DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Heavy Minerals in Turbidite Sands from the Southern Lobe of the Monterey Deep-sea Fan

by

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Open-File Report 89-91

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1989

INTRODUCTION

The Monterey deep-sea fan extends from the base of the continental slope (3,000 m water depth) to 300 km off the coast of California (4,700 m water depth). Sediment is delivered to the fan by turbidity currents from Ascension and Monterey canyon systems and to a lesser degree from the Lucia-Partington-Sur canyon system (Figure 1; Dill and others, 1954; Menard, 1960; Shepard and Dill, 1966; Normark and others, 1984). The southern lobe of the middle fan is actively growing and being fed by the modern Monterey fan valley (Normark and others, 1984). This southern depositional lobe (~4,400 m water depth) approximately 360 km southwest of the head of Monterey Canyon exhibits low to high acoustic backscatter characteristics in GLORIA images of the area (EEZ-SCAN 84 Scientific Staff, 1986). High-resolution seismic data do not explain these differences so samples were taken to determine if various mechanical or sedimentological properties of the sediment varied backscatter (Figures 1, 2; Gardner and others, 1988a, b; Lee and others, 1988).

Box cores were taken from a 12 km x 15 km area having both low and high GLORIA backscatter intensities (Figure 2). Box cores exhibit a common stratigraphy: an upper oxidized clay layer, an underlying reduced clay layer, and turbidite sand. Subsamples for heavy mineral analysis were taken from sandy layers near the top of 10 box cores to determine mineral provenance and whether or not the mineralogy contributed to the variation in backscatter (Table 1). Additional subsamples were also taken from a near-bottom sand layer for four box cores to determine the within-core diversity.

PREVIOUS WORK

Monterey Bay is fed primarily by the Salinas and Pajaro Rivers, which provide about 80% of the drainage and probably an equal amount of sediment to the bay; a lesser source of sediment is the southward longshore drift from the northern Santa Cruz Mountains (Figure 3; Yancey and Lee, 1972). The sediment discharge of the Salinas River is ~140,000 metric tons/yr and that of the Pajaro River is ~20,000 metric tons/yr (Griggs and Hein, 1980). Heavy minerals in sediments from the Salinas River consist of a hornblende-garnet assemblage derived from the Sur Series metamorphic rocks in the Santa Lucia and Gabilan Ranges (Galehouse, 1967; Yancey and Lee, 1972). The Pajaro River carries sediment with a glaucophane-jadeite heavy mineral assemblage derived from Franciscan rocks of the Diablo block that flanks the Pajaro and San Benito river valleys (Yancey and Lee, 1972). Southward longshore drift carries augite-rich sediment into Monterey Bay from Pliocene volcanic sediments of the Purisima Formation in the northern Santa Cruz Mountains (Yancey and Lee, 1972).

In Monterey Bay, Yancey (1968) described five heavy mineral provinces, which readily reflect the input from the Salinas and Pajaro Rivers as well as the longshore transport mentioned above, but these provinces remained distinct only close to shore (Figure 4). As he sampled toward the edge of the continental shelf and down into the upper parts of the canyons, the mineralogy became more homogeneous. His province 2 is probably most representative of the outer shelf sediments. This province included—in order of decreasing abundance—green hornblende, augite, hypersthene, brown hornblende, epidote, and sphene; other minerals amounted to less than 4% each (Table 2).

Wilde (1965) sampled the Monterey Fan sediments for heavy minerals from lat 35°N to 37°N and from about 3,400 to 4,300 m. He generated an average heavy mineral suite (his Figure 18) consisting of green hornblende, augite, basaltic hornblende, hypersthene, epidote, and actinolite/tremolite (Table 2). For comparison with this study, it is unfortunate that the standard deviations were not provided nor was his averaging method clear so these statistics could be calculated to give an idea of the variability of his samples. Yancey (1968) reexamined some of Wilde's samples while studying Monterey Bay and concluded that the fan samples could well be derived from bay sediments. Wilde (1965) determined that the source of the >62-µm sediment was primarily from the quartz diorite plutons of the Salinian block with minor contributions from central belt Franciscan rocks—all via Monterey Bay and the submarine channels that head there. He discounted any contributions from the Great Valley drainage to the sand-size fraction because the shallowing at the Golden Gate barred passage of all sands to the continental shelf.

METHOD

Splits of sample prepared for grain-size analysis (63 µm - 2 mm) and additional samples were sieved to retain the 63-250 µm size fraction for heavy mineral analysis. Tetrabromoethane, with a specific gravity of 2.93-2.96, was used for heavy mineral separation. Samples were weighed before and after separation to determine weight percent. Grains were mounted in piccolyte (r.i. = 1.52) and examined under a petrographic microscope. Grain counts of 350-600 were used to ensure that at least 250 nonopaque, nonmicaceous monomineralic grains were identified (Table 3A).

DATA

The mean grain size of the samples used in this analysis ranged between 37 and 202 µm (Table 3A, Figure 5a). Except for Bx7a, the study interval (63-250 µm) accounts for more than 50 weight percent of each sample (Table 3A). The mean grain size is usually defined by the light minerals in a sediment and the hydraulically equivalent heavy minerals can have a mean grain size as great as 1ϕ (31-125 µm) smaller (Hubert, 1971). To test whether the study interval captured most of the heavy minerals, 100 grains from several samples were measured (Table 4, Figure 5b). Except for Bx7a, the modal grain size of the heavy minerals fall comfortably within the study interval. Therefore, the heavy mineral distributions derived from the study interval will be representative of the bulk sample.

Percentages in Tables 3B and 3C are calculated for the number of grains counted in the heavy mineral separates and may be considered volume percent since the size was constrained by sieving. Nonopaque, nonmicaceous monomineralic grains accounted for 62-80% of each sample. In order of abundance, these minerals are common green and brown hornblende, tremolite-actinolite (including blue-green amphibole), clinopyroxene, hypersthene, and epidote group minerals (Table 3C). Minor constituents include sphene and garnet. Trace minerals include enstatite, glaucophane, lawsonite, apatite, and zircon.

Some of the categories in Table 3C were combined to ease comparison of data with those of other workers (see Appendix). The metamorphic amphiboles include tremolite, actinolite and blue-green amphiboles. Actinolite is a pale green amphibole with low extinction angles. The blue-green amphiboles are deep blue-green at maximum absorption and paler green or blue at least absorption. Other green varieties are assigned to the ordinary green or brown hornblende category. Basaltic hornblendes are those brown hornblendes that are red or reddish black at maximum absorption.

The cumulative plot of heavy mineral abundance shows a limited variation among the box cores sampled (Figure 6a). In the four doubly sampled cores (7, 11, 21, 25), the only significant difference in sand top and sand bottom samples was in grain size and in the amount of amphiboles and clinopyroxenes (Figures 5b, 6b). Within the same box core, stratigraphically higher samples were finer grained than lower samples. Mineralogically, there was more hornblende in the upper sample and more hypersthene and clinopyroxene in the lower sample.

A factor analysis demonstrated a tight cluster of samples with one factor accounting for 96.4% of the data and the second 2.7%. Factor one is attributable to the abundance of common hornblende and metamorphic amphiboles. Factor two focuses on clinopyroxene and hypersthene. The factor analysis details are omitted because this kind of analysis is redundant for these samples where a simple average and standard deviation calculation demonstrates equally well that the samples do not differ greatly from each other (Table 3C). The differences that do occur are no greater from sample to sample than from bottom to top of a single box core (Figure 6).

DISCUSSION

The heavy minerals indicate that the sediments in this lobe area of the Monterey deep-sea fan are homogeneous. The slight variation in heavy mineral population does not correlate with and likely does not account for the differences in GLORIA backscatter (Figure 2) or in the age of the sediments (Table 1). The source of these sediments is either homogeneous or sediments from multiple sources have been homogenized by the time they have arrived at the distal end of the fan.

As the most obvious source of sediment for the turbidites, the Monterey Bay area exhibits some heterogeneity in the heavy mineral species but this heterogeneity disappears towards the shelf edge (Yancey, 1968; Yancey and Lee, 1972). Samples from the axis of Monterey canyon and from the upper fan consist of minerals similar to those on the outer Monterey shelf (Table 2; Wilde, 1965; Yancey, 1968). With the well-defined channeling and sediment transport directions imaged by GLORIA (EEZ-SCAN 84 Scientific Staff, 1986), sands in the outer depositional lobe of the Monterey deep-sea fan would be expected to have a similar mineralogy.

At first glance, a cumulative plot comparing data from this study with those from Wilde (1965) and Yancey (1968) and a summary by Rappeport

(1976) does not seem to support the conclusion above that the mineralogy of the lobe and outer shelf would be similar (Figure 7a). A small part of the difference can be attributed to the usual interoperator variation. A large part can probably be accounted for by the groupings made by each worker. Yancey (1968) and Rappeport (1976) apparently grouped all green hornblendes, whether metamorphic or not. When green hornblendes are combined, the remaining mineral populations are not grossly out of line (Figure 7b, "Yancey", "Rappeport", and "Wong").

A larger difference occurs between this study and Wilde's (1965) in the proportions of amphiboles of all varieties (Table 2; Figure 7a, "Wilde"). The description of his basaltic hornblende as "resinous brown" (his p. 69) would incline me to recategorize them as ordinary hornblende, appreciably reducing the anomalous values in Table 2. Moving all but 3% of the basaltic hornblende to green/brown hornblende boosts the latter value to 41%; combined with the 5% metamorphic amphibole this comes to 46%, which is still slightly short of the other total amphibole values in Table 2 and Figure 7b. Wilde's large topaz population is not matched by the other studies. Except for these differences, the rest of the mineral populations are similar. The mismatch between Wilde's "massaged" data and the other three data sets (Figure 7b) is actually no greater than intersample differences in this study (Figure 6a). Hence, the Monterey lobe samples are a relatively good match for sediments from Monterey Bay and fan.

ACKNOWLEDGMENTS

Brian Edwards reviewed this manuscript and made suggestions toward its improvement. Lisa Bader performed the grain size analyses.

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Table 1. General data on box cores examined for heavy minerals from southern lobe of Monterey deep-sea fan.

Sample # [1]	Bx1	Bx3	Bx6	Bx7	Bx9	Bx10	Bx11	Bx21	Bx24	Bx25
Lat (N)	34°14.72′	34°12.13′	34°11.17′	34°10.86′	34°10.02′	34°10.71′	34°12.01′	34°11.34′	34°12.05′	34° 8.92′
Long (W)	124°13.76′	124° 9.08′	124° 9.87′	124° 8.29′	124° 6.20′	124° 5.66′	124° 7.40′	124° 7.83′	124° 4.55′	124° 5.75′
Seafloor depth (m)	4450	4445	4445	4440	4435	4445	4438	4446		4383
Backscatter [2]	high	low	low	high	low	low	low	high	low	high
Age (yr) [3]	10340 +/- 170		10790 +/- 160	15270 +/- 200		6510 +/- 125	17670 +/- 205			

[1] Samples Bx1-11 from M/V Farnella cruise F5-87-SC; Bx21-25 from F1-88-SC.

[2] GLORIA image backscatter intensity.

[3] Radiocarbon years before 1950 A.D. Dates by Beta Analytic Inc., Coral Gables, Florida.

Table 2. Heavy mineral populations from previous workers and this study.

	Wilde Monterey Fan (1)	Yancey Province 2 (2)	Rappeport Factor 5 (3)	Lobe [average] (4)
Hb: grn,brn	32	59	54	29
Hb: basaltic	12	2	3	4
meta-amphibole	5			27
glaucophane		<		1
hypersthene	9	6	6	9
clinopyroxene	16	17	19	16
epidote	9	5	5	6
sphene	3	4	2	3
zircon	3	1		<
garnet	4	4	4	4
apatite		3	5	<
rutile	1			
topaz	6			
others		<	1	1
Total	100	100	99	100

< = < 0.5%

Hb: grn,brn = common green or brown hornblende.

meta-amphibole = metamorphic amphibole: tremolite/actinolite, blue-green amphibole.

(1) Representative Monterey Fan sample. Values measured from Wilde's (1965) Figure 18 and normalized to 100%. Only green hornblende included in 'Hb: grn,brn'.

(2) Mixed heavy mineral province from Monterey Bay (Yancey, 1968). Metamorphic amphiboles included in 'Hb: grn,brn'. Others = staurolite.

(3) Heavy mineral province at edge of continental shelf off Monterey Bay derived by factor analysis (Rappeport, 1976). Metamorphic amphiboles included in 'Hb: grn,brn'. Others = his 'Franciscan'.

(4) Average heavy mineral population on southern lobe of Monterey deep-sea fan (this study). Others = enstatite, lawsonite, tourmaline.

Table 3. Heavy mineral data for samples from F5-87-SC and F1-88-SC.

A.

*		Bx1	Bx3	Bx6	Bx7a	Bx7b	Bx9	Bx10	Bx11a	Bx11b	Bx21a	Bx21b	Bx24	Bx25a	Bx25b
	core dpth cm	40	20	18	17	42	30	20	10	40	25	51	24	10	40
1	wt% 63-250µm	56.2	77.4	59.6	10.1		81.1	60	79.5	76.9		72.9	78.7	63.6	75.9
1	mean sz µm	171	196	89	37		101	75	92	202		198	92	76	191
2	wt% hvy min	5.9	4.6	2.9	0.9	1.9	2.8	2.3	3.2	6.3	4	6.1	4.1	1.4	4.8
3	Total counts	395	422	371	636	404	430	361	416	433	415	406	419	400	439
4	Nopq counts	276	299	287	319	257	292	256	333	303	302	250	305	312	297

B.

	Percent of Total Counts	Bx1	Bx3	Bx6	Bx7a	Bx7b	Bx9	Bx10	Bx11a	Bx11b	Bx21a	Bx21b	Bx24	Bx25a	Bx25b
4	nopq	70	71	77	50	64	68	71	80	70	73	62	73	78	68
	mica	2	3	5	33	1	8	5	1	2	2	<	3	8	2
	opaques	10	12	6	9	16	10	11	8	11	12	15	9	7	13
	rock fragms	5	8	6	3	6	4	5	6	6	5	8	7	1	6
	unknown	3	2	1	1	3	2	2	3	3	3	3	2	4	2

C.

4	Percent of Nopq Counts	Bx1	Bx3	Bx6	Bx7a	Bx7b	Bx9	Bx10	Bx11a	Bx11b	Bx21a	Bx21b	Bx24	Bx25a	Bx25b	AVE	STD
5	Hb: grn,brn	24	33	24	38	22	36	34	35	25	26	18	34	38	25	29	6
5	Hb: basaltic	3	2	5	4	4	4	4	4	3	4	3	6	4	2	4	1
5	Meta-amph	30	27	26	28	30	23	23	28	28	29	33	21	26	32	27	3
	Glaucophane	1	1	<	<	<	1	<	<		1	2	<	<	1	1	<
	Hypersthene	12	11	9	2	16	4	6	5	11	9	12	8	6	10	9	3
	Clinopyx	16	16	15	12	17	17	18	13	19	20	22	14	14	18	16	3
	Epidote	9	4	9	7	4	5	4	5	5	5	4	9	7	5	6	2
	Sphene	3	2	4	3	2	2	3	3	2	2	3	4	1	3	3	1
	Garnet	2	3	5	4	6	5	7	7	7	3	2	3	4	4	4	2
6	Other	1	2	2	1	1	2	1	<	1		2	1	1	<	1	1

* Notes:
< = < 0.5%

1 Mean grain size in µm. Analyses by L.R. Bader, U.S. Geological Survey. Samples Bx7b and Bx21a were not analyzed for grain size.
2 Weight percent heavy minerals in 63-250 µm fraction only.
3 See Appendix for count data.
4 Nopq = Nonopaque nonmicaceous monomineralic grains. AVE = average, STD = standard deviation.
5 Hb = hornblende. Metamorphic amphiboles include actinolite/tremolite and blue-green amphibole.
6 Other = apatite, enstatite, lawsonite, tourmaline, zircon.

Table 4. Grain size distribution of heavy minerals based on measurement of 100 grains.

Size (µm)	Bx3	Bx7a	Bx9	Bx10	Bx11b	Bx21b
63-75	8	52	12	20	7	2
76-112	26	47	49	45	31	24
113-150	36	1	30	24	33	37
151-187	15		7	8	18	14
188-225	6		2	3	5	14
226-250	9				5	9

Appendix. Heavy mineral count data for southern lobe of Monterey deep-sea fan.

Sample #	Bx1	Bx3	Bx6	Bx7a	Bx7b	Bx9	Bx10	Bx11a	Bx11b	Bx21a	Bx21b	Bx24	Bx25a	Bx25b
core depth (cm)	40	20	18	17	42	30	20	10	40	25	51	24	10	40
hornblende														
green	25	36	30	56	31	48	37	47	47	39	25	38	51	25
brown	40	62	40	66	26	56	51	69	30	41	21	67	66	48
basaltic	8	5	14	14	9	12	9	14	8	13	7	19	12	7
amph, blue-grn	68	65	71	71	69	47	45	79	73	79	71	57	68	80
actinolite					3		1	2	5		3		2	1
tremolite	15	17	5	18	4	19	13	12	6	9	8	6	12	14
glaucophane	3	4	1	1	1	3	1	1		2	4	1	1	2
hypersthene	32	32	26	7	40	13	16	16	33	28	29	23	18	30
enstatite		4	4		1	2	1					1		
clinopyroxene														
augite	33	34	35	29	35	34	34	30	45	47	42	30	26	47
colorless	12	13	7	8	8	17	11	13	12	14	13	13	18	5
epidote	12	4	15	12	9	6	9	16	14	14	11	13	21	16
clinozoisite	12	8	11	11		8						14		
lawsonite		1		1		1						1		
sphene	8	5	12	11	5	6	7	11	6	6	7	12	2	10
zircon	2					2	1				3			
garnet	5	8	13	13	15	16	19	22	22	10	4	8	12	11
apatite	1	1	3		1	2	1	1	2		2	2	3	1
tourmaline				1										
mica	9	12	20	213	5	35	17	4	7	7	2	13	30	10
opaques	38	48	23	58	63	45	40	34	44	49	59	38	29	57
Cr spinel	2	1		1			1		2			1		
rock fragments	18	34	21	21	25	19	19	24	26	19	32	28	4	27
unknown	12	8	2	7	12	9	8	11	11	13	12	10	15	8
Total counts	395	422	371	636	404	430	361	416	433	415	406	419	400	439

Nonopaque, nonmicaceous monomineralic grains (nopq) regrouped from above.

Hb: grn,brn *	65	98	70	122	57	104	88	116	77	80	46	105	117	73
Hb: basaltic	8	5	14	14	9	12	9	14	8	13	7	19	12	7
Meta-amphibole	83	82	76	89	76	66	59	93	84	88	82	63	82	95
Glaucophane	3	4	1	1	1	3	1	1		2	4	1	1	2
Hypersthene	32	32	26	7	40	13	16	16	33	28	29	23	18	30
Clinopyroxene	45	47	42	37	43	51	45	43	57	61	55	43	44	52
Epidote	24	12	26	23	9	14	9	16	14	14	11	27	21	16
Sphene	8	5	12	11	5	6	7	11	6	6	7	12	2	10
Garnet	5	8	13	13	15	16	19	22	22	10	4	8	12	11
Other	3	6	7	2	2	7	3	1	2		5	4	3	1
Nopq counts	276	299	287	319	257	292	256	333	303	302	250	305	312	297

* Hb: grn,brn = green, brown ordinary hornblende; Hb: basaltic = basaltic hornblende; Meta-amphibole = actinolite/tremolite, blue-green amphibole; Clinopyroxene = augite, colorless clinopyroxene; Epidote = epidote, clinozoisite; Other = enstatite, lawsonite, zircon, apatite, tourmaline.

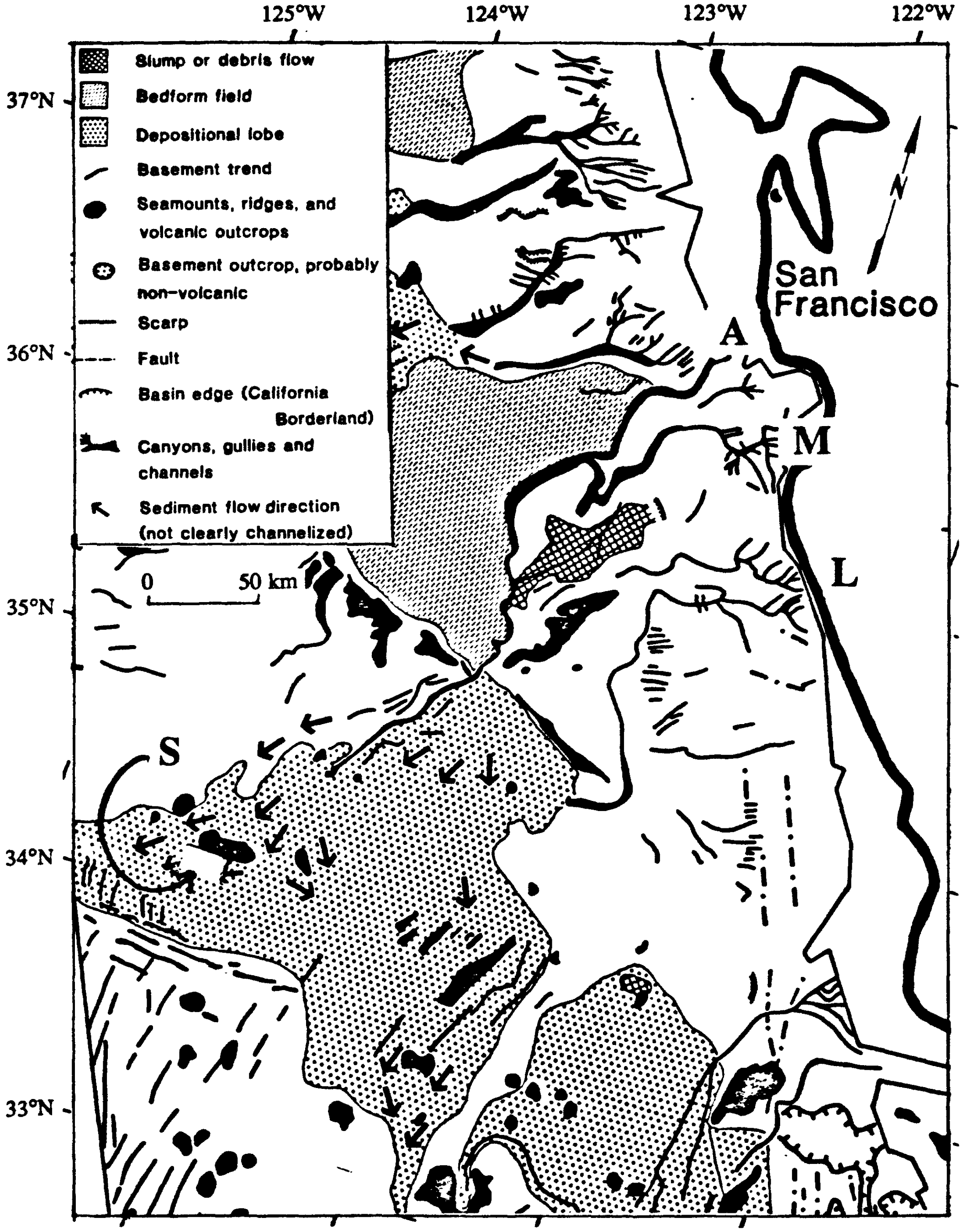

Figure 1. Major tectonic and sedimentological features of the Exclusive Economic Zone off central California (from EEZ-SCAN 84 Scientific Staff, 1988). A = Ascension Canyon, M = Monterey Canyon, L = Lucia-Partington-Sur canyon system, S = sample area in Figure 2.

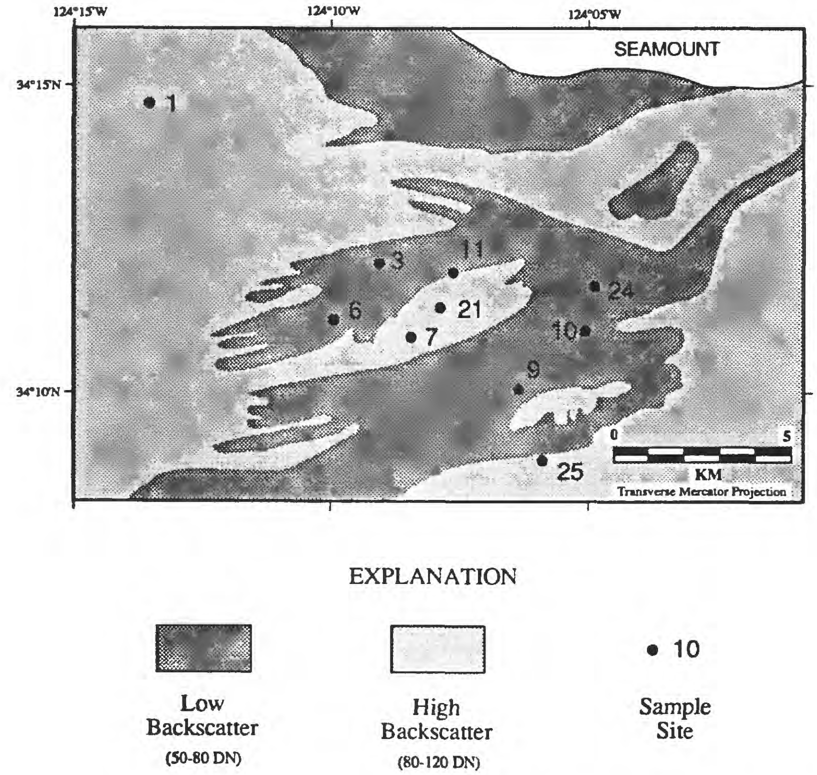

Figure 2. Sites of box cores from M/V *Farnella* cruises F5-87-SC and F1-88-SC sampled for this study. DN = digital number, which can range from 0 to 255 and represents the amount of acoustic backscatter recorded by the GLORIA sonographic system (EEZ-SCAN 84 Scientific Staff, 1986).

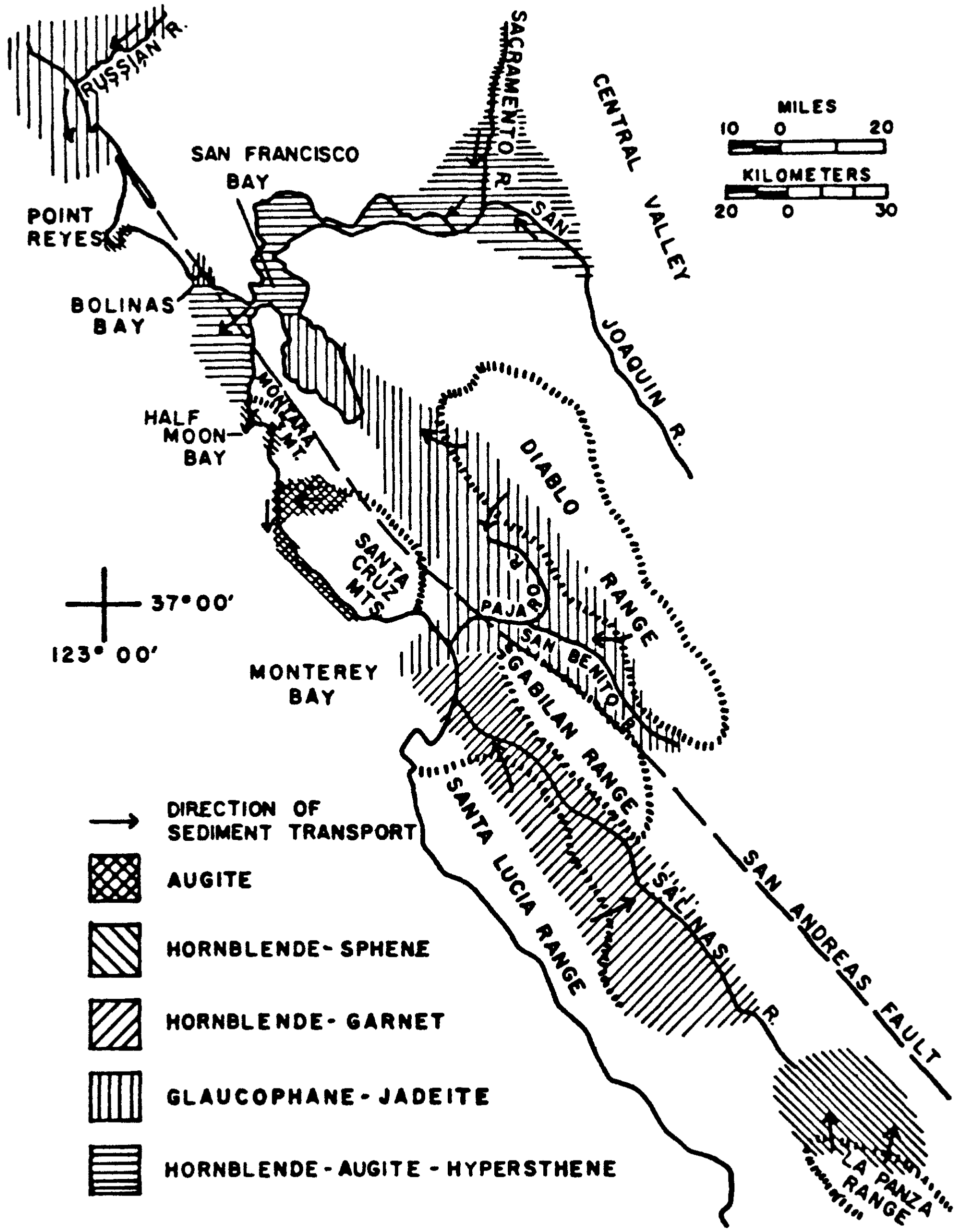

Figure 3. Recent heavy mineral provinces of central California (from Yancey and Lee, 1972).

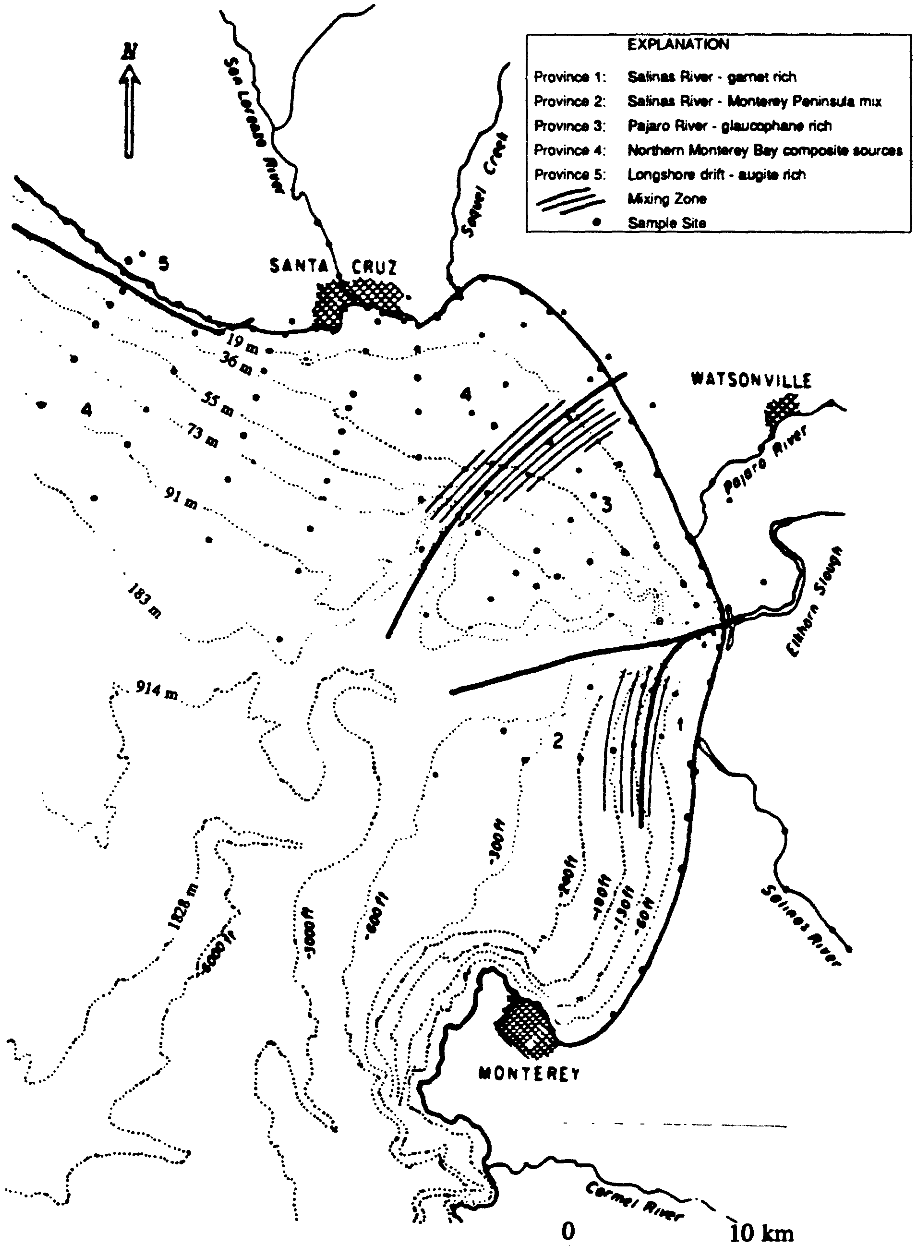

Figure 4. Heavy mineral provinces in Monterey Bay (from Yancey, 1968).

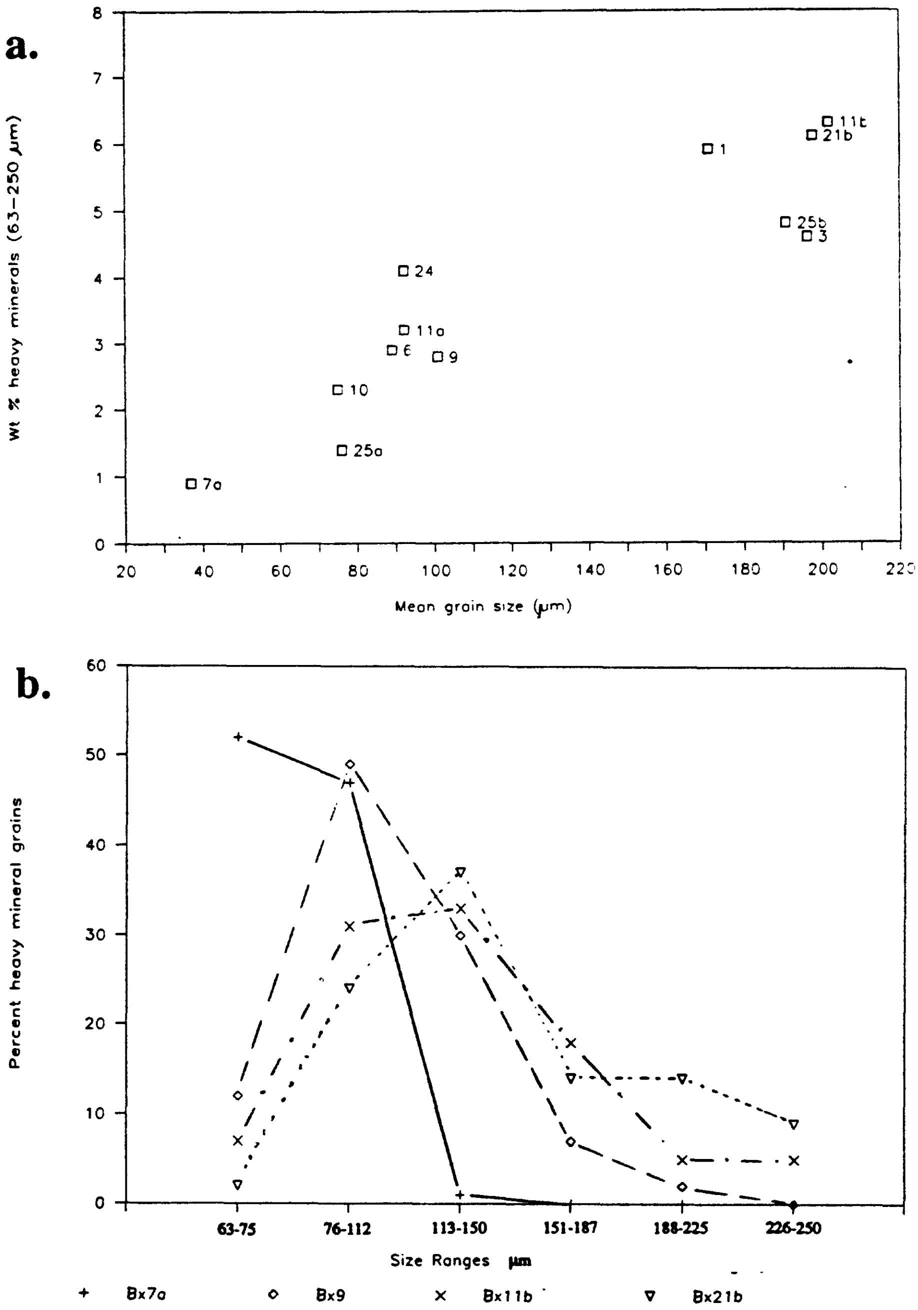

Figure 5a. Comparison of weight percent heavy minerals in the 63-250 µm size fraction and mean grain size of each sample. **b.** Grain size distribution of heavy minerals. Data from Table 4.

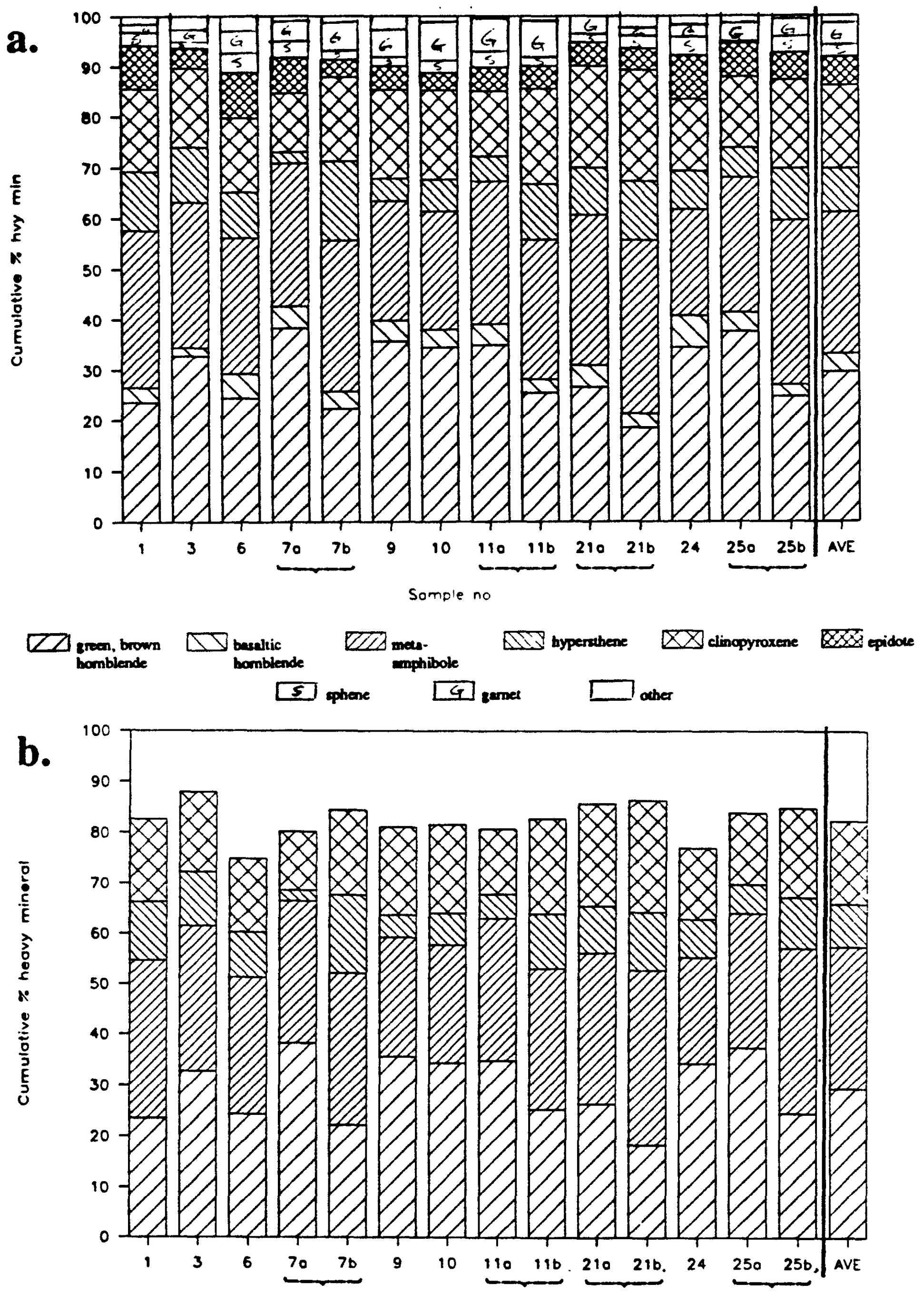

Figure 6a. Cumulative heavy mineral distribution in box core samples from F5-87-SC and F1-88-SC on the Monterey fan lobe. Top (e.g., 7a) and bottom (e.g., 7b) samples from the same core are braced. **b.** Cumulative graph of minerals extracted from 6a.

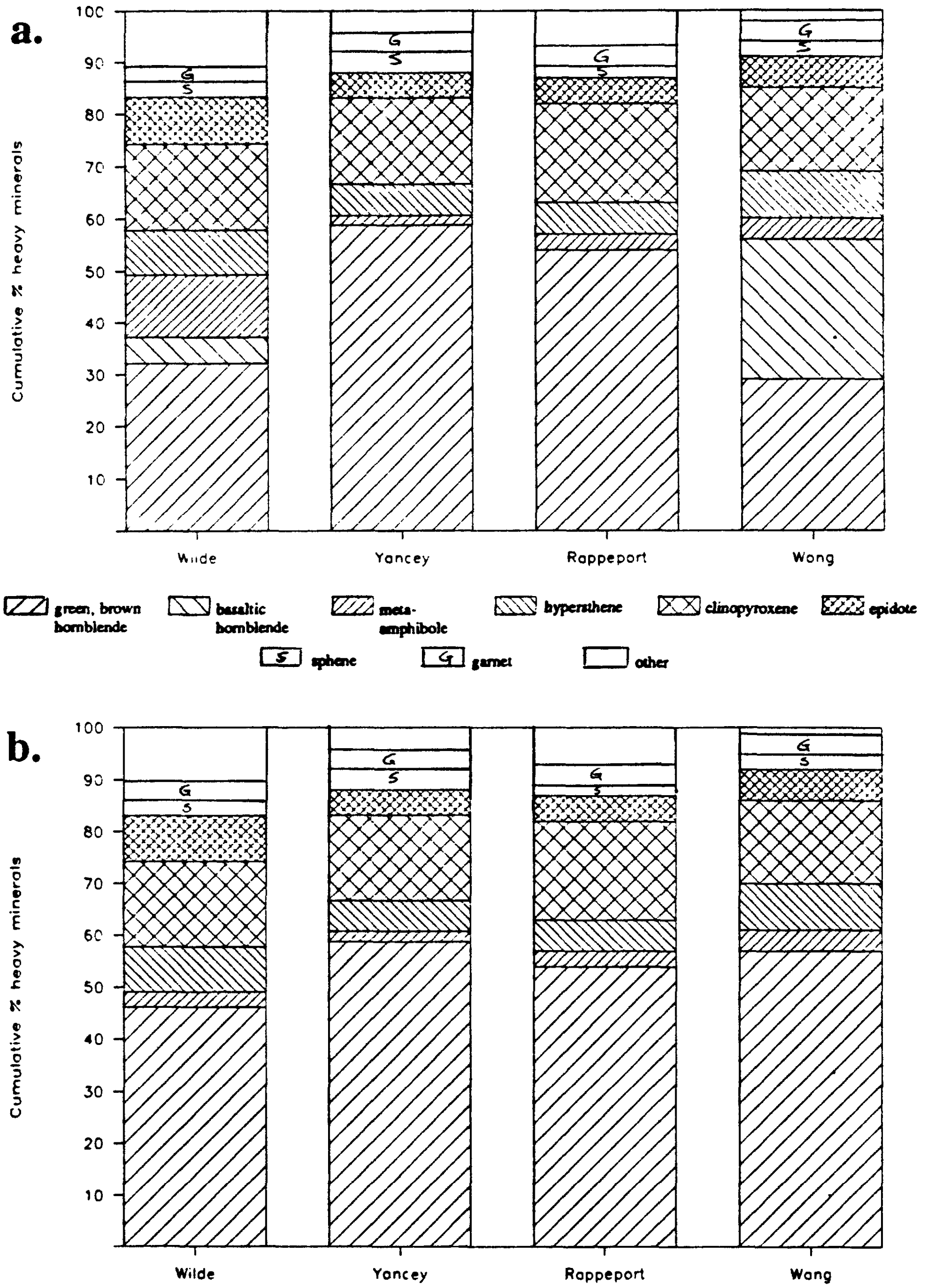

Figure 7a. Comparison of this and previous heavy mineral studies in the Monterey Bay region (after Wilde, 1965; Yancey, 1968; Rappeport, 1976). **b.** As in 7a with hornblende and metamorphic amphibole combined.