Late Pleistocene Glaciations in the Northwestern Sierra Nevada

Field Trip Guide and Road Log

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Part I: Introduction and Background

Field Trip Overview. The primary objectives of the trip are to present new evidence of glaciation in the NW Sierra Nevada (*Sierra*) region at a variety of scales, to link geomorphic form to glacial processes, and to present an outline of the general late Pleistocene stratigraphy in the region. The trip concentrates on evidence of late Pleistocene glaciations between 1400 and 2250 meters (4600-7400 ft) elevation on the west slopes of the Sierra along the Interstate 80 (I-80) transportation corridor. In the morning we leave from the Reno Hilton and drive non-stop west on I-80 up the Truckee

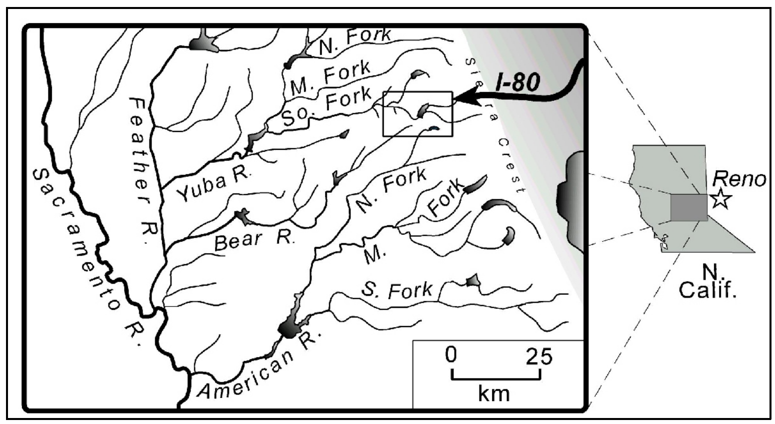

Figure 2. Location of trip and study area in NW Sierra Nevada, California.

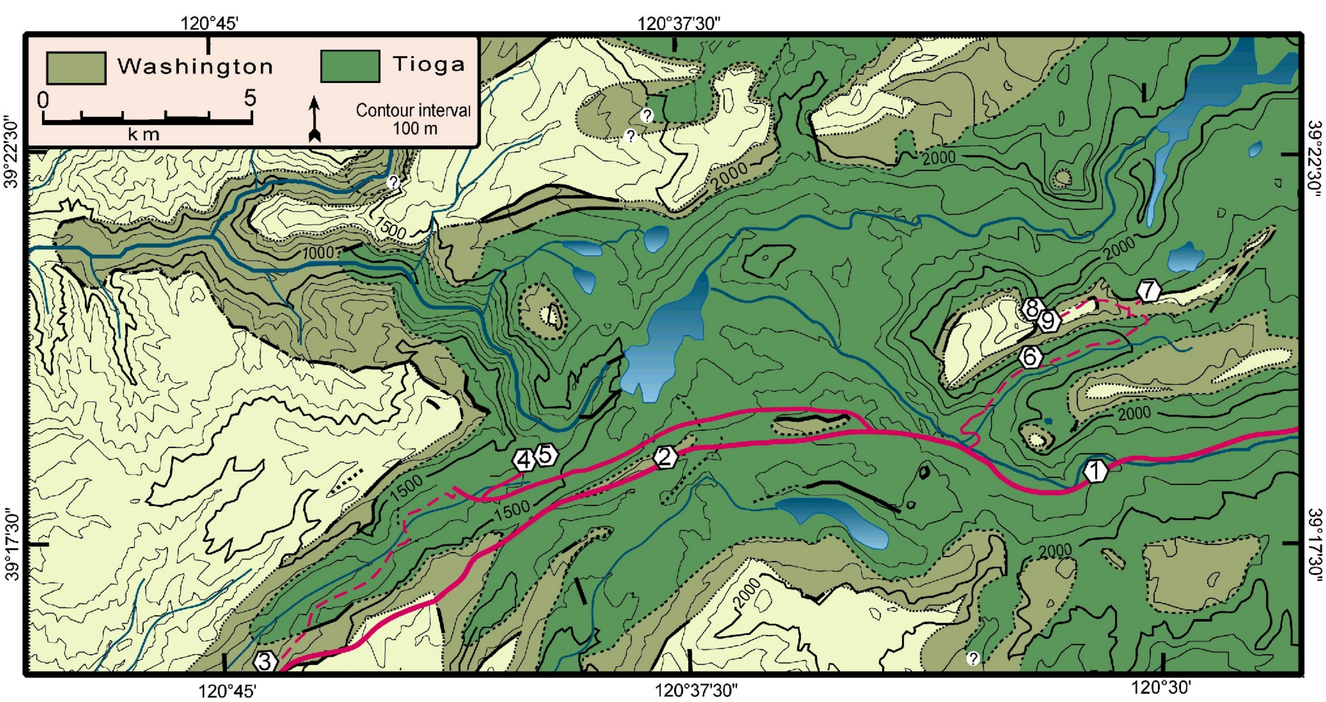

Figure 1. Map of trip with stops (numbers) superimposed on glacial map showing two major units. Tioga is the LGM glacial advance recognized throughout Sierra Nevada. Washington advance is a local name that is not correlated beyond the study area. Dashed road lines (light grey) are unpaved.

River Canyon over Donner Pass to the northwestern Sierra Nevada (Figure 1; also see road log in Part III). We then travel downslope, leave I-80, and work our way obliquely into and up Bear Valley (BV) on dirt and gravel-improved roads (Figure 2). The first two stops in the morning will view local-scale erosion features and a large-scale overview of the lower study area, respectively. The third stop is in Bear Valley (BV) at a 25-meter-deep exposure of a pre-Tioga (pre-Late Glacial Maximum, pre-LGM) lateral moraine. The fourth stop is lunch, and the fifth stop, nearby is at the north end of BV where the upper Bear River was captured by the South Yuba (SY) River. Glaciation probably assisted in the capture if it did not cause it directly (James, 1995). In the afternoon we drive up Rattlesnake Canyon to Stop 6, a bedrock bench high on the valley wall that is interpreted as a kame strath terrace. Stop 7 is a sharp-crested bouldery Tioga (LGM) lateral moraine in Fordyce Summit. Stop 8 is a view of Old Man Mountain and moraines across Fordyce Canyon to the north. Stop 9, the final stop, is a view to the south across Rattlesnake and SY Canyons of Cisco Butte (roche moutonnèe), and Devil's Peak (crag-and-tail). We return the way we came with one stop at the Donner Summit rest area. Details for each stop are provided in Part II.

Rationale and Status of Glacial Mapping in the NW Sierra. Prior to 1989, little Quaternary mapping had been done in the region other than Lindgren's (1897; 1900) geology maps and Tahoe National Forest soil maps. Unlike valleys on the east side of the Sierra where many moraines are large, well-preserved, morphologically distinct, and largely barren of vegetation, valleys on the west side are deeply incised, humid, and thickly forested, so moraine ridges are eroded, missing for long stretches, obscured, and usually difficult to locate. Thus, few detailed glacial studies of the western slopes are available other than Matthes' (1930) studies of Yosemite and Sequoia Parks well to the south. In the northern Sierra, only Birkeland's (1964) mapping on the east side around Donner and Prosser Valleys provides a frame of reference. Due to the lack of Quaternary information when this project began in 1989, the concentration has been on reconnaissance mapping of glacial indicators such as erratics, striae, moraines, and other landforms. Mapping methods are described in detail elsewhere (James and Davis, 1993; James, 1995). At lower elevations in the ablation zone, till deposition was apparently abundant initially, and lateral moraines are mapped wherever preservation allows field identification. At higher elevations in the accumulation zone, till deposition was less abundant other than large erratics and erosional features and their state of weathering have been more important as indicators of glaciation. At present only a preliminary generalized map of glaciation has been produced (Figure 2). It delineates two major glaciations that probably each represent multiple stades as well as isolated evidence of older advances above and beyond those two better-preserved groups. Mapping methods, tend to lump units– especially the pre-Tioga moraines– so this unit may represent more than one advance. Given the reconnaissance nature of mapping, several important aspects of glaciation have not yet been attempted in the area. These include distinctions between stades of the two major glacial groups, recessional moraines of the Tioga (LGM) advance, and neoglacial features at high elevations.

Physiography. The study area is centered in the South Yuba and Bear Basins, and to a lesser degree the northern margins of the American River (Figure 1). The Sierra Nevada crest forms the eastern limit of the Yuba and American Basins, trending NNW with a steep eastward-dipping escarpment to the down-dropped Tahoe Basin and a long, more gradual slope to the west. Crest elevations of the northern range vary between 2700 m (8850 ft) at high peaks to as low as 2200 m (7200 ft) at passes. These elevations are considerably lower than the central and southern Sierra that reach more than 4270 meters (14,000 ft). Basin topography can get extremely rugged at both local and regional scales. At the local scale for example, knock-and-lochain topography of valley bottoms is common on glaciated valley bottoms and continues to pose substantial difficulties for transportation up many valleys (see Stop 8 in Part II). At larger scale, the Yuba Gorge, in the center of the study area, the South Yuba River flows as much as 700 m (2300 ft) below the valley rim only 2 km away (Stop 2). In the Royal Gorge of the North Fork American River, immediately to the south of the study region, local relief reaches about 1200 meters (3940 ft) near Snow Mountain (Figure 2 of James, in press).

The Mediterranean-Montane climate of the study area is characterized by cool, wet winters and warm, dry summers. Summer convective precipitation is common at high elevations, so we could experience lightening and showers although this is unlikely. There is a steep precipitation gradient up the Sierra slope in winter, reflecting orographic uplift of the prevailing maritime westerlies over west-facing slopes of the upper basin. On the Sierra crest precipitation totals reach as high as 180 cm (70 in). Total precipitation for water year 1986 reached more than 250 cm (100 inches) in parts of the American River basin near the study area. Snow-line elevations and snowfall water equivalents vary between years more than between basins of the Sierra Nevada (Aguado, 1990). The nature of pre-European settlement Sierra climate is reviewed by Stine (1996).

Vegetation in the western Sierra is strongly associated with elevation and topography. During the morning and afternoon drives over the crest we will see alpine tundra at the highest elevations such as on Boreal Ridge and Castle Peak. We drive through subalpine forest communities of western white pine (*Pinus monticola*), lodgepole pine (*Pinus contorta*), and mountain hemlock (*Tsuga mertensiana*) at our highest elevations approaching Donner Pass (Munz and Keck, 1973). The vegetation zone of BV, where we will stop in the morning is dominated by mixed coniferous forest and chaparral. The forest community includes large, dense stands of Douglas fir (*Pseudotsuga menziesii*), incense cedar (*Calocedrus decurrens*), western yellow pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), and black oak (*Quercus kelloggii*). South-facing slopes and other dry locations are often colonized by manzanita (*Arctostaphylos spp.*), Huckleberry oak (*Quercus vaccinofolia*), Ceanothus (spp.), and other montane chaparral shrubs (Whitney, 1979). Tertiary and Quaternary vegetation histories of the Sierra are reviewed by Millar (1996) and Woolfenden (1996), respectively. Early cultural impacts of European settlement are reviewed by Beesley (1996).

The complexity of soil patterns in the study area results from highly variable soil-forming factors; i.e., topography, climate, vegetation, parent materials, and time. Altitudinal zonation of climate and vegetation produces the most general trend from primarily thermic temperature regimes and xeric moisture regimes supporting grass at low elevations in the Sacramento Valley, to mesic and udic regimes supporting coniferous forests higher up. At the elevations around BV, deep acidic weathering environments reach a maximum. At higher elevations, cryic temperature regimes limit organic contributions and chemical weathering ceases to increase. The oldest or most fully developed soils–some xeralfs but especially humults and xerults–are found in the Sierra foothills at elevations well below this trip between 500-1000 meters (1600-3300 ft) elevation, where reddish-yellow argillic horizons are often visible inroad cuts. The steep topography of the study area and repeated glaciations have limited soil age through erosion. Xerochrepts often characterize eroded side slopes, Alfisols and Ultisols are found on stable interfluves. Parent material controls the relatively thin xerochrepts developed on granitic exposures at moderate to high elevations.

Geology. The bedrock stratigraphy of the Sierra can be divided into two major groups: the *subjacent* (*basement*) and the *superjacent* series (Lindgren, 1911; Bateman and Wahrhaftig, 1966) (Figure 3). The basement series is dominated by severely deformed and slightly metamorphosed Paleozoic and Mesozoic marine sedimentary and volcanic rocks intruded by granitic batholiths. Basement rocks are located in areas where

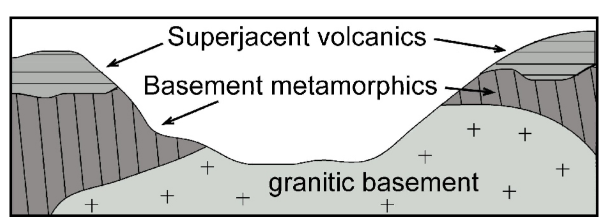

Figure 3. Schematic representation of generalized Sierra Nevada bedrock stratigraphy. Based on Lindgren (1911).

erosion has exposed the deeper rocks such as on canyon walls and bottoms. Many of the basement rocks in this area are part of accretionary terrains that were tectonically emplaced and deformed by subsequent accretionary tectonic events. The superjacent series are relatively gently dipping Cenozoic rocks lacking severe deformation or regional metamorphosis. These rocks are largely on ridgetops that were not severely glaciated. Among the early superjacent rocks are auriferous (gold-bearing) channel deposits (Lindgren, 1911). The bulk of the superjacent rocks are volcanic or volcaniclastic that were generated during two major episodes: a period of rhyolitic volcanism followed by a period of andesitic volcanism. The rhyolitic rocks are overlain stratigraphically by extensive andesitic deposits, such as those in the Mehrten Fm. (Durrell, 1966; Slemmons, 1966). In this area, Lindgren (1911) attributed the andesitic lahar materials to volcanoes at Webber Lake, Mount Lola, and Castle Peak. These andesitic deposits are easily eroded particularly by glacial ice and tend to be best preserved on ridge tops above glacial margins.

An early period of rapid uplift in the Mesozoic or early Tertiary resulted in substantial mountain building of a proto-Sierra. Unruh (1991) suggests that pre-Eocene uplift in the northern Sierra was on the order of 8 to 12 km. This era was followed by a long period of tectonic stability in which considerable erosion occurred. Exposure of the granitic batholith beginning in the early Tertiary is demonstrated by granitic contacts under auriferous gravels in ancestral Yuba channels (Lindgren, 1911) and by provenance studies of Great Valley sediments (Linn and others, 1992). Matthes (1930) constructed an erosional chronology for the Merced River in and above the Yosemite Valley based on three surfaces he named the Broad Valley, Mountain Valley, and Canyon stages. Matthes felt that Broad Valley time represented a long period of stability during the Tertiary (about 6 or 7 Ma before his Mountain Valley erosional stage) in which more than 800 m of incision occurred, although these conclusions were largely discredited by Wahrhaftig (1965).

Modern Sierra topography represents renewed Sierra uplift and erosion that began in the late Cenozoic. In the Yosemite region, Matthes' visualized two episodes of late Cenozoic uplift, one at the end of the Miocene and another at the beginning of the Quaternary. Recent studies suggest that the present Sierra resulted from uplift that was spread out over a long period but may have accelerated during the late Cenozoic. Huber (1990) proposed that slow uplift may have begun as early as 25 Ma, but that the rate increased with time and may be continuing to increase. Unruh (1991) concluded that late Cenozoic tilting of the northern Sierra began between 8.4 and 3.4 Ma and proceeded at a more or less uniform rate (0.28 m/m.y.) throughout the late Cenozoic. Causes of this phase of Sierra uplift remain controversial and include theories related to Basin and Range extension, migration of the Mendocino triple junction, and thinning of mantle lithosphere by convection, thermal erosion, and mechanical stretching which increased buoyancy. Down-faulting of the eastern Sierra face affected drainage evolution not only by simple deformation of channel profiles, but also by beheading major channels. Lindgren (1911) shows a substantial length of the Tertiary American channel system extended beyond the present Sierra crest and Durrell () has indicated similar processes to the north. Based on the lack of bedload, deep valleys, and steep gradients of paleochannels near Soda Springs, however, Lindgren (1911) concluded that the Tertiary Yuba channel headed in close proximity to the present crest. Faulting along the eastern margin was recognized early on as an on-going process structurally related to Basin-and-Range faulting, and with an asymmetric or westward rotational component of movement. Most of the down-dropping occurred toward the close of the Tertiary after the uplift of the range. Evidence of down-dropping east of Donner Pass shortly before 2.3 Ma includes bracketing dates of 7.4 Ma for mudflow breccias that predate faulting, and 2.3 Ma for basalt flows at the foot of the escarpment (Birkeland, 1963; Dalrymple, 1964; Christensen, 1966).

Quaternary Glacial Stratigraphy. The glacial stratigraphy of the Sierra Nevada has been summarized elsewhere including by Fullerton (1986), Phillips et al. (1990), and recently by Clark et al. (2003), Gillespie and Zehfuss (in press) and Gillespie et al. (in press). The basic prevailing nomenclature is briefly reviewed here to put the tills and erratic boulders in the study area into the proper stratigraphic context. Blackwelder (1931) identified four stages in the east-central Sierra: McGee, Sherwin, Tahoe, and Tioga, correlated the Sherwin with Matthes' (1930) El Portal, and split Matthes' Wisconsin into the Tahoe and Tioga. He correlated the Tahoe with Bull Lake and Early Wisconsin advances of the central North American continent and, likewise, the Tioga with Pinedale and Late Wisconsin. The McGee till is oldest (~1.5 Ma) as there has been ~800 meters of erosion since its deposition (Gillespie and Zehfuss, in press). The Sherwin till and an "old red till" are associated with weathered deposits that are magnetically reversed. The old red till is capped by a soil with an estimated ~100 ka of development, and the overlying Sherwin till underlies the Bishop tuff that has an age of 759 ± 2 ka (Gillespie and Zehfuss, in press). In the northeastern Sierra near Truckee, the Hobart Till stratigraphically overlies the highly weathered and eroded Donner Lake Till (Birkeland, 1964; Fullerton, 1986).

Several well- to moderately well-preserved tills apparently fall within the range of oxygen isotope stages 2 through 6, including the Mono Basin, Tahoe, Tenaya , and Tioga advances (Table 1). It is likely that they include some of the deposits in the study area. The Tahoe advance may be the most prominent late Pleistocene moraine in the region, and near Truckee they are the oldest unit with recognizable moraine morphology (Birkeland, 1964). Unfortunately, there is considerable confusion regarding the age and nomenclature of the glaciations in this chronstratigraphic range (Gillespie and Zehrfuss, in press), so moraines in the study area are not correlated with these units. Lateral moraines are well preserved, but most terminal and recessional moraines have been eroded fluvially, and lateral moraine crests are usually subdued and dissected. (The moraine at Stop 3 is an exception.) Given the uncertainties and limited number of numeric dates, mapping of apparent MIS 4-6 glacial features uses local place names rather than correlating regionally. The Tioga (LGM) glaciation, on the other hand, is within the range of reliable dating and is fairly well constrained stratigraphically. Tioga moraines tend to have sharp-crested, bouldery moraines. Although previously mapped by the local name "Jolly Boy" (James, 1995), subsequent cosmogenic surface exposure dating of granitic erratics has clearly indicated these are Tioga in age (James et al., 2002).

Table 1. Generalized late Quaternary Sierra Glaciations. Adapted from Gillespie and Zehfuss (in press) where details and sources are given.

Glaciation	Mean Age (ka)
Matthes	0.6-0.1
Recess Peak	14.2-13.1
Tioga (retreat)	15-14
Tioga (start)	21-20
Tioga (T2-T4)	25-16
Tenaya (T1)	31-32
Tahoe II	50-42
Tahoe I	?
Mono Basin	80-60
Casa Diablo	126-62
Walker Creek	~550
Sherwin	~820
Lower Rock Crk	~920
McGee	2700-1500

Part II: Details on Stops

Stop 1. Big Bend. This site on the bottom of South Yuba (SY) Canyon was under ~320 m of ice during the Tioga (LGM) maximum advanced and shows signs of severe erosion. Between the Loch Leven trailhead and the visitors' center and between Hampshire Rocks Road and I-80, there is a large whaleback eroded in the ubiquitous granodiorite we have traversed down this valley. This whaleback is approximately symmetrical in the down-valley direction and shows evidence of ice-contact erosion on its lee side in the form of crescentic gouges at least part of the way downslope (James, in press). In accordance with theory of whaleback formation, this feature was under a relatively thick mass of ice which increases the overburden pressure relative to down-valley forces, thus discouraging flow separation and encouraging lee-side erosion (Benn and Evans, 1998). Such a form is in contrast to roches moutonnées that tend to occur under thin ice where flow separation results in plucking and steepening of the down-ice side and an overall asymmetry in the longitudinal direction.

A broad array of many unusually large crescentic gouges occur approximately 50 m up-valley from the trailhead and 20 m north of the road. These are the largest crescentic gouges found thus far in the NW Sierra region, although similarly large features were documented from the central Sierra by Gilbert (1906a) who provided a detailed explanation of their formation. Essentially, pressure applied by a boulder in the base of the ice generates a spherical tensile stress field from the point of contact (cf. Iverson, 1995). The largest crescentic gouge found here has a segment length of 134 cm and a depth of 91.6 cm (Figure 5 in James, in press). Although Harris (1943) concluded that size is primarily a function of the surface area of rock contact, there appears to be a relationship to depth and perhaps velocity as well. Iverson (1995) notes that the cross-section area of fracturing is proportional to the applied force.

A guest presentation will be made by Phil Sexton, Interpretive Specialist for the Tahoe National Forest, U.S. Forest Service, on difficulties encountered by travelers on the Emigrant Trail when they traversed this glaciated landscape.

Stop 2. Nyack overlook into Bear Valley (BV). The angular disconformity exposed in the side of Lowell Hill Ridge across BV is a cross section of the ancestral Yuba River Tertiary channel system that was flowing away from us to the west (Lindgren, 1911). The gold-bearing Cenozoic deposits of these channels were of great economic importance to California, although the greatest geologic wealth of the channels arguably has been their rich Cenozoic record including a tropical forest fossil assemblage and evidence of early Sierran tectonics. Gradients of the these channel beds were used to reconstruct the amount of Sierra uplift since the early Tertiary (Lindgren, 1911). Ancestral Yuba channel erosion was in response to an early period of uplift in the Sierra, long in advance of late Cenozoic Sierra uplift. By the time the deep channels had formed, a series of low hills were in the west with more rugged topography eastward (Lindgren, 1911; Yeend, 1974). Filling of these ancestral channels with volcanics during the Miocene and early Pliocene, combined with rapid late Cenozoic Sierra uplift, resulted in a redefinition of drainage into a series of consequent streams flowing perpendicular from the present crest of the modern range on the Sierra homocline. The modern southwestern channel orientation of most rivers such as BV forms a parallel (steep dendritic) drainage pattern.

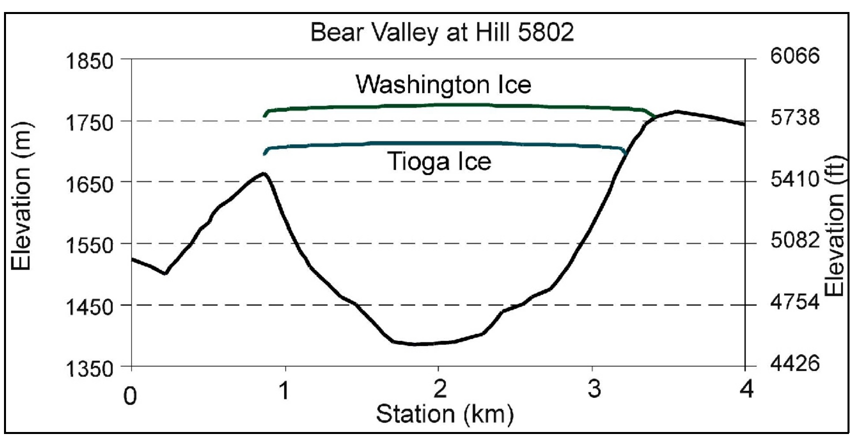

Figure 4. BV Cross Section showing two approximate ice levels. Left side of transect terminates over Emigrant Gap; our vantage point is much higher. (From James, 1996)

The base of the ridge is composed of Paleozoic Shoo Fly Complex weakly metamorphosed sedimentary rocks as will be seen at Stop 5. Paleovalley walls of resistant Shoo Fly rocks form spurs normal to BV directly west and below our observation point at a high bench that impeded ice flow and lowered ice gradients in BV. Weak volcaniclastic rocks filling the paleovalley allowed glaciers to widen BV to the characteristic U-shaped trough cross-section form (Figure 4).

Bear Valley is an underfit glacial trough, since the Bear River heads a short distance away on the valley side. The Bear River above this point was beheaded by the SY River that displays a barbed pattern (110°) where it turns abruptly into the SY Gorge (Figure 2). Presence of the Tertiary paleochannel in BV constrains the timing of SY Gorge incision and Bear River capture to after the Miocene-Pliocene volcanic epoch and supports a Quaternary age of the derangement (James, 1995). Glaciation of the uplands around the Gorge suggest that glaciation played an important role in the capture of the upper Bear River (See Stop 5). Glacial striae and lateral moraines indicate that ice branched into both the BV and the Gorge. From this vantage the stream capture can be envisioned clearly. Ice was flowing down through Spaulding basin and nearly filled BV at least three times. Granitic erratics on this andesitic hill indicate that ice was above the overlook here. These boulders are above the Tioga moraine and are tentatively grouped with the Washington advance associated with a broad, moraine we visit at Stop 3. The degree of development of BV and the SY Gorge during pre-Washington advance(s) is unclear.

Longitudinal profiles of the SY and Bear rivers reveal why the stream capture took place. Gradients are much steeper in the SY Gorge than in BV which is controlled by the Shoo Fly bedrock benches (Figure 5). Both the Bear and SY Rivers have complex, double-concatenary long profiles. The cause of these stepped profiles is not known, although both major faults and geologic contacts cross the profiles. The accordance between the upper Bear and the lower SY profiles supports the capture premise.

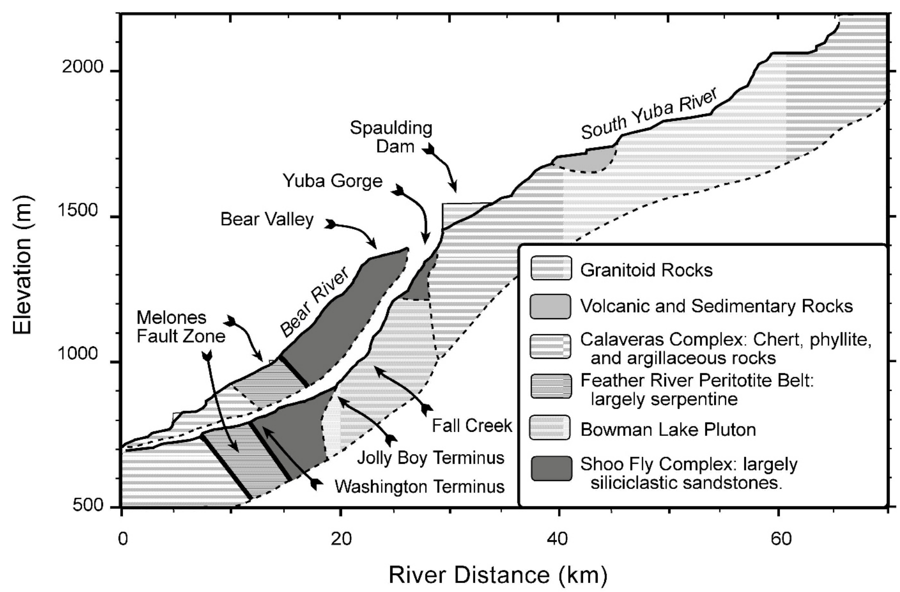

Figure 5. Longitudinal profiles of the Bear and SY valleys and structural relationships.

The V-shaped trough cross-section form of the glaciated SY Gorge was discussed at length by James (1996) and James and Davis (1994). Many glaciated valleys in this region are V-shaped and many non-glaciated valleys have hanging tributaries, so valley morphology must be used with discretion in mapping glacial extent. The V-shape of SY Gorge may be explained in part by the steep longitudinal gradients and intense subglacial melt-water erosion (cf. Embleton and King, 1975).

The South Yuba Canal along the base of the far valley wall is an example of the water transfers that were so important to early mining and agriculture in the state. This canal was initially constructed between 1853 and 1858 to deliver up to 6 m^3/s (210 cfs) from its diversion point at the site of Lake Spaulding to the mines around Nevada City (Larson, 1983). The low canal gradient brings it progressively higher up on the far ridge down BV until it crosses over the BV bench and passes into the Steephollow drainage through a tunnel a few km below Zeibright Mine.

Stop 3. Washington moraine in BV. This exposure provides the best view into the till structure of any lateral moraine in the region. This is all the more remarkable in that it is a pre-Tioga (pre-LGM) moraine, difficult to find so well preserved let alone with a good exposure. A single cosmogenic radionuclide surface explosure (CRSE) date from a granodiorite boulder on the crest of this moraine about 0.6 km up from this site provides a minimum limiting age of 48.8 ± 3.2 (10.4) ^{10}Be ka for this moraine. CRSE dates reported in this log present two error values. The first ± value gives one sigma analytical uncertainty that can be compared with other CRSE ages within this study, while larger parenthetical ± one sigma values also include uncertainty in production rates (20%) and radioactive decay constants (3%) and should be used when comparing these ages to other studies that use different methods (James et al., 2001). An AMS age of 47,510 ^{14}C yr BP (Beta 12339) was obtained from charcoal in a buried soil at this site. Together, the two ages indicate that this moraine is older than about 48 ka. Compared with stratigraphic units elsewhere in the Sierra (Table 1). While technically this moraine could be any of the old advances, preservation of the moraine morphology and limited soil development suggest that it is not an extremely old moraine. Thus, it is likely a Tahoe II, Tahoe I, or Monobasin, with a tentative preferrence for the Tahoe II. Clearly, more CRSE dating is needed. We will pass an immense granodiorite boulder (3 m high x 7 m wide) on the crest of this moraine that has been sampled but awaits funding for future dating.

This moraine site has been greatly disturbed by recent erosion from the tributary and by slope-stability engineering to stabilize the slope that we are standing on. During a large storm in the 1990s, a large discharge was released down the tributary from a canal above and that initiated an on-going period of slope instability and erosion. When first visited in the late 1980s, the slope graded down almost to the channel and gullies in the slope could be entered from below. For most of the past decade, however, erosion has been so active that the exposure is different every year. It was impossible, therefore, to sample the identical site from which the charcoal was extracted.

Caution! Going down the gully to the soil exposure is the single most dangerous aspect of this trip. The ropes do not extend to the base, gravel in the gully bed is highly mobile providing unreliable footing, and the gully ends in a patch of wet, slippery clay followed by an abrupt cliff. The soil begins at this treacherous juncture. No more than four or five people should go down at a time, and avoid packing in near the base because you could push someone over the cliff. Furthermore, these are not climbing ropes, so don't trust them to support your entire weight or the partial weight of more than one person at a time. Please do not feel it is necessary to go down the gully to see the buried soil. The important story here is the overall moraine morphology, best seen from up above.

Charcoal was extracted from the right side of the gully going down. That exposure has been eroded back at least 0.5 m and now has an abrupt wavy boundary between the overlying andesitic diamicton and the underlying charcoal-rich soil that once capped the moraine. The soil stratigraphy has not been properly described, but following is a brief description of the soil from the left side of the gully where the contact is transitional. Approximately 15 m of overburden has buried the soil. The tape was place arbitrarily such that zero was near the base of this material and the contact with the underlying soil was at 60 cm.

Depth (cm)	Description
40	Grain-to-grain andesitic diamicton. Matrix gritty with angular fine pebbles & coarse sand. Tacky; does not ribbon. Lithic sandy loam. Weak fine subangular blocky structure. 10 YR 4/4
60	Wavy gradual boundary between 60 and 90 cm. At some points, a thin 3-cm tan silt layer caps soil. Few pebbles or coarse sand. Ribbons somewhat and forms cohesive ball. Silt loam. Medium subangular blocky structure. 7.5 YR 4/6
80	Few pebbles or coarse sand. Ribbons fairly well and forms cohesive ball. Clayey silt loam. Medium subangular blocky structure. 10 YR 5/6
100	Few pebbles or coarse sand. Already wet. Tacky; does not ribbon well but forms cohesive ball. Silt loam. Medium subangular blocky structure. 7.5 YR 4/6

Stop 4. Lunch at Sierra Discovery Trails. Russell Towle will discuss local history.

Stop 5. South Yuba Gorge. While walking out to the edge, note the numerous large granodiorite erratics. When standing on the top of the ledge, we are on the floor of BV approximately 75 m above the bed of the SY River, indicating this much incision has occurred since capture of the upper Bear River. Low-angle grooves on the face of the ledge below us indicate ice flowed up and toward the Gorge (James, 1995; Fig. 9). The Paleozoic Shoo Fly Complex rocks are weakly metamorphosed, dark reddish-brown, quartz-rich psammites or greywackes and phyllites mapped largely as interbedded or feldspathic quartzite a few km to the southeast (Harwood, 1980). Due to their hardness, these rocks retain glacial polish and striae quite well. These and other directional indicators in this area such as grooves and small roches moutonnées, document two ice flow directions: down BV and down the SY River. The bench in the SY Valley bottom is striated and trenched indicating most of the erosion was accomplished prior to Tioga (LGM) recession. High amplitude, short wavelength entrenched meanders in the inner Gorge are structurally controlled to some extent, but suggest that catastrophic fluvial outburst erosion was not responsible for the final incision of this Gorge. At least some incision of the innermost Gorge was contemporaneous with Tioga glaciation since in the proper light grooves can be seen on the inner edge of the incision ~10 m down from the bench surface. It is likely that high subglacial hydrostatic pressures in the Gorge were highly erosive. At least three glacial advances were very deep at this location; almost topping the ridges on all sides of the gorge. After Tioga ice retreated from BV to this position, it continued to flow into the Gorge below BV floor near this site. The forested hummocky surface near Stop 4 is interpreted as lateral moraine materials and the flat fill in BV is interpreted as outwash deposited during this recessional Tioga phase.

Capture of the former upper Bear River was discussed at Stop 2. In spite of several extensive Quaternary glaciations, few channel derangements have been documented in the Sierra other than capture of a tributary to the upper Tuolumne River (Huber, 1990). Surprisingly little has been written of the Bear River capture (see reviews in James, 1995). Most accounts that recognize capture have attributed it to fluvial headward erosion; the classic explanation for stream capture (e.g., McPhee, 1992). Channel diversion by slow, progressive, headward erosion throughout the Cenozoic implies a substantive uniformitarian perspective that piracy is not only old, but also that valley bottoms in both systems have had considerable time to adjust hydraulically to the changes in their respective drainage areas. An important exception is the brief passage written by Cordell Durrell (1971):

> "...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)

Stop 6. Bedrock Benches in Rattlesnake Canyon. Several erosional benches were located in the study area that are described in detail elsewhere (James, in press). The morphology is striking given that the benches are often more than 150 meters (490 ft) and as much as 350 m (1100 ft) above the valley bottom and cut into steep (35°and greater) canyon side slopes of approximately vertical-dipping metamorphics. They are not severely eroded and are considered to be of late glacial age, although they may be polygenetic and exploited by multiple glaciations. Some areas of the bench surfaces have bedrock exposures showing they are rock cored and at least two of these surfaces are striated. Thus, they are erosive landforms rather than lateral moraine deposits, although lateral moraines may be associated with them. The Rattlesnake Canyon bench at this stop has a low Tioga moraine along parts of its inner margin indicating that the ice margin was adjacent to the bench at least during recession. In other cases, benches grade up-valley to till surfaces such as lateral moraines. Periglacial or glacial processes are not likely explanations for these surfaces because their flat tops dip down valley at a gradient approximately parallel with the inferred ice surface slope. In some cases flat-topped bedrock benches form on valley spurs that protrude out into the valley. In other cases they form on the up-valley leading edges of ridges that were nunataks. In the latter cases there is often a till capped ridge further up-valley and the benches represent a point where the ice flow divided around the ridge. The benches may be slightly lower in elevation than the glacial surface as erratics are often located slightly above the bench on valley walls.

The benches in the NW Sierra are interpreted as kame strath terraces; that is, the result of ice-marginal channel erosion (James in press), although no evidence has been found of fluvial deposits. In fact, no good sedimentary exposures have yet been found (I need to dig trenches). The valley-wall is often over-steepened where the bench meets it, suggesting scour in the cross-section direction; presumably by glaciofluvial undercutting. This hypothesis could be tested by trenching to see if rounded glaciofluvial gravels overlie bedrock on the valley side (now buried by a mantle of colluvium) and glaciofluvial gravels or till on the ice side represent kame terraces. Benches appear to occur preferentially on south-facing and up-valley sides of ridges; less commonly on north-facing slopes. This may be explained by the rapid production of meltwater on south-facing slopes early in the warm season before subglacial conduits have developed. Meltwater cannot percolate down into the ice so it forms ice-marginal channels (James, in press). These benches may have formed near an ice margin that shifted up and down with interannual and interdecadal climate variability. Thus, till, conglomerate, talus, and striae may occur in close association on these surfaces. Ice marginal channels may also be encouraged by asymmetric ice-surface cross-valley profiles regardless of slope aspect. This may be an important factor in the formation of the Rattlesnake Canyon bench where high ice in the South Yuba Canyon poured over the Tuttle Lake col area generating an ice-surface slope toward Red Mountain.

The down-valley slope is gentle and uniform, so the erosive agent was not moving from the side slopes. This is corroborated by the striae on some benches that are oriented approximately down-valley. The striae indicate glacial scouring of the benches although the benches were not created by glacial erosion. The down-valley striae orientation does not preclude cryoplanation or ice-marginal fluvial processes but requires an episode of erosion by valley glaciers where the bedrock is exposed.

Stop 7: Tioga moraine on Fordyce Ridge. We crossed from an older surface on the south side of the ridge to a Tioga (LGM) surface here. Tioga ice was on the Fordyce Canyon side to the north, not on the south side at this elevation. The sudden increase in boulder size and frequency at the contact is typical of Tioga moraines and is explained by the small amount of time for boulder weathering. The surface we drove in on was also glaciated but by an earlier advance and the boulders have been severely weathered so that granodiorite cobbles are largely gone and the frequency of large boulders is much lower. We will walk southeast up the ridge along this moraine to see how it merges with the ridge crest. To the west, the moraine seals off the col although an opening for meltwater is located about 200 m from the road. This opening supplied Tioga outwash to the meadow in the floor of the col and to Rattlesnake Canyon. This Tioga moraine may be correlated with the advance that retreated from OMM ~14.1 ka (see at Stop 8), or it may represent an earlier Tioga indicated by CRSE ages in BV of 18.6 ka. We have no evidence of muliple advances at ca. 18 and 16 with an interstade between them, but this is implied by more complete data from the east-central Sierra and pluvial lakes (Phillips et al., 1996; Benson et al., 1996; Benson, 1999). There is a complex of Tioga moraines in this col that may represent two or more ages.

Stop 8: View north into and across lower Fordyce Canyon. Across canyon is Old Man Mountain (OMM) and lateral moraines in front of Beyers Lake. Nine CRSE ages were obtained from a 420-meter transect up the SE flank of OMM on striated or polished granodiorite (James et al., 2002). The age of the highest surface was rejected because it is anomalously young. The remaining eight ages average 14.1 ^{26}Al ka representing our best estimate of the time when ice left this canyon. Below us is a low Tioga moraine. From its edge can be seen two low cirque lakes in Fordyce Canyon. Lower Fordyce Canyon is characterized by rugged Knock and Lochaine topography caused by glacial plucking of large granodiorite blocks.

Stop 9: View south across Rattlesnake and South Yuba Canyon. From east side of high col, walk south ~50 m out to the ledge for view of Red Mountain (at right), Cisco Butte (230°) and Hill 6542 to its left, Snow Mtn. (180°), and Devil's Peak (140°). The granodiorite contact with older metamorphic rocks can be seen across Rattlesnake Canyon down to near Stop 6 and traced back to where we stand. This igneous contact zone explains the mine claim here.

Part III: Trip Log

Incremental		Cumulative		
Miles	km	Miles	km	Features and Notes
0.0	0.0	0.0	0.0	Start from south side of Hilton
0.40	0.64	0.6	1.0	Go north in parking lot, turn right at stop, go east turn left, go north to 2nd St and turn left. Stay in left lane.
0.10	0.16	0.7	1.1	Turn left onto I-395 northbound. Stay in right lane, go over I-80 overpass.
0.80	1.29	1.5	2.4	Veer right on I-80 westbound ramp. Stay on I-80 ~an hour without stopping.
0.60	0.97	2.1	3.4	South Virginia St. Main boulevard for the cultural heart of Reno centered around casinos, hotels, and tourism non-stop, around-the-clock.
2.20	1.93	4.3	6.9	Rapid urbanization on sageland
2.00	3.22	6.3	10.1	Hill crest: Truckee fan terraces ahead. Canal midway up scarp to left.
1.80	2.90	8.1	13.0	Down to low Truckee River terrace. Exposure in high terrace to left.
1.40	2.25	9.5	15.3	On a middle-level terrace.
0.80	1.29	10.3	16.6	Exposure in middle-high terrace.
1.60	2.58	11.9	19.2	View ahead of Verdi Range on Calif. side of border (N-S ridge). Truckee River left gorge, forming a fan that has been deeply incised.
0.40	0.64	12.3	19.8	Cross Truckee River
3.10	2.58	15.4	24.8	State line; Welcome to California... and to the Sierra Nevada!
6.40	0.81	21.8	35.1	Burn area from forest fire summer, 2001. Andesitic lahars with primary structures preserved.
1.50	0.32	23.3	37.5	Climbing up Truckee Canyon at base of Boca Hill through andesitic lahars.
0.80	0.16	24.1	38.8	Highway tops andesitic ridge. Sierra Nevada crest ahead.
2.10	1.45	26.2	42.2	Cross Truckee River
0.60	0.97	26.8	43.1	Cross Prosser Creek
1.60	2.58	28.4	45.7	Cross Truckee River
0.70	1.13	29.1	46.9	Climb to flat plain (Sherwin Outwash). Young outwash below on left being quarried.
0.30	0.48	29.4	47.3	Truck weighing station.
0.80	1.29	30.2	48.6	Low hummocky Sherwin(?) moraines; high Tahoe moraine ahead (Birkeland 1964).
0.50	0.81	31.3	50.4	Junction Hwy 89 north
2.30	2.74	33.6	54.1	Ramp to central Truckee
0.70	1.13	34.3	55.2	Junction Hwy 89 south
0.70	0.97	35.0	56.3	Agricultural inspection station. Stay in single line; leader will explain lunches. Calif. seeks to stop import of agricultural pests by stopping produce.
0.50	0.81	35.5	57.2	Begin climbing to Donner Pass. Donner party camped along broad area of

				meadows to left.
0.60	0.97	36.1	58.1	Tahoe moraine on high ridge at right. Granodiorite erratics on andesite.
0.90	1.45	37.0	59.6	Donner Lake at left; Central Pacific Railroad snowsheds on ridge beyond.
1.20	1.93	38.2	61.5	Vista turnout; don't stop. View of granitic Sierra Nevada Crest to left.
0.60	0.97	38.8	62.5	Junction road to upper Donner Lake
1.10	0.81	39.9	64.2	Steep east-facing Sierra Nevada front to left. Popular rock-climbing site.
1.30	1.45	41.2	66.3	Exposure of granodiorite batholith.
0.20	0.32	41.4	66.7	Castle Peak to right; andesitic flows with subalpine forest (open woodland up to timberline).
0.60	0.97	42.0	67.6	Sierra Crest; elevation 2200 m (7220 ft). Lodgepole pine forest.
0.10	0.16	42.1	67.8	Rest area; don'stop, five minutes to first stop.
0.60	0.97	42.7	68.7	Norden/Castle Peak ramp
1.20	1.93	43.9	70.7	View of Norden Valley to left.
0.80	1.29	44.7	72.0	View ahead of Lower Castle ice field and andesitic ridge.
0.60	0.97	45.3	72.9	Soda Springs ramp
0.50	0.81	45.8	73.7	Andesitic ridge ahead to right.
1.20	0.32	47.0	75.7	Flat-topped andesitic bench to right. Ice topped bench but not top of ridge.
1.30	2.09	48.3	77.8	Kingvale ramp; on left glaciated granodiorites slope up steeply to moderately low glaciated plateau with glacial lakes (out of view). About 3.5 km (2.2 mi) to south is Devils Peak.
1.50	0.97	49.8	80.2	Cross South Yuba River. Granodiorite outcrops are ubiquitous. Bedrock in Inner valley is granodiorite but ridge to north (right) is capped with andesite. Granodiorite boulders on andesitic ridge are erratics.
1.40	2.25	**51.2**	82.4	**Exit I-80 at Big Bend / Rainbow Road Ramp**; take left at end of ramp, go under highway and follow road to right.
0.80	0.81	52.0	83.7	Cross South Yuba River.
0.40	0.64	**52.4**	84.4	**Stop 1: Big Bend parking lot**; Crescentic gouge. Rest rooms; if line is long can walk to visitors' center.
0.20	0.32	52.6	84.7	Big Bend; TNF Visitor's Information Center
0.50	0.48	53.1	85.5	First overpass; crossing from granodioritic batholith into Sailor Cn Fm; contact obscured.
1.95	2.66	54.2	87.3	**Turn left then right onto I-80 westbound**.
3.80	0.40	58.0	93.5	Hwy 20
0.25	0.40	58.3	93.9	Tioga moraine up to left
0.40	0.64	58.7	94.5	Exposure of Tioga moraine up to left
0.65	1.05	59.3	95.6	Burned area on left revealing erratics
2.25	3.62	61.6	99.2	Emigrant Gap ramp
0.70	1.13	62.3	100	Emigrant Gap vista point
0.50	0.81	**62.8**	101	**Exit Freeway at Nyack Exit** to right; go to end of ramp.
0.30	0.48	63.1	102	Turn left under bridge to service center; trip leader gets gate open.
0.40	0.64	**63.5**	102	Go back under bridge and up hill. **Stop 2: Nyack Hill overlook**
0.30	0.48	63.8	103	Return to I-80 turn right on westbound ramp.
0.80	1.29	64.6	104	Flat stretch with occasional granitic erratics. Old Man Mtn directly to rear.
0.60	0.97	65.2	105	BV to right; brief view of large boulder on bedrock bench.
1.00	1.61	66.2	107	Last Washington erratics on right at right (out of view)
3.40	5.47	**69.6**	112	**Exit Freeway at Drum Forebay Road**
0.50	0.48	70.1	113	Go to end of ramp; make hard right turn; bear to right at first junction.
0.90	1.45	71.0	114	2nd junction; go up to left
0.30	0.48	71.3	115	3rd junction; take hard right onto power line road; then bear to left staying

				on power line road across penstock
0.80	1.13	**72.1**	116	**Stop 3: Washington Moraine**. Park at road junction; hike ~70 down through gate then bear right ~50 m downslope to exposure.
0.20	0.32	72.3	116	Regolith in road cut; no till. We're presumably above maximum glaciation
0.30	0.13	72.6	117	View of Washington moraine ahead at power lines.
0.10	0.16	72.7	117	2 junctions; bear left then right; stay on main road
0.05	0.08	72.7	117	Extremely large granodiorite boulder on crest of Washington moraine
0.55	0.89	73.3	118	Low granodiorite frequencies across this Washington (preTioga) surface
1.35	0.56	74.6	120	Bench below road; Tioga moraine?
0.05	0.08	74.7	120	Granodiorite boulders; entering Tioga complex
1.00	0.32	75.7	122	Narrows between Bear Valley benches
0.50	0.80	76.2	123	1st bridge; over Bear River
0.10	0.16	76.3	123	2nd bridge
0.20	0.32	76.5	123	junctions; bear right then left; stay on main road.
1.00	1.37	77.5	125	Bear right then left.
0.12	0.03	**77.6**	125	Turn right onto Hwy 20
0.28	0.45	77.9	125	Cross Bear River
0.45	0.72	**78.3**	126	Turn left on Nation Forest 18
0.55	0.89	78.9	127	**Stop 4: Lunch at Sierra Discovery Trail; cedar grove**
0.40	0.48	79.3	128	**Stop 5: South Yuba Gorge.** Hike north across striated Shoo Fly rocks
0.90	1.45	80.2	129	Back to Hwy 20
0.40	0.64	80.6	130	Cross Bear River Canal
1.20	1.93	81.8	132	Tioga recessional moraine
0.60	0.97	82.4	133	Nevada/Placer County Line
1.60	2.58	84.0	135	Go straight to E-bound I-80
0.30	0.48	84.3	136	Old Man Mtn and Spaulding ice field ahead
3.40	0.81	87.7	141	**Exit I-80 at Cisco Grove Exit**
0.20	0.32	87.9	142	Go left (north) across bridge (.2 mi) then left at T junction (.1 mi)
0.30	0.48	88.2	142	Turn right on Rattlesnake Canyon Rd.
2.30	3.70	90.5	146	**Stop 6: Bedrock bench.** Park near gate. Choice: (1) explore contact metamorphism, granodiorite/metamorphic contact, and waterfalls. (2) steep hike up ATV trail to bedrock bench
0.30	0.48	90.8	146	Woodchuck Flat campground
1.00	0.89	91.8	148	View Washington moraine high up on valley wall between 305 and 280°
0.55	0.56	92.3	149	Junction; go left toward BSA camp, Lake Sterling, and Fordyce Lake
0.70	1.13	93.0	150	Junction; go left toward Lake Sterling
0.15	0.24	93.2	150	view of Tioga moraine to left
0.15	0.24	93.3	150	Crossing bouldery sharp-crested Tioga moraine
0.10	0.16	93.5	151	**Stop 7: Tioga moraine.** Park along road and hike up ridge to south along Tioga moraine that obliquely climbs ridge.
0.40	0.64	93.9	151	back to Lake Sterling/Fordyce Rd junction; turnj right onto Fordyce road
0.10	0.16	94.0	151	Turn left onto unmarked dirt road to Signal Peak
0.10	0.16	94.0	151	Bear right at first junction across one of the Tioga moraines; keep bearing right at next junction
0.10	0.16	94.2	152	Follow road up to left; road ahead is rough. This area above the Tioga has abundant large boulder erratics but few fine granitics and no moraine morphology. Interpreted as Washington Till.
0.10	0.16	94.2	152	End of Washington till; andesitic volcanic diamicton (lahar) ahead.
0.05	0.08	94.3	152	Crest of andesitic hill

0.10	0.16	94.4	152	Anomalous small fresh granitic boulder at left.
0.10	0.16	94.5	152	**Stops 8&9: Fordyce and Rattlesnake Canyon overlooks**. Park along road. Drivers please set up refreshment table near edge of ridge ~50 m to south then catch up with us. We hike forward on road ~250 m then leave road at bearing ~320 to overlook of Fordyce Canyon and Old Man Mtn. Return to cars and up east side of col, leave road to south ~50 m out to overlook across Rattlesnake Canyon.

Return to Hilton Hotel, Reno with restroom stop at Donner Pass rest area.

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