ORIGIN AND CHRONOLOGY OF RELICT SLOPE RINGS AND TALUS FLATIRONS IN THE COLORADO PIEDMONT, USA

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ABSTRACT

In the Colorado Piedmont, talus flatiron chronosequences are associated with buttes that consist of highly erodible arkosic sandstone and resistant caprock. Following the removal of the caprock, some buttes evolve into crater-like relict slope rings resulting from the differential erosion of the soft bedrock in the core of the hills. These unique landforms are only documented in the Colorado Piedmont. Their development is attributed to the unusually high erodibility contrast between the low-cohesion sandy bedrock and the bouldery colluvial armour. The talus flatiron sequences and relict slope rings mapped in three study areas record alternating periods of accumulation and incision in the slopes that are likely controlled by changes in moisture availability and vegetation cover density. The obtained OSL dates place slope accumulation phases at >124 ka, and ca. 73 ka, 50-40 ka, 15 ka, and 10-6 ka.

Key words: *Triangular slope facets, relief inversion, OSL dating, paleoclimate*

RESUMEN

En el Colorado Piedmont se han desarrollado secuencias de facetas triangulares de ladera asociadas a cerros testigo, constituidos por areniscas arcósicas muy fácilmente erosionables coronadas por niveles resistentes de conglomerados y/o ignimbritas. Tras la erosión del nivel superior, algunos cerros han evolucionado a anillos de laderas relictas con morfología de cráter, debido a la erosión diferencial de los materiales lábiles del sustrato que ocupan el interior de estos relieves. El desarrollo de estas morfologías, documentadas exclusivamente en esta región del SO de Estados Unidos, se atribuye al marcado contraste existente entre la erodibilidad de las arenas friables del sustrato y los depósitos de ladera, con una elevada proporción de bloques. Las secuencias de facetas triangulares de ladera y los anillos de ladera relictas cartografiados en tres zonas registran diversos periodos de acumulación e incisión en las laderas, muy probablemente controlados por variaciones en la disponibilidad hídrica y la densidad de la cobertera vegetal. Las edades OSL obtenidas sitúan de forma aproximada las fases de acumulación en >124 ka, and ca. 73 ka, 50-40 ka, 15 ka, and 10-6 ka.

Palabras clave: *Facetas triangulares de ladera, inversión de relieve, OSL, paleoclimatología*

1. INTRODUCTION

Talus flatirons, also known as tripartite slopes and triangular slope facets, are relict slopes detached from the source that once supplied the debris that armor their surface (Gutiérrez, 2013). These landforms generally are associated with mesas, buttes and cuestas, where a resistant caprock overlies easily erodible sediments. Talus flatirons have a triangular or trapezoidal geometry with the apex pointing toward the scarp. They typically display a concave-up parabolic longitudinal profile with a progressive increase in gradient towards the apex (e.g., Gutiérrez-Elorza & Sesé-Martínez, 2001; Boroda *et al.,* 2011). The development of talus flatirons involves two successive stages with opposing morphogenetic processes in the debris slope. During the initial stage, detrital material derived from the erosion of the rock scarp accumulates on the debris slope. Subsequent dissection of the debris slope accompanied by the retreat of the free face scarp, eventually leads to the isolation of talus flatirons disconnected from their sediment source. Alternating periods of accumulation and incision of the debris slopes below the retreating scarp may result in the generation of talus flatiron chronosequences. Different temporal groups of flatirons may be differentiated by means of detailed geomorphological mapping and on the basis of their relative spatial distribution; inset relationships and distance to the scarp (e.g., Gutiérrez *et al.,* 2010; Boroda *et al.,* 2011; Roqué *et al.,* 2013). Numerical dating of talus flatirons also allow establishing temporal relationships with other paleoenvironmental records and exploring the potential role played by external factors (i.e. climate, anthropogenic activity) on the generation of these landforms (Gutiérrez *et al.,* 2010; Boroda *et al.,* 2011). Most researchers agree that the colluvial deposits of talus flatiron sequences developed in semiarid areas record more humid phases during which an increase in vegetation density prevented dissection on the slopes, whereas incision is related to drier conditions (Bull, 1991; Schmidt, 2009; Gutiérrez, 2013 and references therein).

Relict slopes may also develop through a different mechanism. The progressive retreat of the rock cliff in small buttes may eventually lead to the complete removal of the caprock. Once the protecting layer is eliminated, the underlying soft bedrock may be eroded at a much faster rate than the more resistant colluvium covering the slopes. Differential erosion of the bedrock in the core of the butte and the evacuation of those sediments through one or several gully systems breaching the debris slopes may result in the formation of relict slope rings or talus flatiron rings (Morgan *et al.,* 2008). These crater-like features consist of an inner depression excavated in soft bedrock and surrounded by an annular ridge of bedrock shielded on its outer flank (relict slopes) by colluvial debris. This is a peculiar example of relief inversion only documented in the Colorado Piedmont, whereby a rounded depression surrounded by relict slopes forms where a prominent butte once stood. These features, together with the talus flatirons of the area, were erroneously interpreted to be landslide deposits during the production of geological maps.

The main issues addressed by this work include: (1) Describing and establishing a relative chronology for the talus

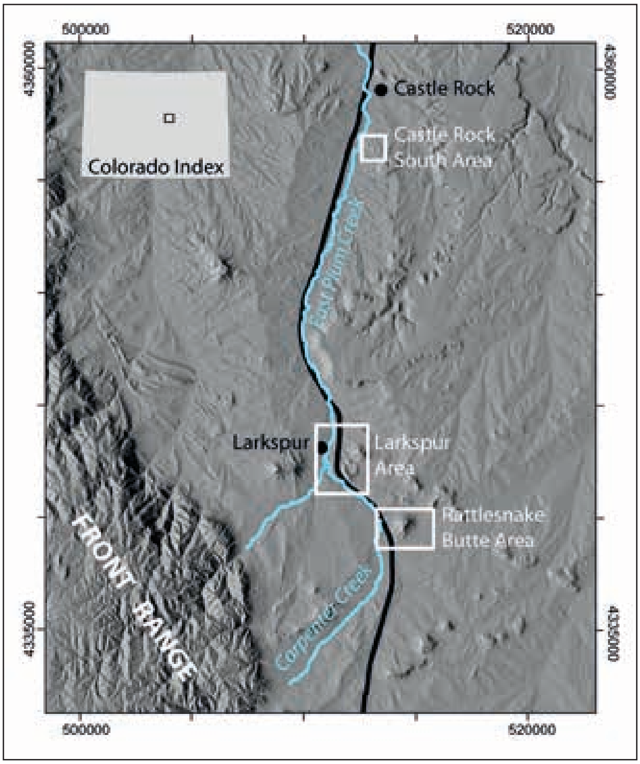

Figure 1. Location map of the three study areas (Castle Rock South, Larkspur, Rattlesnake Butte) on the eastern margin of East Plum Creek and Carpenter Creek, in the Colorado Piedmont section of the Great Plains, western United States.

flatiron sequences and relict slope rings found in three selected areas of the Colorado Piedmont on the basis of detailed geomorphological mapping; (2) Analyzing the factors that favor the development of relict slope rings, endemic to this area; (3) Estimating the age of the colluvial deposits associated with the talus flatirons and relict slope rings by means of optically stimulated luminescence (OSL). The correlation of the relict slopes with other paleoenvironmental proxies in the area and their paleoclimatic significance will be presented in a coming paper.

2. THE STUDY AREA

The study area is located in the central part of the Colorado Piedmont section of the Great Plains, western United States (Fig. 1). The bedrock exposed is gently dipping (<6º) and includes the following lithostratigraphic units, in ascending order (Thorson, 2011): (1) The upper part of the Dawson Arkose of the Denver Basin Group of Paleocene and Eocene age (ca. 65-50 Ma). This unit, with an exposed thickness of around 300 m, mainly consists of fluvial cross-bedded, arkosic sandstones. (2) The Larkspur Conglomerate, of probable late

Eocene age. This unit, up to 35 m thick and restricted to paleovalleys, consists of cross-bedded brown to pink granitic and arkosic pebble cobble conglomerate. (3) The Wall Mountain Tuff is a pinkish-brown, welded tuff of rhyolitic composition dated radiometrically at 36.69 Ma (late Eocene). This ignimbrite, up to 15 m thick, records a single glowing ash flow that expanded across an erosional topography blanketing the Dawson Arkose and the valleys partially filled by the Larkspur Conglomerate. (4) The Castle Rock Conglomerate, late Eocene in age, was deposited in paleovalleys excavated into the preceding sedimentary and volcanic formations. This fluvial sediment is a granite-rich conglomerate up to 70 m thick similar to the Larkspur Conglomerate.

The areas of the Colorado Piedmont selected for our study are located on the east margin of the north-flowing Carpenter and East Plum Creeks, which are tributaries to the South Platte River (Fig. 1). Here, there are numerous prominent buttes in which the poorly indurated Dawson Arkose is shielded by a caprock consisting of either the Larkspur Conglomerate, the Wall Mountain Tuff, or the Castle Rock Conglomerate. Locally, the debris slopes developed below the retreating caprock scarps of the buttes have evolved into the talus flatiron sequences and relict slope rings analyzed in this study. The elevation of the study area ranges from 2300 to 1900 m a.s.l. Mean annual temperature and precipitation are 10.5-9.4 ºC and 398-420 mm, respectively. The mean yearly number of days with minimum temperature below freezing point in Denver and Colorado Springs reach 156 and 162, respectively, suggesting that frost shattering may play a significant role in the erosion of the caprocks. On the hillslopes of the buttes and relict slope rings the vegetation is dominated by gambel oak and ponderosa pine and show significantly lower density in the south- and southeast-facing slopes.

3. METHODOLOGY

Three areas on the eastern margin of Carpenter and East Plum Creeks were selected for detailed geomorphological mapping and geochronological sampling (Fig. 1): Rattlesnake Butte, Larkspur Butte and the adjacent relict slope ring (Larskpur area), and a relict slope ring south of Castle Rock (Castle Rock South area). Detailed geomorphological maps (1:6,000 scale) of the selected areas were produced on the basis of aerial photograph interpretation and field surveys. The mapped relict and active slopes were classified chronologically into groups on the basis of their relative spatial distribution (e.g. inset relationships, distance to the scarp). The active slopes connected with the scarps have been designated as SX1; the second letter refers to the study area (R: Rattlesnake Butte, L: Larkspur, C: Castle Rock South). The codes SX2 and SX3 indicate the younger and older generations of talus flatirons, and SXr the outer relict slopes of the rings. As the numerical dates revealed, the numbers used for the local relative chronologies do not imply temporal equivalence among the different study areas.

A total of 13 samples were collected for optically stimulated luminescence (OSL) dating (Table 1). Six samples correspond to exposed sandy alluvial deposits from the Larkspur area, and two of them were collected from alluvium interdigitated with colluvium of a talus flatiron. Four

Table 1. Optically stimulated luminescene (OSL) ages and associated chronological data.

Lab code	Field code	Geomorphic unit	Quartz grain size (µm)	Equivalent dose (Grays)[a]	U (ppm)[b]	Th (ppm)[b]	K_2O (wt%)[b]	In situ H_2O (%)	Depth (m)	Cosmic dose (mGrays/yr)[c]	Total dose rate (mGrays/yr)	Alliquots (n)	OSL age[d]
Rattlesnake Butte													
UIC3341	RSO	Flatiron SR3	150-250	375.29±20.56	2.5±0.1	16.3±0.1	4.63±0.05	10±3	0.4	0.30±0.03	5.14±0.33		73,000±4,700
UIC3340	RSy2	Flatiron SR2	150-250	90.75±4.82	4.5±0.1	22.3±0.1	4.77±0.05	10±3	0.5	0.31±0.03	6.09±0.40		14,900±1,200
Larkspur													
UIC3370	S2-1	Alluvium interfingered with colluvium of flatiron SL2	250-355	Dose saturated	3.6±0.1	14.9±0.1	4.67±0.05	10±3	6.15	0.14±0.01			Incalculable
UIC3347	S2-2	Alluvium deposits interfingered with colluvium of flatiron SL2	250-355	>523	3.3±0.1	12.5±0.1	3.88±0.04	10±3	5.1	0.16±0.02	2.26±0.13		>124,000
UNL-1591	Lark 1	Alluvium		118.3±0.8	2.1	11.1	4.7	4.0	2.0		5.1±0.3	25/30	23,300±2000
UNL-1592	Lark 2	Alluvium		78.1±4.3	1.8	8.0	4.4	2.2	3.5		4.6±0.3	26/28	17,100±1600
UNL-1593	Lark 3	Alluvium		117.2±4.3	2.5	13.4	4.9	4.3	7.3		5.3±0.4	24/26	21,900±1900
UNL-1594	Lark 4	Alluvium		98.1±4.5	2.3	13.2	3.5	5.7	13.0		4.1±0.3	24/27	23,900±2200
UIC3358	LR-B	Relict slope ring (SLr)	250-355	289.54±16.49	5.5±0.1	25.5±0.1	4.96±0.05	10±3	2.5	0.30±0.03	7.13±0.46		40,620±2,480
UIC3346	LR2	Relict slope ring (SLr)	150-250	>357	4.5±0.1	37.1±0.1	5.00±0.05	10±3	0.35	0.30±0.03	7.24±0.47		>49,000
Castle Rock South													
UIC3348	PCF	Flatiron SC3	250-355	42.29±2.92	4.9±0.1	25.8±0.1	3.68±0.04	10±3	0.6	0.29±0.03	5.98±0.30		~~7,170±540~~[e]
UIC3349	PCR-1	Relict slope ring (SCr)	250-355	31.49±2.11	4.0±0.1	24.8±0.1	3.61±0.04	10±3	0.8	0.27±0.03	5.16±0.29		6,095±355
UIC3369	PCR-2	Relict slope ring (SCr)	250-355	55.02±3.05	2.4±0.1	12.4±0.1	4.66±0.05	10±3	0.7	0.28±0.03	5.34±0.32		10,300±750

[a] Equivalent dose determined by the multiple aliquot regenerative dose method under blue (470 nm) excitation (Jain et al., 2003). Blue emissions are measured with 3-mm-thick Schott BG-39 and one, 3-mm-thick Corning 7-59 glass filters that blocks >90% luminescence emitted below 390 nm and above 490 nm in front of the photomultiplier tube.

[b] U ,Th and K20 determined by ICP-MS, Activation Laboratory Ltd., Ontario.

[c] Cosmic dose rate component from Prescott and Hutton (1993).

[d] All errors are at one sigma and ages are calculated from AD 2010. Analyses performed by the Luminescence Dating Research Laboratory,

Dept. of Earth & Environmental Sciences, Univ. of Illinois-Chicago (UIC samples) and by the Luminescence Geochronology Laboratory, University of Nebraska-Lincoln.

[e] Sample tube 60% full; mixing of light and unlight exposed sediments; spurious younger age.

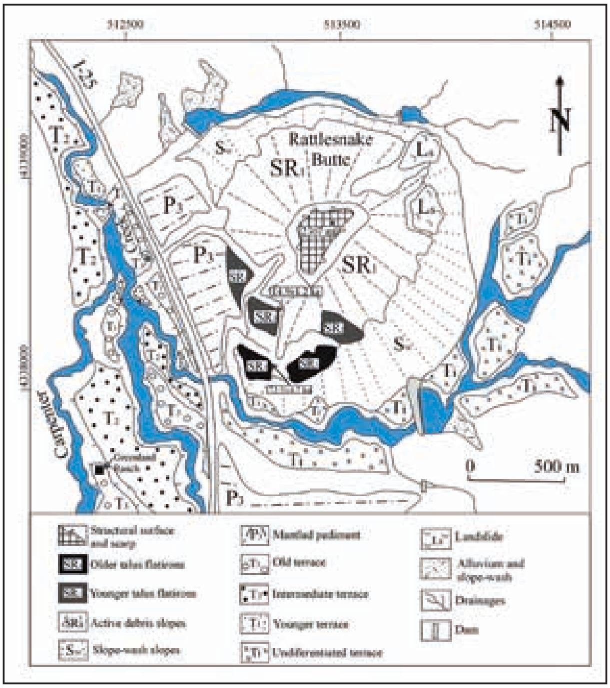

Figure 2. Geomorphological map of Rattlesnake Butte, showing the talus flatiron chronosequence, location of samples, and OSL ages (see location in figure 1).

samples were obtained from the colluvial deposits underlying the relict slope rings of Larkspur and Castle Rock South, two from each site. Three samples correspond to colluvial deposits underlying talus flatirons, two from Rattlesnake Butte and one from Castle Rock South. Most of the samples collected in relict slopes were obtained in pits dug by hand in the upper of apical part of the slopes.

4. RESULTS

4.1. Talus flatiron sequence at Rattlesnake Butte

Rattlesnake Butte, with a local relief of around 200 m, is located next to Carpenter Creek on its eastern margin (Figs. 1, 2). It consists of Dawson Arkose overlain by a caprock around 40 m thick of Larkspur Conglomerate and Wall Mountain Tuff. The butte is 390 m in diameter at the top surface and 1320 m at the base of the debris slopes. The aspect ratio, given by the relationship height/basal diameter, is 0.15. Two generations of talus flatirons restricted to the SW sector of the butte adjacent to Carpenter Creek have been mapped (Figs. 2, 3). This spatial relationship suggests that the butte's proximity to the local base level and the associated entrenchment episodes, has played a significant role in the development of the talus flatirons. Samples collected from pits excavated in the apices of SR2 and SR3 slope

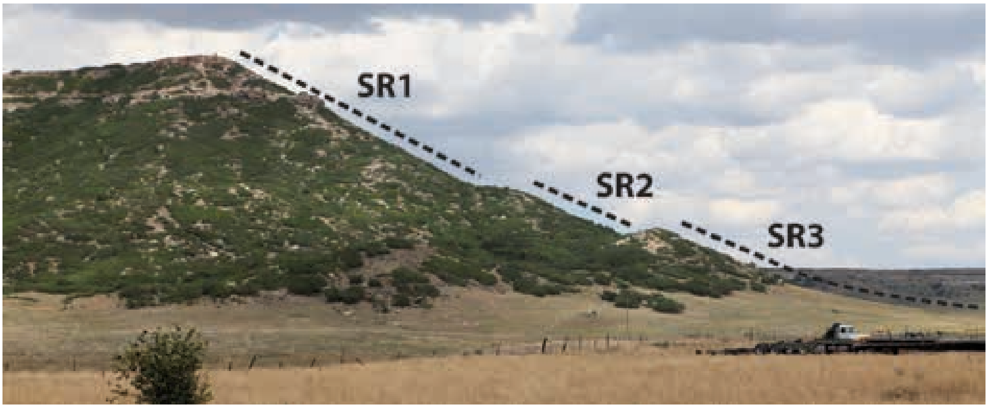

Figure 3. Talus flatiron sequence in Rattlesnake Butte. SR1 corresponds to the active slope. SR2 and SR3 depict successive generations of relict slopes disconnected from the source scarp of the butte.

facets provided OSL ages of 14,900 ± 1,200 yr BP and 73,000 ± 4,700 yr BP (error margin at 1 sigma here and elsewhere) (Fig. 2, Table 1).

4.2. Relict slope ring and talus flatirons at Larkspur

The relict slopes in this area are associated with Larkspur Butte and the adjacent crater-like depression resulting from the erosional inversion of a pre-existing butte (Figs. 4, 5). Larkspur Butte reaches 155 m in height and consists of a caprock of Larkspur Conglomerate and Wall Mountain Tuff resting on the Dawson Arkose. It reaches 240 m in diameter at the top structural surface and 1140 m at the base of the debris slopes. The butte has an aspect ratio of 0.14. Similarly to Rattlesnake Butte, the debris slopes (SL1) on its southern half of the hill have higher gradients, are more dissected, and have less vegetation (Fig. 4).

The relict slope ring is located next to the confluence of Carpenter Creek and East Plum Creek on their eastern margin. This ring consists of an annular ridge armored by colluvium on the outer slopes and an inner subcircular depression excavated in the Dawson Arkose (Figs. 4, 5). The depression is drained by an ephemeral creek towards the East Plum Creek through a narrow outlet that breaches the ring on its northwest side. The ring reaches 1170 m in diameter at the base of the debris slope and has a local relief of 120 m. As expected, it has a much lower aspect ratio (0.1) than the nearby buttes. The ring results from the differential excavation of the highly erodible Dawson Arkose in the center of a pre-existing butte, once the protecting caprock was removed by progressive scarp retreat.

In addition to the relict slopes of the ring (SLr), two generations of talus flatirons (SL2 and SL3) have been mapped in this area (Fig. 4). The relict slopes of the ring (SLr) represent an intermediate phase of accumulation in the slopes between SL2 and SL3, which occurred before the removal of the caprock of the pre-existing butte. Samples of sandy slope-wash sandy

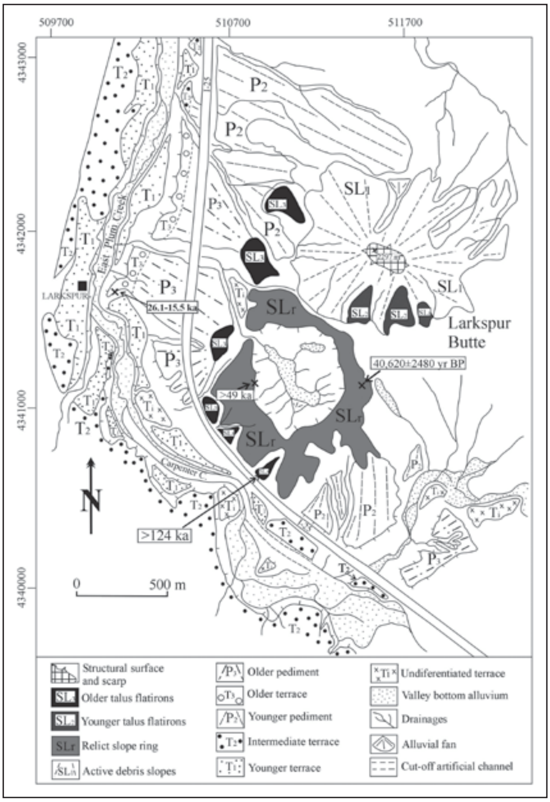

Figure 4. Geomorphological map of Larkspur Butte and the adjacent relict slope ring, with the talus flatiron chronosequence, location of samples, and OSL ages (see location in figure 1).

deposits collected from colluvial deposits of the ring have yielded OSL ages of >49 ka and 40,620±2,480 yr BP (Fig. 4, Table 1). Two samples from fluvial sands interfingered with slope deposits of a SL3 facet were dose-saturated and the upper one yielded a minimum age of >124 ka. The excavation of the depression surrounded by the annular ridge commenced after 40 ka, following the deposition of the SLr colluvium derived from the caprock that once capped the pre-existing butte. Most probably, the development of the depression took place over a long time span in the late Quaternary, coevally with the formation of the mapped pediment-terrace sequence.

4.3. Relict slope ring and talus flatiron in Castle Rock South area

This relict slope ring is located approximately 3 km south of the town of Castle Rock, on the east margin of East Plum Creek (Figs. 1, 6). An adjacent butte is 80 m high and is capped by Larkspur Conglomerate and Wall Mountain Tuff. The ring

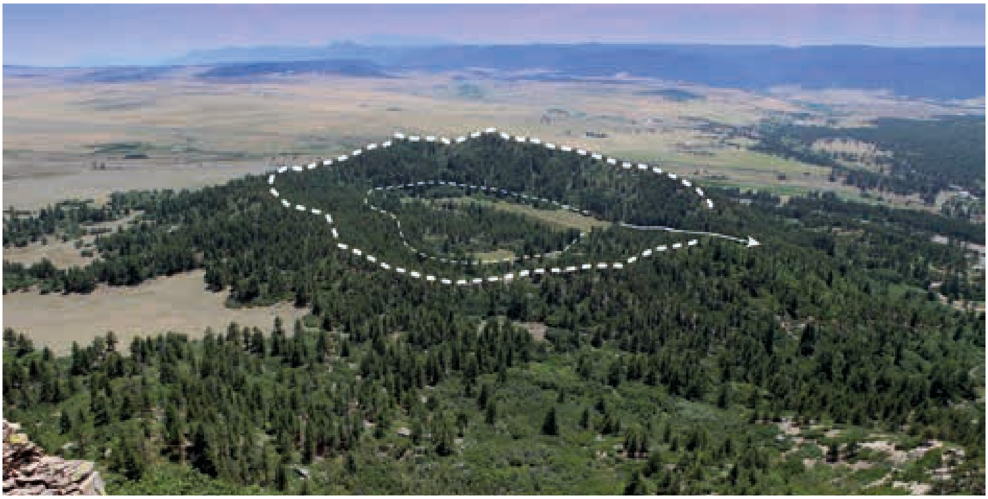

Figure 5. View of the relict slope ring from the top of Larkspur Butte. Thick and thin dashed lines indicate the crest of the ring and the edge of the inner depression, respectively. Note the Front Range on the background.

reaches 660 m in diameter at the base of the debris slope and has a local relief of 35 m (aspect ratio 0.05). The colluvium-armored ring is breached on its western side by three tributary streams of the East Plum Creek. In this case, the inner depression excavated in the Dawson Arkose is still in a juvenile stage. Two samples were collected from fresh exposures of colluvium underlying the relict slope of the ring (SCr) that yielded OSL age estimates of 6,095±355 yr BP and 10,300±750 yr BP. A sample of sandy facies collected from a pit excavated in the apex of flatiron SC2 provided a spurious OSL age of 7,150±540 yr BP. Unfortunately, the sediment was loose within the 60% full sampling tube, suggesting mixing of light- and unlight-exposed sediments (Table 1).

5. DISCUSSION AND CONCLUSIONS

To our knowledge, the Colorado Piedmont is the only area worldwide where relict slope rings are documented. Favorable factors concur in this region for the development of such unique landforms. The majority of the relict slopes and talus flatiron sequences reported in the literature are associated with buttes and mesas consisting of erodible mudstones and marls and typically capped by well-bedded limestones (e.g. Spain, Gutiérrez *et al*., 2010; Israel, Boroda *et al*., 2011). The formation of relict slope rings endemic to the Colorado Piedmont is probably related to a higher erodibility contrast between the colluvial armor and the underlying bedrock than in other regions. The Dawson Arkose, a low-cohesion and friable sandy sediment, can be eroded and evacuated from the core of an uncapped butte more rapidly than the cohesive argillaceous sediments found in the majority of the areas where relict slopes are documented. On the other hand, the colluvial deposits in the studied areas seem to be more resis-

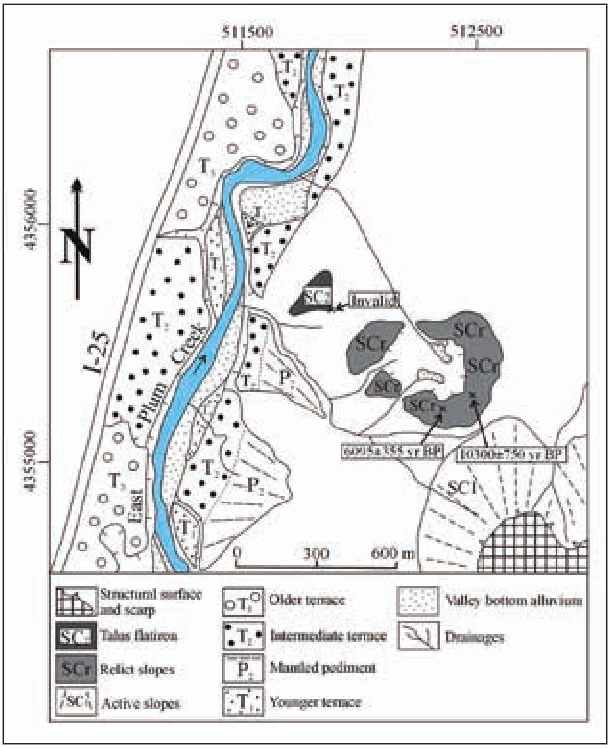

Figure 6. Geomorphological map of the relict slope ring and the associated talus flatiron of Castle Rock South area, depicting location of samples, and OSL ages (see location in figure 1).

tant to erosion than similar deposits in other regions with relict slopes because of two main factors: (1) They include a relatively high proportion of large boulders mainly derived from the massive Larkspur and Castle Rock Conglomerates, whereas the coarse fraction in the colluvial deposits from other regions mostly consists of pebble-cobble-sized clasts derived from a well-bedded limestone caprock. (2) In the Colorado Piedmont, the nearly subhumid climate (~400 mm annual precipitation) and the high elevation (~2000 m a.s.l.) allow the development of a dense plant cover on the slopes that plays a significant role in protecting against erosional processes. For instance, the relict slopes in the hyperarid Dead Sea basin are vegetation-free, in semiarid Spain are mostly covered by sparse shrubs, whereas in the study areas they consist of a dense tree and shrub vegetation, especially on the N- and NW-facing slopes (Figs. 3, 5). These circumstances indicate, as confirmed by the obtained dates, that the relict slopes in the study areas have a high preservation potential and reach a high persistence time (>100 ka).

In semiarid areas, talus flatirons typically occur around the whole perimeter of buttes and mesas (e.g., Gutiérrez, 2013). In contrast, in the study areas the colluvium-armored facets are restricted to slopes adjacent to drainages and south-facing slopes. The latter slopes are typically steeper, more dissected and have less dense vegetation cover than the more humid N-facing slopes. Additionally, the majority of the relict slope rings identified in the study area are associated with drainages. This spatial distribution pattern suggests that the development of relict slopes rings and facets is controlled by two limiting factors: (1) The proximity to the base level and the relatively higher local gradient favor the dissection of the slopes, as well as the excavation and evacuation of the bedrock sediments from the core of the buttes after the removal of their caprocks. The retrogressive propagation of incision waves related to downcutting episodes in the base level, as recorded by the mapped terrace sequences, may only reach nearby slopes. (2) It seems that in this almost subhumid area, the contrast in the vegetation cover between the N- and S-facing slopes embraces the geomorphic threshold that determines the development of talus flatirons (Schumm, 1979). During periods of lower vegetation cover and dissection in the southern slopes, the protective effect of the denser vegetation cover in the northern slopes may be high enough to prevent incision and the individualization of relict slope facets.

The OSL dates obtained from the colluvial deposits of the relict slopes in each area are consistent with the relative chronology inferred on the basis of geomorphic mapping (Figs. 2, 4, 6). To our knowledge, the only numerical dates of relict slopes published in the literature correspond to talus flatiron chronosequences from Spain (Gutiérrez *et al*., 2010; Roqué *et al*., 2013) and Israel (Boroda *et al*., 2011). The OSL ages from the Colorado Piedmont presented in this work indicate that the mapped chronosequences of talus flatirons and relict slope rings record multiple slope accumulation and dissection cycles spanning from Eemian (Sangamonian) or pre-Eemian time (>124 ka; SL3) to the mid-Holocene (SCr; Table 1). It is probable that the geomorphic record includes other cycles that have not been captured by our geochronological data; SL2 in Larkspur area has not been dated and the age obtained for SC2 in Castle Rock South is spurious, most probably due to exposure to light. Nonetheless, the available numerical dates indicate that the temporal lapse between aggradation phases, considering the three areas, may range from a few millennia in the case of the youngest late glacial slopes (SR2, SCr), to tens of millennia for the older relict slopes. These time intervals are even larger when considering each study area individually (e.g. ≥60 kyr in Rattlesnake and Larkspur). The temporal clusters of talus flatirons identified in the Tertiary basins of Spain are separated by time spans ranging from 10 to 25 kyr (Gutiérrez *et al*., 2010). The two temporal groups of talus flatirons dated in the Dead Sea basin seem to record an aggradation-incision-aggradation cycle of around 440 kyr. The chronological distribution of the relict slopes in the Colorado Piedmont, as well as in the other regions where they have been dated, indicate that (1) relict slopes that are armored by coarse-grained colluvium and with a negligible runoff contributing area, may persist in the landscape over tens or even hundreds of millennia; (2) the development of successive generations of talus flatirons require long time spans, which may be influenced not only by the intensity and duration of the environmental changes, but also by the need of a long preparation phase. The accumulation of an extensive colluvial cover succeeding each incision phase may require long periods of scarp retreat and sediment supply. The dates obtained for the colluvial deposits of the relict slopes SCr (10.3 ka, 6.0 ka) and SLr (>49 ka, 40.6 ka) support that accumulation phases may span broad time periods.

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