

# Field Trip Guide and Road Log:

## *Tracking Hydraulic Mining Sediment in the Sierra Foothills and Sacramento Valley*

April 15-17, 2007

Annual Meeting of the Association of American Geographers, San Francisco

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Crevasse splays and natural levee formation where the Feather River enters Sutter Bypass.  
1958 aerial photograph scanned from collection at U.C. Davis map library.



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Welcome to the *Tracking Hydraulic Mining Sediment in the Sacramento Valley* field trip. Over the next couple days we will examine the effects of hydraulic mining on fluvial sedimentation, channel morphology, alluvial geochemistry, and flood conveyance in the Sacramento Valley. The trip will begin at the source of the sediment in the mining districts high in the Sierra 'foothills' and will proceed down to the Sacramento Valley. This field trip 'Guide' will provide an itinerary for the trip and a background to help orient you to the geographic, geologic, hydrologic, and social aspects of the region that are relevant to the hydrogeomorphic issues to be covered by the trip.

### BRIEF OVERVIEW OF ITINERARY

The emphasis of this trip is on hydraulic gold-mining tailings and the impacts they have had on environmental and flood-conveyance systems in the Feather, Yuba, and Bear Rivers (Figure 1). We will highlight linkages between the episodic production of mine tailings and their reworking and deposition downstream, including in flood bypasses. Methods and preliminary results of an on-going study that involves sediment inventories and fingerprinting of historical sediment will be discussed. The trip will depart from the San Francisco Hilton Hotel at 9:00 am Sunday morning and will return to the same location by 3:30 pm Tuesday. We will visit hydraulic gold-mine pits of the northern mines, deep gravel deposits immediately below the mines, channels in the Sacramento Valley, and depositional areas in the Sutter and Yolo Bypasses.

Figure 1. Oblique view to east across San Francisco Delta to Sierra Nevada and Lake Tahoe in distance. Trip itinerary is shown by day. Satellite imagery draped over digital elevation model (DEM). Source: William Bowen; Used with permission.



On the first day we follow Interstate 80 ENE to Colfax and take Highway 174 north and back roads to the Red Dog-You Bet Mine. After a brief stop we go to Steephollow Crossing for lunch. Steephollow Creek is a tributary of the Bear River. This will be followed by visits to two sites on Greenhorn Creek, another tributary of the Bear River, and dinner and lodging in Nevada City. We will hike up Greenhorn Creek about one mile (1.6 km). River shoes are recommended (sandals or canvas sneakers).

On the second day, we will cross the South Yuba River to San Juan Ridge, and hike into the Cherokee hydraulic mine in upper Shady Creek. This will be a short hike on a gravel road. We will then drive down San Juan Ridge to the South Yuba River at Bridgeport where we will have lunch. After lunch we leave the foothills for the Sacramento Valley following the lower Yuba and Feather Rivers to the Sutter Bypass flood conveyance system. If time allows we will stop at the Bear River levee setback and along the Feather River to examine alluvial strata in the streambank. In the late afternoon we will drive north to Colusa where, after a visit to the Colusa Weir (if time), we will spend the evening in Colusa.

In the morning of the third day we will drive south to the Fremont Weir and return to San Francisco.

## BACKGROUND

[Much of this section was excerpted in abbreviated form and revised from James and Davis, 1994]

The following discussion provides a brief introduction to the physical geography of the region. Additional, more specific information will be presented in the context of individual stops.

### Geologic History

The stratigraphy of the Sierra Nevada is conventionally divided into two major groups: the subjacent series and the superjacent series (Lindgren, 1911; Bateman and Wahrhaftig, 1966). The *subjacent series*, also known as 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 often exposed in glaciated areas or in lower canyon walls where they have been exposed by fluvial and colluvial erosion. 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* lay unconformably on top of the basement rocks and dip gently to the southwest with relatively little deformation or regional metamorphism. These rocks are largely on ridgetops at moderate elevations, and on reaching the eastern margin of the Sacramento Valley they plunge beneath Quaternary alluvium. Early superjacent rocks include the auriferous (gold-bearing) channel deposits that were worked by hydraulic gold mining. Later superjacent rocks are largely volcanic or volcaniclastic that were deposited during two major volcanic episodes; a period of rhyolitic volcanism followed by an extensive period of andesitic volcanism. Andesitic deposits, such as those in the Mehrten Fm., are largely lahars in the foothills region (Durrell, 1966; Slemmons, 1966).

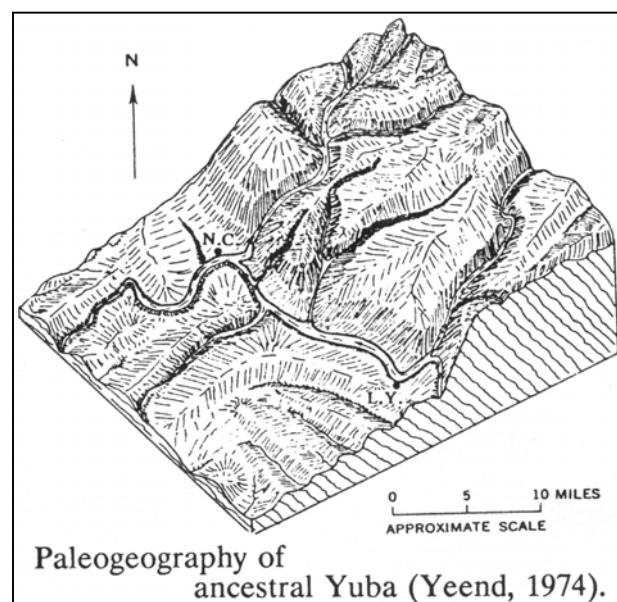
An early period of rapid uplift in the late Mesozoic or early Tertiary resulted in substantial mountain building of a proto-Sierra range. Pre-Eocene uplift in the northern Sierra was on the order of 8 to 12 km (Unruh, 1991). A long period of tectonic stability followed and deep erosion had begun to expose the granitic batholith by the early Tertiary as evidenced by granitic contacts under Eocene gravels in ancestral Yuba channels (Lindgren, 1911: 72) and by provenance studies of Great Valley sediments (Linn and others, 1992).

Modern Sierra Nevada valleys are the result of renewed Sierra uplift and erosion in the late Cenozoic. On the basis of prominent erosional features in the Yosemite region – a high Mountain Valley erosional surface and inset canyons – Matthes (1930) postulated two episodes of late Cenozoic uplift: one at the end of the Miocene and another at the beginning of the Quaternary. He concluded that the Pliocene was an orogenically quiet period during which the *Mountain Valley* erosional surface formed. He envisioned sudden recommencement of tilting and uplift in the Quaternary ~1 Ma B.P. that lifted summit peaks to twice their heights and resulted in incision of the deep gorges seen today. This incision included glacial erosion in some locations, but was not dominantly glacial erosion (Matthes, 1930). Subsequent studies have recognized some degree of Pliocene tectonic activity. Huber (1990) suggested that slow uplift may have begun as early as 25 Ma, but accelerated. Working in the northern Sierra, Unruh (1991) concluded that late Cenozoic tilting began between 8.4 and 3.4 Ma, proceeded at a uniform rate (0.28 m/Ma) through the late Cenozoic, and was too late to be caused by Basin and Range extension. He questioned the time-transgressive tilting hypothesized by linking uplift to migration of the Mendocino triple junction (Crough and Thompson, 1977).

We will see rocks of the superjacent series on ridgetops and in mine pits and subjacent rocks in canyon bottoms. We cross the deeply eroded gorge of the South Yuba twice on the second morning.

**Early Tertiary Channels.** Gold-bearing upland Tertiary channel deposits were the initial source of gold exploited by hydraulic mining and led to settlements such as Nevada City and Grass Valley that were centers of California population at one time. The channels also contained a wealth of geologic fossil information about the Cenozoic history of the Sierra Nevada and were studied in great detail (Whitney, 1879; LeConte, 1880; Lindgren, 1911). Erosion of the Ancestral Yuba channel had been in response to the early period of uplift of a proto Sierra described earlier, long before the late Cenozoic uplift. At the time the deep upland channels were flowing, hills to the west were gentle and rolling with more rugged topography eastward (Lindgren, 1911; Yeend, 1974). This paleo landscape is illustrated for the region between Little York (near Dutch Flat) and North Columbia on San Juan Ridge (Figure 2). Details of the Tertiary channels are provided at the Red Dog You Bet Mine stop on the first day.

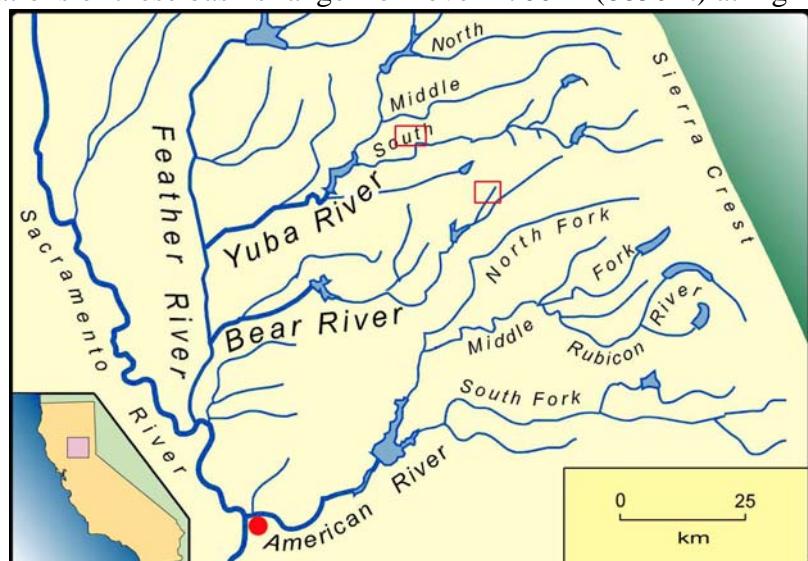
Figure 2. Paleogeography of ancestral Yuba. (NC = North Columbia; LY = Little York) Source: Yeend, 1974.



## The Modern Physiography of the Region

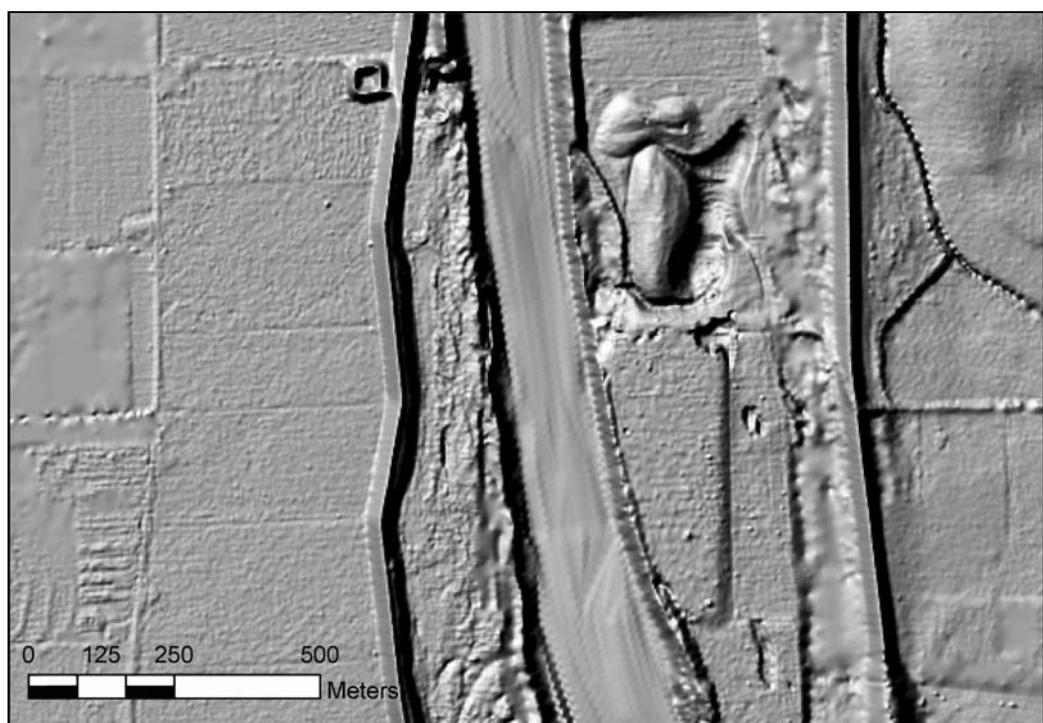
The Feather, Yuba, and Bear Rivers flow southwest out of the Sierra Nevada into the Sacramento Valley (Figure 3). The upper basin of the Yuba River heads at the Sierra Nevada crest to the east. The Bear River was beheaded by the South Yuba (Durrell, 1971; James and Davis, 1994; James, 1995) and heads at a lower elevation around 2000 meters (6000 ft). The Feather River heads to the east beyond the Sierra crest. In a relatively short distance, elevations of these basins range from over 2700 m (8850 ft) at high peaks on the Sierra crest down to around 5 m (15 ft) in the lower Feather River near the Sacramento River.

Figure 3. Regional map showing major rivers draining southwest from the Sierra Nevada.



The major rivers are incised into deep ravines – often more than 600 meters (1800 ft) deep – separated by high ridges with hanging tributaries. In contrast, the Sacramento Valley is characterized by low local relief. Where main channels leave the narrow mountain canyons and enter the Valley, each has formed a broad fan lined by Quaternary terraces. Further down-fan, natural levees take high topographic positions and flood basins dominate away from the channels (Figure 4).

Figure 4. Lidar imagery of lower Feather River including Lidar bathymetry. The dominant topographic features in the lower rivers are artificial levees, stream banks, and quarries. Source: Data from US Army Corps of Engineers.



**Climate, Vegetation, and Soils.** The regional climate grades from Mediterranean in the Valley with cool, wet winters and warm, dry summers to Montane at higher elevations that have colder, wetter winters. Summer precipitation is common at higher elevations but does not provide a reliable water supply or generate floods. A steep precipitation gradient up the Sierra slope, results from orographic uplift of prevailing maritime westerlies over the steep, west-facing slopes of the upper basins. The Sacramento Valley annual rainfall is only 45 cm (18 in) while up on the Sierra crest totals reach as high as 180 cm (70 in) (USACE, 1991, App.K-5) and occurs mostly from November to March. At high elevations, winter precipitation falls primarily as snow which is stored and released through the spring and summer. Sierra Nevada snow-water equivalents and snow-line elevations vary inter-annually. In warm years, rainfall may dominate, generating intense early spring runoff events, high flood peaks, and less snow-pack storage (Aguado, 1990; Aguado and others, 1992; Pupacko, 1993). Thus, climate warming appears to be raising snow lines, generating earlier spring melt-offs, and exacerbating flood hazards.

The vegetation of the western Sierra and Sacramento Valley is closely tied to elevation. Glaciated upper basins are vegetated by alpine tundra at high elevations down to subalpine forest communities of western white pine (*Pinus monticola*), western juniper (*Juniperus occidentalis*), lodgepole pine (*Pinus contorta*), and mountain hemlock (*Tsuga mertensiana*) (Munz and Keck, 1973). The mining districts are dominated by mixed coniferous forest and chaparral. The mixed forests contain dense stands of large Douglas fir (*Pseudotsuga menziesii*), western yellow pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), incense cedar (*Calocedrus decurrens*), and black oak (*Quercus kelloggii*). At lower elevations of the piedmont and on south-facing slopes in the foothills, grassland, chaparral, and woodland dominates. Woodland and chaparral species include manzanita (*Arctostaphylos spp.*), California buckeye (*Aesculus californica*), oaks (*Quercus spp.*), and digger pine (*Pinus sabiniana*). In the Sacramento Valley, uplands were colonized by grassland savanna, and slightly elevated surfaces such as natural levees maintained a gallery forest with oaks and riparian hardwoods. Lowland basins were dominated by tule marshes (large sedges or bull-rushes in fresh-water wetlands).

Soils in the region reflect the altitudinal zones through strong differences imparted in climate, vegetation, and local relief. Valley soils have thermic temperature and xeric moisture regimes and often support grasses. Soils at intermediate foothill elevations have mesic and udic regimes supporting coniferous forests, while at high elevations (beyond the limits of this trip) cryic temperature regimes prevail. Old Ultisols and Alfisols with red argillic horizons are common on stable interfluvial surfaces where they are exposed in road-cuts in the foothills. Some Ultisols can be seen along the rims of the hydraulic mines where they have developed in the Tertiary “auriferous” gravels. The youngest soils in the Central Valley are Inceptisols and Entisols developed on Quaternary alluvium with occasional Histosols on peaty soils of marshy areas.

**Quaternary Stratigraphy.** The Quaternary history of these watersheds is important to proper interpretations of the alluvial stratigraphy. Climate changes -- especially glacial advances -- were directly linked to aggradational periods recorded in the Valley as Quaternary terraces. The glacial stratigraphy of the Sierra Nevada has been reviewed by Fullerton, 1986, Phillips et al. (1990; 1996), and James et al. (2002). Soil and alluvial stratigraphies in the Central Valley have been related to Sierra climatic changes and glacial advances (Marchand and Allwardt, 1981; Atwater and others, 1986). The basic glacial nomenclature can be summarized by four well-documented stages: McGee, Sherwin, Tahoe, and Tioga (Blackwelder, 1931). The McGee and Sherwin surfaces are old, weathered, and magnetically reversed (> 730,000 B.P.) with eroded and poorly preserved moraines (if any) (Bateman and Wahrhaftig, 1966). The dominant geomorphic features in the mountains are often represented by

Tahoe and Tioga moraines, although other units are possible and time-stratigraphic correlations are poorly constrained beyond the Tioga advance (James et al., 2002). Details and additional glacial stratigraphic units are beyond the scope of this brief review.

At the margin of the Central Valley where main channels emerge from the Sierra foothills, Pleistocene terraces record fluvial responses to climatic changes and glacial advances in the high Sierra (Bryan, 1923). Low terrace sequences in the San Joaquin River have been stratigraphically interpreted as the Arroyo Seco Gravel (early Pleistocene), Riverbank Fm. (middle Pleistocene), Modesto Fm. (late Pleistocene), and Recent Alluvium (Piper et al., 1939; Davis and Hall, 1959; Janda, 1965; Marchand and Allwardt, 1981). Key Quaternary alluvial units of the Central Valley are outlined in Table 1. In spite of several extensive Quaternary glaciations, few channel derangements have been documented other than capture of a tributary to the upper Tuolumne River (Huber, 1990). Piracy of the upper Bear River is of particular interest in this context because it may have occurred in the late Quaternary (James, 1995) and, if so, should be recorded in the alluvial stratigraphic record of the Valley.

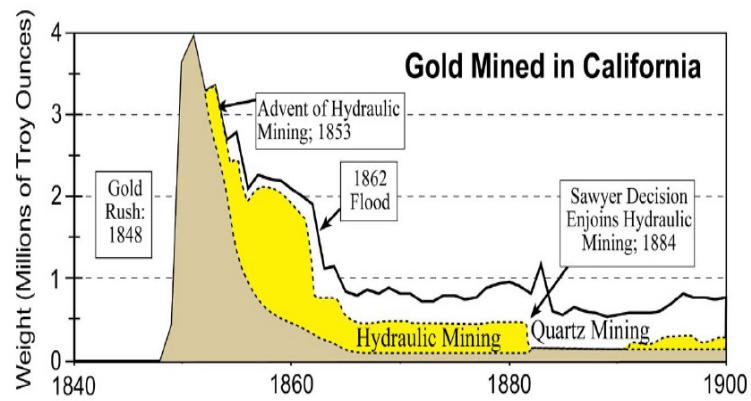
**Table 1.** Generalized Quaternary Chronostratigraphy.

Fm./Unit	Age (ka)
Modesto Upper	14 to 9
Modesto Lower	42.4
Riverbank Upper	140 45; 150 20
Riverbank Middle	260 45
Riverbank Lower	~336-356
Turlock Lk Up.	~600
Turlock Lk Low.	> 730

## A BRIEF HISTORY OF HYDRAULIC MINING

Mining technology evolved rapidly in California between 1849 and 1884, especially after hydraulic mining was invented in 1853 (Paul, 1947). Placer mining began in 1848 and gold yields quickly peaked in 1851 as yields from shallow river gravel had already begun to decline (Figure 5).

Figure 5. Revenues from gold mining in California reached a maximum very quickly after the onset of the Gold Rush. As easily mined placer gold was quickly exhausted, mining began to require more labor-intensive methods. Hydraulic mining began in 1853 and quickly expanded through the 1860s. It was enjoined in 1884. Total weights are from Loyd and Bane (1981); subdivisions approximated by James (1994)



Miners soon realized that gold could be traced upstream to upland Tertiary paleochannels. These deposits could be worked but profitable mining required moving large volumes of sand and gravel. Hydraulic mining, which uses water under pressure, was invented near Nevada City between 1853 and 1854. Miners extracted gold by excavating immense pits on ridge tops and washing the waste materials into the deep ravines below (Gilbert, 1917; Paul, 1947; Kelley, 1954; 1956; 1959; 1989; May, 1970; Rohe, 1985; Burgess, 1992). Until the early 1860's hydraulic mining exploited the upper bench gravels because the deep channel gravels were coarse and cemented and mining technologies had not yet been developed (Paul, 1947). Volumetrically, the upper bench gravels cocomprised most of the sediment produced by mining as demonstrated by pebble lithologies in tailings below the mines (James 1991a). The deep gravels began to be mined in the early 1870's with technological developments and large foreign capital financial investments. The advent of dynamite and large water canons (hydraulic giants and monitors) greatly improved the ability to remove the deep gravels. Hard-rock mine engineering methods from Wales and Cornwall were applied to develop tunnels up into the base of the mine pits, and extensive canals from the high country were developed to deliver water supplies to the mines. Although the deep channel gravels were richer, they produced less sediment to the rivers below because they were volumetrically much less extensive, and the coarse, heavily cemented gravels were hard to move.

**Hydraulic Mining-Sediment Production.** Annual sediment production by hydraulic mining was estimated by analyzing volumes of water used by the mines (Hall, 1880; Mendell, 1881). Initial estimates of sediment produced in the Bear River were too low. The estimates were derived assuming only 3.0 cubic yards of sediment were moved per miner's inch of water because the Bear River mines were working the coarse, well-cemented, lower gravels in the late 1870's (Benyaurd et al., 1891; Hall, 1880; Mendell, 1881). Yet hydraulic mining had begun earlier in the Bear River basin than most basins, and most of the fine bench gravels had been removed, so when the estimate was made many of the pits were down onto the coarse lower gravels. Sediment production would have must have been much greater in the early years when gravel extraction was easier. This was realized by Manson (1882) who rejected the earlier estimates of sediment production made by Hall and Mendell for the Bear River. Using a more common value of 4.5 cubic yards of sediment per miner's inch, he calculated a much greater annual sediment yield for the Bear River:

“The State Engineer, in his report of 1880, estimates 3 yards as the average duty, but the direct measurements upon which this estimate was based were confined to a few mines on the south bank of Bear River, where the amount of water used is smaller and the material coarser than on the north bank. There is no apparent reason why a miner's inch on the north bank of Bear River, where most of the water is used and where the largest deposits are worked, should not have as high a duty as on the mines of the American, where an estimate of 4.5 cubic yards per inch is given.” (Manson, 1882)

A survey by Turner (1891) shortly after mining had ceased estimated that the Bear River received more sediment per unit drainage area than other large basins. The Bear, South Fork Yuba, and North Fork American Rivers received more sediment than other basins  $>1000 \text{ km}^2$ . The Middle Fork Yuba and Deer Creek were smaller basins with large sediment productions. Topographic surveys of the mine pits led Gilbert (1917) to increase Turner's estimates by 51%. Gilbert rejected his estimate of production in the Bear Basin, however, because an estimate of sediment storage in the lower Bear was very small (Benyaurd et al., 1891), so the sediment delivery ratio was too small (Gilbert, 1917: 48). Thus, Gilbert (1917: 40) lowered his initial estimate of production in the Bear River basin by 28%. Subsequently, the early estimate of storage in the lower Bear Basin has been shown by coring through the deposits to have been far too low (James, 1989). Gilbert's original estimate of sediment production in the Bear River is unbiased, comparable to other basins, and compatible with the vast deposits remaining in the basin.

**Table 2.** Sediment Production Statistics by Basin. Adapted from James (2004) based on Gilbert's recommend 1.51 adjustment to previous estimates.

Basin	Drainage Area (km <sup>2</sup> )	Volume Prod. (m <sup>3</sup> 10 <sup>6</sup> )	Volume Vol/Yr (m <sup>3</sup> yr <sup>-1</sup> )	Vol/Dr.Area (mm)	(Dr.A*Yr) p=2.2*	Mass Prod (t 10 <sup>6</sup> )	Spec.Prod (10 <sup>6</sup> t yr <sup>-1</sup> )	Spec.Prod (t km <sup>-2</sup> yr <sup>-1</sup> )
<b>Feather Basin</b>								
at Yuba City	10,301	77	2.5	7.4	0.2	168	5.4	527
<b>Yuba Basin</b>	3,499	523	16.9	149.6	4.8	1,151	37.1	10,616
North Yuba	1,351	165	5.3	122.4	3.9	364	11.7	8,683
Middle Yuba	536	109	3.5	203.7	6.6	240	7.7	14,455
South Yuba	988	165	5.3	167.2	5.4	363	11.7	11,866
Deer Creek	233	29	0.9	126.4	4.1	65	2.1	8,968
<b>Bear Basin</b>	1,143	271	8.7	236.8	7.6	596	19.2	16,807
<b>American Basin</b>	5,014	197	6.3	39.2	1.3	433	14.0	2,783
North Fork	900	164	5.3	181.7	5.9	360	11.6	12,895
Middle Fork	1,586	33	1.1	20.9	0.7	73	2.4	1,486
<b>Totals:</b>	19,957	1,067	34.4	53.5	1.7	2,348	75.74	3,795

**Aggradation from Mining.** Sacramento Valley lowlands were frequently flooded prior to the arrival of American settlers or miners (Thompson, 1960; Kelley, 1989). Nevertheless, channel aggradation greatly exacerbated flooding by filling channel bottoms, decreasing conveyance of flood-waters, and generating channel avulsions (Gilbert, 1917). Aggradation also threatened navigation in the lower Sacramento and Feather Rivers (Kelley, 1959; 1989). In 1880 Congress directed the U.S. Army to conduct field surveys in the Sacramento Valley to determine volumes and locations of sediment storage in the American, Bear, and Yuba River canyons, and downstream in the Feather and Sacramento Rivers. Surveys in 1879 (Mendell, 1880; 1881), in 1889 soon after hydraulic mining had ended (Heuer, 1891), and from 1908 to 1914 (Gilbert, 1917) provide abundant descriptions of sediment deposits and volumetric estimates of sediment production and storage.

The South Yuba, lower Yuba, Bear River, and North Fork American Rivers were the most seriously aggraded (Figure 6). Middle Fork Yuba deposits probably rivalled the others but had been altered by an extreme dam-break flood prior to Turner's (1891) survey. The Middle Fork American River had little hydraulic mining sediment as did the other rivers to the south. The mouths of the Yuba, Bear, and Feather Rivers were aggrading and narrowing in the early 1880s (Mendell, 1882). The bed at the mouth of the Feather River had risen about 0.9 to 1.2 m (3-4 ft) above its pre-settlement level by 1879, and the Feather River channel near the mouth of the Bear River was obscured (Hall, 1880). The Sacramento River between the Feather River and the City of Sacramento had risen about 1.5 m (5 ft) and narrowed. Channel deposits were colonized by willows, but the high pre-mining banks were visibly lined with the old riparian forest, and were set back from the contemporary channel (Mendell, 1882). Similar channel aggradation and narrowing at the mouths of major tributaries to the Mississippi River occurred in response to high suspended sediment loads from 19<sup>th</sup> century agricultural practices (Knox, 1977).

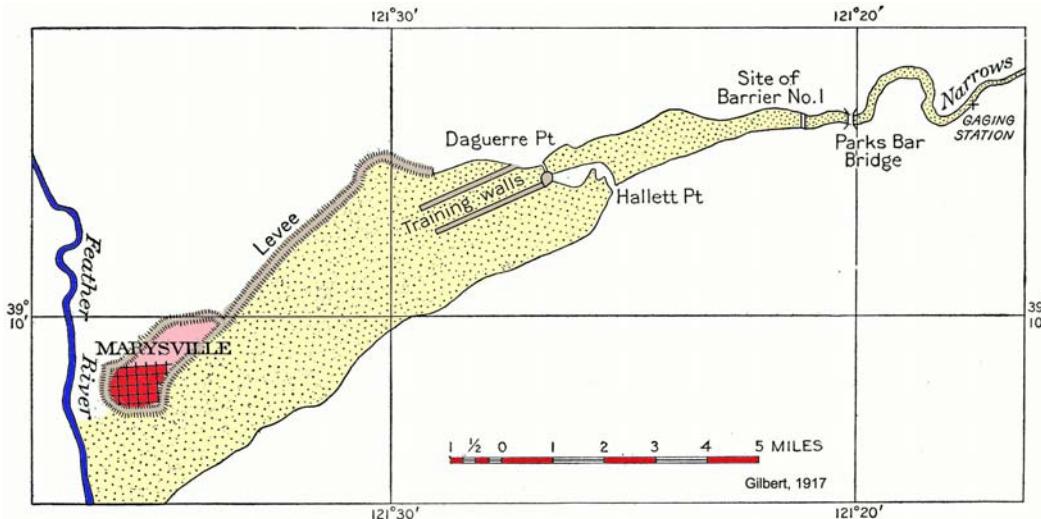


Figure 6. The historical sediment deposit (mostly hydraulic mining sediment) up to three miles wide along the lower Yuba River near its confluence with Feather River. Without artificial levees to constrain its lateral spread, the extent of deposits would have been wider in lower reaches. The deposit was initially surveyed in 1879 (Hall, 1880). This map shows engineering works associated with the Daguerre Point Dam which was constructed to arrest the sediment and prevent its transportation lower into the Valley. The Dam failed to achieve this objective. Source: Gilbert, 1917.

Hydraulic mining was enjoined in 1884 and sediment production from mining soon decreased, although sediment loads in the mountains and the Valley remained high from the reworking of stored sediment. When Turner surveyed the Bear River mining districts in 1889, the mountain channels had incised less than 3 m (10 ft) except at tailings fans where incision reached as much as 9.1 m (30 ft). At some locations, mountain channels continued aggrading, such as on the Bear River near confluences of Steephollow and Greenhorn Creeks (Turner, 1891). Little is known of mountain channel conditions at the turn of the 20th century, but Gilbert's (1917) photographs and topographic surveys during the first decade of the century indicate that most mining sediment was gone from main mountain channels except in some stretches of the Bear River. Tailings below the mines persisted in several small tributaries of the Yuba and Bear Rivers, such as Scotchman, Shady, Spring, Steephollow, and Greenhorn Creeks.

Mining sediment in the Sacramento Valley has been more persistent than in the main channels of the mountain canyons. Channel incision had begun and low terraces had formed in the lower Yuba and Bear Rivers by 1908 (Gilbert, 1917), but lateral erosion was limited. The Yuba and Bear River deposits are vast and protected by levees. Substantial channel erosion has been recorded by changes in cross-section surveys on the lower Bear River between 1985 and 1989 in response to the 1986 flood (James, 1993), but these changes are small in comparison to earlier sediment transport rates.

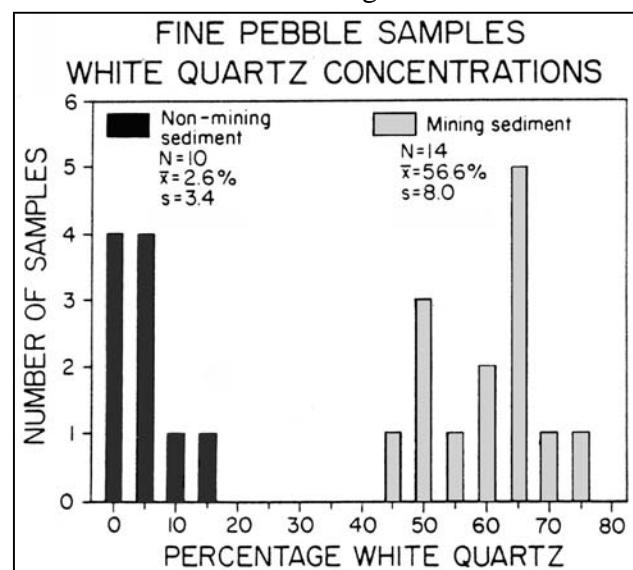
**Lithology and Geochemistry of Mining sediment.** The early Cenozoic conglomerates are substantially different than other rock materials in the region due to abrasion during fluvial transport and subsequent deep tropical weathering (Peterson et al., 1968; Yeend, 1974). The intense weathering left high quartz concentrations and presumably other geochemical signatures that may be traceable downstream by sediment fingerprinting methods. Although some mines also moved substantial overburdens of late Cenozoic volcanics, examination of pebble lithologies in terraces immediately below the mines suggests that the quartz-rich materials of the bench gravels is dominant; at least in the pebble fraction. Work is underway to extend the lithological analysis to the sand fraction, to analyze elemental compositions of the fines, and measure total mercury concentrations associated with the very fine sand (63 to 125  $\mu\text{m}$ ). A few preliminary findings of the sand lithology, elemental, and mercury analysis will be presented in the context of the samples during this trip.

Most of the tailings deposits immediately below the mines is rich in white quartz pebbles. Thus, the quartz-rich nature of the pebble fraction of hydraulic mine tailings can be used to estimate mining sediment concentrations and mixing of sediment from other sources. Fourteen samples of small pebbles (intermediate axes 6 to 16 mm or -2.5 to -4 phi) were drawn from high terraces grading from mine outlets and composed primarily of tailings (James, 1991a). The tailings samples had percentages of white vein quartz ranging from 45 to 67% with a mean percentage of 57% white quartz compared to samples of non-mining sediment which have only about 2.6% white quartz (Figure 7). Assuming that these terrace samples are representative of the sediment produced in other mines, an index of mining sediment mixing was derived that allows estimations to be made of sediment mixing based on the percentage quartz:

$$\%MS = 1.9 \%Q_s - 5.6\% \quad (\text{Equation 1})$$

where %MS is the percentage of mining sediment and %Q<sub>s</sub> is the percentage of fine pebbles in the sample that are white quartz.

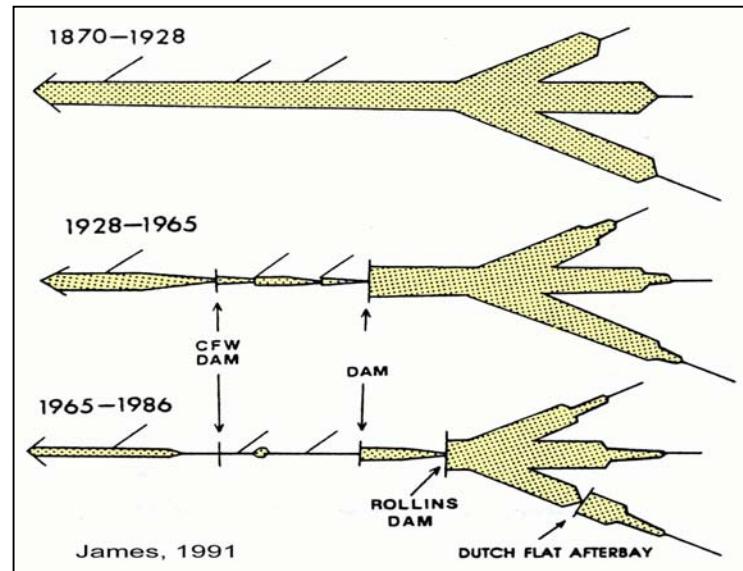
Figure 7. White quartz concentrations in control-group samples of mining sediment and non-mining samples (James, 1991a).



Forty-six terrace and bedload samples were collected in the Bear Basin from (1) high terraces (pre-dam), (2) medium terraces (post-early small dams), and (3) modern [ca. 1989] channels (post-large dams). Mining sediment concentrations were calculated for each sample Using Equation 1 and a hypothetical relationship between mining sediment concentrations and longitudinal position was developed that reveals the importance of dams to sediment mixing in the basin (Figure 8). Mining sediment concentrations decrease in modern channel materials below dams because sediment rich in mine tailings is detained by the dams. The proportion of non-mining sediment exposed in pre-mining materials increases in bed material below the dam. Concentrations of mining sediment increase within a few miles below the small dams, because new material is entrained by erosion of deposits stored below dams.

Modern, large dams have been effective at reducing mining sediment concentrations for greater distances downstream.

Figure 8. Schematic maps of mining sediment concentrations for three periods. Widths proportional to percent of mining sediment in samples. (James, 1991a).



Your geochem intro stuff here? Save specific findings for the road log at the sites where they occur but general relationships would go well here.

## ROAD LOG AND ITINERARY

[In some sections, material was excerpted and revised from James and Davis, 1994]

### DAY ONE

Key: S = Stop, TR = Turn right, TL = Turn left

\*) Leave SF at 9:00 A.M. on April 15<sup>th</sup>. Mileage begins from Hilton Hotel in SF.

\*) Oakland: Take 80 to northeast

\*) Toll booth on north side of Carquinez Strait; stay on 80E to Vallejo/Sacramento.

A few miles upstream is Suisun Bay and beyond it the Sacramento-San Joaquin Delta, an inland delta formed by marine transgression during Holocene sea level rise. The Delta and Suisun Bay received substantial volumes of mining sediment during the gold mining era (Gilbert, 1917), although modern confirmation of this inevitability has been slow to develop. Subsidence of peatlands and levee failures continue to plague the Delta Region.

**Lower Sacramento Channel Sedimentation.** Channel morphology and navigation on the lower Sacramento River were severely affected by hydraulic mining sedimentation between 1861 and 1891:

“In this distance of 81.2 miles, the river has a fall of 16 feet, which gives it an average slope or grade of about 2.4 inches per mile. Over the greater portion of this length, mining debris has been lodged to very unequal heights, the effect of which has been to raise the low water plane of the river at Sacramento about 7.5 feet and at other places below this to a lesser height; has thus reduced the carrying capacity of the river for its flood waters; has caused property owners to build levees to protect their property against inundations; and has lessened the available depth of water in the river for purposes of navigation, and to some extent injured the value of the river as a drain...”

“In the earliest records of the Sacramento River which we had available, viz.: The Wilkes survey of 1841 and Ringgold's survey of 1849-'50, we find shallow depths of 7 to 8 feet of water at the junction of Old River and Steamboat Slough, and at various places in both these branches extending for several miles in each of them... In the next 27 miles of river up to the City of Sacramento the records show two shoals, viz., at Heacocks and Russian Embarcadero situated about 9 to 10 miles below Sacramento... The depths on these shoals are believed to have been between 10 and 12 feet, and at this locality a tidal influence from 2 to 2.5 feet was felt. Repeated surveys made on these shoals since 1870 show depths of 5.5 to 7 feet at low water, and in consequence of the rise in the river bed the tidal influence is no longer felt there. In addition to these shoals there are two others, one near Sutterville, about 4 miles below Sacramento, and one which has disappeared, in consequence of a crevasse below it, and which shoal in the summer of 1889 had at lowest stage of river a least depth of 3 feet 10 inches over it. This shoal was opposite the lower end of the city of Sacramento. It is therefore evident that in 40 years the effective depth of water in the river during seasons of extreme low water, lasting from 3 to 4 months in the year, has been reduced from 12 feet to depths of 5.5 feet, and during 1 year, at one locality, to 3 feet 10 inches...” (Heuer, 1891: 3014)

An 1870 Army survey below Sacramento showed depths of ~2 m (7 ft) at Heacocks Shoals and Sutterville. Comparisons between 1870, 1879, and 1889 surveys indicated both filling and deepening of the lower Sacramento and a net fill of about 19 million m<sup>3</sup> (25 10<sup>6</sup> yd<sup>3</sup>) suggesting an average fill of about 18 cm (7 inches) over 81 miles of channel.

“In 1890 this [1870] survey was repeated so as to ascertain the effect of the freshet of 1889-'90, the heaviest ever known. It was found that in consequence of a crevasse, known as Payne's Break situated on the right bank of the river about a mile below the City of Sacramento, millions of cubic yards of sand were scoured out from the bed of the river in front of Sacramento, the good effects of which extended for several miles higher up river. Some of this scoured material was carried through the break and deposited in the Yolo basin, and other portions were lodged in the bed of the river below the break, which can be traced down as far as Heacocks Shoals, some 7 miles below the crevasse. This crevasse was closed... during the summer of 1890.” (Heuer, 1891: 3014).

Heuer recognized the dichotomy between channel responses at narrow reaches which scoured vs. wide reaches which tended to aggrade and erode their banks. He recommended structures protruding from the banks to deepen flows and encourage channel scour.

"It is also found, as a result of a survey of 1890, that in nearly or quite all localities the greater shoaling occurred where the river was exceptionally wide and, conversely, that the greater scouring occurred in localities where the river was below the average width. It is therefore reasonable to suppose that in all localities where these shoals occur,... that the depth of water can be effectively increased by a contraction in width of the low-water channel, and this is the method which the Board recommends in the treatment of the river. To accomplish this object it is recommended that brush mattresses be used, projecting from the bank towards the channel as far as may be required..." (Heuer, 1891: 3014-3015)

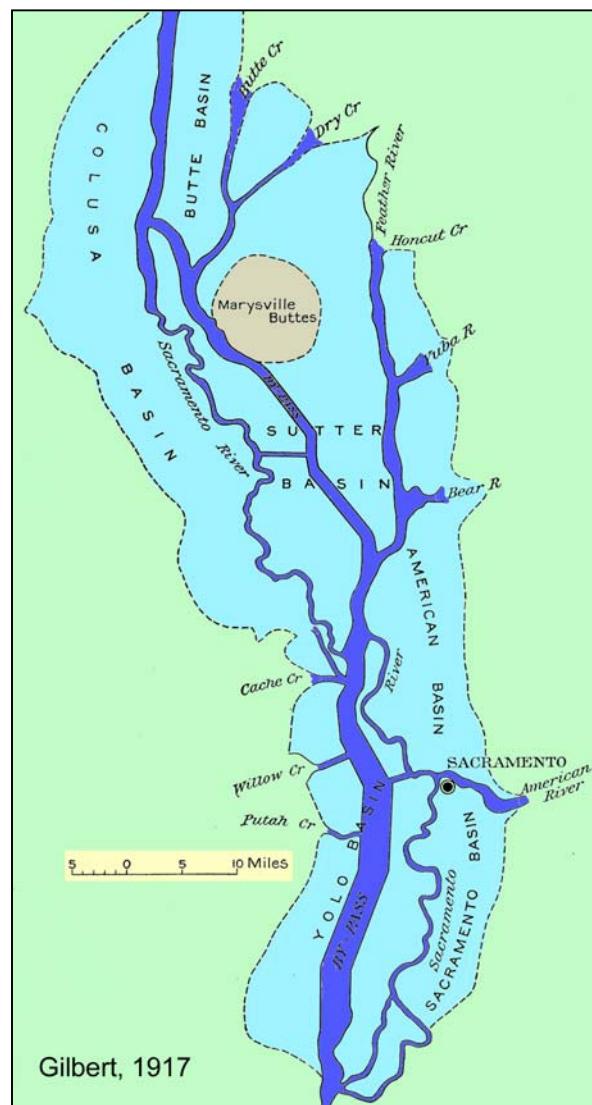
Gilbert (1917) repeated this recommendation in his seminal work on hydraulic mining sediment.

\*) Davis, continue on I-80.

\*) Begin Yolo causeway.

Flood control in the Sacramento Valley is now maintained by a system of large bypasses that convey excess water during floods. Land use within the bypasses is limited to agriculture and natural environmental systems such as wetlands on the Pacific flyway. The flood season does not correspond with the peak growing season, so agricultural use has been fairly successful in most years. Flows into the bypasses are controlled by weirs (Figure 9). The Yolo Bypass takes Sacramento River flood water from the Fremont Weir below the Feather River confluence and from the Sacramento Weir above the American River confluence. Historically, the Sacramento Valley has been prone to annual flooding (Thompson, 1960; Bishopberger, 1975). The bypass system has greatly decreased the frequency of lowland flooding in the Sacramento Valley, but conveyance of floods through the weirs is limited and Sacramento at present has a substantial hazard from large floods on the American River. We will stop at the Sutter Bypass on Monday and the Fremont Weir on Tuesday to present evidence of sediment accumulations in the bypass system and discuss the implications to flood hazards.

Figure 9. Flood bypass system in the Sacramento Valley. The general concept of the system was largely described by Will Green in the 1860s but it was not constructed until after Congress approved the first Flood Control Act in 1917 which included the Jackson Report. Source: Gilbert (1917) presented this as a planned project; not yet constructed.



\*) End Yolo Causeway TR

\*) Bear right on 80 to Reno (avoid business 80, Hwy 50, downtown Sacto., etc.)

\*) Cross the Sacramento River.

Sacramento is off to the right. In the 19th century, this area was subjected to repeated flooding and floodplain aggradation by hydraulic mining sediment was substantial. Sediment deposition was considerable at the American River confluence (downstream to the right):

"At the upper end of the city of Sacramento the American River enters the Sacramento. Much of the mining debris which this stream brought down during freshets was lodged in front of and below the City of Sacramento, and the effect was to make a partial submerged dam, thus obstructing the free flow of that portion of the Sacramento River below the mouth of the Feather, decreasing its slope and giving better effective depths of water for navigation above Sacramento than were ever known before the days of hydraulic mining." (Heuer, 1891: 3014)

Aggradation in the lower American River was substantial during the late 19<sup>th</sup> century. Flood prevention measures in Sacramento could not control the aggrading channel system. Neither levee construction nor raising the streets from 1 to 5 feet prevented devastation by the December 1861 and January 1862 floods which were followed by higher set-back levees (Bishofberger, 1975). High terraces between the levees between Watt Avenue and H Street represent historical channel aggradation along the lower American River after levee construction (NRC, 1995). Although sedimentation was substantial on the lower American River and the nearby Sacramento, deposits were much less extensive than upstream along the Yuba and Bear that drain the center of the hydraulic mining districts.

\*) (No stop) Rocklin paleochannel off to right; a case of inverted topography. Hudson (1960) interpreted this ridge and an accordant ridge to the north as a pediment; that is, a continuous erosional surface that extended across the area to the north at the level of the top of the ridges. In contrast, Shlemon (1967) argued that the ridges at this site are channel remnants representing a broad relief inversion; i.e., these ridges are former valley bottoms left as ridges following deep weathering and erosion of the former granitic valley walls. Conglomerates exposed in road cuts across the ridges support the interpretation that the ridges represent relief inversion rather than a broad pediment.

\*) Take Exit 135 from I-80 at Colfax. Brief rest stop at gas station.

(Mapquest: 134 miles; estimated time 2 hours, 13 minutes)

\*) Go west across I80, turn right at T (South Auburn St.), turn right onto Hwy 174 (Central St) and follow it north over the railroad bridge out of town.

\*) Cape Horn view to right (just past Cape View Bar); famous railroad bend.

\*) Turn left (stay on 174)

\*) Turn off on N side of Bear River Bridge. Bear River Dam and Canal. (~3 miles north of Colfax)

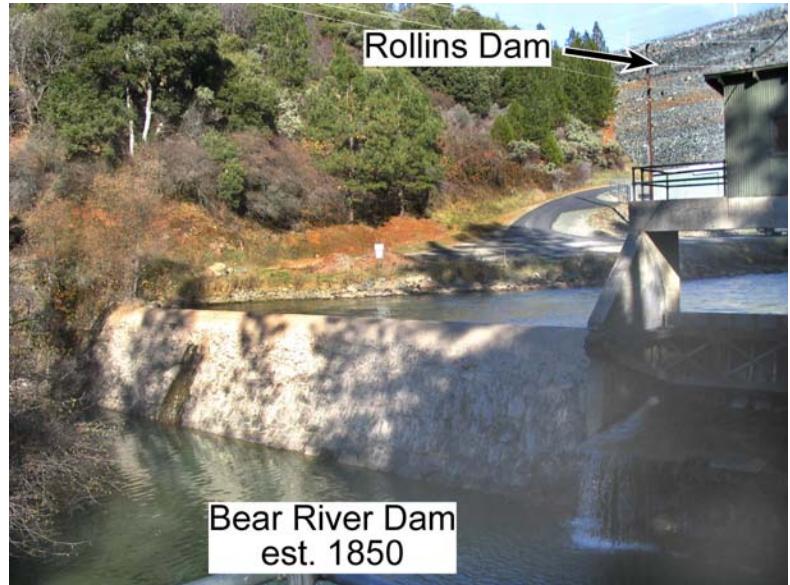
## **Stop 1 BEAR RIVER DAM** (Also known historically as the Birdsall Dam)

This is a brief stop on the main bridge. We will not see the BR Dam ( a short distance upstream) but will review the history. Bear River Dam was built in 1861 at the head of the Bear River Canal after the original upstream structure had to be moved due to sedimentation. This dam figured prominently in testimony concerning hydraulic mining sediment transport in the Bear River during litigation as attorneys for the miners attempted to argue that the dam prevented sediment from moving down valley and attorneys for the plaintiffs used it as evidence for increased sediment loads due to mining. Valuable information about the arrival of mining sediment at this site is provided in contemporary testimony.

Rollins Dam, a large earth-fill structure about 0.7 km upstream of the bridge, was built in the 1960s with a reservoir capacity of 66,000 acre-feet. Rollins Dam overshadows the tiny but historically important

Bear River Dam which is nestled below it out of view in a thicket of alders upstream (Figure 10).

Figure 10. Bear River dam (lower foreground) is a low-head structure built in 1861 to divert canal water for irrigation. Evidence of sedimentation at this site figured prominently in litigation over damages caused by sediment derived from hydraulic gold mining (Keyes, 1878).



Turbidity at Bear River Dam, first noted in 1856, increased considerably after the 1861-62 floods when substantial dam and canal sedimentation began. Detailed descriptions of the Bear River Dam and Canal are available from testimony by James Harrison, superintendent of the Bear River Ditch and resident at the Bear River Greenhorn Creek confluence from ca. 1856 (Keyes, 1878: 104-108). Harrison first noticed sedimentation in 1860 and noted high levels through the 1870s:

"The fill at that time [1856] was quite immaterial; small; did not amount to anything as an obstruction; but continued year after year, about up to the present time... The water was not clear from 1856; the water was what we would call muddy, or roily; but; no sediment of any consequence. There was some sediment, but very little; such as may be made by agitating water; but it was comparatively clear; left no deposit... The character of the water commenced to change about 1861 - 1860 or 1861 - getting very muddy, at times remarkably so. The direct cause I was not familiar with to know it; But then, of course, the cause is supposed to be debris from mining - hydraulic mining... It is [in 1878] remarkably muddy. There is a great quantity of material in suspension in the water; also it carries along a large quantity of gravel, sand and other debris... I have... [measured suspended sediment concentrations in 1876] and I should judge, probably one quarter [was sediment]. But then it was not solid, what we would call solid sediment. It would settle in a few hours." [Water was taken from near the surface at the shore in a bucket for black-smith work and allowed to settle.] (Harrison in Keyes, 1878)

Harrison's account of the facilities and the efforts required to rid the canal of sediment provide clear descriptions of the high sediment loads being transported in the early 1860s and 70s. He estimated that more water was required to dispose of the sediment than ran down the canal. Otherwise, the canal would fill with sand in an hour or two. A set of sluice gates draining a sediment detention basin remain along the canal a few hundred meters below the bridge on the left bank.

"About 1862 it was discovered necessary to erect works, which, previous to that, we had not... sluiceways at the head of the ditch... The dam, previous to 1861, was about half a mile farther up the stream than at the present time. It was found necessary to erect a dam about half a mile down the stream, and raise the water to the height of the original dam, on a level, for the purpose of having a reservoir, and also a dump below the dam. Then there were erected some 6 or 7 sluiceways, within, probably, a thousand yards of the dam, and also settlers... which are large embankments across ravines... This was found necessary to keep the ditch open... In 1873, '74 and '75,.. it was necessary to keep one, two, and frequently three or four gates open; part

way open. Those gates were about 3 feet below the grade of the bottom of the ditch, for the purpose of taking all the heavy material out... They had then reservoirs, or settlers, for settling such material as was in suspension; the heaviest portion of that which was in suspension, such as sand, lay there. There was one about half a mile below the dam, and there were two, seven miles below the dam which I had control of myself. These would probably fill up every day, once in the day, but we usually cleaned them out 3 times a week... There are also 2 waste gates in the dam, iron gates and iron troughs... Those gates probably were 8 feet below the top of the ditch... [the reservoir] would fill up in one day. [It was] Probably 100 feet long and 100 feet wide at the lower end, where the gate was... Twenty-five feet [deep]. That is the exact depth of the two that I know..." (Harrison in Keyes, 1878)

Arrowsmith, a civil engineer testifying on behalf of the farmers, visited the dam in 1876 and 1878 and estimated sediment discharges across Bear River Dam based on knowledge of (1) canal and reservoir dimensions, (2) frequency of sluicing, and (3) discharge through the canal. His procedure required unmeasured estimates of discharge passing over the dam, sediment discharges through the dam waste gate (which was kept open), and the assumption that sediment concentrations in the river were the same as in the canal. From this he estimated sediment discharges around  $23,000 \text{ m}^3$  ( $30,000 \text{ yd}^3$ ) per day in addition to discharges into the canal (Arrowsmith, in Keyes, 1878: 320-334).

The Bear River Dam was partially filled during the 1880s, probably enough to allow bedload transport over the dam during moderate-magnitude flow events. In March and April of 1882, Bassett visited the dam and determined that the dam was sufficiently filled with sediment to transport bedload:

"We took... two or three different cobbles of the size of your double fist, about 4 inches by 5... tied a float to them and threw them into the stream some 15 or 20 feet above the dam, and observed that they were carried over the dam, the floats showing that they were carried along and thrown over the dam... We found by this experiment that it was filled to the crest." (Bassett in Woodruff v. N. Bloomfield, 1883)

He testified that water below Bear River Dam was just as muddy as the water above the dam. Kinder, owner and operator of another dam ~2 miles downstream, tape-measured depths of ~3.5 m (11.5 ft) at the dam and estimated ~2 m (6 ft) of sand in August, 1883. These measurements were presumably on the downstream side of the dam because he also testified (as did Hamilton Smith, the dam operator) that the dam had been 'filled up' with sediment since at least 1861 (Woodruff v. N.Bloomfield, 1883).

Continue north on Highway 174; go ~4.5 miles to You Bet Road.

\*) Turn right on You Bet Road; follow it ~2 miles to Greenhorn Creek.

\*) **Greenhorn Creek Bridge at You Bet Road** [No stop; drive across slowly. Watch out for gravel trucks.] This crossing of Greenhorn Creek has been around since early in the gold mining era. Historical records describe a series of simple log bridges laid across the tailings. During the peak of the hydraulic mining era, this site acted as a constriction obstructing the passage of sediment downstream. Some miners apparently felt that the road explained sediment retention, but it may also have decreased valley gradient or base level effects from the Bear River confluence about 3 miles downstream.

"There are trees... felled across the stream, down at the crossing of You Bet... It was put there over the tailings, to build a road. Trees were put in, and brush, to cross there. The road being dug down to cross that point, they built this road on the tailings, and built it up so as to make a good road across there... I have seen [You Bet Bridge obstructions ] there for years; I would say positively, 6 or 7 years... they were there long before [1873]... They obstruct the flow of the tailings, and cause them to spread out and stop... That the water may be riley that goes over those tailings, I have no doubt. But, anything in the nature of sand or sediment is stopped. I think the water would need to be filtered below the dams to be drank... Whenever I visit my mining claims [upstream], I see that same dreary spread of tailings away out on Greenhorn Creek, added to, year after year, and remaining there." (Sargent, in Keyes, 1878: 348)

Mining sediment terraces pinch out here and are somewhat obscured by substantial gravel mining from the channel. Terraces get much higher upstream where we'll be later today. Shifting of the sediment to these downstream positions has been going on for a long time (Turner, 1891; Wildman, 1981; James, 1989). Survey data on Bear River from 1878 and 1890, plotted longitudinally on an estimate of the pre-mining profile (Turner, 1891), reveals that the down-valley shifting of sediment had already begun by that time. Large volumes of mining sediment are quarried from the cahnnel upstream by the Hansen Brothers gravel company. Similar gravel-mining operations are active at the mouth of Steephollow Creek and on the Bear River behind Combie Dam.

A masonry debris dam was built downstream to catch sediment to satisfy licensed mining requirements upstream. This dam is now inundated by sediment, but a photograph in 1939 (U.S.Army COE archives; James, 1989) suggests aggradation since that time. In fact, aggradation in the lower Greenhorn is substantial and probably predates construction of Rollins Reservoir downstream and the subsequent base level changes that it has made. Repeat photographs of the You Bet Bridge reveal the instability of the channel since none of the three periods represented have the same configuration.

\*) Continue east on You Bet Road ~4 miles; stay to the left after you pass Lowell Hill Road and go ~200 m beyond to vista on right of Red Dog - You Bet Mines; Stop.

## Stop 2 RED DOG-YOU BET MINE

This is one of the larger hydraulic mine pits in the Sierra Nevada (Figure 11). Sediment from two coalesced pits was delivered down Wilcox Ravine and Hawkins (Birdseye) Canyon to Steephollow Creek, and down Missouri Ravine to Greenhorn Creek. Hydraulic mining was invented nearby in 1853 but required water pressure. Mining began early here and by 1854 ground sluicing (unpressurized) was being practiced. A description by a contemporary of the You Bet area in 1854 gives a glimpse of conditions of the Birdseye claim at Red Dog in 1854:

“Part of them were being worked by a number of companies. The Chalk Bluff Ditch Company was supplying them with water. They were then working by the ground sluice process... Some of the claims that were being washed, then situated in Walloupe, now belong to... the Birdseye Company... Below You Bet, at a place called Brown's Hill, on the shallow rock, they were being worked at that time... On the claims called Red Dog Hill there were a great many men employed, ground sluicing.” (Williams, in Keyes, 1878: 375)

Gilbert conducted topographic surveys of mines to the north and estimate volumes of sediment exhumed from this and other mines. The combined production of the many mines operating in this Red Dog-You Bet Mine pit produced more sediment than any other mine in the Bear Basin except those at Dutch Flat.



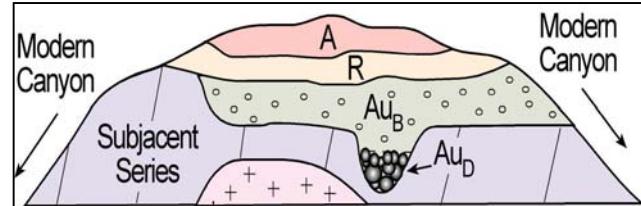
Figure 11. Red Dog You Bet hydraulic mine pit resulted from the coalescence of several mines.

The stratigraphy and history of the early Cenozoic channels was described by Lindgren (1911) and Yeend (1974). Early Cenozoic uplift and erosion caused deep incision which was followed by alluviation. Deep inner gorges formed and were lined with boulders during the high energy stage of development. The lower boulder fill is richest in gold, poorly drained, and gleyed, and became known to the miners as the '*Blue Lead*' (rhymes with *feed*). Channels later filled with coarse gravel, then fine gravel and sand as channels aggraded up and across their floodplains. Although the upper gravels tend to be light or red in color, the color distinction between the two units is due to secondary mineral alterations (reducing conditions below the water table) and has no stratigraphic significance other than lower positions tend to be richer in gold (Peterson et al., 1968; Yeend, 1974).

The channel fill that spilled out onto floodplains left deposits known as *bench gravels*. These deposits are very weathered due to deep tropical weathering that removed weak minerals and concentrated resistant materials such as quartz and gold (Peterson and others, 1968; Yeend, 1974). The bench gravels can be deep and extensive. Textures fine upwards through the sequence from bouldery gravel to sand with lenses of silt and clay (Lindgren, 1911).

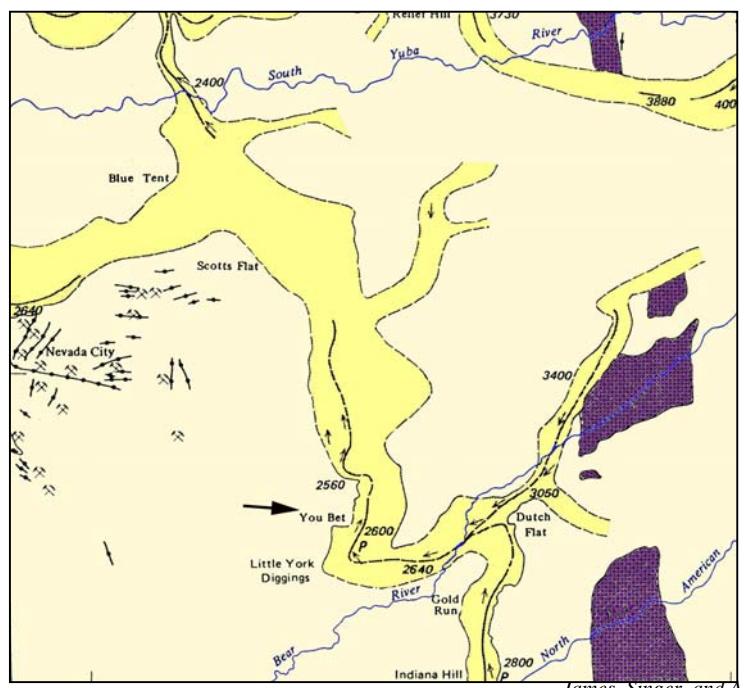
In the foothills, the Tertiary channel network was buried by two stages of volcanics: rhyolitic followed by andesitic volcanics. These deposits are known as the intervolcanic gravels (Lindgren, 1911). At higher elevations, the later Cenozoic, intervolcanic streams tended to reoccupy the narrow valleys so early Cenozoic deposits are less common (Lindgren, 1911: 135). Glaciation also removed many of the conglomerates at high elevations. When the modern foothill drainage developed with rapid Quaternary incision, many of the Cenozoic channels were left up on ridgetops (Figure 12). The '*bench*' gravels were economic to mine, but only if large amounts of sediment could be quickly and easily moved, processed, and dumped into the canyons below.

Figure 12. Tertiary channel stratigraphy on foothill ridgetops.  $Au_D$  = early Cenozoic auriferous deep gravels (blue lead);  $Au_B$  = early Cenozoic auriferous bench gravels; R = Cenozoic rhyolitic Volcanics; A = Cenozoic andesitic volcanics and lahars. (Adapted from Lindgren, 1911).



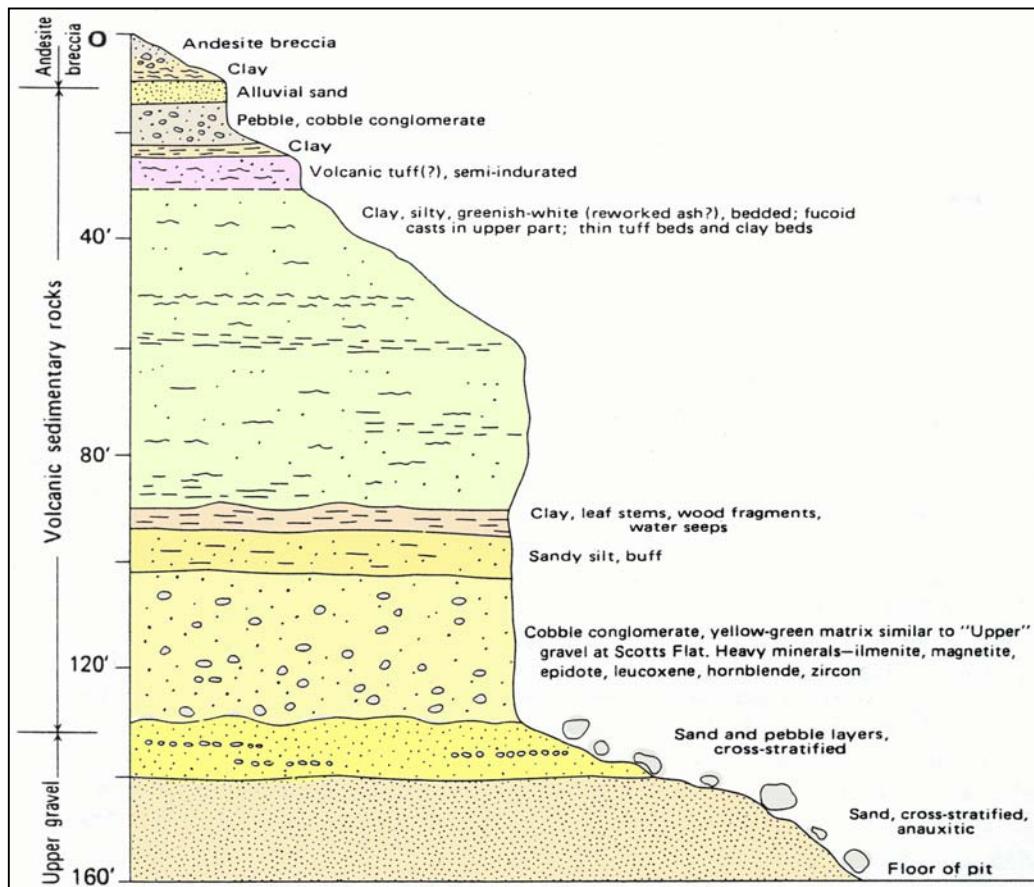
A regional map of the ancestral Yuba was developed by Lindgren (1911) and refined by Yeend (1974). The Red Dog - You Bet mine is located on the southern portion of Yeend's map (Figure 13).

Figure 13. Southern portion of ancestral Yuba River drainage. Arrow points to You Bet (our location at this stop). The main channel flowed north from here then veered to the west along the south margin of the South Yuba canyon. Source: Yeend, 1974.



The Red Dog- You Bet Mine has a large exposure of the interval volcanic cover along the east wall. The stratigraphy of ‘Chalk’ Bluff (a misnomer for rhyolite tuff) exposed in the mine is shown in Figure 12. At You Bet the deep gravel (not shown in the section) is coarse, cemented, up to 12 m (40 ft) thick, and capped by up to 100 m (350 ft) of fine gravel (Lindgren, 1911: 34-35), so the stratigraphic section is showing only the upper portion of the bench gravels and the volcanic cap.

Figure 14.  
Stratigraphic  
section of Tertiary  
channel and  
overburden at  
Chalk Bluff,  
exposed  
in Red Dog-You  
Bet Mine (Yeend,  
1974).



The upper bench gravels were stripped from this mine very rapidly by a number of companies that dumped their tailings to Steephollow Creek through Wilcox Ravine and Birdseye Canyon from this side and to Greenhorn Creek on the north side through Missouri and Arkansas Ravines. Ultimately, the two mining pits coalesced. The ease of mining bench gravels prior to 1871 was described by Williams:

“That dirt was very easily washed off. They washed off millions of tons. That came down the canyons and filled up the canyons very fast... prior to 1871. [Also prior to 1871:] ...In the Chalk Bluff Channel they washed the most of the dirt that was washed off down into Wilcox Ravine, and it went down to Steep Hollow and on below... Some of it went down into Greenhorn; there was a great deal went there. There were three or four companies on... the Red Dog side, and... four or five or six companies on the other side... [The Missouri Canyon deposit] came from the upper channel; the Chalk Bluff Channel. [Below the town of Red Dog], 10 to 14 acres were washed to bedrock and tailed into Missouri Canyon and (some) into Arkansas Canyon.” (Williams, in Keyes, 1878: 377-78)

The surface material washed from the Birdseye claims up to 1871 was extensive and mostly concentrated around the outer parts of the ridge:

“There was a large amount, especially of that which was easily to be got at, on the front and around the rims. In the middle of the hills it was not worked very much, as it was getting deeper and more expensive to be worked.” (Williams, in Keyes, 1878: 377)

\*) Return back on You Bet Road to Lowell Hill Road junction, go left (south) towards Steephollow Crossing. At ~0.8 mile you will cross a tunnel from a Red Dog – You Bet mine outlet to Hawkins (Birdseye) Canyon. The tunnel discharge tailings from the lower deep gravels into Hawkins Canyon below. Potholes on basement rocks here were exhumed by mining and represent early(?) Cenozoic fluvial abrasion at the onset of auriferous gravel deposition at this site.

Continue ~1.3 mile to Steephollow Crossing at end of road (collapsed bridge site). Lunch stop.

### Stop 3 - STEEPHOLLOW CROSSING & WILCOX RAVINE TAILINGS FAN.

Steephollow Creek at this site is a relatively small mountain watershed draining  $55 \text{ km}^2$  ( $21 \text{ mi}^2$ ). The tailings fan coming out of Wilcox Ravine is from the Red Dog - You Bet Mines above. The fan began damming Steephollow Creek soon after mining commenced and maintained a lake upstream during the mining period:

"There has been water there for years, dammed back, almost as far back as I can recollect - since the mine commenced, in fact. Ever since they commenced hydraulicing there, there has been a discharge through there, and that has had the effect to create a dam... to stop [tailings]... the first or second season after the work commenced in those claims... that dam commenced forming. I think, perhaps, it was taken out by the floods the first winter or two. But from 1860, say, it has been established a permanent dam - from 1860 to 1862." (Gaylord, in Keyes, 1878: 369-70)

Deep laminated clay deposits up around the first bend provide evidence of the lake upstream.

"There is a reservoir over there. I should conclude by observation that it was 3/4 of a mile long... [caused by] The tailings from Wilcox Ravine... It has been there since June, 1872, to my knowledge. How much prior to that I don't know... Knight, Wyck, and Swamp Angel claims all tail in above that reservoir." (Ludlum, in Keyes, 1878: 299)

Topographic surveys in 1870 and in 1879 document 42 m (136 ft) of aggradation on this fan during that nine-year period (Pettee, in Whitney, 1880). This minimum depth must be added to an estimated 15 to 23 m (50-75 ft) of mining deposits that were already here in 1871 (Pettee). The fan forced Steephollow Creek up against the opposite valley wall which resulted in the stream incising down into the weak phyllitic bedrock spur in a narrow channel about 3 m (10 ft) deep (Turner, 1891) (Figure 15). The channel incised into this spur over the next 100 years (Figure 16). Depth measurements of the bedrock notch were taken here using the bridge as a vertical datum. Unfortunately, the bridge across Steephollow Creek washed out in the winter of 1990-91, putting an end to monitoring of channel incision here.

Figure 15. Steephollow Valley Cross sections of (1) before, (2) during mining when the fan forced the channel up across a valley ridge (spur), and (3) after mining when the channel incised. View upstream.  
Source: James (2004).

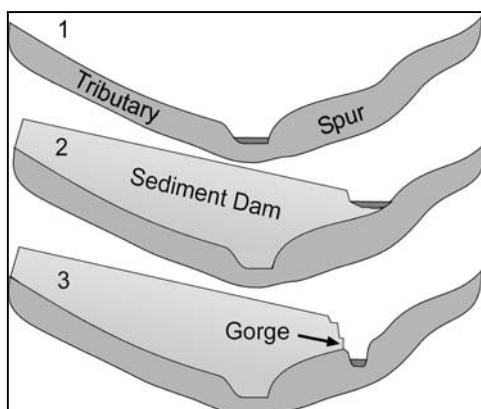


Figure 16. Deeply incised gorge where fan pushed Steephollow Creek up over a valley spur through which it incised.



The Steephollow gorge was dammed with a 14.6 meter-high concrete structure in 1924 in order to qualify for a license to hydraulically mine  $29,000 \text{ m}^3$  of sediment stored upstream.

The tunnel through the bedrock spur beneath the road (where we will eat lunch), acted as the spillway and tail race for the ball mill and other mining machines here (Figure 17). The dam failed in 1925 (James, 2004).

Figure 17. Tunnel beneath the right road abutment at Steephollow Crossing was the spillway for a dam at this site from 1924 to 1925.

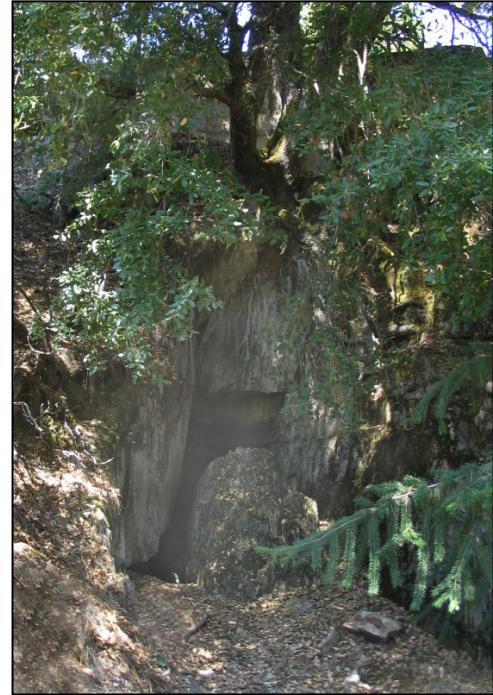


Figure 18. Steephollow fan from left side (view downstream). We will be on right side so this is the view you'd get if you hiked across. The fan formed from sediment coming out of Wilcox Ravine from the Red Dog – You Bet mine.

The area below the fan was monitored for channel changes from 1985 through the 1990s including channel cross-section surveys, photographs, and bedload samples (Figure 18). Frequent flows are competent to move the relatively fine-grained mining sediment in these systems (James, 1989). The channel has incised more than 30 m into the fan, yet bedrock is not yet exposed in the bed except where cutting the spur.

Numerous tailings fans dammed the major tributaries draining the mines. A fan from the Christmas Hill mine can be seen entering from the left downstream ~1/2 km and another fan formed ~1 km downstream on the right bank at the mouth of Hawkins Canyon (Ludlum, in Keyes, 1878: 301; photograph in James, 1999). The latter fan was below the Little York Dump which entered Steephollow Creek on the left bank within view of Steephollow crossing:

“The Little York claims empty into Steep Hollow a short distance below Wilcox Ravine, emptying through the old Macauley Hill Ravine... It is about 500 or 600 yards... below Wilcox Ravine; perhaps a little further... [Birdseye dam] would have the effect of restraining their flow down; that is, as long as the dam would hold.” (Gaylord, in Keyes, 1878: 370)

Tailings on the main Bear River also dammed up sediment in Steephollow Creek suggesting that aggradation on Bear River had been earlier, more rapid, or more severe than on Steephollow Creek:

"At the mouth of Steephollow, the tailings of Bear River act as a bar to restrain coarser tailings. Those bars are not as effective as those previously mentioned [Wilcox and Birdseye]." (Ludlum, in Keyes, 1878: 302)

\*) Return to You Bet Road, turn left and return to Highway 174.

Normally we would turn right on You Bet Road, drive to Red Dog Ford and cross there. Recent channel incision has lowered the channel substantially at the Ford, and climbing the high mining sediment terrace on the far side is not practical with the vans. We'll go the long way around.

\*) Turn right on Hwy 174, go 2 miles and turn right onto Brunswick Road. Go another 2 miles to Idaho Maryland Road and turn right. Follow Idaho Maryland about 3.5 or 4 miles to Red Dog Road and turn right. Follow Red Dog Road ~2.5 down to Red Dog Ford. Stop before Greenhorn Creek; don't drop down from the high terrace.

## Stop 4 – RED DOG FORD

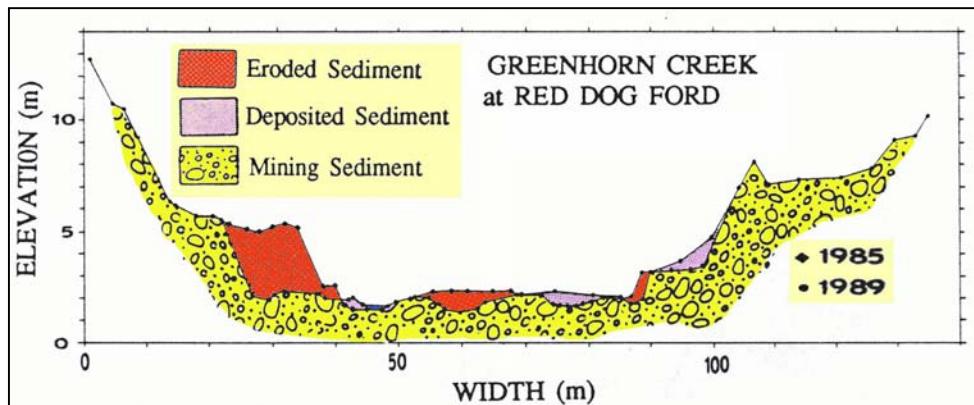
Across Greenhorn Creek and downstream is Arkansas Ravine where a tailings fan from the Red Dog You Bet mine entered Greenhorn Creek (Figure 19). A survey across the fan in 1989 showed the width of the fan near its mouth is 110 m. Assuming the depth to be 8 m (at a minimum), then the cross-section area there is  $\sim 880 \text{ m}^2$  and a 100 m section of contains  $88,000 \text{ m}^3$  of mining sediment. We need Lidar data here to measure and monitor these sediment deposits!

Figure 19. View up Greenhorn Creek across Red Dog Ford from high left-bank terrace at mouth of Arkansas Ravine. Stop 4 is near the vehicle shown in the upper left. Photo from June, 2006.



Massive supplies of mining sediment delivered to Greenhorn Creek in the 1860s and 1870s caused the system to metamorphose into braided, multithread channels. The channels probably began to incise soon after the cessation of mining. Sediment continues to shift from upper reaches to lower reaches similar to what Turner (1891) showed on the Bear River. Responses were complicated by extensive gravel mining and construction of Rollins Reservoir downstream, but erosion upstream and deposition downstream was already in progress in the late 19<sup>th</sup> century long before these disturbances had taken place. Terraces on Greenhorn Creek are higher upstream and decrease downstream until they pinch out below You Bet Bridge. Here at Red Dog Ford, incision rates have accelerated in recent years. Severe erosion at this site in response to the 1986 flood is shown by cross-section surveys in 1985 and 1989 that document net erosion of  $35 \text{ m}^2$  at the section between the Ford and the spur we will visit at the next stop. This erosion was dominantly caused by removal of the left terrace; there was little change in bed elevation (Figure 20). Subsequently, however, considerable amounts of vertical incision have ensued.

Figure 20. Channel cross-section surveys in 1985 and 1989 showing areas of scour and fill above Red Dog Ford due to 1986 flood (James, 1993).



Erosion along this stretch

of Greenhorn Creek has accelerated in recent years showing that the depth of sediment in this reach is quite deep (Figure 21). The channel has probably incised more than four meters over the past 20 years. To some extent incision is being encouraged by gravel mining operations by Hansen's Gravel Company coming up from near the You Bet Bridge. Upstream of this location, however, a local baselevel is maintained by the cutoff spur we will visit at our next stop. That base level limits the amount of sediment passing down the valley from above so that erosion here is proceeding more rapidly than upstream. The spur is being breached as we will see, and base level is about to be lowered several meters.

Figure 21. View up Greenhorn Creek from Red Dog Ford. Trees were buried by mining sediment and are being exhumed by rapid channel incision. Cutoff Spur of Stop 5 is in distance. F=fan entering from left bank and damming main channel which passes through narrow gorge across a waterfall (W). S=sample site from tailings terrace shown in Figure 22.



Figure 22. Sample site in right bank historical terrace where total mercury concentration of  $63 \mu\text{m}$  very fine sand fraction was found to be 730 ppb. June, 2006.

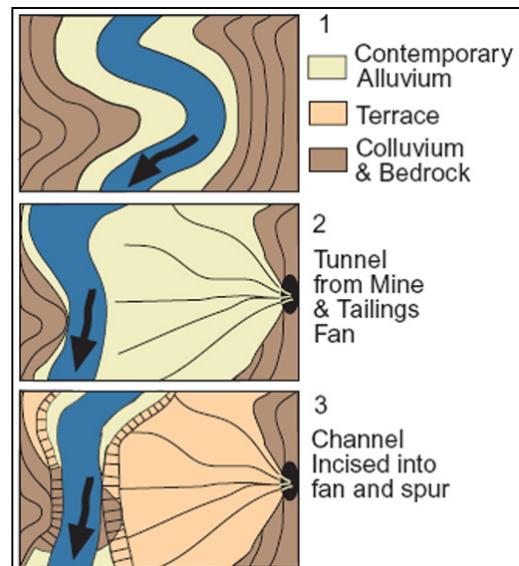
\*) Drivers follow the dirt road upstream along the high terrace to the end and park above the spur cutoff. Stop on northwest side of Greenhorn Creek and disembark. Passengers have a choice of hiking down to

the creek and upstream to the waterfall (and returning to Red Dog Ford the same way) or riding/hiking out on the terrace to the overlook across. The terrace walls are too steep to climb below the falls, although it may be possible to get through the falls and climb up on the terrace from the upstream side.

## Stop 5 - TAILINGS FAN FROM RED DOG TUNNEL AND CUTOFF SPUR

Similar to the process at Steephollow Crossing, Greenhorn Creek narrows here and forms a waterfall through a bedrock narrows. Prior to mining the channel meandered east around the bedrock which formed a spur (Figure 23). Up until the 1980s, it was possible to drive through this reach of channel across graded gravels. Bed rock knobs began to appear in the bed ca. the 1990s, and the route became impassable by the late 1990s.

Figure 23. Schematic diagram of (1) premining meander, (2) fan dam across Greenhorn Creek pushing channel up over bedrock spur, and (3) subsequent incision into spur. Source: James, 2004.



The Birdseye Company discharged sediment through the Red Dog tunnel from their claim to the east (north of Arkansas Ravine) into Greenhorn Creek at this location (a glory hole in the mine above shows on the Chicago Park topographic map and air photos). The tailings fan dammed Greenhorn Creek here and pushed the channel west. Subsequent incision let the channel down across the bedrock spur where it is now constrained by relatively resistant rock.

"There is an obstruction at the Red Dog tunnel which belongs to the Birdseye Company... That dump fills up the stream and backs the tailings on it... I think they had from 50 to 60 feet of dump when they started on the old tailings; and I think it is about filled up... There is a crossing there at the toll road. [Red Dog Ford downstream] They used to fell trees there in the winter. I think it is about 700 or 800 feet wide there; and Arkansas Canyon comes in at that place... [The bridge] dams up the stream and takes the grade off and stops the tailings..." (Williams, in Keyes, 1878: 384-85)

At least three substantial tailings fans dammed Greenhorn Creek: here above Red Dog Ford, about a mile downstream at the mouth of Missouri Canyon, and in lower Greenhorn Creek, probably at You Bet Bridge but described as at the mouth by Sargent, a Congressman and hydraulic mine owner upstream:

"I am very familiar with Greenhorn Creek... there are dams below, which stop our tailings, because if we could have the original grade of the creek we could work to much more advantage than we can now. The dam at the mouth of the Missouri Canyon is a very important obstruction to the flow of matter from our claims, it causes it to spread out through Greenhorn, above. That dam is caused by the tailings at right angles to Greenhorn, and pile up there at great height. Our tailings are confined up above. There is also a similar obstruction at the mouth of Greenhorn Creek, and another one at the mouth of Arkansas Canyon; there are three of them which are important; there are some minor ones." (Sargent, in Keyes, 1878: 347-348)

\*) Return up Red Dog Road ~1 mile to Buckeye Road; turn right, follow Buckeye Road ~1.5 miles to Greenhorn Creek at Buckeye Ford. Stop for hike upstream; bring river shoes.

## Stop 6 - BUCKEYE FORD

In 1994, terraces here were about 17 m above the channel bed, representing a mean depth of channel erosion of 15 cm per year over the previous 110 years (James and Davis, 1994). That process is ongoing as severe erosion occurred at this site in response to the 1986 flood when net erosion was  $83 \text{ m}^2$  including ~1 m incision of the thalweg (Figure 24). If that is representative of erosion in this area, then channel storage produced  $83,000 \text{ m}^3 \text{ km}^{-1}$  during the 1986 flood. Recent erosion here has not been as rapid as downstream at Red Dog Ford; perhaps due to the base level control at the Red Dog spur. A tunnel can be seen at Buckeye Ford high above the western road that drained the mine above into Greenhorn Creek. This tunnel must have been dammed by tailings in the main Greenhorn channel at the time of maximum aggradation because its mouth is lower than the highest terrace.

Figure 24. Valley cross sections on Greenhorn Creek at Buckeye Ford surveyed in 1985 and 1989. (James, 1993)

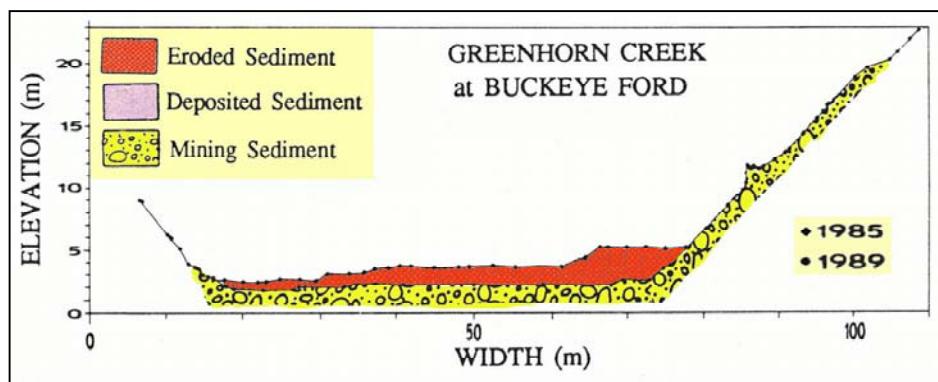


Figure 25. View up Greenhorn Creek at Buckeye Ford, July, 2003. Prominent terrace scarp across left half of photo is the middle terrace shown on the right bank of Figure 24. The high terrace can be seen in places behind the chapparal.



**Hike up Greenhorn.** Bring river shoes. We will hike approximately 2 km (~1.6 km as crow flies) to the high terraces at the mouth of Prior Creek (Figure 26).

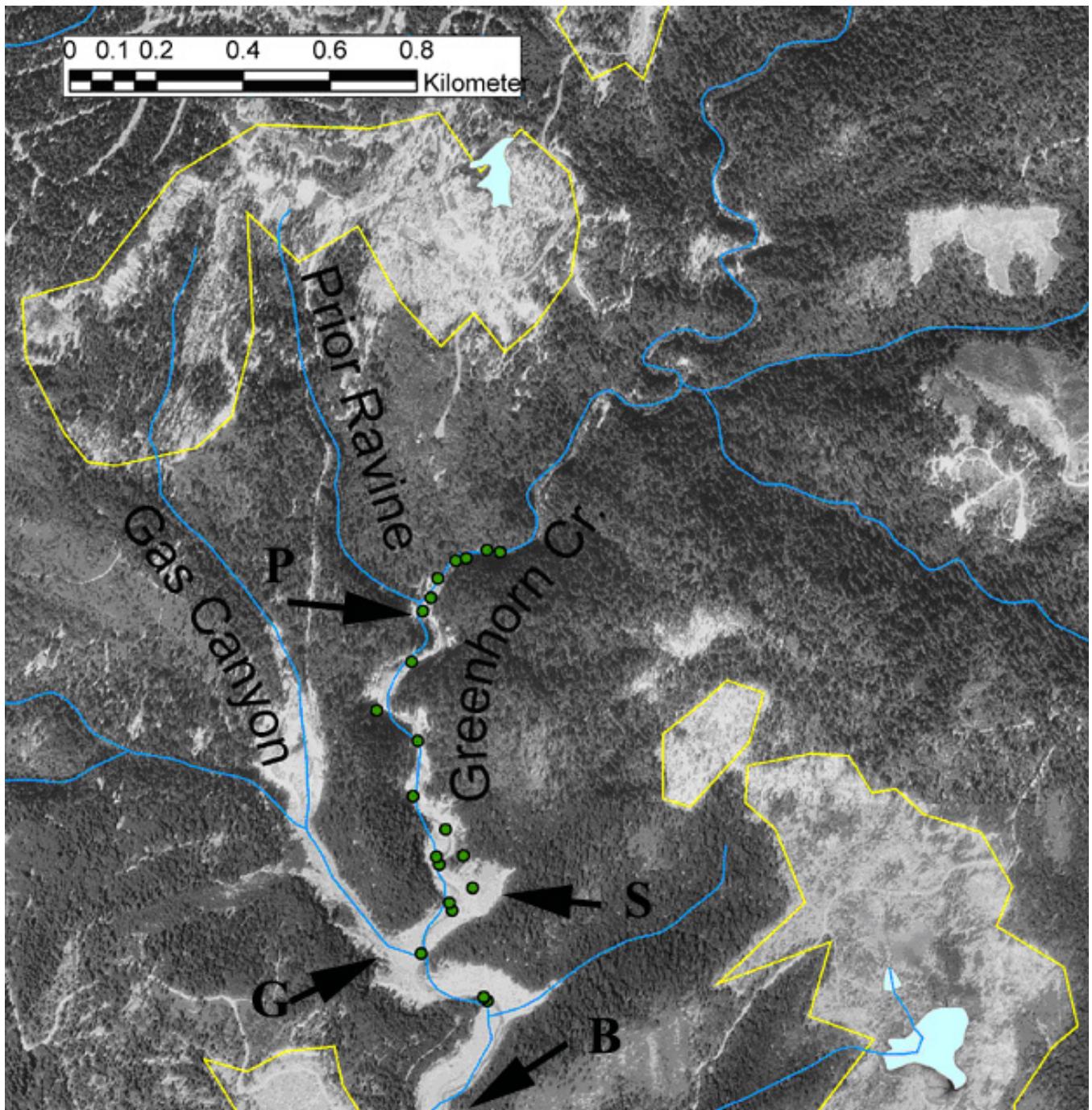
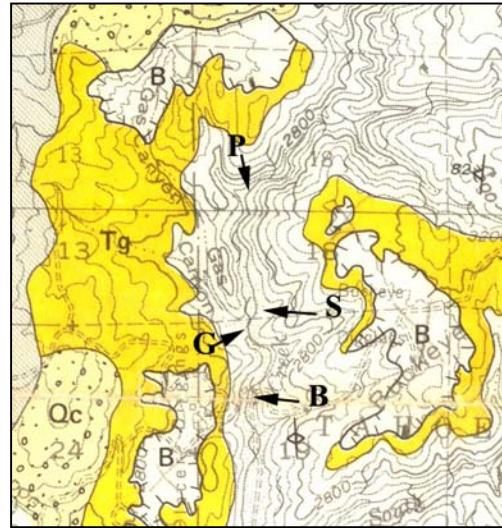


Figure 26. Upper Greenhorn Creek. Base map is a digital orthophoto quad (DOQ). B=Buckeye Ford (begin here); G=Gas Canyon confluence; S=incipient cutoff spur; P=high terrace at mouth of Prior Canyon (end here and turn back). Points show GPS survey points extending ~250 m beyond the limit of our hike.

The hydraulic mines of this area included the Buckeye Mine (to the east), a series of mines up the canyon at the base of Quaker Hill (due north), and the Park Avenue Mine that we drove through (west of Buckeye) (Figure 27). The mines are too high up on the ridge to be seen from the creek, but tailings fans can be seen in some locations.

Figure 27. Geologic map showing hydraulic mine pits (B), remaining Tertiary gold-bearing deposits (Tg), and Quaternary cover (Qc). Letters are the same as in Figure 26. Source: Yeend, 1974.



### GAS CANYON CONFLUENCE (+0.4 miles)

This canyon received sediment primarily from mines to the north at the base of Quaker Hill and filled deeply and quickly. Contemporary descriptions from court testimony in 1878 document sediment deliveries as fast as the channel could remove it:

"The deposit in Greenhorn Creek widens out and grows deeper and deeper every year. The tailings in Greenhorn now, I suppose, are 150 feet deep, made by gradual accretions in that way..." (Sargent, in Keyes, 1878: 356).

"The first tailings we put in Osborne Ravine. The next ones went into Knickerbocker Canyon; then Kaleseed Canyon and down to Gas Canyon. The present outlet is Greenhorn... In many places [Gas Canyon fill] is 350 feet wide, and from 40 to 100 feet deep... [Filled by] The recent washings... The earlier washings... in Kaleseed Canyon and Osborne Canyon... was very light material, and a great deal of it has gone off... The dump in Greenhorn Creek is, I should think, about 150 feet deep, and about 500 feet wide. In the Arkansas Canyon, I should judge it was from 800 to 900 feet wide... We let them lie [in Gas Canyon]; they still lie in Gas Canyon, if they have not washed out... It filled up there so as to prevent us from washing there any more; but there is hardly any water goes down Gas Canyon, except what we use. It is nearly a dry canyon. Although the water seeps through the gravel, it hardly ever comes to the surface... [Our flume] extends down Gas Canyon about half a mile, and then we have a tunnel through the hill... because Gas Canyon had filled up so we could not use it any longer." (Jacobs, in Keyes, 1878: 383-384)

The abundance of white quartz and fine gravel shows that most of the sediment is derived from the upper bench gravels. Although deep channel (blue lead) gravel are exposed in the mines above, working them was inhibited by aggradation of downstream reaches that reduced gradients:

"For years past we have dumped into Gas Canyon... We have piled up the tailings in that canyon... over 100 feet deep... that remain undisturbed by any freshet whatever lay there. Prior to 1870 we worked principally in the Kaleseed ground, where there was a great deal of red earth, and light stuff that would run off... We worked that... prior to 1870... We then moved into the railroad claims - the Green Mountain claims - and there the matter is directly over the Blue Lead. It gouges quite deeply into the Blue lead, although we are not able to get to the bottom for want of fall. The matter is very heavy, and troublesome to run through the sluices and ground sluices... we have piled it up in Gas Canyon, and it remains there, year after year, undisturbed, and no freshet touches it... it was 5 or 6 years ago that we ceased washing that light matter..." (Sargent, in Keyes, 1878: 347)

"...take Gas Canyon, where we tailed for several years. There I find, from the shallow place where it leaves the diggings down to Greenhorn, it is filled up several hundred feet deep, and 500 or 600 feet across..." (Sargent, in Keyes, 1878: 362)

Bear right and continue up main Greenhorn Canyon. These channel reaches remain choked with mining sediment due to the massive storage in the high terraces.

### INCIPIENT BEDROCK SPUR CUTOFF (+0.1 miles)

Immediately upstream from the Gas Canyon confluence a tailings fan draining the Buckeye Mine enters Greenhorn Creek from the east (Figure 28). The channel has been pushed to the west across a bedrock spur into which it has cut ~2 m

and is now prevented from laterally migrating. This is an incipient spur cutoff. Deposits in the bed are apparently deep throughout this area, so much channel incision is to be expected and this point will probably develop into another narrow constriction with cataracts like the Red Dog Spur and ultimately like Steephollow Crossing.

Figure 28. Bedrock spur exposed in the bed of Greenhorn Creek; a spur cutoff in the early stages of development. View upstream from Gas Canyon confluence.



Continue up Greenhorn Creek. The canyon narrows, terraces get higher, and bedrock exposures become more frequent upstream. Large woody debris and coarse lag cobbles become more common as side-slope processes deliver material to the channel in the narrow canyon. Stepped terraces are well preserved on some of the point bars and large trees on them suggest the potential for dating erosion in this area through dendrochronologic studies.

### PRIOR RAVINE CONFLUENCE WITH GREENHORN (+0.3 miles)

Prior Ravine enters Greenhorn from the north and drains a large mine at the base of Quaker Hill which also fed into Gas Canyon (Figures 26 & 27). Prior Ravine is not named on modern maps but is shown by that name on Whitney's (1880) map. This is the point at which terraces on Greenhorn Creek now reach their highest level above the stream bed (Figure 29). Combined with narrowing widths, the canyon in this area takes on a haunting aura where one can feel remote and isolated.

Figure 29. Terrace at confluence with Prior Ravine. Two people on terrace scarp show scale.



Lake sediments upstream provide evidence that the tailings coming out of Prior Creek dammed the creek here. Terraces in this area are on the order of 18 m high as measured at a section upstream from this site (James, 1988). As bedrock begins to appear in the channel above this point, depths of fill give the maximum depth of aggradation.

We will not continue further upstream because time is limited and the hiking becomes more difficult above this point. Although several major mines operated above this point, the amount of sediment storage decreases up-valley from this point, and locations where the channel has incised to bedrock begin to appear and become more frequent upstream. Step pools and other mountain stream features begin to emerge from beneath the mining sediment a few hundred meters upstream. This is an example of passive stream restoration, although the process has been very slow.

\*) Return to vans and Buckeye Ford for refreshments.

From Buckeye Ford; drive back west through the Park Avenue Mine across the upper area of a slide area where the road is hummocky.

**Mass wasting.** A series of tensional cracks opened here around 1990 feeding an earthflow into Gas Canyon. The slide mechanism may involve two processes: loss of internal strength due to prolonged cement leaching by groundwater during deep burial, and loss of mechanical support as channel incision removes the gravel from the slope base. If this slide resulted from channel incision, it could herald a series of failures yet to come, and the colluvium would represent an addition of sediment production indirectly attributable to mining.

Return the way we came out Red Dog Road to Idaho-Maryland Road, to Brunswick Road. Turn right on Brunswick Road, go ~3/4 mile to Hwy 49, get on northbound H49 towards Nevada City, go ~2 miles to Sacramento Street (Exit 185B), exit, turn right, turn right onto Sacramento Street, and right again onto Railroad Ave. We are staying at the Northern Queen Inn, 400 Railroad Ave, Nevada City.

### **DINNER AND ORIENTATION.**

We are staying at the Northern Queen Inn. Meet at the Trolley Junction on the south side of the inn around 7:15 pm. They will begin serving salads at 7:30, the main course shortly after, and the kitchen will close at 8:00 pm. We'll eat, socialize, enjoy the cash bar, and view slides until 10:00 pm.

## **DAY TWO from Nevada City.**

The itinerary for this day is full (much unavoidable driving), so we'll depart promptly at 8:00 a.m. You're on your own for breakfast in the Trolley Junction restaurant which opens at 7:00 am. Please be packed and ready to leave at 8:00 am.

- \*) Leave Northern Queen Inn, get on Hwy 49 north. Highway 49 soon joins Hwy 20 at north end of town with a left turn. Stay on 49 north by turning left.
- \*) Drive ~6 miles on Hwy 49, drop down into South Yuba Canyon, pull over onto old bridge on right side and park.

## **Stop 7 – SOUTH YUBA RIVER AT HIGHWAY 49**

The channel hydraulics of the South Yuba in this gorge are distinctly different than those of the Bear River and its tributaries. Channel slopes are not substantially different between the two systems in the mining districts but the South Yuba heads in the high Sierra, and has a much larger drainage area here ( $801 \text{ km}^2$ ). Thus, it has much larger discharges, stream powers, and sediment transport capacities through the mining districts. Fine-grained mining sediment deposits are poorly preserved in the main canyons of the South and Middle Yuba rivers for this reason. This site is one of the steeper reaches of river on the South Yuba main channel and little mining sediment remains. Even here, however, 75% of the pebbles in samples from fine material in the interstices of the cobbles and boulders (intermediate diameters  $< 50 \text{ mm}$ ) are white quartz, showing that some mining sediment continues to move through the reach (James, 2005). This sediment is being produced from upland tributaries such as Shady Creek.

Total volumes of sediment produced by mines upstream of this location were similar to loadings in the Bear River basin (Table 2; p.8). Tailings fans in mountain channels of Yuba River were observed in the 1880s shortly before hydraulic mining was enjoined, but were localized due to the low storage potential:

“I have observed at the dumps of the different mines the remains of former deposits which were left on the sides of the canyon showing the heights of former deposits and showing also that these deposits had been washed out by some former high stage of water. And I have observed that these banks that were left standing were invariably very loose in nature, such a bank as one could not climb up, for instance. The gravel and sand would cave down so as to prevent his getting up the face of it.” (Pierson, in Woodruff v. N. Bloomfield, 1883: 1160)

**Guest Speaker:** *Katrina Schneider* of the South Yuba River Conservation League will speak to the group about on-going river monitoring and mitigation efforts.

\*) Proceed across the river and climb up San Juan Ridge. Go about 2 miles and turn right on Tyler Foote Road. Continue to the Northeast ~3 miles to the edge of the Cherokee Mine (aka North Columbia mine). Stop along the right side of the road at a dirt road.

## **Stop 8 - Hike into Cherokee Mine**

In addition to the clear exposure of Tertiary channel stratigraphy, the Cherokee Mine provides an example of the powers of humans to alter the face of the earth (Figure 30). Anthropogenic geomorphology was not born here in the California mines, but it was pushed to an extreme.

Figure 30. Cherokee hydraulic mine pit on San Juan Ridge with Shady Creek behind it. Our stop is to the right of this site on the far side of Shady Creek. Photo by A. James, Sept., 2003.

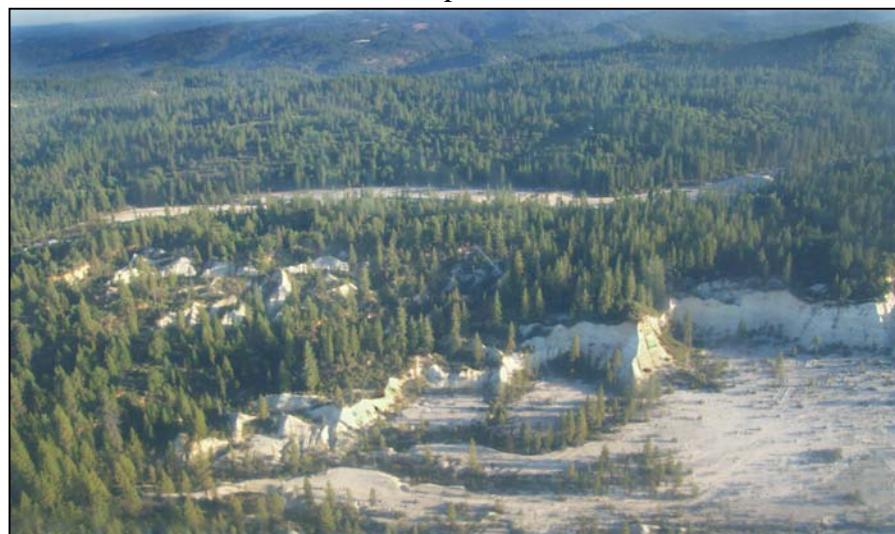


Figure 31. Cherokee hydraulic mine pit on San Juan Ridge.  
 (Top) The abundance of white quartz pebbles indicates that portion of mine was exploiting bench gravels.  
 (Below) Reddish soil zone represents former land surface before mining.  
 Gilbert used these surfaces to constrain topographic surveys for computations of sediment production volumes. Rolf for scale.



The Cherokee mine drains to the south into a tributary of upper Shady Creek where a broad, low gravel terrace was sampled on June 7, 2006 (Figure 32). This sample yielded the highest total mercury concentration of any of our samples processed so far: 3690 ppb.

Figure 32. Terrace along upper Shady Creek tributary immediately below Cherokee Mine. Total mercury in sample contained 3.69 ppm of total mercury.



\*) Return back on Tyler Foote Road to Highway 49. Cross Hwy 49 (becomes Birchville Road) and go ~2 miles to 'T' at Pleasant Valley Road – go left ~1.5 miles to town of French Corral.

**French Corral** (drive by): This is a ghost town (OK, ~70 people live here) named for the mule pen built by a French settler in 1849. The Wells Fargo Express building on the right was built in 1854. This was a major mining town when the French Corral hydraulic mine was operating. The mine exploited deep deposits of the main Ancestral Yuba River:

“...the united branches of the [Ancestral Yuba] river broke through the greenstone ridges of the foothills in a valley, which, as can be seen at Smartsville and French Corral, had a depth of more than 1,000 feet. At Smartsville the bed of the Tertiary river was 200 feet above the present Yuba; at North San Juan about 700 feet. Coarse gravels to a depth of 170 feet filled this old trough and they are directly overlain by andesitic gravels and tuffs. Between French Corral and North San Juan the average thickness of the gravels was probably 200 feet.” (Lindgren, 1911: 34)

\*) Continue south on Pleasant Valley Road ~2.5 miles steeply down into the South Yuba Canyon to Bridgeport. The foothill rivers are incised into deep canyons. This promoted the rapid delivery of mining sediment downstream to the Valley.

## Stop 9 - LUNCH AT BRIDGEPORT

This covered bridge was constructed in 1862 using a single 251-foot span supported by a wooden arch ([http://www.ncgold.com/Museums\\_Parks/syrp/Bridgeport/](http://www.ncgold.com/Museums_Parks/syrp/Bridgeport/)). White pebbles in the concrete foundation suggest that hydraulic mining sediment was present at this location and was used for aggregate when the bridge was built in 1862. This is not surprising; December 1861, and January, 1862 floods delivered large amounts of mining sediment to the Sacramento Valley. Little mining sediment remains at this site, but downstream about one mile much is stored in the delta to Englebright Reservoir. The bridge is now managed by the *South Yuba River State Park* which includes a linear strip of land and trail system along the lower South Yuba River from Englebright Reservoir up to the Tahoe National forest. Englebright Dam was the subject of extensive study as a candidate for removal in hopes of restoring Salmon to the upper Yuba River (James, 2005).

\*) Continue south on Pleasant Valley Road ~6 miles to Hwy 20, turn right. Go ~3.5 miles, cross the county line at Mooney Flat Road, continue another half mile to Smartville Road.

If there's time, turn right on Smartville Road, go about ¼ mile to Krista Trail Road on right. If gate is open, turn right onto Krista Trail Rd, go through gate and ~1/4 mile to Blue Point Mine overlook. If the gate is closed continue on Smartville Rd ~1/4 mile to Blue Gravel Rd, turn right, go ~1/4 mile, turn right onto Krista Trail Rd, go right ~1/4 mile to Blue Point Mine overlook. Park for brief stop.

## Potential Stop 10 - Blue Point Mine (Brief stop if time). (Figure 33)

This mine differs from most hydraulic mines in the region for two reasons. First, it worked the lower Ancestral Yuba River, so it presumably worked finer-grained materials than mines further upstream. Second, this is one of very few mines located downstream of all substantial dams. Little sediment appears to be available for transport from the mine, and a brief reconnaissance below the mine suggests little storage between the mine and sites near the Yuba River. Extensive mining sediment deposits at Rose Bar and near Parks Bar, on the upper and lower ends of Timbuctoo Bend, respectively.

Figure 33. View to east into Blue Point Mine from near Smartville.



James, Singer, and Aalto

Gilbert noted mass wasting in the Blue Point mine and other hydraulic mines that inspired him to recall his theory of Basin and Range tectonics:

"The face of the larger Smartville Pit (facing N) has fallen away in immense blocks, which hold up there except they also are systematically broken and faulted... The faulting largely follows joints (in cemented gravel). Each large mass cant outward and is step faulted backward...: The process is probably gradual. It can be seen in various steps. Some are so fresh that the terraces incline with them, and yet no terraces are broken - as might be expected if the drop were sudden." G.K. Gilbert, Field Notebook #3506, April 24, 1908: p.28-29; Library of Congress

"At Mooney Flat the mining pit has induced a slide of the whole gravel formation apparently... The Blue Point slides illustrate a possible theory of Basin Range structure." Gilbert, Field Notebook #3506, April 28, 1908: p.31.

\*)Return to Hwy 20, turn right and continue west. Cross the South Yuba at Parks Bar.

**Parks Bar Bridge.** No stop; drive by. Gilbert photographed this site in 1908 (Figure 34). The fine-grained deep sediment in Gilbert's photograph represents deltaic effects of the Daguirre Point Dam ~6 miles downstream. Gilbert returned in 1913 and estimated that the low-water channel here had incised by about 10 feet in that five years (Gilbert, Field Notebook Book # 3508, 1913: 34; Library Congress).



Figure 34. The lower Yuba River at Parks Bar experienced severe aggradation.

(A) Channel aggradation in 1908 was still near its maximum stage. Very little incision had yet occurred at this site as evidenced by lack of high terraces. Photograph by G. K. Gilbert (1917).



(B) Lower Yuba River a Parks Bar from lower vantage point showing high remnant terraces and single-thread channel. We will cross just below this site at the Highway 20 bridge.

Gilbert's (1917) classic model of sediment transport as a sediment wave was based largely on his observations of sediment movement through the Yuba River. This model is often used to argue that sediment yields have returned to pre-mining levels. That argument conflates channel vertical changes

(channel-bed elevations upon which Gilbert's analysis is based) with sediment loads which include lateral channel adjustments and floodplain storage (James, 1989; 2006). Large deposits of historical sediment remaining in the Sacramento Valley, however, continue to produce sediment during floods.

\*) Continue west on Hwy 20, go 17 miles to Marysville. (no stop)

**Lower Yuba River.** We are passing vast expanses of land that were deeply and extensively aggraded by hydraulic mining sediment (Figure 6, page 9). Local farmers were devastated by aggradation and exacerbated flooding caused by the sediment, particularly in the Yuba and Bear Rivers. Deposition was negligible until the 1861 flood when the channel-bottom suddenly filled with sand and gravel (Mendell, 1881). Aggradation and flooding worsened through the 1870s when channels avulsed in spite of levee construction and other engineering attempts to control sedimentation and flooding (Hall, 1880; Mendell, 1881). The deposits cannot be seen from Hwy 20 once we leave the bridge area. Yuba Dredge Field is across to the south, mostly out of view (Figure 35).

Figure 35. Dredge spoils in the Yuba Gold Fields. Dredging is a form of strip mining for gold that involved barges with large clam-shell dredges. It is not to be confused with hydraulic mining but was environmentally devastating in its own way. Dredging worked both historical hydraulic mining sediment deposits and older Quaternary alluvium along the rivers. Major dredge fields are located in the lower Feather, Yuba, Bear, and American Rivers. The Yuba Gold Fields near Hammonton are the most extensive of them all and can be seen from far out in space on satellite imagery. Photo by A. James, Fall, 2001.



As we near Marysville, the high levee to the left marks the northern limit of the deep deposits, although occasional levee failures may have resulted in some sediment north of the levees. Marysville is known as the *Walled City* because it was completely encircled by levees to protect it from flooding as the river aggraded from the 1860s to 1880s. Channel incision into the sediment in the lower Yuba (Adler, 1980) has lowered flood stages, but there is still a considerable flood hazard. Major flood damage in residential areas south of Marysville resulted from a levee failure during the 1986 flood.

By the turn of the 20<sup>th</sup> century, long after mining had ceased, lower Yuba channels had not stabilized:

"From the foothills to the mouth of the river at Marysville the channel is over a surface of gravel, sand, and clay, recently built up from the mines above. The channels are irregular and change from winter to winter and sometimes during the summer... The changes in the bottom and in the position of the channel are so great that the gaging at the flood stages of the river would be unsatisfactory, and if undertaken from boats would be highly dangerous, if not impossible." (Manson, 1901: 39-40)

Gilbert observed in 1913 that the Yuba was delivering gravel to its mouth:

"...so coarse as to include pebbles 1-2 inches diameter" He noted that a fan into the Feather River at the mouth of the Yuba had produced a lake upstream in the Feather River that was four to five miles long (Gilbert, Field Notebook Book # 3508, 1913: 37; Library of Congress).

The mouth of the Yuba River at the Feather River continues to receive much sediment (Figure 36). During floods, backwater may develop at the Feather River causing rapid sedimentation and potential levee failures.

Figure 36. Jeep buried in sandy alluvium along left bank of lower Yuba River below the Hwy 70 bridge at Marysville. Photo taken May, 2006.



- \*) Stay on Hwy 20 in downtown Marysville as it dogs left on B Street, right on 9th Street, and right on E Street (which is also Hwy 70 north).
- \*) Stay on Hwy 20 as it makes a hard left to the west. Follow it ~2.5 miles across the Feather River into Yuba City to Hwy 99. Turn left (south) onto Hwy 99.
- \*) Go south ~ 15 miles to Sacramento Ave.

**Feather River** (no stop). To the west of us is the lower Feather River. The pre-mining channel was broad, with steep banks lined with oaks and sycamores:

"We arrived upon the southeast bank of the Feather river, six miles below the junction of the Yuba,... This is the most beautiful situation that I have seen in California. The river, which at this place is about six hundred yards in width, is lined on either bank with majestic sycamores, in a fine grove... The river is filled with salmon... we crossed... about one mile below the farm<sup>a</sup>house, having much trouble in getting up the bank on the west side... we now entered upon a fine, level prairie, the soil of which was of the richest description, and its surface dotted with the 'long-acorn oak' for a distance of two or three miles from the river..." (Derby, 1847, in Farquhar, 1932: 112-113)

This description also fits the Feather River downstream below the Bear River confluence at that time:

"Feather river, near its mouth, is a very broad and beautiful stream. Its banks are heavily timbered, and some fifteen feet in height, coming down abruptly to the water. There is a sufficient depth of water as far as the mouth of Bear creek to float any small-size vessel; but the frequent occurrence of extensive sand-bars renders the navigation to this point at present impracticable..." (Derby, 1847, in Farquhar, 1932: 17).

- \*) Turn right on Sacramento Ave.
- \*) Drive ~1 mile to end and climb levee; turn left at top of levee.
- \*) Follow levee south ~1 mile, drop down onto Feather River floodplain, continue across it ~3/4 mile to Feather River. Stay on left bank of Feather River through gate (we have permission for access). Watch for 'sand' signs, go past rice field, Park.

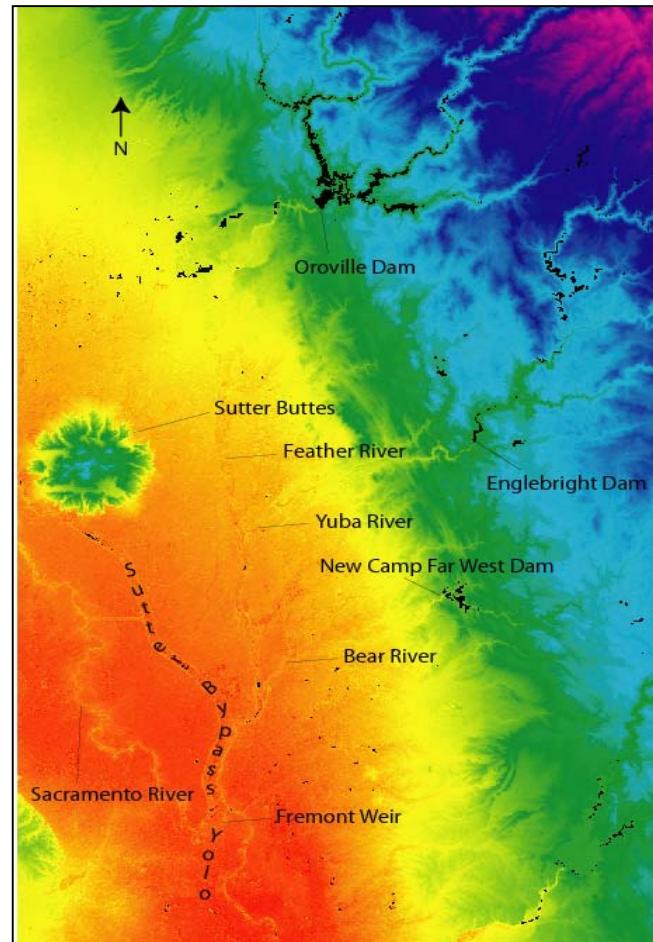
## Stop 11 – CONFLUENCE OF FEATHER RIVER AND SUTTER BYPASS

**Summary** - Feather River delivers the majority of mining-derived (historical) sediment to the lower Sacramento Valley, but the extent of its mixing with surrounding sediments and its primary deposition zones are not well constrained. We have begun to characterize the mixing of sediments using a suite of chemical and physical tracers and to identify major zones of net sedimentation. One such zone of sediment accumulation is this confluence, where a large fan has built up through a succession of large

floods. We have documented one episode of sedimentation at the downstream end of this confluence that occurred during a major flood in 1986. The sediment delivered to this region buried several square kilometers of a rice farm more than a meter thick. Such deposition affects agricultural activities, vegetation recruitment, and flood conveyance in Sutter Bypass.

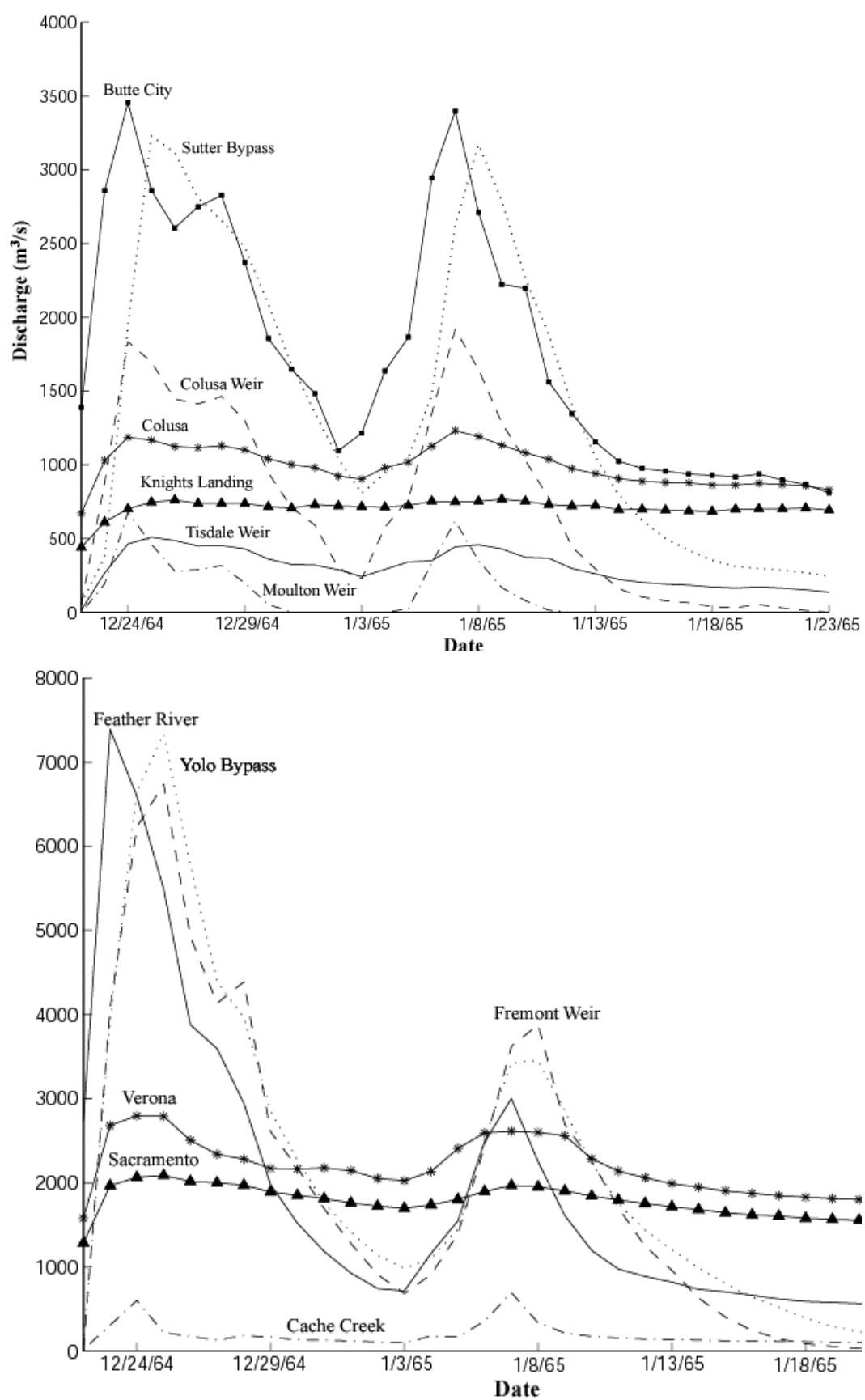
**Details** - The Sacramento Valley comprises the northern half of California's Central Valley and is drained by the Sacramento and Feather Rivers (Figure 37). Under natural conditions (i.e. before floodplain development), these rivers had insufficient capacity to convey winter and spring floods generated by frontal storms [US Army Corps of Engineers, 1965]. They frequently overflowed into subsiding flood basins [Ikehara, 1994] on either side of the aggraded channels [Kelley, 1998], leading to inundation of ~40% of the valley floor [McGlashan, 1929]. The primary flood basins of the Sacramento Valley were delineated in early studies of surface water supply [McGlashan, 1929], groundwater resources [Bryan, 1923], and the impact of hydraulic mining [Gilbert, 1917]. The frequency of large floods impacted the growing floodplain population of farmers in the late-1800s and questions arose about the extent to which flooding in the Sacramento Valley was influenced by hydraulic mining [Kelley, 1998]. However, frequent, large floods predated hydraulic mining, including those documented in 1826, 1840, 1847, 1850, 1852, and 1853 [US Army Corps of Engineers, 1965; Kelley, 1998].

Figure 37. Study area in Sacramento Valley shown on Shuttle Radar Topography Mission elevation data.



Under the Sacramento River Flood Control Act of 1917, the Army Corps of Engineers and the California Department of Water Resources (CDWR) planned to construct levees upon natural banks and a system of flood weirs and bypasses to convey high flows to the Sacramento-San Joaquin Bay-Delta, reducing flood risk at sites along the lower Sacramento River [US Army Corps of Engineers, 1998] (Figure 38). In his assessment of the proposed flood control system involving the construction of bypasses in the historic flood basins, Gilbert [1917] noted that although large amounts of sediment had accumulated in the flood basins, if the bypass channels were designed with appropriate slope, flow velocities would be high enough to maintain the bypasses as self-scouring channels. We have been testing this notion via sediment coring field campaign.

Figure 38.  
Floods in the  
Sacramento  
Valley are  
controlled  
primarily by the  
weir and bypass  
system (Singer  
and Aalto,  
Submitted to  
Journal of  
Geophysical  
Research-Earth  
Surface).



The water year of 1986 brought a major flood to the Sacramento Valley that was the largest of record for the Feather River and several of its tributaries. The estimated peak discharge for the event at the (discontinued) Nicolas gauging station is  $> 10,000 \text{ m}^3/\text{s}$ . The flood broke levees along the Yuba River and scoured sediment from the bed, bars, and failed terraces from the upland basin delivering a huge (but unknown) volume of sediment to this confluence. For example,  $\sim 1.0 \times 10^7 \text{ m}^3$  of sand and silt was deposited in a discrete packet within Sutter Bypass adjacent to the right bank of the Feather River (*Singer and Aalto, unpublished data*). This deposit completely covered a rice field  $\sim 6.0 \times 10^5 \text{ m}^2$  to an average depth of 1.5 m, forcing the landowner to lease to a sand mining operation for several decades. Indeed, a collection of such deposits along this boundary from major floods of the past has resulted in the topographic expression of onlapping overbank sediments from Feather River (Figure 39). These sediments may prove problematic for flood conveyance and could be a source of mercury and other metals to sensitive wetland ecosystems. We have extracted tens of sediment cores from this region and are dating them radiometrically using  $^{210}\text{Pb}$  to identify the role of individual floods in sediment deposition. We expect to find a thick lens of high excess activity in these recent deposits, overlying a zone of much lower (older) activity – similar to deposits we have characterized downstream (Figure 40).

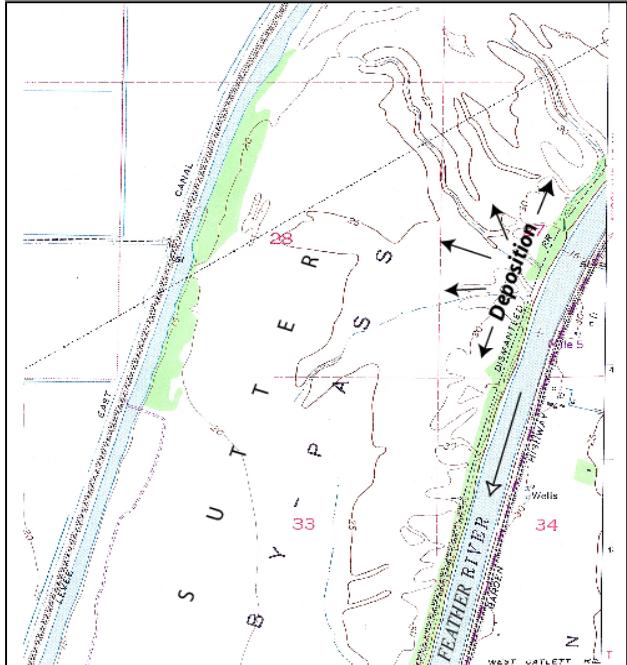


Figure 39. Lower Feather River confluence with Sutter Bypass (right: 1958 aerial photo) showing deposition. Left: Deposition along margin of Feather River downstream of confluence shown on 1:24K USGS topo quad. Inset: Photo of 1986 flood deposit (see also cover of Guide).



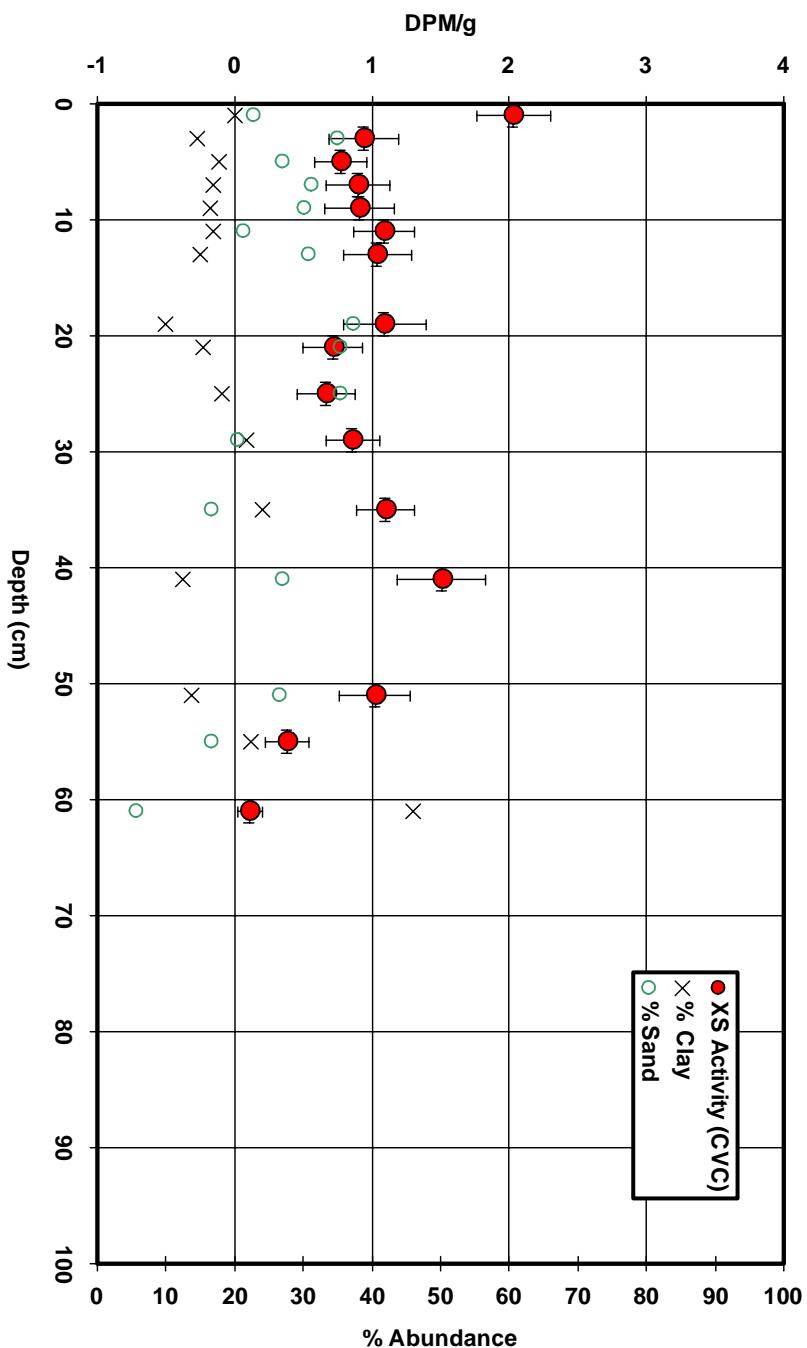


Figure 40. Core from upstream of Fremont weir on Yolo bypass, just across from the Feather River confluence. This location received copious, recent accumulation of ~ 50 cm of sediment as a single event, as evidenced by the high, relatively uniform XS  $^{210}\text{Pb}$  concentrations. We expect recent deposits of Feather River sediment from locations further upstream to exhibit a similar form in their profiles.



Figure 41. (below) Sampling sand splay in Sutter Bypass a few hundred meters west of Feather River.



\*) Drive back out to Feather River floodplain, pull to the right and stop.

### **Stop 13 - FEATHER RIVER AT SUTTER BYPASS CONFLUENCE (if time)**

The Sutter Bypass was constructed to be hydraulically smooth but subsequent deposition of alluvium from the Feather River has resulted in substantial filling and topographic relief. A series of splay deposits in this area are collectively forming a natural levee between the river and the bypass in this vicinity (Figure 39; see also Guide cover). We will discuss floodplain cores and geomorphic processes in this area.

\*) Return to Hwy 99: Drive back up on levee, take right off of levee to Sacramento Ave., and retrace route to Hwy 99. Drive 17 miles north into Yuba City, turn left on Hwy 20, drive roughly 10 miles to east side of Sutter Bypass (don't cross over), turn right on West Butte Road, drive north ~1/4 mile, turn left on Long Bridge Road, and park.

#### **No Stop. Shanghai Bend (no time).**

We are in the early stages of working out the basic alluvial stratigraphy along the lower Feather and Yuba Rivers. Our primary goal is to develop sedimentologic and pedologic methods of differentiating historical from pre-historical alluvium so that we can identify storage locations, estimate storage volumes, and compute volumes of sediment mobilization from historical aerial photographic reconstructions. Lidar terrestrial and bathymetric topographic data are available and are being analyzed to assist in the field surveys and volumetric computations (Figure 42).

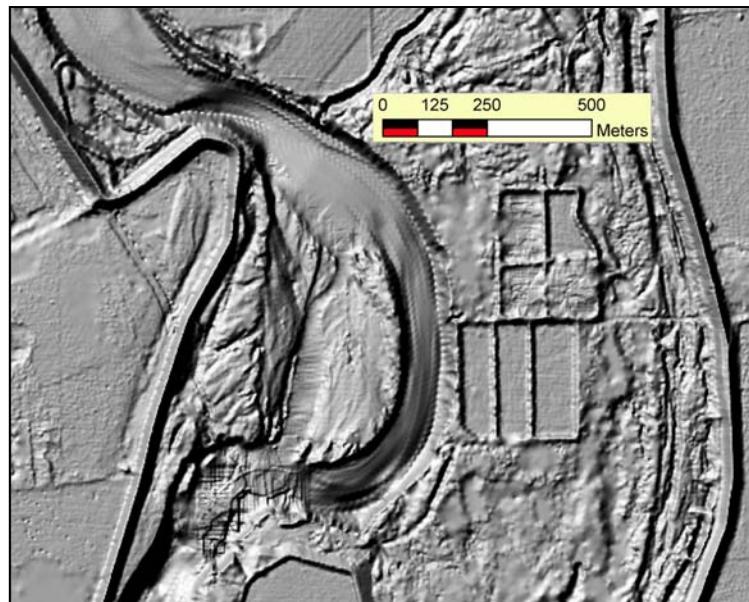


Figure 42. Lidar image of Shanghai Bend on lower Feather River below Yuba confluence.

### **Stop 14 – UPPER SUTTER BYPASS (if time)**

We are in the upper Sutter Bypass near where Butte Slough, historically flowed into the Sutter Basin to the southwest. As with many of the sloughs in the lower and middle Sacramento Valley, Butte Slough was a distributary stream that naturally diverted large amounts of Sacramento flow during floods into a neighboring low basin. After a long history of failed attempts to train Sacramento River flood flows into a single channel using levees (a policy based on practices in the lower Mississippi River), flood control ultimately was forced to adopt an innovative approach in which the natural distributary and basin system was exploited during high water (Kelley, 1989). During floods, much of the Sacramento River flow is diverted past this point into the Sutter Bypass where it joins the Feather River near Stop 13.

\*) Return to Hwy 20, turn right, cross Sutter Bypass, go ~12 miles west through Meridian and WNW to the town of Colusa.

\*) Drive through Colusa on Hwys 20/45 which will become Bridge Street trending NNE. Stay on straight on Bridge St when first Hwys 20 then Hwy 45 turn sharply to the left, and cross the Sacramento River. Continue straight (Bridge St. become River Rd) ~2 miles to Colusa Weir. Stop.

## Stop 15 – COLUSA WEIR/SUTTER BUTTES

*Summary* - Colusa Bypass is the first major shunt for the Sacramento River to siphon off water and sediment (Figure 43). It was constructed at a natural overflow point where the Sacramento built an extensive splay deposit well before engineered bypass construction. During floods, flow from the Sacramento River overtops Colusa Weir and is released into Colusa Bypass. This flow joins flood flow from Butte Sink and travels into Sutter Bypass (near the Sutter Buttes) where it heads south to the Bay-Delta. Figure 38 emphasizes the role of Colusa Bypass in decreasing downstream flood risk along the Sacramento River. Sediment from the Sacramento River deposits in distal portions of Colusa Bypass near the Sutter Buttes and the head of Sutter Bypass. This large sink area appears to be a major depocenter in the Sacramento Valley.

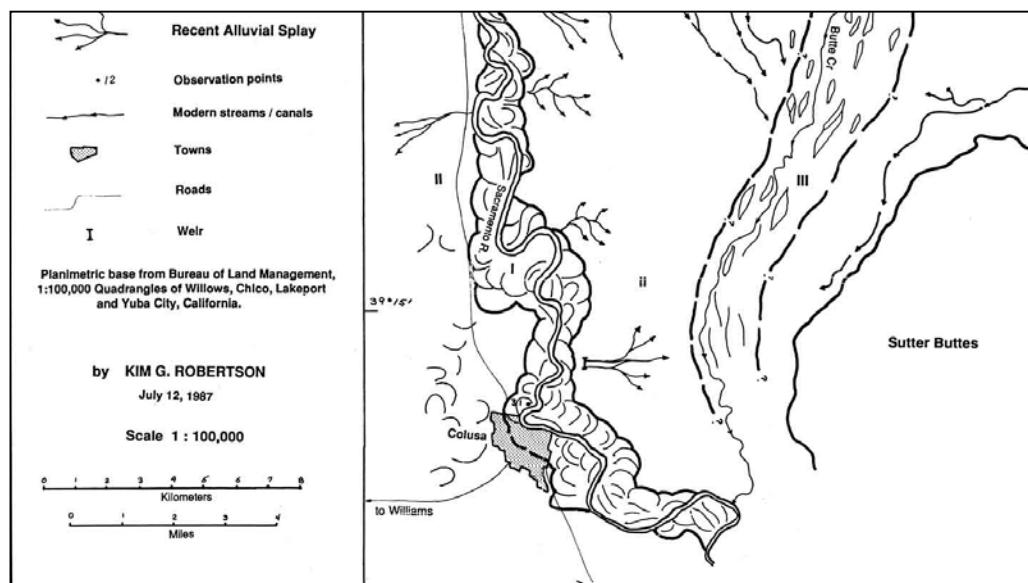


Figure 43. Oblique aerial photograph over Colusa Weir and Colusa Bypass with the Sacramento River in the background. During floods stage rises in the Sacramento until flow overtops the concrete weir (under the bridge) and moves east (down in the photo) into the bypass system. The flow first enters Colusa Bypass, then Butte Basin, before entering Sutter Bypass (not shown). (Singer and Aalto, Submitted to Journal of Geophysical Research-Earth Surface)

**Details-** In the late-1860s, Will Green, mayor of Colusa, recognized that rapidly rising floods, high frequency of overbank flows and a large number of levee crevasses prevented even an enlarged Sacramento River from conveying its floods [Kelley, 1998]. He argued with engineers who had cut their teeth on the Mississippi about how best to control floods in the Sacramento. In spite of his lack of engineering training, Green outlined a flood control plan that used portions of the existing flood basins as bypass conveyance channels for high flows. His plan was later formally drawn up by two engineers from the Army Corps of Engineers (the report of M. Manson and C.E. Grunsky is outlined in [US House of Representatives, 1911]), and was later modified after two large Sacramento Valley floods in 1907 and 1909 [US House of Representatives, 1911; McGlashan, 1929].

Gilbert [1917] also wrote that the channel capacity between Colusa and the Feather River confluences declines to 10% of its ‘flood discharge’. The reduction in width generally corresponds with two tectonic features. The Sacramento River follows the trace of the Willows Fault toward Colusa. The fault dips steeply to the east and crosses the Sacramento 8 km north of the Colusa gauge. Just over 1 km downstream of Colusa, the river is diverted 2 km eastward for 13 km to traverse Colusa Dome, a southward plunging anticline which displays over 150 m of structural relief on basement rocks [Harwood and Helle, 1987; Singer and Dunne, 2001]. These factors induce sequestration of water upstream of Colusa and force flow and sediment to leave the channel near what is now Colusa Weir and Bypass. Indeed, the area near Colusa Weir is one of a longitudinal sequence of mapped alluvial splay deposits along the margins of the Sacramento River (Figure 44, [Robertson, 1987]) that were incorporated into the modern flood control system as later weirs. Since the flood control project, flow has been constrained within the narrow swath of Colusa Bypass until it reaches the Sutter Buttes area, which is the most downstream part of Butte Sink, a natural overflow area draining the northeast part of the Sacramento Valley.

Figure 44.  
Paleochannel map showing pre-historic alluvial splays that predate the flood control system. The one directly opposite of the Sutter Buttes is the current site of Colusa Weir.



Our coring data and modeling results suggest that up to 2 Mt of suspended sediment is transported over Colusa Weir during floods (Figure 45) and most of it deposits at the intersection of Colusa Bypass and Butte Sink, apparently a major depocenter in the Sacramento Valley. We have documented very high sediment deposition in this area (of order 1 m per flood for large floods, Figure 46). Sediment-depleted

flow makes its way via gravity from this area into Sutter Bypass to begin its journey toward the Bay-Delta.

Figure 45. Schematic map of the lower Sacramento River and bypass system, including main channel, tributaries, flood diversions, and bypass channels. Event-based sediment discharge (for the 1964 flood) computed for each station and net erosion/deposition are shown for each reach. All values expressed in megatonnes. Not to scale. (Singer and Aalto, Submitted to Journal of Geophysical Research-Earth Surface)

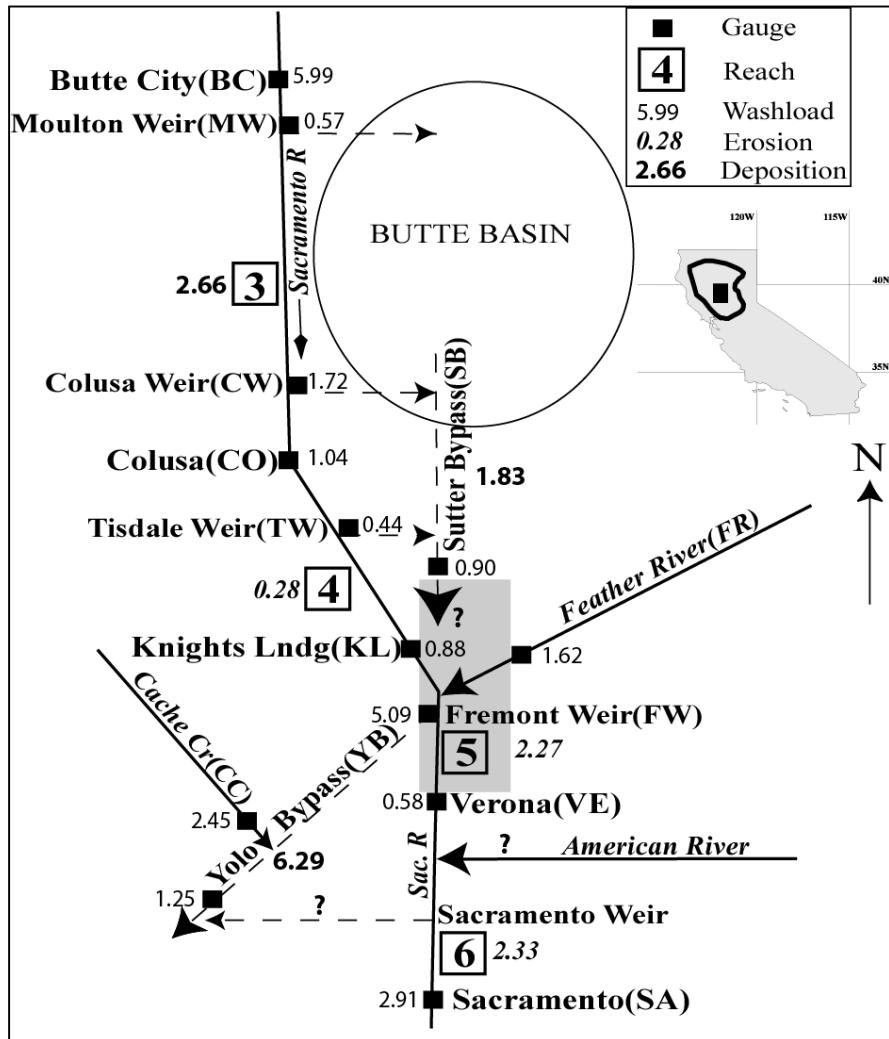
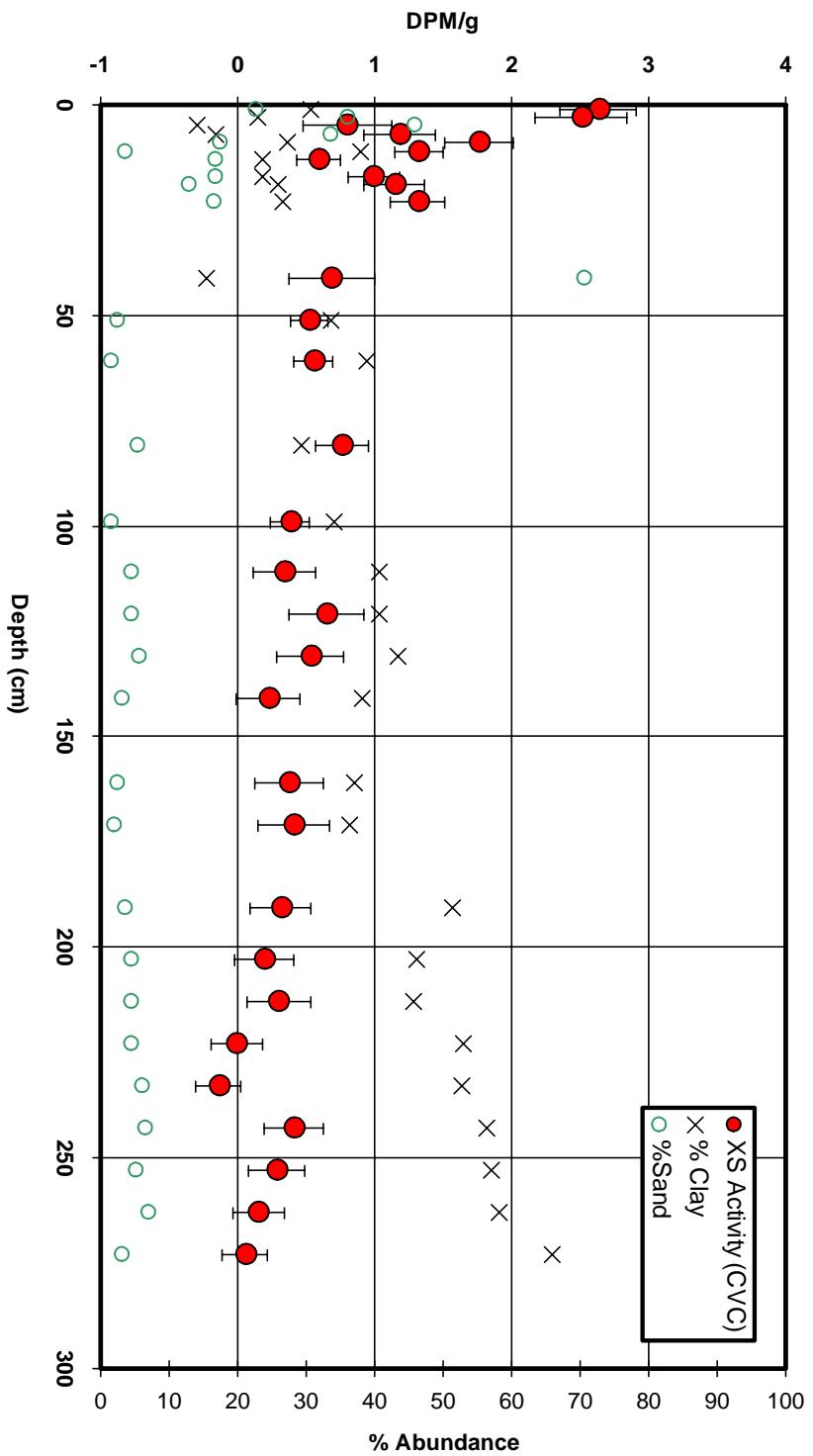


Figure 46. Core in depositional area of Colusa bypass. Top ~20 cm of sediments are a mixture of recent deposition and meteoric fallout. They overlay sediment from 40-80 cm depth that arrived in the mid 1990s. The zone of elevated activity from 100-220 cm depth was most likely deposited in the mid 1960s.



This is our last stop of the day. We will enjoy refreshments and a sunset (we hope) at base of Sutter Buttes.

\*) Return south on River Road to Colusa, turn right (east) on Hwy 45, drive north ~3 miles to the Colusa Casino and Bingo, 3770 State Highway 45, Colusa, CA. We will spend the night at the casino.

## **DAY THREE from Colusa.**

We will make one stop in the morning followed by lunch and the drive back to the San Francisco Hilton. We will depart the Casino promptly at 8:00 a.m. You're on your own for breakfast in the Colusa Casino. Please be packed and ready to leave at 8:00 am.

\*) Take Hwy 45 south to ~40 miles to Knights Landing. (Alternate route: get onto I-5 to County Rd 13 (~50 miles) instead of Hwy 45 all the way.) Go north on 113 to Sacramento River and park on right. Brief stop.

\*) Go south on Hwy 113 across Knights Landing ridge cut and veer south on County Rd 102 (E8). Go ~2 miles south to County Rd 16, turn left (east), go ~2 miles to levee, and turn left (north) at 'T' onto County Rd 116B. Go ~3/4 mile and turn right on County Rd 116A on levee to the end. Park.

### **Stop 15 – FREMONT WEIR**

*Summary* - Fremont Weir is the crux of the Sacramento Valley flood control system. It is overtopped by flood flow from Sacramento River, the Sutter Bypass, and the Feather River, which pours into Yolo Bypass (Figure 47) and subsequently to the Bay-Delta. Floods deposit sediment on the upstream and downstream sides of the weir forming a modified natural levee that is divided by the weir and its drop structure. The sediment accumulation is a concern for flood control managers, inducing recent campaigns of sediment removal.

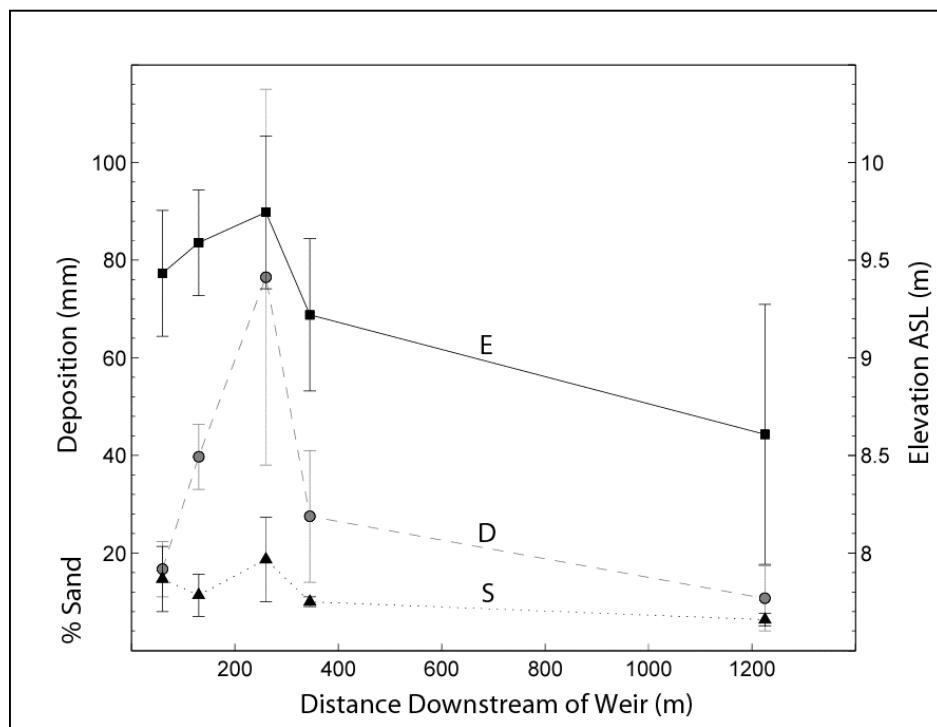


Figure 47. Flow (left to right) over Fremont Weir (looking east) during the 2006 flood.

**Details** - The majority of floodwaters generated in the Sacramento Valley pass over Fremont Weir into Yolo Bypass. The composition and magnitude of the flow and sediment flux depends on the location of the storm center within the basin. However, the largest floods are generated from high rainfall in the Sierra Nevada (Figure 38; p.38) and have deposited masses of sediment along Fremont Weir. In spite of efforts to grade these deposits for flood conveyance, topography continues to develop near these weirs at the entrances to the flood bypasses, necessitating vast campaigns of sediment removal by the CDWR. For example  $\sim 2.6 \times 10^6 \text{ m}^3$  of sediment were removed from upstream portions of Yolo Bypass alone between 1986 and 1991 (CDWR, unpublished data). This amounts to removal of 80 cm depth of sediment removed if averaged over the removal area.

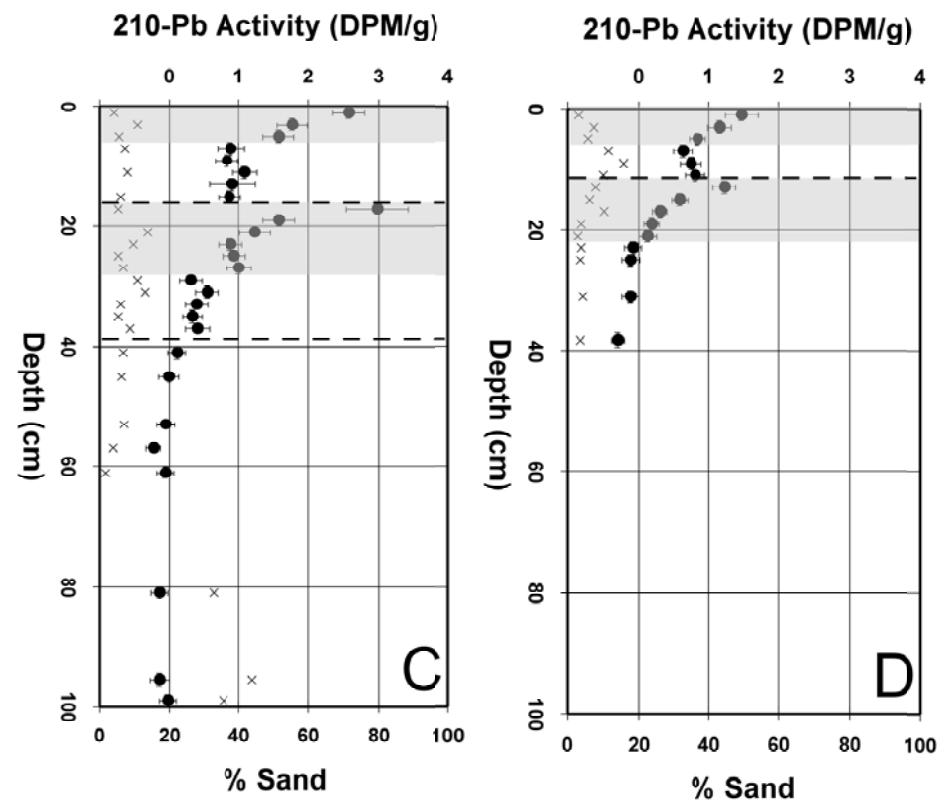
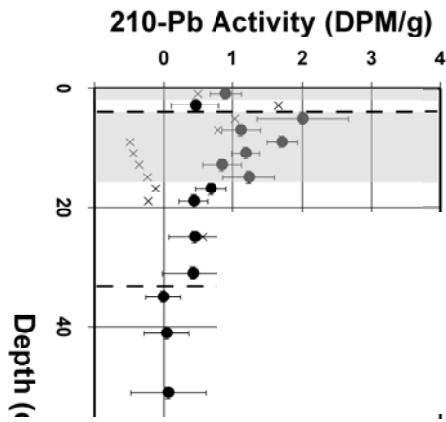
In order to better understand and model the pattern of topographic development associated with sedimentation, we worked with the CDWR to install within Yolo Bypass an array of feldspar clay pads that serve as stratigraphic markers above which the event sedimentation from the flood of 2006 was measured. The results of the pad analyses, presented in Figure 48, demonstrate a pattern of increasing sedimentation with distance from the weir reaching a peak, which is followed by a rapid decline. As in the case of a natural levee, the sedimentation pattern mimics patterns of down-bypass elevation and sand content [Bridge, 2003].

Figure 48. Elevation (E), pattern of deposition (D) in 2006 flood, and sand content (S) for the same flood with distance downstream of the Fremont Weir. (Singer and Aalto, Submitted to Journal of Geophysical Research-Earth Surface)



We also conducted a sediment coring campaign in Yolo Bypass before and after the 2006 flood that can assist in interpreting spatial patterns of sedimentation in the recent past. Figure 49 shows coring results. Core A, located upstream of Fremont Weir, exhibits a sediment deposit of  $\sim 30$  cm, with a level of excess activity that corresponds to the late 1990's. This deposit is overlain vertically by a truncated meteoric cap that was buried by sediment from a small  $\sim 4$  cm depositional event upon which a new cap has begun to grow. Core B contains a  $\sim 30$  cm deposit of similar age overlain by a buried cap and a smaller  $\sim 8$  cm deposit with a newer cap. The same pattern is repeated in Core C, although the primary deposit in this core is smaller ( $\sim 22$  cm) and the secondary (more recent) deposit is larger ( $\sim 16$  cm). Core D, farther down the bypass (Figure 44; p.43) barely expresses the older depositional event, but has a secondary deposit similar in size ( $\sim 12$  cm) to that of Core C. Following the downstream sequence, Core E (not shown) reflects an environment of net erosion, rather than deposition.

Figure 49. Excess  $^{210}\text{Pb}$  activity profile of floodplain cores A-D from Yolo Bypass. Meteoric caps are shaded gray, transitions between sediment deposits are depicted with a dashed line. (Singer and Aalto, Submitted to Journal of Geophysical Research-Earth Surface)



The sedimentation data from the pads and cores indicate that large floods entering the bypass carry high sediment loads and primarily drop their coarser sediment load upstream and downstream of the weir. However, after sufficient distance downstream from the weir, no net sedimentation occurs (e.g. Core E), and indeed there is evidence that the downstream bypass surface may be scoured by the largest floods flowing over them (Figure 50). Our analyses suggest that the largest floods tend to be responsible for most of the geomorphic change in Yolo Bypass and in other bypasses of the Sacramento Valley (Aalto and Singer, *in prep.*). For example, the sedimentation in Yolo Bypass consists of decimeter-scale deposition during the moderate flood of 2006, several decimeter-scale deposition during the flood of 1997, and several decimeter-scale deposition in the large floods preceding the sediment removal projects (e.g. dividing the 0.8 m of sediment removal between the floods of 1986 and 1964 and perhaps 1955). This deposition is confined to a relatively small region near the entrance to the bypass that tends to promote further deposition in subsequent floods due to increasing topography. Indeed, the depositional surface has built up since the last sediment removal, such that another sediment removal campaign is currently ongoing (i.e. in fall, 2006)

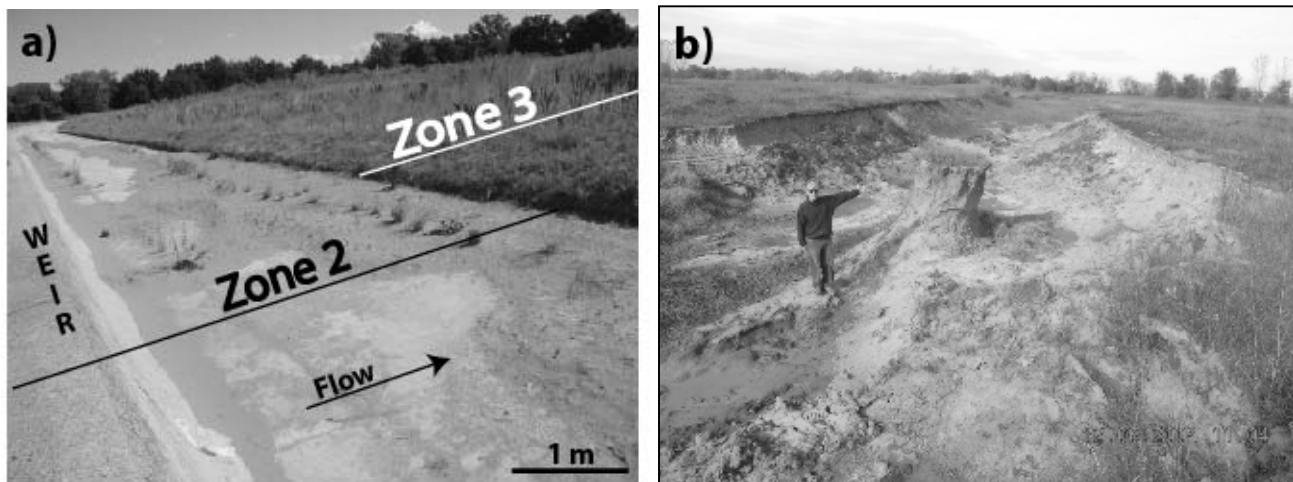
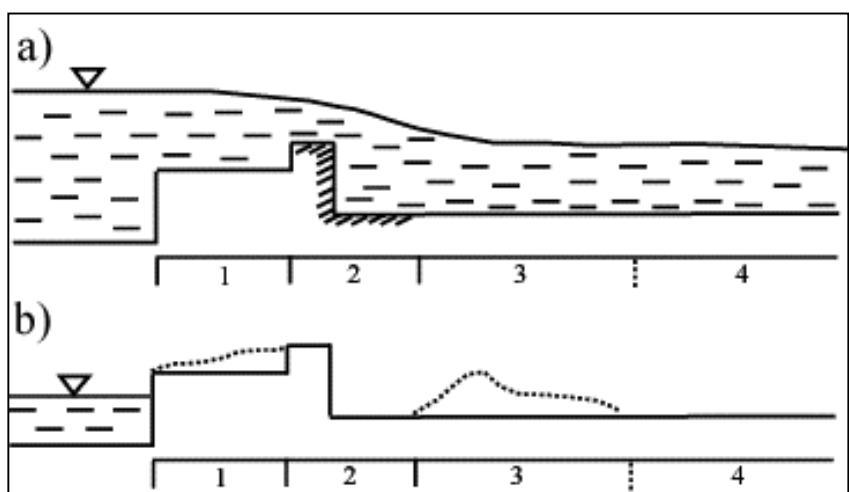


Figure 50. Photo of Fremont Weir leading to Yolo Bypass after the 2004 flood season  
 (a). Lag deposits are visible on the drop structure (Zone 2) and the upstream portion of the hydraulic shadow (Zone 3) is shown. Headward erosion of prior sediment deposits at the downstream end of Zone 3 (hydraulic shadow) within Yolo Bypass (b). The view is upstream (north) toward Fremont Weir. (Singer and Aalto, Submitted to Journal of Geophysical Research-Earth Surface)

The entrance to each flood bypass can be thought of as a special case of a natural levee. Previous work on natural levees (e.g. [Cazanacli and Smith, 1998; Aalto *et al.*, 2003; Bridge, 2003; Hudson and Heitmuller, 2003; Adams, *et al.*, 2004; Aalto *et al.*, *in press*]) documents high rates of deposition close to the channel, relatively steep slopes between the crest of the levee and the outboard flood basin, and concomitantly abrupt textural declines. Cazanacli and Smith [1998] described how the steepness of the leeward levee slope is inversely related to levee width, and that levees become broader with continual overbank deposition of progressively finer sediments because of depletion of coarse grain sizes transferred overbank. Adams, *et al.* [2004] highlighted broad, gently sloped levees with gradual declines in sediment size formed by advective transport, which occurs when there is ‘appreciable elevation head between the channel and its floodbasin’. Such a mechanism would occur in an aggraded physiographic environment with a large surrounding flood basin, such as the Sacramento Valley, where the river bed lies above the surrounding floodplain.

The flood weir, over which flow and washload must be transported, may be thought of as a local perturbation that interrupts natural levee formation such that the levee is broken into two parts: a proto-levee upstream and an elongated, low-amplitude levee downstream of the flood weir (Figure 51). The levee-building process essentially begins anew downstream of the flood weir, where sedimentation occurs once the flow loses energy downstream of the drop structure. The proto-levee is an incomplete levee with high sand content (up to 50%) and a sedimentation peak that backs up against the flood weir. The downstream levee is broad with a moderately defined topographic peak and relatively lower sand content (up to 20%). Downstream of the peak, this surface grades gradually in slope and grain size (to a maximum of 10% sand at the downstream end). A positive feedback may develop on both levee surfaces, such that floods carrying sediment drop a portion of their load on the topographic rise that impedes flow conveyance, formed by sedimentation from previous floods. This is illustrated in the plot of average deposition measured from an array of feldspar clay pads in Yolo Bypass (Figure 48; p.47) at the end of flooding in 2006 and in the core data (Figures 51).

Figure 51. Schematic of sediment laden flow over a weir at the beginning of a flood (a) and the resulting deposits after the flood (b). The floodplain is divided into four zones.  
 Zones 1 and 3 exhibit net sedimentation and Zones 2 and 4 exhibit no net sedimentation.  
 (Singer and Aalto, Submitted to Journal of Geophysical Research-Earth Surface)



Downstream of this depositional zone, the topography is simple and flat. This area, low in sand content (maximum of 5%), appears to confirm Gilbert's hypothesis about efficient sediment conveyance through the bypasses. However, the ample evidence from various sources (i.e. sedimentation pads, sediment cores, sediment removal, topography, surface grain size) of net sediment accumulation near the weirs during large floods adds complexity to Gilbert's concept for the bypass system as a whole and sand-sized sediment in particular. These factors have motivated us to develop a conceptual model for sediment transport and deposition in Sacramento Valley bypasses.

When subcritical flow from the main channel encounters an abrupt rise in the channel bottom (e.g. at a flood weir), flow depth decreases and velocity increases. Weirs are generally designed to force flow into a supercritical state at some point over the weir during flooding, causing energy loss through the transition [Dingman, 1984]. Energy is further dissipated by the engineered concrete armoring of the scour zone downstream of the weir. Therefore, the capacity of the flow to maintain sediment in suspension declines downstream of the weir, resulting in rapid sediment deposition downstream of the drop structure. This effect has been hypothesized to explain observed grain sizes in turbidity current deposits [Hiscott, 1994] and increased settling along the continuum from high capacity to low capacity conditions in laboratory suspension experiments [Cellino and Graf, 1999]. It can result in the rapid

settling of a wide range of grain sizes because local water surface slope is essentially zero, leading to an exceedance of the threshold for settling (e.g. in the ratio of settling velocity to shear velocity in [Kneller and McCaffrey, 1999]), as the denominator approaches zero. The weir thus imposes a ‘hydraulic shadow’, or selective zone of sedimentation, with a length that varies according to discharge, sediment concentration, grain size, and the evolving local topography. Downstream of this shadow the flow becomes more uniform, the coarse sediment has mostly deposited, and therefore there is no net sediment deposition (although scour is possible).

This is illustrated in Figures 50 and 51, which demarcate zones of net sedimentation (1 and 3) and zones of no net sedimentation (2 and 4) or scour. Zone 1 receives net sedimentation when sediment-laden flows go overbank (out of the river channel), but do not overtop the weir. In addition, the topography built up by such sedimentation induces further deposition in subsequent floods, whether or not the weir is overtopped. Zone 2 corresponds to the drop structure itself, which is generally armored by concrete or riprap and will only accumulate sediment temporarily (e.g. at the tail end of a flood, Figure 50a). However, little net sedimentation is likely in Zone 2, due to the high turbulence from the hydraulic jump at the drop structure, sediment supply exhaustion during floods, and swift evacuation of sediments on the rising limb of the hydrograph. Zone 3 receives net sedimentation due the hydraulic shadow effects previously discussed. The shadow may be longer with increases in sediment concentration and washload grain sizes, and shorter with increases in discharge (i.e. through dilution). As was described for Zone 1, the increasing topographic expression of prior Zone 3 deposits will augment sedimentation during subsequent events, a positive feedback that is becoming increasingly relevant to flood control managers of Fremont Weir (e.g. [CDWR, unpublished data]). A decrease in the length of the hydraulic shadow between floods may induce erosion at the downstream end of Zone 3 that propagates headward toward the weir (Figure 50b).

Most intriguingly, the processes of splay development in the Sacramento Valley that were documented to have existed in prehistory are still present, albeit altered in their character by the flood control system. Washload carried by the Sacramento River now exits the river channel at fewer loci, potentially producing larger deposits at the entrance to each bypass than would occur under natural conditions at those same locations. Likewise, the confinement of the levees on each side of the bypass further affects the spatial extent of the deposits, possibly leading to a longer depositional lens emplaced within a narrower swath. It should be noted that the described patterns of topographic development are also evident on maps for the other flood weirs, although their patterns of sedimentation have not yet been explicitly analyzed.

@sawl Folks!

Leave Fremont Weir by noon in order in for SF by 3:30 pm.

- \*) Go back out Road 16, turn left (south) on Road 102 (E8).
- \*) Get onto I-5 southbound.
- \*) Take I-80 westbound - follow signs to San Francisco.

## CONCLUSIONS

The introduction of hydraulic mining sediment in these river systems generated an episode of sedimentation that was catastrophic from both geologic and environmental viewpoints. Sedimentation began with the rapid aggradation of small tributaries below hydraulic mines, was introduced to main channels by floods in the winter of 1861-62, and continued throughout most systems through the 1870s and 1880s. During the 1870s, there was a shift from mining of fine upper gravel to coarse, well-cemented lower gravel, and the character of both mining and the sediment produced changed markedly. Mining was enjoined by court order in 1884 and incision of the deposits began soon after. Sediment preservation in mountain channels varied between systems. In the main South Yuba channel, most mining sediment was removed by the turn of the century. In the Bear River, much mining sediment remains stored today and continues to shift down valley. In the lower Feather, Yuba, and Bear rivers, vast deposits of mining sediment remain in piedmont deposits and on out into the Sacramento Valley. We are testing to see to what extent these deposits extend into the Sacramento River and the bypass systems at Sutter and Yolo Bypasses.

The deposits apparently grow thinner and finer in the downstream direction, but little mapping of them has been done. Field mapping of coarse-grained deposits is facilitated by distinctive lithologies, but differences are more subtle in the downstream fine-grained facies. We are presently developing geochemical and sedimentological methods to differentiate the mining sediment from other alluvium in fine-grained alluvium of these rivers. Preliminary results hold promise for using trace concentrations of total mercury and gold as indicators of these deposits and for providing absolute (radiometric) dating . Stay tuned....

**Acknowledgements.** We are grateful to the local arrangements committee and to Sheri Stachowski and other staff of the Association of American Geographers (AAG) for clerical support and planning. The AAG was quite supportive in providing guidance and assistance that made this trip possible. Tom Dunne has been supportive and a source of many scientific insights (Figure below). Douglas Allen processed raw Lidar and bathymetric data for some of the maps. William Bowen provided oblique draped satellite images. Special thanks to the student drivers and field assistants: Nina Kilham (UC Santa Barbara), Carl Legleiter (UC Santa Barbara), Mary Megison (Univ. South Carolina), and Toby Minear (UC Berkeley). Financial support was provided by the National Science Foundation (Grant BCS 0520933) for research on hydraulic mining sediment.

Tom Dunne examining cross-bedded sands in historical alluvium on left bank of lower Yuba River across from Marysville.

