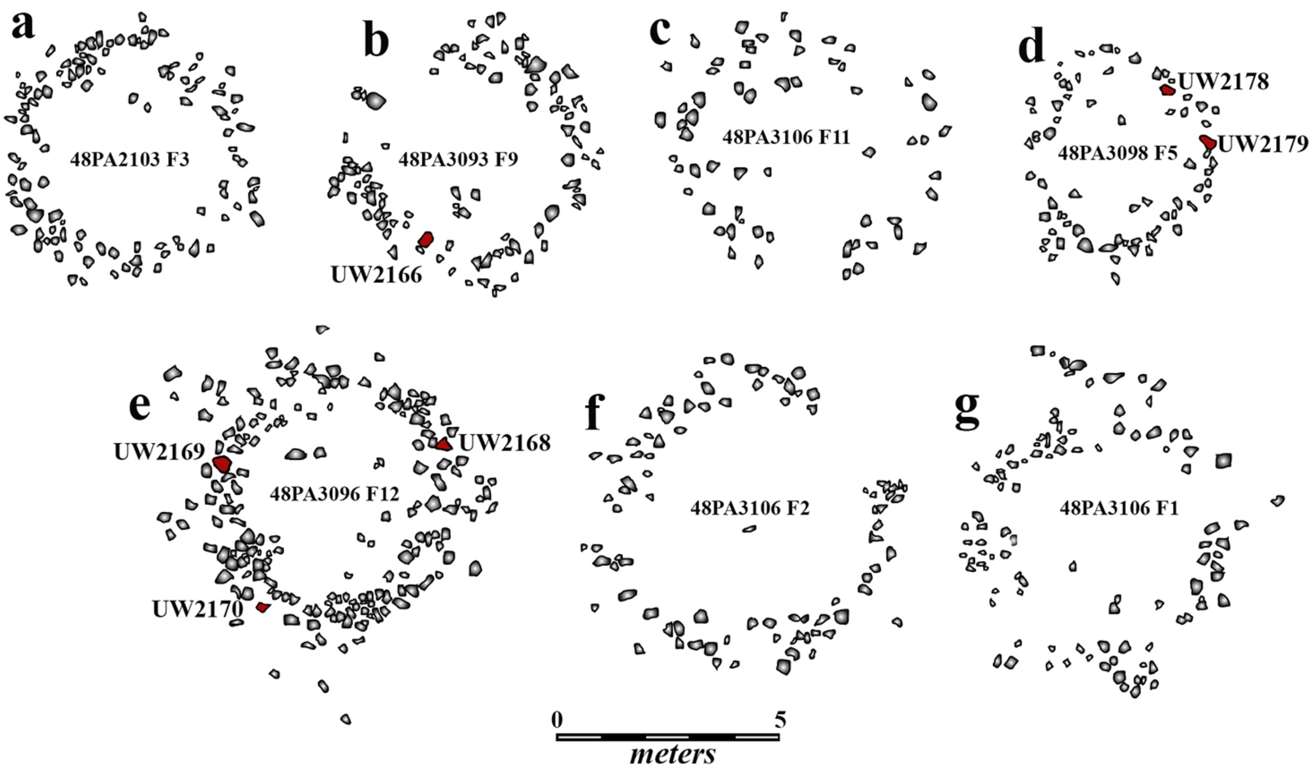


FIGURE 10. Examples of variation in stone circles at Corral Creek complex with locations of OSL sampled stones indicated in red for circles b, d, and e.

the cluster. Other clusters in the Corral Creek area have much less temporal uniformity. In particular, at 48PA3098, which has a surface assemblage that includes glass beads, the three samples suggest rock emplacement during Early Archaic (8000–5500 years ago), Late Archaic, and Late Prehistoric (after 2000 years ago) uses of the landscape, and at 48PA1151, sample ages range from Middle Archaic to Late Prehistoric for the sampled rings. Variation in ages for the three rings with multiple samples at 48PA3096 (Features 12, 14, and 16) includes one Archaic age (Middle and Late) for each feature and two Late Prehistoric ages. Interestingly, for two of the circles (Features 14 and 16), the Archaic age is also associated with the largest, presumably least mobile, of stones sampled (Table 4: stone surface area).

Finally, the stone alignment at 48PA2888 falls well within the Late Prehistoric period and may well represent a component of the well-known mountain drive line pattern associated with this period in the Absarokas (Frison 2004; Frison et al. 1990). As noted above, the lack of associated wooden materials may be indicative of regional fire history (Reiser 2010) rather than original feature construction techniques.

CONCLUSIONS

We believe that OSL provides a promising solution to the longstanding problem of dating stone features in the northern Plains and Rockies. The distributions of grain ages down the sampling column matched what would be expected from the proposed zeroing mechanism, giving validity to the method. We also found that post-depositional turbation is probably not a serious problem, modern samples give near zero ages (although still with some residual), and rocks from the same rings generally gave the same age within error. The latter was not true in all cases, which for Corral Creek might be a sampling size issue, but for the case at Whitewater might be related to more recent movement of one of the rocks. A systematic study of the probability of this happening, and whether it is correlated with rock size or depth to which the rock is embedded, is required. The derived ages were consistent, for the most part, with regional cultural history and available "independent" dating evidence. Where these did not coincide, the problems could well be associational, i.e., the independent dates addressed different events. The potential for documenting different ages at complex sites was demonstrated at Kutoyis and Corral Creek, even producing some surprising results, such as the older dates from Memorial Monument at Kutoyis. The less than optimal precision of the dates was due to several factors. First and foremost is the uncertainty in the correction for anomalous fading. Continued research into circumventing fading in feldspars may lead to improvements in this area. One reviewer of this article suggested taking the grains from the youngest components of the sample (those responsible for the minimum age) and plotting De vs. fading rate and then extrapolating to zero fading. Other sources of error include the low sensitivity of some samples, small sample sizes when calculating minimum ages, and spatial

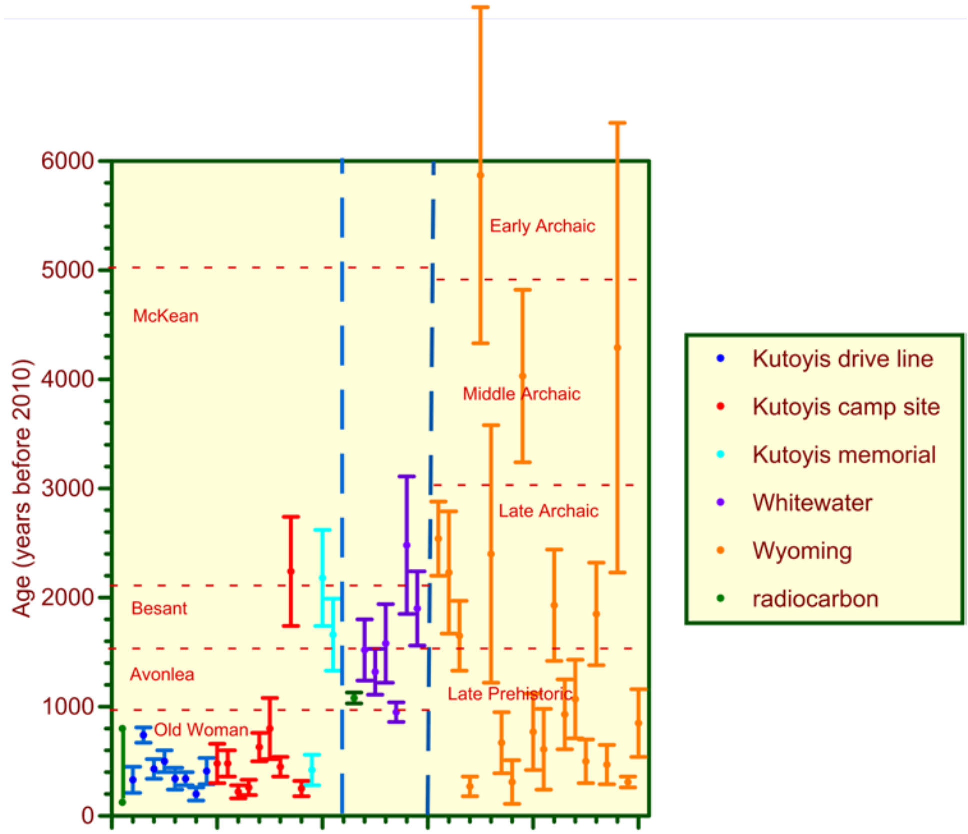


FIGURE 11. OSL sample ages (ka) for all samples in this study, compared to a few radiocarbon ages and general Plains cultural chronological periods.

variation in dose rate that put more reliance on less precise dosimeters. Better precision might be obtained with quartz, if it is sufficiently sensitive. Finally, a lot of dates are required to realize the potential of luminescence dating to provide the chronological outlines of settlement and subsistence change that these features document. Unfortunately, luminescence dating is expensive and time-consuming, so judicial choice of samples will be needed to maximize returns.

Acknowledgments. The senior author was supported by the National Science Foundation (BCS-0909553), who funded all the dating for this project. Shoshone National Forest archaeologists Jeremy Karchut, Molly Westby, and Kyle Wright have all helped with funding and administrative support for the Wyoming site documentation, and BLM archaeologist Kierson Crume made the work at 48PA1151 possible. Colorado State University students spent untold hours mapping at the Wyoming sites. and graduate students Abe Thompson, Christopher Kinneer, Allison Bohn, Marcy Reiser, and Jillian Bechberger helped supervise aspects of the fieldwork. The idea for this work stemmed from conversation between the senior author and Christopher Kinneer in a poster session at an SAA meeting. The Kutoyis work was made possible by the Blackfeet Tribe and its Historical Preservation Office, funding from the National Science Foundation (BCS-091801 and BCS-1266118), and the National Park Service Tribal Heritage Program (Grants #30-07-NA-3015 and #30-09-NA-3017). Work at Whitewater was supported by the Montana Department of Transportation.

Data Availability Statement. The data from this project are stored at the laboratory website at http://depts.washington.edu/lumlab/index.html. Click on the link "Dating Rock Alignments in the Rocky Mountains and Great Plains." This provides links to the various data files and to a directory showing which files are available. Some of the files require knowledge of luminescence data structure. The bin files can be accessed only by the Risø Analyst program.

Supplemental Material. Supplemental materials accompanying this article are available online through IngentaConnect: http://saa.publisher.ingentaconnect.com/content/saa/aap;jsessionid=1aye32k7kxuvp.victoria

Supplemental Text. Methods and Results.

Supplemental Table 1. Dose Rate Information.

Supplemental Table 2. Internal Cation Concentrations.

Supplemental Table 3. Acceptance Rates from Segment A.

Supplemental Table 4. Fading Rates (g-value).

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