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#### ABSTRACT

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Hydraulic gold mining delivered large volumes of sediment to northern California stream channels from 1853 to 1884. Distinctive quartz compositions of this sediment allow development of a *sediment mixing index* for determination of tailings concentrations in contemporaneous and reworked deposits. This index reveals patterns of sediment mixing in the Bear River, California over the last 100 years.

A conceptual model summarizes the nature of sediment mixing in the Bear River basin through time and space. High terrace sediment compositions suggest that hydraulic mining sediment was diluted by about 22% other alluvium as it moved more than 60 km to the Sacramento Valley. This substantial volume of other alluvium was introduced during the mining period by human activities in addition to hydraulic mining. Sediment compositions in modern low-flow channels indicate that most channel reaches within the mining districts remain dominated by tailings due to sustained reworking of stored alluvium. Tailings are substantially diluted downstream in modern channel deposits, however, due to trapping of sediment by dams and local erosion of Quarternary alluvium.

#### Introduction

Geomorphologists have a strong interest in fluvial sediment transport and storage as important geomorphic agents (Knox, 1972; Schumm, 1977; Meade, 1982, 1988; Walling, 1983). Geomorphic interpretations of sediment mobility, however, often require observations over extended time periods longer than are afforded by contemporary process-oriented studies. Many modern problems require a long-term geomorphic perspective in addition to knowledge of short-term process rates (Graf, 1983). The geologic record provides many examples of sedimentation events over centennial or longer time scales, but interpretations are generally limited by lack of observations and measurements of incipient conditions, processes, or rates of sediment production and transport.

A greater understanding is also needed of the spatial aspects of sediment transport (Graf, 1982, 1990). Sediment production is highly variable, and extrapolation from one basin to the next is dangerous because a few tributaries can dominate the sediment loads of rivers. For example, Meade (in press) estimates that more. than 90% of the suspended sediment discharged by the Amazon River is supplied by the 12% of the drainage area that heads in the tectonically active Andes Mountains. Spatial analysis of sediment transport over extended time scales requires reliable methods to identify and map sedimentary units and to recognize sediment mixing. Such methods include the use of trace elements and heavy minerals.

Several radionuclide studies provide infor-

mation on the longitudinal and transverse diffusion of fluvial sediment. For example, studies have documented local dilution below tributaries (Carrigan, 1969), dilution over hundreds of km of transport (Hauschild et al., 1975), and concentrations as a function of stream power (Graf, 1988). Other studies have used heavy minerals to identify provenance (Blatt, 1967; Stattegger, 1986) or to identify patterns of heavy metal deposition downstream of mines (Wolfenden and Lewin, 1977, 1978; Lewin et al., 1977; Yim, 1981; Marcus, 1987; Knox, 1987; Leenaers et al., 1988). Sediment mixing studies based on metal concentrations have reported various rates of longitudinal sediment dilution including a negative exponential function (Wolfenden and Lewin, 1978) and a linear function (Leenaers et al., 1988) of stream distance. Macklin and Lewin (1989) document a greater than four-fold decrease in lead concentrations in terrace deposits associated with the peak period of mining downstream along 22 km of the River South Tyne, UK. They found that lead concentrations in younger surfaces decreased downstream more rapidly than concentrations in sediment associated with the peak period of mining.

Radionuclides and trace metals provide information on reservoirs of toxic pollutants, and provide stratigraphic markers that allow dating and volumetric analysis of alluvial units. There are limitations to their use, however, as indicators of total sediment transport rates or sediment dilution because their concentrations may not provide an unbiased indicator of spatial patterns of the bulk of sediment deposition. Radionuclides have strong affinities to particular sediment types such as finegrained particle sizes, organics, or oxide coatings (Sayre et al., 1963; Horowitz, 1985). Heavy minerals behave differently than most sediment, because their hydrodynamically equivalent grain size is smaller than other grains (Rubey, 1933; Rittenhouse, 1943; cf. Schumm et al., 1987, pp. 76-86). In addition,

the toxicity of heavy metals (especially lead) may reach such high levels as to effect recolonization of vegetation and retard floodplain stability (Macklin and Lewin, 1989). These limitations add a constraint to generalizations that can be drawn from the distribution of trace elements or heavy minerals about spatial distributions of the sediment body as a whole.

This paper presents a sediment identification method based on index materials with characteristics similar to the host sediment and that are uniformly represented by all textural grades. Hydraulic gold-mining sediment compositions and mixing in the Bear River basin are examined. The distinct quartz lithology of tailings is documented and used to: (1) distinguish between tailings and other alluvium, (2) develop an index for sediment mixing, (3) determine proportions of tailings in samples throughout the Bear River basin, and (4) demonstrate spatial and temporal patterns in tailings concentrations.

### Background

Hydraulic gold mining sediment in northern California provides an unusual opportunity to study sediment transport and mixing in a large, well-documented deposit. From 1853 to 1884 hydraulic gold mines in the Sierra Nevada, employing water under high pressure, excavated large pits and delivered large volumes of gravel, sand, and fine-grained sediment to channels downstream. Government surveys (Hall, 1880; Mendel, 1881, 1882; Heuer, 1891), including a classic study by Gilbert (1917), establish an early record of the extent and behavior of mining sediment deposits that invites restudy and enables the determination of volumetric and morphologic changes.

This study was conducted along the Bear River which flows into the Sacramento Valley from the Sierra Nevada in northern California (Fig. 1). The Bear River strikes west between the larger Yuba and American rivers and joins the Feather River about 35 km north of the city



Fig. 1. Bear River basin location map. Mines form a northwest-striking band through Dutch Flat.

of Sacramento. The Bear River longitudinal profile forms a double concave-upward curve with steep portions above and below the mining districts. The two low-gradient zones of the profile, above Combie Reservoir and below Camp Far West Reservoir, are sites of substantial alluviation. Hydraulic mining in many Sierra stream channels produced so much sediment that the tailings overwhelmed all other sediment sources (Gilbert, 1917). Much of this mining sediment remains today in large terrace and channel fill deposits (Fig. 2) (James, 1989).

The source of mining sediment was a series of upland conglomerates representing early Tertiary paleo-channels that drained northnorthwest across the strike of the modern drainage (Lindgren, 1911). White quartz, eroded from veins of granite and aplite porphyry (Lindgren, 1896; Johnston, 1940), was concentrated in these conglomerates during an early Cenozoic cycle of erosion by intense tropical weathering and fluvial abrasion (Yeend, 1974). This distinctive lithology provides a means of identifying the presence and concentration of tailings in deposits of unknown origin.

Large deposits of hydraulic mining sediment and reworked mining sediment (henceforth referred to collectively as *tailings*) can easily be distinguished without the aid of trace elements or heavy minerals. This paper utilizes sediment lithology as an independent, objective method for the identification of tailings and determination of its concentration in deposits. Sediment mixing studies, if possible at all, usually require laborious chemical or microscopic analytical techniques. It will be shown that quartz pebbles consistently dominate the tailings, but are negligible in other alluvium. Specific weights and settling velocities of quartz are similar to most other alluvial materials, so results are representative of the bulk of the tailing deposits and of fluvial deposits in



Fig. 2. Steephollow Creek, view downstream. High terrace at right grades up to Red Dog - You Bet mine.



Fig. 3. Gravel high terrace in lower Bear River. Pebble lithology is 57% white quartz, which signifies 100% mining sediment.

most other basins. The rare combination of reliable control over sedimentary populations and knowledge of event history provide a valuable means for study of the hydrogeomorphic activity of episodically introduced sediment over a centennial time scale.

#### **Overall sediment lithology**

Study of sediment mixing in the basin requires the identification of mining sediment and its differentiation from other alluvium in deposits such as the small lower basin terrace shown in Fig. 3. In the early stages of the study eight preliminary samples were collected primarily in the upper basin (Fig. 4) to document the lithologic heterogeneity of samples and to develop a method for tailings identification. Pebbles were broken and examined with a hand lens and sizes and frequencies of various rock types were recorded in the field.

To characterize variation in the source of the tailings, two paleo-channel samples from within the Nichols hydraulic mine pit were extracted with a rock hammer (Fig. 5). The large amount of serpentine in the lower bench gravel sample is due to fragmentation of foliated rock during sampling and incorporation of local country rock in deposits near contacts. Lower bench gravel typically has much more locally derived mafic material than upper units (Lindgren, 1911; Yeend, 1974), but it comprises only a small proportion of the mining



Fig. 4. Map of hydraulic mines in upper basin. Sample sites A to E were used in lithologic analysis (site F is off map). Samples t1-t14 are the tailings control group. Samples n6 and n10 are in the other alluvium control group (the rest of the other alluvium sites are located off the map).



Fig. 5. Lithology of two early Tertiary gravel samples from Nichols hydraulic mine.

sediment source material (Mendell, 1882, p. 93).

Due to recent transport and to the intense abrasion and weathering of the source rocks, hydraulic mining sediment is easily distinguished in the field from other sediment in the basin which tends to be iron-stained, less wellrounded, and mafic (Fig. 6). To determine if tailings could be differentiated from other alluvium on the basis of sample lithologies, six bed-material samples from modern low-flow channels in the upper basin were collected by a stratified random grid method (Wolman, 1954). These samples display a high degree of lithologic variation, but quartz is clearly an important component (Fig. 7). Spatial relationships between sample quartz concentrations and mine locations suggests that quartz is associated primarily with tailings. One sample from above the mining districts and two from near the upper margins of the mining districts have relatively little quartz (Figs. 7A, 7B, 7C, respectively). Coarse bed-material textures or bedrock exposed in the channel bed indicate that these sample sites are eroded to a pre-mining lag deposit. Two samples from within and immediately below the mining dis-



Fig. 6. Mining sediment (top) is rounded, spheroidal, and quartz rich; distinctly different from other alluvium or colluvium (bottom).

tricts have about 50% white quartz (Figs. 7D, 7E). Lack of bedrock in the channel bed and abundant supplies of tailings from adjacent vertical terrace scarps indicate that these two sample sites are dominated by tailings. A sixth sample from the lower Bear River has much less white quartz and is dominated by mafics and low-grade meta-sedimentary and metavolcanic clasts (Fig. 7F). Quartz concentrations in the bed-material samples are not strongly related to grain size (Fig. 8). The proportion of quartz in a given size class is approximately 50% of each class at sites dominated by tailings, but only slightly greater than 0% at sites lacking mining sediment. The lack of relationship between quartz concentration and grain size is even more pronounced in tailings outside of the channel bed as will be doc-



Fig. 7. Channel gravel lithology (Key in Fig. 5). (A) Upstream of mines. (B,C) Upper margin of mining districts). (D,E) In and immediately below mines. (F) Lower basin.



Fig. 8. Percent frequency white quartz (by particle size) in two modern bed-material samples. (a) Site lacking tailings; upstream of Dutch Flat Afterbay (see Fig. 7B). (b) Site dominated by tailings; Little York Crossing (see Fig. 7D).

umented with larger samples in a later section. The dominant trend displayed by quartz concentrations is spatial in nature. In short, sites above the mining districts have very little quartz, sites within the mining districts have high quartz concentrations, and lower basin sites have moderate quartz concentrations. These relationships imply that quartz is derived from the mines and that quartz concentrations could provide a numerical means of identifying tailings in downstream locations where mixing has occurred.

#### Sample methods

The distinctive quartz lithology of the tailings has been documented by earlier reports (Goldman, 1961, 1964; Dupras and Chevreaux, 1984) but was not utilized for identification purposes. This potential prompted an extensive pebble-sampling program to record both texture and quartz contents of terrace and channel sediments in the Bear River basin. A total of 56 samples from 1 to 5 kg (enough to yield 100 small pebbles) were collected with a shovel and sieved on a 6 mm screen, discarding fines. Pebble *b*-axes were measured to the nearest mm with a ruler and recorded as *white quartz* or *other*. Clasts were classified as quartz only when comprised of more than about 75% white or translucent quartz; dark pebbles or those dominated by veinlets or inclusions were excluded from the quartz group. Impure quartz grains are not common in the tailings, and similar-appearing minerals such as feldspars or dense rhyolite tuff are rare (James, 1988). The method is intended to facilitate rapid determination of large numbers of pebbles with minimum variation between workers.

A control group of 14 *tailings* samples was collected from high terraces near the mines to characterize quartz concentrations of the mining sediment. Sample sites were selected along main channels immediately downstream of mines at well-spaced intervals (Fig. 4; Table 1). Samples were drawn from vertical exposures in the top half meter of high terraces that are distinctly graded to a mine outlet and in which primary sedimentary structures are identifiable (Fig. 9). These control group sample compositions are representative of undiluted tailings deposited directly from the mines during the period of peak aggradation between 1870 and 1884.

A control group of 10 other alluvium (nonmining) samples was drawn from sediment that is clearly free of tailings. These samples were primarily from (1) vertical exposures

#### TABLE 1

#### Pebble data from control groups.

Sample ID#	Sample size	Nmbr Quartz			% Quartz			Geomorphic	Location of sample site:	
		Lª	M <sup>b</sup>	Sc	M <sup>b</sup>	Sc	All	position	Relative to mining districts	Upper, middle, or lower basin
Tailings					_					
TI	96	6	8	47	67	61	64	High terrace	Downstream	Upper
Т2	111	0	8	44	53	46	47	High terrace	Downstream	Upper
Т3	41	0	0	19	_*	48	46	High terrace	Downstream	Upper
T4	88	0	1	53	_*	62	61	High terrace	Within	Upper
T5	65	6	6	31	55	71	66	High terrace	Within	Upper
T6	94	2	9	36	50	51	50	High terrace	Within	Upper
Т7	91	4	11	39	69	57	59	High terrace	Within	Upper
T8	164	0	5	87	56	57	56	High terrace	Downstream	Upper
Т9	129	0	5	59	62	49	50	High terrace	Downstream	Upper
T10	159	0	8	87	53	60	60	High terrace	Downstream	Upper
<b>T</b> 11	87	3	9	44	56	67	64	High terrace	Within	Upper
T12	278	3	14	109	47	45	45	High terrace	Within	Upper
T13	197	1	15	104	60	61	61	High terrace	Within	Upper
T14	141	0	5	80	<u>63</u>	<u>60</u>	<u>60</u>	High terrace	Within	Upper
Mean percent quartz			58	57	56					
Standard deviation:			6.7	8.0	7.3					
Sediment	t free of taili	ngs								
N1	240	0	2	5	6	3	3	High terrace	Below	Lower
N2	108	Õ	0	0	Ō	0	0	Modern channel	Below	Lower
N3	181	õ	Õ	Õ	Ō	0	Ō	Modern channel	Diff. Drainage	Middle
N4	50	õ	Õ	1	Ō	3	2	Low terrace	Diff. Drainage	Middle
N5	131	Õ	Ō	0	0	0	0	Low terrace	Below	Middle
N6	60	Õ	0	5	Ō	11	8	Low terrace	Above	Upper
N7	129	0	0	7	0	6	5	Low terrace	Above	Upper
N8	108	Ō	2	1	8	1	3	Low terrace	Above	Upper
N9	139	0	0	0	0	0	0	Low terrace	Above	Upper
N10	94	0	0	3	_*	4	3	Colluvium	Within	Upper
Mean					1.5	2.6	2.5			
Standard deviation				3.0	3.4	2.8				

<sup>a</sup>Large pebbles  $\geq 5\phi$ .

<sup>b</sup>5 $\phi$ > medium pebbles  $\geq 4\phi$ .

 $^{c}4\phi$  > small pebbles  $\geq 2.5\phi$ .

\*Subsample size too small.

near the top of low terraces upstream of the mining districts, (2) from the surface of modern channel beds in tributaries lacking mine tailings, or (3) from other alluvium that is clearly not of historical age as is evidenced by well-developed soils (Table 1). This group is comprised of alluvium except for one valleywall colluvium sample from near the mines.

An additional 32 alluvial pebble samples were collected throughout the basin, processed by the same methods as for control groups, and analysed for determination of sediment mixing. High and intermediate terraces were sampled near the surface of vertical exposures (Fig. 10) and low-flow channels were sampled at relatively fine-grained portions of active gravel



Fig. 9. Greenhorn Creek tailings in high terrace near mines. Top of terrace is about 10 m above channel bed. Samples from upper strata are assumed to be undiluted mining sediment.



Fig. 10. Steephollow Creek channel cross-section showing typical high terrace (T14 in Table 1) and low terrace sample sites.

bars and channel margin-deposits. High terraces sampled below the mining districts range from 2 to 10 m above the modern channel bed, and have morphologies ranging from subtle berms to large, distinct treads and scarps.

## Quartz concentrations of tailings

Tailings in the mining districts tend to be finer-grained than other alluvium, so estimations of sediment mixing in the downstream



Fig. 11. Histogram of mean percent quartz (frequency) for the two control groups. Quartz proportion varies little with texture. Number of pebbles in each size class is shown over columns. High quartz percentages in tailings coarse classes are due to small sample sizes.



Fig. 12. Number of control group samples of given quartz concentration (% frequency). Tailings in high terraces are invariably quartz rich ( $\bar{X}$ =57%). Other alluvium has little quartz ( $\bar{X}$ =3%).

direction must consider possible complexities introduced by selective transport of tailings downstream. This potential source of bias is controlled by the uniformly high proportion of quartz in all sampled size classes. Average per-

centages of quartz pebbles are shown in a frequency histogram by particle size for both the tailings and the other alluvium control groups (Fig. 11). Tailings samples from high terraces consistently display high quartz percentages across all pebble sizes represented (N=1783pebbles). A chi-square goodness of fit test on individual sample distributions supports this conclusion. The null hypothesis that quartz is distributed uniformly across the various textural classes could only be rejected for 4 of 25 high terrace samples ( $\alpha = 5\%$ ). Three of the four non-uniform sample sites were in the lower basin more than 60 km from the mines. In contrast to the tailings samples, very little white quartz occurs in any of the size grades of the other alluvium (N=1250 pebbles).

Samples were grouped into small, medium, and large size classes divided at 16 and 32 mm to minimize compositional variations caused by fragmentation, shape, and sorting. For the sake of brevity and due to larger sample sizes, only the small pebble values (6 to 16 mm, -2.5to  $-4\phi$ ) are presented in this report. Small pebble mean percent frequency quartz is 57% in the 14 tailings control group samples but is only 3% for the 10 other alluvium control group samples (Fig. 12). A T-test for unequal sample variances indicates that these two group means are significantly different at the 0.01 level. Quartz concentrations of small pebbles, therefore, are distinctly different between tailings and other alluvium. This difference facilitates the distinction of tailings from other alluvium and allows the calculation of sediment mixing ratios in reworked mining sediment.

#### Sediment mixing index

An index expressing mining sediment concentration as a function of percent quartz was derived using two equations. The number of pebbles in a sample  $(N_s)$  equals the number of pebbles contributed by tailings  $(N_t)$  plus the number of pebbles from other sources  $(N_o)$ :

$$N_{\rm s} = N_{\rm t} + N_{\rm o} \tag{1}$$

In addition, the number of quartz pebbles in the same sample equals the number of quartz pebbles from tailings plus the number of quartz pebbles from other sources. This can be expressed in terms of percent frequency quartz pebbles:

$$N_{\rm s} \cdot \mathscr{W} Q_{\rm s} = N_{\rm t} \cdot \mathscr{W} Q_{\rm t} + N_{\rm o} \cdot \mathscr{W} Q_{\rm o} \tag{2}$$

where  $\&Q_s$  is percent quartz in the sample,  $\&Q_t$ is percent quartz contributed by tailings, and  $\&Q_o$  is percent quartz contributed by other sources. Combining and rearranging eqs. (1) and (2) yields a general equation for the percentage tailings in a sample based on the percent quartz pebbles in the sample and the percent contributed by tailings and other alluvium:

$$\%MS = \frac{N_{t}}{N_{s}} \cdot 100\% = \frac{(\%Q_{s} - \%Q_{o})}{(\%Q_{t} - \%Q_{o})} \cdot 100\%$$
(3)

where %MS is percentage of the pebble sample that is mining sediment. Accuracy of the estimate provided by eq. (3) is maximized when  $%Q_t$  is much different than  $%Q_o$ ; in fact, the equation will be undefined if  $%Q_t$  equals  $%Q_o$ .

The best estimate of percent mining sediment in the Bear River is derived by using mean values of pebble counts for the control groups; that is, 57% for the percent quartz contributed by tailings and 3% for the percent quartz contributed by other sources (Fig. 12). Substituting these values into eq. (3) and rearranging yields a sediment mixing ratio for the Bear River:

$$\% MS = \frac{(\% Q_{s} - 3\%)}{(57\% - 3\%)} \cdot 100\%$$
  
= 1.9 \cdot (\% Q\_{s}) - 5.6\% (4)

Thus, the percentage quartz in small pebble samples of Bear River deposits yields an objective, numerical estimate of the percentage tailings contained in the deposit. The use of mean values for  $\%Q_t$  and  $\%Q_o$  results in the potential for estimates of mining sediment concentrations greater than 100% or less than 0%. Values greater than 100% tailings in high terraces are truncated to 100%.

The sediment mixing index is simple to use and allows determination of sediment dilution in the downstream direction and through time. The method will now be applied to Bear River tailings to examine the nature of sediment production, reworking, and transport in the basin. The method may also be applicable to tailings identification and sediment mixing studies throughout the mining districts of the northern Sierra Nevada through application of eq. (3) and appropriate sampling.

## Dating sediment concentrations

Terrace surface materials are assumed to be composed of a thin mobile layer rather than lag materials. Thus, terrace surfaces and modern channel bed materials should consist of sediment deposited contemporaneously with the

development of their surface morphologies. Sampling of older primary tailings deposits exposed by erosion was unlikely, because hydraulic, compositional, and morphological evidence indicates that channel bed surfaces dominated by tailings in the Bear River are composed of a layer of active sediment mixing. The mobility of the surface layer of tailings stored in channels is implied by (1) indication of empirical hydraulic equations that available grain sizes can be eroded and mixed during frequently occurring floods (James, 1989), (2) deposition of quartz-rich sediment in active deltas of Rollins and Combie reservoirs, and (3) presence of stored tailings in active meso-scale bedforms including longitudinal, transverse, unit, and point bars. Focus on the fine fraction of samples minimizes the possibility that residual channel lags are represented in samples. Assuming that former channel beds were also mobile, samples from channel and terrace surfaces should be representative of contemporary sediment load concentrations when channels were at the level of the sampled surfaces. It follows that sediment concentrations of intermediate level terrace surfaces represent compositions of sediment deposited later than the high terraces in the

basin, and surficial low-flow channel-bed materials represent the modern sediment load.

Ages of high terraces in the mining districts are well constrained by historical sources to the late 1870's or early 1880's (James, 1988). Although the highest surfaces may have been time transgressive as centers of sediment deposition shifted downstream, high terrace surfaces in the lower basin are not much older and probably date to the early 1890's. Channels in the lower basin had begun to incise by 1890 (Von Geldern, 1891) and terraces were observed by Gilbert (1917) in 1908. Ages of low and intermediate terraces are poorly constrained and some variance in tailings concentrations of these surfaces may be due to the inclusion of data from surfaces of various ages. Work is underway to date terraces using tree ring cores and to relate these dates to tailings concentrations. The age of modern low-flow channel data is 1985 when samples were collected.

#### Downstream dilution of high terrace sediment

High terrace samples include the 14 control group samples in the mining region plus 11 additional samples primarily from sites in the middle and lower basin. Quartz in these sam-



Fig. 13. Tailings concentrations in high terrace deposits. Width of pattern is proportional to percent tailings; lines across channel represent one sample site. Note negligible downstream dilution within upper basin at time of high terrace deposition.





Fig. 14. Regression lines of percent tailings in alluvium as functions of drainage area. (a) Moderate downstream sediment dilution in high terraces. (b) Substantial downstream dilution in low to intermediate terraces, and (c) in modern channel bed material.

ples indicates that tailings concentrations in high terraces decrease moderately in the lower basin, as shown by Fig. 13 which depicts percentages of tailings by widths of stippling. Pebble samples were limited in the middle basin by poor terrace preservation and in the lower basin by prevalence of fine-grained deposits lacking pebbles. As a first approximation, the decrease in tailings concentrations downstream during the peak mining period can be expressed as a linear function of drainage area (Fig. 14a), although it will be argued later that the relationships would be more complex functions if samples could be obtained throughout the basin. There is considerable scatter in the lower basin data, but the linear regression is significant at the 0.01 level. A T-test supports rejection of the null hypothesis (P < 0.001) that there is no difference in mean percent mining sediment between samples above and below Camp Far West Dam. Even though the upper basin estimates are truncated at 100%, their mean mining sediment concentrations are significantly larger than samples downstream.

The downstream trend and differences in mean concentrations suggest that high terrace deposits in the lower basin were diluted by an average 22% alluvium from other sources  $(\sigma_{n-1}=12\%)$ . This indicates that during the period of maximum main channel aggradation, over a transport distance of more than 65 km, a sizeable proportion of the sediment was introduced by sources other than hydraulic mining. During the mining era, several human activities contributed sediment in addition to the hydraulic mine tailings. These endeavors included logging, agriculture, hard-rock mining, construction of roads, canals, and the Southern Pacific Railroad, and extra-basin imports of water for mining. Based on the regional extent of agriculture, roads, and population, Gilbert (1917, pp. 45-46) estimated non-mining sediment production to be about 5% of the total sediment production in the Yuba Basin which received more tailings than any other basin, and about 23% of the total sediment production in the entire Sacramento Basin. He made no direct estimate of the proportion of other alluvium in the Bear Basin, but it should have been lower than in the Yuba Basin, because tailings production per unit drainage area was considerably higher in the Bear Basin than in the Yuba Basin (James, 1989). The amount of sediment dilution in the lower Bear Basin during the 1870's, however, is apparently much greater than the Yuba River. In fact, dilution is not substantially less

than Gilbert's (1917) estimate for sediment dilution in channels of the Sacramento Basin. many of which received no tailings at all. This high proportion of other alluvium delivered to the lower basin was, in spite of the production of large volumes of tailings, estimated to have been between 194 and  $271 \times 10^6$  m<sup>3</sup> (Gilbert, 1917) or from 257 to  $358 \times 10^3$  m<sup>3</sup> km<sup>-2</sup> (James, 1988). Much work is needed to refine these preliminary results based on the mixing data. Incorporation of fine-grained samples into the sediment mixing index may allow refinement of lower basin results, and extension of the method may allow calculation of sediment mixing in other basins of the Sacramento Valley including the Yuba River.

## Sediment mixing through time

Tailings concentrations in middle and low terraces show a more rapid rate of dilution downstream than in the high terraces (Fig. 14b). There is little dilution within the mining districts except for one low berm sample from Steephollow Creek near the upper margin of the mining districts (Fig. 10). The lack of dilution in the mining districts demonstrates active production of reworked tailings and will be discussed below. Based on two samples, there appears to be considerable dilution in low terraces of the lower basin. The degree of sediment mixing in the lower basin represents an increased importance of other sources of alluvium through time.

Observations of bouldery textures, bedrock exposures, and a generally low concentration of white quartz pebbles or cobbles between Combie Dam and the Camp Far West delta suggest that much less mining sediment is stored in these reaches ( $350 \text{ to } 670 \text{ km}^2$ ) than elsewhere. There are too few samples in the middle basin for detailed conclusions in these reaches, but hypothetical relationships are presented later. The high outlier at drainage area  $600 \text{ km}^2$  (Fig. 14c) is a sample from a point bar about 1 m above the low-flow channel

sentative of low terraces. Sediment concentrations in modern low-flow channel alluvium display high concentrations of reworked tailings near the mines (Fig. 14c). These findings are corroborated by an independent sample of about 200 coarse pebbles from near the mines that had 66% quartz (Goldman, 1964), indicative of undiluted tailings. Such high concentrations show that tailings storage and mobility continue to dominate the sediment budget of Bear River channels in the mining districts after more than 100 vears, in confirmation of earlier observations (James, 1989). This conclusion is contrary to Gilbert's (1917) symmetrical sediment wave model, however, which implies that fluvial sediment loads recover relatively quickly from episodic sedimentation. The sediment mixing data support a conceptual model of long-term sediment storage and release in response to episodic sedimentation that is compatible with many modern studies of sediment storage and remobilization (Meade, 1982, 1988; Walling, 1983; Meade et al., 1990).

Tailings concentrations in modern bed material are much less in the lower basin than in the mining districts. Considerable dilution of tailings in lower basin channels apparently occurred since the early 1960's when an independent sample of about 200 coarse pebbles documented 76% quartz (Goldman, 1961) indicating undiluted tailings in an area where there was only about 35% tailings in 1985. This dilution downstream is due to depletion of inchannel storage of tailings and to increased importance of local sediment sources. No major tributaries enter between the lower basin sample sites and Camp Far West Dam, and floodplains are covered with tailings, so other alluvium must be derived primarily from local within-channel storage. This local sediment is

produced by vigorous lateral channel migration that proceeded through the 1980's, and by channel vertical incision that, near Wheatland, began in December, 1955 and continued through the 1970's (James, 1991). Local erosion in the lower basin produces mostly Quarternary alluvium for two reasons: (1) channel avulsion in response to aggradation in the 1870's superimposed the channel over a high area on the paleotopography through which it subsequently trenched (James, 1989), and (2) detention of down-valley sediment deliveries by dams created a sediment-starved environment dominated by channel erosion.

# Abrupt longitudinal changes in sediment concentrations

Decreased delivery of tailings to the lower basin is not due to depletion or ceased reworking of tailings stored in the upper basin, but to the arrest of down-valley sediment transport by large dams. The lower Bear Basin has been isolated for about 60 years by dams: the Combie and Camp Far West dams were built in 1928; Camp Far West was enlarged in 1963, and Rollins was built in 1965. These dams limit conclusions that can be drawn about unconstrained down-valley sediment mixing, but they provide a series of experiments to test the local effects of barriers on sediment transport and mixing.

The three trend lines in Fig. 14 accurately depict the persistantly high tailings concentrations in the mining districts and decreased concentrations in the lower basin, but the linear longitudinal decreases for post-dam deposits are probably an over-simplification. Field and historic evidence of erosion suggests that post-dam concentrations of tailings decreased abruptly below dams following the two periods of dam construction. Schematic maps for three periods provide a conceptualization of tailings concentrations (not storage volumes) in the basin inferred from the sediment mixing index and field evidence (Fig. 15). These models are



Fig. 15. Hypothetical maps of mining sediment concentrations for three periods. Widths of stippling are proportional to percent tailings.

presented as working hypotheses based on preliminary findings. During the peak mining period, high tailings concentrations were abruptly encountered at locations where channels entered the mining districts, and there was a slow gradual decrease in mining sediment concentrations downstream (Fig. 15a). At the base of the basin, about 22 percent of the sediment was derived from sources other than mining. A linear decrease in concentration downstream is shown because it is unknown which tributaries supplied the diluting sediment. The actual decrease may have been stepped at confluences with certain tributaries due to the importance of a few sediment-producing basins (Meade, in press).

The construction of the Van Geisen (Combie) and Camp Far West dams in 1928 caused an abrupt decrease in tailings concentrations below the dams that is reflected by compositions of intermediate terraces (Fig. 15b). These decreased concentrations relaxed downstream due to supplies of tailings from channel storage. There has been little sediment storage in the middle basin below the Van Geisen Dam during historical time due to steep gradients, so dilution by other alluvium at local tributary confluences is presumed to be substantial in this part of the basin, and the relaxation is depicted as less complete than below Camp Far West Dam.

Construction of the Rollins Dam in 1965 cut off tailings and decreased concentrations in modern bed materials above the Van Geisen Dam (Fig. 15c). Rapid removal of tailings from this area after dam closure is well documented by photographs, U.S. Geological Survey stream-flow gaging records, and personal accounts (James, 1988). Dutch Flat Afterbay (Fig. 4) was also built in 1965, but its effect on sediment concentrations has been confined to the area immediately downstream due to large volumes of tailings stored in this area within the mining region. Near the upper margins of the mining districts on all three main channels, erosion of tailings is exposing coarse channel lag deposits dominated by other alluvium. Tailings concentrations are low in the lag deposits but increase rapidly downstream in these transition zones due to high deliveries of fine-grained, spheroidal pebbles stored in vertical terrace scarps and in veneers on steep valley walls.

## **Geomorphic implications**

Sediment yield responses to episodic environmental change may continue long after the initial change (Knox, 1972, 1989). The sediment mixing data presented here suggest longitudinal patterns of sediment storage, transport, and redeposition similar to those described by earlier studies of these deposits. It was recognized shortly after sediment production had peaked in the late 1870's that the deposit was already shifting longitudinally from the mining districts to locations downstream (Turner, 1891). Main channel sites near tailings fans, which experienced the deepest fill, began to scour by 1883 (Woodruff, 1884), and much of the sediment produced by this incision was deposited near the aggrading confluences of Steephollow and Greenhorn creeks with the Bear River (Turner, 1891). This process, which may be continuing (Wildman, 1981; James, 1989), implies that sediment loads to channels of the Sacramento Valley would have remained high if dams did not detain the tailings.

The graded channel as envisioned by Mackin (1948, p. 478) represents a long-term adjustment of the channel profile and should not be confused with perturbations of an ephemeral nature such as seasonal scour or fill. The longitudinal profile changes wrought by hydraulic mining have persisted for more than 100 years and are sufficiently persistent to change the graded condition of a channel. Although the initial response to hydraulic mining was aggradation, subsequent responses have been a regradation; that is, simultaneous aggradation and degradation in different locations leading to a change in gradient (Mackin, 1948). Regradation may result from changes in the volume or texture of sediment delivered (Mackin, 1948), from differing periodicities of transport events between tributaries and main channels (Knox, 1989; Muhs et al., 1987, p. 556), from complex response to changes in base level (Wildman, 1981; Schumm, 1977), or from combinations of these factors.

The sediment mixing data and other field evidence indicate that regradation by the down-valley shifting of the loci of sediment storage continues in the upper Bear Basin above Rollins Reservoir as channel incision near the upper margins of mining districts progresses down-valley. This incision is a response to changing sediment loads as tailings are depleted by erosion and sediment production from storage decreases in the upper zones. Further downstream within and for several km below the mining districts, however, there are high rates of sediment production from terrace scarps, tributaries, and local channel storage. High sediment loads retard channel incision and may be associated with sustained aggradation in low gradient reaches at the confluences of Steephollow and Greenhorn creeks with the Bear River that now form deltas in Rollins Reservoir.

## Conclusions

Hydraulic mine tailings are compositionally distinct from other alluvium due to uniformly high concentrations of white vein quartz  $(\bar{X}=57\%)$ . This distinct lithology allows derivation of a sediment mixing index for the Bear River that produces numerical estimates of percent tailings in a sample from percent frequency of quartz pebbles in the sample:  $MS = 1.9 \cdot (MQ_s) - 5.6\%$ . Alluvium was sampled throughout the basin and 5665 pebbles were sieved, measured, counted, and classed as quartz or other minerals. The sediment mixing index was used to estimate the percentage mining sediment in each of 46 samples from various geographic and geomorphic positions in the basin. Although more samples are needed to refine these estimates, the preliminary results presented here have several provocative implications.

Downstream decreases in tailings concentrations indicate the degree of sediment mixing throughout the Bear Basin during various periods. During the peak mining period, tailings in high terraces were diluted by about 22% other alluvium between the mines and the lower basin (60 to 100 km) in spite of extremely high rates of tailings production. This estimate suggests that other sources of alluvium in the Bear River, including logging and construction of roads, canals, and railroads, were more important than previously assumed.

Differences in tailings concentrations between high and low terraces document sediment mixing through time. Modern low-flow channel alluvium within the mining districts is composed of undiluted tailings indicating that the tailings deposits continue to erode and produce most of the fluvial sediment in these channel reaches. Sediment loads have been augmented by reworking of stored tailings, therefore, for more than 100 years. A limited number of samples suggests that tailings concentrations in the lower Bear Basin decreased through time to between 35 and 50% as tributaries delivered sediment from other sources and main channels incised into Quarternary alluvium. Concentration decreases are related to the location and construction history of dams that cut off sediment deliveries from the mine districts and encouraged erosion of local alluvium. Sediment supplies in the lower basin are now limited to local floodplain and channel storage which are dominated by tailings and other alluvium, respectively. The presence of up to 50% tailings below the dams more than 60 years after cessation of down-valley sediment transport is a strong indicator of the importance of remobilization of stored sediment to the modern sediment budget of the lower basin.

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