



## ***Glaciations of the San Juan Mountains: A review of work since Atwood and Mather***

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# GLACIATIONS OF THE SAN JUAN MOUNTAINS: A REVIEW OF WORK SINCE ATWOOD AND MATHER

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**ABSTRACT**—Atwood and Mather’s 1932 map of glaciers restored to their Last Glacial Maximum (LGM) dimensions in the San Juan Mountains is the starting point for any geomorphologist working in the region. Here, we examine more recent work completed in the Animas valley and eastern and central San Juan Mountains to update the work of Atwood and Mather. Specifically, we look at attempts to constrain the timing of glaciation using methods developed since the publication of the original map. We also present modern field descriptions of a number of sites and discuss the morphology of glacial landforms. Much of the work done in the San Juan Mountains has not been published and here we attempt to present as much of that data as possible. This examination of previous work highlights the detailed pre-LGM stratigraphy of the Animas Valley compared with moraines in the eastern and central San Juan Mountains which tend to be LGM in age.

## INTRODUCTION

The detailed and comprehensive map (Fig. 1) of glacial extent during the Last Glacial Maximum (LGM) produced by Atwood and Mather (1932) is the seminal work on glaciation in the San Juan Mountains. Their mapping, and the associated paper, focused on the extent of two large ice caps which were connected as one at their maximum. They also considered the small ice cap in the La Plata Mountains and a number of smaller valley glaciers.

Atwood and Mather’s (1932) paper omitted their methodology which can make it difficult to reassess their more complicated glacial landforms. For instance, their map precisely places an ice free corridor between the Cumbres and Conejos Glaciers yet the area is characterized by complicated hummocky topography without context for which glacier would have deposited the material. It is particularly concerning when they refer to the volcanic bedrock in the eastern San Juan Mountains as tillite – indicating that they could not differentiate between till and volcanic rocks. Nonetheless, modern authors have typically found their maximum LGM extent to be generally quite accurate.

Atwood and Mather (1932) mapped Durango and Cerro (later interpreted as landslide debris; Dickinson, 1965) glaciation till deposits that are likely the local equivalent to Bull Lake or older. Remapping created additional subdivisions (Richmond, 1965) but a lack of dates makes it difficult to be certain about ice extent during different glaciations. For the Late Pleistocene, they present mainly landslides and alluvial sediment. They make no mention of neoglacial deposits which is consistent with recent dates at other sites in the western U.S. (e.g., Marcott, 2011) although little has been done in the area to date cirque moraines.

Compared with the scale of their work, much less has been done since the publication of their paper. Dating moraines and glacial features is difficult using radiocarbon so little dating was

done between 1932 and 2000. More recent chronological tools, including optically stimulated luminescence (OSL) and cosmogenic radionuclides (CRN), have not been applied as widely as they have in the rest of the western United States. The lack of age control has led to glacial advances generally being associated with marine oxygen isotope stages (MIS) and/or regional glacial names (Table 1). Here, we review the research that has been done to update the world of Atwood and Mather’s summary of the glacial history of the San Juan Mountains. Specifically, we will examine work done in the Animas River valley as well as research completed in the central and eastern San Juan Mountains. Ice in the Animas River valley deposited complex moraine sequences, perhaps as a response of a large south-facing glacier to environmental changes. The moraine sequences are more straightforward in the central and eastern San Juan Mountains either because the stratigraphy is simpler or because work has generally focused on post-glacial processes (e.g., Johnson et al., 2011; Layzell et al., 2012; Carver and Beeton, 2014; Johnson et al., 2015). We have omitted discussion of the Uncompahgre River valley and surrounding areas, as they are discussed in more detail elsewhere in this volume (Jarrin et al., this volume).

## ANIMAS GLACIER

Deposits of the Animas Glacier, which occupied the Animas River valley north of Durango, are the most-studied in the San Juan Mountains (Fig. 1). The glacier was one of the longest in the southern Rocky Mountains, extending 80-90 km southward from the river’s headwaters and covering approximately 1000 km<sup>2</sup>. Its location on the moist windward side of the range likely contributed to its huge ice volume and ability to reach terminal elevations as low as 2000-2100 m (Leonard, 1984).

End moraines of several glacial advances form bouldery ridges in northern Durango (Figs. 2 and 3). This moraine record is compressed within a narrow belt 1-2 km wide and at least 200 m high (deposits below river level are not visible).

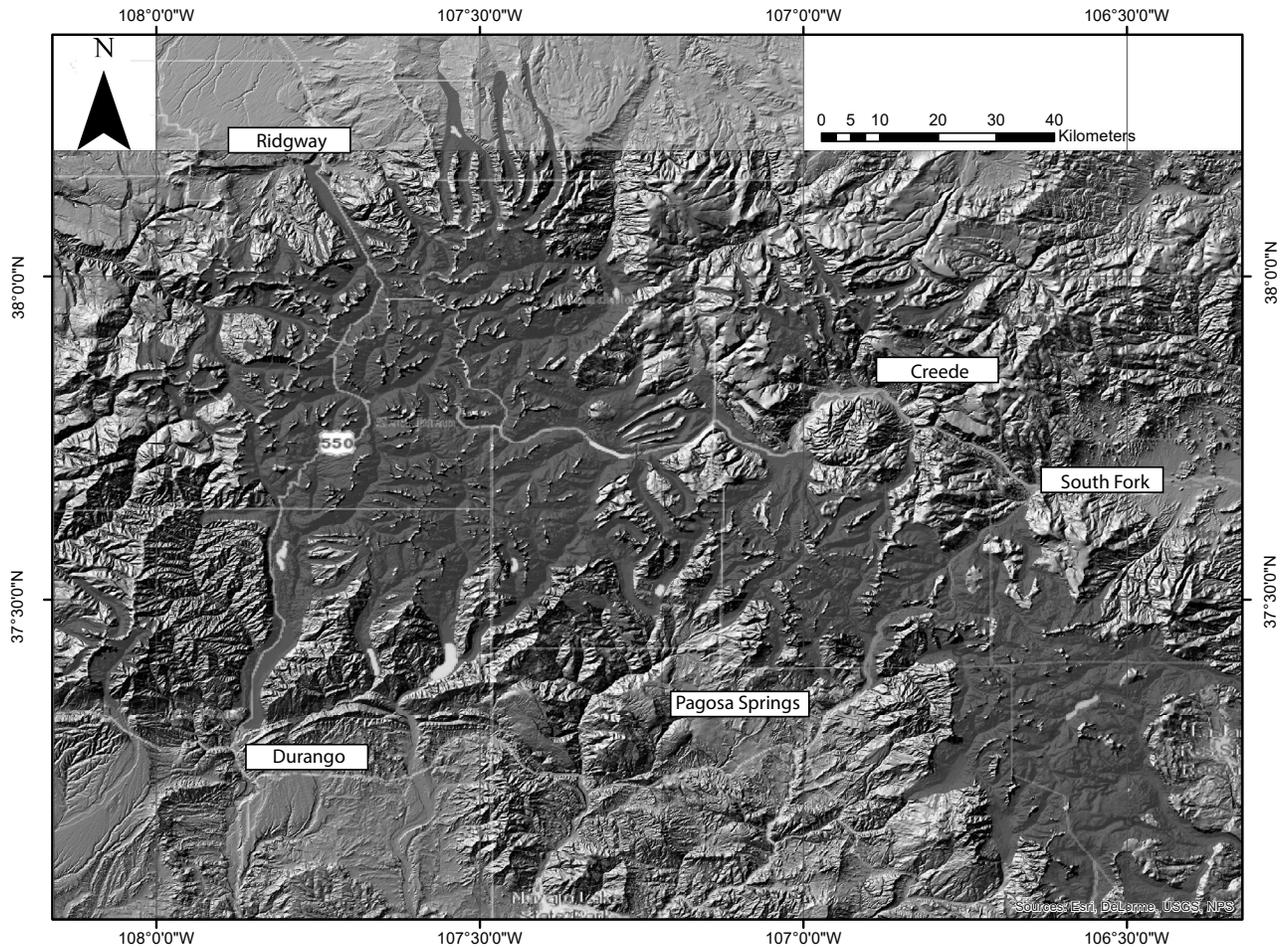


FIGURE 1. Map of the entire San Juan Mountains with a version of Atwood and Mather's (1932) ice extent map as interpreted by Brad Johnson. For a color version, see Color Plate 12.

The glacier's toe was deflected along the strike of sedimentary rocks exposed in the south-dipping Hogback monocline. Most of the moraines are underlain by Mancos Shale. Its erodibility and the confinement of meltwater to narrow channels may have facilitated moraine erosion. However, underlying sandstones (Burro Canyon Formation, Dakota Sandstone and a Da-

kota-like lentil within the lower Mancos) apparently controlled the locations of some younger moraines and probably helped to protect them. Most moraines have now been modified for development and a few parts have been completely excavated.

Outwash gravels and associated terraces extend downstream to Farmington, New Mexico, where they merge with

TABLE 1. Marine Isotope Stages with age ranges (from Lisiecki and Raymo, 2005) and glaciation/moraine names.

MIS indicating higher global ice volumes	Age range	San Juan Moraines	Rocky Mountain Name	Continental Name	Alpine Name
16	~676-621 ka		Sacagawea Ridge	Pre-Illinoian	Günz
8-10	~374-243 ka	Durango			Riss
6	~191-130 ka	Spring Creek	Bull Lake	Illinoian	Riss
4	~71-57 ka	Early Wisconsinan	Early Wisconsinan	Early Wisconsinan	Würm
2	~29-14 ka (LGM)	Animas City	Pinedale	Wisconsinan	Würm

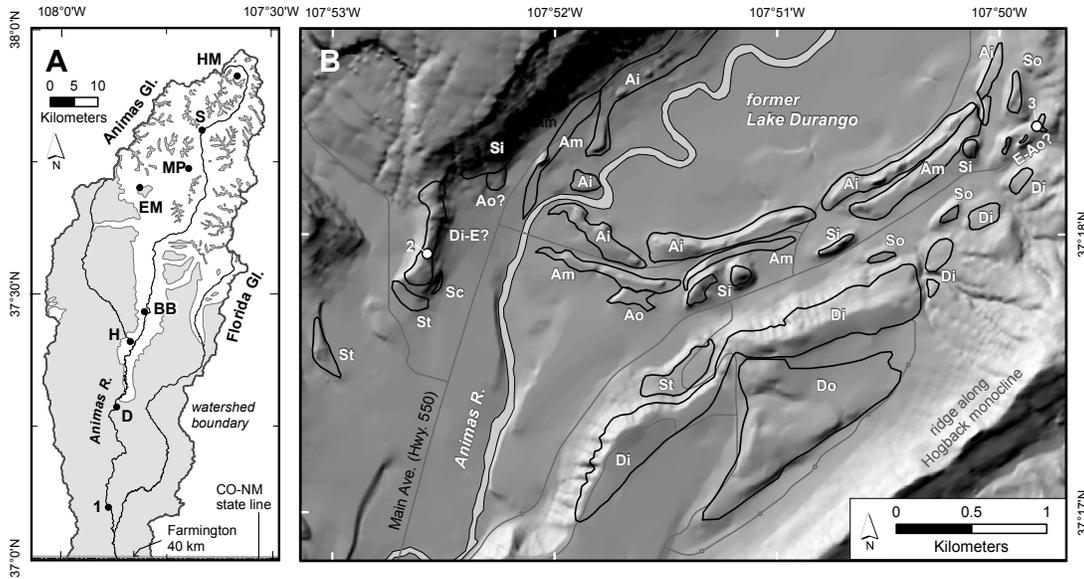


FIGURE 2. A. Selected locations and ice extent in the Animas River watershed (Atwood and Mather, 1932, slightly modified northwest of Durango): BB – Bakers Bridge moraine; D – Durango; EM – Engineer Mountain; H – Hermosa; HM – Highland Mary Lake; MP – Molas Pass; S – Silverton; 1 – outwash dating site (Guido et al., 2007). B. Glacial moraines and selected features in northern Durango as they appeared on 1950 air photos: Do, Di – Durango outer and inner moraines; Di-E? – Durango inner moraine, early Wisconsinan moraine, and/or mass-wasting deposit; So, Si – Spring Creek outer (?) and inner (?) moraines; St, Sc – Bull Lake moraines (Richmond, 1965) reinterpreted as outwash terraces or colluvium; E-Ao? – early Wisconsinan or Animas City outer moraine; Ao, Am, Ai – Animas City outer, middle and inner moraines; 2 – dating site (Passehl and Kenny, 2015); 3 – dating site (Applegate, 2005; Anderson and Kenny, 2015). Modified from Gillam (1998), Carroll et al. (1999) and Kirkham et al. (1999).

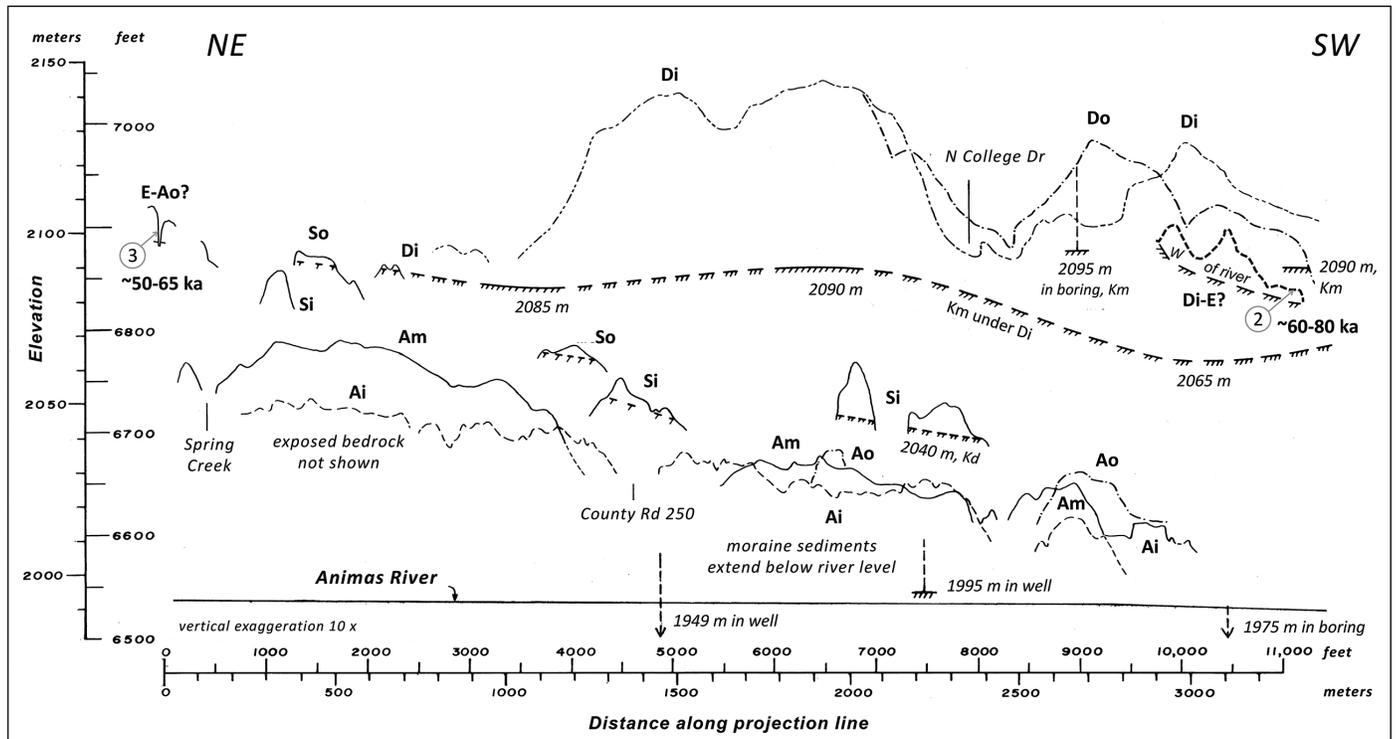


FIGURE 3. Relative heights of end moraines in northern Durango, mostly east of Animas River, projected to N45°E (several small remnants at northeast end of profile not shown). Most symbols as in Figure 2. Kd – Dakota Sandstone and Burro Canyon Formation; Km – Mancos Shale. Based on City of Durango mapping with 2-ft contour interval, 1974 and 2014. Modified from Gillam et al. (1984) and Gillam (1998).

terraces of the San Juan River. Older terraces and moraines are perched higher in the landscape indicating that the river has progressively cut down through time. Terraces that project above existing moraines are probably related to earlier glaciations as discussed below (Gillam, 1998).

Upstream from Durango, lateral moraines mostly from the LGM are discontinuous but extend as far north as Engineer Mountain (~45 km). In places, the ice dammed unglaciated tributaries as evidenced by small lakes or thickening alluvial fills. Other features formed during deglaciation including a moraine-dammed lake north of Durango that is now covered by the Animas River floodplain. Small kame terraces and recessional moraines, drift, and erratic boulders are scattered below the ice margin.

Richmond (1965) divided the moraines into three groups that he correlated with Pinedale, Bull Lake, and Sacagawea Ridge glaciations based on moraine location, morphology, and weathering. Since 2005, numeric dates from two sites have shown that the glacial sequence may be more complex than previously thought.

### Onset of Glaciation

It is not known when periodic glaciations began in the upper Animas valley or the San Juan Mountains generally. Low-energy fluvial sediments of the Rio Grande in the San Luis basin contain climatic indicators which suggest that the first significant cool/wet period occurred around 0.83 to 0.74 Ma; that age is estimated from calibrated sedimentation rates (Rogers et al., 1992). That interval corresponds roughly with MIS 20 (Lisiecki and Raymo, 2005). Blair and Gillam (2011) therefore proposed that the first large glaciers in this region may have formed around that time.

At least six terraces probably formed during early glacial advances for which no moraines are preserved. These terraces resemble outwash terraces graded to existing moraines, but project well above those moraines. Four of the terraces are ~145-195 m above the river near Durango. Farther south, two terraces higher in the sequence are preserved at lower elevations because the terraces converge downstream (Gillam, 1998). Two terraces, at heights of ~165 and ~195 m near Durango, are overlain by small lenses of Lava Creek B tephra (Gillam, 1998; Scott and Moore, 2007; identification verified by Nelia Dunbar, written communication, 2011). This tephra has been dated elsewhere at 620-640 ka (Lanphere et al., 2002). Average river incision rates, calibrated with the age and position of the tephra, suggest that these terraces formed between MIS 12 and 20 and could be as old as ~800 ka or MIS 20 (Gillam, 1998; Table 1). These correlations are tentative but show that many more glaciations could have occurred than are recorded by existing moraines. Older, rare terrace remnants, at several levels up to 420 m above the river, could have formed during earlier climatic cycles. While the terrace ages are uncertain, terraces provide the best evidence for early glaciations in the San Juan Mountains.

### Durango Moraines

The oldest preserved moraines in the Animas valley are composed of Durango Till and lie on a bench east of and 80-150 m above the river (Figs. 2 and 3). Relatively broad, rounded and weathered ridges have been divided into subgroups that may have formed during two glaciations. The 'outer' (down-valley) group consists of several cross-cutting ridge segments. The 'inner' (up-valley) group now consists of two aligned and partly eroded segments along the steeply undercut, front edge of the bench. One of the inner segments cross-cuts a ridge of the outer group but elsewhere outwash separates the groups.

No numeric dates have been obtained for either group but Gillam et al. (1984) inferred that they formed during two glaciations because the river apparently incised during an intervening interglacial. In one part of the terminal area, a step in the top of the shale coincides with the upstream side of the outer moraine group (Fig.3). Also, an outwash terrace that projects to the outer moraines is higher than several outwash terraces that are graded to the inner moraines. Finally, lithologic differences between the two outwash fills suggest that they formed at different times.

Gillam (1998) estimated ages for the Durango moraines from average river incision rates for their outwash terraces, calibrated with the height of the nearby Lava Creek B tephra. She concluded that the Durango moraines formed during marine isotope stages (MIS) 8 and 10. Richmond (1965) and Scott and Moore (2007) correlated the Durango moraines with the Sacagawea Ridge glaciation. However, the Lava Creek B tephra overlies Sacagawea Ridge outwash, which places it during MIS 16 (Chadwick et al., 1997). The Durango moraines must be younger than Sacagawea Ridge because the tephra-bearing terraces project above them.

### Spring Creek Moraines

Richmond (1965) first mapped small moraine-like deposits that appear intermediate in position and weathering characteristics to adjacent moraines (Figs. 2 and 3). He correlated them with the Bull Lake glaciation (MIS 6), now locally called Spring Creek (Gillam et al., 1984). Remnants that are too small or eroded to have clear moraine- or terrace-like shapes are difficult to interpret because moraines in this area include some meltwater deposits (Johnson, 1990), and proximal outwash contains many large boulders (Gillam, 1998). Some deposits east of the river and all west of the river have been reinterpreted as coarse outwash, colluvium, or younger moraine remnants. Most likely to be Bull Lake equivalents are several hills east of the river where the deposits' basal contacts are clearly intermediate in height between those of the Durango and younger moraines. No dates have been obtained from any of these deposits or from outwash terraces thought to correlate with them. Recently obtained OSL dates from site 3 (Figs. 2 and 3, discussed below), suggest that some remnants now interpreted as Bull Lake could be early Wisconsinan.

### Possible Early Wisconsinan Moraines

Recent OSL dating at two sites suggests that an early Wisconsinan (MIS 4) glaciation may be represented in the Animas valley (Jarrin et al., this volume, describe early Wisconsinan deposits in the Uncompahgre River valley). Passehl and Kenny (2015) studied a small cut on a narrow ridge 100-110 m above the west side of the river (site 2 in Figs. 2 and 3). This bedrock ridge is thinly capped with diamicton and other deposits previously interpreted as eroded Durango moraine because they lie within the elevation range of deposits beneath Durango moraines east of the river (Atwood and Mather, 1932). Passehl and Kenny (2015) described the sampled beds as 'on' adjacent deposits as if inset above an unconformity. However, the sampled alluvium and loess appear to interfinger with folded diamicton on the inner side and to be overlain by cobbly alluvium on the outer side, as could occur within a moraine (preliminary observations by Gillam and Rob Blair, 2015). OSL dates, from bottom to top, are  $82 \pm 15$ ,  $60 \pm 11$ , and  $62 \pm 12$  ka. These dates suggest that the sampled deposits are inset below and younger than the Durango moraine crests (thick loess caps and deep, strongly developed soil profiles show that the Durango moraines are much older). More work is needed to determine whether these dates indicate a previously unknown glacial advance or a mass-wasting event.

Several more OSL dates, partly younger, have been obtained from fine-grained alluvial and lacustrine deposits near the northeast part of the terminal area, ~60 m above the river (site 3 in Figs. 2 and 3). The lowest bed was dated at  $60.9 \pm 12.2$  /  $-10.8$  ka (Applegate, 2005) and  $65 \pm 13$  ka (Anderson and Kenny, 2015); overlying beds yielded three ages as young as  $\sim 50 \pm 10$  ka (Anderson and Kenny, 2015). This sequence is overlain unconformably by ridge-capping diamicton that could be either early Wisconsinan (MIS 4) or younger Animas City (Richmond mapped it as late Bull Lake). The site lies at nearly the same elevation as the first but ~2.4 km up-valley and therefore much lower in relation to likely former ice-surface slopes, which are generally represented by the youngest moraines in Figure 3. These dates suggest that some moraine remnants now interpreted as Spring Creek (MIS 6) or outer Animas City (see below) could be early Wisconsinan (MIS 4).

### Animas City Moraines

The youngest end moraines include two curving ridges that are sub-parallel and nearly continuous (Animas City middle and inner moraines; Figs. 2 and 3). These moraines have relatively sharp, irregular crests but very small volumes. Basal bedrock contacts are slightly above or below river level.

These moraines have always been correlated with the LGM (Atwood and Mather, 1932; Richmond, 1965) but they haven't been dated directly. Interbedding among moraine sediments and the small size of the moraines compared to the huge volume of the glacier suggest that these moraines were built quickly, in years to decades. They may be the last moraines of many that formed earlier but were eroded by continuing glacial or meltwater processes (Johnson and Gillam, 1995). Guido et al. (2007)

obtained a date of  $19.4 \pm 1.5$   $^{10}\text{Be}$  ka on some of the youngest outwash 27 km downstream from the moraines (site 1 in Fig. 2A). A later value for the  $^{10}\text{Be}$  production rate slightly increases this age to  $21.5 \pm 1.5$  ka (Laabs et al., in prep.). When ice retreated from the moraines, coarse sediment would have been trapped in a proglacial lake (described below), leading to river under-loading, incision, and rapid terrace abandonment (Johnson and Gillam, 1995; Guido et al., 2007). Therefore, this date roughly constrains initial retreat and the age of the inner moraine.

Age assignments of other small moraine remnants on the distal side of the middle moraine have varied. Gillam (1998) interpreted them as parts of highly eroded, outer Animas City moraines because they lie at roughly the same elevation as other Animas City moraines. Also, the outwash terrace graded to them is more similar in height and preservation to Animas City terraces than to Spring Creek terraces. These moraine remnants could have formed during either the Pinedale or early Wisconsinan glaciations (Blair and Gillam, 2011). However, the model for rapid moraine construction and erosion (Johnson and Gillam, 1995) suggests they may be close in age to other Animas City moraines.

### Types of Moraine Sediments

Excellent exposures within the Animas City deposits have allowed unique sedimentary sequences to be studied. Johnson (1990) and Johnson and Gillam (1995) examined mixed sedimentary sequences including a mix of debris flow deposits, alluvium, till, and lacustrine deposits. They interpreted the sediment to have formed in pro-glacial, ice-contact aprons or 'dump' moraines with complex internal structures. The complexity would have been the result of rapid changes in local ice topography, sediment supply, and meltwater routing. In a few places, sediment is folded or deformed as a result of retreat and readvance. Underlying a number of moraines are alluvial, lacustrine, or landslide deposits indicating that the glacial sequence prograded over those deposits.

The huge volume and low elevation of the terminal Animas Glacier would have produced large amounts of meltwater, at least during warmer months. This water volume may explain the unique stratigraphy of moraines in this area. Similar deposits may not have been exposed elsewhere.

### Last Glacial Recession

When the last Animas Glacier began to recede, a proglacial, moraine-dammed lake (Lake Durango) formed in the overdeepened bedrock basin north of the Animas City moraines (Atwood and Mather, 1932; Figure 2). Varved silt has been found in several deep water wells and in at least one shallow excavation near the valley axis. An exploratory oil well showed that these sediments are at least 134 m (440 ft) thick (Gillam, 1998). Post-glacial alluvium and valley-side deposits now conceal the lakebeds but they likely extend roughly 14 km north to the vicinity of Hermosa, where the modern floodplain steepens and the buried bedrock surface probably rises above the lake's outlet level (Johnson and Gillam, 1995).

Outwash and younger terraces cover parts of the valley floor farther upstream to a bedrock step 21 km north of the Animas City moraines near Bakers Bridge. Below and on the step are small remnants of till that have been interpreted as the recessional Bakers Bridge moraine (Richmond, 1965, 1986). Exposed deposits consist of lodgement till that accumulated under active ice (Johnson, 1990) so their present ridge forms could reflect post-glacial erosion. A  $^{10}\text{Be}$  surface exposure date on granite at the top of the step indicates that the deposits must be older than  $17.1 \pm 1.3$  ka (Guido et al., 2007). This date has been recalculated using slightly different models as both  $20.0 \pm 0.9$  ka (Shakun et al., 2015) and  $18.8 \pm 1.3$  ka (Laabs et al., in preparation).

Two sets of small cirque moraines have been described in the upper Animas basin (Carrara, 2011). Yankee Boy moraines are common in northwest- to northeast-facing cirques throughout the region, 0.4 to 2.0 km from the headwalls. Only Grenadier moraines, possibly younger, have been found in north-facing cirques of the Grenadier Range in the Animas basin, usually within 450 m from headwalls. Carrara suggested that these moraines likely formed during the Younger Dryas between roughly 12,800 and 11,600 years ago.

Multiple dates show that the Animas Glacier, and probably others in the San Juan Mountains, may have disappeared by about 11–14 ka. Guido et al. (2007) obtained a date of  $12.3 \pm 1.0$   $^{10}\text{Be}$  ka from glacially striated bedrock near Highland Mary Lake. This date has been recalculated as  $13.7 \pm 0.7$  ka (Shakun et al., 2015) and  $12.7 \pm 1.1$  ka (Laabs et al., in preparation). The lake lies in a high, north-facing cirque where ice remnants might be expected to persist. The original dates of Guido et al. (2007) suggest that recession from the Animas City moraines took around 7.32 kyr at an average rate of 15.4 m/yr, although recalculated dates suggest the rate was slightly slower. A U-series date was later obtained from a postglacial speleothem near Molas Pass, roughly halfway up the glacier's former length. This date,  $13,446 \pm 170$  yr, shows that retreat began more rapidly and then slowed, partly in response to Younger Dryas cooling (Kenny, 2015). The oldest accepted radiocarbon dates from the high mountains,  $\sim 11$ – $12$  cal  $^{14}\text{C}$  ka, are younger than the date from Highland Mary Lake and appear to closely follow deglaciation (Guido and others, 2007). These dates are from basal sediments in tarns (Carrara, 2011) and from ferricrete-cemented stream alluvium (Sjostrom et al., 2004).

## EASTERN AND CENTRAL SAN JUAN MOUNTAINS

### Southeastern San Juan Mountains

Till in the southeastern San Juan Mountains can be very difficult to identify, especially in the Hinsdale volcanic field where volcanoclastic rock (e.g., Lipman, 1974, 1975) can resemble till (i.e., poorly sorted, ashy matrix containing cobbles; Johnson et al., 2010). Further, many moraines are severely eroded or buried in outwash from the retreating glacier. Compared with many of the classic glacial sequences in the western United States, the moraine stratigraphy in the region can be enigmatic. For instance, few glacial striations remain because

either the bedrock is generally too soft for striations to form or they have weathered away since deglaciation. The Hinsdale volcanic rocks also add to the complexity of dating glacial sequences. Specifically, the volcanic rocks in the area tend to have little quartz making beryllium-10 cosmogenic radionuclide dating difficult. It appears that much of the silica in the rocks is present not in crystals but in volcanic glass. Johnson et al. (2017) attempted to date felsic rocks but found the pre-treatment dissolved the entire rock. They were able to obtain ages using chlorine-36, a less common method that could be used in future studies. OSL dating has been used further to the west in the South Fork drainage indicating a better source for quartz in the South Fork drainage.

Atwood and Mather (1932) stopped mapping at the Colorado – New Mexico border and the Cumbres Glacier extends off of their map down the Chama Valley (Fig. 4). It is the only place where glaciers extend beyond the borders of their map, and it is unclear where they would have mapped the terminal moraine. Ten kilometers down-valley, towards Chama, NM, are a set of moraines that appear much older than LGM based on morphology and soil development. It is likely that these are the older, MIS 6 (or perhaps MIS 4) moraines. Further up-valley, the valley bottom is dominated by mass-wasting deposits making the identification of glacial deposits almost impossible. The first recognizable moraine is just west of Cumbres Pass and dams Cumbres Bog in Colorado (Fig. 4; Johnson et al., 2013). Atwood and Mather (1932) must have thought this was a recessional moraine since their ice extent continues down-valley. Johnson et al. (2013) cored the bog dammed by the moraine and found that it was  $\sim 12$  meters to glacial gravel, a good indication of a kettle feature. Their basal age, on bulk sediment from a section of lacustrine rhythmites interpreted as varves, was calibrated to  $\sim 18,300$  years before present. This age is close to the timing of the onset of deglaciation (e.g., Clark et al., 2009) but does not clarify the location of the terminus.

The Cumbres Glacier, which is mapped as separate from the main ice cap (Fig. 4), also flowed north towards La Manga Pass terminating just over the north side of the pass. Atwood and Mather (1932) mapped a narrow unglaciated strip between the Cumbres Glacier in the La Manga Valley and the Conejos Glacier down below in the Conejos Valley (Fig. 4). It is unclear what the geomorphic evidence is for the unglaciated strip. Features near La Manga Pass look like moraines, but it is unclear if they were deposited by the Cumbres or Conejos Glacier (Fig. 5). Further complicating the matter is the fact that much of the area north of the pass has been reworked by mass wasting (similar to the mass wasting at Cumbres Pass). Indeed, much of the sediment in the area is diamicton but little else can be interpreted from these deposits.

The terminal moraines for the Conejos Glacier lie at the confluence of the Conejos River and Sheep Creek. The moraines are unimpressive, rising less than 2 meters above the surrounding surfaces (Fig. 5). However, it is clear that till occurs upstream but not downstream of the site indicating the terminal moraine is correctly mapped. The quantity of till and outwash in the area indicates that, perhaps, the moraines are

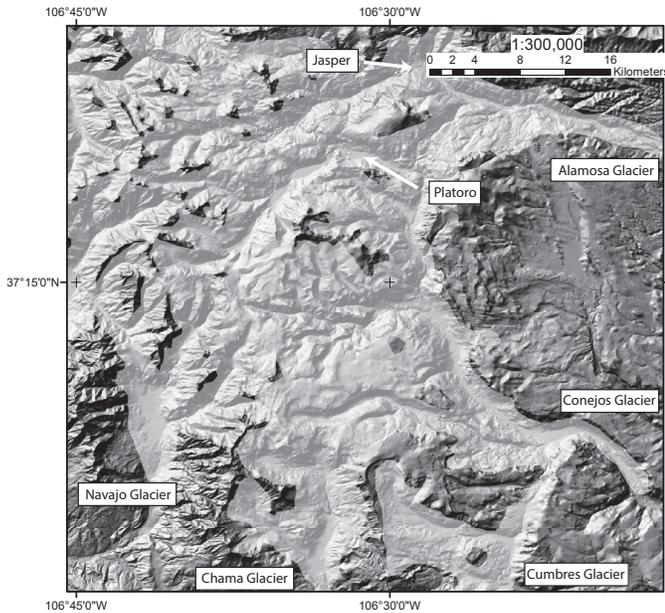


FIGURE 4. Map of the southeastern San Juan Mountains and the LGM glacial extent as mapped by Atwood and Mather (1932) as interpreted by Brad Johnson. Note that Atwood and Mather stopped mapping at the Colorado – New Mexico border.

buried in glaciofluvial sediment. This burial would help to explain the relatively small size of this and other moraines in the area. Recessional features are present up-valley but not well preserved and striations are only visible in a handful of locations despite the nearly 40-km-long glacial valley.

If we assume that the timing of glaciation was similar to that in the Animas (Guido et al., 2007), we can calculate a retreat rate for the ~40 km Conejos Glacier of 5.6 m/yr (Sheep Creek to Blue Lake). As the glacier retreated past hanging valleys, knickpoints were initiated. The amount of headward erosion on those knickpoints appears to be related to the strength of the bedrock and not to the time when the glacier passed. For instance, the Adams Fork is near the headwaters of the glacier and yet this tributary migrated 4.5 km via headward erosion and incised 100 m vertically in poorly cemented volcanoclastic rock (Johnson et al., 2010; Johnson et al., 2011). Lake Ann and Bear Lake are tarns in the uppermost drainages of the Conejos Valley. Both are dammed by moraines but it is unclear whether these are neoglacial or the last recessional moraines (possibly Younger Dryas). Most neoglacial moraines in the western US were recently reattributed to the Late Pleistocene (Marcott, 2011) so we do not favor a neoglacial interpretation.

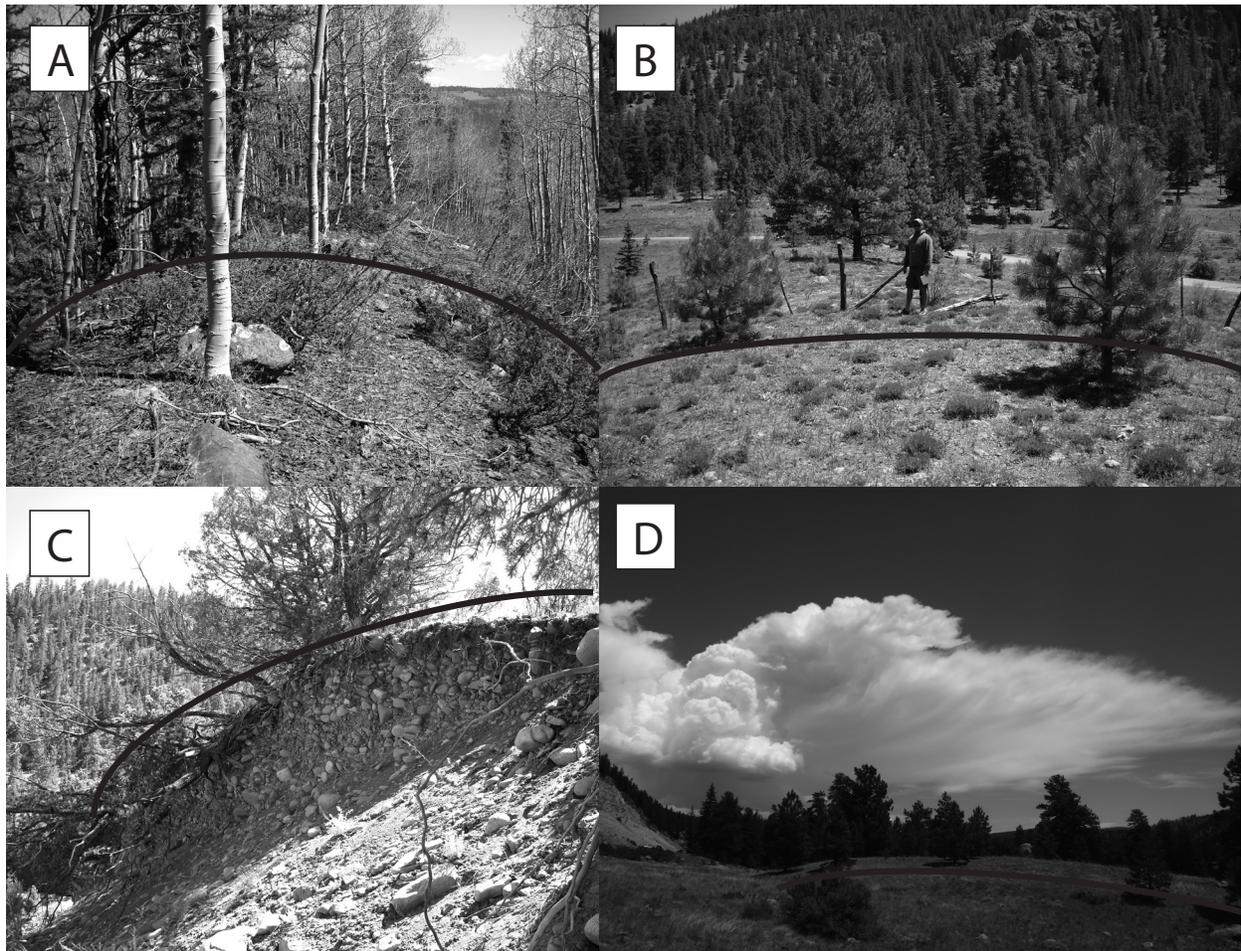


FIGURE 5. Terminal moraines for the Cumbres Glacier at La Manga Pass (A), Conejos Glacier at Sheep Creek (B), Alamosa Glacier at Alamosa (Terrace) Reservoir(C), and South Fork Glacier near the town of South Fork (D). Lines trace the crests of each moraine (photos by Brad Johnson).

Further to the northeast, the Alamosa Glacier flowed as far as the modern Alamosa (Terrace) Reservoir. The left lateral and terminal moraines make up most of the dam with only a small gap filled with an earthen dam. The emergency spillway is cut into the left lateral moraine exposing the sediment (Fig. 5). The moraine here is much larger than those on the Conejos, Cumbres, and South Fork. There is little outwash in the drainage so perhaps the river gradient is steep enough to carry fluvial material away instead of burying the moraines. Soils examined on the moraine were oxidized but lacked Bk horizons which is consistent with other LGM in the eastern San Juan Mountains.

### South Fork and Upper Rio Grande Glaciers

Glacial landforms are prominent in the upper Rio Grande basin (Atwood and Mather, 1932; Small, 1995; Benson et al., 2005; Carrara, 2011). The Rio Grande Glacier and the Red Mountain Glacier combined to occupy the main stem of the upper Rio Grande and deposited terminal moraines just southwest of Creede at 2,620 m. Benson et al. (2005) dated these terminal moraines using  $^{36}\text{Cl}$  cosmogenic dating to between 20 and 19 ka (recent recalculations by Laabs et al., 2017, in prep., give similar results). Unpublished OSL data (Beeton) on sand lenses within the Brown's Lakes moraine complex higher in the basin at 2,926 m suggest that moraines were developing at 14.4 and 12.3 ka, indicating a 19 km and 300 vertical m retreat up the main Rio Grande valley in 5,000 to 8,000 years (2.4 to 3.8 m/yr). The Brown's Lakes moraine complex is exceptionally large, covering an area of  $\sim 3 \text{ km}^2$  at the mouth of South Clear Creek valley near the location where the Rio Grande Glacier dammed proglacial Lake Atwood (Atwood and Mather, 1932; McMillan, 1993) between 15 and 13.5 ka (MacGregor, 1993). McMillan (1993) maps the moraine complex as a series of moraines, kame moraines, and kame terraces. Kames, kettles, and eskers also have been mapped down-valley of the Brown's Lakes moraine in the upper Rio Grande Basin (Small 1995). An interesting result of Small's (1995) work relates the low valley gradient of the upper Rio Grande to ice stagnation. When climate warms and the ELA rises in steep terrain a glacier will recede actively, but when the gradient is shallow, like the Rio Grande, the ice is stagnated and landforms such as kames, kettles, and eskers are preserved. Roche moutonnees also have been mapped higher in the upper Rio Grande drainage along the main stem between Rio Grande Reservoir and Box Canyon, along Crooked Creek, and near Stage Station Flat in Long Canyon (Grumet, 1993).

A terminal moraine and set of at least five recessional moraines of the South Fork Glacier are located along a  $\sim 2.5 \text{ km}$  stretch (Fig. 6) between the town of South Fork and the confluence of Beaver Creek and the South Fork of the Rio Grande (Fig. 5). Glacial outwash fills the valley with 9 to 10 m of sediments exposed along the modern river and partially buries the moraines. The moraines have rounded profiles and stand  $\sim 2$  to 4 m above the outwash terrace suggesting that the moraines are large and may be  $\sim 11$  to 14 m in height. Million Reservoir is surrounded by related laterals and was originally dammed by a small, now-reinforced, recessional moraine. Current work by

Jared Beeton and Brad Johnson suggests that the glaciofluvial outwash terrace, the highest terrace along the South Fork of the Rio Grande (our T-1), is late Pleistocene in age. Based on OSL ages from the C horizon and soil development (stage I-II Bk horizons), the T-1 was aggrading  $\sim 12.2 \text{ ka}$  and is likely an outwash terrace associated with glacial retreat. Erratics associated with shallowly-buried till commonly protrude through the T-1 fill fill. This pattern suggests that T-1 aggradation immediately followed LGM retreat, net deposition continued through  $\sim 12.2 \text{ ka}$ , and later cut-and-fill events constructed lower terraces. Further work along the mainstem of the Rio Grande between Wagon Wheel Gap and the town of South Fork suggests that the high terrace (T-1) there is also outwash. Soil development in this T-1 fill is similar to that of the dated late-Pleistocene terrace along the South Fork with a stage I-II Bk horizon. An OSL sample has been collected, painstakingly, from this dense and bouldery terrace fill, and will provide additional chronological data.

Fischer Glacier flowed east of Fisher Mountain down through the Fisher Creek Valley and into the Goose Creek Valley, terminating just south of the Rio Grande near Wagon Wheel Gap. Nearby glacial deposits were studied by Eppes (1993). Weathering rind, boulder frequency, slope profile, and soils data were used to define relative ages of terminal, recessional, and lateral moraines. Eppes (1993) mapped a downslope limit of glaciation at 10,500 ft, followed by a set of drumlin-shaped and kettled recessional moraines. Ice-stagnation features including two eskers were also mapped in the Middle Roaring Creek Valley (Eppes, 1993).

The Red Mountain Glacier flowed north and met up with the Rio Grande Glacier near its terminus at Hogback Mountain. Near the contact of these two glaciers, Kitchens (1993) mapped eighteen Rio Grande moraines and eight Red Mountain Creek moraines. Moraines of these two glaciers can usually be differentiated by the small presence of metamorphic crystalline rocks from the Needle Mountains area in the Rio Grande moraines, however this distinction is not found here at the confluence of these glaciers because the moraine complex is a mix of both tills (Kitchens, 1993). The moraines can be differentiated by the  $40^\circ$  angle between the planform trend of the moraine crests. It is unknown if the glaciers were temporally congruent. Santa Maria Canyon, just north of the Rio Grande and west of Hogback Mountain, also was likely glaciated based on the presence of glacial drift and erratics (Panfil, 1993).

### CONCLUSIONS

Many more researchers have worked in the Animas River valley than in the rest of the San Juan Mountains. Animas valley moraines have been correlated with several glacial advances but even there, present age estimates could change if more numeric dates are obtained. In contrast, valleys in the central and eastern San Juan Mountain seem to be dominated by LGM deposits. It may be that the detailed stratigraphy found in the Animas River valley is also present in other parts of the range but simply has not yet been mapped. However, it may also be that older fluvio-glacial sediments were not deposited or preserved in other parts of the range. Atwood and

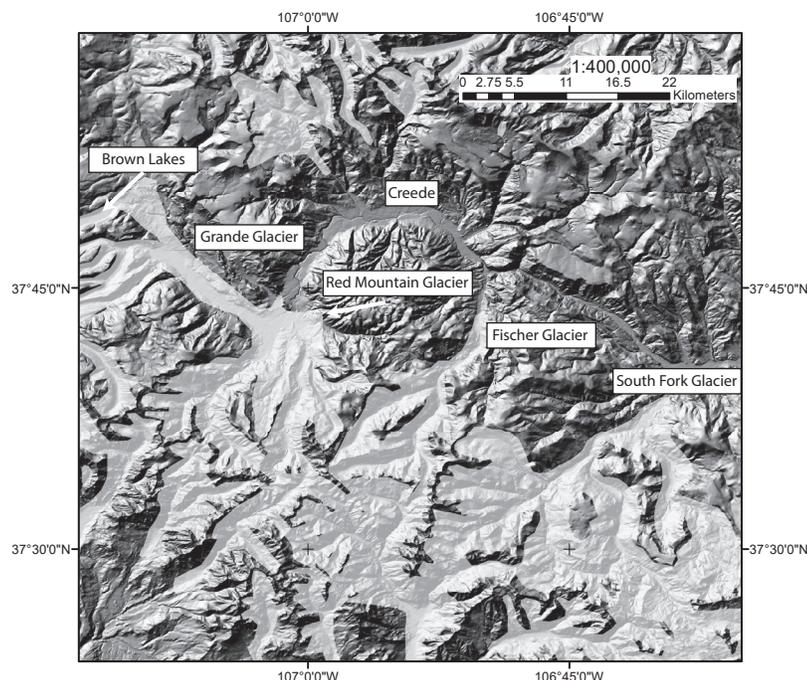


FIGURE 6. Map of the central San Juan Mountains and LGM glacial extent as mapped by Atwood and Mather (1932) as interpreted by Brad Johnson.

Mather (1932) mapped far less Durango Till in the eastern San Juan Mountains than in the western San Juan Mountains and the soft volcanoclastic rocks in the area are more susceptible to erosion. The result may be that recessional moraines and older glacial features are not well preserved on the eastern side of the mountains. It seems equally possible that fundamental differences in the ice sheet dynamics created different sets of deposits in different parts of the range. In fact, all of the valleys dominated by LGM features trend between north and east while the two valleys that are oriented southward, the Animas and the Chama, have large, pre-LGM deposits. It seems likely that these south facing valleys may have been more responsive to changes in climate and therefore deposited additional moraines during the same number of glacial cycles.

In the end, it is clear that there are many unanswered geomorphic questions in the San Juan Mountains. Compared with the scale of the work of Atwood and Mather (1932), little has been done in the 85 years since and only a fraction of what has been done has been published. Further, numerical age dates are limited given the extent of ice during the LGM. Here, we have summarized the work that has been done and highlighted much of the unpublished work. Yet, it is clear that the majority of the valleys containing glaciers during the LGM have not been reexamined since Atwood and Mather. Thus, we can only conclude that further work is needed to understand the timing and nature of past glaciation in the San Juan Mountain.

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