STATE OF OREGON
DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES

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ELEMENTAL CONTENT OF HEAVY-MINERAL CONCENTRATIONS ON THE CONTINENTAL SHELF OFF OREGON AND NORTHERNMOST CALIFORNIA

By

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NOTICE

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ABSTRACT

A total of 73 surface and near-surface sediment samples from the continental shelf off Oregon and northernmost California was analyzed for their elemental content using instrumental neutron activation analysis (INAA). The elements chromium and titanium were the most abundant economic metals of the 26 elements analyzed in the opaque mineral phase of the heavy-mineral assemblage of the sand fraction. Chromium, which is found mainly south of Coos Bay, Oregon, and into northern California, ranges in concentration from a trace up to 7% by weight across the middle and inner shelf. Titanium is present in large quantities (2 to 23%) on the inner shelf from Tillamook to Cape Blanco. Both elements are present in abundance in the vicinity of Cape Blanco.

INTRODUCTION

Previous geological studies of the Oregon coastal region have identified several areas where strategic and economic heavy minerals (chromium-bearing chromite, titanium-bearing ilmenite, and zircon) and metal (gold) placer deposits occur in substantial quantities in modern beach and ancient uplifted marine terrace deposits (Pardee, 1934; Griggs, 1945; Komar and Wang, 1984; Peterson and others, 1986, 1987). The modern rivers and beaches have been mined for placer deposits containing gold since 1850. During mineral shortages of World War II, the coastal terrace deposits of southwest Oregon were explored for chromite and ilmenite. These black sands were mined in 1943 to produce a chromite concentrate that was then stockpiled for potential use during the war (Griggs, 1945).

Previous geological and geophysical studies of the continental shelf off southern Oregon strongly suggest that placer deposits occur on the shelf and that they may contain the same minerals and metals found in the adjacent coastal region (Kulm and others, 1968; Clifton, 1968; Chambers, 1969; Bowman, 1972a,b). Anomalous concentrations of heavy minerals found in the surface sediments of the southern Oregon shelf as well as the magnetic anomalies associated with these concentrations suggest that ancient beach placers may be present in the subsurface deposits (see Background).

While chromite is presently the chief strategic mineral in these Oregon deposits, it is associated with the other potentially strategic and economic minerals (ilmenite and zircon) and precious metal (gold). The continental shelf deposits could become a valuable national resource if these minerals and metals are present in sufficient concentrations and quantities to be mined.

The objective of this study was to determine if economic mineral phases occur within the surface sediments of the continental shelves off Oregon and northernmost California. This was accomplished by the analysis of the elemental content of widely distributed samples from the shelf.

BACKGROUND

According to Kulm and others (1975), the unconsolidated sediments on the Oregon continental shelf are classified into three sedimentary facies: (1) a transgressive sand, composed of well-sorted fine sand; (2) a modern mud, consisting of silt and clay; and (3) a mixture of sand and mud, created by the burrowing of benthic organisms, which mix the mud into the underlying sand (Figure 1). The sand facies extends to a water depth of 90 to 100 meters off northern and central Oregon but retreats to a depth of 50 meters off southern Oregon, where the shelf is much narrower. The mud facies is thin and patchy and concentrated in areas near rivers that have a fairly high discharge. The mixed facies extends seaward from the sand facies to the edge of the shelf except where it is overlain by mud.

Several well-defined heavy-mineral concentrations occur in these surface sediments on the northern and southern Oregon shelf (Kulm and others, 1968). Heavy-mineral percentages range from 10 to 33% by weight of the total sand fraction of the surface sediment (Figure 2) and from 10 to 56% in the subsurface sediment. These heavy-mineral percentages were obtained previously by separations with tetrabromoethane (specific gravity 2.96), whereas the values listed in Appendix I represent heavy mineral percentages obtained with sodium polytungstate (specific gravity 3.0, see Methods section); the former percentages are generally higher than the latter. The most extensive concentrations are located off the Columbia River, Umpqua River, Cape Blanco , and Rogue River. These concentrations extend to a subsurface depth of 40 to 60 centimeters in short box and piston cores taken in the area. Rather large magnetic anomalies (up to 300 gammas) are associated with these

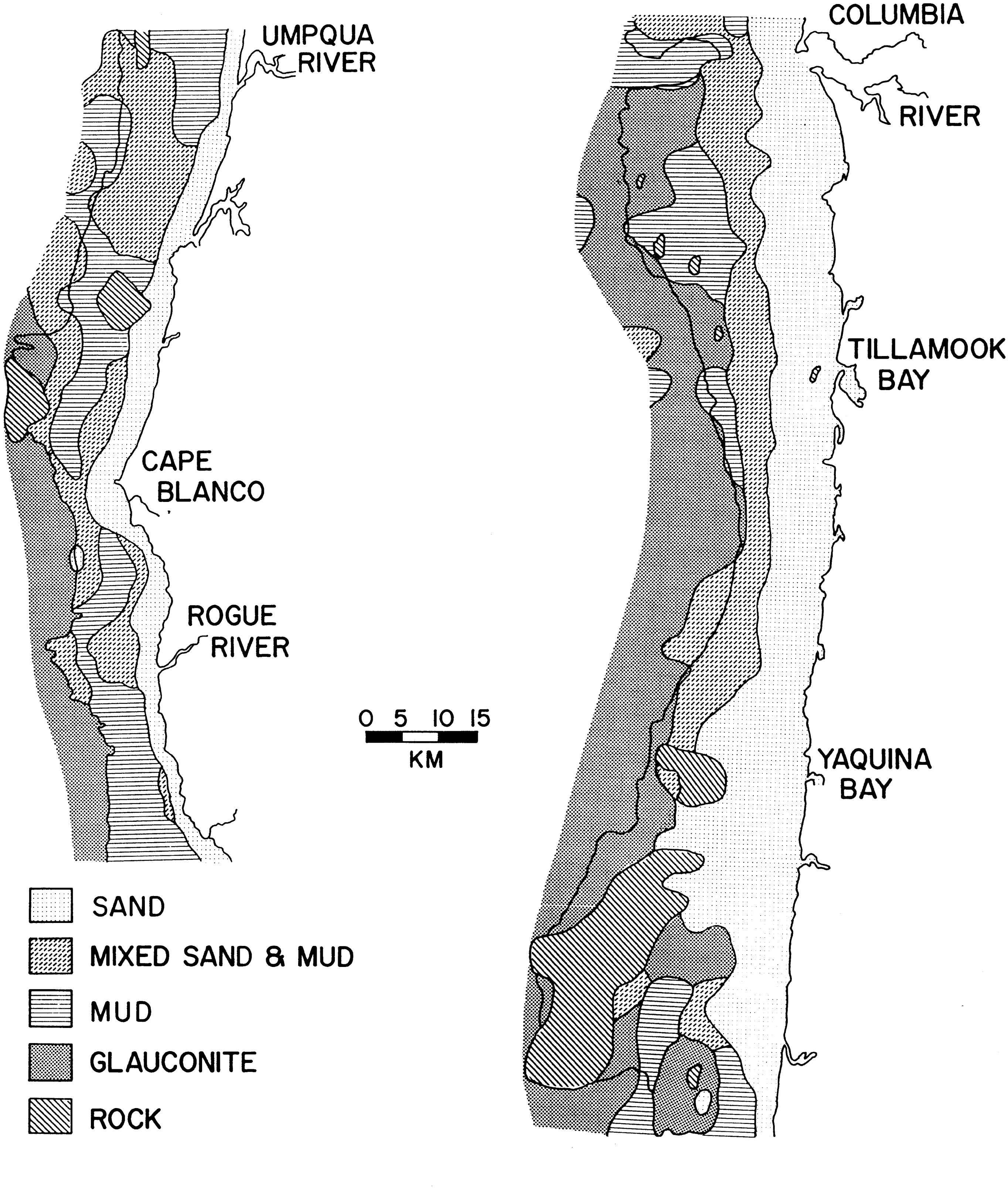

Figure 1. Sedimentary facies of the Oregon continental shelf (After Kulm and others,1975). Solid line crossing patterns near the edge of shelf is the 180-meter contour.

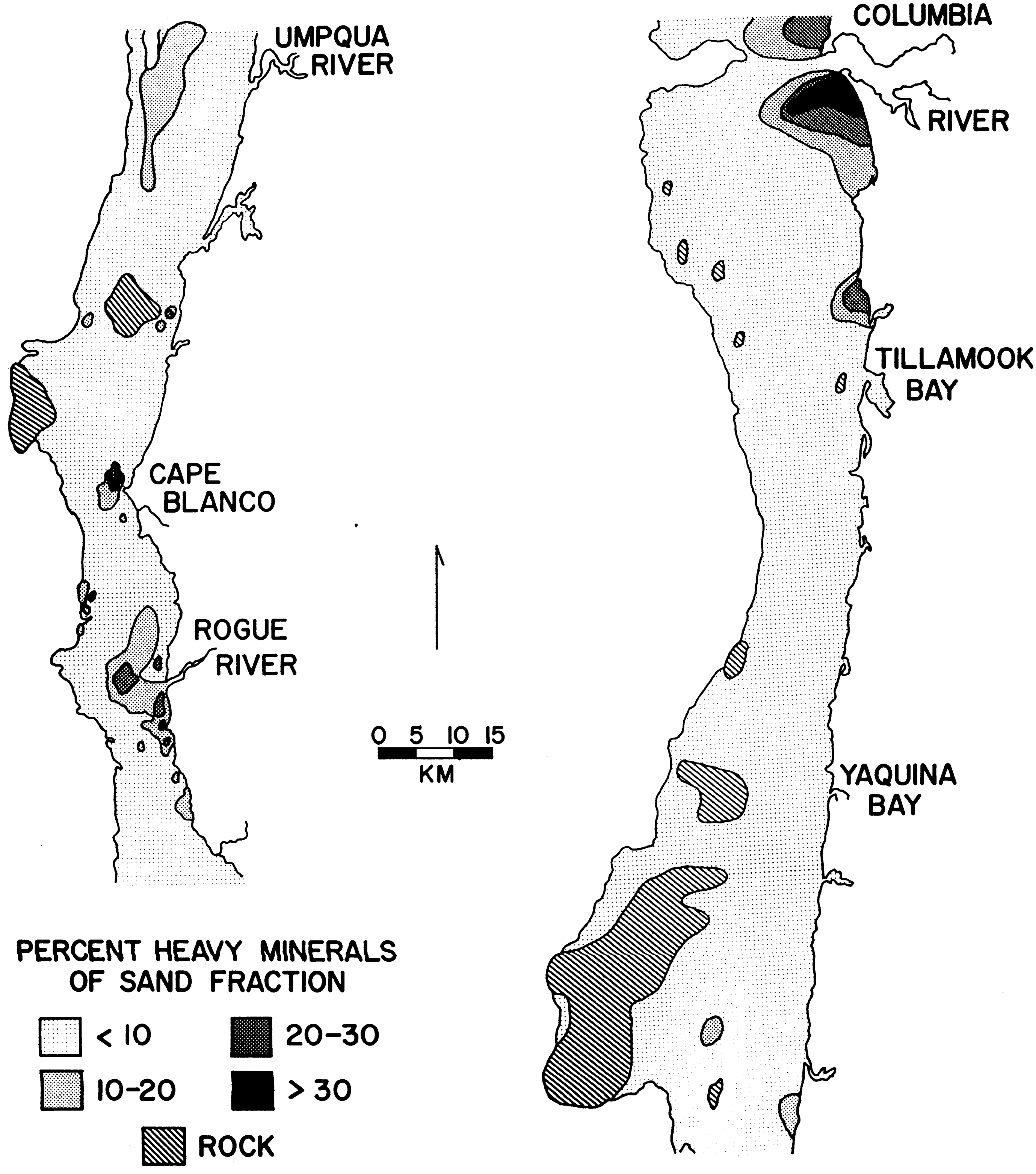

Figure 2. Heavy mineral concentrations (i.e., nonopaque and opaque minerals with specific gravities >2.96) of Oregon continental shelf sands. Data compiled from Runge (1966), Chambers (1969), and unpublished data (L. Kulm). Outer edge of the shelf is the 180-meter contour. See Appendix I for the heavy-mineral percentages of the sediment samples analyzed in this study.

heavy-mineral concentrations, and magnetic depth-to-source modeling suggests that placers, concentrated in iron-rich phases, lie at depth (Kulm and others, 1968).

METHODS

A total of 73 surface and near-surface samples was selected from more than 1,000 samples available for the continental shelf off Oregon (Figures 3A,B) These samples included grab samples, short box cores (<45 cm), and short piston or gravity cores (<60 cm). The sediment samples were selected on the basis of their geographic distribution relative to known coastal deposits containing economic minerals, their probable fluvial sources of economic minerals, and their high heavy-mineral content. In a number of cores, one sample was taken from the surface sediment and one from the bottom sediment in the core. Additional short gravity cores were obtained for the northernmost California shelf from the U.S. Geological Survey, Marine Geology Branch, Menlo Park California. Few samples have been collected offshore of northernmost California, and we have used those that were available. All samples used in this study range in water depths from 17 to about 200 meters.

Surface sediments from the continental shelf off Oregon and northwest California were processed for opaque-mineral concentrates, which were then analyzed by Instrumental Neutron Activation Analyses (INAA) in order to compare compositions of potential offshore mineral resources from different regions of the shelf. Samples from 73 surface and near-surface sediments were wet sieved to retain the 0.062- to 2.00-mm size fractions that were used for heavy-mineral separation in sodium polytungstate. Sodium polytungstate is a nontoxic, water-based heavy liquid, specific gravity up to 3.0 g/cc, that has proved ideal for heavy-mineral separations. Centrifuging the sample-liquid mixture speeded up the mineral separation in the viscous polytungstate fluid. Isolation of the heavy-mineral fraction was accomplished by freezing the heavy-mineral concentrate at the bottom of the separatory tube and selectively pouring off the light mineral-fluid mixture. Mineral grains were rinsed with

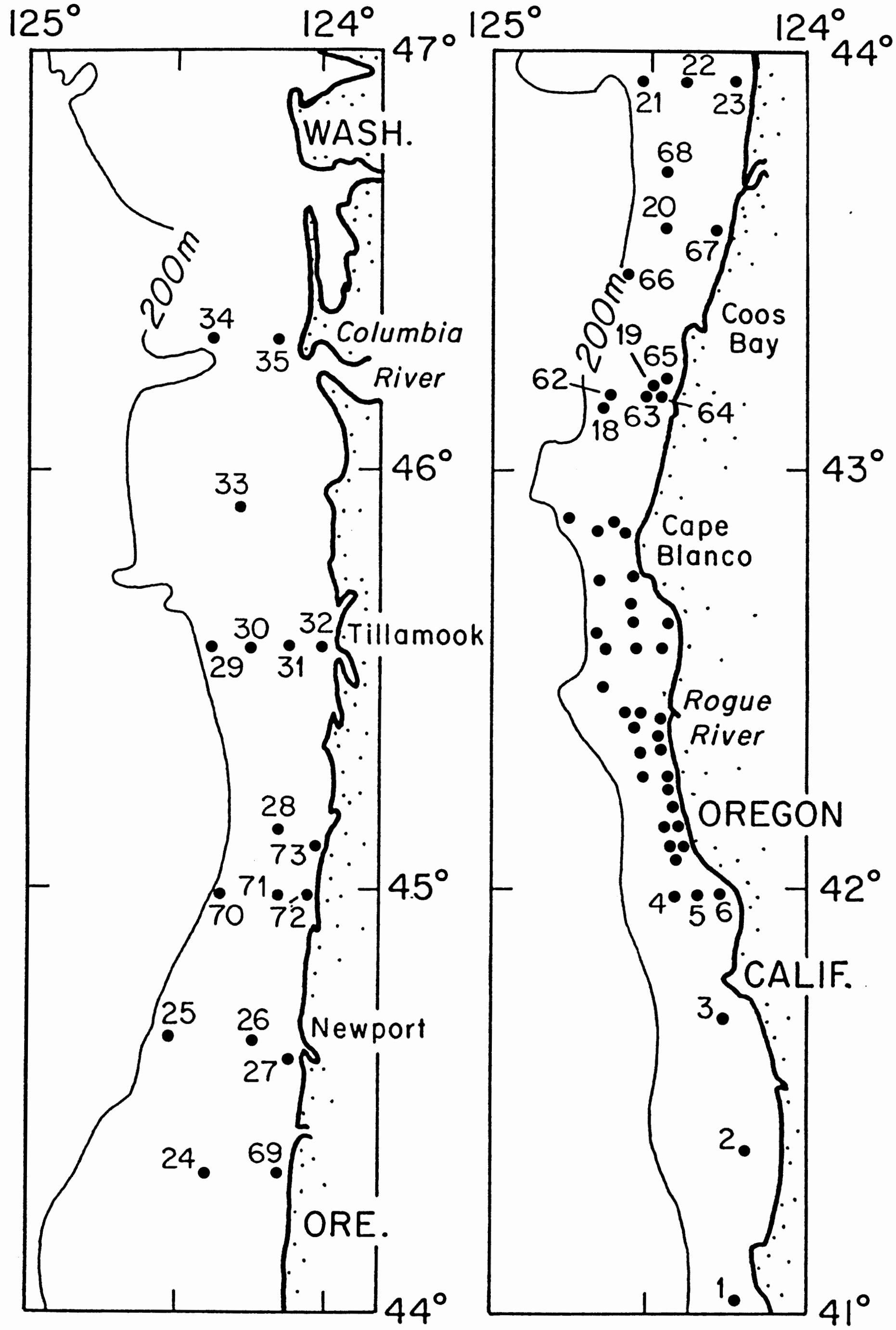

Figure 3A. Sediment sample location map for the Oregon and northernmost California continental shelves. See Appendix I for the sample number, type of sampling device, and water depth at each sample site. Refer to Figure 3B for inset map of sampling area (unlabeled solid dots) between Cape Blanco and the Oregon-California border.

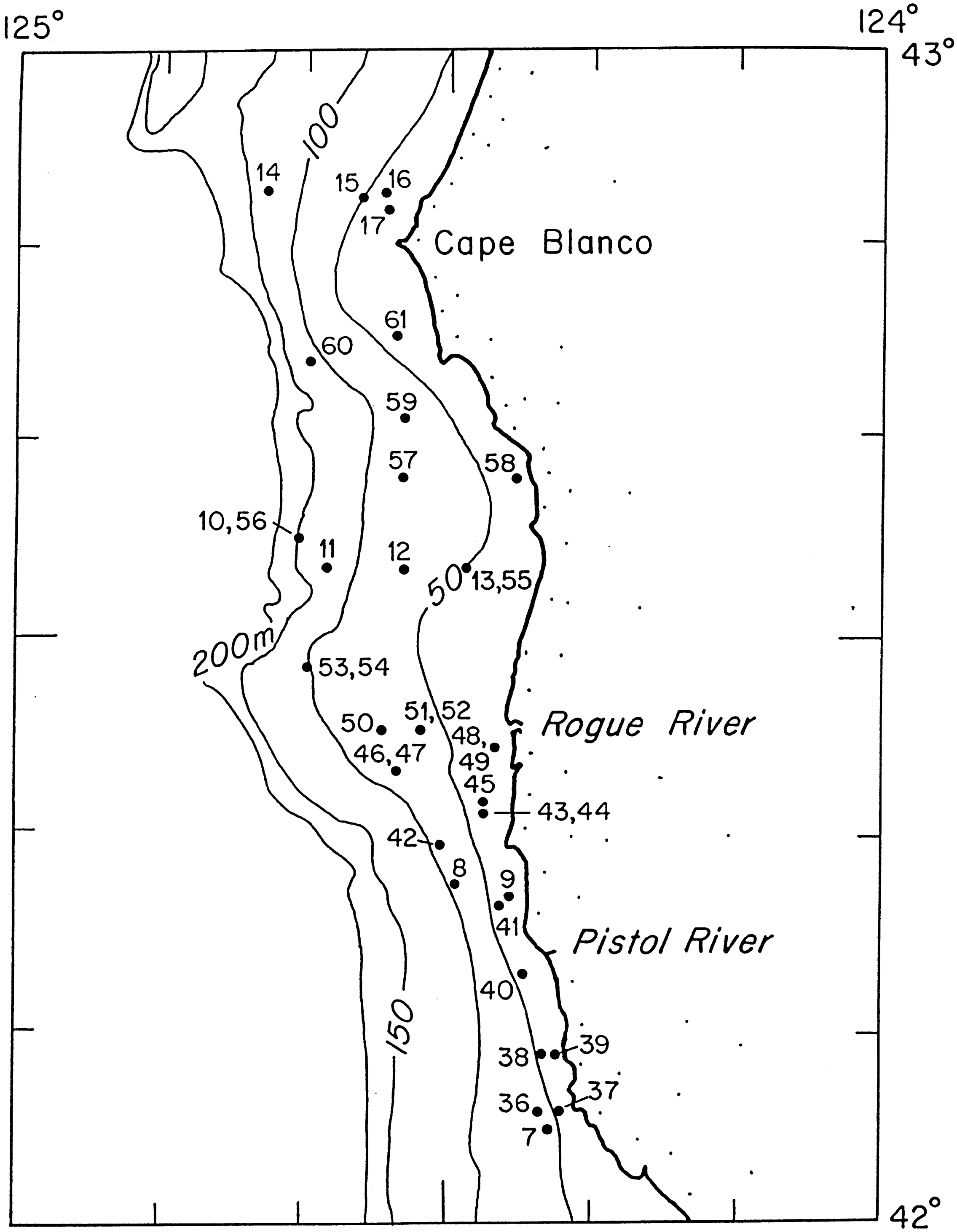

Figure 3B. Sediment sample location map for southern Oregon continental shelf. See also Figure 3A for reference map.

distilled water, and the filtered polytungstate wash was dehydrated in an oven to return the liquid to its maximum density of 3.0 g/cc.

The heavy-mineral fractions of the shelf samples were then passed beneath a hand magnet and through a Frantz isodynamic magnetic separator to pull out iron-rich (opaque) phases including magnetite, ilmenite, and chromite. Iron-rich garnets, pyroxenes, and rock fragments were also observed in the magnetic fraction. A colloid solution of tungsten carbide and sodium polytungstate, specific gravity =4.4 g/cc, was then used to isolate the opaque phases (densities greater than 4.5 g/cc) from the less-dense garnets and pyroxenes (densities less than 4.3 g/cc). Opaque-phase separates were rinsed in distilled water, and filtrates were examined under a microscope to confirm a pure concentrate of opaque-mineral grains. Final weights of the light, heavy, and opaque fractions were then compared to the bulk sand grain counts under a petrographic microscope to establish the efficiency of mineral separations.

Elemental analyses of the opaque fractions were performed by INAA to compare the relative abundances of the iron, titanium, and chromium phases and their associated trace elements of the shelf samples. The full suite of 26 elements was run on 70 samples, and a limited suite of 7 elements including titanium was analyzed on three additional samples. The prepared opaque mineral fractions were encapsulated in doubly sealed polyethylene containers prior to irradiation in the Oregon State University Reactor. Elements with relatively short radioactive half lives (several hours) were irradiated (2 minutes) in the rabbit pneumatic transfer system (3.5×10^{11} neutrons/cm^2-s), while elements with longer half lives were irradiated (7 hours) in rotating Lazy Susan rack (3×10^{12} neutrons/cm^2-s). Absolute determination of elemental concentrations in parts per million (ppm) was established by sample comparison to standards of known concentrations that were irradiated along with the sample capsules. Standards used included USGS BCR-1 and DTS-1[3], NBS SRM 688

(Basalt Rock), SRM 1571 (Orchard Leaf), SRM 1632 (Coal), and SRM 1633 (Fly Ash). Detector signals were routed to a Nuclear Data Model 66 4096 channel analyzer for processing. Peak areas were converted to elemental abundances with an in-house computer program.

RESULTS

In this preliminary study, we have identified two major economic elements, chromium and titanium, in the opaque phase of the heavy-mineral fraction of the surface and near-surface sands of the Oregon and northernmost California continental shelf. These elements correspond roughly to the abundances of the minerals chromite and ilmenite. Preliminary microprobe analysis of the opaque phases from widely different river sources indicate that all of the chromium is carried in the chromite phase (average 42% Cr_2O_3) and that most of the titanium is carried in the ilmenite phase (average 45% TiO_2). A small amount of titanium is also carried in a titaniferous magnetite phase (Peterson and others, 1987). An approximation of the relative abundance of chromite and ilmenite in each sample can be obtained by multiplying the percent chromium or titanium times 3. For example, 5% chromium would indicate roughly 15% chromite and 20% titanium would indicate roughly 60% ilmenite, assuming that all of the titanium is contained in the ilmenite phase.

The chromium and titanium elemental content of the 73 samples is shown in weight percent for the sediment samples collected at each sampling site on the shelf (Figures 4A,B and 5A,B). Chromium is present in quantities ranging from a trace up to 7 percent. The highest values are found on the inner shelf from Coos Bay, Oregon to the southernmost part of the study area off California (Figures 4A,B). Titanium is present in very large quantities (2 to 23 weight percent) compared to chromium. The largest titanium content is found on the inner shelf between Tillamook and Cape Blanco off central Oregon (Figures 5A,B).

Wt % Elemental Cr (Opaques)

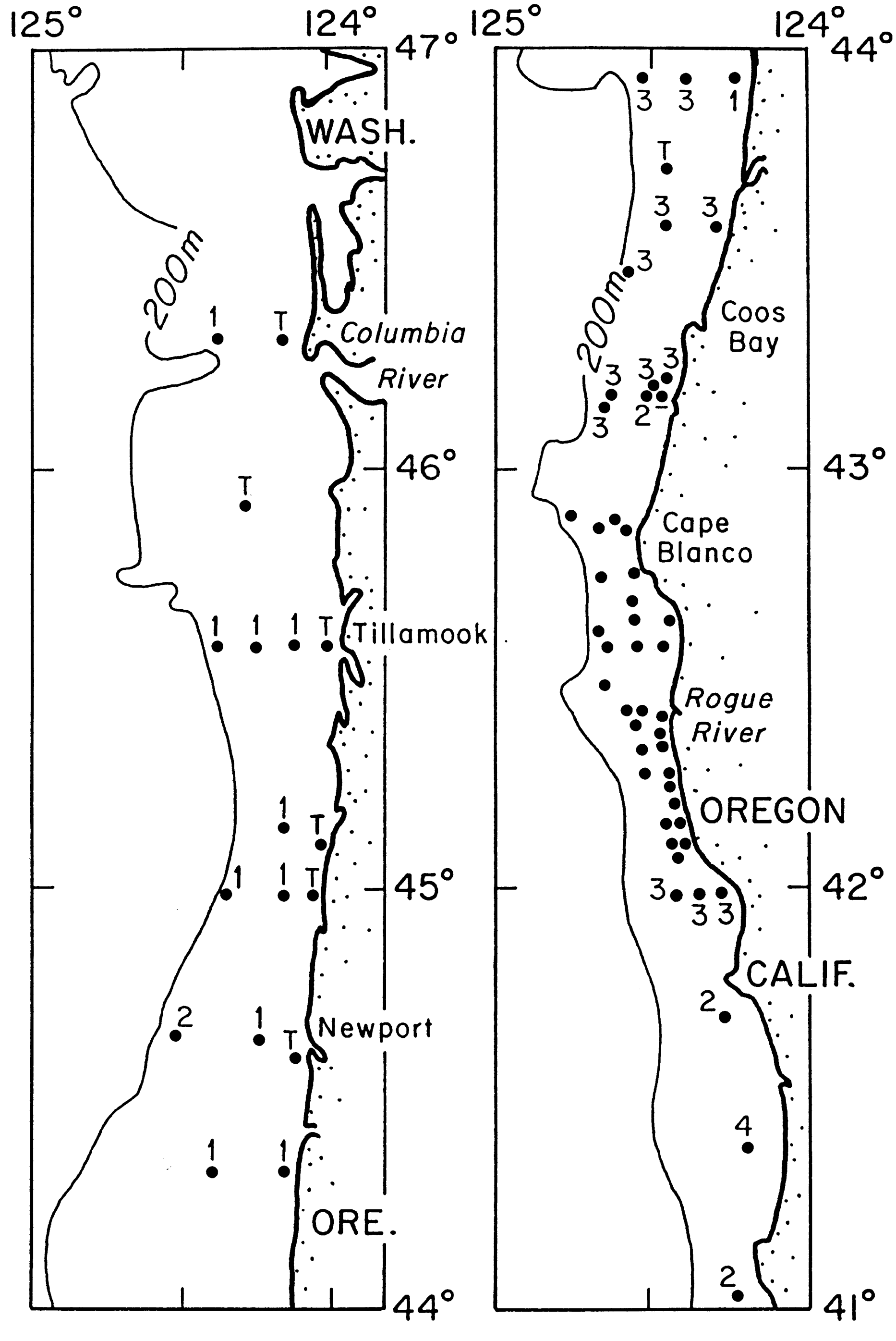

Figure 4A. Weight percent elemental chromium in the opaque-mineral fraction (specific gravity >4.4) of surface sands on the Oregon and northern California continental shelves. Solid dot is sample location, and number is percent; two numbers separated by comma are from box cores (i.e., 19,20 = top, bottom of core) See expanded diagram for percents of samples shown between 42° to 43° N latitude. Analyses were conducted by INAA. Outer edge of shelf indicated by 200-meter contour.

Wt. % Elemental Cr (Opaques)

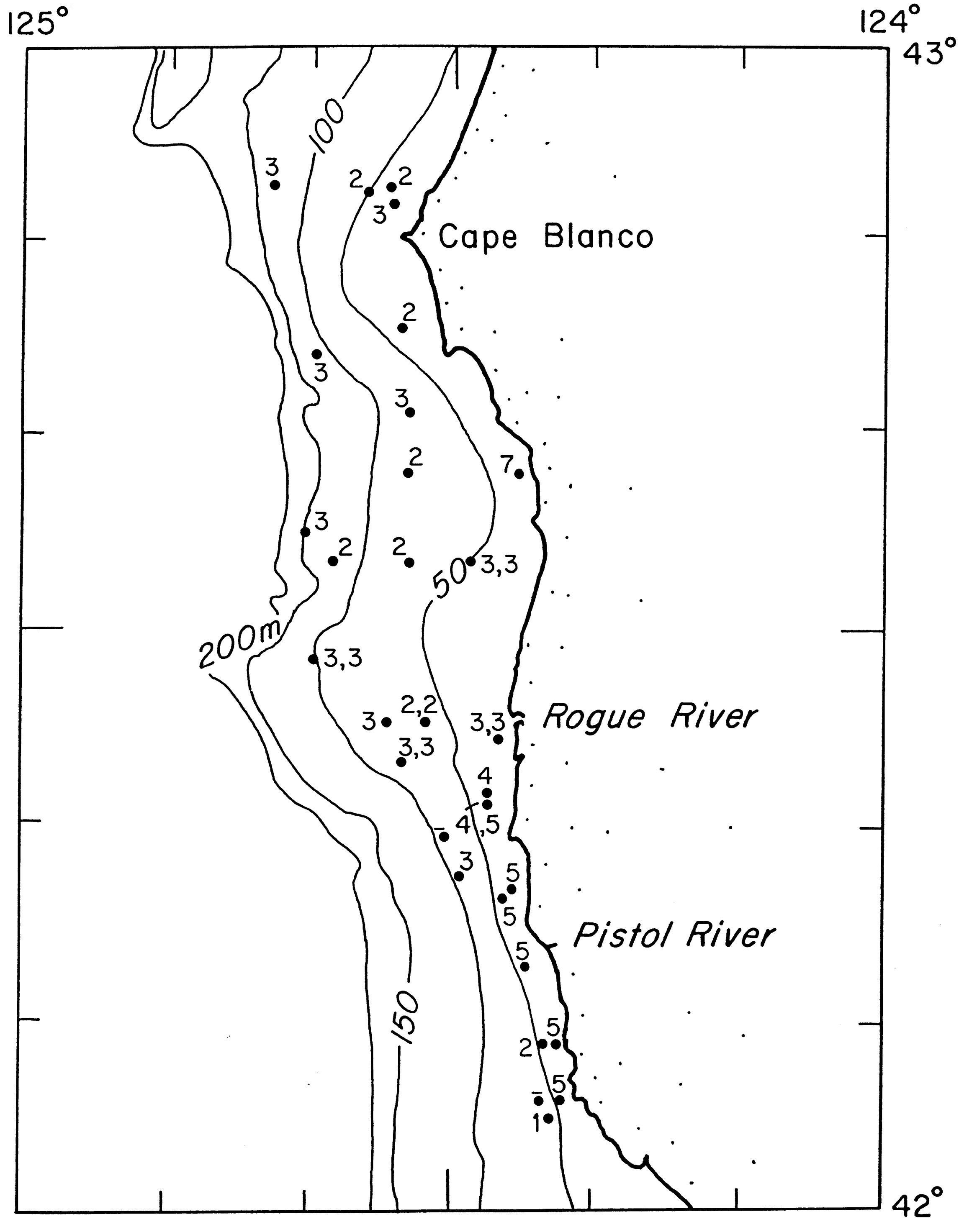

Figure 4B. Weight percent elemental chromium in the opaque-mineral fraction (specific gravity >4.4) of surface sands on the southern Oregon continental shelf from 42° to 43° N latitude. Solid dot is sample location, and number is percent. Analyses were conducted by INAA. Contours in meters.

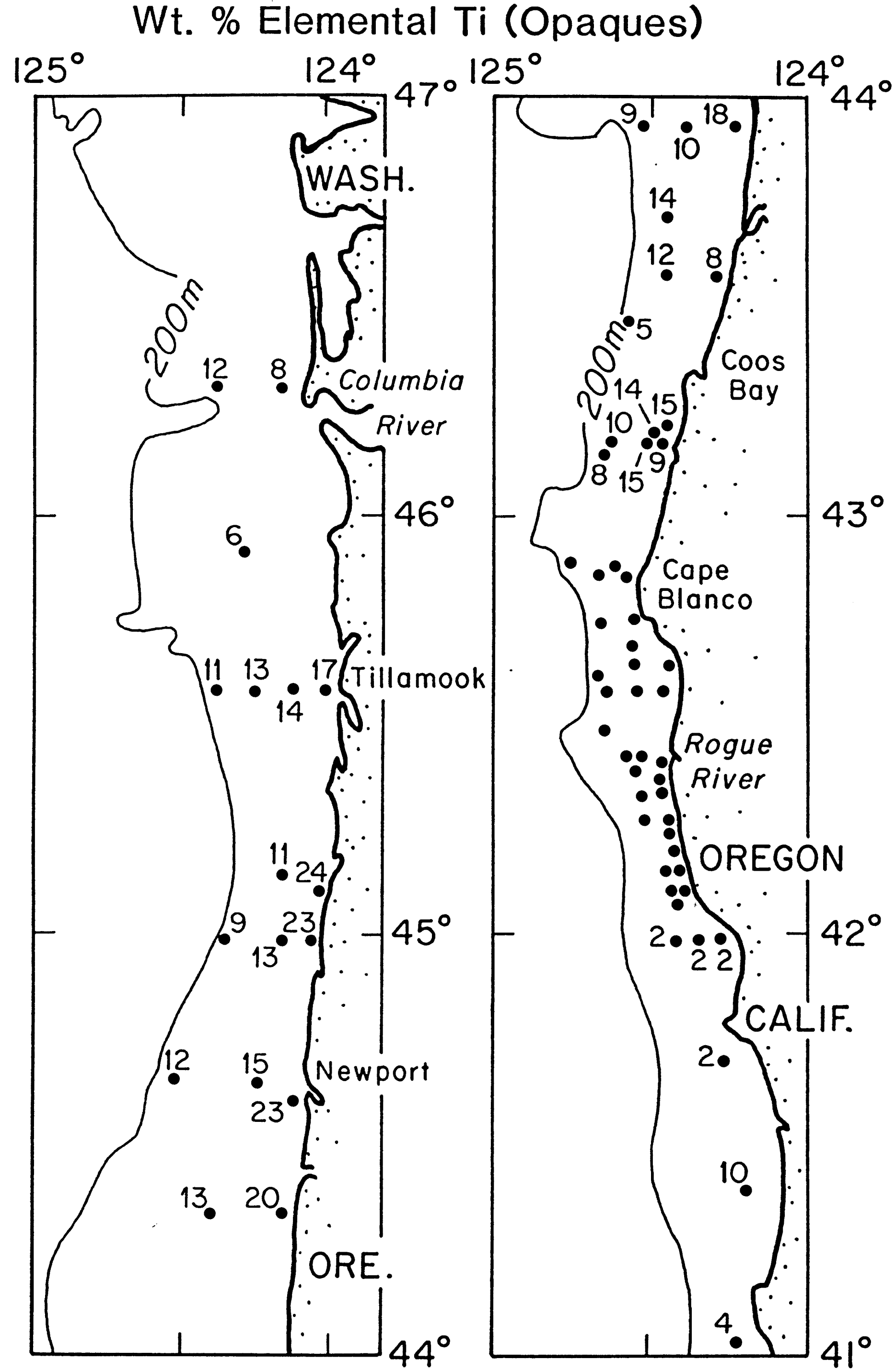

Figure 5A. Weight percent elemental titanium in the opaque-mineral fraction (specific gravity >4.4) of surface sands on the Oregon and northern California continental shelves. Solid dot is sample location, and number is percent; (i.e., 19,20 = top, bottom of core). See expanded diagram for percents of samples shown between 42° to 43° N latitude. Analyses were conducted by INAA. Outer edge of shelf indicated by 200-meter contour.

Wt. % Elemental Ti (Opaques)

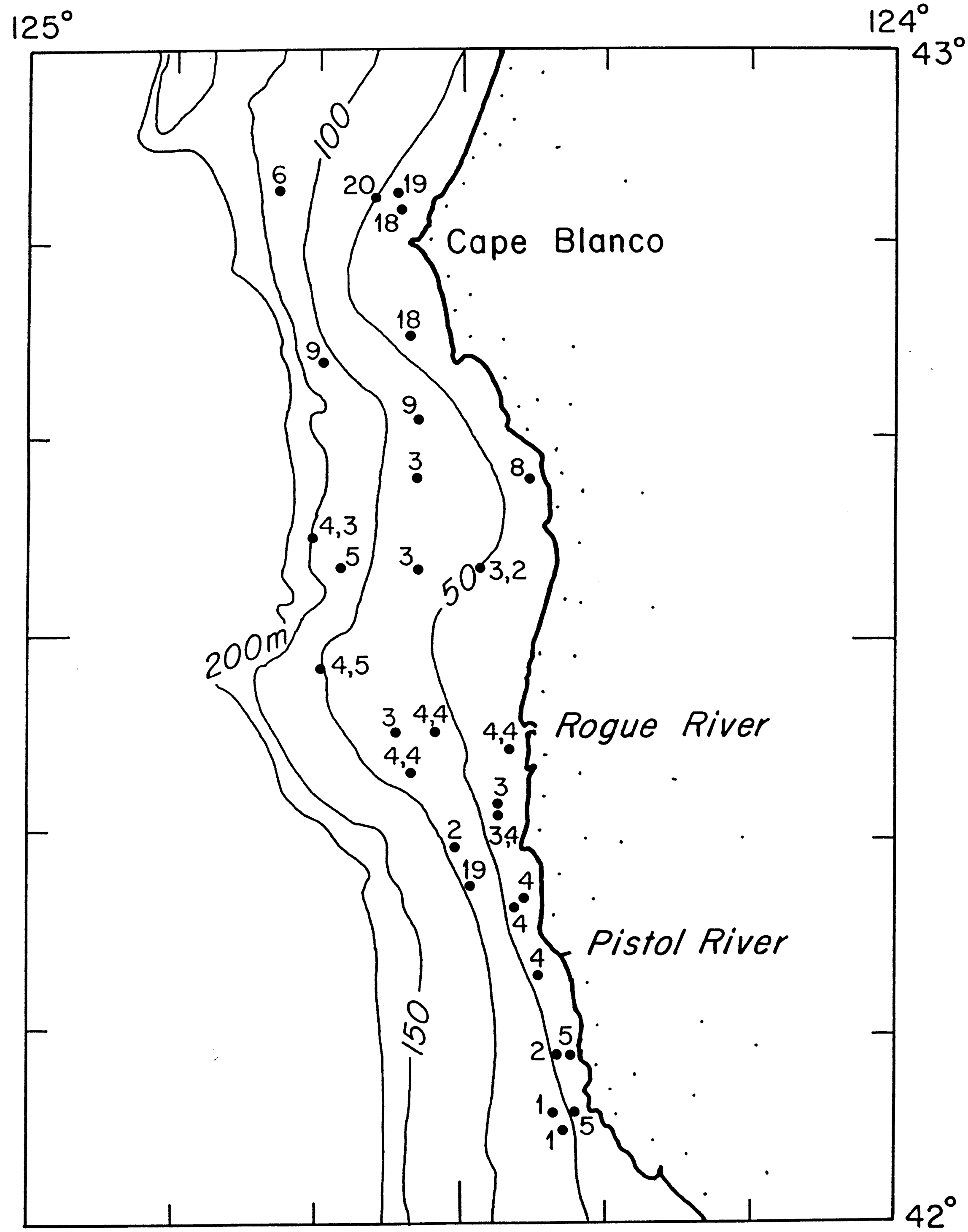

Figure 5B. Weight percent elemental titanium in the opaque-mineral fraction (specific gravity >4.4) of surface sands on the southern Oregon continental shelf from 42° to 43° N latitude. Solid dot is sample location, and number is percent. Analyses were conducted by INAA. Contours in meters.

There is an overlap in the chromium and titanium abundances in the vicinity of Cape Blanco. Chromium ranges from 2 to 3% and titanium from 19 to 20% in a region where Kulm and others (1968) have identified an anomalously high heavy-mineral concentration (10 to 33%). These sand deposits are located in water depths <50 meters just north of the Cape.

The elemental titanium/chromium ratio (i.e., weight percent titanium divided by weight percent chromium) ranges from 1 to 122 (Figures 6A,B). The highest ratios, which are located off central Oregon, reflect the low chromium content of these sands. They occur in the sands of the inner shelf in water depths of <50 meters.

We emphasize that the above weight percents of the economic elements and other elements (Appendix I) in the shelf surface sediments are based upon our analysis of the opaque phase of the mineral fraction (specific gravity >4.4) of the total sand sample. The percentages of opaque minerals range from <1% to 6% in this super heavy fraction of the shelf sands. We have excluded a certain amount of titanium and chromium, which also resides in the lighter opaque fraction (specific gravities 3.0 to 4.4), from this INAA analysis because we wished to obtain a nearly pure concentration of the mineral phases. For this reason, the percentages of opaque minerals and corresponding economic elements given in this study should be considered as minimum values for the shelf sands.

DISCUSSION AND CONCLUSIONS

Substantial quantities of elemental titanium and/or chromium comprise the opaque-mineral fraction (specific gravity >4.4) of the surface and near-surface sediments of the continental shelf off Oregon and northernmost California. The highest elemental contents are generally present within surface and near-surface heavy-mineral concentrations previously outlined on the continental shelf (Figures 2,4,5), although titanium is present in high quantities off central Oregon, where the

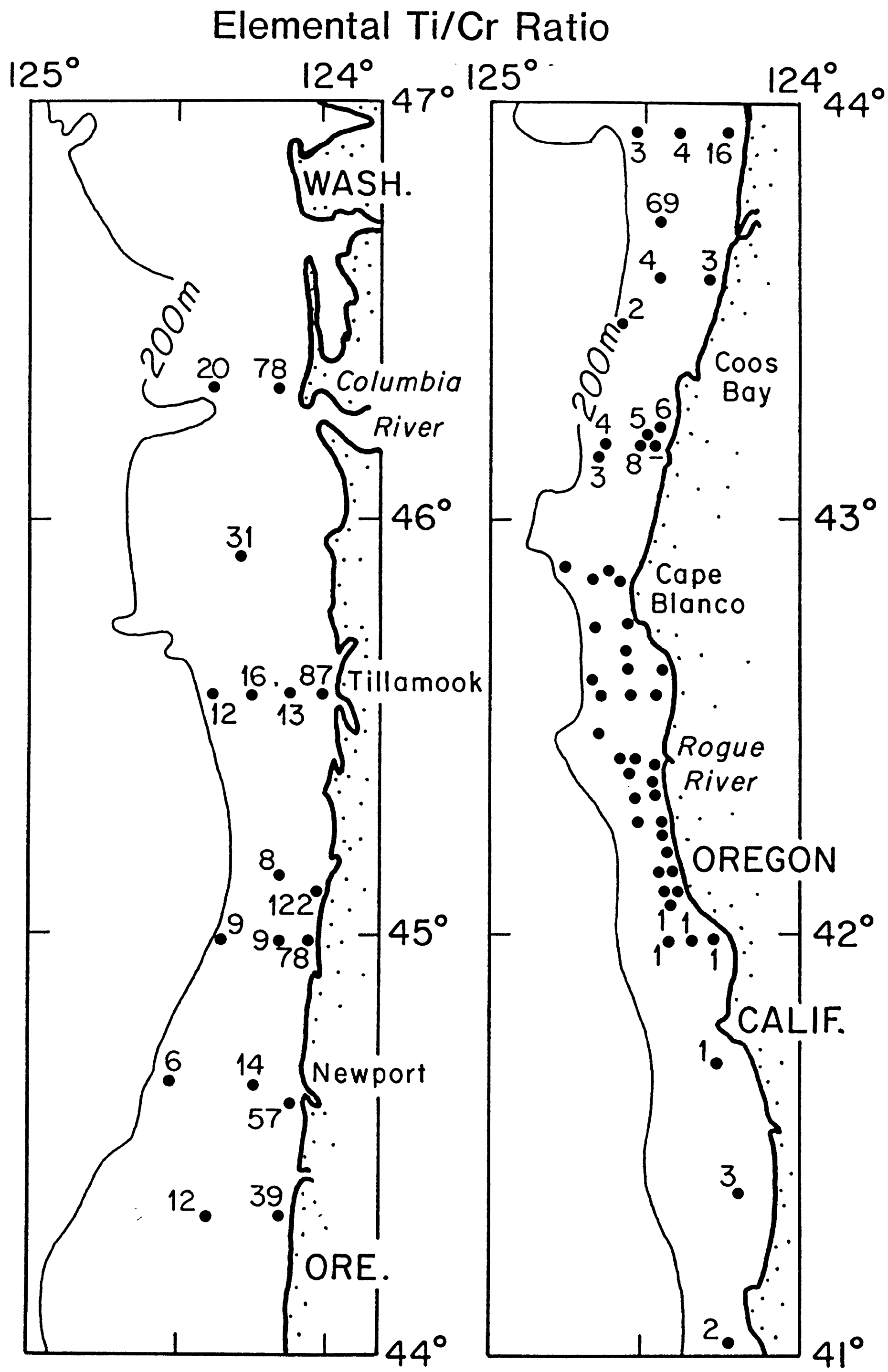

Figure 6A. Elemental titanium/chromium ratio (i.e., 10% titanium/2% chromium = 5) in the opaque-mineral fraction (specific gravity >4.4) of surface sands on the Oregon and northern California continental shelves. Solid dot is sample location, and number is percent (i.e., 19,20 = top, bottom of core). See expanded diagram for percents of samples shown between 42° to 43° N latitude. Analyses were conducted by INAA. Outer edge of shelf indicated by 200-meter contour.

Elemental Ti/Cr Ratio

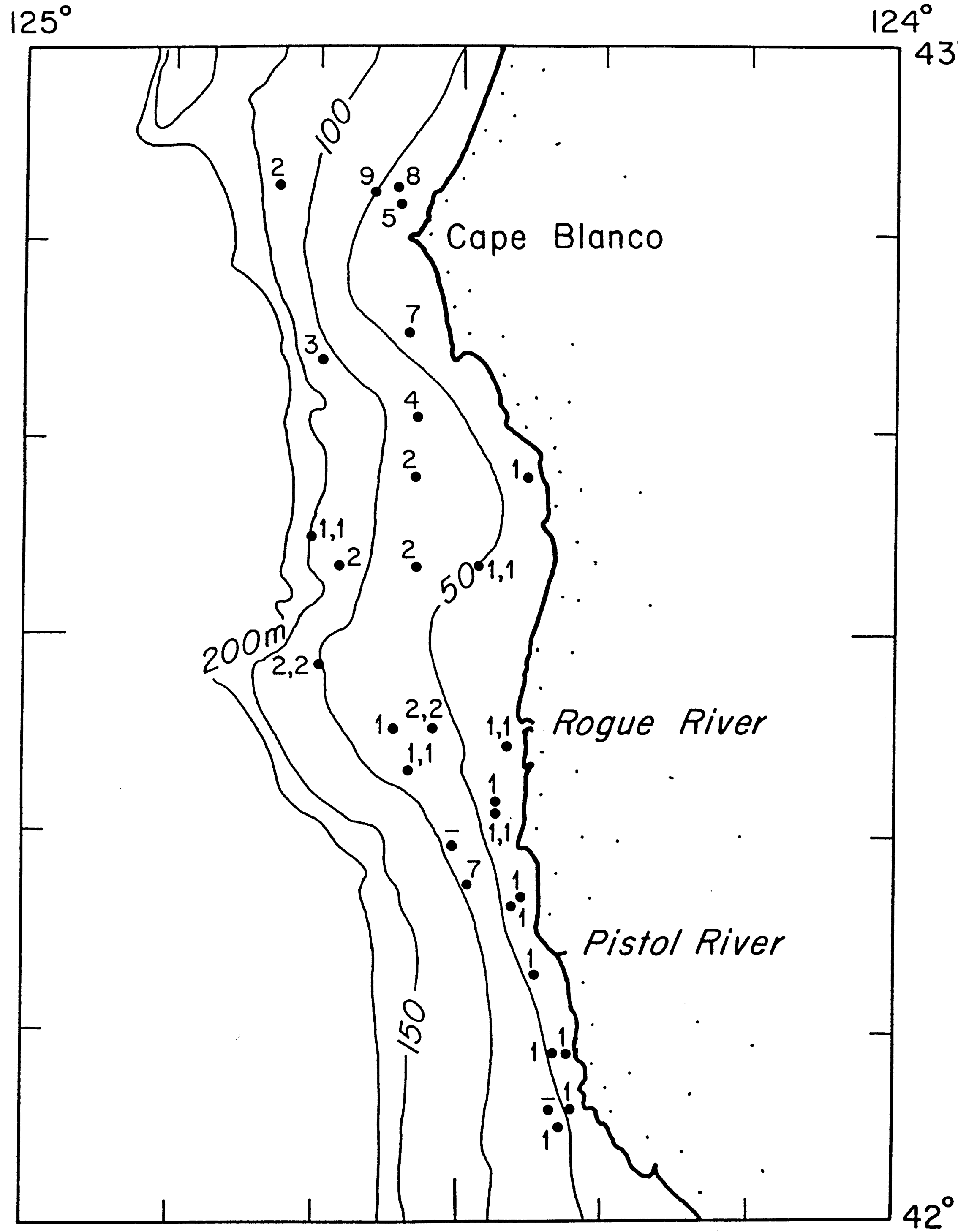

Figure 6B. Elemental titanium/chromium ratio in the opaque-mineral fraction (specific gravity >4.4) of surface sands on the southern Oregon continental shelf from 42° to 43° N latitude. Solid dot is sample location, and number is percent. Analyses were conducted by INAA. Contours in meters.

percentage of heavy minerals range from 1 to 9%.

Placer deposits in the coastal beaches and uplifted marine terraces of southern Oregon generally contain from 90 to 100% heavy minerals, most of which consist of the opaque minerals chromite and ilmenite and the nonopaque minerals garnet and zircon (Peterson and others, 1986,1987). If well-developed placer deposits do exist in the subsurface deposits of the adjacent continental shelf, they should have similar opaque-mineral contents. However, the titanium/chromium ratio may not be the same as that found in the adjacent coastal placers, since a substantial northward longshore transport is indicated by the heavy-mineral assemblages present in the shelf sediments (Scheidegger and others, 1971), whereas the present coastal headlands tend to inhibit this northward longshore transport and the mixing of minerals from different river sources (Peterson and others, 1986).

We are continuing our studies of the INAA data presented here and companion analyses from the beaches, terraces, and rivers of the coastal region. The results of all these studies will be reported in a series of publications in the near future.

ACKNOWLEDGMENTS

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Appendix I. Elemental content of heavy-mineral concentrations of the Oregon and northernmost California continental shelf.

Sample number	Water depth (m)	Sample type	%Sand	%Heavy minerals	Elements (ppm) Na	Mg	Al	Ca	Sc	Ti	V	Cr
1	NA	GC	NA	1	3175.9	113388	25951	72635	46.9	35571	648.5	20894
2	NA	GC	NA	9	1411.3	40477	22447	36244	35.7	102892	1254.7	41534
3	NA	GC	NA	4	2320.6	123557	25095	44432	41.3	21826	635.6	22066
4	55	S	NA	10	2190.3	100433	26369	57632	42.5	15097	849	25068
5	37	S	NA	13	1869.3	92481	27098	57438	44.1	21194	802.1	34622
6	24	S	NA	8	1697.1	106004	25023	50357	39.8	21750	863	31780
7	62	S	NA	4	2363.8	144350	22775	63616	49.1	11804	520.8	14703
8	99	S	NA	29	613.6	28138	15877	8333	76.2	189361	1357.2	26844
9	25	BC	NA	11	878.8	49376	22081	12072	23.7	45050	2056.9	45470
10	150	BC	77	10	2903	74980	24589	30002	39.2	40314	1271.2	28771
11	115	BC	47	7	3348.2	96056	35214	33297	42.1	45100	1466.9	24015
12	86	BC	22	8	3285.2	65508	26214	35145	37.8	34854	1229.3	20193
13	50	BC	89	5	2535.3	105352	26292	37205	37.6	29122	1180	25324
14	137	S	NA	5	2877.4	65633	25361	30134	52.6	61329	1236.2	26525
15	50	BC	NA	20	486.2	26341	13824	8565	74.9	203994	1264.6	22843
16	27	BC	NA	28	461.7	36641	13298	6022	72.5	190171	1346.6	24821
17	21	BC	NA	16	426.2	28751	15816	7166	69.3	178102	1396.9	34137
18	192	BC	NA	4	2737.9	68594	23723	36558	59.5	83223	1281.5	25203
19	42	BC	NA	5	1436.9	32116	18437	12913	59.4	138874	1297.6	30015
20	121	G	49	3	1763.5	44160	21238	17474	56.9	117312	1408.8	31631
21	135	G	72	9	2434.9	72318	23572	31361	56.5	92738	1193.6	30310
22	108	G	61	6	2335.4	50671	22388	23817	57.6	104445	1284.5	26655
23	64	G	91	6	1245.3	41632	15479	11225	76.1	176993	1045.5	11178
24	88	G	100	2	2566.9	66301	19840	21859	70.1	126382	1106.5	11109
25	190	BC	NA	2	2476.7	50662	20775	25705	64.1	115570	1324.5	19191
26	78	BC	NA	1	1519.4	32731	16960	19284	69.5	149018	1286.5	10976
27	51	G	100	2	294.3	26501	8847	4164	75.2	226027	1427.8	4143
28	140	G	64	2	3175.3	40340	21172	27946	58.5	105783	1458.5	14355
29	190	G	47	2	3760.3	33262	21230	27579	57.5	107425	1208.4	8615
30	151	G	49	2	3148.2	33522	18613	24233	58.7	126180	1373.8	7819
31	95	G	100	5	2689.5	46637	18362	32723	64.4	137372	1336.4	10657
32	27	G	100	2	2691.3	35547	15240	20608	62.6	173823	1207.7	1823

Sample types: GC = gravity core; S = Shipek grab; BC = box core; G = grab; NA = not available

Appendix I. Continued

Sample number	Water depth (m)	Sample type	%Sand	%Heavy minerals	Elements (ppm)							
					Na	Mg	Al	Ca	Sc	Ti	V	Cr
33	128	G	44	4	3586.5	34406	19115	28895	43	60631	1276.5	1548
34	130	G	59	5	2697.7	26090	16253	19417	45.9	117620	1564.6	6654
35	75	G	49	6	4799	47858	22526	33736	57.2	77912	1419.7	985
OL	-	-	-	-	87.3	7972	410	20899	-	-	0.5	-
COAL	-	-	-	-	-	525	16952	3203	-	995	34.4	-
36	69	S	27	4	2457.8	124772	22726	64387	-	14282	514.5	-
37	49	S	94	5	1157.5	65874	27436	22435	31.9	52578	1804.5	51720
38	49	S	93	7	2218.9	111129	29201	59305	58.5	16420	578.9	19857
39	20	S	97	18	383.9	29385	21206	8054	22.7	49270	2170.3	52594
40	47	S	96	13	1126.9	57686	26085	22739	31.5	36418	15150	46838
41	35	S	97	11	872.3	47288	25479	16615	26.7	44180	1756.3	50582
42	95	S	NA	3	2433.9	90253	23911	40842	-	23968	973.1	-
43	27	BC	98	19	1245.3	60338	25624	21328	28.7	32791	1570.7	42776
44	27	BC	98	18	1212.7	52523	26688	24344	29.9	38400	1491.4	46195
45	22	S	NA	21	1065.4	53446	22595	19676	25.7	34464	1795	43417
46	85	BC	45	12	2267.3	56122	23149	21479	35.1	36561	1580.2	29002
47	85	BC	78	12	2078	66995	2364	23102	35.8	40001	1654	32224
48	17	BC	97	11	1679	74702	24297	30196	30.7	36151	1386.6	28319
49	17	BC	95	8	1853.7	57783	23712	20074	32.8	38111	1335.3	29490
50	75	BC	64	13	2178.9	60847	22419	22654	33.2	32758	1683.8	27154
51	70	BC	29	18	2303	49113	18934	15983	35.2	39439	1518.2	20315
52	70	BC	48	16	2298.4	59304	21013	20713	34.3	44907	1587.2	21494
53	104	BC	55	4	2731	65563	22422	31206	42.3	40772	1240	27960
54	104	BC	82	5	2335.5	71424	24354	25306	37.1	48314	1433.4	29723
55	50	BC	92	6	2087.1	76634	25649	33909	3.8	24688	1218	26379
56	150	BC	88	24	2688.8	83372	23726	27044	35.6	34695	1236.9	25843
57	92	S	NA	5	2713.5	63141	23860	26162	40.9	31642	1125.6	20354
58	28	S	NA	3	700.3	50318	29425	17651	40.6	80261	1082.2	72440
59	79	S	NA	2	1887.9	53786	20841	24773	52.4	91791	1319.1	25093
60	120	S	NA	3	1566	42747	22591	25205	56	86100	1183.1	31277
61	35	BC	97	6	759.9	32547	15738	9155	76.2	184369	1238.8	24847
62	157	G	53	6	1757.1	62671	21527	18120	56.7	101982	1231.2	27852

Appendix I. Continued

Sample number	Water depth (m)	Sample type	%Sand	%Heavy minerals	Elements (ppm)							
					Na	Mg	Al	Ca	Sc	Ti	V	Cr
63	48	G	100	10	1109.5	37277	17772	15335	71.1	151093	1081.7	19653
64	20	G	100	8	1704.1	53886	23922	25261	-	91491	908.8	-
65	31	G	100	13	650.8	29646	18938	10548	65.4	154744	1170.1	27277
66	199	G	24	1	2899.9	61966	28988	29435	38.2	46283	1443.1	25865
67	80	G	64	2	3111.1	53905	28020	33954	51.3	79872	1119.3	26010
68	123	G	64	6	1529.3	40542	20386	10859	60.9	137058	1237.8	2258
69	38	G	100	5	562.8	33246	13788	6545	64.1	196223	1413.6	5464
70	329	G	42	1	3889.1	57916	23589	20143	47.3	91935	1405	11058
71	117	G	94	2	1937.1	48613	19065	20598	65.4	127812	1128.8	14238
72	35	G	100	10	435.3	13898	8068	4586	71.5	233899	1196.1	3337
73	21	G	100	5	594.3	18304	7926	6129	70.4	242831	1142.5	2320
BCR-1	-	-	-	-	24653.1	39983	73476	46552	32.6	13915	396.6	15
DTS-1	-	-	-	-	-	-	-	-	3.5	-	-	4277
FLYASH	-	-	-	-	3112.6	-	-	-	26.4	-	-	131
NBS-688	-	-	-	-	1885.6	70977	93219	88098	-	6867	255.6	-

Appendix I. Continued

Sample number	Water depth (m)	Sample type	%Sand	%Heavy minerals	Elements (ppm) Mn	Fe	Co	Ni	As	Sb	La	Ce	Nd	Sm
1	NA	GC	NA	1	5045.3	213551	113.2	515	38.56	5.61	11.85	30.38	-	3.978
2	NA	GC	NA	9	9092.8	334271	134.4	440	6.46	1.82	6.5	15.14	-	2.577
3	NA	GC	NA	4	3442	210242	120	785	8.07	1.33	8.58	14.96	-	2.79
4	55	S	NA	10	2919	221349	113.9	758	6.68	0.97	5.71	9.8	-	1.722
5	37	S	NA	13	3099.2	237744	130.9	649	5.77	0.58	4.22	7.34	-	1.527
6	24	S	NA	8	3043.5	243085	127.8	822	7.15	0.76	4.14	8.46	-	1.498
7	62	S	NA	4	2560.4	192957	106.9	742	9.19	1.33	5.81	13.55	-	2.08
8	99	S	NA	29	9059.2	360133	115.7	-	4.06	0.97	15.42	24.66	-	2.332
9	25	BC	NA	11	4772.5	432265	161.2	477	5.01	0.88	3.33	9.41	-	1.131
10	150	BC	77	10	4044.7	303340	123.8	456	4.77	0.96	7.01	16.36	-	2.002
11	115	BC	47	7	4043.5	307336	117.4	624	6.54	1.06	6.57	16.21	-	2.327
12	86	BC	22	8	3851	293002	109.9	285	9.7	1.23	7.36	15.5	-	2.589
13	50	BC	89	5	3666.1	309705	124.4	575	12.34	1.58	7.43	14.45	-	2.216
14	137	S	NA	5	5324.2	315971	118.3	388	6.82	0.79	11.79	20.92	-	2.783
15	50	BC	NA	20	10526.1	331172	100.2	-	3.94	1.13	12.45	17.54	-	2.115
16	27	BC	NA	28	9092.5	357023	112.5	-	3.66	1.13	11.01	16.35	-	2.205
17	21	BC	NA	16	8939.5	378069	131.5	167	5.4	0.92	9.06	14.84	-	1.644
18	192	BC	NA	4	5798	301051	107.3	-	4.24	1.01	9.62	18.42	-	2.688
19	42	BC	NA	5	8513.3	363146	125	269	5.69	1.14	14.12	27.41	21.8	2.831
20	121	G	49	3	6937.3	375584	126.9	508	4.35	1.04	13.8	24.69	-	2.737
21	135	G	72	9	6422.4	331380	125.9	308	5.38	1.48	15.14	30.31	-	3.455
22	108	G	61	6	7344.3	314829	109	-	5.72	1.54	17.43	36.79	-	3.791
23	64	G	91	6	10629.3	299356	79.2	-	7.64	1.23	17.74	30.62	-	3.714
24	88	G	100	2	9049.1	270644	87.3	-	7.03	3.39	14.92	37.28	-	3.925
25	190	BC	NA	2	7316.2	353973	107.4	115	6.82	1.78	15.61	31.41	-	3.142
26	78	BC	NA	1	10916.9	328099	78.4	-	7.51	2.4	26.49	47.03	27.8	4.468
27	51	G	100	2	10495.7	390776	66.5	-	5.28	0.84	14.2	21.51	-	2.011
28	140	G	64	2	6319.1	347389	97	279	11.07	2.23	20.6	44.27	19.4	4.343
29	190	G	47	2	6143.2	298428	80.7	-	8.72	2.08	21.38	38.94	14.9	4.495
30	151	G	49	2	5840.3	329891	84.2	-	8.57	1.52	20.99	44.74	23.2	4.695
31	95	G	100	5	7135.9	316342	85.5	-	8.88	2.27	24.69	65.55	28.7	4.784
32	27	G	100	2	7293.5	301666	72.9	-	5.24	0.51	12	21.35	-	3.38

Appendix I. Continued

Sample number	Water depth (m)	Sample type	%Sand	%Heavy minerals	Elements (ppm) Mn	Fe	Co	Ni	As	Sb	La	Ce	Nd	Sm
33	128	G	44	4	4667.4	351907	59.8	-	8.32	1.28	41.79	84.61	30.3	7.377
34	130	G	59	5	5764.7	379509	75.3	-	13.26	2.02	32.22	82.89	31.7	5.424
35	75	G	49	6	4323.7	274720	74.9	151	8.2	1.45	55.97	112.7	48.4	9.585
CL	-	-	-	-	89.7	-	-	-	-	-	-	-	-	-
COAL	-	-	-	-	40.6	-	-	-	-	-	-	-	-	-
36	69	S	27	4	2757	-	-	-	-	-	-	-	-	-
37	49	S	94	5	4304	402908	176.2	513	6.07	1.21	5.26	9.25	-	1.666
38	49	S	93	7	3322.1	201994	104.1	373	6.5	0.77	6.02	13.17	-	2.315
39	20	S	97	18	4961.6	510830	193.2	445	3.64	0.57	4.52		-	1.025
40	47	S	96	13	4665.8	388495	164.8	623	6.13	1.08	4.93	8.46	-	1.533
41	35	S	97	11	4695.3	411683	167.4	427	5.23	0.82	4.04	6.49	-	1.274
42	95	S	NA	3	3289.5	-	-	-	-	-	-	-	-	-
43	27	BC	98	19	4180.3	378230	156.4	591	6.91	0.88	4.86	13.25	-	1.634
44	27	BC	98	18	4577.5	375226	161.2	544	6.31	0.82	4.66	8.77	-	1.397
45	22	S	NA	21	4447.3	446895	171.9	561	4.95	0.58	4.51	9.02	-	1.368
46	85	BC	45	12	4117.7	384400	129.9	355	4.49	0.68	6.99	13.74	-	2.063
47	85	BC	78	12	4269.8	413127	138.1	354	4.53	0.72	6.76	16.26	-	1.894
48	17	BC	97	11	3728.1	354986	140.3	563	6.02	0.89	7.13	12.57	-	2.106
49	17	BC	95	8	4174.7	365107	143.7	638	7.73	0.94	7.4	13.39	-	2.297
50	75	BC	64	13	3883.8	395443	131.4	418	6.98	1.05	7.11	9.44	-	1.974
51	70	BC	29	18	3962	406612	131	201	5.24	0.71	7	15.09	-	2.429
52	70	BC	48	16	4085.7	394322	129.7	263	4.54	0.79	9.35	16.95	-	2.503
53	104	BC	55	4	4526.3	338789	130.4	478	5.31	1.27	7.68	16.11	-	2.599
54	104	BC	82	5	4799.4	355625	130.4	349	6.93	1.49	10.04	23.29	-	2.598
55	50	BC	92	6	3750.1	343583	138.7	621	10.16	1.4	6.37	10.64	-	2.01
56	150	BC	88	24	4266.9	294078	127.9	460	6.92	0.72	5.76	8	-	1.958
57	92	S	NA	5	4212	314103	125.3	478	9.74	1.35	9.5	23.88	-	3.156
58	28	S	NA	3	9174.4	345656	233.5	735	5.16	2.38	8.2	18	-	1.802
59	79	S	NA	2	6200.8	363490	125.6	326	5.68	1.02	15.68	25.63	-	3.551
60	120	S	NA	3	6946.2	326471	126.1	447	5.66	1.03	15.45	28.8	-	2.831
61	35	BC	97	6	9573.2	349149	115.8	-	4.26	1.67	14.47	23.69	-	2.647
62	157	G	53	6	6244.6	334839	120.9	324	5.19	0.79	11.24	22.42	23.3	2.702

Appendix I. Continued

Sample	Water	Sample	%Sand	%Heavy	Elements									
number	depth (m)	type		minerals	(ppm)									
					Mn	Fe	Co	Ni	As	Sb	La	Ce	Nd	Sm
63	48	G	100	10	10605.3	323751	103.8	-	5.2	0.94	38.43	62.25	23.6	5.428
64	20	G	100	8	9156.9	-	-	-	-	-	-	-	-	-
65	31	G	100	13	11713.5	347140	116.6	-	6.06	1.29	18.32	28.56	26.1	3.304
66	199	G	24	1	4615.6	310960	114.9	446	7.21	1.85	15.23	28.96	-	3.303
67	80	G	64	2	8065.9	274905	115.4	295	7.19	1.83	23.01	45.73	-	4.904
68	123	G	64	6	8070.2	335435	105.6	-	4.11	1.31	25.07	49.3	30	4.035
69	38	G	100	5	12426.3	372356	80.2	-	4.4	1.23	16.27	25.94	23.8	2.842
70	329	G	42	1	5752.3	354875	108.3	-	6.95	3.04	15.35	27.76	-	4.08
71	117	G	94	2	8691.5	307240	91.5	-	6.99	2.66	26.64	51.66	-	4.933
72	35	G	100	10	9230.1	367176	64.2	-	2.72	0.79	12	14.57	-	2.021
73	21	G	100	5	8178.3	361059	61.8	-	2.33	0.47	12.66	17.97	9.9	1.78
BCR-1	-	-	-	-	1423.4	95438	36.7	-	-	-	28.38	55.51	37.8	6.551
DTS-1	-	-	-	-	-	60611	138.6	2350	-	-	-	-	-	-
FLYASH	-	-	-	-	-	61252	39.5	-	58.62	6.9	79.08	168.8	62.6	12.181
NBS-688	-	-	-	-	1278.1	-	-	-	-	-	-	-	-	-

Appendix I. Continued

Sample number	Water depth (m)	Sample type	%Sand	%Heavy minerals	Elements (ppm)							
					Eu	Tb	Yb	Lu	Hf	Ta	Th	U
1	NA	GC	NA	1	1.476	1.179	4.461	0.435	2.01	1.52	2.01	10.9
2	NA	GC	NA	9	0.718	-	3.145	0.361	4.37	4.45	1.12	1.69
3	NA	GC	NA	4	0.59	-	1.824	0.243	1.3	0.77	1.95	1.66
4	55	S	NA	10	0.408	0.32	1.14	0.172	0.83	0.31	-	-
5	37	S	NA	13	0.482	0.425	1.322	0.158	1.2	0.92	-	-
6	24	S	NA	8	0.429	-	0.965	0.115	1.7	0.51	0.77	-
7	62	S	NA	4	0.762	0.329	1.254	0.111	1.43	-	1.09	0.83
8	99	S	NA	29	0.481	0.631	5.949	1.054	13.85	16.11	2.86	1.64
9	25	BC	NA	11	0.402	-	1.256	0.188	3.06	1.85	-	0.66
10	150	BC	77	10	0.558	0.575	1.459	0.214	2.65	2.34	0.85	0.82
11	115	BC	47	7	0.613	-	1.632	0.266	2.24	1.48	1.18	1.13
12	86	BC	22	8	0.554	0.518	1.945	0.171	2.12	1.06	0.67	1.06
13	50	BC	89	5	0.531	0.408	1.724	0.143	2.51	0.83	0.62	2.25
14	137	S	NA	5	0.756	0.439	2.329	0.286	4.48	4.58	2.17	1.79
15	50	BC	NA	20	0.529	0.64	7.447	1.174	12.23	19.06	2.37	2.02
16	27	BC	NA	28	0.399	0.61	6.386	0.848	13.33	17.22	2.34	1.37
17	21	BC	NA	16	0.289	0.526	6.198	0.9	15.48	15.63	1.58	1.17
18	192	BC	NA	4	0.798	-	2.706	0.45	4.76	5.6	1.57	1.54
19	42	BC	NA	5	0.6	0.357	4.584	0.907	9.38	13.24	3.84	1.13
20	121	G	49	3	0.556	-	3.817	0.492	8.1	10.45	2.63	1.55
21	135	G	72	9	0.981	0.893	4.367	0.501	6.04	8.51	2.69	1.8
22	108	G	61	6	0.746	0.607	4.618	0.652	7.42	8.9	4.03	1.8
23	64	G	91	6	0.689	0.91	9.812	1.339	12.5	16.34	4.24	1.94
24	88	G	100	2	0.807	0.67	8.485	1.398	10.02	12.68	3.95	4.29
25	190	BC	NA	2	0.708	0.519	4.71	0.768	11.19	12.51	4.23	3.66
26	78	BC	NA	1	0.66	1.185	11.092	1.883	14.26	15.98	4.49	2.8
27	51	G	100	2	0.258	0.896	11.857	2.094	25.14	22.24	3	2.44
28	140	G	64	2	0.956	0.817	3.815	0.468	9.77	10.3	6.79	4.65
29	190	G	47	2	0.951	0.632	4.982	1.1	8.84	9.79	4.85	2.5
30	151	G	49	2	1.205	0.749	4.462	0.784	10.78	12.09	6.18	3.49
31	95	G	100	5	1.054	0.933	5.108	0.8	12.9	13.08	5.87	3.43
32	27	G	100	2	0.823	1.101	8.048	1.195	14.64	15.23	1.32	1.75

Appendix I. Continued

Sample number	Water depth (m)	Sample type	%Sand	%Heavy minerals	Elements (ppm)							
					Eu	Tb	Yb	Lu	Hf	Ta	Th	U
33	128	G	44	4	1.276	1.102	5.885	0.849	8.99	5.55	7.45	2.58
34	130	G	59	5	1.181	0.664	3.87	0.594	10.93	11.27	7.82	4.31
35	75	G	49	6	1.844	1.345	6.221	0.84	10.87	7.46	10.23	1.8
CL	-	-	-	-	-	-	-	-	-	-	-	-
COAL	-	-	-	-	-	-	-	-	-	-	-	-
36	69	S	27	4	-	-	-	-	-	-	-	-
37	49	S	94	5	0.252	0.378	1.375	0.184	1.79	1.16	-	1.23
38	49	S	93	7	0.646	0.844	1.717	0.235	1.19	0.72	-	0.52
39	20	S	97	18	0.257	-	0.993	0.367	3.02	1.46	-	0.72
40	47	S	96	13	0.47	-	1.387	0.15	2.4	1.32	-	0.55
41	35	S	97	11	0.366	-	1.389	0.166	2.74	1.54	-	0.79
42	95	S	NA	3	-	-	-	-	-	-	-	-
43	27	BC	98	19	0.356	-	1.02	0.169	1.67	0.91	-	-
44	27	BC	98	18	0.397	-	1.254	0.117	1.84	1.55	-	-
45	22	S	NA	21	0.511	-	0.956	0.158	2.37	1.13	-	0.68
46	85	BC	45	12	0.476	-	1.263	0.213	2.17	1.25	-	0.47
47	85	BC	78	12	0.582	0.381	1.5	0.212	2.98	1.38	1.06	0.76
48	17	BC	97	11	0.457	-	1.45	0.212	2.46	1.22	1.03	0.86
49	17	BC	95	8	0.716	-	1.809	0.171	198	1.48	-	0.88
50	75	BC	64	13	0.623	-	1.532	0.168	2.26	0.85	1.11	-
51	70	BC	29	18	0.538	0.372	1.475	0.137	3.09	0.61	0.69	0.64
52	70	BC	48	16	0.543	-	1.236	0.113	2.73	0.59	1.14	0.8
53	104	BC	55	4	0.851	-	1.896	0.286	1.75	1.75	1.52	1.14
54	104	BC	82	5	0.774	0.514	2.186	0.243	2.6	2.08	1.26	2.91
55	50	BC	92	6	0.623	-	1.004	0.161	1.58	0.45	0.85	1.15
56	150	BC	88	24	0.556	-	1.488	0.184	1.77	1.88	-	1.78
57	92	S	NA	5	0.713	0.529	2.145	0.141	2.44	1.14	1.66	1.65
58	28	S	NA	3	0.386	-	4.629	0.703	4.39	5.92	-	1.14
59	79	S	NA	2	0.932	0.812	3.379	0.85	10.12	9.27	3.54	2.13
60	120	S	NA	3	0.71	0.818	3.846	0.7	8.84	7.8	2.2	1.52
61	35	BC	97	6	0.61	0.782	-	0.953	12.97	15.64	2	2.12
62	157	G	53	6	0.635	0.899	3.839	0.543	8.47	7.7	1.85	0.86

Appendix I. Continued

Sample number	Water depth (m)	Sample type	%Sand	%Heavy minerals	Elements (ppm) Eu	Tb	Yb	Lu	Hf	Ta	Th	U
63	48	G	100	10	1.179	1.225	12.38	1.868	11.44	13.56	6.91	1.99
64	20	G	100	8	-	-	-	-	-	-	-	-
65	31	G	100	13	0.653	1.453	12.276	1.8	16.25	15.11	4.27	1.55
66	199	G	24	1	0.908	-	1.896	0.303	2.49	2.12	2.72	2.32
67	80	G	64	2	1.182	1.612	5.39	0.815	6.4	6.77	4.12	4.35
68	123	G	64	6	1.104	1.072	5.753	0.796	11.42	12.47	4.3	1.98
69	38	G	100	5	0.57	1.53	16.764	2.433	18.66	19.1	4.28	2.24
70	329	G	42	1	1.079	0.727	3.807	0.429	9.61	6.56	4.01	2.68
71	117	G	94	2	1.173	0.996	7.519	1.132	9.6	12.35	5.25	3.7
72	35	G	100	10	0.265	0.881	10.499	1.95	20.18	22.22	2.77	1.31
73	21	G	100	5	0.486	0.637	9.661	1.694	20.06	21.88	2.17	0.94
BCR-1	-	-	-	-	1.964	1.13	3.616	0.517	5.57	1.02	6.05	1.7
DTS-1	-	-	-	-	-	-	-	-	-	-	-	-
FLYASH	-	-	-	-	2.527	1.799	6.354	0.928	7.8	2.2	23.95	11.76
NBS-688	-	-	-	-	-	-	-	-	-	-	-	-