New age constraints on Late Pleistocene glacial outwash deposits near Ridgway, Colorado, northern San Juan Mountains

D. Jarrin, A. Aslan, S. Mahan, and P.R. Hanson

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NEW AGE CONSTRAINTS ON LATE PLEISTOCENE GLACIAL OUTWASH DEPOSITS NEAR RIDGWAY, COLORADO, NORTHERN SAN JUAN MOUNTAINS

Donald Jarrin[1], Andres Aslan[1], Shannon Mahan[2], and Paul R. Hanson[3]

[1] Dept. of Physical and Environmental Sciences, Colorado Mesa University, Grand Junction, CO 81501, aaslan@coloradomesa.edu;
[2] U.S. Geological Survey, MS 974, Bldg. 15, Luminescence Geochronology Lab, Denver, CO 80225;
[3] Conservation and Survey Division, School of Natural Resources, University of Nebraska at Lincoln, Lincoln, NE 68583

Abstract—Optically stimulated luminescence (OSL) and post-infra-red stimulated luminescence (post-IR IRSL) geochronology provides the first numerical age estimates for the timing of glaciation in the Uncompahgre River valley of the northern San Juan Mountains of Colorado. A quartz OSL date of 23.0±1.6 ka from the youngest outwash terrace located north of Ridgway, Colorado fits well with previously documented timing on Pinedale glaciation and marine-isotope-stage (MIS) 2. However, there is no correlative terminal moraine located in the study area, which shows that Pinedale glaciers did not advance as far north as Ridgway during the Last Glacial Maximum (LGM).

Post-IR IRSL ages of 48.2±2.9 ka and 68.1±4.4 ka, and OSL ages ranging from 36.4±2.1 ka to >76 ka for the next oldest outwash terrace near Ridgway, correspond to MIS 4/3. The terrace tread of this older outwash terrace can be traced directly to a series of hills that form a small, sinuous terminal moraine, which is cross-cut by the LGM terrace. Two sets of older and larger moraines, and corresponding outwash terraces, are present slightly farther downvalley from the small, sinuous moraine. These older moraines remain undated, but based on the new luminescence data and their larger size, it is plausible that they represent Bull Lake glacial advances.

While past workers have assumed that the Ridgway moraines correlate with Pinedale glaciation, the new luminescence age estimates, along with relative age relationships, indicate that all the moraines are older than recognized previously. Lastly, the recognition that ca. 70-40 ka Uncompahgre River valley ice advanced almost as far downvalley as presumed Bull Lake moraines raises the possibility that the effects of glaciation during MIS 4/3 were greater than generally recognized in the San Juan Mountains.

INTRODUCTION

Despite the long-standing recognition of glacial deposits in the San Juan Mountain region (Howe and Cross, 1906; Atwood and Mather, 1912; 1932), there is surprisingly little data on the numerical chronology of the glacial episodes. The advent of cosmogenic radionuclide surface-exposure dating of moraine boulders and bedrock scour surfaces, along with OSL dating of fluvial outwash deposits, has improved our understanding of glaciation in the Animas River valley near Durango, Colorado (Guido et al., 2007; Anderson and Kenny, 2015). However, there is no geochronological information for landforms and deposits in the northern San Juan Mountains region. Prior study of the northern San Juan Mountains has involved generalized descriptions and mapping of glacial deposits (Atwood and Mather, 1932; Richmond, 1954; Steven and Hail, 1989), correlation of moraines and outwash terraces based on landform elevations (Sinnock, 1981), and documentation of Holocene periglacial features (Carrara and Andrews, 1975; White, 1979a; 1979b).

Glacial landforms and deposits in the Ridgway area of the Uncompahgre River valley were first described by Howe and Cross (1906). Atwood and Mather (1932) described three sets of till and moraines near Ridgway, represented from youngest to oldest, by the ‘Wisconsin, “Durango,” and “Cerro” tills. Portions of the “Cerro” till, however, were misidentified as glacial in origin (Mather and Wengerd, 1965). The two youngest sets of Ridgway moraines and till (“Wisconsin” and “Durango”), as well as till along nearby Dallas Creek, were later correlated with Pinedale and Bull Lake glaciations (Richmond, 1954; Sinnock, 1981). Sinnock (1981) further subdivided the youngest (“Wisconsin”) Ridgway moraines and outwash terraces mapped by Atwood and Mather (1932) into two groups representing a younger and older Pinedale glacial advance. These youngest Ridgway moraines and outwash terraces are the subject of the present study.

This paper provides detailed mapping of the youngest glacial moraines and correlative outwash terraces in the Uncompahgre River valley near Ridgway, Colorado. This study also presents the first age control for two of the youngest outwash terraces using a combination of OSL and post-IR IRSL dating.

STUDY AREA

The glacial moraines and outwash terraces reported on in this study are present immediately north of Ridgway, Colorado, along the northern edge of the San Juan Mountains (Fig. 1). The youngest moraines and terraces are represented by a series of hummocky hills that occupy the floor of the Uncompahgre River valley on both sides of the modern river. Older moraines recognized by Atwood and Mather (1932) and correlated with Bull Lake glaciation by Sinnock (1981) are present on bedrock ridges that border the valley at elevations ~120-200 m above the Uncompahgre River. These moraines are not addressed in the present study.

The moraines of the present study lie along the footwall of the east-west-trending Log Hill Mesa Fault, which separates upper Jurassic and lower Cretaceous rocks of the Uncompahgre Plateau located north of the fault, from lower Creta-

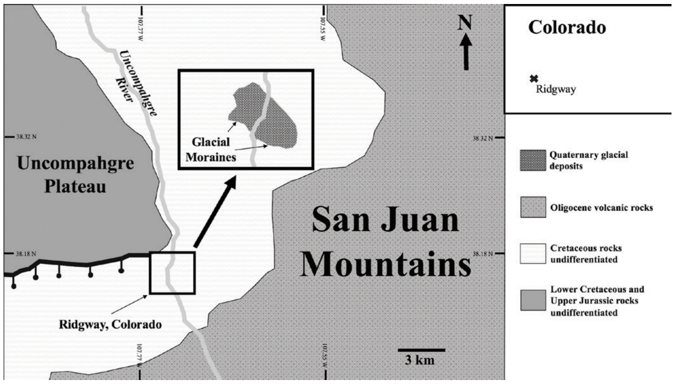

FIGURE 1. Map of the Ridgway study area showing the generalized bedrock geology and the location of glacial moraines. Map is adapted from Steven and Hail (1989). Inset map shows Colorado and the approximate location of Ridgway.

ceous rocks to the south (Steven and Hail, 1989). Cretaceous Mancos Shale underlies all the major glacial landforms in this study. Oligocene volcanic rocks of the San Juan Mountains overlie Mesozoic and Paleozoic sedimentary rocks and Proterozoic metasediments in upper portions of the Uncompahgre River watershed.

FIELD METHODS

Data presented in this article are from field investigations that took place between 2006 and 2016. Field work consisted of mapping glacial landforms and deposits over an area of ~4 km^2 and describing sedimentological and weathering characteristics, including weathering rinds and pedogenic carbonate accumulations, at selected locations. Relative age relationships were established based on cross-cutting relations and elevations of terrace treads and moraine crests.

LUMINESCENCE DATING: CONCEPTS AND METHODOLOGY

This study used two types of complimentary luminescence dating techniques: i) quartz OSL and ii) feldspar post-IR IRSL.

OSL dating (equivalent dose)

OSL dating provides an age estimate of the last time minerals, such as quartz and feldspar, were last exposed to sufficient light or heat to reset a prior luminescence signal (Preusser et al., 2009; Rhodes, 2011). Latent luminescence is generated by exposure to natural ionizing radiation (K, U, Th, cosmic rays) and results from the accumulation of electrons within defects of the quartz and feldspar mineral lattices. When stimulated by exposure to light, heat, or high pressure, the latent luminescence is emitted either naturally or within a laboratory setting. If it is within a laboratory setting, this luminescence can be precisely measured and simulated to calculate how long it has been since buried sediments were last exposed to sunlight, which occurs when sediments are eroded and/or transported.

Post-IR IRSL dating (equivalent dose)

Post-infrared stimulated luminescence dating (post-IR IRSL) is similar to OSL dating, but differs in several important ways that can lead to older age estimates than those possible using conventional OSL techniques alone. Post-IRSL dating employs feldspar grains, stimulation by infra-red light at a lower temperature as an "optical wash" and then at a significantly higher temperature (250-300°C vs 100-150°C), and differs from conventional IRSL dating by the re-heating of samples to higher temperatures following the initial exposure to light (Rhodes, 2015). Feldspar IRSL emission is often more intense than quartz OSL, but can suffer from reduced bleachability (that is, ease of signal removal by light) and from anomalous fading, requiring an additional fading assessment and correction step in the measurement procedure, and consequent reduction in dating precision. Recent technical and theoretical advances, coupled with positive dating results, make post-IR IRSL a useful method to consider (Rhodes, 2015).

Sample collection and analysis

Luminescence samples were collected by hammering metal tubes into sandy river-bank or gravel-pit exposures. The tube was pushed horizontally into a sandy layer, subsequently dug out, and capped to prevent light exposure during sampling. OSL dating of bulk samples of quartz was completed at the Luminescence Geochronology Laboratory at the University of Nebraska. OSL measurements were made on a Risø model DA-20 luminescence reader, and the equivalent dose (D_e) values were calculated using the Single Aliquot Regenerative (SAR) method (Murray and Wintle, 2000). Aliquots were rejected if their recycling ratios were >10%, or if they had measurable signals during stimulation with IR diodes. A total of 32 aliquots were accepted for one of the samples analyzed, and its final age estimate was calculated using the Central Age Model (Galbraith et al., 1999). One sample had a saturated equivalent dose (D_e) value for which a minimum age was estimated based on the highest regenerative dose that was administered to the sample. Environmental dose rate estimates were based on elemental concentrations of K, U, and Th measured using inductively coupled mass spectrometry (ICP-MS). The cosmogenic component of the dose rate was calculated using equations from Prescott and Hutton (1994), and the final dose rates calculated following equations from Aitken (1998).

Post-IR IRSL dating of bulk samples, as well as additional OSL dating of bulk samples, was completed at the U.S. Geological Survey Luminescence Geochronology Lab. Sample preparation and analysis protocols followed those described in Nelson et al. (2015) and Gray et al. (2015). The dosimetry samples were taken from the same sample location as the luminescence samples, thus the dosimetry or dose rate (D_R) data were measured from the same sediment and context. This sediment was dried, homogenized by disaggregation, weighed, sealed in planchets, and then placed in a gamma ray spectrometer for determination of elemental concentration of potassium (K), uranium (U), and thorium (Th). Field moisture (water content) was measured from the sediment at the center of each tube in which the sample was collected. Saturation moisture was determined by putting dry sediment in a tube, weighing the tube, filling the tube with water, centrifuging the tube (to simulate compaction), and then draining the water out of the tube and reweighing the sediment. The saturation moisture content is the difference between this new weight and the initial dry sediment weight.

The dose rate (D_R) results for the luminescence samples were relatively homogenous (Table 1) despite measurement by two different methods: lab gamma spectrometry (USGS) and inductively coupled mass spectrometry (ICP-MS) (UNL). Thus potential problems such as OSL signal variation, bioturbation, or disequilibrium in the U–Th decay chain were not considered to be significant impediments to OSL age determination. The largest variation that we could not discount was caused by in-situ dose hot-spots (concentrations of heavy minerals or minerals with large K or U contents) that accumulated during sediment deposition or due to the heterogeneous grain sizes inherent in the source material. We acknowledge that in-situ measurement would have been preferred to accurately differentiate the hotspots. Throughout this paper, the luminescence ages are reported in years before the measured date (AD 2006 to 2016; Table 1) with a 1-sigma standard deviation of the age uncertainty.

ALLUVIAL AND GLACIAL LANDFORMS AND DEPOSITS

Based on landform elevations, cross-cutting relationships, and sedimentological characteristics, we identify five (5) sets of alluvial deposits and three (3) sets of glacial moraines in the study area (Figs. 2, 3). Alluvial sediments were identified by the presence of relatively flat, gently sloping surfaces (treads) and sandy and gravelly sediments characterized by moderately-sorted, subrounded to rounded clasts. Glacial till representing moraines was mapped based on the presence of sinuous to irregular, hummocky landform geometries and by the abundance of fine-grained matrix surrounding poorly sorted, angular to subangular pebble- to boulder-sized clasts.

Alluvial landforms and sediments

Qag 1 is the modern Uncompahgre River and its floodplain. The river has incised older alluvial and glacial deposits, and bedload deposits are characterized by gray, rounded pebble-cobble gravel in a sand matrix. Gravel compositions are dominated by volcanic lithologies derived from the San Juan Mountains.

Qag 2 represents sediments of the lowest alluvial terrace, which crop out along both banks of the Uncompahgre River. The terrace tread is ~4 m higher than the adjacent Uncompahgre River floodplain, and this measurement also represents the minimum thickness of the unit. Sediments consist of rounded, pebble-cobble sandy gravels dominated by volcanic lithologies. Examination of cutbank exposures shows that weathering rinds and pedogenic carbonate are absent from Qag 2 sediments.

Qag 3 is the youngest terrace in the study area that can be directly correlated to a glacial moraine (Figs. 2, 3, 4A). This unit is the most aerially extensive terrace in the study area, and it is present both east and west of the Uncompahgre River. The average elevation of the tread is ~18 m above the modern floodplain, sloping gently to the north. Exposures in a small gravel pit on the west side of the river near the Ridgway Elementary School show that this unit consists of a minimum of ~12 m of crudely bedded, poorly to moderately sorted, angular to subrounded pebble-cobble gravel in a brown sand matrix.

TABLE 1. Summary information on luminescence sample locations and ages.

Sample Name	Map Unit	Lat.	Long.	Elev. (m)	% Water Content[a]	K (%)[b]	U (ppm)[b]	Th (ppm)[b]	Total Dose (Gy/ka)[c]	Equivalent Dose (Gy)	n[d]	Scatter[e]	Age (ka)[f]	Dating Method and Lab[h]
Bike Path 1-1	Qag 2	38.162	-107.7514	2319	-	1.9±0.06	2.6±0.13	9.7±0.44	2.97±0.15	68.4±1.6	32 (42)	13%	23.0±1.6	OSL (UNL)
Ridgway 1-1	Qag 3	38.1615	-107.7537	2335	11 (28)	1.69±0.05	3.97±0.30	10.3 ±0.73	3.16±0.16	115±4.0	15 (15)	12%	36.4±2.1	OSL (USGS)
	Qag 3	38.1615	-107.7537	2335					4.96±0.25[g]	239±9.4[g]	20 (20)	17%	48.2±2.9[g]	Post-IRSL (USGS)
Ridgway 1-2	Qag 3	38.1615	-107.7537	2335	-	2.0±0.06	2.4±0.08	8.7±0.39	2.88±0.15	> 220			> 76	OSL (UNL)
Ridgway 1-3	Qag 3	38.1615	-107.7544	2335	15 (38)	1.69±0.05	3.88±0.30	9.7 ±0.73	3.05±0.15	134±7.4	10 (10)	16%	43.9±3.1	OSL (USGS)
	Qag 3	38.1615	-107.7544	2335					4.76±0.24[g]	324±15[g]	20 (20)	20%	68.1±4.4[g]	Post-IRSL (USGS)

[a]Field moisture, with figures in parentheses indicating complete sample saturation %. Dose rates calculated using 40% of saturated moisture (i.e., 15 (38) = 38 * 0.4 = 15).
[b]Analyses obtained using high-resolution gamma spectrometry (high purity Ge detector).
[c]Includes cosmic doses and attenuation with depth calculated using the methods of Prescott and Hutton (1994). Cosmic doses were between 0.12-0.10 Gy/ka.
[d]Number of replicated equivalent dose (D_E) estimates used to calculate the total equivalent dose. Figures in parentheses indicate total number of measurements included in calculating the represented D_E and age using the minimum age model (MAM); analyzed via single aliquot regeneration on quartz or feldspar.
[e]Defined as "over-dispersion" of the D_E values. Values >35% are considered to be poorly bleached or mixed sediments.
[f]Dose rate and age for fine-grained 125-63 micron sized quartz. Exponential + linear fit used on D_E, errors to one sigma.
[g]Dose rate and age for fine-grained 125-63 micron sized K-feldspar. Exponential + linear fit used on D_E, errors to one sigma. Tests indicated there was no fading correction.
[h]Lab abbreviations are as follows: UNL = University of Nebraska-Lincoln Luminescence Lab; USGS = U.S. Geological Survey Luminescence Geochronology Lab

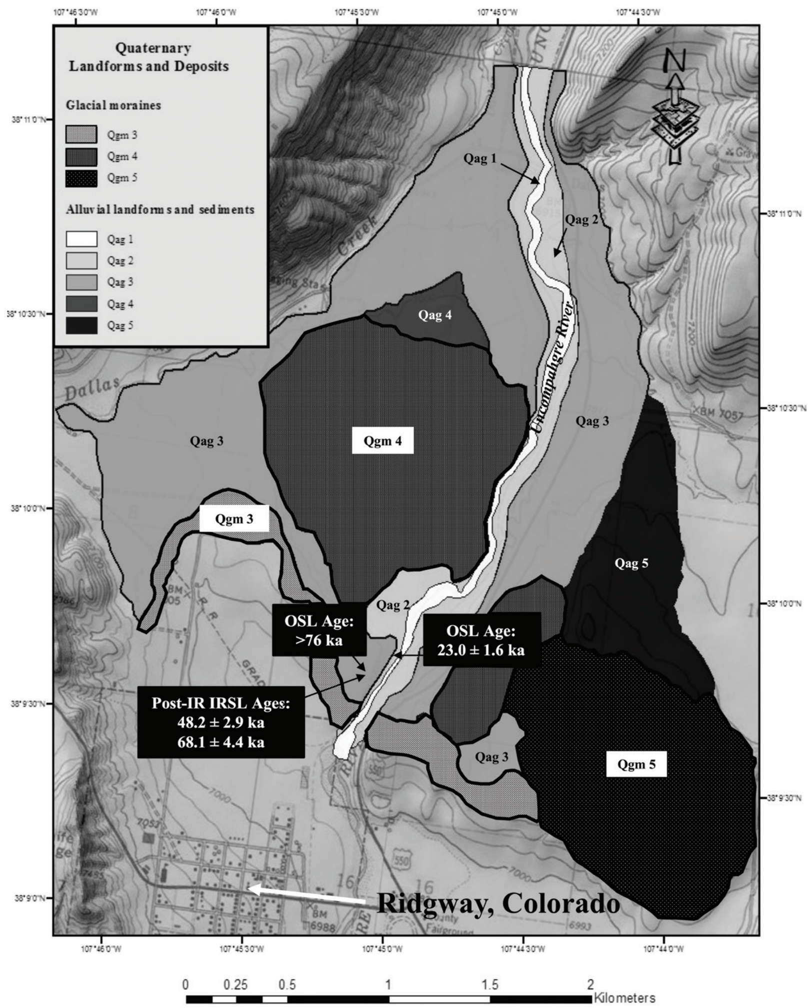

FIGURE 2. Geologic map of alluvial and glacial deposits located immediately north of Ridgway, Colorado. Locations and age estimates of luminescence samples are also shown.

The upper ~1 m of soil has a slightly more reddish-brown hue than the more deeply buried sediments, which suggests that iron oxidation due to surface weathering has affected this unit. However, no significant weathering rinds or pedogenic carbonate accumulations are present near the surface.

Qag 4 is a terrace unit found only in a small area immediately north of its correlative moraine (Fig. 2). The tread is ~21 m above the Uncompahgre River floodplain, and sediments of this unit are poorly exposed. The best exposure consists of ~2 m of brown-gray sand and silt with minor quantities of pebble gravel. The majority of the unit is not exposed. A few calcium carbonate rinds are present on pebble- and cobble-sized clasts associated with the terrace tread, but no significant weathering rinds were observed.

Qag 5 is the highest, and therefore oldest, mapped terrace unit, and it abuts the northern edge of a moraine (Fig. 2). The tread slopes northward. This unit is found only on the east side of the river and the tread is ~49 m above the modern floodplain. Sediments of this unit are not well exposed. Calcium carbonate and weathering rinds are relatively common among clasts present on the tread surface.

Glacial moraines

Qgm 3 is represented by a narrow, sinuous low ridge that trends northwest to southeast, roughly perpendicular to the orientation of the Uncompahgre River (Figs. 2, 4A). The river as well as Qag 2 cross-cut this unit. Qgm 3 merges into the southern margin of the Qag 3 terrace, and it likely represents a terminal moraine. The crest of the moraine is ~25 m above the Uncompahgre River floodplain. Compared to other moraines in the area, Qgm 3 is represented by significantly lower elevations (Fig. 3) and relatively subtle, sagebrush-covered hills. Noncompacted sand and silt matrix dominates the moraine surface, and some of this fine-grained material could be loess. Shallow hand-dug holes revealed angular to subangular pebble-sized clasts surrounded by brownish-red sand and silt matrix, similar in color to the soil developed in the uppermost sediments of Qag 3. Rare weathering rinds were observed on gravel clasts, and, in a few instances, clasts are partially coated by pedogenic carbonate.

Qgm 4 is the largest moraine in the study area, in terms of area, and it is also found on both sides of the Uncompahgre River as a series of irregular, sagebrush-covered hills and mounds (Figs. 2, 4B). Moraine crests are ~68 m above the Uncompahgre River floodplain. Shallow hand-dug holes show a greater percentage of clasts than associated with Qgm 3, and digging was markedly more difficult. Both weathering rinds (1-3 mm in thickness) and pedogenic carbonate coatings are common on pebble- to cobble-sized clasts. The matrix consisted of brown sand and silt.

Qgm 5 is the oldest moraine in the study area, and was mapped by Atwood and Mather (1912) as a terminal moraine. The moraine consists of a roughly northwest to southeast-trending ridge that rises ~120 m above the Uncompahgre River floodplain (Figs. 2, 3, 4B). The maximum relief between

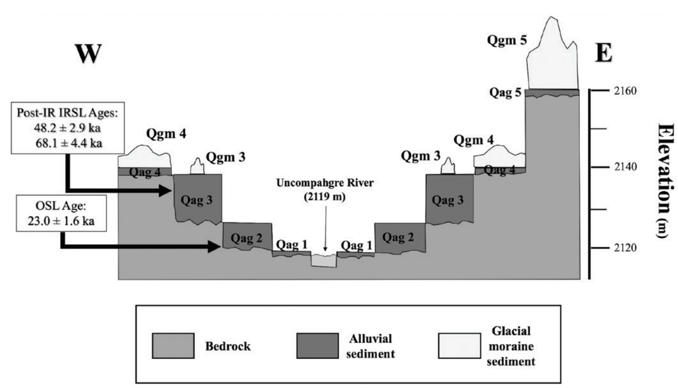

FIGURE 3. Uncompahgre River valley cross-section showing generalized geomorphic and stratigraphic relations among alluvial and glacial deposits as well as luminescence age-dating results.

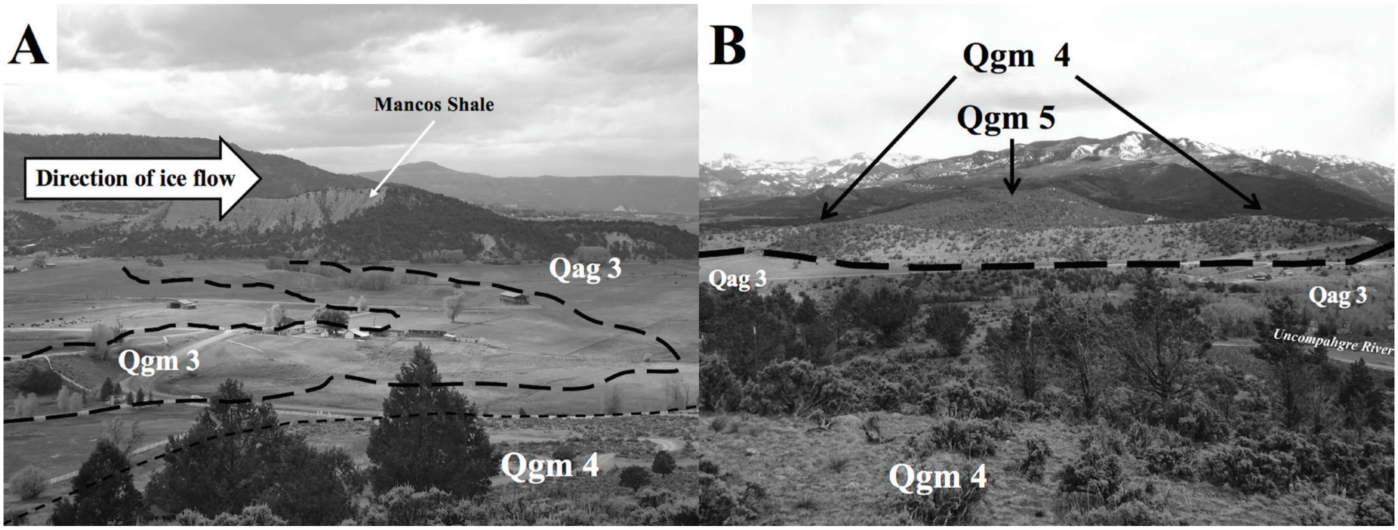

FIGURE 4. Field photographs showing glacial moraines and outwash terraces north of Ridgway. **A.** View looking west across the valley showing an arcuate terminal moraine (Qgm 3) comprised of low hills and ridges, and the correlative outwash terrace (Qag 3). Ice flowed downvalley to the north (right side of photograph). Photograph was taken from an older moraine crest (Qgm 4). **B.** View looking east across the valley showing the Uncompahgre River (flow direction is to the left) and adjacent ~20 m tall bluff representing an outwash terrace (Qag 3). Older moraines (Qgm 4, Qgm 5) are present in the background. Oligocene volcanic rocks of the San Juan Mountains form the skyline.

the moraine crest and the modern floodplain is 166 m. Unlike the other moraines, Qgm 5 is only found on the eastern side of the Uncompahgre River, and it is covered by juniper trees, rather than by sagebrush. Shallow hand-dug holes revealed common pedogenic carbonate and weathering rinds (1-8 mm in thickness) on gravel clasts. Small to large boulders are common at the surface, and this moraine surface is distinctly more bouldery than the younger moraines. Most of the clasts observed in the shallow holes were pebble- to cobble-sized, and angular to subangular. Clasts were surrounded by a brown silt and sand matrix.

LUMINESCENCE GEOCHRONOLOGY

A total of four alluvial terrace samples were analyzed using a combination of quartz OSL and feldspar post-IR IRSL methods (Table 1). One sample was from Qag 2 and three samples were from Qag 3. The sample from Qag 2 (Bike Path 1-1) was acquired from a sand interbed within a package of pebble-cobble gravel at a depth of 2.6 m below the terrace surface (Fig. 5A). Quartz OSL dating produced an age of 23.0±1.6 ka.

The three samples from Qag 3 were acquired from the small gravel pit on the west side of the Uncompahgre River (Fig. 5B). The pit exposes ~12 m of crudely bedded, reddish-brown to brown sandy pebble-cobble conglomerate with interbeds of conglomeratic sand. The initial attempt to produce an age estimate for this deposit was from a quartz OSL date on a sample (Ridgway 1-2) of a sand lens exposed in the pit wall 8.1 m below the terrace surface. This effort produced a saturated luminescence signal and a minimum age of >76 ka (Table 1).

A follow-up effort included using quartz OSL and feldspar post-IR IRSL age dating of two additional samples from the same gravel pit. One of the samples (Ridgway 1-1), analyzed by the U.S. Geological Survey lab, was from the same stratigraphy as sample Ridgway 1-2, which was analyzed by the University of Nebraska-Lincoln (UNL) lab. Each lab prepared and analyzed separate aliquots of luminescence samples. The results are >200 Gy and 115±4.0 Gy for the quartz OSL (corresponding ages are >76 ka and 36.4±2.1 ka) (Table 1). When the radial plots of the samples are examined, Ridgway 1-1 shows two population peaks at 98 and 124 Gy as well as remarkably low scatter at 12% (Table 1). Ridgway 1-2 reports a much higher D_e grain population, more than likely because that particular sample had a much higher percentage of unbleached grains. The post-IR IRSL age for sample Ridgway 1-1 is 48.2±2.9 ka (Table 1). The third sample from the Ridgway pit (Ridgway 1-3) was acquired from a different sand lens located ~150 m laterally from the previous samples, at a depth of 9.3 m below the surface (Fig. 5B). Analysis of this sample produced an OSL age of 43.9±3.1 ka and a post-IR IRSL age of 68.1±4.4 ka.

The post-IR IRSL ages are consistently older than those produced using OSL methods for the same sample (Table 1). To explore why this might be so, we considered a number of factors. These factors were: i) incomplete bleaching of the grains at time of deposition or transport, ii) heterogeneity in grain size, iii) heterogeneity of grain composition, iv) variable water content, and v) internal chronostratigraphic consistency.

There are a number of ways to mitigate the problems caused by incomplete bleaching. One protocol would be to duplicate and triplicate sampling from the same layer to determine the range of variation in the OSL and post IR-IRSL ages. Another technique would be to determine the severity of partial bleaching in the samples by comparing quartz OSL with feldspar IRSL ages. Yet another idea would be to access the bleaching seen in very young or modern samples within the same area and source geology, to ascertain whether modern samples contain residual luminescence. Finally, another idea would be to carefully cull the equivalent dose data looking to see if there

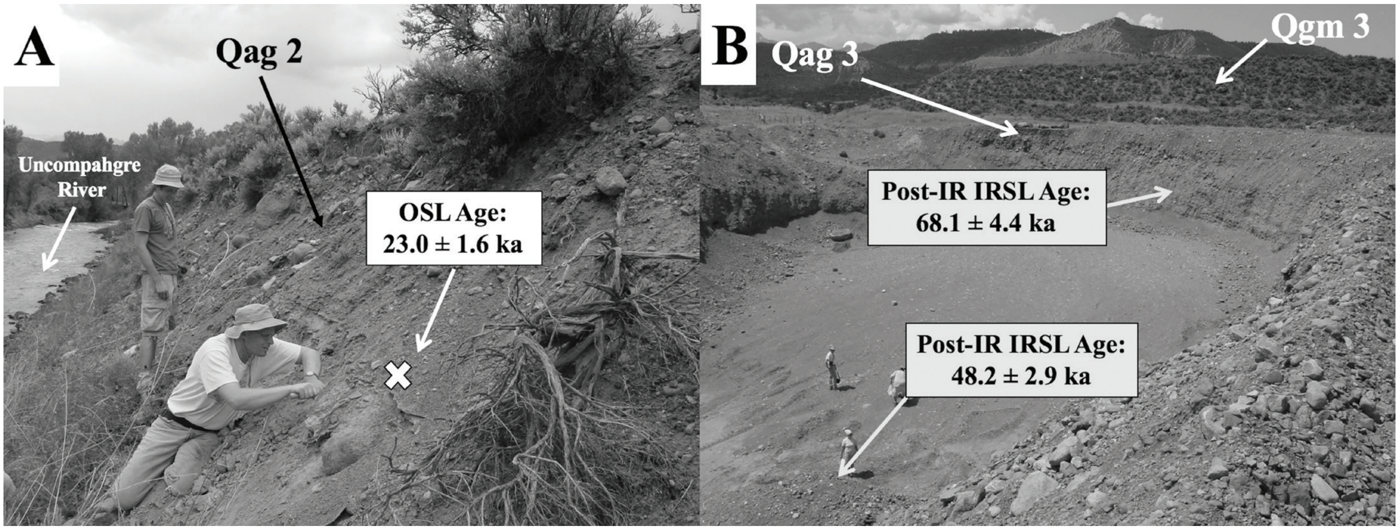

FIGURE 5. Field photographs showing locations of luminescence samples from Uncompahgre River outwash terraces. Sample locations are shown on Figure 2. **A.** View of cutbank exposing pebble-cobble gravel in a sand matrix of the youngest outwash terrace (Qag 2). Luminescence sample was acquired from a ~20-cm-thick sand lens. People for scale. **B.** View of the Ridgway School gravel pit. The pit was excavated into an outwash terrace (Qag 3), and is located immediately downvalley of and within ~100 m of the correlative moraine (Qgm 3). The exposure shows ~10 m of sandy pebble-cobble gravel with subangular to rounded clasts of predominantly volcanic lithologies. The approximate locations of the luminescence samples that were acquired from the pit walls are shown. People are for scale.

is a large scatter (i.e., over dispersion) in the equivalent measurements.

A wide range of OSL dates are commonly produced in fluvial and fluvially reworked sediments such as those sampled in this study, and the problem is multiplied in glacial moraines (Jain et al., 2004; Fuchs and Owen, 2008; Rittenour, 2008; Murray et al., 2012). Beta dose heterogeneity plays a large role in the variation because of the role of water content, inadequately thick sediment layers to sample in, and differing grain sizes or composition (Fuchs and Owen, 2008; their Table 3). Samples in this study are coarse to very coarse sand with abundant grains >250 microns in diameter.

It is well known that feldspar IRSL bleaches at a much slower rate than quartz OSL (Rhodes, 2015), and that the post-IR IRSL signal bleaches slower than the IRSL signal. Thus it is reasonable to infer that the post-IR IRSL signal represents the very oldest age of outwash deposition while the quartz OSL age represents the youngest age range of deposition. The range of the quartz OSL dates for samples Ridgway 1-1 and 1-3 is 47-34 ka, and the range of the post-IR IRSL dates for the same samples is 73-45 ka. It is our opinion that the range in ages is caused by a combination of incomplete bleaching in some of the sediment, and beta dose heterogeneity. The dominant factor is almost certainly the beta dose heterogeneity caused by differing clast compositions, sizes, and water content. In summary, the luminescence data indicate that the age of the Qag 2 terrace is ca. 25-20 ka, and the age of the Qag 3 terrace is ca. 70-40 ka.

DISCUSSION

Traditional interpretations of Rocky Mountain glaciation assign the youngest moraines and outwash terraces to the Pinedale glaciation and the next oldest set of moraines and terraces to the Bull Lake event (Yeend, 1969; Sinnock, 1978; 1981; Richmond, 1986; Pierce, 2003; Scott and Moore, 2007). In general, these glacial events are correlated to marine-isotope stages 2 and 5d/6, respectively (Pierce, 2003). With the advent of cosmogenic radionuclide surface-exposure and luminescence dating, numerical age estimates of glacial deposits in the Rocky Mountain region have identified a significant number of MIS 2 sediments (Benson et al., 2005; Brugger, 2007), whereas older deposits have remained difficult to constrain in terms of absolute ages. One exception to this generalization is the Ziegler Reservoir site located near Snowmass, Colorado, which has been dated at 110-120 ka using a combination of quartz OSL and feldspar IRSL (Mahan et al., 2014).

All of the moraines and outwash terraces described in this study have been previously correlated with Pinedale glaciation (Atwood and Mather, 1912; 1932; Sinnock, 1981). However, based on the new mapping and age constraints, it is likely that all the moraines are older than previously thought, and that the youngest paired moraine-outwash sequence (Qgm 3-Qag 3) dates to ca. 70-40 ka (MIS 4/3). This age assignment is also consistent with the reddish-brown soil colors and evidence of iron oxidation seen in the upper 1 m of Qgm 3 and Qag 3 soils. These weathering colors are essentially absent from younger Pinedale glacial sediments (Birkeland, 1999). Only the Qag 2 age estimate (ca. 25-20 ka) correlates with MIS 2 and typical Pinedale age estimates. The absence of a Pinedale-age moraine in the Ridgway area, indicates that Pinedale glaciation terminated somewhere upvalley. Although there are no terminal moraines mapped along the valley floor south of Ridgway, one possible candidate for the terminus of Pinedale glaciation in the Uncompahgre River valley is Ouray, Colorado where glacial deposits are present (Luedke and Burbank, 1962).

Mapping shows that the Qgm 3/Qag 3 deposits represented a significant glacial advance in the Ridgway area. The sediments cover a broad area and cross-cutting relations show that Qag 3 outwash incised older moraine and outwash landforms. These observations, coupled with the luminescence age estimates, suggests that MIS 4/3 was a time of significant glaciation in the northern San Juan Mountain region. Luminescence ages of ca. 65-50 ka from fluvial sediments in proximity with glacial deposits near Durango, Colorado could also represent a similar ~MIS 4/3 glacial advance in the Animas River valley (Anderson and Kenny, 2015; Passehl and Kenny, 2015). This possibility is supported indirectly by the presence of ca. 70-60 ka Colorado River terraces that occupy broad areas of the Grand Valley near Grand Junction, Colorado (Aslan and Hanson, 2009). The lack of greater recognition of MIS 4/3 glaciation in the Rocky Mountain region could simply reflect a combination of insufficient age dating of glacial sediments, and/or the minimal amount of Pinedale-related erosion and sediment reworking that occurred near Ridgway. Perhaps Pinedale glaciation was more effective at removing MIS 4/3 glacial sediments elsewhere in the region. In either case, additional geochronologic work in the San Juan Mountain region would undoubtedly better characterize the mode and timing of glacial events.

CONCLUSIONS

There are four (4) outwash terraces (Qag 2-5) and three (3) glacial moraines (Qgm 3-5), representing terminal moraines, north of Ridgway, Colorado. While it has been assumed that the moraines and terraces correspond to Pinedale glacial events, new quartz OSL and feldspar post-IR IRSL dates provide a different interpretation. A quartz OSL date of ca. 25-20 ka for Qag 2 suggests that this terrace correlates with the Last Glacial Maximum and Pinedale glaciation. There is no correlative moraine present in the immediate Ridgway area, and it is likely that Pinedale glaciers never flowed north of present-day Ouray, Colorado. Post-IR IRSL dates indicate that the next oldest outwash terrace is ca. 70-40 ka. This terrace merges with a small, sinuous terminal moraine complex, which shows that glacial ice flowed north at least as far as Ridgway during MIS 4/3. Older glacial moraines (Qgm 4-5) are located slightly further downvalley than Qgm 3, and have crest elevations that are substantially higher than those of Qgm 3. For these reasons, it is likely that the glaciations represented by these moraines involved greater ice volumes than those that produced Qgm 3. These moraines remain undated, but could plausibly correlate with Bull Lake glaciation. Geochronological results presented here hint at the possibility that MIS 4/3 glaciation was more extensive in the San Juan Mountain region than generally recognized.

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