Glacial Avulsion in Pleistocene Moraine Complexes of the East-central Sierra Nevada, California

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Abstract. During late Pleistocene full glacial periods, glaciers grew out of the Sierra Nevada into the tectonic basins to the east of the range. Morphostratigraphic relations of glacial moraine complexes at 18 canyons indicate that when not confined within their bedrock walls, younger glaciers chose paths different from previous glaciers. The process of a glacier changing its path is here termed glacial avulsion. Glacial avulsion may be caused by several exogenic and endogenic mechanisms: basin infilling/morainic accumulation, tectonic movement, lateral moraine collapse/erosion, differential sediment load, changes in ice volume, gradual shifting of ice flow, glacial surging, or differential melting. The tectonic activity within the eastern Sierra Nevada may be the principal mechanism initiating glacial avulsion as the region has been highly active throughout late Quaternary time. Morphostratigraphic and age relations of moraine complexes determine where and when the avulsion events took place, but do not satisfactorily explain the mechanisms which caused the avulsion.

Moraine relations at Pine Creek suggest two types of glacial avulsion: (1) interglacial fluvial erosion cut several gaps through a right-lateral moraine, allowing a subsequent advance to flow through a water gap that was wide and deep enough to accommodate the ice, (2) another advance flowed on top of low-lying glacial deposits within its valley, raising its base to near the level of the confining lateral moraines and allowing its melt-water and small lobes of ice to flow down the steep outer side of the confining left lateral moraine.

Glacial avulsion appears to be polygenic. Avulsion events identified in moraine complexes may be valuable indicators of climatic change (*i.e.*, stadial/interstadial events) within glacial periods and/or tectonic events. Glacial avulsion causes moraine surfaces to be preserved such that surface exposure dating techniques may be used to determine when glacial periods occurred. Numeric chronologies from glacial deposits in the eastern Sierra Nevada can then be compared with other paleoclimatic and paleohydrological data to better understand how the climate of the western United States has changed through time.

INTRODUCTION

Recognition of the number and extent of glacial events in a mountain valley is one of the basic goals in making correlations of landforms and establishing a glacial chronology. The extent of past glaciers is usually inferred from the positions of lateral and terminal moraines marking former ice margins [Embleton and King, 1975]. New surface-exposure dating (SED) techniques have proven to be a powerful tool for estimating the ages of suites of Pleistocene moraines [Phillips *et al.,* 1990; Dorn *et al.,* 1990, 1991; Dorn and Phillips, 1991]. However, obliterative overlap destroys or obscures the surface expression of older glacial deposits, except in those instances where later ice advances followed a different path [Gibbons *et al.,* 1984]. Because as many as 24 major glaciations may have occurred during Quaternary time, the predicted survival of two to three deposits of different ages is not satisfactory for establishing a Quaternary climatic record from glacial deposits [Gibbons *et al.,* 1984]. To determine a more complete glacial record, areas where Pleistocene glaciers deviated from previous pathways must be located for surficial dating. Glacial deposits in much of the eastern Sierra Nevada offer such a situation.

The Sierra Nevada has been repeatedly glaciated throughout Quaternary time (Table 1) [Wahrhaftig and Birman, 1965]. During full glacial periods, glaciers flowed down mountain canyons into the tectonic basins east of the crest of the range (Figure 1). Upon leaving the mountain canyons, most glaciers apparently did not spread out laterally, so as to

Table 1. Chronologic terminology for late-Pleistocene glacial deposits in the eastern Sierra Nevada. SED techniques are providing numeric age estimates for moraines that agree with relative-age sequences, but not with speculative ages at some canyons.

TABLE 1

CHRONOLOGIC TERM	Chlorine-36 dates from Bloody Canyon *	Rock varnish dates from Pine Creek **	GENERAL MORPHOLOGY	OXYGEN ISOTOPE STAGE ***
TIOGA +	~21 ka	~20 ka	Sharp crested, fresh boulders, typically multiple crests.	2
TENAYA ++	~24 ka	~33 ka	Commonly absent, only slightly greater extent than Tioga moraines.	Early 2 or 3
TAHOE +	~65 ka	~65 ka	Weathered, most massive moraines at most canyons.	4
MONO BASIN ++	~115 ka	—	Rounded crests, weathered, less extensive than Tahoe moraines.	5d
late ROVANA **	~140 ka	~140 ka	Rounded crests, weathered, often less extensive than Tahoe. May be described in literature as Tahoe, as relative dating cannot differentiate.	Late 6
early ROVANA **	~200 ka	~180 ka		Early 6

* Phillips *et al.,* 1990.
** Dorn *et al.,* 1990.
*** Martinson *et al.,* 1987.
\+ Blackwelder, 1931.
\++ Sharp and Birman, 1963.

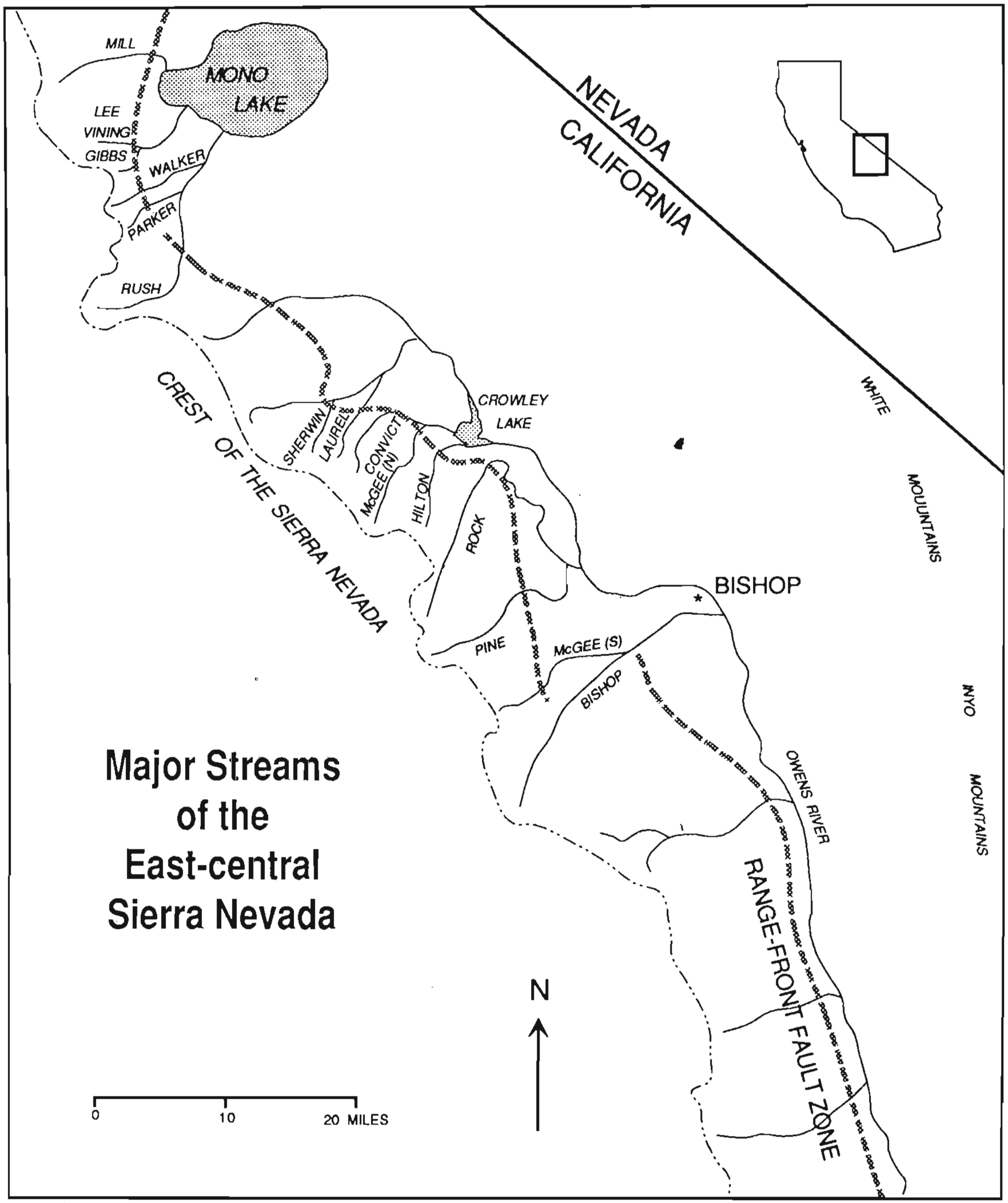


Figure 1. Major streams of the east-central Sierra Nevada that were glaciated during late-Pleistocene time. Labeled creeks show evidence of glacial avulsion.

form fan-shaped piedmont glaciers, but continued their former courses with little apparent change in cross-sectional form. The ice did not expand laterally when no longer confined within the bedrock walls because its sides were heavily loaded with debris, which formed strong retaining walls (lateral moraines), directing the ice downslope and acting to direct subsequent ice advances along the same pathway. However, several canyons in the eastern Sierra Nevada show evidence that some of the younger glaciers were able to breach their lateral embankments and flow in directions different than previous glaciers. The resulting geometrical

TABLE 2

LOCATION	MORAINE RELATIONS	CAUSES SUGGESTED IN THE LITERATURE	REFERENCES	LARGER SIDE OF DRAINAGE
West Walker River	Tahoe right lateral moraine truncates a Mono Basin moraine.	Range-front faulting allows more extensive Tahoe to take different path. Analogous to Bloody Canyon situation.	Clark, 1967	
Robinson Creek	Tahoe right lateral moraine truncates Mono Basin moraines.	No explanation suggested.	Sharp & Birman, 1963 Sharp, 1972	South
Mill Creek (Lundy Canyon)	Younger moraines turn northward, not following greatest gradient.	Stream incision caused by drop in level of pluvial Lake Russell.	McGee, 1885 Russell, 1889 Kesseli, 1941	South
Lee Vining Creek	Younger moraines turn progressively northward.	Greater sediment supply from south side of basin (1,000 X greater than north) repeatedly forced glaciers to north. Stream incision, as at Lundy, may have contributed.	McGee, 1885 Russell, 1889 Kesseli, 1941 Putnam, 1950 Bursik, 1991	South
Gibbs Creek	Older advance flowed southward, younger advance(s) deflected northward to be tributary with Lee Vining Creek.	Change in ice volume.	McGee, 1885 Russell, 1889 Kesseli, 1941	Symmetric
Walker Creek (Bloody Canyon)	Larger Tahoe right lateral moraine truncates pair of Mono Basin moraines, as well as some other older, low moraines near the Tahoe terminus.	About 60 m of faulting, different sized lateral moraines, changes in ice volume, stream incision, differential solar inputs, or the explanation for Parker Creek have all been suggested. All may have contributed.	McGee, 1885 Russell, 1889 Kesseli, 1941 Putnam, 1949 Sharp & Birman, 1963 Clark, 1967, 1972 Burke & Birkeland, 1979 Phillips *et al.*, 1990	South
Parker Creek	Three moraine sets are nested. The present creek has breached the left lateral moraine. The gap may allow next ice advance to flow through.	Youngest ice advance flowed on top of an older, lower moraine, raising its base to near the top of the confining lateral. A larger right lateral forced meltwater to flow over the left lateral and cut through it.	McGee, 1885 Russell, 1889 Kesseli, 1941 Putnam, 1949	South
Rush Creek	Moraines at June and Grant Lakes (separate drainages on the peidmont) came from single bedrock canyon.	The glacier flowed around Diversion Hill (bedrock), splitting it into two distinct tongues of ice.	McGee, 1885 Russell, 1889 Blackwelder, 1931 Kesseli, 1941 Putnam, 1949, 1950	North
Sherwin Creek	Older moraines continue straight out of bedrock canyon. Younger moraines, ending in two well-separated tongues, each outside the older moraines.	The glacier of the younger advance was split and flowed around either side of the older moraines.	Kesseli, 1941	West (left lateral)
Laurel Creek	The oldest moraines, extending straight out of the bedrock canyon, are buried under younger moraines which flowed over the right lateral. These moraines are, in turn, buried under younger moraines of a glacier which turned even farther to the right.	None suggested.	Kesseli, 1941	East (right lateral)
Convict Creek	Older moraines continue straight out of bedrock canyon. Younger moraines break through the left lateral embankment, depositing smaller moraines.	Interglacial fluvial erosion of retaining embankment, or debris from a tributary canyon blocked the canyon, forcing the glacier to flow through the retaining lateral moraine.	Blackwelder, 1929, 1931 Kesseli, 1941 Putnam, 1962 Sharp, 1969	West (left lateral)
McGee Creek (N)	Younger moraines lie on top of older moraines at an abrupt angle.	None suggested, possibly faulting.	Kesseli, 1941 Putnam, 1962	West (left lateral)
Hilton Creek	Older moraines continue straight out of bedrock canyon. Younger moraines lie on top of (>500 m) the right lateral moraine.	None suggested, but today the Tioga moraine is cut by a +20 m fault scarp.	Kesseli, 1941	West (left lateral)

TABLE 2 (continued)

LOCATION	MORAINE RELATIONS	CAUSES SUGGESTED IN THE LITERATURE	REFERENCES	LARGER SIDE OF DRAINAGE
Rock Creek	Older moraines are along a different bedrock canyon than younger moraines in the lowest reaches of the drainage.	Headward erosion by another creek captured lower Rock Creek and diverted subsequent glaciers. The younger canyon is incised over 100 m through granite bedrock.	Kesseli, 1941 Putnam, 1960	East (right lateral)
Pine Creek	See Figures 3 and 4.	See case studies.	Bach *et al.*, 1992 Bach, 1992	South
Horton Creek	Deposits not mapped, but when viewed from afar, cross-cutting moraines can be seen.	Spill moraines following the steepest topographic gradient.	This study	South
McGee Creek (S)	Deposits not mapped, but when viewed from afar, cross-cutting moraines can be seen.	Spill moraines following the steepest topographic gradient.	This study	Symmetric
Bishop Creek	Massive moraine complex has four to ten cross-cutting relations in what may be called a glacial fan.	Unknown, possibly related to tectonic warping.	Bach *et al.*, 1992 Phillips *et al.*, in prep.	South

Table 2. Creeks of the east-central Sierra Nevada with evidence of glacial avulsion.

relationships allow separate glacial pulses to be easily identified [Kesseli, 1941].

Given the position of the moraine complexes on piedmonts, these directional changes in drainage of the glacier are analogous to stream avulsion on an alluvial fan; thus the processes of changing the direction of glacial paths is termed *glacial avulsion*. Avulsion is defined as a generally rapid shift in the channel from one part of the valley to another by development of a new course [Schumm, 1977]. The examples described in this paper are based primarily on field mapping and aerial photograph interpretation of the major and minor features in the moraine complex at Pine Creek [Bach, 1992]. Most of the other canyons discussed in this paper have also been visited by the authors.

Occurrence of Directional Changes of Pleistocene Glaciers

These changes in the direction of the path of the glaciers have long been recognized in the Sierra Nevada (Table 2). The changes in paths of the glaciers offer opportunities to study ice dynamics and apply surface exposure dating and relative age dating to moraines of different ages which would otherwise be buried. Glacial avulsion appears to be relatively common in the east-central part of the Sierra Nevada, identified here along 18 major streams (from north to south): West Walker River, Robinson, Mill (Lundy Canyon), Lee Vining, Gibbs, Walker (Bloody Canyon), Parker, Rush, Sherwin, Laurel, Convict, McGee, Hilton, Rock, Pine, Horton, McGee, and Bishop (Figure 1). Table 2 provides a brief description to the moraine relations at these locations and summarizes published accounts. This activity is not limited to the Sierra Nevada, as it has been reported in Tibet, the Rocky Mountains, Iceland, and Bavaria ([Chengfa *et al.*, 1986]; J. D. Ives, pers. comm., 1991; A. R. Orme, pers. comm., 1991).

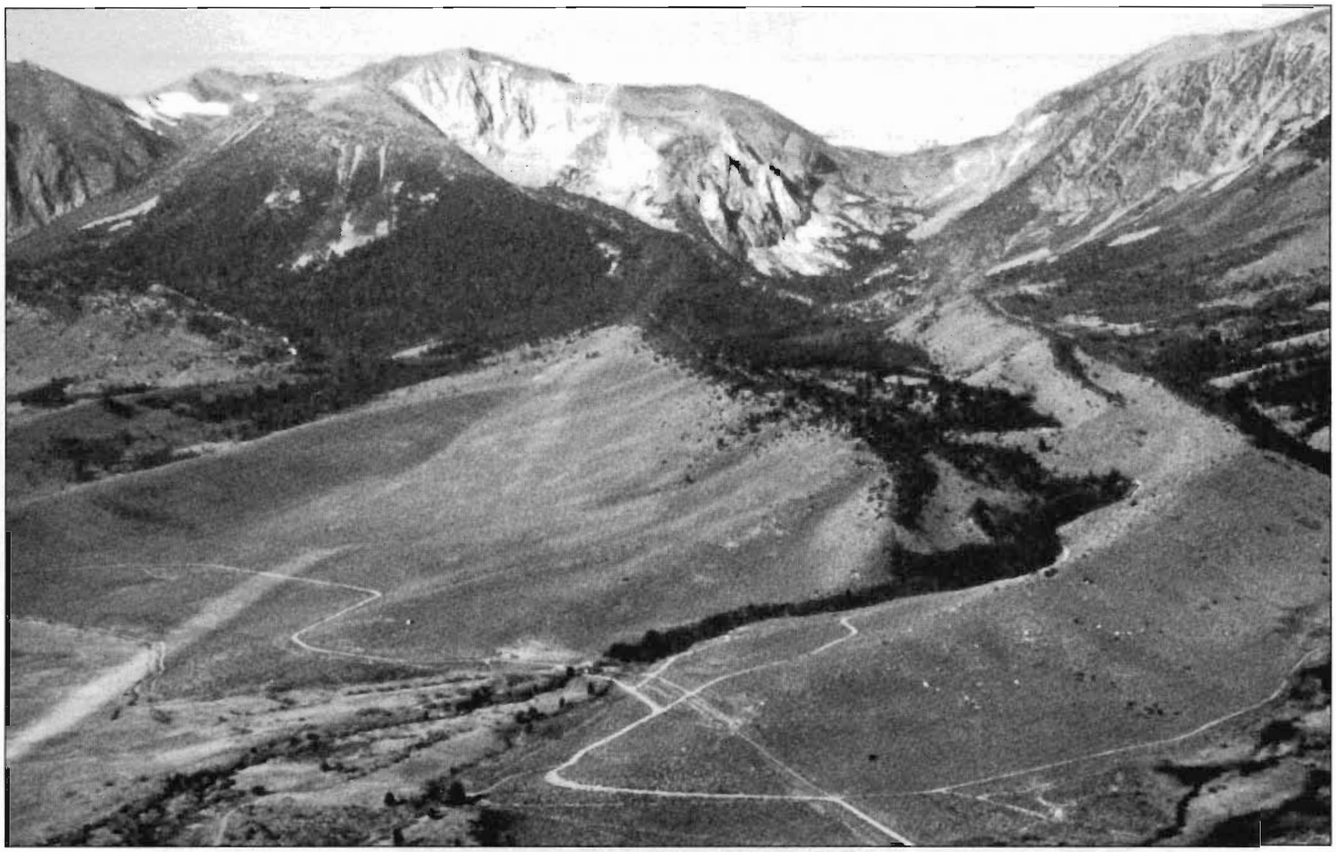


Figure 2. Looking southwest at the moraines along Walker Creek, with Bloody Canyon in the background. The oldest recognized glacial advance flowed straight toward the camera, depositing the small ridges in the center of the photo. The next advance left the two Mono Basin moraines, seen on the left center portion of the photo. The third advance again flowed toward the camera, leaving the tall, tree-covered moraines that cross-cut both sets of older moraines. Younger moraines are nested inside these ridges.

The moraines along Walker Creek offer the most striking example of a directional change and thus have received the most speculation regarding the origin of the avulsion phenomenon (Table 2). The type Mono Basin lateral moraine pair is truncated by a younger Tahoe moraine (ages discussed below) (Figure 2). The Mono Basin glacier flowed approximately straight out of the bedrock canyon, in an east-northeasterly direction. The younger Tahoe glaciers followed a more northeasterly course. The Tahoe-age moraine that cross-cuts the Mono Basin moraines stands about 60 m above the crests of the older moraines. Had the younger advance followed the same path as the older, the older moraines would have been buried and unrecognizable [Sharp and Birman, 1963]. Chlorine-36 analysis of moraine boulder surfaces suggests two changes in direction have taken place along Walker Creek [Phillips *et al.*, 1990]. Two advances at about 140 and 200 ka flowed in a direction similar to the "younger" Tahoe glacier and are now represented only by low eroded moraines projecting from under the Tahoe moraine [Phillips *et al.*, 1990]. These older moraines have previously been interpreted as the ends of the "younger" Tahoe moraines, but geomorphic relations and the chlorine-36 data suggest that they are older [Sharp and Birman, 1963; Burke and Birkeland, 1979]. Following deposition of these older moraines, the glacier (retreated and) shifted farther south, depositing the Mono Basin moraines at about 115 ka, then (retreated and) shifted northward again to deposit the Tahoe and younger moraines [Phillips *et al.*, 1990].

Origins of Changes in Direction of Pleistocene Glaciers

Several plausible mechanisms have been suggested for the causes of the directional changes: basin infilling/morainic accumulation [Russell, 1889; Kesseli, 1941], tectonic movement [Clark, 1967, 1972; Chengfa *et al.*, 1986], lateral moraine collapse/erosion [Blackwelder, 1929; Kesseli, 1941], differential sediment load [Russell, 1889; Kesseli, 1941], changes in ice volume [Kesseli, 1941], gradual shifting of ice flow [Kesseli, 1941], glacial surging or differential solar melting [McGee, 1885]. Since any one, or any combination, of these exogenic and endogenic mechanisms could lead to avulsion, glacial avulsion should be considered polygenic and assessed on a site-by-site basis. Morphostratigraphic and age relations of moraine complexes determine where and when the avulsion events took place, but do not satisfactorily explain the mechanisms which caused the avulsion.

Basin infilling or aggradation can cause the glacier's base to be elevated, in essence changing its potential base level. Basins or canyons can be filled by volcanic flows or airfall (especially into a moraine-dammed lake), lake sedimentation, landslides, or by morainic accumulation. A glacier that advances over an infilled valley may have its base elevated to the level of the retaining lateral moraines. If the flow can be directed toward one of these laterals, the ice will encounter a typically very steep outer slope of the lateral moraine. Given the choice between flowing down its previous valley or flowing down the steeper outer slope of a lateral moraine, the glacier will likely flow down the greater gradient. If the ice advance is sustained, the glacier should erode a deep valley, changing the subsequent stream flow and building a lateral moraine which cross-cuts the old flow direction.

Climate change can result in aggradation of a valley. Huntington's principle suggests that increasing aridity can lead to vegetation reduction and an increase in mass wasting, which would choke streams with sediment [Fairbridge, 1968]. In the Sierra Nevada, increasing aridity would probably be associated with some deglacial periods. Then an increased sediment supply would come not only from increased mass wasting, but also from the sediment that had been stored in the glacier. Aggradation would result from glaciofluvial processes and the deposition of ground and recessional moraines during deglaciation. During deglaciation, proglacial streams would become choked with excessive loads supplied to them from the melting glaciers, and aggradation would result as the stream built up its alluvial bed. Therefore, a change in climate from a glacial to interglacial period would set in motion a series of processes which would prepare a valley for glacial avulsion. The valley bottom could be elevated to such an extent that an avulsion could result during the next glacial advance.

The tectonic activity along the eastern part of the Sierra Nevada may provide the principal mechanism initiating glacial avulsion. The region has been tectonically active throughout Quaternary time [Martel *et al.*, 1987], and most of the piedmont glaciers crossed faults (Figure 1). Vertical range-front faulting down drops the downstream moraines. Significant offset could allow subsequent glacial advances to cross the fault near the level of lateral moraine crests [Clark, 1972]. The younger advance would either override the older moraines; or, if flow tended toward one side, the glacier could cross the lateral moraine. Displacement of glacial material of Mono Basin and Tahoe age at Bloody Canyon is about 60 m (197 ft), which may have caused the avulsion there [Clark, 1972]. Currently no moraines show enough fault displacement to allow an avulsion to occur. However, the rate and location of late-Quaternary faulting along the eastern Sierra Nevada has been shown to be quite variable and could result in significant offset during an interglacial period at a single location [Clark, 1972; Martel *et al.*, 1987].

Strike-slip fault movement would provide a clear-cut mechanism for avulsion. A laterally offset stream would clearly provide a new pathway for a readvancing glacier. An active glacier in the Kunlun Pass region of Tibet is deflected about 70 m (229 ft) by a left-lateral fault, and one of its lateral moraines is offset by over 100 m (328 ft) [Chengfa *et al.*, 1986]. This region is suggested to have an average Quaternary slip rate of at least 11 mm/yr and an astounding minimum rate of 20 mm/yr during the Holocene [Chengfa *et al.*, 1986]. Although the average slip rates for the eastern Sierra Nevada during the late-Quaternary are not as large (~0.3 mm/yr) and the horizontal movement component is minimal [Martel *et al.*, 1987], the tectonic activity there is likely to be responsible for some avulsion events.

Valley glaciers ultimately respond to gravity, thus will typically flow down the greatest topographic slope [Russell, 1889; Sugden and John, 1976]. Normally this is down the valley that previous glaciers followed; however, any stream incision which has cut a large and deep enough canyon can provide a new pathway for subsequent glacier advances. Confining lateral moraines effectively direct glacial ice, but they are susceptible to erosion, which can open a pathway for a subsequent glacier to follow. Stream erosion on the outside of moraines is typically not possible because moraine slopes are too short to permit the establishment of long-lived streamflow [Kesseli, 1941]. Supraglacial discharge can cut gullies through lateral moraines, but generally are not long lived enough to cut a channel large enough to redirect the ice. Subsequent glacial deposition often refills the breached area with till. It is conceivable, however, that the repeated reoccupation of a supraglacial stream flowing over a lateral moraine could excavate a valley large enough to allow an avulsion.

Several saddles in the lateral moraines at Pine Creek suggest supraglacial erosion. The saddles are always associated with gullies on the outer slope of lateral moraines. Some of the gullies are of impressive size, yet do not have tributaries, suggesting they were formed by stream flow over the top of the moraine and not by headward erosion. The gaps may have been produced by collapse, but analysis of sediments in the channel bottom show a high percentage of large, well-rounded clasts, indicative of powerful glaciofluvial activity, rather than exposure by less-powerful colluvial or fluvial erosion processes [Bach, 1992].

Once a lateral moraine has been breached, a sustained stream flow must exist in order to cut a canyon large and deep enough to redirect subsequent ice. The time required to permit enough erosion would be considerable and could probably only be accomplished during an extended interglacial period [Blackwelder, 1929; Kesseli, 1941]. Several aforementioned gullies at Pine Creek removed a considerable amount of material from one lateral moraine, yet a subsequent readvance followed the previous pathway. Indeed, today both McGee (N) and Parker Creeks have breached their lateral moraines, but the gaps which have been cut may not be large enough to redirect the ice flow during the next advance.

A reduction in the base level of a stream might cause stream incision into the valley fill. Lee Vining and Mill creeks in the Mono Basin both built large deltas into pluvial Lake Russell [Russell, 1889]. During a subsequent interglacial, the lake level dropped, resulting in the streams cutting relatively wide and deep valleys through their deltas. Today there is a similar incision seen along lower Rush Creek. When ice readvanced at Mill Creek, it followed the valley excavated by the interglacial erosion, deflecting the ice toward the north away from the apparent steepest down-slope gradient [Kesseli, 1941].

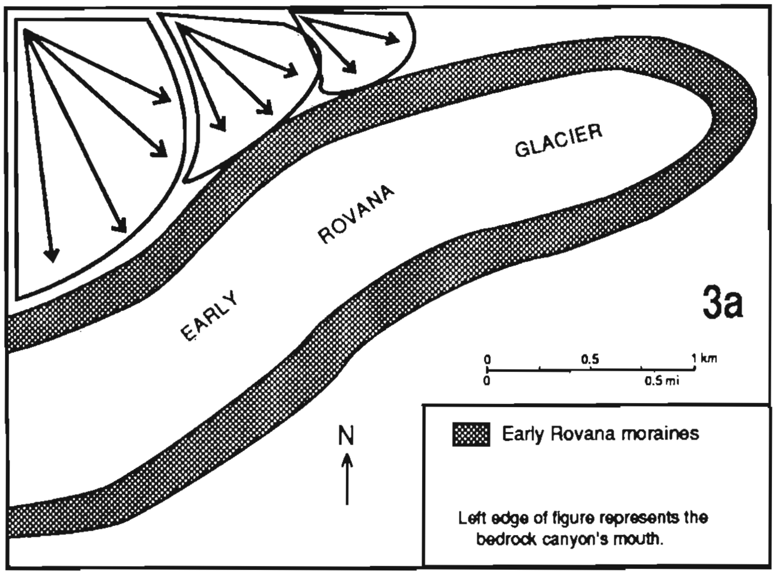
The direction of flow of a glacier could be directed by marked inequalities in the magnitude and strength of the enclosing embankments, deflecting the flow toward the weaker side [Russell, 1889]. Russell [1889] suggested that the side of a glacial canyon that receives more sediment from tributary canyons will form a larger lateral moraine and help to push the glacier in the opposite direction. In the Sierra Nevada, glaciers tend to form on north-facing slopes, while south-facing slopes are commonly free of ice. During Pleistocene time, larger glaciers would grow on the south sides of major drainages, contributing a larger amount of sediment to the south side lateral moraine (right lateral) than would be provided to the north side lateral moraine. The larger right lateral moraines would cause most Sierra Nevada glaciers to be diverted to the north, opposite of the larger moraine. Indeed, seven of the eight streams where avulsion occurred and which have a general east-to-west orientation, have more tributaries and/or a larger proportion of their drainage basins on the south side (Table 2). Of these seven drainages, six have a considerably larger right lateral moraine complex.

Marked asymmetry of lateral moraines may force the glacial creek to be issued from the side of the smaller lateral moraine. If the asymmetry is great enough, the creek may be issued from the extreme side of the terminus and, if given the chance, will flow down the steeper outer slope of the confining lateral moraine. Once established, the main glacial creek may cut a significant gully through the lateral moraine, as presently seen at Parker Creek. A sufficient amount of time must elapse from when the gully is cut and the advance of the subsequent glacier to allow a gap large enough to deflect the glacier [Kesseli, 1941].

Many of the once-independent valley glaciers in the eastern Sierra Nevada gave way to ice caps as the ice divide migrated westward during full glacial periods [Wahrhaftig and Birman, 1965]. For example, ice with a depth of more than 60 m (197 ft) flowed over cols from the western slope into the Pine Creek Basin. The change from a valley glacier to an ice cap fed outlet glacier would result in changes in ice flow dynamics. The types and amounts of till deposited and the morphology of the resulting moraines depends on the moraine's location in relation to the water/ice divide position [Sugden and John, 1976; Garnes, 1979]. A larger volume of ice could raise the surface of the glacier above the confining lateral moraines, allowing supraglacial breaching or the ice to find a low saddle through which to flow.

If the geometry of the moraines and glacier are conducive, a glacial surge may be able to push ice through or over a confining lateral moraine. Such a situation may have occurred at Pine Creek, where the bedrock canyon is oriented to the northeast. When the glacier entered the piedmont, the alluvial fans issuing from the north forced the glacier to turn eastward. If a glacier surged when its terminus was at or near the bend, the ice may have been forced over the confining lateral moraine.

McGee [1885] suggested that solar radiation would melt the exposed northern side of an east-west flowing glacier, allowing the south side of the glacier to flow faster and deflect the ice to the north. The effects of insolation are slow and continuous and would result in a gradual turning, not the abrupt change in direction seen at most canyons [Russell, 1889; Kesseli, 1941]. Insolation may exert only a small force in controlling the direction of flow of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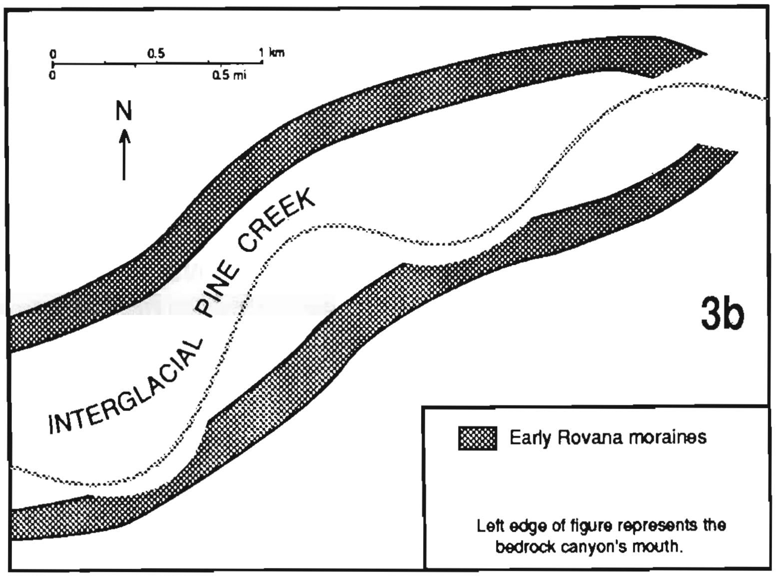
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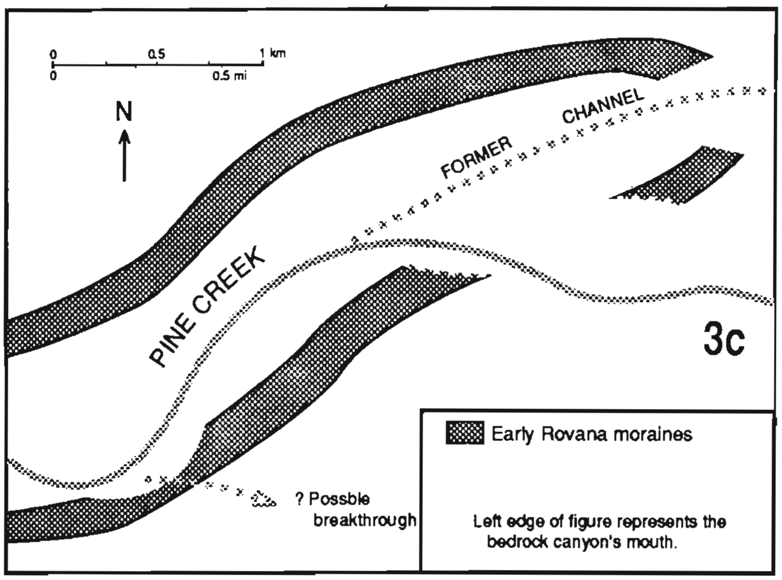
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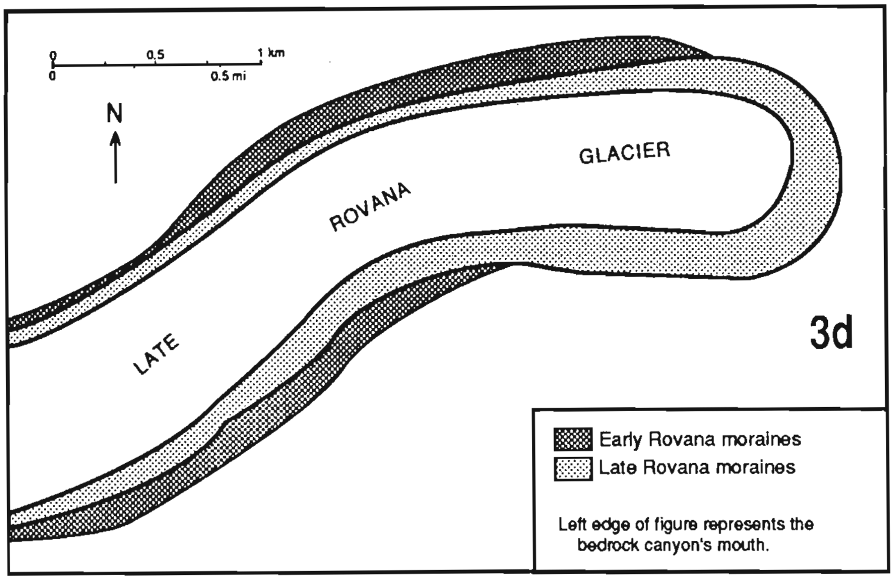


Figure 3. Rovana avulsion sequence at Pine Creek. The extent of the glacial advances is reconstructed from moraines and moraine remnants dated by rock varnish and soil development [Dorn et al., *1990; Bach, 1992]. Facing page:* ***(3a)*** *The earliest recognized glacial advance at Pine Creek deposits its moraines.* ***(3b)*** *Subsequent interglacial erosion of lateral moraines.* ***(3c)*** *Pine Creek erodes gap(s) through the right lateral moraine. This page:* ***(3d)*** *The next glacial advance flowed through the water gap, creating the cross-cutting relationship seen today.*

a valley glacier, but it is a continual force that may contribute to the avulsion process.

CASE STUDIES OF AVULSION

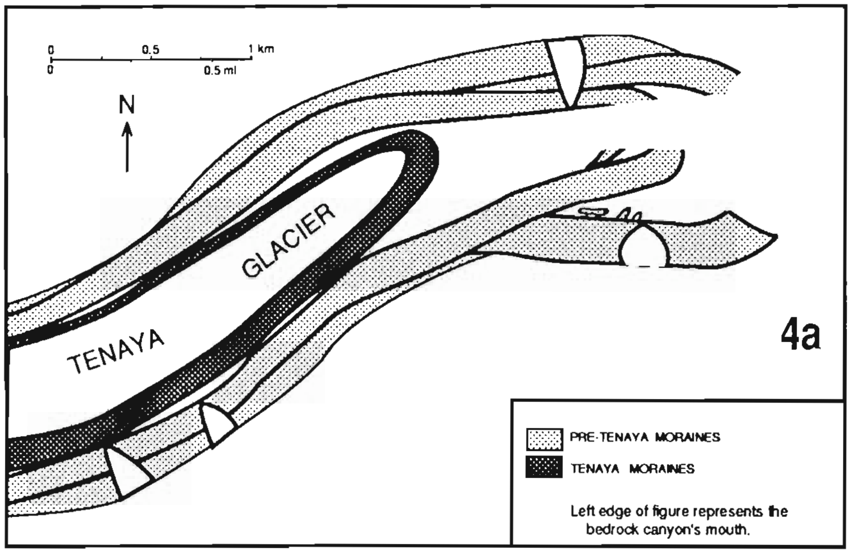
Moraine relations at Pine Creek suggest two types of glacial avulsion: (1) interglacial fluvial erosion cut a gap through a right lateral moraine, allowing the next glacial advance to flow through the water gap (Figure 3); (2) a glacier deposited a low moraine or series of low moraines and a large right lateral moraine. The next ice advance was lifted and forced to the opposite side. Meltwater and small lobes of ice flowed over the confining lateral embankment, but did not cause enough erosion to allow the next advance to flow through (Figure 4).

The early Rovana glacier extended out of the Pine Creek bedrock canyon at least 4 km (2.48 mi) onto the piedmont (Figure 3a). Remnants of a right lateral moraine are rock varnish cation-ratio dated at 180 ka [Dorn *et al.*, 1990]. The orientation of the Pine Creek canyon caused the glacier to move in a northeasterly direction; however, debris cones and alluvial fans extending off Wheeler Ridge deflected the lower course of the glacier to the east. Following deposition of the early Rovana moraines, the ice retreated at least part way up the bedrock canyon.

During glacial retreat and the subsequent interglacial period, fluvial processes eroded the inner flanks of the early Rovana moraines, oversteepening them in places (Figure 3b). This could have allowed Pine Creek to cut through the right lateral moraine to follow a more easterly path (T. Chinn, pers. comm., 1990) (Figure 3c). Fluvioglacial processes are particularly potent in destruction of moraines as a glacier retreats [Sugden and John, 1976]. Today, Pine Creek is oversteepening the inner flank of the left lateral moraine near the town of Rovana.

At about 140 ka, the late Rovana glacier was the next to leave distinctive glacial deposits at Pine Creek [Dorn *et al.*, 1990]. The glacier flow was confined within the early Rovana moraines for about 2 km from the canyon, then abruptly turned due east, flowing through the gap eroded by the interglacial creek (Figure 3d). The moraine sequence at Convict Creek has been interpreted in a similar fashion by Blackwelder [1929, p. 171]:

> Near Convict Lake, moraines of two distinct epochs are readily distinguished by the notable differences in the effects of weathering and erosion. During the interglacial epoch the creek excavated a spacious valley in the north flank of the largest moraine. Being deflected by this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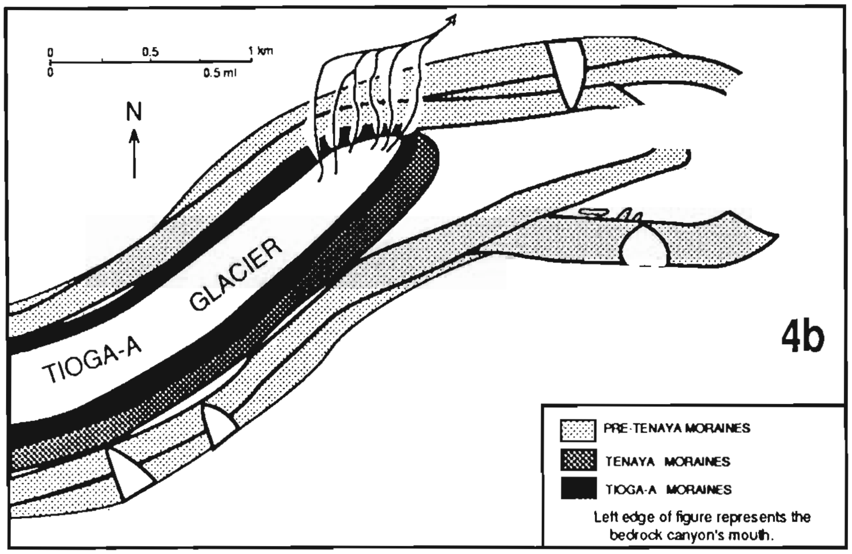
PRE-TENAYA MORAINES
TENAYA MORAINES
Left edge of figure represents the bedrock canyon's mouth.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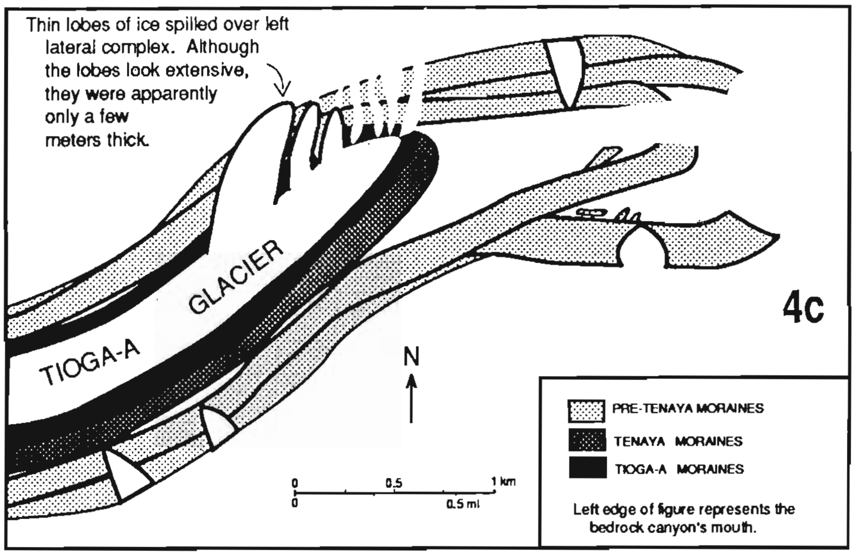
TIOGA-A MORAINES
Left edge of figure represents the bedrock canyon's mouth.


Thin lobes of ice spilled over left lateral complex. Although the lobes look extensive, they were apparently only a few meters thick.
TIOGA-A GLACIER
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0
0.5 mi
PRE-TENAYA MORAINES
TENAYA MORAINES
TIOGA-A MORAINES
Left edge of figure represents the bedrock canyon's mouth.

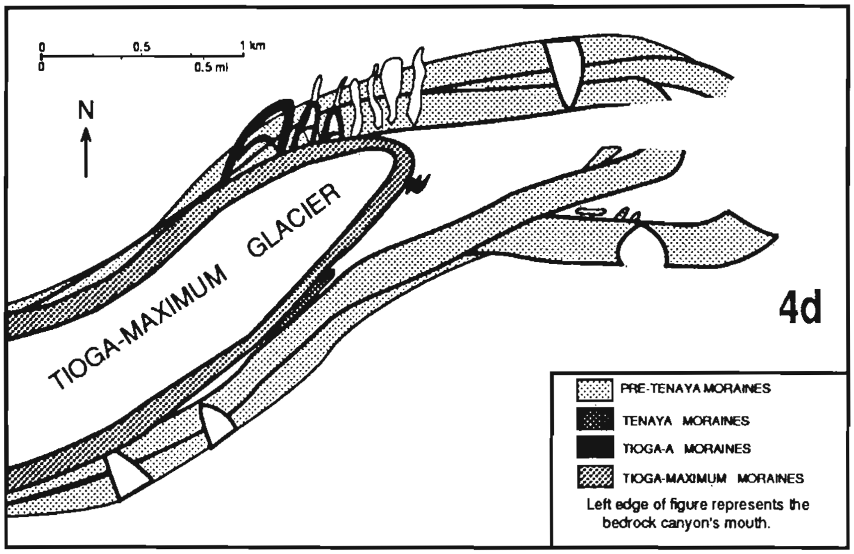

Figure 4. Tioga avulsion sequence at Pine Creek. The extent of the glacial advances is reconstructed from moraines and moraine remnants dated by radiocarbon from rock varnish and a conventional radiocarbon date (19.6 ka) on peat found within the till matrix of the Tioga-maximum moraine [Dorn et al., *1990; Bach, 1992]. Facing page:* ***(4a)*** *Tenaya advance was confined within the older lateral moraines.* ***(4b)*** *A subsequent glacial advance flowed on top of the Tenaya moraines, allowing meltwater to flow over the retaining left lateral moraine.* ***(4c)*** *Small lobes of glacial ice flowed down gullies cut on the outer side of the left lateral moraine. This page:* ***(4d)*** *The Tioga-maximum glacier, which had a larger body of ice, followed the previous valley.*

valley, the later glacier pushed its way entirely through the old moraine and built a conspicuous terminal lobe outside the latter.

Evidence of an attempted glacial avulsion is seen in younger deposits at Pine Creek, where two major glaciers extended down-slope and stagnated at about the same location. At 33 ka, the Tenaya glacier, confined within the older lateral moraines, extended just past 3 km down valley (Figure 4a) (R. I. Dorn, unpub. data). The next glacier advance, Tioga-a, flowed over the top of the Tenaya terminal moraine and was deflected northward into the Tahoe left lateral (Figure 4b). The meltwater issued from this glacier flowed down the steep outer side of the Tahoe left lateral rather than down the previous channel. The Tahoe left lateral moraine in this region is low and sagging when viewed in a skyline profile. Small lobes of the Tioga-a ice also flowed over the Tahoe left lateral moraine (Figure 4c). The small lobes of ice deposited small (1- to 2-m-high) 'spillover' moraines that are dated at about 21 ka [Dorn *et al.*, 1990]. The features are considered to be of glacial origin, rather than debris flow levees for the following reasons: (1) the features are wide (10 to 30 m) loops, debris flows are typically thin, and (2) the features occur about one-third of the way down the slope; had debris flows been initiated on these steep slopes (~13°) they would have continued to at least the bottom. There are at least two sets of spillover moraines on the outer side of the Tahoe moraine (Figure 4d).

Had the Tioga-a stadial continued, the ice may have been able to burst through the Tahoe left lateral, and Pine Creek would presently be flowing to the north of the left lateral moraines. However, the Tioga-a stadial ended, and the ice front retreated from this position. At about 19.5 ka, the Tioga-maximum glacier advanced, following the previous valley and deposited a moraine across the aforementioned gullies and spillover moraines [Bach, 1992] (Figure 4d). All subsequent glacial activity has been contained within these moraines.

SUMMARY AND CONCLUSIONS

The eastern Sierra Nevada has been, and continues to be, a highly active geologic region. This activity is manifested within the Pleistocene glacial deposits of the range. Glacial avulsion is the act of a glacier changing its course and appears to be polygenic. Glacial avulsion produces surfaces of multiple ages in juxtaposition which may aid chronology construction, while moraines in drainages without avulsion are superposed (buried) and can not be easily identified or dated.

Avulsion events identified in moraine complexes may be valuable indicators of climatic change, as avulsion probably requires a long interglacial period for changes of large enough magnitude to alter the direction of subsequent ice flow. Timing of the avulsion can be determined using surface-exposure dating techniques, allowing comparison to other paleoclimatic and paleohydrological data which may enable the trigger of the avulsion event to be identified [Phillips *et al.*, 1990]. Avulsion appears to be more common in the Sierra Nevada than previously recognized. Some moraine complexes that have been studied may need to be reevaluated due to the dynamic behavior of the glaciers during the late Quaternary. Continued avulsion over a long period of time would result in the formation of a glacial fan, as seen at Bishop Creek where as many as seven avulsions are recorded in the massive moraine complex [Phillips *et al.*, in prep.]. Abandoned paleochannels and paleovalley fills created by avulsion could be of economic importance, as they could contain placer deposits or provide conduits for groundwater.

REFERENCES

Bach, A. J., Pleistocene glacial history of Pine Creek, east-central Sierra Nevada, California, M.S. thesis, 287 pp., Univ. Calif., Davis, 1992.

Bach, A. J., R. I. Dorn, D. L. Elliott-Fisk, and F. M. Phillips, Paleohydrological and paleoclimatological implications of glacial moraine complexes from Pine Creek, Bloody Canyon and Bishop Creek, eastern Sierra Nevada, [abst.] in *The History of Water: Eastern Sierra Nevada, Owens Valley, White-Inyo Mountains,* edited by C. A. Hall, Jr., V. Doyle Jones, and B. Widawski, pp. 440-441, University of California, White Mountain Research Station, *Symp. Vol. 4,* 1992.

Blackwelder, E., Moraines of Convict Lake Glacier [abst.], *Geol. Soc. Am. Bull., 40,* 171, 1929.

Blackwelder, E., Pleistocene glaciation in the Sierra Nevada and Basin Ranges, *Geol. Soc. Am. Bull., 42,* 865-922, 1931.

Burke R. M. and P. W. Birkeland, Reevaluation of multiparameter relative dating techniques and their application to the glacial sequence along the Eastern escarpment of the Sierra Nevada, California, *Quat. Res., 11,* 21-51, 1979.

Bursik, M., Relative dating of moraines based on landform degradation, Lee Vining Canyon, California, *Quat. Res., 35,* 451-455, 1991.

Chengfa, C. and 26 others, Preliminary conclusions of the Royal Society and Academia Sinica 1985 geotransverse of Tibet, *Nature, 323,* 505-507, 1986.

Clark, M. M., Pleistocene glaciation of the drainage of the West Walker River, Sierra Nevada, California, Ph.D. diss., 130 pp., Stanford University, 1967.

Clark, M. M., Range-front faulting: cause of anomalous relations among moraines of the eastern slope of the Sierra Nevada, California [abst.], *Geol. Soc. Am. Abst. Progs., 4,* 137, 1972.

Dorn, R. I., T. A. Cahill, R. A. Eldred, T. E. Gill, B. H. Kusko, A. J. Bach, and D. L. Elliott-Fisk, Dating rock varnishes by the cation ratio method with PIXE, ICP, and the electron microprobe, *Int. J. PIXE, 1,* 157-195, 1990.

Dorn, R. I., and F. M. Phillips, Surface exposure dating: review and critical evaluation, *Phys. Geog., 12,* 303-333, 1991.

Dorn, R. I., F. M. Phillips, M. G. Zreda, E. W. Wolfe, A. J. T. Jull, D. J. Donahue, P. W. Kubik, and P. Sharma, Glacial chronology of Mauna Kea, Hawaii, as constrained by surface-exposure dating, *Nat. Geog. Res. and Explor., 7 (4),* 456-471, 1991.

Embleton, C. and C. A. M. King, *Glacial geomorphology, Vol. 1,* 573 pp., Edwin Arnold, London, 1975.

Fairbridge, R. W., Terraces, fluvial-environmental controls, in *Encyclopedia of geomorphology,* edited by R. W. Fairbridge, pp. 1124-1138, Reinhold Book Corp., New York, 1968.

Garnes, K., Weichselian till stratigraphy in central South-Norway, in *Moraines and Varves,* edited by A. A. Schluchter, pp. 207-222, Balkema, Rotterdam, 1979.

Gibbons, A. B., J. D. Megeath, and K. L. Pierce, Probability of moraine survival in a succession of glacial advances, *Geology, 12,* 327-330, 1984.

Kesseli, J. E., Changes in the courses of some Pleistocene glaciers and their relation to interglaciation, *Univ. Calif. Pubs. Geog., 6,* 327-346, 1941.

Martel, S. J., T. M. Harrison, and A. R. Gillespie, Late-Quaternary vertical displacement rate across the Fish Springs Fault, Owens Valley Fault Zone, California, *Quat. Res., 27,* 113-129, 1987.

Martinson, D. G., N. G. Pisias, J. D. Hays, J. Imbrie, T. C. Moore, Jr., and N. J. Shackleton, Age dating and the orbital theory of the Ice Ages: development of a high-resolution 0-300,000-year chronostratigraphy, *Quat. Res., 27,* 1-29, 1987.

McGee, W. J., On the meridional deflection of ice streams, *Am. J. Sci., 3rd series, 29,* 386-392, 1885.

Phillips, F. M., M. G. Zreda, S. S. Smith, D. Elmore, P. W. Kubik, and P. Sharma, Cosmogenic chlorine-36 chronology for glacial deposits at Bloody Canyon, Eastern Sierra Nevada, *Science, 248,* 1529-1532, 1990.

Phillips, F. M., R. I. Dorn, M. G. Zreda, and others, Glacial chronology of Bishop Creek, *Geol. Soc. Am. Bull.,* (in prep.).

Putnum, W. C., Quaternary geology of the June Lake District, California, *Geol. Soc. Am. Bull., 60,* 1281-1302, 1949.

Putnum, W. C., Moraine and shoreline relationships at Mono Lake, California, *Geol. Soc. Am. Bull., 61,* 115-122, 1950.

Putnum, W. C., Origin of Rock Creek and Owens River gorges, Mono County, California, *Univ. Calif. Pubs. Geol., 34,* 221-280, 1960.

Putnum, W. C., Late Cenozoic geology of McGee Mountain, Mono County, California, *Univ. Calif. Pubs. Geol., 40,* 181-218, 1962.

Russell, I. C., Quaternary history of Mono Valley, California, *U.S. Geol. Surv. 8th Ann. Rept.,* pp. 261-394, 1889.

Schumm, S. A., *The fluvial system,* 338 pp., John Wiley and Sons, New York, 1977.

Sharp, R. P., Semiquantitative differentiation of glacial moraines near Convict Lake, Sierra Nevada, California, *J. Geol., 77,* 68-91, 1969.

Sharp, R. P., Pleistocene glaciation, Bridgeport Basin, California, *Geol. Soc. Am. Bull., 83,* 2233-2260, 1972.

Sharp, R. P. and J. H. Birman, Additions to classical sequence of Pleistocene glaciations, Sierra Nevada, California, *Geol. Soc. Am. Bull., 74,* 1079-1086, 1963.

Sugden, D. E. and B. S. John, *Glaciers and landscape,* 376 pp., Edward Arnold Ltd., London, 1976.

Wahrhaftig, C. and J. H. Birman, The Quaternary of the Pacific mountain system in California, in *The Quaternary of the United States,* edited by H. E. Wright, Jr., and D. G. Frey, pp. 299-340, Princeton University Press, New Jersey, 1965.