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Glacial outburst floods on the Animas River, Colorado and New Mexico

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ABOUT THIS REPORT

From the overview:

"Four catastrophic floods ran down the Animas River valley of southwest Colorado during the Pleistocene. Outlet valley glaciers from the San Juan icefield flowed southward down the Animas River valley and reached Durango during the last three glacial advances. Each of these glacial advances caused glacial outburst floods, and the earliest flood probably had a similar origin. Nested end moraines at Durango show each glacier reached the same end point, with less than a mile separating the three moraines. Upstream from these moraines is a long, flat-floored valley with extremely low gradient that represents the infilled proglacial lake that formed behind the end moraines as the glaciers receded. Failure of the morainal dams led to catastrophic draining of the proglacial lakes. The floods ran the length of the Animas River, carrying flood deposits more than 50 miles downstream to the confluence of the Animas River with the San Juan River at Farmington, New Mexico."

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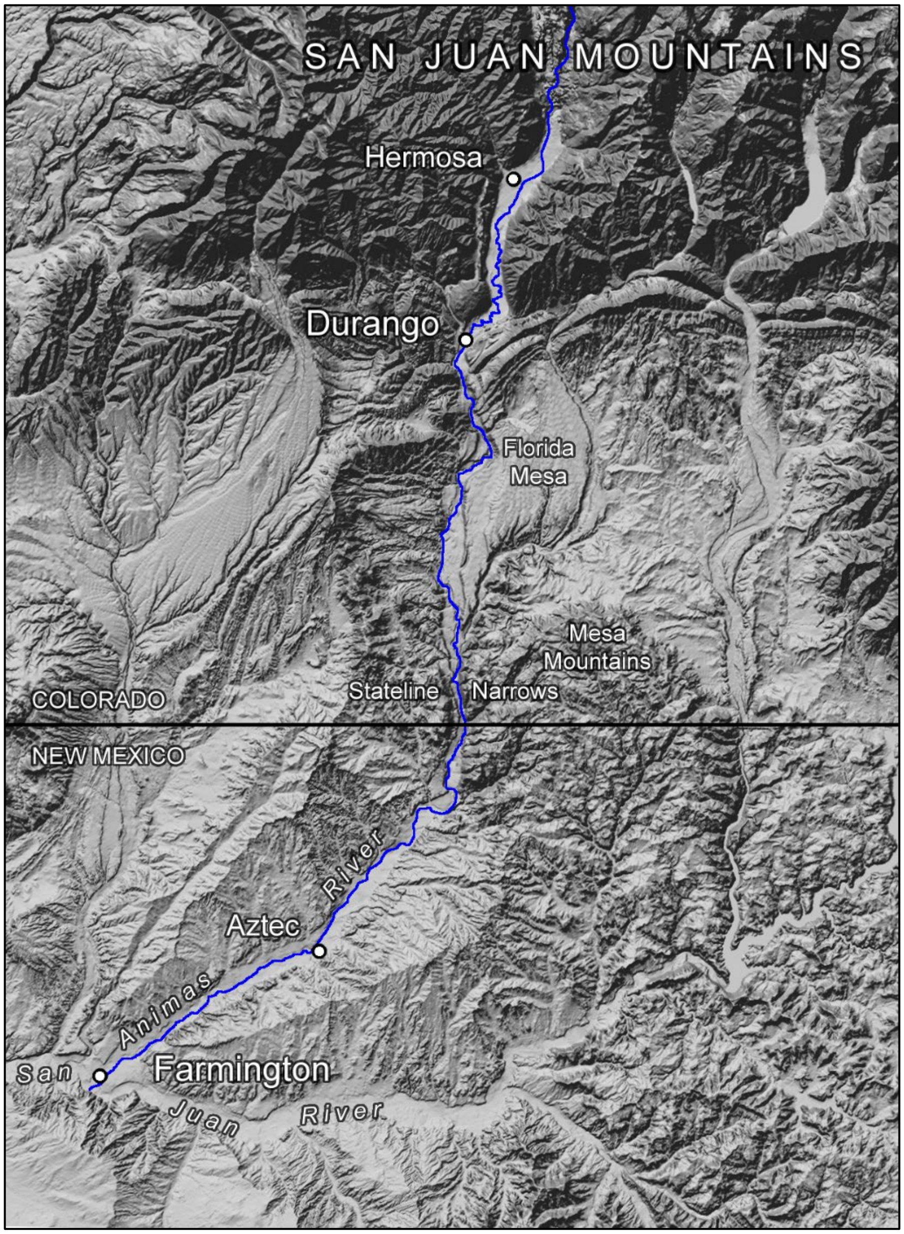
GLACIAL OUTBURST FLOODS
ON THE ANIMAS RIVER
COLORADO AND NEW MEXICO



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2025

CONTENTS

FIGURES

GLACIAL OUTBURST FLOODS ON THE ANIMAS RIVER

COLORADO and NEW MEXICO

OVERVIEW

Four catastrophic floods ran down the Animas River valley of southwest Colorado during the Pleistocene. Outlet valley glaciers from the San Juan icefield flowed southward down the Animas River valley and reached Durango during the last three glacial advances. Each of these glacial advances caused glacial outburst floods, and the earliest flood probably had a similar origin.

Nested end moraines at Durango show each glacier reached the same end point, with less than a mile separating the three moraines. Upstream from these moraines is a long, flat-floored valley with extremely low gradient that represents the infilled proglacial lake that formed behind the end moraines as the glaciers receded.

Failure of the morainal dams led to catastrophic draining of the proglacial lakes. The floods ran the length of the Animas River, carrying flood deposits more than 50 miles downstream to the confluence of the Animas River with the San Juan River at Farmington, New Mexico.

INTRODUCTION

Headwaters of the Animas River are in the Silverton caldera on the southwest flank of the San Juan Mountains. The Animas River flows southward from the Continental Divide for about 100 miles to its confluence with the San Juan River at Farmington, New Mexico (fig. 1). Elevations range from about 12,000 ft to 14,000 ft along the divide (maximum 14,088 ft) to 5,239 ft at the confluence with the San Juan River. The rugged alpine environment of the headwaters area transitions to foothills and hogbacks of the San Juan monocline at Durango (fig. 2), and below the hogbacks the Animas River flows through open drylands of the Colorado Plateau. The Animas River valley below Durango is relatively broad throughout its length down to the San Juan River except for a bedrock constriction near the Colorado-New Mexico border that is referred to here informally as the *Stateline Narrows* (fig. 2).

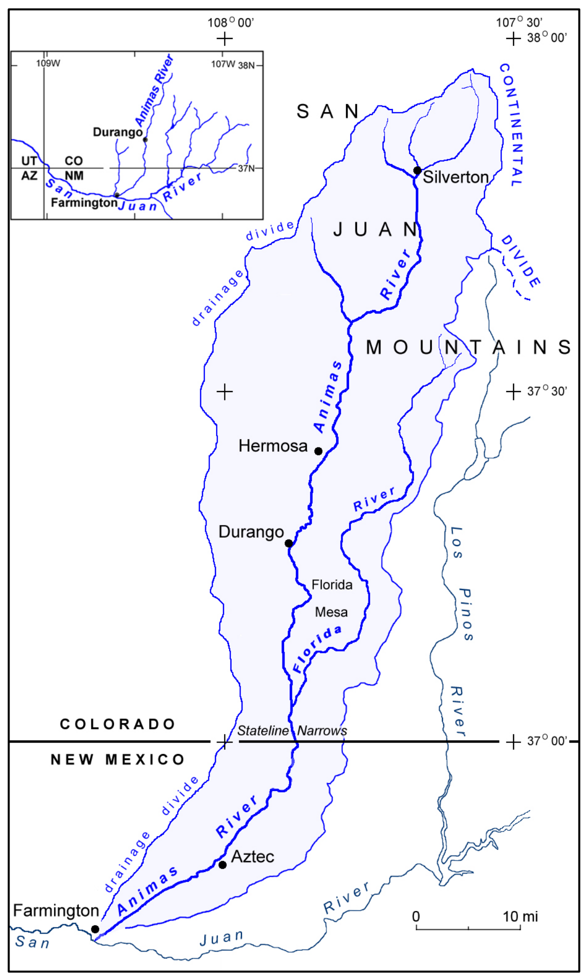


Figure 1—Index map of the Animas River drainage basin.

The main part of the San Juan Mountains is a dome cored by Precambrian plutonic and metamorphic rocks, with Paleozoic and Mesozoic sedimentary rocks capped by Tertiary volcanic rocks (Cross and Larsen, 1935). Proterozoic 1.7 Ga gneisses and schists are overlain by 1.4 Ga metaquartzites and lesser phyllites and slates and intruded by numerous granitic batholiths. Cambrian to Pennsylvanian

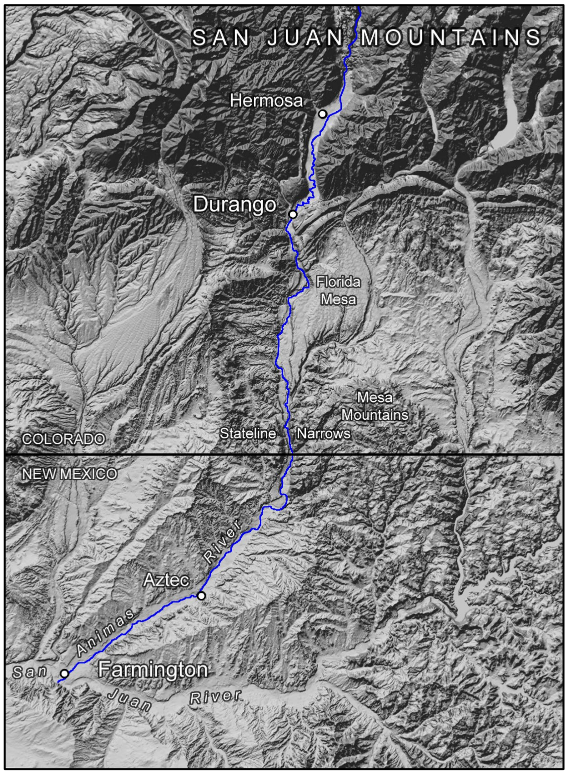


Figure 2—Shaded-relief map shows the area of the Animas River floods.

Three glacial advances are recognized that reached Durango, and each built end moraines that impounded proglacial lakes. In this report, I use the term Pinedale for the latest of the three glaciations.

Following the usage of Johnson et al. (2017, table below) based on the work of Lisiecki and Raymo (2005), Pinedale refers to deposits of the latest major glaciation, approximately 29—14 ka, Marine Isotope Stage (MIS) 2.

Bull Lake refers to deposits of approximately 191—130 ka, MIS 6.

The Durango glaciation (described below) is of less certain age, estimated by Mary Gillam, using calibrated incision rates, to be MIS 8—10 (Gillam,1998, tables 7.1, 7.2).

marine sedimentary rocks are overlain by Permian to Cretaceous continental sandstones and shales. Oligocene intermediate-composition lava flows and volcaniclastic rocks are capped by extensive ash-flow tuffs from numerous calderas in the San Juan Mountains.

Erosion that exposed the interior of the San Juan dome culminated with the extensive and intensive glaciation of the Pleistocene ice field that covered much of the San Juan Mountains (fig. 3). Among the outlet glaciers from this icefield, the Animas valley glacier was the largest, about 230 square miles (Leonard, 1984) and longest, about 53 miles (Gillam, 1998).

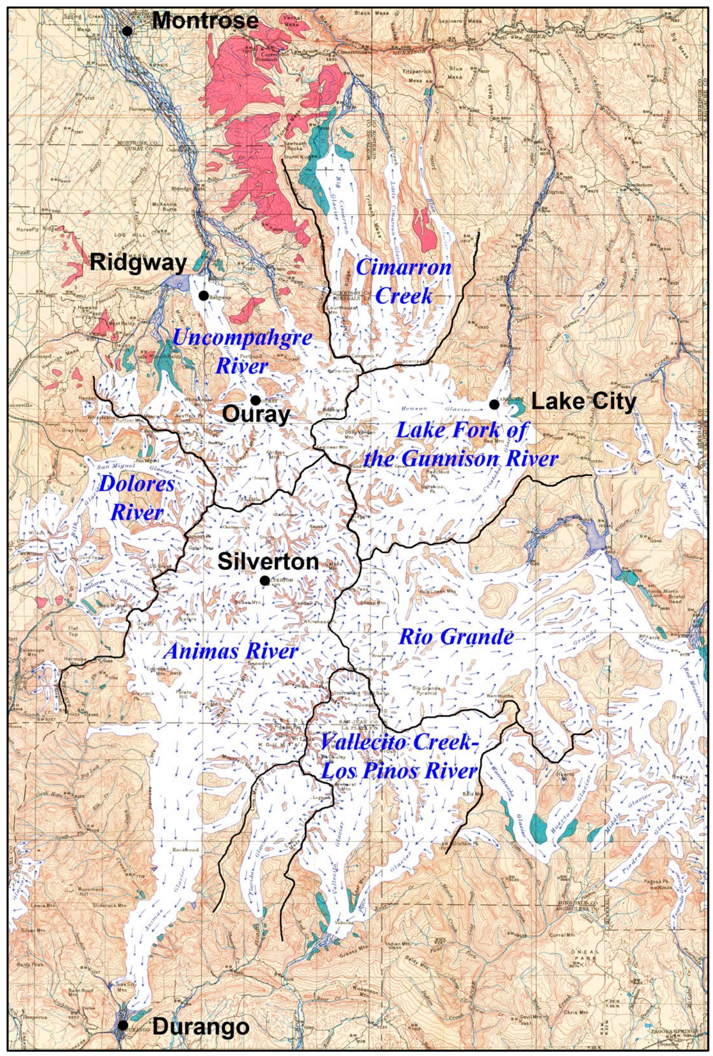


Figure 3—San Juan icefield reconstructed by Atwood and Mather (1932); divides and towns added.

Age	Stratigraphic unit at Durango	Range of absolute age	Marine Isotope Stage
Pinedale	Animas City	~29–14 ka	MIS 2 (Last Glacial Maximum)
Bull Lake	Spring Creek	~191–130 ka	MIS 6
Durango	Durango	~374–243 ka	MIS 8–10

Data from Johnson et al., 2017

Upstream from the end moraines, the Animas River valley is anomalously flat for about ten miles, up to and slightly above Hermosa (fig. 2). This was the site of a proglacial lake, named Lake Durango by Atwood and Mather (1932). The paleolake filled during each of the three glaciations, providing the source of flood waters when the morainal dams failed.

Many geologists have contributed to our knowledge of the Quaternary history of the Animas River valley, summarized by Gillam (1998, and references therein). Glenn Scott recognized the flood origin of boulder-rich deposits at the top of two of the outwash terraces (Scott, oral communication, 1978; Moore and Scott, 1981; Scott and Moore, 2007). In Mary Gillam's definitive study of the terraces of the Animas River, she also reported flood deposits (Gillam, 1998, p. 135, 138-141, 152). This report simply describes the flood deposits in a more systematic manner, placing them in the solid framework established by these geologists.

FLOOD SOURCE AREA

MORAINES

The Animas glaciers produced a suite of seven nested morainal loops at Durango, with the oldest and youngest of the moraines separated by less than a mile. Relative age criteria separate these moraines into three major glacial advances, each of which reached, and ended, at Durango.

Atwood and Mather (1932) named the two oldest, outer moraines Durango moraines and attributed them to the Durango glaciation. The intermediate moraines were assigned to the Bull Lake glaciation and the youngest inner moraines to the Pinedale glaciation (Richmond, 1965; Scott, written communication, 1978). The most definitive study of these moraines was done by Mark Johnson and Mary Gillam, who named the middle two Bull Lake moraines Spring Creek and the inner three Pinedale moraines Animas City (Johnson, 1990; Johnson and Gillam, 1995; Gillam, 1998). In this report, I refer to the Animas City moraines as Pinedale moraines, the Spring Creek moraines as Bull Lake moraines, and the Durango moraines by the same name.

LAKE DURANGO

The Pinedale glacial advance built an end moraine loop at Durango. Glacial retreat from the moraine provided conditions for impoundment of proglacial Lake Durango (Atwood and Mather, 1932) that probably extended about 10 miles upriver. Failure of the morainal dam led to the catastrophic draining of the lake as the Pinedale flood, the fourth and last of the catastrophic floods. Similarly, glacial lakes formed during the Bull Lake glaciation and the Durango glaciation, and their resulting floods are here called the Bull Lake flood (the third catastrophic flood) and the Durango flood (the second catastrophic flood). The first catastrophic flood, here called the early

Pleistocene flood, perhaps had a similar origin, but its age is less certain, and its possible glacial association is unknown.

Lacustrine sediments in Lake Durango have been deeply buried by the aggrading river in the last twenty thousand years, but remnants can be seen on the upstream face of the inner moraine, probably plastered there as push moraine during the latest re-advance of the Pinedale glacier (fig. 4). Lacustrine sediments have also been reported in wells (Guido et al., 2007; Johnson et al., 2017).

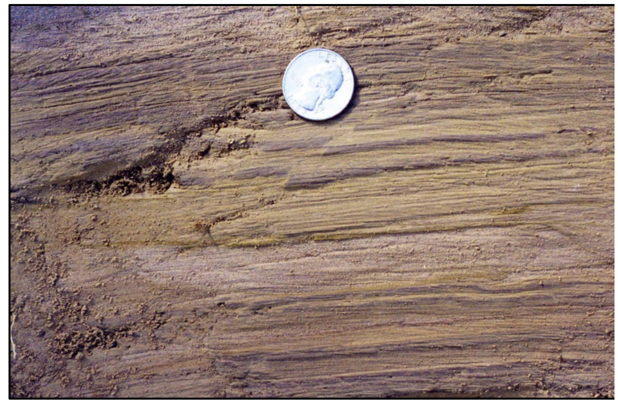


Figure 4—Lacustrine rhythmites from Lake Durango.

A reasonable reconstruction of Pinedale Lake Durango shows the lake impounded an estimated volume of 1,300,000 acre-feet (ac-ft). This estimate is based on a pool level of 6600 ft, slightly below the elevation of the Pinedale 3 end moraine, which created a lake 10.3 mi long, averaging 4600 ft wide, with a maximum depth of 500 ft (fig. 5). This estimate assumes the glacier had retreated 10 mi, the lake filled to the top of the moraine, and no significant lacustrine sedimentation had occurred. An important assumption is lake depth, based on a gas well about 3.3 mi upstream from the moraine that did not reach bedrock after 440 ft (Gillam, 1998, p.59). Even greater depths to bedrock have been reported (490 ft, Guido et al., 2007; 600 ft, Blair et al., 1996, p. 256; and 750 ft, Carroll et al., 1999, cross-section A-A').

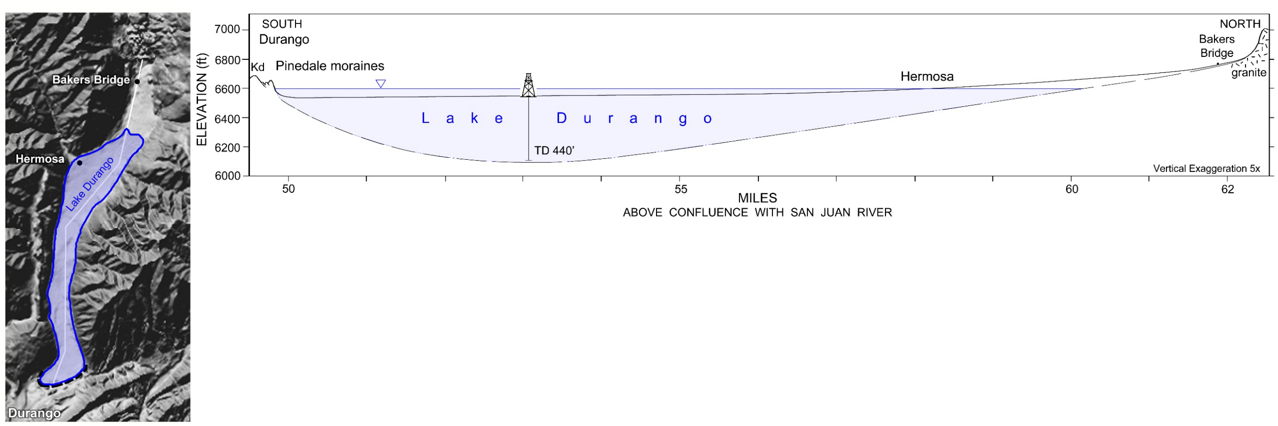


Figure 5—Possible extent of glacial Lake Durango in Pinedale time. Longitudinal cross section shows the lake 500 ft deep and extending 10 mi up valley. Pinedale moraine is slightly above 6600 ft; even today a lake surface at 6600 ft would project to Hermosa, but without significant lacustrine sediments the lake would have extended two miles farther north. Kd, outcrop of Dakota Sandstone beneath the distal Pinedale moraine. Map shows approximate extent of Lake Durango.

For comparison, the volume of Pinedale Lake Durango was greater than the storage capacity of Blue Mesa Reservoir, but less than Navajo Reservoir (table below). It is an order of magnitude greater than Lake Nighthorse, the off-stream reservoir of the Animas River southwest of Durango.

CAPACITY OF SOME COLORADO RESERVOIRS
AND
ESTIMATED VOLUMES OF GLACIAL LAKES

Reservoirs and Glacial Lakes*	Capacity, acre-feet	Reference
Navajo Reservoir	1,708,600	[1]
Glacial Three Glaciers Lake	1,400,000	Brugger et al., 2011
Glacial Lake Durango	**1,300,000**	
Blue Mesa Reservoir	940,800	[2]
Granby Reservoir	539,800	[3]
Glacial Lake Atwood	138,000	Leonard et al., 1994
Lake Nighthorse [reservoir]	123,541	[4]

* Glacial Lake Alamosa was estimated to be much larger (81,000,000 ac-ft; Machette et al., 2013), but it did not cause a catastrophic flood
[1] U.S. Bureau of Reclamation, 2018, Navajo Unit: usbr.gov/uc/rm/crsp/navajo/index.html (updated 11 Oct 2018)
[2] U.S. Bureau of Reclamation, 2018, Aspinall Unit: usbr.gov/uc/rm/crsp/aspinall/index.html (updated 11 Oct 2018)
[3] U.S. Bureau of Reclamation, Description of the Colorado-Big Thompson Project: usbr.gov/aop/cbt/11cbt.pdf (accessed 22 April 2020)
[4] U.S. Bureau of Reclamation, 2020, Animas-La Plata Project: usbr.gov/uc/progact/animas/index.html (updated 26 February 2020)

Lake Durango stored about the same amount of water as the Pinedale glacial lake in the upper Arkansas River valley, Three Glaciers Lake (table above). Three Glaciers Lake drained catastrophically, in less than 22 hr, with an estimated peak discharge of 1,630,000 ft^3/s (cfs) (Brugger et al., 2011).

If Lake Durango had a similar discharge, it would be more than 200 times as great as the average annual peak flow of the Animas River at Durango (7,531 cfs; U.S. Geological Survey, 2020). The actual volume discharged from Lake Durango, however, would have been considerably less, due to the Dakota Sandstone sill at the damsite (fig.5), and because the flood occurred after the initial Pinedale 1 advance (discussed below).

Lake Durango at the time of the Durango glaciation may have been even larger, perhaps 13 miles long and slightly wider. With its morainal dam about a mile farther downstream than the Pinedale moraine, and with an elevation about 400 ft higher, the lake would have extended upstream to the granite bedrock step beyond Bakers Bridge (fig. 5).

The mechanism of morainal dam failure is unknown, but the extent of flood debris downstream indicates the failure was catastrophic; flood boulders were carried more than 50 miles down to the San Juan River in New Mexico. The breach was at about the position of the present channel, because there is no evidence of flood debris outside the end moraine loop on the east bank.

CATASTROPHIC FLOOD DEPOSITS

NATURE OF FLOOD DEPOSITS

The catastrophic floods[1] that tore down the Animas River valley are documented by the flood deposits that remain today. Flood deposits consist of flood gravels and flood boulders. The term *flood gravels*, as used here, refers to gravels deposited by catastrophic floods that have discharges orders of magnitude greater than normal floods from storms or annual peak runoff. Flood gravels are mostly unsorted or poorly stratified masses of gravel containing flood boulders.

The term *flood boulders*, as used here, refers to boulders much larger than those that can be transported by normal floods and thus must have been transported by much larger (catastrophic) floods. There is no definitive size above which a boulder is considered a flood boulder, because the size is a function of the local fluvial regime and hydraulic gradient. For example, along the Animas River about 25 to 30 mi below the moraine area, near the state line, flood boulders are as large as five feet in long dimension, whereas the nominal maximum boulder size in river sediments there is less than two feet, which is an order of magnitude difference in volume and weight. When considering boulder sizes, it is helpful to remember that volume and weight of a round boulder increase as the cube of the boulder diameter. For example, one could hold a one-foot diameter spherical boulder of granite, which weighs 87 pounds, whereas a two-foot boulder weighs 698 pounds.

An exposure of flood gravel is shown in figure 6. Note both the size of the clasts and the lack of sorting. The largest flood boulder in this view is about 5 ft, but flood boulders up to 9 ft are exposed nearby.

Figure 6--Flood gravel on Ewing Mesa 2 mi below end moraine (location fig. 12 mile 46). Mosaic shows Durango flood gravel on top of Durango outwash (lower right, inset). Pick handle is 16.5 inches long.

Flood deposits lie at or near the top of normal outwash (fig. 6, fig. 7), indicating the catastrophic floods were terminal or near-terminal events at the peak of each glacial advance, occurring when glaciers retreated sufficiently to create proglacial lakes behind their abandoned moraines.

[1] "The term catastrophic flooding may be applied to flooding of high magnitude and low frequency…Catastrophic floods may result from… failure of natural or man-made dams", from Preface to "Catastrophic Flooding", edited by Larry Meyer and David Nash, 1987.

Flood deposits have been variably buried over time by loess, side-stream alluvium and alluvial fans, and mass wasting deposits. Exposures are thus rare, and usually only flood boulders are observed. When flood boulders are at the top of a terrace deposit, they are assumed to represent a flood gravel of the age of that terrace. Flood boulders can, however, be lagged from earlier floods, in which case they are at the bottom of the outwash. Because most gravels are exposed along the eroded edges of the terraces, flood boulders along or at the bottom of the slope cannot be used for dating their flood; they attest only to the occurrence of a flood at that location.

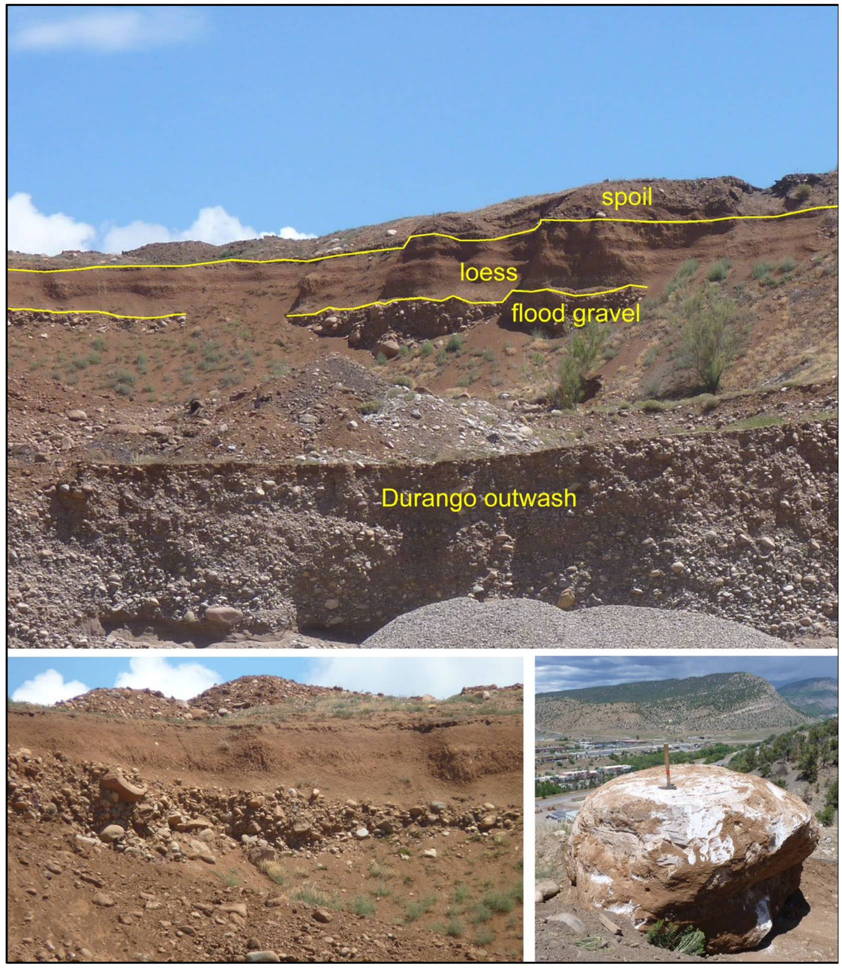


Figure 7—Flood gravel on top of outwash in Crossfire's Helmericks Pit 3 mi below end moraine (location fig. 12 mile 45). Flood boulder extracted from flood gravel is quartzite 11 ft x 10 ft x 5.7 ft.

Flood boulder lithologies represent all the bedrock types exposed above Durango, and occasionally local bedrock is incorporated as well. Granite and quartzite are the most common, probably being selectively retained because they are less prone to be destroyed in the violent discharge than less resistant lithologies.

Floods from the last three glacial advances followed approximately the course of the modern Animas River. The first flood, referred to here as the early Pleistocene flood, had a different course, however, which is poorly constrained; only three small patches of flood gravel remain, and lag flood boulders provide the primary evidence for mapping the route of the flood.

EARLY PLEISTOCENE FLOOD DEPOSITS

Prior to the early Pleistocene flood, the ancestral Animas River ran considerably farther east than the modern river. The ancestral river ran through the Mesa Mountains (fig. 8, 1), based on reworked Animas gravels found near Los Pinos River in New Mexico (Lee, 2025a). The ancestral Animas River migrated or diverted westward to approximately the position of the modern Animas River's eastern divide (Gillam, 1998, fig. 4.14) (fig. 8, 2). Residual patches of gravels high on the crests of the hogbacks southeast of Durango (Gillam, 1998, Pl. 1) attest to these early routes.

At the time of the early Pleistocene flood, the ancestral Animas River still ran through Florida Mesa (fig. 8, 3), based on lag flood boulders found there in the younger Florida Gravel. The river at that

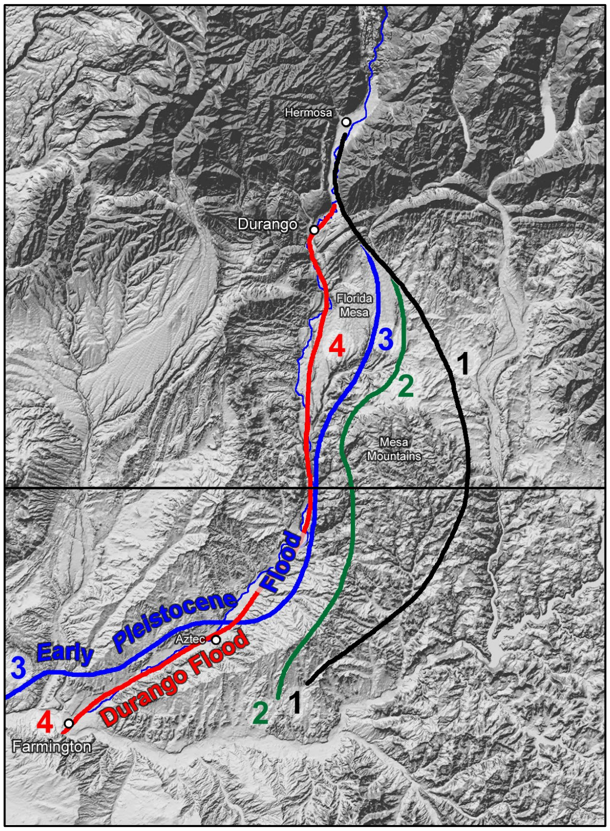


Figure 8—Early routes of the ancestral Animas River were considerably farther east than the modern Animas River. Ancestral Animas River 1 (AAR1) ran through the Mesa Mountains, AAR2 is a route at ~2.2—2.6 Ma estimated by Gillam (1998, fig. 4.14), AAR3 is the approximate route of the early Pleistocene flood, and AAR4 is the route of the Durango flood. The Bull Lake and Pinedale floods followed the present river's course.

time swung to the west to pass through Stateline Narrows, where the only flood gravels from this flood remain (fig. 9).

Figure 9—Early Pleistocene flood gravel at Stateline Narrows. The flood boulders are quartzite and granite, 3½ ft to a little over 4 ft. Inset shows nearby granite flood boulder >58 in. x 49 in. x 44 in. (location fig.12 mile 31). Only three small patches of these flood gravels remain.

In New Mexico, the route of the early Pleistocene flood ran east of the modern river between the border and Aztec, based on one lag flood boulder from the Florida Gravel just upstream from Aztec (fig.10A). This 5-ft granite boulder was carried 34 miles from the moraine area. Similar lag flood boulders beyond Aztec show the flood route had crossed west of the modern river (fig. 8, AAR3), and some were even carried down the San Juan River more than 52 miles from the moraine area (fig. 10B).

The age of the early Pleistocene flood is poorly constrained. From the height of flood gravels above the modern Animas River at Stateline Narrows, Gillam's calculations using incision rates suggested an age of about 1.5 Ma (Gillam, 1998, Tbl. 7.2).

The early Pleistocene flood was clearly a catastrophic flood, as evidenced by the flood gravels and numerous flood boulders carried far downstream. It cannot be demonstrated, however, that it was a glacial outburst flood, because evidence of glaciation that old is lacking. A glacial mechanism is certainly applicable, based on analogy with the three younger floods whose sources were demonstrably glacial outbursts.

DURANGO FLOOD DEPOSITS

Glenn Scott recognized flood deposits at the top of the Durango gravels at several sites (Scott, oral communication, 1978; Moore and Scott, 1981). By the time of the Durango flood, the second of the four catastrophic floods, the ancestral Animas River was flowing very close to the route of the modern river.

Mary Gillam (1998) mapped all the terraces of the Animas River valley using morphostratigraphic names based on relative-age criteria: heights above modern drainages, distribution of terraced remnants, soil development, and – where applicable – associated moraines. She mapped eight major groups of terraces, with the oldest terrace group, T1, Pliocene (?) to the youngest, T8, of post-glacial age.

The early Pleistocene flood corresponds to her T2 terrace group, and the three glacial outburst floods correspond to her T5, T6, and T7 terrace groups, which grade to the Durango, Bull Lake, and Pinedale moraines, respectively.

For simplicity and ease of discussion, this report uses Durango for terrace group T5, Bull Lake for T6, and Pinedale for T7. The Durango flood, the second of the four catastrophic floods, followed approximately the modern Animas River, as can be seen by the distribution of the Durango terrace in figures 11A and 11B.

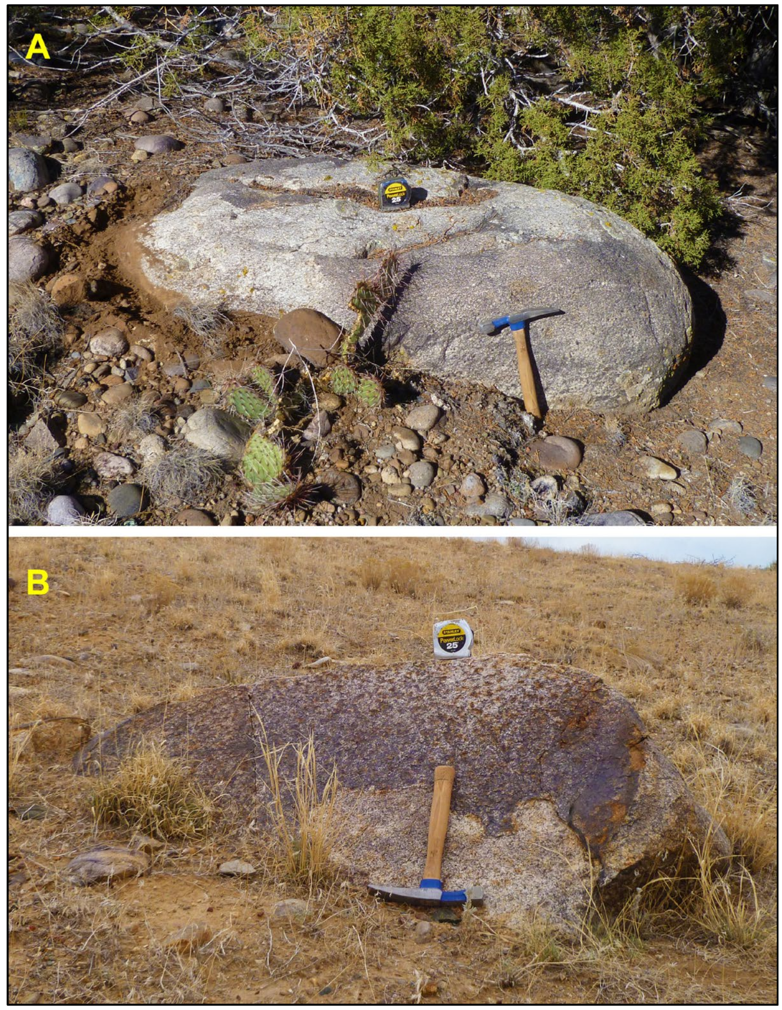


Figure 10—Lag flood boulders from the early Pleistocene flood. (A) lag granite flood boulder in the Florida Gravel was carried 34 miles from the moraine area; exposed dimensions 66 in. x 38 in. x 23 in. (location fig. 12 mile 17); (B) lag granite flood boulder in a gravel older than the Florida Gravel is downstream from Farmington on the San Juan River more than 52 miles from the moraine area; exposed dimensions 57 in. x 36 in. x 21 in. (location fig. 12, 2 mi down the San Juan River).

Flood deposits of the Durango flood are the best documented of all the flood deposits, owing to their almost continuous preservation from Durango to Farmington (fig. 11) and to their position high above the modern Animas River that led to numerous exposures on the high, steep slopes at their terrace edges (figs. 6, 7). Numerous exposures of flood gravels occur in Colorado and numerous flood boulders mark the terrace in New Mexico (fig. 12). Indeed, flood boulders from the Durango flood have the most extensive range of all the floods; flood boulders are exposed in Durango less than two miles from the end moraine, they are at the confluence with the San Juan River, and one is five miles down the San Juan River (figs. 11A, 11B, 12).

The Durango flood resulted in catastrophic aggradation on top of thick outwash deposits just downstream from the moraine (Figs. 6, 7). Farther downstream, however, flood waters were

Figure11A—Map of Animas River terraces in Colorado, generalized from Mary Gillam's detailed map (Gillam, 1998, Pl. 1A), showing flood deposits.

Glacial outburst floods are associated with the three youngest terraces - Durango, Bull Lake, and Pinedale.

Flood gravels from the early Pleistocene flood are preserved only near the New Mexico border, although lag flood boulders from this flood are found on the east part of the Florida Mesa.

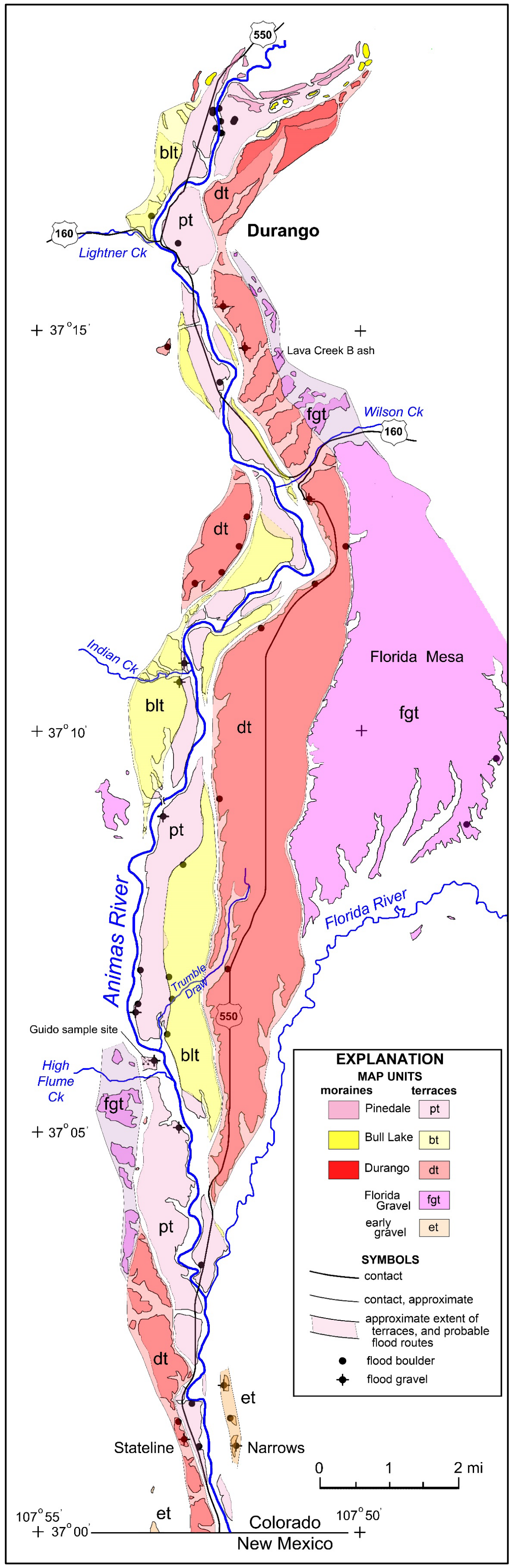
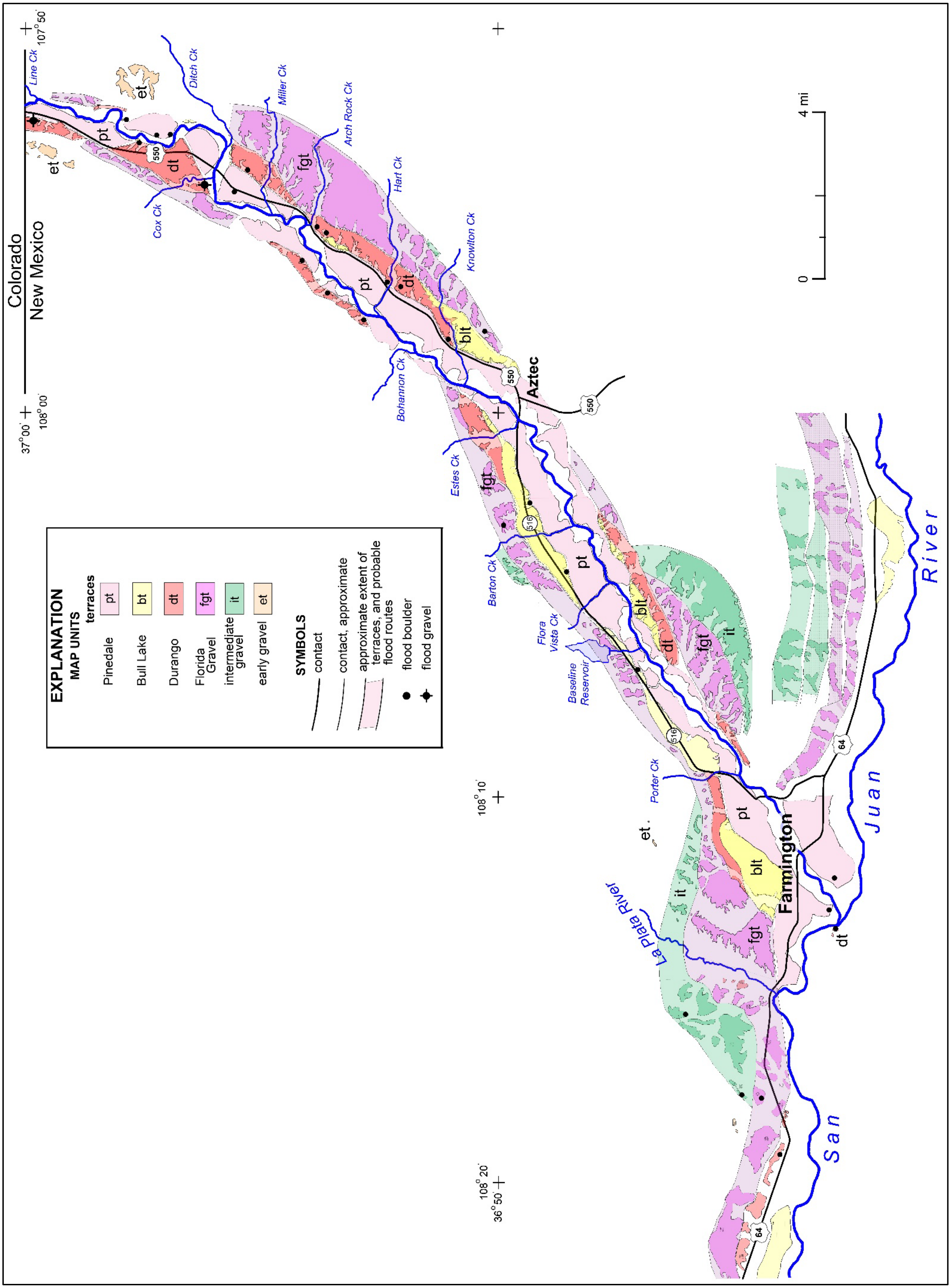


Figure11B—*Next Page*

Map of Animas River terraces in New Mexico, generalized from Mary Gillam's detailed map (Gillam, 1998, Pl. 1B), showing flood deposits. Terraces on the San Juan River, showing by color their age correlation, are by author. Glacial outburst floods are associated with the three youngest terraces - Durango, Bull Lake, and Pinedale. Flood boulders shown in Florida Gravel and the intermediate gravel are lag flood boulders from the early Pleistocene flood.



Colorado
New Mexico
37° 00'
108° 00'
107° 50'
108° 10'
108° 20'
36° 50'
0
4 mi
Line Ck
Ditch Ck
Miller Ck
Arch Rock Ck
Hart Ck
Knowlton Ck
Cox Ck
Bohannon Ck
Estes Ck
Barton Ck
Flora Vista Ck
Baseline Reservoir
Porter Ck
La Plata River
San Juan River
Aztec
Farmington
550
516
64
pt
dt
fgt
blt
et
it
EXPLANATION
MAP UNITS
terraces
Pinedale
pt
Bull Lake
bt
Durango
dt
Florida Gravel
fgt
intermediate gravel
it
early gravel
et
SYMBOLS
contact
contact, approximate
approximate extent of terraces, and probable flood routes
flood boulder
flood gravel

carrying less load and became more erosive. Where flood flow concentrated at Stateline Narrows, no Durango outwash remains, and flood gravels sit directly on bedrock (fig. 13).

The Durango flood was the terminal event of the Durango glaciation. Richmond (1965) considered this glaciation Sacagawea Ridge in age (MIS 16, 621—676 ka), but this is contraindicated by Lava Creek B ash on Ewing Mesa, 3 mi downstream from the Durango end moraine (fig. 14). This air-fall and water-laid ash was deposited on top of the Florida Gravel, which is about 160 ft higher and considerably older than the Durango gravel (fig. 12). The Lava Creek B ash was dated at 639 ka (Lanphere et al., 2002), making the Florida Gravel Sacagawea Ridge age and the Durango flood gravels considerably younger.

Gillam estimated the age of the gravels to be approximately 240 ka (MIS 8) (Gillam, 1998, tbls. 7.1, 7.2). I am unaware of evidence for a coeval glaciation elsewhere in Colorado.

BULL LAKE FLOOD DEPOSITS

Glenn Scott first recognized flood deposits at the top of the Bull Lake gravels at several sites (Moore and Scott, 1981). Flood deposits occur along the full extent of the terrace down to Farmington (figs. 11, 12). The Bull Lake flood, the third of the four catastrophic floods, was confined to a relatively narrow

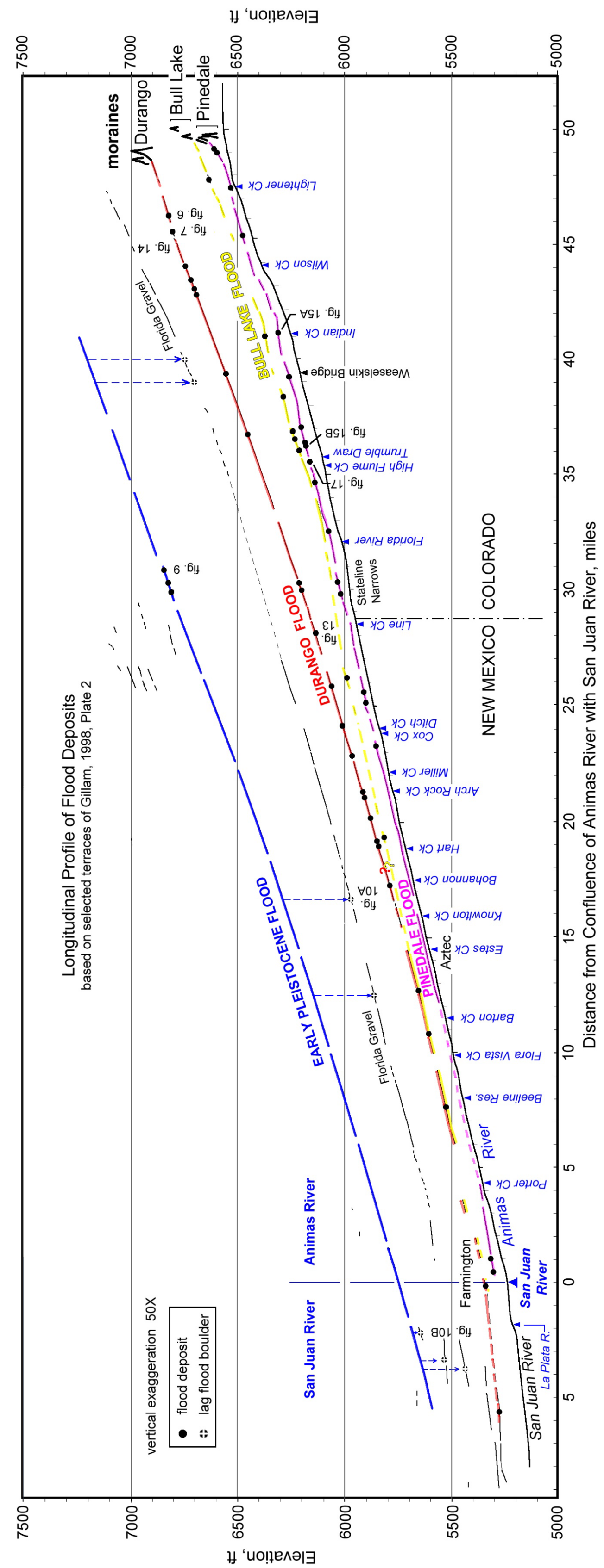


Figure 12—Longitudinal profile of Animas River showing flood deposits on terrace surfaces from Gillam, 1998, Pl. 2; early Pleistocene flood surface and terrace surfaces on the San Juan River by author.

Figure 13—Flood gravels from the Durango flood, including two four-foot granite boulders in center (with tools on top), sit directly on sandstone bedrock just downstream from Stateline Narrows (location fig. 12 mile 28).

valley along the route of the modern Animas River, as shown by the extent of the Bull Lake terrace (fig. 11).

The Bull Lake flood is presumed to be the terminal event of the Bull Lake glaciation (MIS 6). As such, its age would be about 130 ka.

It should be noted that there is ambiguity associated with flood boulders downstream from Aztec; it is uncertain whether a given flood boulder is from the Durango flood or the Bull Lake flood. This ambiguity arises from the unusual merging of the two terraces near Aztec (Gillam, 1998, p. 102) (figs. 11B, 12).

Figure 14—Lava Creek B ash exposed in gravel pit on Ewing Mesa 3 mi below the Durango moraine (location fig. 11A, fig.12 mile 45). The ash, dated at 639 ka, lies on the Florida Gravel, assigning that gravel to Sacagawea Ridge age, 676—621 ka, MIS 16.

PINEDALE FLOOD DEPOSITS

The Pinedale flood, the last of the four catastrophic floods, was restricted to the route of the modern Animas River, and the Pinedale terrace is the narrowest of the floodways (fig. 11). Flood boulders occur in Durango and they reached the confluence with the San Juan River (figs. 11, 12).

Flood boulders from the Pinedale flood are the most commonly seen flood boulders, usually as lag boulders in the channel of the modern Animas River and often excavated in Durango construction sites. At Stateline Narrows, Gillam described bars of flood boulders on the surface of the Pinedale terrace (Gillam et al., 1985; Gillam, 1998, p. 138-141).

Flood gravels are exposed at the river edges of the Pinedale terrace at Indian Creek (fig. 15A, location fig.12 mile 41) and just upstream from Trumble Draw (fig. 15B, location fig.12 mile 36). In these exposures, flood boulders are common, and they occur at the tops as well as within the flood gravels.

Pinedale moraines and outwash at Durango indicate the Pinedale glacial outburst flood was not at the terminal stage of the Pinedale glaciation. Three separate Pinedale moraines are recognized (Gillam, 1998; Carroll et al., 1999). The youngest, inner moraine has a breach width of only 600 ft, barely enough to pass the modern Animas River, the intermediate moraine has only a 1000 ft breach, but the oldest, outer moraine has a breach width of 3500 ft, and only three small patches of its moraine survive (fig. 16).

Additionally, flood boulders are observed only in the oldest Pinedale outwash, and lag flood boulders exposed along the Animas River occur only downstream from the oldest Pinedale moraine (fig. 16).

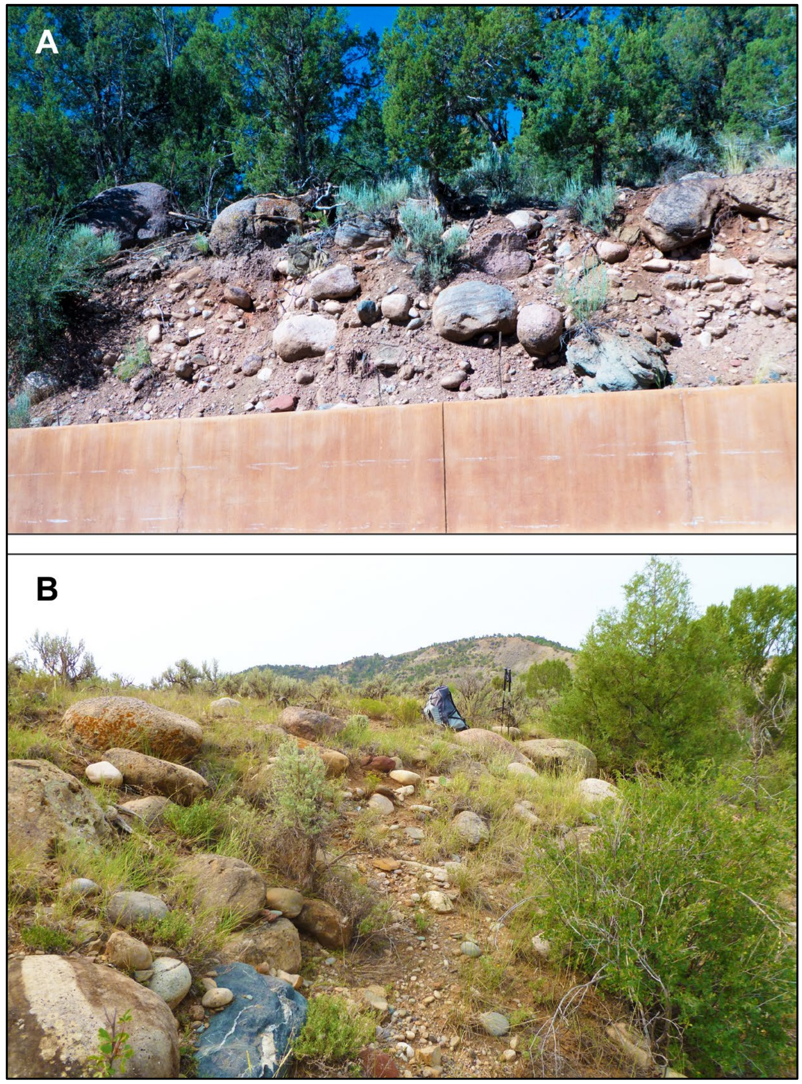


Figure 15—Flood gravels from the Pinedale flood. (A) Roadcut at Indian Creek shows stacked flood boulders; the round one upper left is 5 ft, far upper left partly in shadow is 6—7 ft (location fig. 12 mile 41); (B) Streamcut on Sunnyside Mesa near Trumble Draw; trekking poles between 4-foot granite and 4-foot sandstone flood boulders (location fig. 12 mile 36).

Time of the Pinedale flood can be determined by the exposure age of flood deposits below the dam, dated by Guido et al. (2007). The sample site used by Guido et al. is an abandoned 1930s gravel pit at High Flume Canyon, 15 miles below the Pinedale moraines (Zackry Guido, 2020, written communication) (location figs. 11A, 12 mile 35). The gravel in the pit appears to be a flood gravel; although the exposure is not fresh, no stratification is apparent, and numerous 3 ft to 4 ft boulders are distributed through the deposit, including flood boulders at the very top of the deposit partially buried by loess (fig. 17). Additional support is provided by exposures of flood gravel that bracket this deposit less than a mile upstream and downstream (fig. 11A). Guido et al. (2007) used cosmogenic ^{10}Be to date the surface of the Pinedale terrace here at 19.4±1.5 ka.

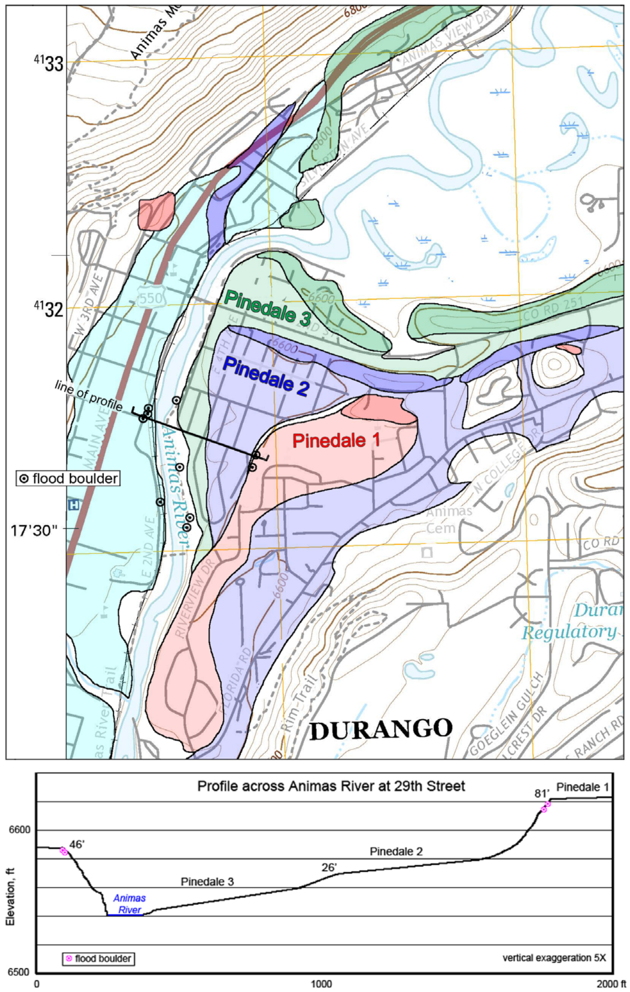


Figure 16—Pinedale moraines, outwashes, and flood boulders. Moraines denoted by darker colors; deposits west of Animas River from Carroll and others (1999), who map the outwashes of Pinedale 2 and Pinedale 3 together, shown in cyan. The two youngest moraines, Pinedale 2 and Pinedale 3, have intact end moraines with only narrow breaches, whereas only three small, widely separated patches of the oldest moraine, Pinedale 1, survive. Flood boulders are found in Pinedale 1 outwash, and lag flood boulders in the Animas River occur only downstream from the projected Pinedale 1 moraine. Flood boulders on west bank probably reworked Pinedale 1 boulders, as suggested by the profile.

Figure 17—Flood gravels exposed in abandoned gravel pit at High Flume Canyon used by Guido et al. (2007) to date Pinedale terrace at 19.4±1.5 ka.

HISTORY OF CATASTROPHIC FLOODS

More than two million years ago the ancestral Animas River flowed east of Durango across Florida Mesa into the area of the Mesa Mountains. At the time of the early Pleistocene flood, about 1.5 Ma, the river still flowed across Florida Mesa before turning south through Stateline Narrows, where flood gravels are found today. In New Mexico, the river ran east of the present course until crossing westward near Aztec. From analogy with the other three known floods, the early Pleistocene flood presumably was a glacial outburst flood, but this cannot be stated with certainty.

Two major terraces exist along the Animas River intermediate in age between those of the early Pleistocene flood and the Durango flood (Gillam, 1998). In neither of these gravels is there any indication of a flood, although both gravels locally contain lag flood boulders from the early Pleistocene flood.

The Durango flood originated at Durango as a glacial outburst flood that ran down the approximate route of the modern Animas River to the San Juan River. Near the moraines, flood gravels were dumped on top of outwash, but as floodwaters concentrated through Stateline Narrows, they stripped away previous outwash and deposited flood gravels directly on bedrock.

The Bull Lake flood and the Pinedale flood were constrained to the modern valley of the Animas River from the moraines to the San Juan River. Flood deposits of both are nearly continuous throughout that reach, with one notable exception: the Pinedale flood scoured out all the Bull Lake flood deposits in the Stateline Narrows (fig. 18).

The Pinedale flood ran down the Animas River about 19,400 years ago. Although the Pinedale glacier re-advanced twice after this flood, it did not cause additional flooding.

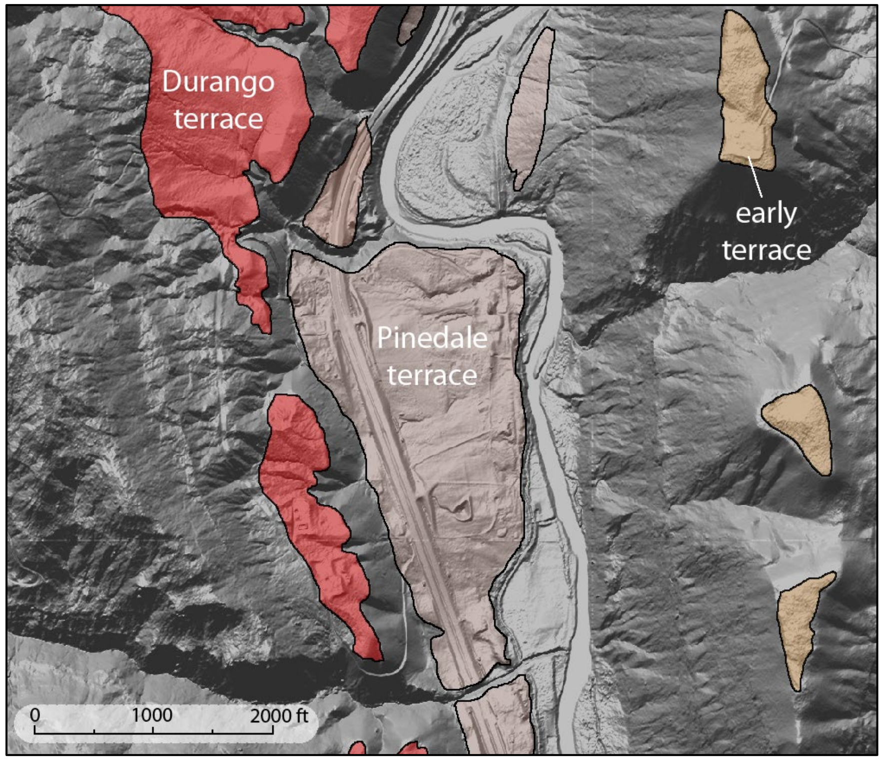


Figure 18—Lidar image of Stateline Canyon shows the highest early Pleistocene terrace, the high Durango terrace, and the floor of the canyon covered by the Pinedale terrace. Bull Lake sediments were flushed from the canyon by the Pinedale flood.

RELATIONSHIP TO OTHER CATASTROPHIC FLOODS IN COLORADO

Catastrophic outburst floods have also been recognized in valleys of the other outlet glaciers from the San Juan icefield: the Uncompahgre River, the Lake Fork of the Gunnison River, the Rio Grande, and Los Pinos River (see figure 3). All the outburst floods were glacial in origin, except perhaps the flood on Los Pinos River, whose origin is unknown. There were also catastrophic glacial outburst floods on the upper Arkansas River.

Uncompahgre River Outlet glaciers from the San Juan icefield flowed down the Uncompahgre River valley 23 miles to Ridgway, Colorado (Lee, 2025b). Similar to the Animas River, three major glacial advances are recognized, with each glacier reaching a maximum extent within a half mile of each other. Suggested ages are Durango, Bull Lake, and Pinedale.

The last two glaciers created proglacial Lake Uncompahgre that ultimately failed catastrophically to produce outburst floods. The Bull Lake flood carried flood boulders at least 23 miles down valley to Montrose, Colorado. The Pinedale flood occurred when the distal proglacial lake's morainal dam was breached at two places, perhaps from overtopping. This flood was smaller than the first, but it carried flood boulders nine miles downriver and diverted the river's course both at Ridgway and at Montrose.

Lake Fork of the Gunnison River Glaciers of the San Juan icefield formed in the circular topographic basin of the Lake City caldera and flowed down the Lake Fork of the Gunnison River (Lee, 2025c). Only the latest glacier, the Pinedale, left a record; the glaciers in the basin converged at Lake City and ran about 22 miles down to the north.

A recessional moraine below Lake City dammed proglacial Lake Hinsdale that was fed by all streams in the basin. Erosion of the morainal dam at the right abutment led to a glacial outburst flood that scoured the outwash train in the valley below. Much of the moraine remained intact, however, and alluvial fan gravels plugged the outlet gap. Lake Hinsdale persisted until failure of the left abutment caused a second outburst flood that tore out most of the moraine. One of the floods left a flood boulder 70 ft above the valley floor.

Rio Grande Pinedale glaciers on the Rio Grande impounded glacial Lake Atwood (Leonard et al., 1994). With a volume of about 138,000 acre-ft, Lake Atwood drained catastrophically twice along ice-bedrock spillways.

Farther down the Rio Grande, the very large glacial Lake Alamosa formed in the closed portion of the San Luis Valley behind a sill of volcanic rock, setting up conditions for a potentially catastrophic flood (Ruleman et al., 2016). Such a flood was suspected but not documented (Machette et al., 2007, p. 76). I see no evidence for such a flood - rather, the alluvial deposits immediately downstream suggest that the incision of the sill and draining of Lake Alamosa was gradual.

Los Pinos River The catastrophic Vallecito flood, perhaps the largest of all the San Juan floods, ran down Los Pinos River and the San Juan River, carrying flood boulders 72 miles to Farmington, New Mexico (Lee, 2025a).

The cause of the flood is unknown, but the most likely origin was a glacial outburst flood. Outlet glaciers in the two main forks, Vallecito Creek and Los Pinos River, merged, and the earlier arrival likely dammed the other fork, creating a glacial lake that lead to conditions for an outburst flood. Evidence for the actual dam is lacking, however, so it is possible the flood had a different origin - perhaps a landslide.

The time of the flood is constrained to early to middle Pleistocene, probably early Pleistocene. The Vallecito flood may have been synchronous with the early Pleistocene flood on the Animas River.

Arkansas River Similar to the Animas River valley, the upper Arkansas River valley experienced three glacial outburst floods, (Lee, 2010, 2019). Their histories differ, however, in both the mechanism of dam formation and synchronicity; Three Glaciers Lake on the Arkansas River formed behind tributary glaciers that dammed the main valley and formed ice dams or ice-and-moraine dams.

The Pinedale glacial outbursts were nearly synchronous, about 19.4 ka for the Animas flood and about 19.0 ka for the Arkansas flood (Schweinsberg et al., 2016). Both Bull Lake floods are presumed to have been terminal events at about 130 ka. The preceding floods, however, occurred at different times: the Durango flood ran about 240 ka, whereas the earliest Arkansas River flood was about 640 ka (Lee, 2019).

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