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Diversion of the upper Bear River: Glacial diffluence and Quaternary erosion, Sierra Nevada, California

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Abstract

Deep canyon erosion and diversion of more than 300 km^2 of the former upper Bear River is documented with stratigraphic and morphologic evidence. Stratigraphic relationships constrain canyon incision to no older than late Miocene in age. A hypothesis is advanced that channel diversion was caused by ice spilling over a divide between the Bear and South Yuba drainages leading to development of glacial diffluence and deep incision. The local glacial stratigraphy is mapped based on lateral moraines, erratics, and striae which indicate that at least two and probably three glacial advances occupied both South Yuba and Bear valleys. Stratigraphic relationships constrain most valley incision to before the last major glacial stage and probably by the end of an earlier, larger glacial advance. Morphologic evidence supports a hypothesis of dominantly sub-glacial erosion at an outlet glacier through the Yuba gorge where steep valley gradients, high shear stresses, and large meltwater discharges led to rapid erosion and formation of a deep V-shaped valley.

1. Introduction

The relative importance of Quaternary glacial erosion to the evolution of modern Sierra Nevada topography is one of the oldest geomorphic debates in the region. This debate, which involved such eminent scholars as Whitney, Muir, and LeConte (cf. Bateman and Wahrhaftig, 1966), has not yet been fully resolved. Most modern studies of the evolution of the northern Sierra Nevada agree that the present drainage was produced primarily during the late Cenozoic prior to Quaternary glaciations. Modern valley incision was initiated following late Miocene deep burial of earlier valleys with mudflows, conglomerates, and in response to uplift of the Sierra block in the east (Lindgren, 1900; Lindgren, 1911; Bateman and Wahrhaftig, 1966; Christensen, 1966). The post-volcanic drainage was redefined into a series of consequent streams flowing west-southwest down the Sierra fault block. In spite of extensive and repeated Quaternary glaciations, few substantial derangements attributable to this period have been documented other than the beheading of an upper Tuolumne River tributary due to faulting (Huber, 1990).

This paper documents a diversion of about 300 km^2 of the former upper Bear River down the South Yuba River in the northern Sierra Nevada (Fig. 1). Deep volcaniclastic burial of an early Cenozoic valley adjacent to a modern deep gorge constrains the timing of incision providing an opportunity to constrain rates of erosion in a Sierra canyon. A hypothesis is presented that the channel diversion and much of the local South Yuba valley incision at the site were induced by glacial erosion during the Quaternary period. Morphologic and stratigraphic evidence are reviewed that constrain the age of the deep Yuba canyon at this site and the diver-

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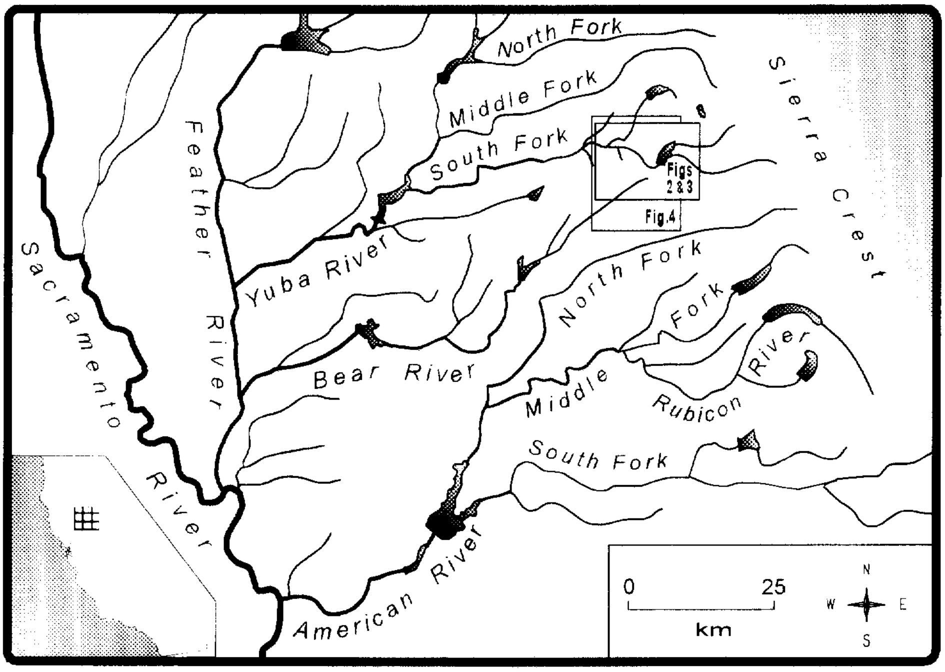

Fig. 1. Regional map of the study area.

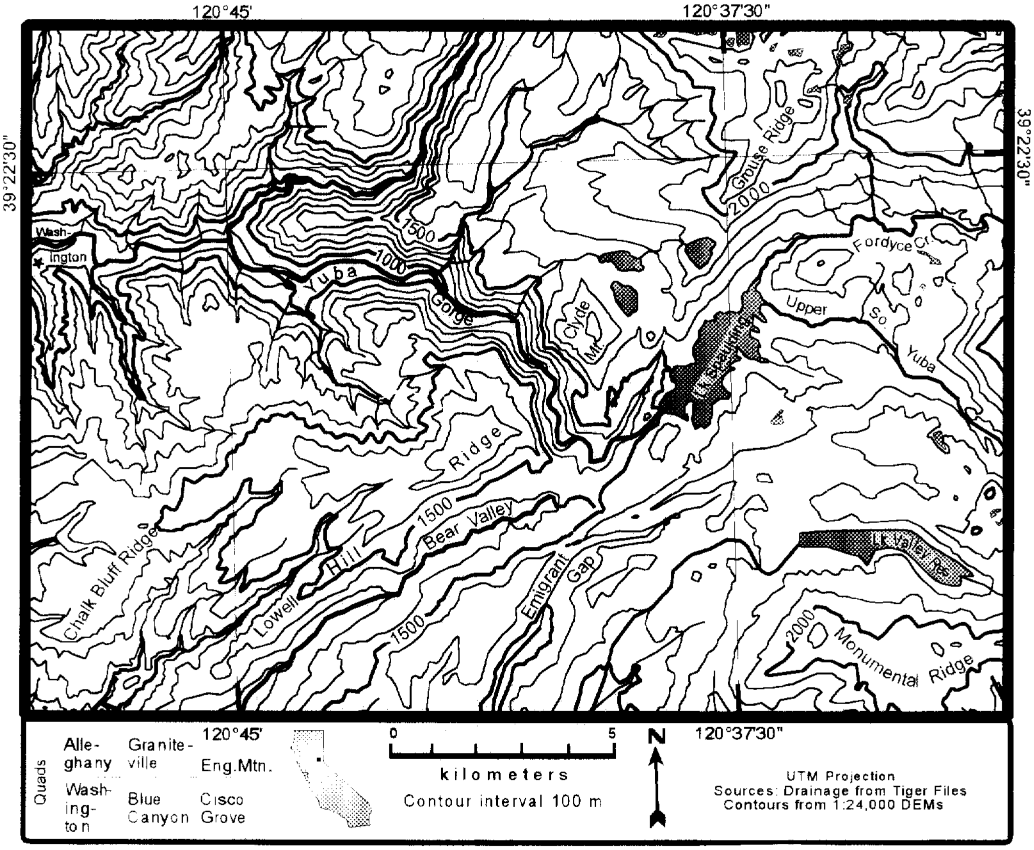

Fig. 2. Topography of Yuba Gorge, Bear Valley, Spaulding basin, and diversion site.

Fig. 3. View to north into Yuba Gorge across upper Bear Valley; from Emigrant Gap.

sion of the upper Bear River to post-Miocene and pre-late Wisconsinan. Stratigraphic evidence is outlined of at least two and probably three glacial advances that spilled over the South Yuba–Bear River divide and flowed into both basins.

If correct, this model of Quaternary drainage diversion has important implications: (1) rapid rates of glacial valley incision in a Sierra canyon, (2) the Bear and South Yuba channels down-valley from the diversion may not be geomorphically and hydraulically adjusted to their present loads of water and sediment, and (3) general principles of sediment storage potential may be based on non-representative systems. The latter implication arises from the fact that Gilbert's sediment wave model (Gilbert, 1917) is based largely on field work in the South Yuba River, which may be ill-adjusted to the addition of more than 300 km^2 of upstream catchment area.

The broad basin around and east of Lake Spaulding (Fig. 2) was deeply filled with ice repeatedly during the Quaternary and will be referred to informally as the *Spaulding basin* or *ice field*. The Spaulding ice field was fed by high cirque glaciers from the north and by valley glaciers in the upper South Yuba and Fordyce valleys. Both Bear Valley and the deep, steep-walled, bedrock gorge of the South Yuba (hereafter referred to as the *Gorge*) emanate from the southwest end of the Spaulding basin.

The South Yuba River heads at the crest of the northern Sierra Nevada near Donner Pass; the Bear River heads abruptly on the side of Bear Valley near the diversion site. Like most modern Sierra rivers, the Bear River, Fordyce Creek, and the South Yuba at Lake Spaulding flow southwest down the dip of the Sierra Nevada towards Sacramento Valley. Near Emigrant Gap less than 1 km from the Bear River, however, the South Yuba River turns abruptly about 110° from this course to the northwest and flows into the Gorge (Fig. 3). This has long been recognized as the site of a stream diversion although the time and cause have never been seriously studied.

2. Early knowledge of glaciation and diversion

Early descriptions of the study area indicate an awareness of valley glaciation although no evidence of multiple glaciations has been previously presented. Lindgren (1900) provides the only glacial mapping in the area; glacial units of Burnett and Jennings (1962) in this area are derived from Lindgren's map. Lindgren (1900) did not map moraine ridges, but mapped thick till and described three valley glaciers below the Spaulding ice field (Fig. 4). He recognized tills in both valleys, but found no evidence of multiple glaciations. He postulated that the primary ice lobe occupied Bear Valley and recognized two other lobes: one following the present South Yuba River into the Gorge and one passing across the Fuller Lake area to the lower Gorge:

"The heaviest moraines found in this quadrangle extend from Fuller Lake [north] to Bowman Mountain. Fall Creek, with its beautiful cirques near the head, certainly contained an important glacier, which may have reached down as far as the South Fork of the Yuba, but this would have been utterly inadequate to accumulate such large morainal masses, which must, therefore, be considered as largely having been carried down from higher ridges by the main ice sheet...The main ice stream did not follow the present course of the Yuba below Emigrant Gap... The *deep gap* separating the Yuba from the Bear River at Bear Valley represented the valley of the Neocene river formerly filled with lava and gravel and again worn out during the early part of the Pleistocene period. Through this gap the main ice stream must have flowed, continuing on below Bear Valley, as evidenced by the heavy moraines on both sides, which gradually thin out 4 or 5 miles below that point. It is probable, however, that a branch of the South Fork of the Yuba glacier followed the main river for a certain distance..." (Lindgren, 1900). [emphasis added]

This quote is crucial to an understanding of Lindgren's interpretation of glaciation and erosion of these valleys (Lindgren, 1900). His geologic maps show the pre-volcanic channel passing beneath Lowell Hill Ridge only 2 km southwest of the Gorge and turning to the northwest up Bear Valley through the site of Lake Spaulding (Fig. 4) (cf. small scale maps in the work by Lindgren, 1893; Bateman and Wahrhaftig, 1966). Thus, the "deep gap" he refers to as being exhumed by glacial erosion is within the uppermost Bear Valley; it is not the Gorge. The pre-volcanic channel, henceforth referred to informally as the *Omega paleo-valley* after the Omega hydraulic mine to which it is graded, is exposed in Bear Valley as a high relief angular disconformity between Paleozoic quartzite of the Shoo Fly Complex and Cenozoic andesitic rock.

Gilbert (1905) also recognized the importance of glaciation along the upper South Yuba and the abrupt geologic changes at the diversion site:

"Westward from [Donner] pass the Yuba valley is well glaciated to the bend near Emigrant Gap. The rock is granitic and a dark plutonic; much of it is bare... and the canyon is broad. Glaciation was active... At Emigrant Gap several things change abruptly. Plutonic rocks give place to bedded rocks and metamorphic... Glacial sculpture is succeeded by non-glacial." (Gilbert, 1905)

Manson (1901) argued that ice did not occupy the Gorge and that Bear Valley was glacially eroded. It is not clear if he believed the Gorge existed prior to glaciation. By erroneously concluding it contained no glacier, he seems logically forced to conclude that the Gorge did not exist during the glacial period; yet, he postulated the South Yuba channel was old:

"The upper one-third of the drainage basin of the South Yuba was the gathering ground for a glacier. This glacier, instead of following the channel of the river through the tortuous, deep, and narrow channel which turns northwest through 110°, plowed its way in a direct course through the lava ridge and eroded Bear Valley, in which Bear River heads."

"Upon the disappearance of the ice age, Yuba River took the northerly course along a deeply eroded channel, leaving a portion of its glacial channel below this bend for Bear River. This river therefore occupies a channel far larger than its feeble forces could have excavated... Yuba River below the bend probably occupies a very old channel..." (Manson, 1901)

Causes of the Bear River diversion are poorly understood. One interpretation assumes the diversion was the product of long-term headward erosion by fluvial processes. An example of this common view appeared in a popular account explaining the diversion as the result of both streams eroding headward, evidently before the upper South Yuba drainage had developed. Although upper basin glaciation was recognized, it played no role in the diversion by this scenario:

"A deep gorge cut through this ridge. It contained the Yuba River, where the Yuba had captured the Bear. The two rivers, *each eroding headward from opposite sides of the ridge*, had struggled toward each other until the divide between them broke down, and the Bear giving up its direction of flow, joined the Yuba and went the other way. To the northeast,... was a lake gouged in granite by an alpine glacier.." (McPhee, 1992). [emphasis added]

The view that channel diversion resulted from slow, progressive fluvial erosion is the conventional model of stream capture, and implies a substantive uniformitarianism in which the diversion is typically regarded as pre-Quaternary. This view implies that both systems have had considerable time to adjust hydraulically to the changes in their respective drainage areas.

Only one hypothesis of glacially induced diversion has been located in the literature:

"Bear Valley and the South Fork of the Yuba River are separated by only about 100 feet [33 m; actually ~70 m] of elevation, yet the

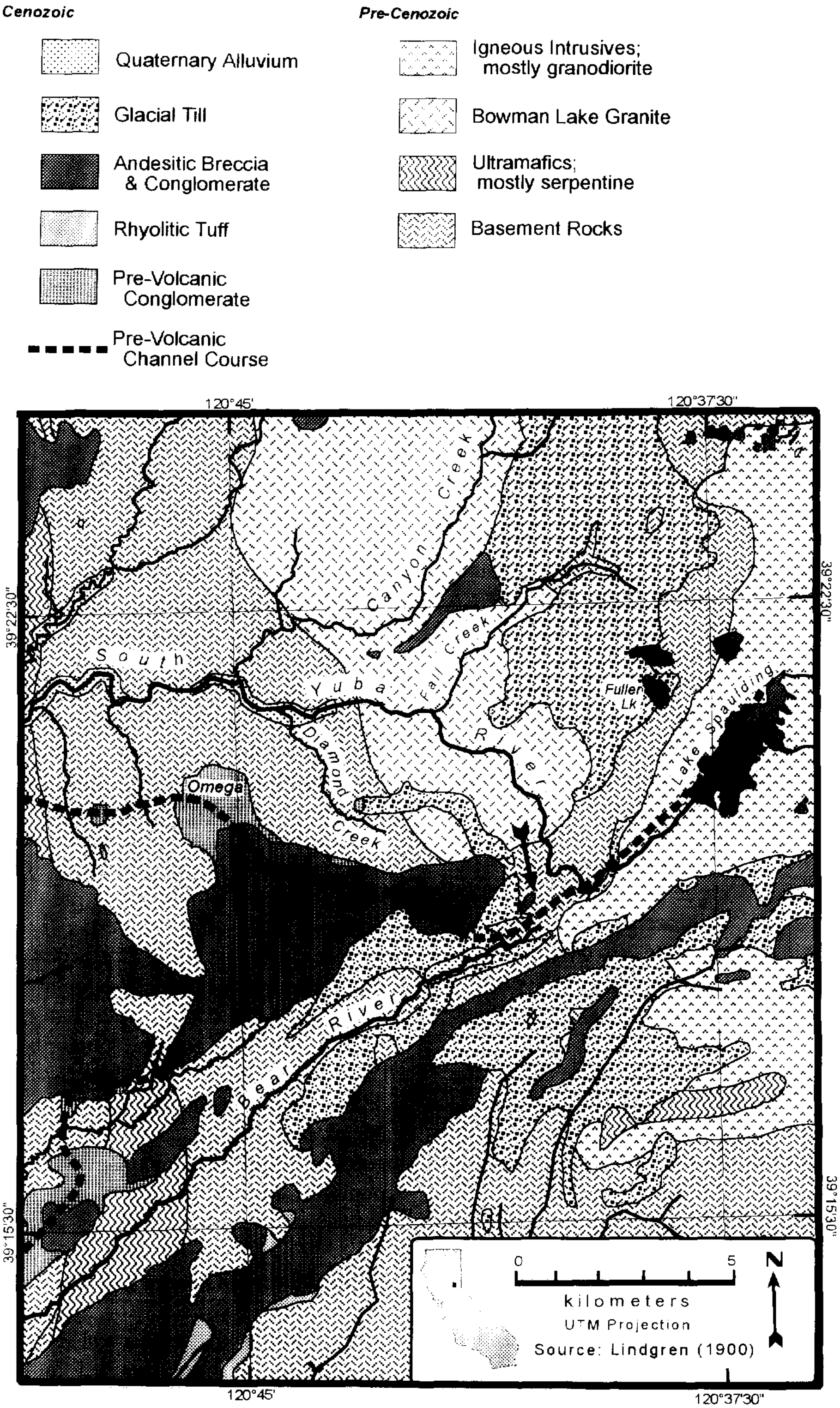

Fig. 4. Geologic map of study area. Arrow points to andesitic lahar deposit (not on original map) in Bear Valley indicating course of pre-volcanic channel was very near Gorge. "Omega" is location of Omega hydraulic mine in pre-volcanic conglomerate. Most of map replicates Lingren's (1900) original units, although alluvial deposits have been expanded.

gorge is 1600 feet [525 m] deep. Evidently *the headwaters of the South Yuba were once the headwaters of the Bear River, but were captured by the South Fork of the Yuba*. The details are not clear, but *this change in drainage is evidently connected with glaciation*." (Durrell, 1971) [emphasis added]

To evaluate competing hypotheses of the timing and cause of Gorge incision and channel diversion, the geomorphic evolution of the Sierra Nevada must first be considered.

3. Cenozoic landscape evolution

Most modern studies agree that the long-term evolution of the northern Sierra Nevada topography involved two phases of orogenic activity and a series of late Cenozoic volcanic episodes. Sierra uplift has been analyzed by numerous workers comparing paleogradient restorations of Cenozoic strata with modern stream profiles (e.g. Lindgren, 1911; Bateman and Wahrhaftig, 1966; Huber, 1981, 1990). These studies indicate that following an early period of Cretaceous uplift, there was a long period of quiescence, erosion, and relief reduction. Early Cenozoic erosion removed several kilometers of overburden exposing the granitic batholith during the Cretaceous, as is shown by granitic contacts and inclusions in Tertiary paleochannels (Lindgren, 1911) and by provenance studies of the Great Valley sedimentary sequence (Linn et al., 1992).

Incision of most northern Sierra valleys occurred during the late Cenozoic in response to decreased vulcanism and renewed uplift rather than in response to Quaternary glaciation. The early Cenozoic drainage was largely obliterated in the northern Sierra by deep late Miocene volcanic deposits that buried pre-existing valleys (Durrell, 1966; Slemmons, 1966). Radiometric dating indicates ages of rhyolitic deposits ranging from 16.1 to 33.4 Ma overlain by andesitic deposits ranging from more than 10 Ma to 5 Ma (Slemmons, 1966; Noble et al., 1974). Volcanism was intermittent and separated by periods of intervolcanic channel development, but these channels rarely eroded below the level of the pre-volcanic channels (Bateman and Wahrhaftig, 1966). As volcanic deposits stacked up and extended westward they ultimately ranged from a hundred to a thousand meters in depth and extended from Nevada across the present Sierra crest to the foothills.

Rapid late Cenozoic uplift instigated substantial preglacial valley incision. Matthes' (1930) belief that the entire Pliocene was orogenically quiet and that tilting began in the early Quaternary, has been rejected by most modern scholars (Wahrhaftig, 1965; Christensen, 1966). Huber (1981, 1990) concluded that uplift in the southern and central Sierra began early, was spread over a long period, but accelerated in the last 10 Ma of the Cenozoic. Unruh (1991) suggested that northern Sierra tilting began between 8.4 and 3.4 Ma and proceeded at a uniform rate (0.28°/m.y.) through the late Cenozoic. Deeply weathered surfaces of large segmented fans in the Central Valley indicate substantial pre-glacial late Cenozoic canyon erosion (Marchand and Allwardt, 1981). As a result of volcanic burial of the earlier drainage and late Cenozoic uplift along the northwestern axis of the modern range, northern Sierra Nevada drainages were largely reorganized into a series of southwest-flowing consequent streams (Bateman and Wahrhaftig, 1966).

Although not the dominant cause of valley incision, substantial Quaternary glacial erosion occurred in some valleys. At an elevation and position comparable to the Yuba Gorge, Matthes (1930) estimated that Quaternary glacial erosion was 150 m and 460 m in the lower and upper Yosemite Valley, respectively (not including present depths of alluvium). He postulated that a large, poorly documented, pre-Wisconsinan advance performed most of this Quaternary erosion. Although only a fraction of the great pre-glacial erosion of Yosemite Valley, this Quaternary incision is comparable to depths of Yuba Gorge down-cutting, and is much greater than the depth required to initiate channel diversion of the upper South Yuba drainage. Huber (1990) concluded that the longitudinal profile of the Tuolumne valley in a steep, narrow canyon east of the Grand Canyon of the Tuolumne was primarily due to glacial erosion. Glacial plucking and dense jointing were important factors explaining irregularities in the longitudinal profile.

4. Hypotheses of Gorge incision and diversion

This paper evaluates several hypotheses of Gorge development that are grouped into two categories depending on whether or not the Gorge existed during the early Cenozoic (Table 1). The first hypothesis,

Table 1
Categorical evaluation of Gorge incision and channel diversion hypotheses

Hypothesis	Plausibility
Pre-Volcanic Gorge. Occupied by a tributary to the Omega Channel.	
1. Continuous through Cenozoic	Reject
2. Aggraded by volcanics and exhumed during late Cenozoic.	
A. Northeast-flowing main channel in present South Yuba.	Reject
B. Southeast-flowing tributary to Omega Channel See hypotheses 3 through 6.	Good
No Pre-Volcanic Gorge. Omega paleo-valley under Lowell Hill to Bear Valley.	
No Diversion.	
3. South Yuba channel avulsed directly from Omega channel and Gorge incised through volcanics into present course by fluvial superpositioning.	Unlikely
Diversion. Bear Valley eroded and graded to basement rocks, then diverted into South Yuba:	Very good
4. Gorge eroded by fluvial capture.	
A. Pre-Quaternary	Unlikely
B. Rapid interglacial	Unlikely
5. Gorge eroded by Quaternary glacial and glaciofluvial erosion.	Very good
6. Gorge eroded by pro-glacial freeze shattering followed by glaciation.	Possibly with glaciation

that a deep ancestral Gorge was maintained through the late Cenozoic, is rejected outright. This area was deeply buried by late Miocene(?) andesitic lahars that cover most ridges in the area including Lowell Hill Ridge (1770 m) south of the Gorge, and ridgetops along both sides of Yuba Valley below the Gorge for many kilometers (Fig. 4). Andesitic mudflow, breccia, and conglomerates exposed in Bear Valley have not been dated, but they are similar to andesitic deposits elsewhere in the Sierra (Durrell, 1966). Their depth and tabular bedding indicate a continuous cover across the Gorge and Bear Valley area. Additional reasons for rejection of this hypothesis apply also to the next hypothesis.

A second hypothesis, in which a pre-volcanic Gorge was buried by volcanics and exhumed, takes two forms: a northwest-flowing main channel, and a southeast-flowing tributary (Table 1). Existence of a major northwest-flowing pre-volcanic Gorge draining the upper South Yuba would be very difficult to explain due to close proximity of the Omega paleo-valley, lack of pre-volcanic conglomerates or volcanic channel fill in the Gorge area, and lack of a connection with the lower Omega valley through granitic rocks on the south canyon wall above the mouth of Diamond Creek. The Omega valley passed from Bear Valley northwest under Lowell Hill Ridge across the Diamond Creek basin to the Alpha and Omega hydraulic mines (Fig. 4). A projection of elevations beneath Lowell Hill Ridge places the paleo-valley bottom near the floor of Bear Valley where Lindgren (1893, 1900) mapped it through the upper Bear Valley to the northeast through Spaulding basin. The presence of a well-cemented andesitic outcrop at 1460 m elevation in the mouth of Bear Valley between the Gorge and the exposure under Lowell Hill Ridge (arrows in Figs. 4 and 5) indicates the Omega paleo-valley connected with the Spaulding area. The paleo-valley passed so close to the Gorge, therefore, that a pre-volcanic channel flowing northwest through the Gorge would have to have been a distributary channel. Hypotheses postulating a major northeast-dipping pre-volcanic Gorge are rejected because of the need to explain how and why such a system of three distributary valleys formed (Gorge, Omega paleo-valley, and Bear Valley), and how the lower Bear Valley was later eroded.

It is far easier to support a hypothesis of a pre-volcanic tributary flowing south-southeast from the Bowman Lake granitics through the Gorge to the Omega channel in the upper Bear Valley (2B, Table 1). Although there is no evidence of such a tributary, it would be consistent with the Omega channel drainage pattern and with north-trending rock structures in the Gorge. Existence of a pre-volcanic tributary through the Gorge does not alter the fundamental time constraint that Gorge exhumation could not have begun until the volcanic epoch had subsided enough to allow

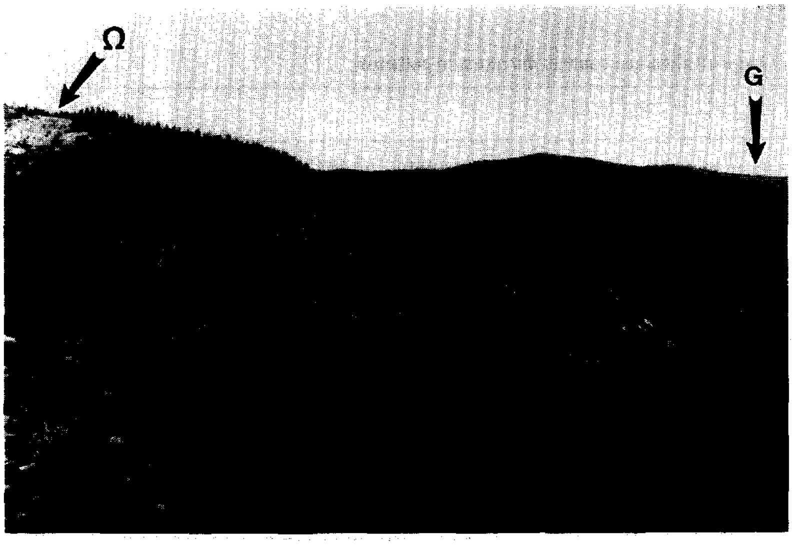

Fig. 5. View northwest into Gorge (G) showing upper north side of Omega paleovalley volcanic fill (Ω). Low andesitic valley fill in mouth of Bear Valley (A) indicates paleovalley extended northeast toward Lake Spaulding near Gorge (cf. Fig. 4).

channels to incise; not before the late Miocene. It does change the implications about rates of erosion in less resistant volcanic fill rather than granite from the Gorge.

Hypotheses of Gorge incision that do not assume a pre-volcanic valley have a similar time constraint: erosion of the Gorge must have occurred after the late Miocene. These hypotheses can be divided into two categories: the South Yuba channel pattern developed during the volcanic period as a channel avulsion a few kilometers north of the Omega channel without a diversion from the Bear River, or the Bear Valley was eroded first and the South Yuba was diverted from it later. The former scenario (3, Table 1) requires Gorge erosion in pre-glacial time, so fluvial erosion processes are presumed. According to this hypothesis, the initial post-volcanic upper drainage flowed down the South Yuba. Erosion by headward retreat of a west-flowing tributary in the Gorge area is ruled out due to the lack of headward erosion of Diamond Creek into unconsolidated andesitic lahar material. Deep fluvial erosion through Paleozoic granites and quartzites of the Gorge would require large stream powers produced by flows from the catchment of the upper South Yuba. Thus, rather than tributary headward retreat, this model implies superpositioning of the channel down through the andesitic overburden to its present course, then knickpoint retreat.

This third hypothesis is unlikely because volcanic burial was very deep and extensive in this area, the volcaniclastic fill in the Omega paleovalley provided a more erodible path to the southwest, tilting was to the southwest, and morphological factors such as long profiles indicate drainage through Bear Valley. This hypothesis requires downstream damming of the Omega channel while sustaining rapid intervolcanic erosion to counteract volcanic burial and uplift so that structural training of the avulsed channel could begin immediately before a southwestern drainage could develop. Sierra uplift along an axis trending north-northwest, steepened most southwest-trending valleys (Lindgren, 1911; Bateman and Wahrhaftig, 1966). This uplift would have steepened Bear River which trends southwest, but not the South Yuba below the diversion site which trends northwest, parallel to the range. Most importantly, erosion of Bear Valley remains to be explained if the primary post-volcanic drainage initially flowed through the Gorge. The small drainage area and low gradient of the modern Bear River in Bear Valley are inadequate to have eroded through the bench of Paleozoic quartzite at the southwest end of Bear Valley. Headward erosion of the Bear River through this bench would not have outpaced headward erosion of much steeper tributaries into the Gorge. In short, early development of the South Yuba drainage through the Gorge is at odds with the upper

Bear River flowing southwest into Bear Valley instead of northwest into the Gorge. Furthermore, Sacramento Valley late Cenozoic alluvial fans are much more extensive to the southwest than to the west along the South Yuba (Olmsted and Davis, 1961; Burnett and Jennings, 1962), suggesting an early and complete development of the upper Bear River drainage. Unless a process can be identified by which the Bear Valley could be eroded without the aid of the upper South Yuba, early non-diversion hypotheses of Gorge incision must be rejected.

5. Evidence of a diversion

Gorge diversion hypotheses in which the Bear Valley was eroded as an initial response to late Cenozoic volcanic filling include fluvial capture early in the post-volcanic era, rapid fluvial incision during interglacials, rapid glacial erosion, or frost shattering in a proglacial environment (4–6, Table 1). These hypotheses hold in common the assumption that the initial response to volcanic aggradation was an avulsion of the upper Yuba drainage to the southwest through Bear Valley. Only after this Bear River drainage from Spaulding basin through Bear Valley was well established did the diversion of upper-basin flows through the Gorge occur. Morphologic evidence that supports diversion after the establishment of southwest drainage through Bear Valley includes drainage patterns and longitudinal profiles. Drainage patterns indicate diversion by close proximity of the two channels and a barbed South Yuba channel planform. The present Bear and South Yuba channels approach to within 0.7 km of one another at the diversion site (Fig. 2). It is unlikely that this proximity is a coincidence, since the two valleys are nearly accordant and are separated by a very low divide. The modern drainage pattern over most of the Sierra Nevada is strikingly parallel, which is indicative of channels developed on steep terrain with minimal structural control (Howard, 1967). At the diversion site, however, the South Yuba main channel turns sharply 110° from its course parallel to the regional trend and flows into the gorge to the northwest (Fig. 2). *Barbed* channel

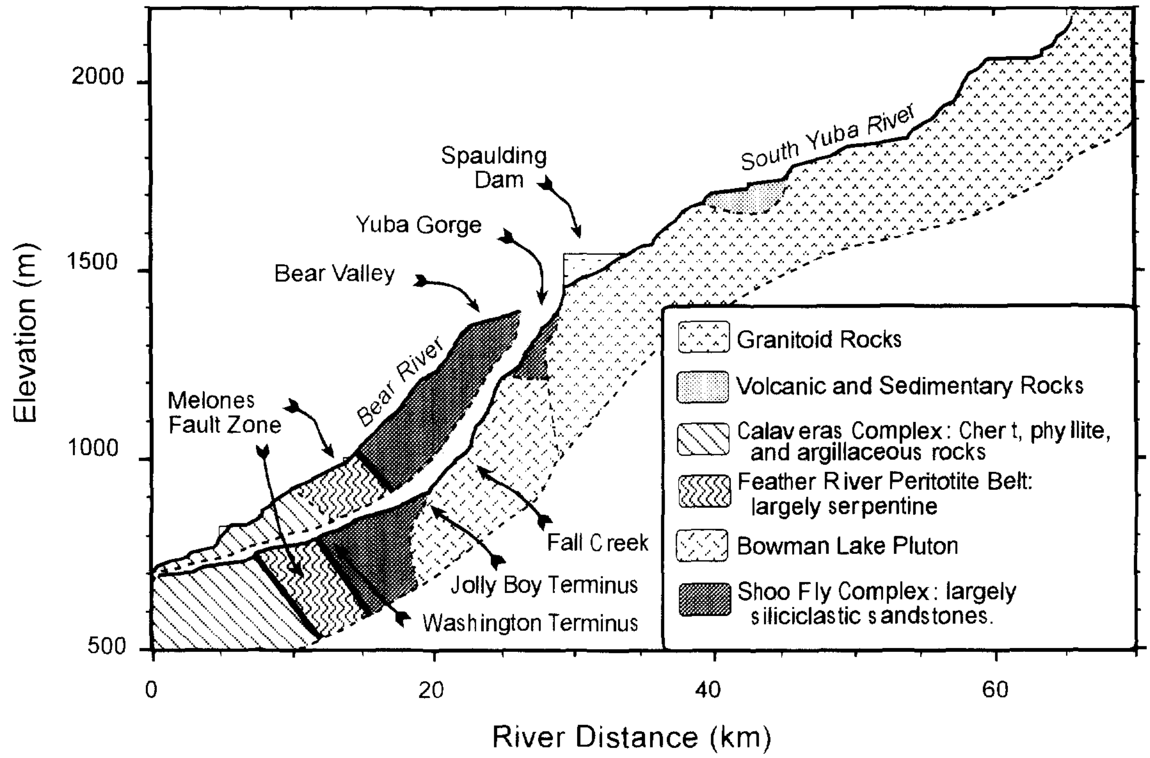

Fig. 6. Longitudinal profiles of South Yuba and Bear rivers with geologic units. Bear Valley is at grade with upper South Yuba, while South Yuba gradient steepens substantially in the Gorge with no apparent structural explanation.

patterns, in which tributaries join the main channel at obtuse angles, can be indicative of stream capture (Doeringsfeld and Ivey, 1964; Howard, 1967; Strandberg, 1967). The sudden turn of the South Yuba channel represents a large barb which is interpreted as the response to diversion of a well-developed southwest-trending drainage system.

Longitudinal profiles of the Bear and South Yuba Rivers also indicate possible diversion. The South Yuba profile steepens suddenly where the river turns northwest and enters the Gorge, and is not graded to the channel above (Fig. 6). Channel gradients within the Gorge range between 0.10 and 0.16 m/m in spite of a high sinuosity within tight entrenched meanders. A structural explanation for the break in profile is lacking. It does not correspond with known faults. The upper inflection point at the base of Spaulding Dam occurs near the contact with resistant granodiorites, but most of the steepened reaches are in Paleozoic quartzites of the Shoo Fly Complex, and the Devonian granitics of the Bowman Lake pluton has no apparent effect. In contrast, the Bear River profile is graded to the upper South Yuba profile through Spaulding basin above the diversion across the same Paleozoic quartzites (Fig. 6). The combined longitudinal profile from the upper South Yuba through Bear Valley suggests that a southwest-trending drainage had evolved over a sufficient period of post-volcanic time for the valley floor to have developed a graded profile in the basement rocks. Sierra uplift steepened channels flowing parallel to Bear Valley, not to the Gorge; yet, the opposite trend is observed in present profiles: the Gorge is over-steepened, while the gradient of Bear Valley is gentle.

The alignment and accordance of the Bear and South Yuba valleys, the abrupt termination of the Bear River headwaters so near the Gorge, and the longitudinal profiles support hypotheses that the post-volcanic Bear River initially headed up beyond the Spaulding basin but was diverted. Given the evidence available, the best hypotheses are those that include abandonment of the Omega pre-volcanic channel due to volcanic aggradation, development of an early post-volcanic drainage southwest down Bear Valley, and later erosion of the Gorge and diversion of the channel. Additional morphological and stratigraphic evidence suggests that Quaternary glacial erosion was an important component of Gorge incision.

6. Glacial stratigraphy

This study presents a hypothesis of deep, rapid canyon incision by glacial action. The glacial history of the study area is important both as an indicator of the magnitude and frequency of glacial erosion events, and as a constraint to Gorge incision. Sierra Nevada canyons were subjected to repeated Quaternary glaciations (Birkeland, 1964; Bateman and Wahrhaftig, 1966; Fullerton, 1986). This report briefly outlines a newly developed, locally referenced glacial stratigraphy for the study area (cf. James and Davis, 1994). Moraine ridges, till-mantled ridge-tops, and upper limits of granitic boulder erratics on Paleozoic (Shoo Fly Complex) or on Cenozoic volcanic rocks were used to map glacial advances. Topographic position and the degree of erosion and weathering of boulders, tills, and moraines were used to distinguish between advances. Lacking absolute dates, no attempt is made to regionally correlate these units which are given informal local stratigraphic names. A more detailed report on the glacial stratigraphy is pending.

Although steep gradients have resulted in poor preservation of deposits, enough consistent evidence has been collected to map two advances. Solid lines in Fig. 7 represent locations established by moraine ridges, till on ridgetops, or upper limits of erratic boulders. Dashed lines are interpolated based on topographic considerations. While Bear Valley and the Gorge have been field mapped extensively, tills to the north in Canyon and Fall creeks, and to the south in the American basin are mapped on the basis of reconnaissance surveys and should be considered hypothetical. Although Lindgren (1900) mapped extensive glacial till in the upper Fall Creek basin (Fig. 4), preliminary mapping suggests that the ice was thin there and that the dominant glaciers came down from Canyon Creek and Linsley Creek and from the Spaulding Basin near Grouse Ridge across the Fuller Lake area.

At least two and probably three distinct glacial advances were identified in the area that were high enough to spill over the divide north and south of Clyde Mountain into the South Yuba drainage (Fig. 7). A number of boulder erratics are located beyond the margin of the most extensive, well-preserved moraines mapped. Although some of these erratics could be explained as outliers of the mapped advance, their position and the severe erosion of till suggest they may

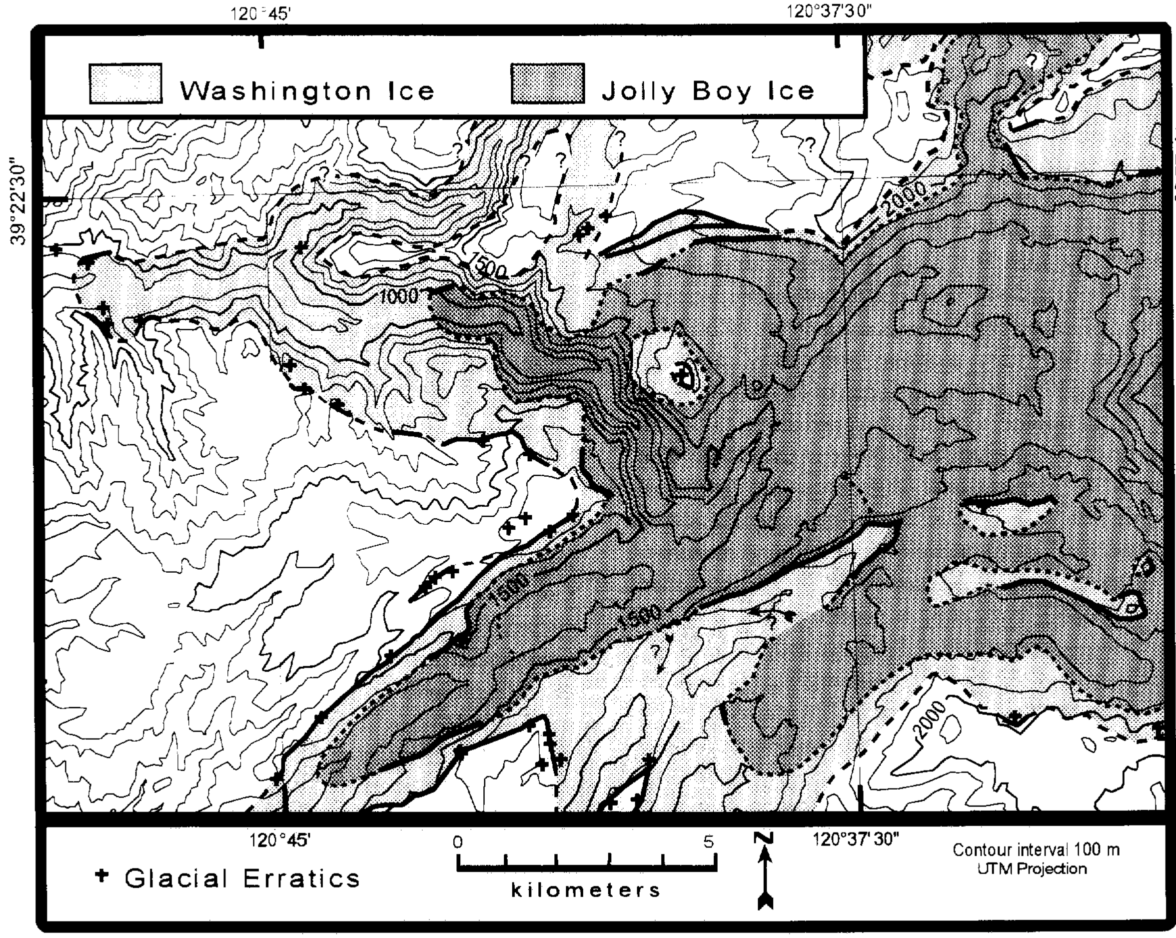

Fig. 7. Glacial map of Spaulding ice field and valley glaciers. Solid lines represent moraine ridges, till-covered ridge-tops, and well defined upper limits of erratics. Dashed lines are interpolated based on topography.

represent one or more earlier extensive advances. These boulder erratics, referred to as "pre-Washington" in regard to the Washington advance described next, lack moraine ridges and occur at higher elevations and more westerly down-valley locations than either of the two subsequent advances. For example, two small biotite granodiorite erratics were found on top of the relatively coarse-grained Bowman Lake granite above the Washington lateral moraine on the peak of Clyde Mountain (1830 m). Similarly, granitic boulders were found on Shoo Fly rocks above and beyond the Washington outwash terrace northeast of the town of Washington (Fig. 7). A possible pre-Washington till-mantled ridge is located northwest of the Washington moraine on Lowell Hill Ridge, although it could be a large isolated spur of a severely eroded Washington morainal complex.

Tills of intermediate age are associated with discontinuous moraine ridges in both the South Yuba and Bear valleys. Although few striae have persisted on boulders or erosional surfaces and moraines are missing from valley bottoms and tributary crossings, boulders and till from this advance are otherwise well-preserved. Moraine crests are rounded and moderately bouldery, and exposed granitic boulders produce a solid hammer ring. The upper limit of erratic boulders associated with this advance can be traced along valley walls grading to glacial termini at elevations below 1100 m in Bear Valley and at 840 m in the South Yuba valley in the town of *Washington* for which this advance is informally named. Washington till is preserved above the falls of Scotchman Creek (Lindgren, 1900) and north of the South Yuba river near the contact with a broad

Washington outwash terrace at about 840 m elevation. A lateral Washington moraine is near the crest of Clyde Mountain (1810 m).

The youngest moraine ridges in the study area below Spaulding basin are often sharp-crested and bouldery. These moraines extend below 1160 m in Bear Valley and terminate at 945 m elevation in the South Yuba valley near the Jolly Boy Mine. These moraines can be traced up both valleys to an accordant source, so they are assumed to be contemporaneous and are informally named the *Jolly Boy* moraine. Jolly Boy moraines extend above 1700 m on both flanks of Clyde Mountain and a line of bouldery till is preserved along the north side of Lowell Hill Ridge at the edge of the Gorge. The freshness of depositional and erosional surfaces, including the retention of clear striae on Paleozoic quartzites, boulder frequencies, and moraine morphology, suggests that this advance was late Wisconsinan in age (Tioga?), but dating is needed to establish this relationship. Younger sharp-crested, bouldery moraines in and above the Spaulding basin could be recessional moraines or readvances, but are not relevant to the diversion under consideration and are not considered in this article.

7. Glacial erosion and stratigraphic constraints

Ice depths and slopes at the capture site were sufficient to produce high shear stresses and sustain rapid glacial erosion. Washington ice was approximately 520 m thick in the mouth of the Gorge. Although Washington ice surface slopes through the Gorge have not been determined, adoption of Jolly Boy ice surface slopes at this location (6.2%) allows an estimation of average boundary shear stress of Washington ice at the mouth of the Gorge. Assuming the specific weight of the ice (γ_I) was 0.9 that of water and ignoring losses of energy to internal friction, average boundary shear was about 280 thousand pascals:

$$\tau_W = \gamma_I D_{max} S$$

$$= 8820 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-2} \cdot 280 \text{ m} \cdot 0.062 = 284 \text{ kPa}$$

Similarly, a first approximation of the average boundary shear of Jolly Boy ice through the Gorge is about 230 kPa based on an ice depth of at least 425 m and an ice surface 6.2% slope measured by maximum elevations of till along the north edge of Lowell Hill Ridge. These shear stress values of Washington and Jolly Boy ice are more than 2 1/2 and 2 times values of typical subglacial shear stresses, respectively (Paterson, 1969). This supports a hypothesis of great erosive competence of ice and high erosion rates within the Gorge.

Erosion rates provide a constraint on Gorge incision and channel diversion processes. Assuming 300 m of Gorge incision occurred since late Miocene (a conservative estimate), rates of Gorge incision leading to channel diversion must have been rapid; that is, an average 60 m/m.y. over 5 m.y. Furthermore, at least 70 meters of post-diversion erosion is necessary to account for the depth of the Gorge below the adjacent floor of Bear Valley. Holocene subaerial weathering and erosion rates have been far too slow to account for Gorge incision or diversion. If striated metamorphic surfaces are assumed to be 14 thousand years old and post-glacial erosion is assumed to be 5 mm (more would have obliterated fresh striae), then the average post-Jolly Boy erosion rate is only about 0.36 m/m.y. Although subsurface weathering encouraged substantial erosion elsewhere in the Sierra, those processes operate best on granitic rock and the associated stepped topography is not recognized in the northern Sierra (Wahrhaftig, 1965). Rocks such as the weakly metamorphosed Shoo Fly quartzite weather slowly, so a hypothesis of Gorge erosion promoted by subsurface weathering must explain why the Gorge developed at least partially in these rocks.

Minimum ages of Gorge incision and channel diversion are provided by glacial evidence. For example, the Washington outwash terrace provides a constraint on the minimum age of incision lower in the South Yuba valley. This terrace, near the Washington terminus across from the town of Washington, is about 40 m above the modern channel 15 km below the Gorge. This indicates that most valley incision at this location had occurred by the end of the Washington advance. Up-valley, an outwash terrace covered by coarse angular colluvium near the Jolly Boy terminus is about 15 m higher than the Jolly Boy outwash terrace and about 30 m above the present channel bed, 5 km down-valley from the diversion site. This terrace indicates the lower Gorge at the Jolly Boy terminus had been largely eroded prior to Jolly Boy time; perhaps by late Washington time if the terrace represents a Washington recession.

Evidence of the Jolly Boy glaciation at the diversion site is well preserved on metamorphic surfaces which are rounded, smoothed, striated, and grooved, with occasional roches moutonnèes. Striae orientations document branching ice-flow paths down the Bear and South Yuba valleys (James and Davis, 1994), and striae on the inner entrenched channel wall in the upper Gorge indicate late Jolly Boy ice at an elevation at least 50 m below the floor of Bear Valley. At least some inner-channel incision was contemporaneous with Jolly Boy glaciation since the inner edge of the cut is grooved about 4 m down from the bench surface. The meandering pattern of the entrenched channel must have been established prior to or during Jolly Boy time. This constrains channel diversion to no later than Jolly Boy time and probably earlier.

8. Morphologic features

Geomorphic forms that can be used to evaluate the various diversion hypotheses include limited tributary incision in the Gorge, valley cross-section shapes, a diffluence step, and hummocky bedrock surfaces at the upper end of the Gorge. Hanging valleys above the Gorge have not incised, and tributary gradients remain very steep near canyon confluences. For example, Fall Creek is about 600 m above the floor of the Gorge (Fig. 8). In addition, incision of a north-flowing South Yuba tributary into Shoo Fly quartzite on the north edge of the Bear Valley floor near the diversion site has been limited. Although this evidence supports hypotheses of recent deep erosion, hanging valleys and slow tributary

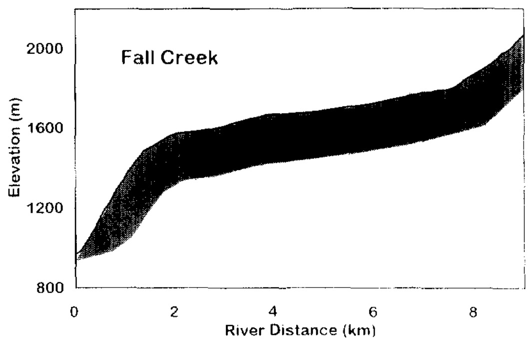

Fig. 8. Fall Creek longitudinal profile illustrating almost 600 m of hanging tributary relief.

erosion are common in unglaciated Sierra Nevada valleys (Matthes, 1930) and most are on granitic rock, so a lithologic explanation cannot be dismissed.

Bear Valley cross-sections have wide, shallow, parabolic shapes due to weak volcaniclastic rocks in the valley walls, a low gradient, and reoccupation of the upper Omega paleo-valley. In contrast, the V-shaped Gorge apparently misled some workers into concluding the Gorge had not been glaciated (Manson, 1901). The deep, narrow cross-section of the Gorge should not be interpreted as evidence of ineffective glacial erosion. Although valley cross-section shape has been related to degree of glaciation (Embleton and King, 1975), this relationship may be complicated by rock structure, valley gradient, and sub-glacial processes. Glaciated V-shaped valleys have been explained by exfoliation (Bateman and Wahrhaftig, 1966), steep gradients, and intense subglacial melt-water erosion (Embleton and King, 1975):

"It is sometimes possible for valleys in which glaciers have flowed to exhibit V-shaped sections in a generally U-shaped valley. The V-shaped sections are usually associated with reaches of greater gradient than the U-shaped portions,... The Gorge du Guil in the French Alps... examined by J. Tricart... was cut by subglacial meltwater flowing under hydrostatic pressure. The glacier in this section of the valley would have been relatively thin, probably less than 300 m, and deep crevasses and moulins would have allowed meltwater to reach the base of the decaying glacier. The meltwater, heavily loaded with abrasive material, would rapidly scour a deep gorge, having a steep V-shaped cross-profile, beneath the ice. The stream that has occupied the valley after the ice retreated has only been able to erode the bottom of the gorge by about 5 m." (Embleton and King, 1975)

Morphological evidence of glacial valley deepening may be located at valley junctions. Penck (1905) in his "*rule of cross-sections*" postulated formation of a discordant valley confluence with step height proportional to the difference in cross-section areas of the respective valley glaciers; i.e., a *diffluence step* (Bates and Jackson, 1987):

"The diffluence of the ice is controlled by the rule of cross-sections... steps occur where branches occurred for here there was a sudden diminution of the ice... steps of diffluence are hanging openings of those valleys that are entered by the ice. The height of... steps will generally be more considerable, the greater the difference between the main glacier and its affluent or diverting branch..." (Penck, 1905)

Penck applied this rule to both confluent glaciers which produce hanging valleys and to diffluent glaciers that produce ledges facing up-valley, and cited several

Fig. 9. View south toward Bear Valley of 60 m high rock ledge, or step of diffluence from within Yuba Gorge. Bedding planes are nearly vertical while low angle grooves indicate Jolly Boy ice rose up from lower left to upper right.

examples. The concept that valleys conveying more ice will be lowered more rapidly leaving the subdominant valley perched, supports the hypothesis that glacial erosion led to the Bear River diversion. An abrupt, grooved, steep rock face cut into the north end of the floor of Bear Valley forms a diffluence step suggesting rapid glacial erosion of the upper Gorge (Fig. 9). Ice flowing into the Gorge established a positive feedback mechanism in which progressively more flow was diverted as Gorge erosion accelerated.

Fluvial incision rates could be sufficient to accomplish the Gorge incision, but local valley bottom morphology is clearly not fluvial in origin. At the mouth of the Gorge the South Yuba valley bottom has a broad hummocky surface developed in Paleozoic quartzite. This bench surface has been eroded into a series of rock bars oriented normal to the upper Gorge axis around which a series of entrenched meanders have developed. Initiation of fluvial capture generally occurs by headward erosion of a tributary, faulting, or by aggradation or damming downstream leading to over-topping of a divide. Headward retreat was dismissed earlier since it requires rapid erosion by a small tributary through the granite and Paleozoic quartzite Gorge area while headward retreat of Diamond Creek through relatively incompetent materials has been limited. There are no known faults above the Melones Fault Zone (Fig. 6). A damming or aggradational hypothesis must assume there was a much lower divide between the Bear and South Yuba basins than is necessary with a glacial diversion hypothesis. Once Bear Valley was substantially eroded, it would have required a very high dam to cause spillage across to the South Yuba. Yet, there is no evidence on the flat, outwash-covered floor of Bear Valley of post-volcanic aggradation or damming. While there was ample sediment in the system during the Pliocene, the fluvial regime was overwhelmingly erosional. Although glacial erosion could have removed such deposits, damming cannot explain why the upper Bear River continues to flow through Bear Valley rather than as a tributary to the South Yuba Gorge. These difficulties suggest that fluvial diversion hypotheses are unlikely.

By the fore-going arguments for elimination of competing hypotheses, hypotheses of Gorge erosion and channel diversion have been reduced to the glacial and pro-glacial erosion processes. Extensive glaciation of the Gorge and evidence of substantial glacial erosion have been demonstrated, and the following section describes sub-glacial erosion processes that may have lead to rapid canyon erosion.

9. Glacial creation and deepening of valleys

In spite of controversy over the concept as it applies in the Sierra Nevada, glacial erosion as an agent of valley creation has been well documented by early European and American geomorphologists. Creation of valleys across drainage divides by transection, ice-landic, outlet, and through glaciers has been mapped, described, and defined by several workers (Tarr, 1909; Embleton and King, 1975; Linton, 1949, 1963), as has progressive valley erosion across continental glacial divides (Coates and Kirkland, 1974).

Outlet glaciers provide a mechanism by which rapid divide lowering may occur. Cols and small valleys may be deepened by outlet glaciers due to positive feedbacks that can exist between steep slopes and valley bottom incision processes (Hooke, 1991). Over-deepened slopes are associated with transverse crevasses which encourage the percolation of meltwater to the base. Fluctuations in meltwater can greatly accelerate basal erosion in temperate glaciers and this can further steepen valley bottom slopes. Evidence of deep sub-glacial meltwater erosion in the Gorge includes a deep hole in the modern channel a few hundred meters upstream of the Jolly Boy terminus. Miners at the Jolly Boy gold mine have been removing boulders for years from a deep pit well below the South Yuba graded bed. This hole presumably developed during Jolly Boy glaciation in response to high pressure subglacial meltwater flows. The potential for hydraulic heads in excess of 100 meters in conjunction with high velocity sub-glacial meltwater flows, freeze–thaw cycles, and glacial abrasion can result in substantial erosion capacities in such environments.

Proglacial mechanical weathering of valley bottoms has been postulated as a mechanism by which deep valley incision can occur, particularly in conjunction with glacial erosion (Embleton and King, 1975). Freeze shattering in periglacial or proglacial environments can cause jointing which prepares the valley floor for glacial erosion. It is not known if such a process operated in Sierra canyons during glacial advances, but the hypothesis is viable.

10. Hypothesis of Quaternary glacial erosion and diversion

Based on stratigraphic and morphological evidence, a hypothesis of the process and timing of Gorge erosion and channel diversion is advanced (Table 2). The pre-volcanic valley extended under Lowell Hill Ridge and up through Spaulding basin. There may have been pre-volcanic tributaries under Emigrant Gap and a south-flowing tributary through the Gorge to the Omega channel. The pre-volcanic channels were deeply aggraded by volcanics and largely abandoned. The early post-volcanic drainage developed on erodible volcaniclastic rock that had aggraded above most structural controls of the basement rocks as a southwest-trending channel from the Spaulding basin through Bear Valley. As the main channel was superposed onto the underlying basement rocks, it exploited the pre-existing Omega paleo-valley through the upper Bear Valley, and maintained a course through the former southwest wall of that valley where there is now a large bedrock bench in lower Bear Valley (Fig. 2).

The post-volcanic, preglacial South Yuba channel was a west-flowing small tributary fed by Diamond Creek that joined the former main channel at Canyon Creek (Fig. 4). Following volcanic aggradation, as this preglacial tributary encountered hard basement rocks, erosional processes shifted from vertical incision to

Table 2
Hypothesis of glacial diversion

1. Prior to glaciation a steep South Yuba tributary was separated from the Bear River by a divide near Clyde Mountain. The Gorge did not exist or was a tributary valley flowing southeast. Fall Creek was graded to that tributary or Canyon Creek at a much higher level than the Gorge.
2. Pre-Washington and Washington ice flowed over divides on both sides of Clyde Mountain from the Spaulding ice field through both the Fuller Lake area and the Gorge site. Gorge incision occurred in response to glaciation across the divide as a steep, shallow ice flow developed into a substantial, highly erosive ice fall with transverse crevasses that allowed meltwater access to the bed. As the proto-Gorge floor was lowered toward the level of the Bear Valley floor, increasing discharges of ice and meltwater were diverted down the steep South Yuba Canyon. Ultimately, during pre-Washington or Washington time, the Gorge was eroded below the floor of Bear Valley, and most meltwater from the Spaulding ice field was diverted through the Gorge. Upon deglaciation, stream flows continued flowing through the Gorge.
3. Jolly Boy ice reoccupied both valleys, and continued cutting the Gorge to its present position more than 70 m below the floor of Bear Valley. The Gorge already existed and carried the South Yuba channel, however, and this advance merely deepened it.

slow headward retreat of a knickpoint at the granite–metamorphic contact near the Jolly Boy mine. Headward erosion of this proto-South Yuba tributary was more rapid up Diamond Creek where the Omega paleochannel was filled with erodible volcanics. The Gorge did not exist prior to Quaternary erosion, although there was a low saddle between tributaries to the South Yuba and the Bear Valley.

Quaternary glacial advances spilled over the divide into the South Yuba basin. Due to steep gradients, incipient ice flows across the low pre-glacial South Yuba–Bear Valley divide rapidly developed into an outlet glacier through the Gorge site. Increasing flows of ice and sub-glacial meltwater led to incremental augmentation of valley cross-section size and established a progressive dominance of ice flow down the Gorge. Sub-glacial meltwater was diverted from the Spaulding ice field which resulted in fluvial derangement in pre-Jolly Boy time. Much Gorge incision may have occurred during one or more very extensive glaciations in pre-Washington time and the Gorge was further deepened by the Washington and Jolly Boy advances. It is not possible with the available information, to specify when channel diversion occurred, but if the logic of previous discussions is sound, and glacial processes are responsible, then Quaternary diversion is the inevitable conclusion. Furthermore, the event can be constrained to pre-Jolly Boy; that is, to pre-Washington or Washington glacial erosion.

11. Conclusions

Most modern Sierra Nevada valleys formed in the Late Cenozoic prior to Quaternary glaciation. Glaciation modified many canyons, but its importance varies from canyon to canyon. The South Yuba Gorge presents an opportunity to examine valley evolution with some clear stratigraphic constraints. Burial of a large paleo-valley by volcanic lahars and conglomerates and its exposure in Bear Valley provide a fortuitous opportunity to study the rate and sequence of valley evolution of Bear and South Yuba valleys.

Existence of a northwest-flowing South Yuba channel through a pre-volcanic Gorge is rejected due to close proximity of the main pre-volcanic paleo-valley under Lowell Hill Ridge and up Bear Valley through Spaulding basin. The hypothesis that the South Yuba channel was superposed in its present course in or shortly after the intervolcanic period is unlikely. This hypothesis ignores regional tilting, requires rapid intervolcanic channel erosion in order for structural controls to prevail over aggradation and uplift effects at the same time that it requires filling of the Omega channel, and it cannot explain how Bear Valley was eroded.

Morphologic and stratigraphic evidence indicates that the initial post-volcanic drainage developed to the southwest down Bear Valley and that Gorge incision occurred after erosion of Bear Valley. This indicates diversion of more than 300 km^2 of the former upper Bear River to the South Yuba basin in post-Miocene time. If this interpretation is correct, incision of the Gorge provides an example of rapid valley cutting through Paleozoic granite and quartzite. Fluvial processes in large basins can attain sufficient erosion rates, but diversion of the upper basin is required. The hypothesis that the upper Bear was captured by headward fluvial erosion is rejected because it requires rapid erosion of a small tributary through Paleozoic granitics while erosion of Diamond Creek through weak volcaniclastic materials was limited. If headward erosion did not cause capture, then fluvial capture requires post-Miocene aggradation or damming of Bear Valley. There is no evidence for such an event, nor does it explain why the upper Bear River continues to flow down Bear Valley. Thus, post-volcanic, fluvial capture hypotheses are unlikely.

Processes of Gorge incision and channel diversion were apparently dominated by Quaternary glacial erosion. Deep and repeated glaciations into the Gorge, steep valley gradients, and large potential supplies of meltwater support the hypothesis that glacial erosion was highly competent at this location. Field mapping documents at least two and probably more extensive glacial advances that occupied both the South Yuba and Bear valleys, and provides stratigraphic constraints on the timing of Gorge incision. Morphological forms indicate that valley bottoms were substantially lowered and modified by glaciation. Rock bars, a diffluence step, a stepped South Yuba longitudinal profile, hanging valleys, and other features indicate a dominance of glacial erosion in the Gorge. This erosion was presumably assisted by sub-glacial meltwater. Evidence of deep glacial erosion in similar positions elsewhere in the Sierra Nevada and a long literature of glacial diffluence indicate that glacial erosion can be rapid and can create new valleys, particularly under conditions of steep valley gradients where large volumes of subglacial meltwater are involved. Thus, rapid pre-late Wisconsinan Quaternary glacial erosion is identified as the preferred hypothesis for evolution of the South Yuba Gorge including deep incision and channel diversion.

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