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Sediment Distribution on a Stream-Dominated Continental Margin, Northern California: Implications from Heavy-mineral Studies

by

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SEDIMENT DISTRIBUTION ON A STREAM-DOMINATED CONTINENTAL MARGIN, NORTHERN CALIFORNIA: IMPLICATIONS FROM HEAVY-MINERAL STUDIES

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INTRODUCTION

The continental margin off northern California receives approximately 38.6 million metric tons of suspended sediment each year from six streams that drain the northern Coast Ranges and Klamath Mountains (Figure 1, Table 1; Griggs and Hein, 1980). Currently, the Eel and Klamath Rivers contribute most of the annual suspended sediment load (32 million metric tons) from the rivers flowing into the Pacific from the western conterminous United States (Janda and Nolan, 1979). Though the Columbia River probably once shed many times more sediment than the Eel or Klamath, it has been dammed in historic time and contributes only 14 million metric tons per year of suspended sediment to the Oregon-Washington continental margin (Curtis and others, 1973). The purpose of this study is to use heavy minerals to distinguish the river sources off northern California, to refine the dispersal pattern previously identified for Klamath sediment, and to determine the contribution of the Eel River to the shelf and slope sediments.

SETTING AND PREVIOUS WORK

Between the Mendocino Ridge and the California-Oregon border, the geomorphic shelf (to ~200 m depth) and margin plateau or upper slope (to ~1200 m depth) cover approximately 9,000 sq km (Figure 2). The continuity of these features is disrupted from north to south by the Trinity, Eel, and Mattole submarine canyons. This area is underlain by the offshore extension of the Eel River sedimentary basin (Ogle, 1953; Field and others, 1980). The Holocene sediment accumulation rate in the offshore Eel River basin is an estimated 1 cm/yr (Field and others, 1980). The sediment is supplied by six major streams, which, in order of total suspended sediment load, are the Eel River, Klamath River, Mad River, Redwood Creek, Mattole River, and Smith River (Table 1). These streams drain an area of more than 41,000 sq km in northwestern California and cross ophiolitic, low- to medium-grade metamorphic, granitic, volcanic, and sedimentary terranes (Table 1, Figure 1). The most areally extensive of these terranes are underlain by (a) the Franciscan Complex in a belt subparallel to the California-Oregon coast and (b) the metamorphic and ophiolitic rocks of the Klamath Mountains province (Blake and others, 1985a,b; Irwin, 1985).

The movement of sediment along the continental shelf is governed by complex current patterns. The California Current induces a southward flow from July to November along the California coast. From November to February, the Davidson Current causes a northward flow offshore coincident with the months of greatest sediment discharge. Between March and August, north winds drive surface water offshore and cause upwelling of cooler bottom water (Pirie and Stellar, 1977; Griggs and Hein, 1980). The current systems are similar off the Oregon and Washington margins where the dispersal patterns have confirmed a net northward movement of sediment (Kulm and others, 1975; Sternberg, 1986).

Previous mineralogical studies indicate that the Klamath River empties into the south end of a dispersal path that can be traced northward along the continental margin as far as the Oregon-Washington border (Kulm and others, 1968; Scheidegger and others, 1971). These studies defined a minimum southern limit to the path since few samples were taken south of the latitude of the Klamath River mouth. The authors also assumed that the mineralogy of the Klamath River typified all of the northwestern

California drainages because only those source rocks were distinguishable in the sediments sampled (Scheidegger and others, 1971).

Borgeld (1985) divided the northern California shelf into three regions on the basis of sediment grain size and density: from the mouth of the Smith River to Patricks Point (the Klamath River shelf), from Patricks Point to Eel Canyon (the Eel River shelf), and south of Eel Canyon. On the basis of mineralogy, he identified two suites—Klamath River and non-Klamath (primarily Eel River). Wong and Klise (1986) also identified separate mineral signatures for the Klamath and Eel Rivers in their study of river sediments.

METHODS

The 76 samples examined in this study were collected by the U.S. Geological Survey on two cruises of the *R/V Sea Sounder* in 1977 (S977NC, 45 samples) and 1978 (S1278NC, 13 samples) and by Humboldt State University (Arcata, California) on cruises of the *R/V Catalyst* from 1972 to 1977 (HSU, 18 samples) (Figure 2). Subsamples were taken within the upper 25 cm of gravity cores for the USGS samples and from grab samples for the HSU samples.

The subsamples were treated with hydrogen peroxide and washed through 250-µm and retained on 63-µm sieves. This size range includes most of the heavy minerals in the sand-size fraction. Heavy minerals were separated in tetrabromoethane diluted to a specific gravity of 2.89 ± 0.01. Sample weights taken before and after separation were used to determine an approximate heavy-mineral weight percent (Appendix). Heavy-mineral grains were permanently mounted on glass slides in piccolyte (r.i. = 1.52). Except for a few samples, more than 300 grains were counted on each slide to include at least 200 nonopaque grains. The data were recalculated to 100 percent nonopaque grains (Appendix) and are summarized in Table 2.

A factor analysis[1] was applied to the mineral data. The factors for this study were determined using the Q-mode method. The data were first scaled using the maximum percent for each mineral and the cosine-theta statistic was used as the measure of similarity. Factors were rotated using the varimax method (see Joreskog et al., 1976, for further discussion of this statistical method). The percentages of 11 heavy-mineral species and the weight-percent heavy minerals for 82 samples constitute the input data. After several test iterations, the final number of factors requested was two, which accounted for 89 percent of the total variability of the data (Table 3).

RESULTS

Available grain size data for the offshore samples indicate that most of the material is silty mud with a sand content of less than 25%. Exceptions are samples from the nearshore area south of Patricks Point (~70% sand) (R.W. Thompson, written commun., 1979) and samples that were taken from diapiric exposures of deformed Tertiary sediments (Field and others, 1980). The heavy-mineral content in the 63-250-µm size range is usually less than 10% by weight, discounting those samples in which the amount of sand (<5%) is too small to determine a reliable weight. Especially heavy-mineral rich (≥ 10%) samples are more common north of Patricks Point.

The focus of this study is on the nonopaque monomineralic grains within the heavy-mineral fraction (Table 2, Appendix). The nonopaque minerals make up as much as 82% of an individual sample; smaller amounts of nonopaque

[1] Factor analysis statistically cross-matches mineral proportions among all the samples in a data set and produces a number of factors or mineral groupings that can be used to define provinces or areas of similar mineralogy. FACAN, the factor analysis program developed for the USGS by M. Noble (1985; last revision 1993; oral communication), was used to process these data.

minerals are offset by increases in opaque grains and (or) rock fragments. The bulk of the monomineralic grains in the heavy minerals exhibit little evidence of alteration. They are generally slightly rounded cleavage fragments or angular grains indicating relatively immature sediments. The most abundant groups of nonopaque minerals are metamorphic amphiboles, nonmetamorphic hornblende, pyroxenes, and epidotes. Sphene, zircon, apatite, and garnet are usually rare (≤5%) nonopaque mineral constitutents (Table 2).

The metamorphic amphiboles include blue-green amphibole, tremolite-actinolite, and glaucophane. Nonmetamorphic hornblendes are green, brown, and basaltic varieties. Clinopyroxenes, the major pyroxene group present, are colorless, green, or buff-colored diopside and augite. Orthopyroxenes are mostly hypersthene with rare enstatite. Epidote group minerals are undifferentiated.

The heavy-mineral distribution off northern California suggests two major depositional provinces separated by a zone trending west-southwest from Patricks Point (Figures 3,4). These two provinces are here informally referred to as the north and south Eel River basin (ERB) provinces. The heavy minerals in the north ERB samples consist of nonmetamorphic and metamorphic amphiboles (less glaucophane), pyroxene, and epidote with rare or absent glaucophane, sphene, and garnet. In the south ERB samples, the amphiboles (less glaucophane), pyroxenes, and epidote persist, but amphiboles and pyroxenes decrease to complement large increases in glaucophane (≤ 16%), garnet (≤13%), and sphene (≤9%). The nearshore samples in the south ERB province have slightly different mineralogic abundances than the rest of south ERB samples (sCST in Table 2).

Except for the apparent increase in percent epidote at the mouth of Eel Canyon, the variation in mineralogy seaward is much less than it is from north to south (Figure 3). The change in mineralogy may be attributable to bottom outcrops in the Eel Canyon area noted by Borgeld (1985).

DISCUSSION

Sources of Sediment

On the basis of suspended sediment discharge, the most likely sources of modern sediment for the northern California margin are the Klamath and Eel Rivers. The Klamath River drainage basin contributes sediment derived from greenschist to almandine-amphibolite facies terranes, which contain abundant metamorphic amphiboles (Irwin, 1966). The sand-size mineralogy of the Klamath River consists of metamorphic amphibole (blue-green amphibole and tremolite-actinolite), ordinary hornblende, and pyroxene (Kulm and others, 1968; Wong and Klise, 1986).

The heavy mineralogy of the Eel River strongly reflects the terranes comprising the Franciscan Complex (Wong and Klise, 1986). The Franciscan Complex hosts rock types ranging from undisturbed sedimentary rocks to low-grade schists, amphibolites, pillow lava, and ultramafic rocks (Blake and others, 1985). Typical heavy minerals from these rocks are blue-green amphiboles plus tremolite-actinolite, ordinary hornblende, pyroxene, and glaucophane. The abundances of glaucophane, garnet, and sphene distinguish sediment of the Eel River from the that of the Klamath River.

The abundance of blue-green amphibole and tremolite-actinolite and the dearth of glaucophane that is characteristic of sediment from the Klamath River clearly identify the Klamath as the source of the north ERB sediments. The abundance of glaucophane in the south ERB and the large sediment discharge of the Eel River point to the Eel as the primary sediment source there; the Mad River and Redwood Creek are probably a secondary sources, especially for the shelf immediately west and north of Eureka. The Mattole River is greatly enriched in epidote and garnet in comparison to the Eel River, but the small discharge and the presence of a submarine canyon nearby preclude much sediment movement northward along the shelf (Table 2; Figure 4C).

As with the Mattole, Smith River is an unlikely major sediment sources. The Smith River mineralogy is distinguished by the reduced metamorphic amphibole and increased pyroxene and nonmetamorphic amphibole components (Figure 4C). The 24 percent olivine noted by other workers in the Smith River was not found in Wong and Klise's (1986) samples and may constitute a trace component or was especially concentrated in the sample taken (Kulm and others, 1968).

Depositional Provinces from Factor Analysis

The depositional provinces and their primary sediment souces as mapped by the occurrence of nonopaque minerals are confirmed by a two-factor Q-mode factor analysis that accounts for 89 percent of the variation in the data. The two factors cover the same area as the north and south ERB provinces described above. The results of the factor analysis are provided in two tables, the rotated factor scores matrix (Table 3) and the rotated factor loadings matrix (Table 4). The rotated factor scores matrix identifies the mineral components of each factor. The rotated factor loadings matrix describes each sample according to its similarity to each factor.

Factor 1 accounts for 57% of the variability of the data and its major components are metamorphic amphiboles (less glaucophane), nonmetamorphic amphiboles, and subordinate pyroxene and epidote. Factor 1 is identified with the north ERB province and is consistent with Klamath River as the main sediment source (Figure 5).

Factor 2 accounts for 31% of the data variability and consists of undifferentiated rock fragments, glaucophane, orthopyroxene, epidote, sphene, opaque heavy minerals, and garnet. Factor 2 covers the south ERB and includes the samples from Redwood Creek and the Mad, Eel, and Mattole Rivers (Figure 5). Each of these rivers contributes to sediment on the shelf, though the Eel River is the main source for sediment moving beyond the shelf via Eel Canyon.

Sediment Movement Beyond the Northern California Margin

The continental margin off northern California is a restricted depositional area fed by several streams with large sediment discharge. The margin is effectively closed off to sediment sources from the south by the Mendocino Ridge, which provides a topographic barrier to sediment dispersal. The huge sediment load of the Eel River is discharged immediately north of this "wall"; about 100 km farther north, the Klamath River contributes another large volume of sediment. In the Holocene, fluvial sediment discharge has created a deposit as much as 50 m thick (Field and others, 1980) in places along the margin. Any contribution by coastal erosion is dwarfed by the river discharge (Griggs and Hein, 1980). Because of the large fluvial contribution, relict sediment is not a major constituent of this shelf and slope area as it is off Oregon to the north, or San Francisco Bay to the south. Towards the shelf edge and at isolated patches on the margin, the Holocene deposit thins to unsedimented areas exposing the underlying Pliocene rocks defomed by Quaternary tectonism.

Two modern fluvial sources are well defined by heavy-mineral abundance in the surface sediments of the northern California continental margin. Klamath River sediments are strongly evident as far south as the latitude of Trinidad and west to the limit of the sampled area. Sediment derived from the Franciscan Complex are discharged by the Eel and Mad Rivers and Redwood Creek on to the shelf on either side of the submarine Eel Canyon (Figure 5). Grain size and density also differ from these two sources (Borgeld, 1985).

The distribution of the offshore Klamath sediment is consistent with Griggs and Hein's

(1980) tracing of the winter and summer suspended sediment plumes. Winter (December-March) plumes are fed by primary influxes of sediment during peak discharge period and are distributed by the southward Davidson current nearshore and then turned northward by the California current operating farther offshore. Non-winter (April-November) plumes are short, without well defined sources, and are apparently also south directed nearshore and are attributed to resuspension of nearshore material (Griggs and Hein, 1980).

The net northward movement of Klamath sediment has been traced along the Oregon continental margin to the Oregon-Washington border (Scheidegger and others, 1971; Kulm and others, 1975). Spigai (1971) used the pyroxene-to-amphibole ratio to distinguish among several heavy-mineral source terranes for the offshore area of southern Oregon. Values from the present study cluster about 0.25 which agrees with the "Klamath-South Coast Basin" values determined by the Oregon workers and eliminates the Columbia River and other Oregon streams, which have much greater ratios, as likely sources. The data from this study extend the southern limits of the sediment dispersal path, which sweeps approximately 50 km south of the mouth of the Klamath River before merging with the main north-trending path (Figure 5,6B).

In proportion to its volume, Eel River sediment has a very limited distribution on the shelf and upper slope off northern California. As with the Klamath discharge, some of the Eel River sediment also is swept southward by nearshore currents (Griggs and Hein, 1980), but the Eel Canyon, which heads a mere 12 km from the mouth of the river, is the probable sink for most of the Eel sediment. Eel Canyon also prevents much sediment from veering northward (Figure 6B). Heavy minerals in samples collected downslope from the mouth of the Eel River approximately 70 km west of Cape Mendocino have a mineralogy similar to that of the Eel River samples (Luepke, 1995).

Trinity and Eel Canyons have been proposed as paths to the deep sea for sediment in Pleistocene turbidites from the lower parts of Deep-sea Drilling Project core 35 that was collected near the south end of the Escanaba Trough (Figure 7; Vallier and others, 1973). In comparison to other heavy-mineral suites in the northeast Pacific and except for the Mattole River, sediments from the northern California rivers and offshore are fairly homogeneous in the major minerals amphibole, pyroxene and epidote (Figure 7). As discussed in a previous section, the abundance of glaucophane is a good discriminant between Klamath and Eel sediment sources. The lower Escanaba sediment originally was traced to a "Klamath" source on the basis of amphibole abundance and the appearance of glaucophane (Vallier and others, 1973). However, this study shows that the presence of glaucophane suggests that an Eel sediment source contributed some possibly large part of the Escanaba sediment, precluding the need for a great deal of glaucophane-poor Klamath sediment to exit the margin via Trinity Canyon. Modern sediment in Escanaba Trough, reflecting a large Columbia River contribution, differs from that in the lower parts of the DSDP cores and is believed to include sediment discharged by floods unleashed by the breaching of glacially dammed Lake Missoula (eastern Washington state) during Wisconsin time and eruption of Mount Mazama in the Holocene (Karlin and Lyle, 1986; Nelson and others, 1988; Normark and others, 1994; O'Connor and Waitt, 1995).

SUMMARY

A large modern suspended sediment load has blanketed the margin off northern California. This study identifies the role of the Klamath River as the primary source of sediment for offshore northern California and southern Oregon and the Eel River as a secondary source. The impact of the enormous Eel River discharge is small in shelf sedimentary processes because of the proximity of the submarine Eel Canyon. On the other hand, the Eel River probably has contributed sediment to the deep seafloor as far west as Escanaba Trough since at least early Pleistocene time.

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Table 1. Drainage area and discharge rate of rivers of the western United States.

River	Drainage Area (km^2)	Avg/Estim Sediment Discharge (1000 metric tons/yr)	Data Source
Columbia	668,738	14,170	1
Rogue	5,317	59	1
Smith	1,577	~680	3
Klamath	29,339	8,211	2
Redwood Creek	420	1,620	2
Mad	1,256	2,512	2
Eel	8,638	23,979	2
Mattole	622	1,600	2,3

1 Curtis and others, 1973
2 Janda and Nolan, 1979, *in* Griggs and Hein, 1980
3 Griggs and Hein, 1980

Table 2. Summary of heavy-mineral abundance in surface sediment, northern California margin.

		RIVERS						ALL OFFSHORE				nERB		sERB		sCST	
1		sml	kla	rdw	mad	eel	mat	min	max	avg	std	avg	std	avg	std	avg	std
2	sand%							0	87	31	30	24	28	20	20	72	11
3	wt% hvy	25	31	2	7	11	2		30	6	7	9	8	2	1	4	3
	Total grains	314	295	584	385	392	473	181	587	375	60	348	46	415	59	418	53
	% nonopaques	65	66	36	53	34	54	24	82	64	12	71	9	58	8	48	5
	% opaques	13	8	29	15	37	24	5	58	14	9	11	8	19	10	21	7
	% rock fragments	18	24	34	30	27	18	6	38	20	7	16	4	22	5	29	4
	% unknown	4	2	2	2	2	3		5	2	1	2	1	1	1	2	1
	Total Nonopaque grains	204	194	209	205	135	255	116	346	237	42	248	43	236	26	203	35
4	hornblende																
	brown	9	13	6	12	7	4		12	7	3	7	2	5	2	6	3
	green	31	16	22	19	19	7	7	34	18	6	19	6	20	7	15	6
	basaltic	0		1		1	1		2	0	0	0	0	0	0	0	0
	glaucophane			2	18	17	2		16	3	4	0	0	5	4	7	6
	tremolite	12	7	4	4	14	2		16	7	3	8	3	8	3	5	2
	amph, blue-green	8	37	25	11	4	2	6	49	31	11	37	6	23	8	18	7
	actinolite								11	1	2	1	2	1	3		
	orthopyroxene																
	hypersthene	3	2	1	0	1	2		13	4	2	4	2	5	2	4	3
	enstatite		2						6	1	1	1	1	1	1	2	2
	clinopyroxene																
	augite	25	13	9	11	19	20	1	18	8	4	7	3	8	4	12	3
	colorless								12	3	3	3	2	3	3	6	4
	epidote grp	11	8	18	19	6	31	5	30	13	5	12	4	17	6	14	4
	lawsonite								3	0	0	0	0	0	1	0	0
	sphene		2	3	4	4	6		9	1	2	0	0	1	1	4	3
	zircon			1	1	1	4		7	1	1	0	0	1	1	2	2
	garnet			0	1	3	16		13	1	2	1	1	2	1	4	4
	apatite			0			2		5	1	1	0	0	1	1	2	2
	Cr spinel			0	0				1	0	0	0	0	0	0	0	0
	tourmaline			1					1	0	0	0	0	0	0	0	0
	other			4		3			4	0	1	0	0	0	0	1	1
5	100*px/amph	48	23	17	19	32	115			24		20		26		45	

NOTES: 1 RIVERS: Smith, Klamath, Redwood Creek, Mad, Eel, and Mattole.
ALL OFFSHORE: average of 76 samples from offshore areas (Figure 2).
min = minimum, max = maximum, avg = mean, std = standard deviation
sERB: offshore samples west of the 50-m isobath and south of Patricks Point.
sCST: nearshore samples south of the mouth of Redwood Creek.
2 Percent sand from grain-size analysis (Field and others, 1980).
3 Percent by weight of heavy minerals in the 63-250um size fraction.
4 Heavy mineral values are percents of total nonopaque monomineralic grains in the 63-250um size range; blank = mineral absent; 0 indicates abundance <0.5%.
5 Pyroxene-amphibole index.

Table 3. Rotated factor scores matrix for factor 1 (north Eel River Basin province) and factor 2 (south Eel River Basin province).

	factor 1	factor 2	Total
% of whole data set explained	57.44	31.42	88.86
hornblende	**0.46**	0.13	
glaucophane	-0.21	**0.47**	
metamorphic amphibole (less glaucophane)	**0.73**	-0.12	
orthopyroxene	**0.24**	0.16	
clinopyroxene	0.13	**0.35**	
epidotes	0.16	**0.34**	
sphene	-0.15	**0.34**	
zircon	-0.07	0.19	
garnet	-0.07	**0.21**	
wt% heavy minerals	**0.25**	-0.07	
opaque heavy minerals	0.04	**0.27**	
rock fragments	0.15	**0.46**	

Bold-face values are scores with magnitudes >0.2 and identify the minerals that are characteristic of a factor.

Table 4. Rotated factor loadings matrix of factors 1 and 2 on samples from this study.

Sample number	Factor 1 load	Factor 2 load	%data explained
25	**0.89**	0.25	85
26	**0.83**	0.46	90
27	**0.89**	0.34	91
28	**0.92**	0.39	100
29	**0.87**	0.37	88
30	**0.89**	0.39	94
31	**0.87**	0.47	97
32	**0.81**	0.31	76
34	**0.92**	0.35	96
38	**0.92**	0.36	97
41	**0.90**	0.39	95
43	**0.90**	0.31	90
44	**0.89**	0.39	94
45	**0.91**	0.39	98
47	**0.90**	0.32	92
48	**0.78**	0.55	91
49	**0.88**	0.46	98
50	**0.90**	0.38	94
51	**0.88**	0.42	94
52	**0.89**	0.34	91
53	**0.91**	0.36	96
54	**0.86**	0.46	95
55	**0.79**	0.53	91
58	**0.74**	0.63	94
66	**0.81**	0.49	90
72	**0.72**	0.56	83
73	0.61	**0.74**	92
74	**0.66**	0.57	75
75	**0.79**	0.39	77
76	**0.87**	0.29	84
77	**0.87**	0.38	90
78	**0.85**	0.47	95
79	**0.90**	0.41	97
80	**0.78**	0.55	92
81	**0.86**	0.43	93
82	**0.78**	0.45	80
84	**0.72**	0.64	92
85	**0.70**	0.64	90
86	**0.66**	**0.67**	89
87	**0.79**	0.59	97
89	**0.76**	0.62	96

Sample number	Factor 1 load	Factor 2 load	%data explained
93	0.56	**0.78**	92
96	0.64	**0.73**	94
97	0.48	**0.82**	90
98	0.33	**0.86**	85
101	**0.89**	0.40	94
102	**0.89**	0.39	94
103	**0.92**	0.34	95
104	**0.89**	0.36	91
106	**0.86**	0.43	93
110	**0.88**	0.46	98
112	**0.93**	0.34	98
113	**0.92**	0.34	97
114	**0.87**	0.40	92
115	**0.83**	0.44	88
116	**0.75**	0.53	84
117	0.53	**0.74**	82
120	**0.75**	0.43	74
TO22	0.56	**0.78**	92
TO35	**0.66**	0.65	85
TO58	**0.70**	0.64	90
TO78	0.24	**0.82**	72
TO82	0.54	**0.78**	90
TO91	**0.71**	0.57	82
TO101	**0.71**	**0.66**	93
TO123	**0.72**	**0.66**	96
TO132	0.41	**0.79**	79
ER1	0.28	**0.91**	91
ER4	0.24	**0.89**	85
ER8	0.18	**0.92**	88
ER12	0.22	**0.95**	94
ER18	0.33	**0.69**	58
K7	**0.86**	0.32	83
K9	**0.91**	0.26	90
K3	**0.89**	0.23	85
K10	**0.75**	0.51	82
Smith	**0.70**	0.46	70
Klamath	**0.81**	0.36	78
Redwood	0.59	**0.72**	87
Mad	0.33	**0.86**	84
Eel	0.32	**0.84**	81
Mattole	0.18	**0.81**	68

Figures in bold-face are factor loadings >= 0.65 and indicate that the factor explains about 42% (0.65*0.65) of the data in the sample.
'%data explained ' = sum of the squares of factors 1 and 2 for each sample, and is the amount of variance in a sample explained by the 2 factors.

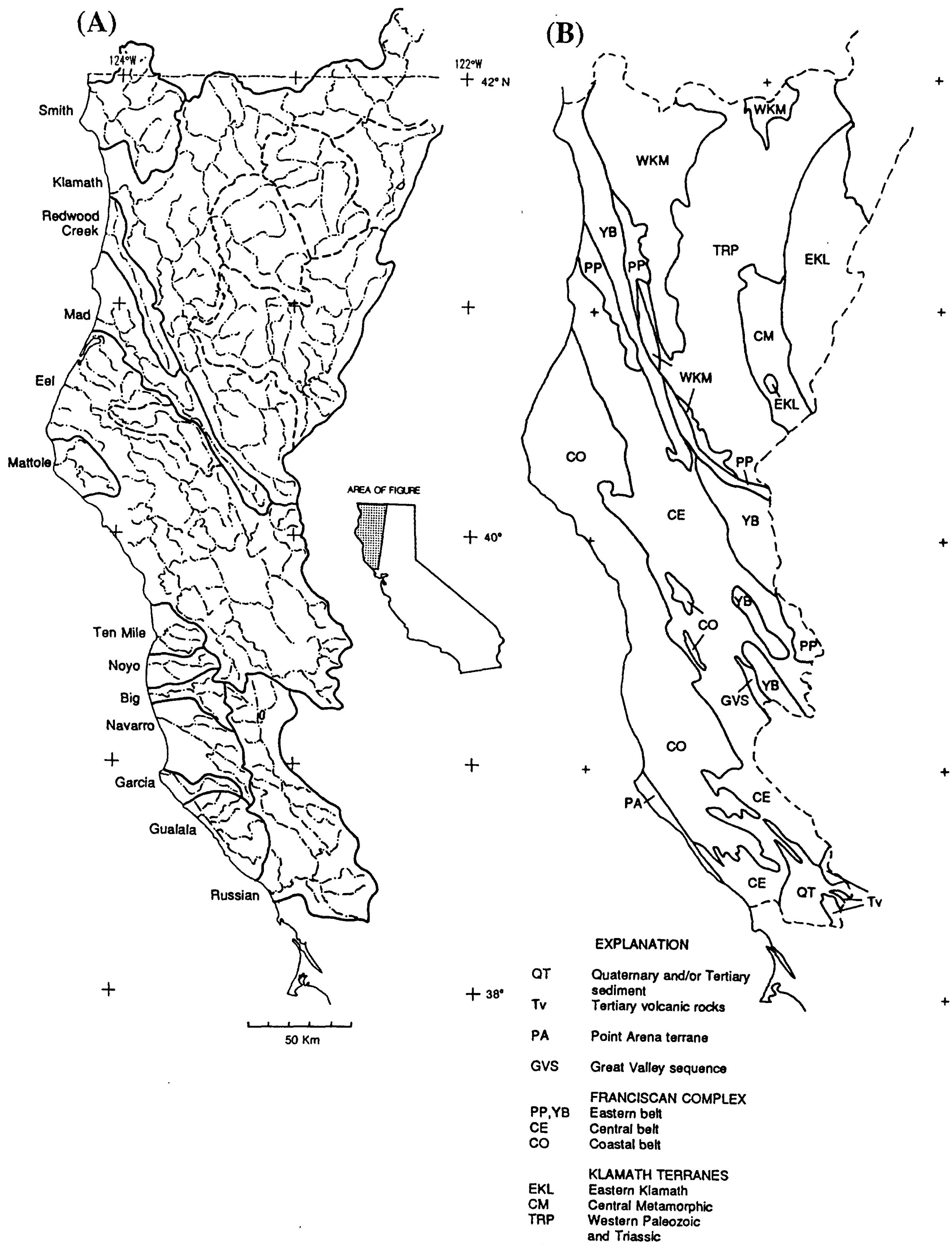

Figure 1. (a) Watersheds of rivers emptying into the northernmost California coast sketched from topographic maps (U.S. Geological Survey, 1959a, 1959b) and (b) generalized geologic map of northwestern California (Blake and others, 1982). The Klamath River drains the terranes of the Klamath Mountains province, the Eel River those of the Franciscan Complex.

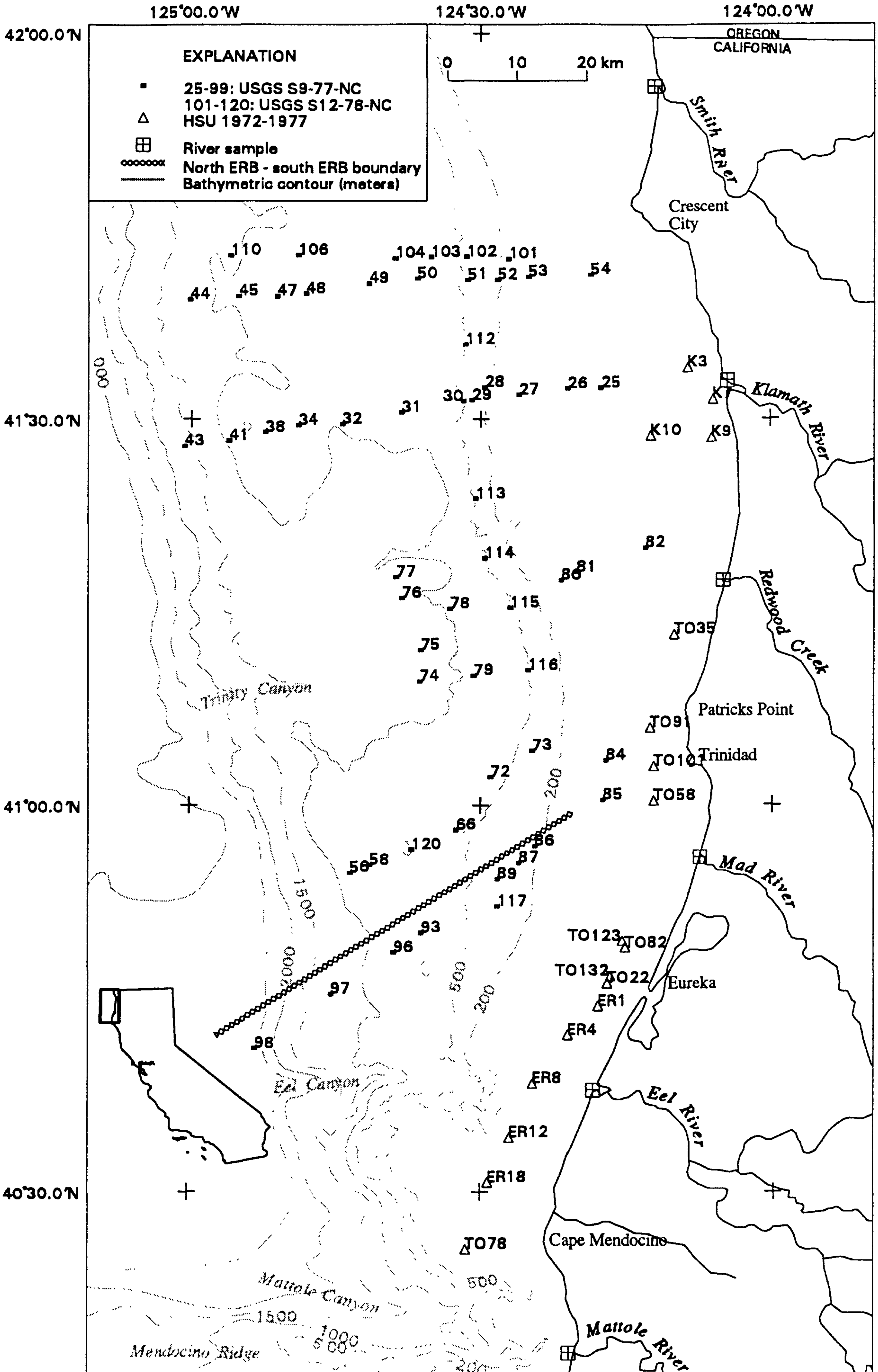

Figure 2. Sample sites offshore northernmost California. The 200-m isobath approximately defines the continental shelf. The area between the shoreline and 1200m depth is about 9,000 sq km.

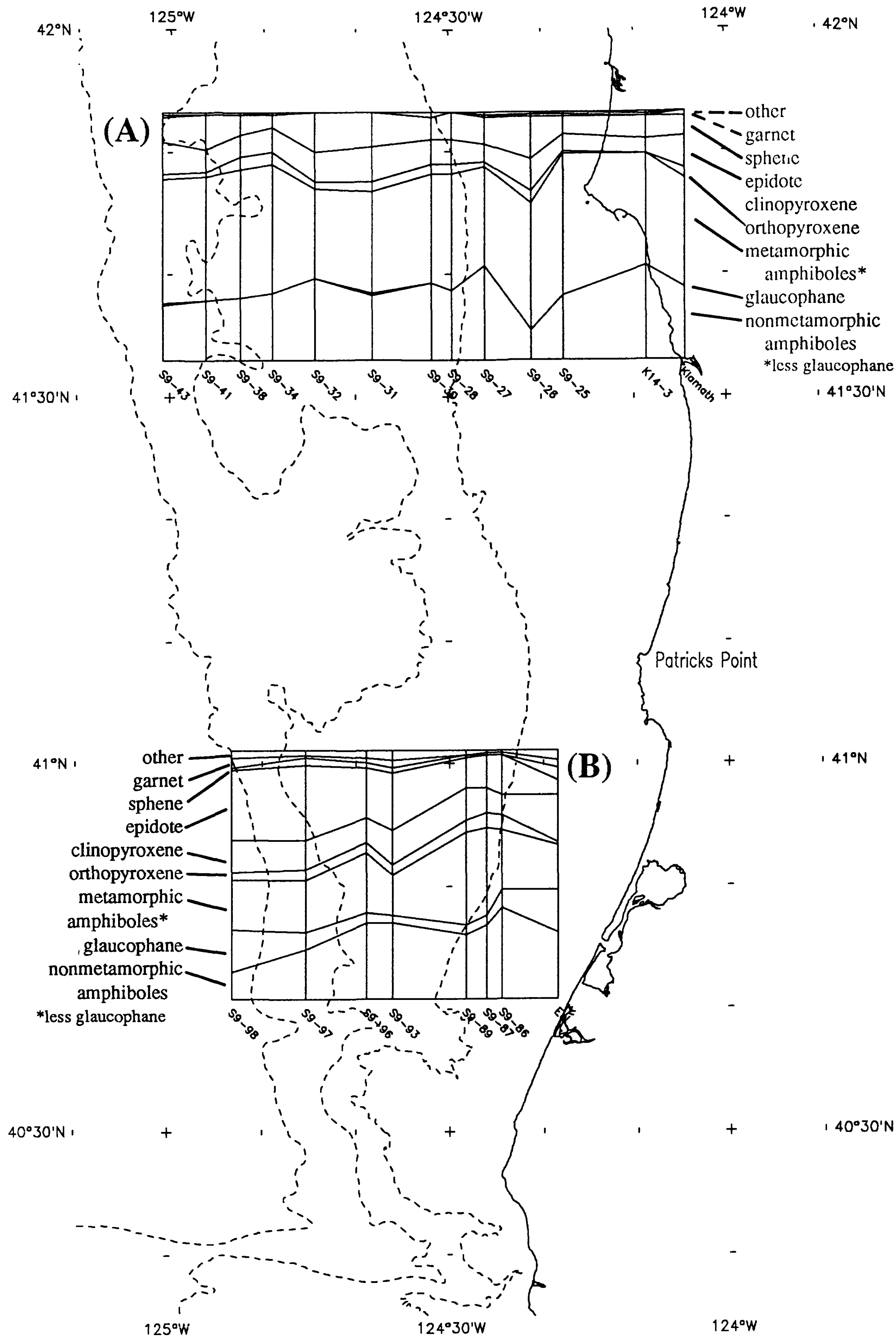

Figure 3. East-west distribution of major nonopaque heavy minerals. (A) Samples enriched in metamorphic amphiboles (less glaucophane) characteristic of Klamath River sediment. (B) Samples enriched in glaucophane and epidote characteristic of Eel River sediment. Dashed lines are 200-, 1000-, and 2000-meter isobaths.

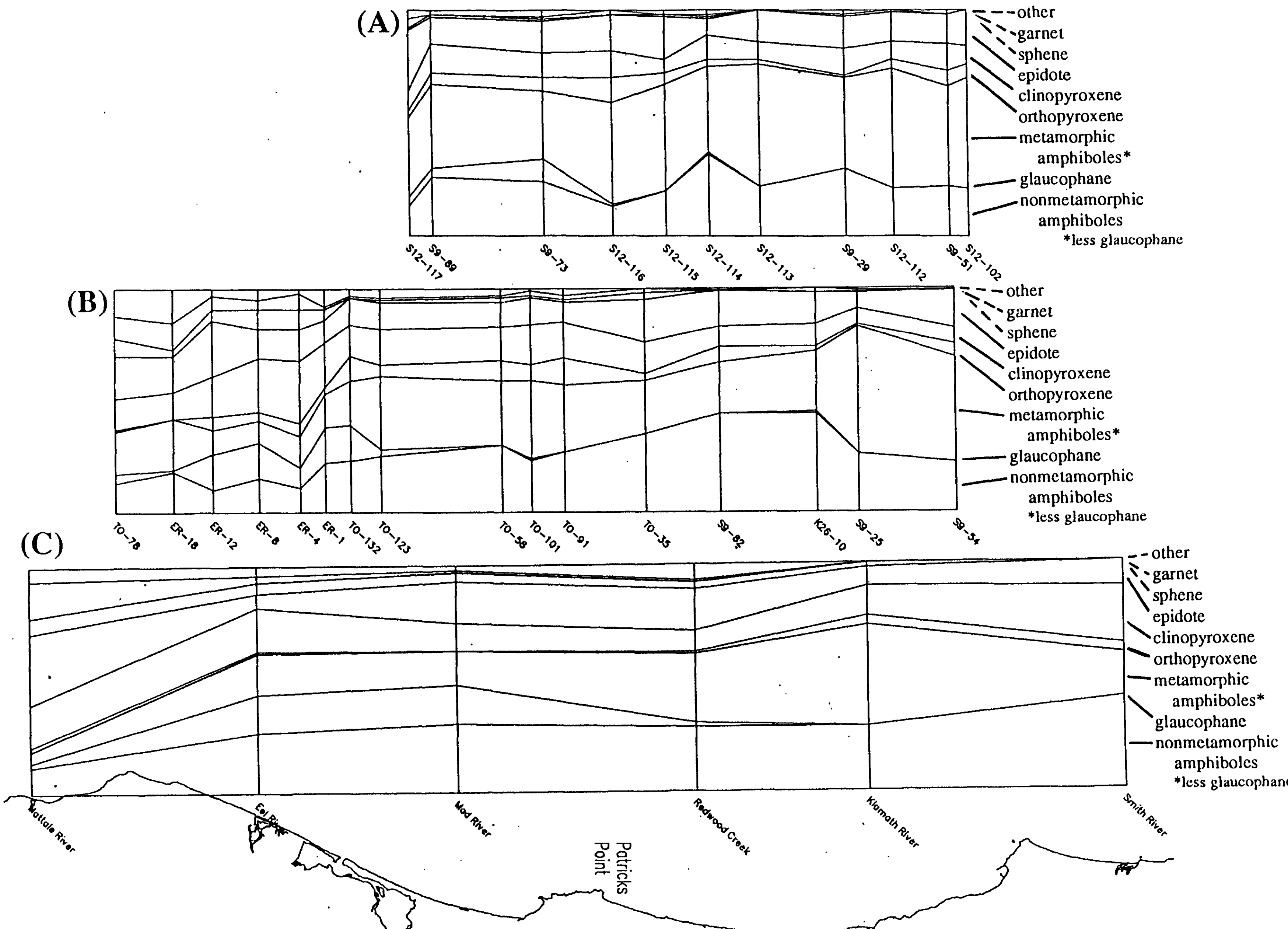

Figure 4. North-south (right to left) distribution of major nonopaque heavy minerals (A) along the 500-m isobath, (B) along the 50-m isobath, and (C) at river mouths. From south to north, garnet, glaucophane, and epidote decrease in abundance. Metamorphic amphiboles increase northward and seaward.

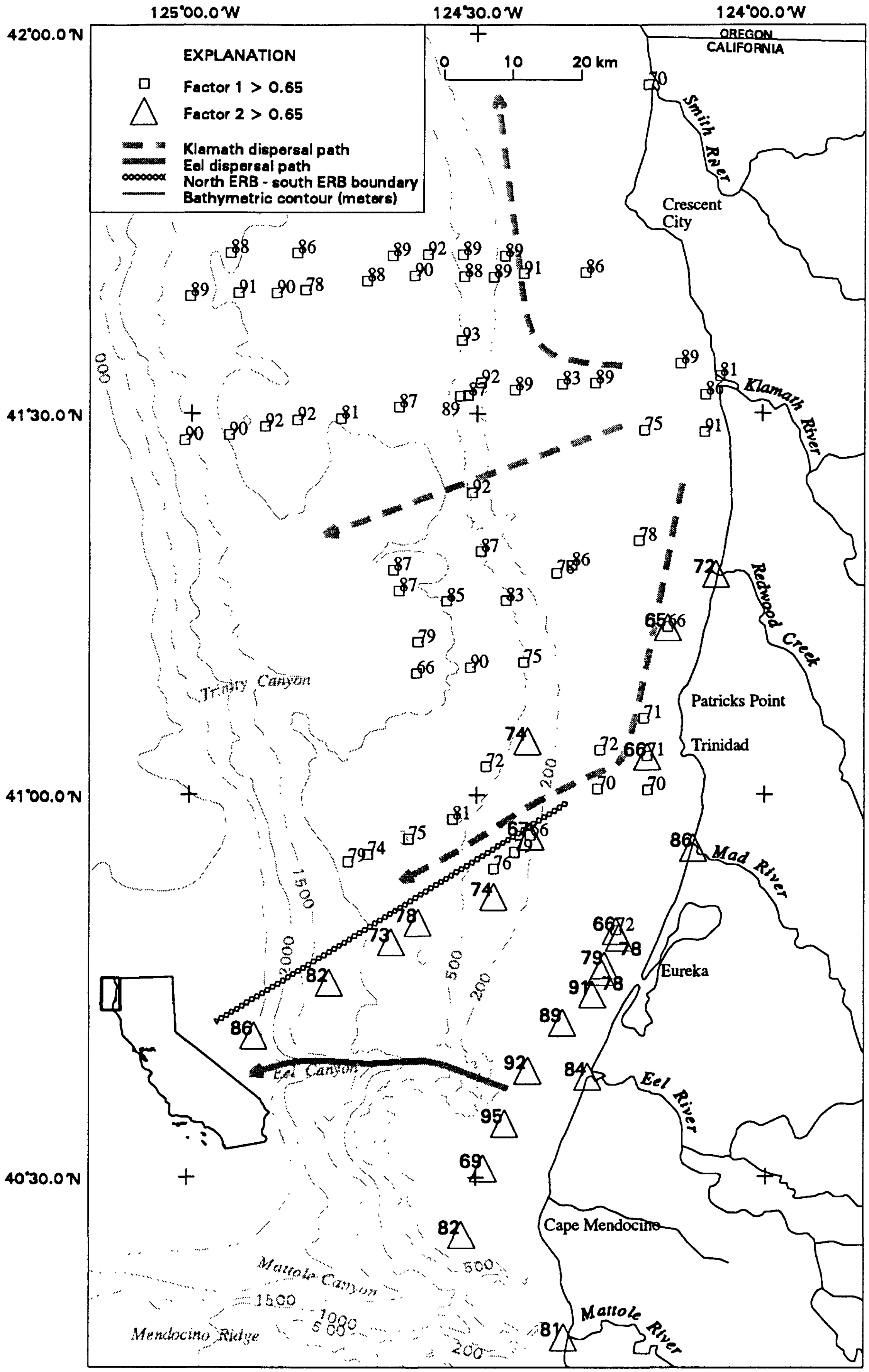

Figure 5. Samples with factor loadings greater than 0.65 for each of factor 1 and (or) factor 2. Four nearshore samples between the mouth of Redwood Creek and Eureka appear to have characteristics of both factors. The northern Eel River basin-southern Eel River basin separation is west-southwest from Patricks Point. Arrows show dispersal paths of sediment from the Klamath and Eel Rivers.

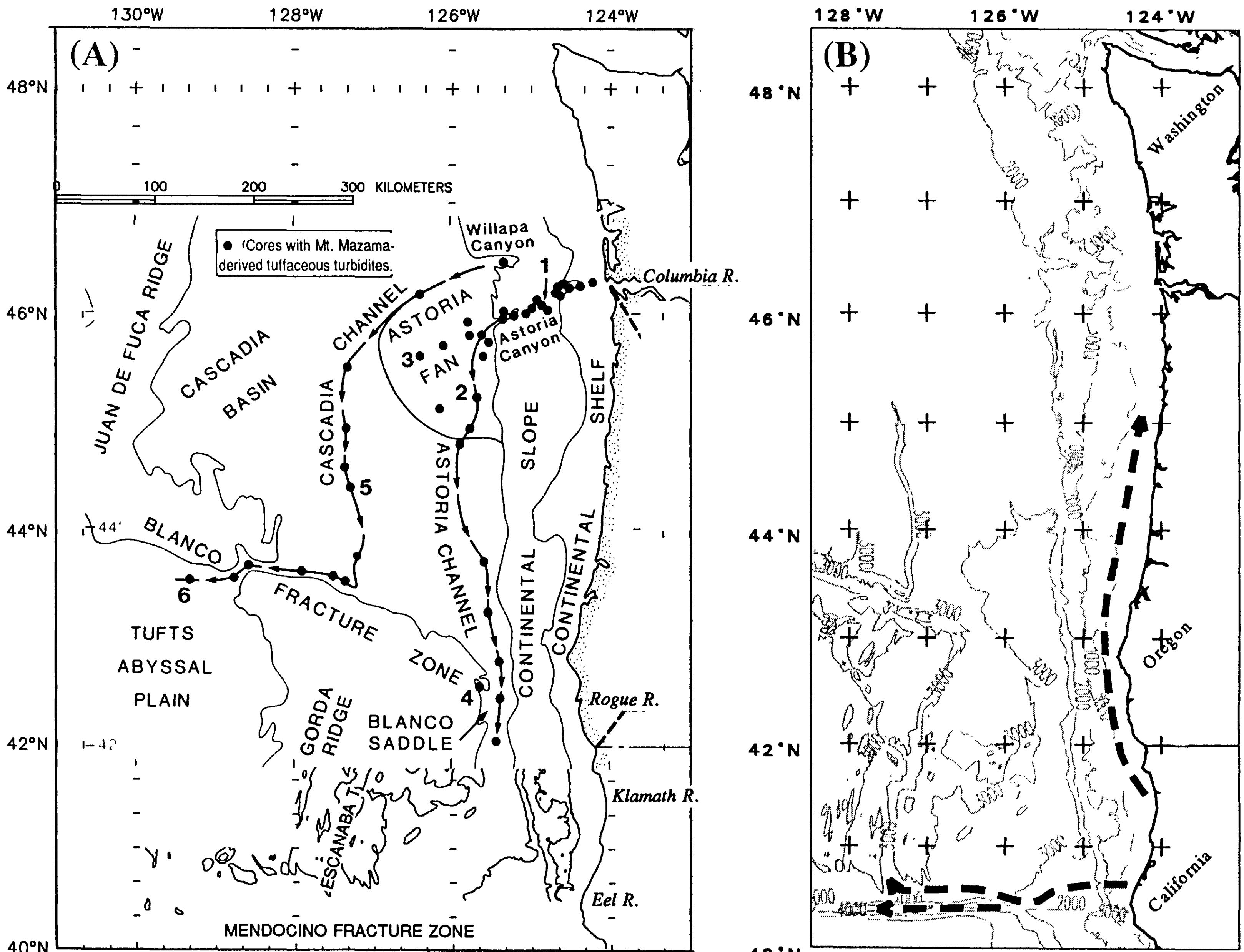

Figure 6. Sediment dispersal paths (A) identified by ash erupted from Mount Mazama (Nelson and others, 1988) and (B) suggested by data from this study. North-trending path is modified from Scheidegger and others (1971).

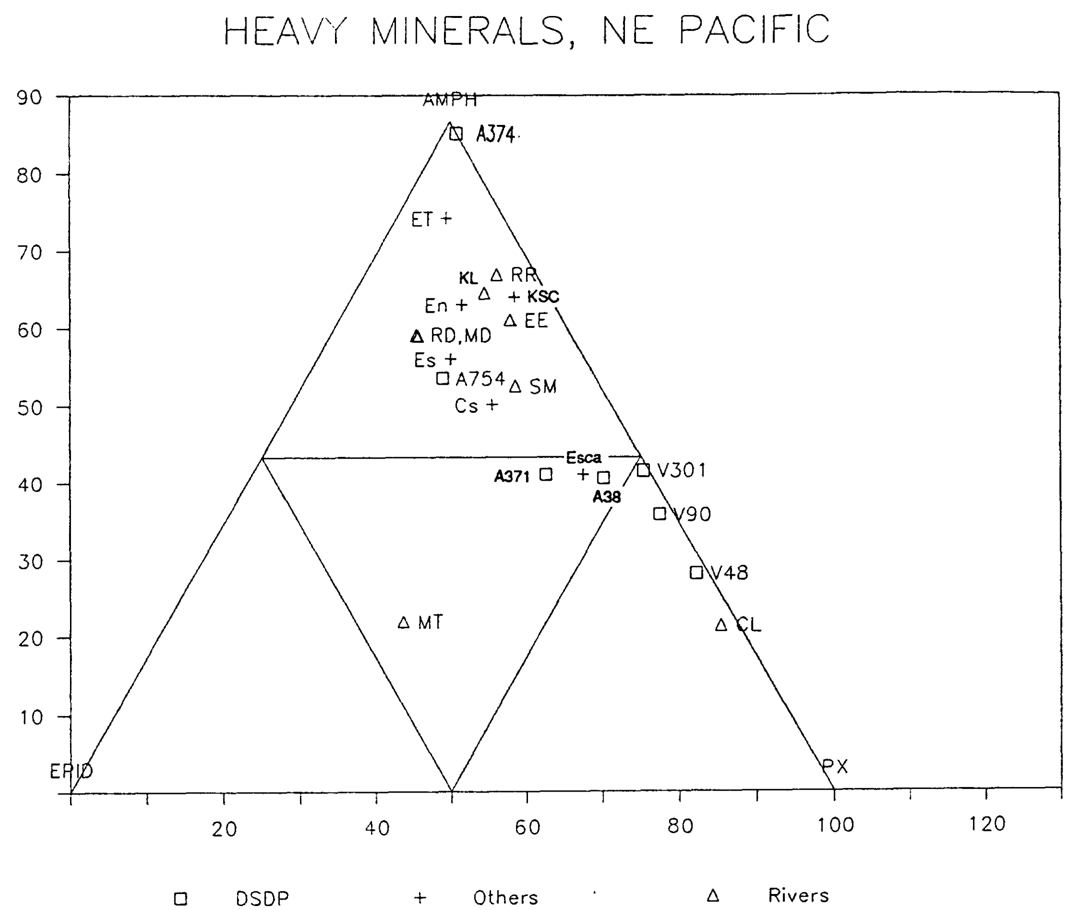

Figure 7. Ternary distribution of amphibole, epidote, and pyroxene in the northeast Pacific. These parameters establish some of the major differences among the different depositional areas, but does not distinguish the Klamath discharge from the Eel.

ET flanks of Escanaba Trough (Fowler and Kulm, 1970)
V48, V90, V301, V374 from DSDP site 35 (Vallier and others, 1973)
A38, A374, A754 from DSDP site 174A on Astoria Fan (Scheidegger and others, 1973)
KSC, RR Klamath-South Coast basin, Rogue River (Kulm and others, 1968)
COL Columbia River (Whetten and others, 1969)
Esca Escanaba Trough (Normark and others, 1994)
Rivers: EE Eel, KL Klamath, MD Mad, MT Mattole, RD Redwood Creek, SM Smith.
Provinces: En northern Eel River basin, Es southern Eel River basin, Cs south coast.

APPENDIX. Raw counts and nonopaque percentages of heavy minerals, northern California.

seq no	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	S9-77-															
sample id	25	26	27	28	29	30	31	32	34	38	41	43	44	45	47	48
hornblende																
brown	24	6	19	23	17	21	18	18	23	9	22	31	30	16	20	15
green	37	19	78	43	60	57	41	56	41	46	34	35	40	52	55	36
basaltic	1		1					3		2	1					
glaucophane							2					3	1			1
tremolite	15	34	23	23	14	13	18	28	11	14	16	27	17	25	19	19
amph, b-g	117	65	82	84	86	91	71	56	109	98	105	120	117	93	125	59
actinolite	7	7		5		8	2		4	9		2	9			
orthopyroxene																
hypersthene	1	9	5	11	4	11	9	7	10	9	4	6	16	13	6	15
enstatite							1		1	2			8	2		5
clinopyroxene																
augite	18	28	19	22	31	14	19	28	24	15	23	38	11	19	16	18
colorless						12	12			6			19	8	6	17
epidote grp	17	35	29	26	35	22	32	36	12	19	32	30	23	21	14	32
lawsonite																
sphene	2	2														
zircon	1					1				2	1	1	1	1	1	
garnet	1		2		3	1			1			3	1		1	1
apatite		2		1		2			1							
cr spinel			1													
tourmaline					1	1										
other			2		3						2	1				
mica	xx															
opaques	24	45	33	36	37	48	23	39	15	18	42	25	25	23	16	49
rock frags	25	68	47	58	39	79	55	34	69	58	54	33	76	57	65	77
unknown	10	4	7		12	2	9	15	5	2	8	18	2		1	
total	300	324	348	332	342	383	312	320	326	309	344	373	396	330	345	344
Percent of nonopaque nonmicaceous monomineralic grains																
Tot Nopq	241	207	261	238	254	254	225	232	237	231	240	297	293	250	263	218
hornblende																
brown	10	3	7	10	7	8	8	8	10	4	9	10	10	6	8	7
green	15	9	30	18	24	22	18	24	17	20	14	12	14	21	21	17
basaltic	0		0					1		1	0					
glaucophane							1					1	0			0
tremolite	6	16	9	10	6	5	8	12	5	6	7	9	6	10	7	9
amph, b-g	49	31	31	35	34	36	32	24	46	42	44	40	40	37	48	27
actinolite	3	3		2		3	1		2	4		1	3			
orthopyroxene																
hypersthene	0	4	2	5	2	4	4	3	4	4	2	2	5	5	2	7
enstatite							0		0	1			3	1		2
clinopyroxene																
augite	7	14	7	9	12	6	8	12	10	6	10	13	4	8	6	8
colorless						5	5			3			6	3	2	8
epidote grp	7	17	11	11	14	9	14	16	5	8	13	10	8	8	5	15
lawsonite																
sphene	1	1														
zircon	0					0				1	0	0	0	0	0	
garnet	0		1		1	0			0			1	0		0	0
apatite		1		0		1			0							
cr spinel			0													
tourmaline					0	0										
other			1		1						1	0				

seq no	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
															S9-77-	
sample id	49	50	51	52	53	54	56	58	66	72	73	74	75	76	77	78
hornblende																
brown	14	18	17	13	11	12	21	19	20	10	11	1	11	16	14	17
green	40	56	59	32	40	46	61	48	31	23	47	17	23	39	53	51
basaltic																
glaucophane				2			2	6	4	15	23					1
tremolite	22	28	26	19	34	21	8	27	14	31	20	8	13	12	12	19
amph, b-g	76	141	125	116	86	100	62	62	83	75	52	39	39	107	96	79
actinolite				8					11	10				2		
orthopyroxene																
hypersthene	9	7	16	10	6	12	12	12	22	13	9	5	7	9	20	12
enstatite		3	7	2	6	2		6	1	7	5	1	3	2	3	6
clinopyroxene																
augite	13	20	17	18	6	8	21	22	13	11	9	11	10	13	21	13
colorless	6	26	22	9	11	11	7	6	7	6	17	10		9	9	9
epidote grp	28	28	45	18	20	43	22	33	38	25	33	19	17	26	26	25
lawsonite											7					
sphene		2		2			2	1			3	2	2			
zircon			1	1	1			5	1	1			2			1
garnet	4		1			2	2	6	3	5	3	3	2	4	1	3
apatite			4			1	5	1	1						2	1
cr spinel																
tourmaline									2							
other		2	2				1								1	
mica										xx						
opaques	29	39	29	17	40	43	65	53	59	71	30	275	20	38	38	22
rock frags	69	57	50	39	52	77	50	91	59	77	99	84	30	50	54	78
unknown	3	6	8	7	3	3	7	4		1		1	2	1	5	2
total	313	433	429	313	316	381	348	402	369	381	368	476	181	328	355	339
Percent of nonopaque nonmicaceous monomineralic grains																
Tot Nopq	212	331	342	250	221	258	226	254	251	232	239	116	129	239	258	237
hornblende																
brown	7	5	5	5	5	5	9	7	8	4	5	1	9	7	5	7
green	19	17	17	13	18	18	27	19	12	10	20	15	18	16	21	22
basaltic																
glaucophane				1			1	2	2	6	10					0
tremolite	10	8	8	8	15	8	4	11	6	13	8	7	10	5	5	8
amph, b-g	36	43	37	46	39	39	27	24	33	32	22	34	30	45	37	33
actinolite				3					4	4				1		
orthopyroxene																
hypersthene	4	2	5	4	3	5	5	5	9	6	4	4	5	4	8	5
enstatite		1	2	1	3	1		2	0	3	2	1	2	1	1	3
clinopyroxene																
augite	6	6	5	7	3	3	9	9	5	5	4	9	8	5	8	5
colorless	3	8	6	4	5	4	3	2	3	3	7	9		4	3	4
epidote grp	13	8	13	7	9	17	10	13	15	11	14	16	13	11	10	11
lawsonite											3					
sphene		1		1			1	0			1	2	2			
zircon			0	0	0			2	0	0			2			0
garnet	2		0			1	1	2	1	2	1	3	2	2	0	1
apatite			1			0	2	0	0						1	0
cr spinel																
tourmaline									1							
other		1	1				0								0	

APPENDIX. Raw counts and nonopaque percentages of heavy minerals, northern California.

seq no	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
														S12-78-													HSU TO-					
sample id	79	80	81	82	84	85	86	87	89	93	96	97	98	101	102	103	104	106	110	112	113	114	115	116	117	120	22	35	58	78	82	91
hornblende																																
brown	20	10	13	24	10	17	9	23	10	11	17	7		12	12	15	23	14	19	14	25	29	26	7	7	12	12	12	27	11	15	26
green	55	50	33	67	27	68	73	56	59	60	57	39	27	48	42	43	25	25	43	34	27	76	34	19	24	38	54	66	39	19	26	33
basaltic									1													1			1		1					
glaucophane	1	2	4		4	17	15	10	9	7	10	18	39						2			2		2	12	2	23		1	10	16	
tremolite	22	17	26	1	12	21	18	8	26	9	14	19	24	22	28	15	14	19	3	10	23	22	14	14	28	27	34	9	13	8	9	10
amph, b-g	81	55	93	48	46	49	36	59	73	26	43	29	24	107	93	137	114	91	96	105	97	91	113	68	54	87	42	45	52	38	48	57
actinolite			11					28						12	4	7	17	8	7	7	7		12	6	8	2						
orthopyroxene																																
hypersthene	13	3	9	12	10	14	12	15	12	11	9	10	8	13	17	12	12	12	12	11	7	7	12	16	4	3	5	4	12	1	8	28
enstatite	3		1	1	2	2		1									2						2	4	2	1		2	8		11	
clinopyroxene																																
augite	8	28	2	9	11	4	9	13	36	31	24	28	31	13	14	13	14	13	24	8	10	34	12	10	11	9	46	12	19	31	16	23
colorless	10		15	10	12	17	9	11						10	5	6	5	7	6	10	7		6	13	13	8		19	13	4	17	12
epidote grp	34	39	41	34	16	37	35	35	30	52	46	71	65	39	41	36	34	34	30	30	33	21	56	32	68	31	27	43	25	45	18	20
lawsonite									1																		2					
sphene					1	1	1	1	3	6	5	6	3									1	3	1	3	1	4	5	4	17	8	2
zircon				2	1					3	1	1	1					1					5		8		3		3	14		3
garnet	1	1	1			1	1	2	1	6	5	3	9			1	2	2	2	2	1	4		3	12	1	1	4	2	24	4	5
apatite						1	3	3	1	6	5	3	6									3	1		1		1		3	13		2
cr spinel									1													2					2					
tourmaline																													1			
other						4			2		1		1		1			1				1						1		2		1
mica		xx																									xx					
opaques	26	32	61	47	93	77	73	66	40	51	48	77	102	46	47	22	20	58	34	26	41	41	47	65	127	297	125	40	56	110	99	78
rock frags	48	77	56	57	112	66	86	109	111	87	105	120	107	61	45	63	54	56	51	40	48	49	40	63	106	66	147	167	134	103	159	111
unknown	1	12	7	5	2		11	17	12	3	10	3	10	6	12	14	6	15	6	11	15	12	12	7	4	2	16	8	8	6	4	5
total	323	326	373	317	359	396	391	457	428	369	400	434	457	389	361	384	342	356	335	308	341	396	395	330	493	587	545	437	420	456	458	416
Percent of nonc																																
Tot Nopq	248	205	249	208	152	253	221	265	265	228	237	234	238	276	257	285	262	227	244	231	237	294	296	195	256	222	257	222	222	237	196	222
hornblende																																
brown	8	5	5	12	7	7	4	9	4	5	7	3		4	5	5	9	6	8	6	11	10	9	4	3	5	5	5	12	5	8	12
green	22	24	13	32	18	27	33	21	22	26	24	17	11	17	16	15	10	11	18	15	11	26	11	10	9	17	21	30	18	8	13	15
basaltic									0													0			0		0					
glaucophane	0	1	2		3	7	7	4	3	3	4	8	16						1			1		1	5	1	9		0	4	8	
tremolite	9	8	10	0	8	8	8	3	10	4	6	8	10	8	11	5	5	8	1	4	10	7	5	7	11	12	13	4	6	3	5	5
amph, b-g	33	27	37	23	30	19	16	22	28	11	18	12	10	39	36	48	44	40	39	45	41	31	38	35	21	39	16	20	23	16	24	26
actinolite			4					11						4	2	2	6	4	3	3	3		4	3	3	1						
orthopyroxene																																
hypersthene	5	1	4	6	7	6	5	6	5	5	4	4	3	5	7	4	5	5	5	5	3	2	4	8	2	1	2	2	5	0	4	13
enstatite	1		0	0	1	1		0									1						1	2	1	0		1	4		6	
clinopyroxene																																
augite	3	14	1	4	7	2	4	5	14	14	10	12	13	5	5	5	5	6	10	3	4	12	4	5	4	4	18	5	9	13	8	10
colorless	4		6	5	8	7	4	4						4	2	2	2	3	2	4	3		2	7	5	4		9	6	2	9	5
epidote grp	14	19	16	16	11	15	16	13	11	23	19	30	27	14	16	13	13	15	12	13	14	7	19	16	27	14	11	19	11	19	9	9
lawsonite									0																		1					
sphene					1	0	0	0	1	3	2	3	1									0	1	1	1	0	2	2	2	7	4	1
zircon				1	1					1	0	0	0					0					2		3		1		1	6		1
garnet	0	0	0			0	0	1	0	3	2	1	4			0	1	1	1	1	0	1		2	5	0	0	2	1	10	2	2
apatite						0	1	1	0	3	2	1	3									1	0		0		0		1	5		1
cr spinel									0													1					1					
tourmaline																													0			
other						2			1		0		0		0			0				0						0		1		0

c:\123\erb\CNTS.XLS: 2

APPENDIX. Raw counts and nonopaque percentages of heavy minerals, northern California.

seq no	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82
				HSU ER-					KO-	K13-	K14-	K26-	RIVERS					
sample id	101	123	132	1	4	8	12	18	7	9	3	10	sml	kla	rdw	mad	eel	mat
hornblende																		
brown	21	18	11	7	2	7	5	11	26	20	21	24	18	25	13	25	9	11
green	24	45	21	23	17	23	12	23	114	59	95	87	64	32	45	38	26	17
basaltic								4	2				1		2		1	2
glaucophane	2	8	23	22	16	32	28	2				2			5	36	23	6
tremolite	10	13	8	7	7	8	5	17	24	26	28		24	14	9	8	19	6
amph, b-g	57	70	19	14	19	12	15	31	111	103	109	69	16	71	53	22	6	6
actinolite																		
orthopyroxene																		
hypersthene	8	10	13	4	3	2	4			1		2	7	4	2	1	1	5
enstatite	5	2	3		7	6	5		1			2		3				
clinopyroxene																		
augite	18	40	12	15	29	24	24	24	30	13	18	18	52	26	19	23	26	50
colorless	18		7	13	21	23	9					9						
epidote grp	22	30	17	14	25	27	43	34	31	19	29	35	22	16	38	38	8	79
lawsonite									1									
sphene	3	3		6	17	18	9	5		1		4		3	7	8	6	16
zircon			4	4	1		2	15	2	1					3	3	2	10
garnet	4	3	2	2	13	7	10	26		4	2				1	2	4	41
apatite	1	1		7	1	3	3	9				1			1			6
cr spinel		2						2							1	1		
tourmaline								2							2			
other		6			1	8		3	4	2	3				8		4	
mica																		
opaques	82	50	122	112	78	90	48	127	30	21	37	27	41	25	170	59	144	115
rock frags	113	117	91	95	128	124	103	109	43	34	23	59	57	70	196	114	106	87
unknown	3	8	2	6	8		8	18	14	7	9		12	6	9	7	7	16
total	391	426	355	351	393	414	333	462	433	311	374	339	314	295	584	385	392	473
Percent of nonc																		
Tot Nopq	193	251	140	138	179	200	174	208	346	249	305	253	204	194	209	205	135	255
hornblende																		
brown	11	7	8	5	1	4	3	5	8	8	7	9	9	13	6	12	7	4
green	12	18	15	17	9	12	7	11	33	24	31	34	31	16	22	19	19	7
basaltic								2	1				0		1		1	1
glaucophane	1	3	16	16	9	16	16	1				1			2	18	17	2
tremolite	5	5	6	5	4	4	3	8	7	10	9		12	7	4	4	14	2
amph, b-g	30	28	14	10	11	6	9	15	32	41	36	27	8	37	25	11	4	2
actinolite																		
orthopyroxene																		
hypersthene	4	4	9	3	2	1	2			0		1	3	2	1	0	1	2
enstatite	3	1	2		4	3	3		0			1		2				
clinopyroxene																		
augite	9	16	9	11	16	12	14	12	9	5	6	7	25	13	9	11	19	20
colorless	9		5	9	12	12	5					4						
epidote grp	11	12	12	10	14	14	25	16	9	8	10	14	11	8	18	19	6	31
lawsonite									0									
sphene	2	1		4	9	9	5	2		0		2		2	3	4	4	6
zircon			3	3	1		1	7	1	0					1	1	1	4
garnet	2	1	1	1	7	4	6	13		2	1				0	1	3	16
apatite	1	0		5	1	2	2	4				0			0			2
cr spinel		1						1							0	0		
tourmaline								1							1			
other		2			1	4		1	1	1	1				4		3	

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