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UNIVERSITY OF WASHINGTON

DEPARTMENT OF

OCEANOGRAPHY

Technical Report No. 118

MODERN SEDIMENTS OF WILLAPA BAY, WASHINGTON:
A COASTAL PLAIN ESTUARY

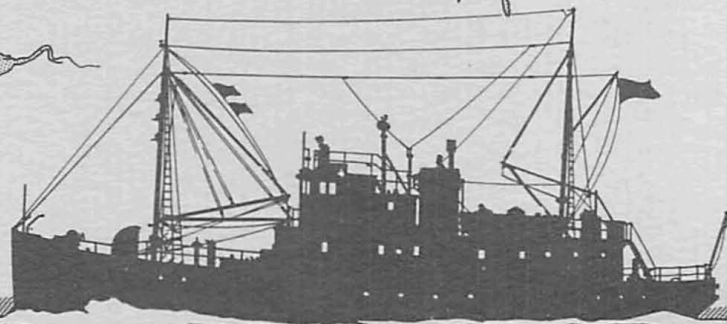
by

Robert S. Andrews

U.S. Atomic Energy Commission
Contract AT(45-1)-1725
RLO-1725-6

Office of Naval Research
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and Nonr-477(37)
Project NR 083 012

Reference M65-8
May 1965



SEATTLE, WASHINGTON 98105

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Clifford A. Barnes
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PRINCIPAL INVESTIGATOR

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ABSTRACT

Willapa Bay, a coastal plain estuary, contains extensive tidal flats cut by channels and distributaries. Well-sorted fine sand occurs throughout the bay, with increasing amounts of silt- and clay-size sediment present on the tidal flats near the south end of the bay and adjacent to the mouths of rivers flowing into the bay. The channels are generally scored of this fine sediment by strong bottom currents. Organic carbon and organic nitrogen contents increased with decreasing mean grain-size, and the ratio of carbon to nitrogen revealed two types of organic matter in the bay. One type, associated with the fine-grained sediment on the tidal flats, had an average ratio of 13.8; the other type, associated with the coarser channel sediments, had an average ratio of 6.1.

At the bay entrance a littoral drift to the north results in extensive shoaling north of Leadbetter Point and erosion on Cape Shoalwater. A southward migration of the channel through the tidal delta off the bay entrance indicates a littoral drift to the south in this area. Spits and shoals forming inside the bay entrance are a result of a net influx of fine sand into the bay from the eroding cape.

The distribution of brackish-water to marine suites of Foraminifera is closely related to the sedimentary environments in the bay. Heavy minerals indicate source areas for the sediment from the Columbia River drainage basin as well as the Willapa Bay drainage basin. Fine sand on the tidal flats east of Long Beach Peninsula is a relict of the growth of the spit.

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INTRODUCTION

The objectives of this research are to describe the physical and chemical properties of the modern sediments in Willapa Bay, Washington, to define the source areas for these sediments, and to determine the relations between the distribution of these sediments and the sedimentary environments. Seventy-three grab samples and five core samples were collected in Willapa Bay.

The only previous study of the bottom sediments in Willapa Bay was several textural analyses in the areas of dredging and harbor construction by the Seattle District Office, U.S. Army Corps of Engineers (unpublished data).

Description of Willapa Bay

Willapa Bay (formerly known as Shoalwater Bay) is an estuary on the Pacific coast of Washington (Fig. 1). The entrance to the bay is approximately 47 km north of the Columbia River mouth and 31 km south of the entrance to Grays Harbor. The bay has two arms, one extending east-west for approximately 19 km and the other extending north-south for approximately 29 km. Long Beach Peninsula, a low spit of sand and sand dunes, separates the south arm of Willapa Bay from the Pacific Ocean (Fig. 2). This spit averages 2.4 km in width and is covered with trees to within 3.5 km of Leadbetter Point. Long Island divides the south arm of Willapa Bay into two channels.

A survey completed in 1963 by the Seattle District Office, U.S. Army Corps of Engineers (unpublished data) showed that Willapa Bay covers an area of approximately 347.42 km² at mean higher high water (MHHW) and an area of approximately 157.94 km² at mean lower low water (MLLW). The calculated tidal prism was 0.720 km³. The bay drains approximately 2360 km² of rugged, wooded land lying between the drainage basins of Grays Harbor and the Columbia River. The major rivers flowing into Willapa Bay are the North, Willapa, and Naselle (formerly Nasel) Rivers.

A tidal delta extends about 4.8 km seaward of the bay entrance. The natural channel across the delta is maintained by dredging to a depth of 26 ft (7.9 m) below MLLW over a minimum width of 500 ft (152 m) (U.S. 83rd Congress, 1954). Prior to the initiation of this dredging in 1927 and to the present, the location of this bar channel has varied. Dredging is done along the natural trend of the channel. Beginning near the north end of the tidal delta, the location of the channel migrated southward until it was nearly parallel to the shoreline, where it shoaled as a new channel formed to the north and again began to migrate south. The period of this cycle, according to the U.S. Army Corps of Engineers Condition Surveys (1890-1962, unpublished charts), appears to be 10 to 20 years. The last shift of the tidal delta channel from its southernmost position to the north occurred in 1962. Figure 3 shows the location of this channel in 1932, 1942, 1953, and 1962.

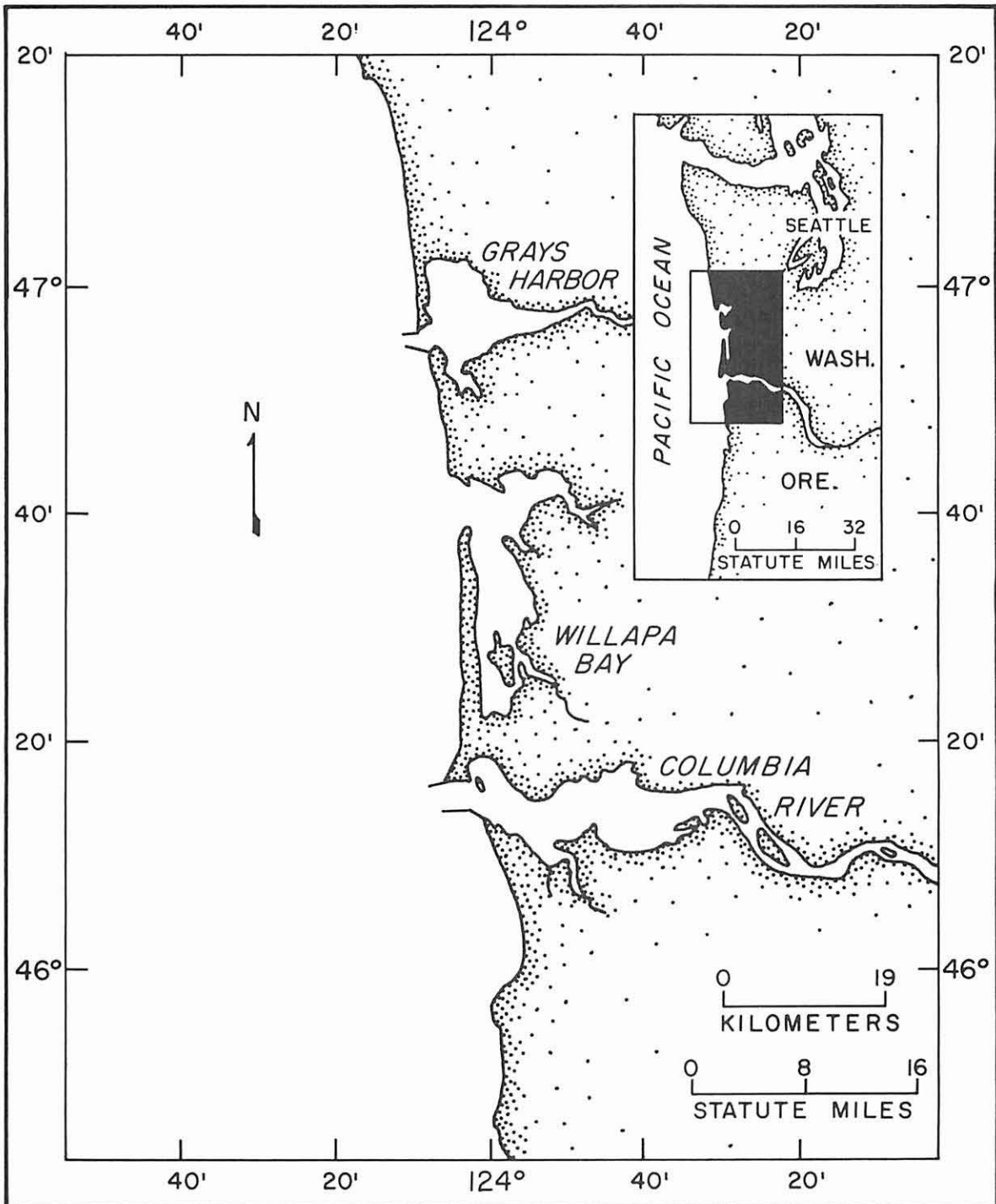


Fig. 1. Willapa Bay and the Washington-Oregon coast.

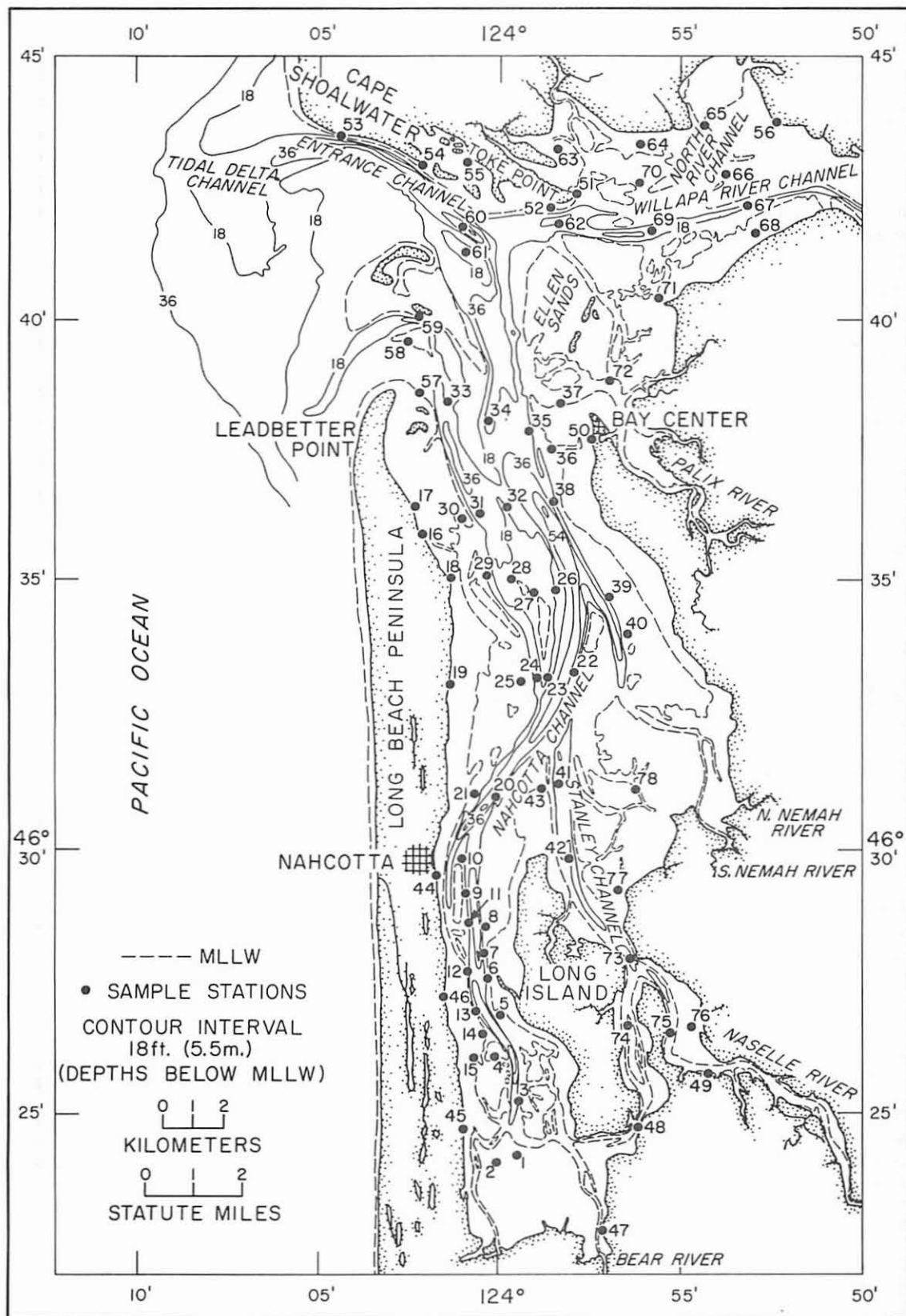


Fig. 2. Bathymetry and sample locations in Willapa Bay.

The predominant littoral drift along Long Beach Peninsula in the vicinity of the entrance to Willapa Bay is to the north due to the net northerly direction of wave energy flux (Ballard, 1964). Ballard (1964) and Cooper (1958) noted that prevailing winds and currents are from the north only during two or three summer months along the Washington coast. From 1932 to 1962, Cape Shoalwater eroded 1350 m toward the north, while the shoal area north and east of Leadbetter Point increased (U.S. Army Corps of Engineers Condition Surveys, 1932-1962, unpublished charts) (Fig. 3). The location of the thalweg of the channel through the entrance to Willapa Bay between Cape Shoalwater and Leadbetter Point migrated 1460 m to the north from 1932 to 1962. The bay entrance channel, unlike the tidal delta channel, requires no dredging and contains some of the greatest depths in Willapa Bay. Leadbetter Point eroded 850 m to the south from 1932 to 1962, and a second smaller bay entrance channel is naturally present through the shoal area north of the point. From 1887 to 1962, Cape Shoalwater eroded approximately 3000 m to the north, the main bay entrance channel thalweg migrated approximately 4000 m to the north, and Leadbetter Point eroded approximately 430 m to the south (U.S. Army Corps of Engineers Condition Surveys, 1890-1962, unpublished charts; U.S. Coast and Geodetic Survey, 1887-1962, unpublished work sheets).

Few cities and communities are located around the bay; there are no large industrial plants. The tidal flats are used extensively for raising oysters. The oyster beds are disturbed at least annually for seeding, breaking of oyster clusters, transplanting, and harvesting. Dredges which transplant and harvest penetrate the tidal flats about 5 to 10 cm (Clyde Sayce, Washington State Shellfish Commission, Ocean Park, personal communication).

Regional Geology

Willapa Bay lies west of the Coast Range in the Pacific Border Province (Fenneman, 1931). The Tertiary stratigraphy was studied by Weaver (1937) and the Tertiary geologic history was discussed by Snavely and Wagner (1963). Waters (1962) differentiated the basaltic rocks in the Pacific Border Province by their characteristic mineral suites.

The basaltic tuffs, agglomerates, and lavas (lower Eocene) outcropping at the northeastern end of Willapa Bay lie in a broad belt within an anticlinal uplift. A second small area of folded lavas occurs between the south end of the bay and the Columbia River. Between the two folds lies a major syncline within which the Oligocene marine shales and sandstones are overlaid unconformably by middle Miocene marine sandstones.

Long Beach Peninsula is a well-developed barrier spit on a marine depositional coast as defined by Shepard (1963). Elevations along the spit range from 6 to 12 m with a maximum of 24 m. The spit consists of low-lying, parallel beach ridges with linear bogs and numerous elongated lakes between them. Cooper (1958) described the sand dunes along the spit and adjacent beaches; Ballard (1964) described the beach sediments.

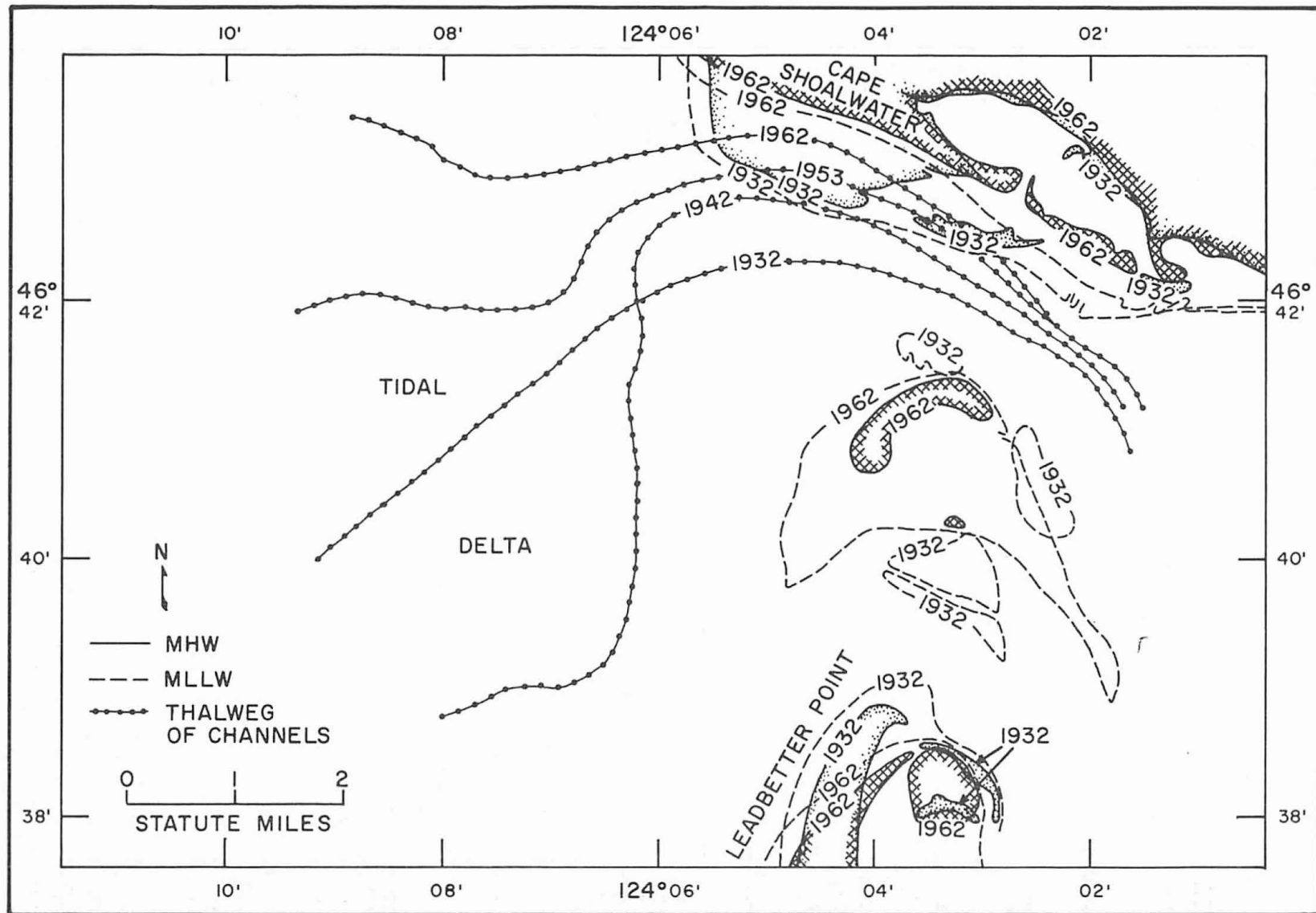


Fig. 3. Bathymetric changes at the entrance to Willapa Bay from 1932 to 1962.

The spit probably resulted from the migration of a barrier island from offshore during a period of submergence (Cooper, 1958) and from the littoral transport of material from the south. Trough blowouts, which appear oriented with the summer onshore winds, indicate transport of material from the spit into the bay.

Bathymetry

Approximately 55% of Willapa Bay is intertidal (between MLLW and MHHW). Major steep-sided channels from both arms meet near the entrance of the bay where the depth is greatest (97 ft; 30 m). Tributaries from the tidal flats and extensions of the river channels feed the main channels trending along the arms and are maintained by tidal currents. Shoaling occurs primarily in Stanley Channel at the confluence with Nahcotta Channel, at the confluence of the North and Willapa River Channels, and along the Willapa River Channel (Fig. 2). The Willapa River Channel is dredged from deep water near Toke Point into the main river channel for ship navigation (U.S. 83rd Congress, 1954).

General Oceanography

Cameron and Pritchard (1963) define an estuary as "a semienclosed coastal body of water having a free connection with the open sea and within which the sea-water is measurably diluted with fresh water deriving from land drainage." In terms of geomorphology, Willapa Bay may be described as a coastal plain estuary (Pritchard, 1952). Hydrographic data from the Washington State Department of Fisheries (1951-1962) showed that Willapa Bay is a well-mixed estuary, with marked stratification in the water column only during the late winter and early spring near the mouths of the major rivers.

The tides in Willapa Bay are the mixed type characteristic of the Pacific coast of the United States, showing a considerable diurnal inequality (Sverdrup, Johnson, and Fleming, 1942). The diurnal difference between MLLW and MHHW varies from 8.1 ft (2.5 m) at the bay entrance to 10.2 ft (3.1 m) at Nahcotta (U.S. Coast and Geodetic Survey, 1962). Average currents at the bay entrance at maximum flood and ebb are 2.5 knots (1.3 m/sec); currents of 4 to 6 knots (2.1 to 3.1 m/sec) occur at the entrance, the velocity being greatest on the ebb, particularly with a southerly wind (U.S. Coast and Geodetic Survey, 1959). Currents elsewhere in the bay were not measured, but water in the channels and the tributaries was characteristically turbid.

During storms, waves generated in Willapa Bay are large enough to move bottom sediment on the tidal flats during high tide. On October 28, 1962, a storm which occurred during high tide buried many oysters beneath sediment. Waves from the ocean breaking over the tidal delta at the entrance to the bay were observed reforming and carrying onto Cape Shoalwater and into the bay.

FIELD WORK

Sample stations were occupied along evenly spaced lines normal to the main channels (Fig. 2). Samples were collected on the tidal flats on each side of the bay where possible, in the channel, and at other points of bathymetric significance. Stations were located using a sextant and a portable depth recorder. Shallow stations of the tidal flats were occupied by wading; deeper stations were occupied from a small boat loaned by the Washington State Shellfish Commission Laboratory, Ocean Park. Some stations at the entrance to Willapa Bay were impossible to occupy because of large breaking waves and strong currents. All samples were collected during the Summers of 1962 and 1963.

Five core samples were obtained on tidal flats by pushing 2-inch (5-cm) inner diameter plastic core liner into the bottom by hand. Seventy-three grab samples were collected using a small van Veen (1936) bottom sampler of approximately 1 liter capacity. The average depth of penetration of the grab sampler was approximately 8 cm. The samples were stored in a cooler to retard decomposition.

DESCRIPTION OF SEDIMENTS

Each grab sample was analysed for texture and carbon content. The organic nitrogen content of selected samples was determined and the heavy mineral composition in certain size ranges of selected samples was studied. Foraminifera were identified.

The uppermost 8 cm and the lowermost 3 cm of each core were analysed for texture and carbon content. The core from Station 56 was also sampled in approximately the middle for texture and carbon content.

Texture of Sediments

Subsamples were subjected to the mechanical analysis outlined in Appendix I. Standard laboratory procedures were used for sieve and pipette analyses to determine the distribution of particle sizes in each sample (Krumbein and Pettijohn, 1938). The phi-grade scale (Krumbein, 1934; McManus, 1963) was used to describe grain sizes. The fractional weights for each 0.5 phi increment of each sample were tabulated and the descriptive size statistics were computed (Creager, McManus, and Collias, 1962; Collias *et al.*, 1963)(Table 1). The size statistics of Folk and Ward (1957), in phi notation, are used (Appendix I). The terms gravel, sand, silt, and clay were based on the size classification of Wentworth (1922).

Mean Grain-Size: Willapa Bay may be divided into two bathymetric areas, the tidal flats lying between MLLW and MHHW, and the channels and distributaries. Samples from only six stations below MLLW contained less than 75% sand (Fig. 4); one of these (Sample 13) contained more than 73% sand, four were from depths less than 5 ft (1.5 m) below MLLW, and one (Sample 69) was located in the Willapa River Channel. One of the tidal

Table 1. Willapa Bay sample locations, sand-silt-clay relationships, and size statistics.

SAMPLE ¹	LATITUDE N	LONGITUDE W	DEPTH ²	SAND-SILT-CLAY RELATIONSHIPS ³					FOLK AND WARD VALUES ⁴		
				GRAVEL %	SAND %	SILT %	CLAY %	CLASS	MEAN	DEV	SKEW
1g	46-24.2	123-59.4	tf	0.00	52.62	41.18	6.20	2	4.12	1.71	0.47
2g	46-24.1	124-00.1	tf	0.00	51.98	39.26	8.76	2	4.07	1.96	0.40
3t	46-25.3	123-59.4	tf	0.00	31.55	54.49	13.96	3	4.92	2.21	0.42
3b	(48 cm from top of core)			0.00	74.27	21.17	4.57	2	3.38	1.27	0.74
4g	46-26.1	124-00.1	tf	0.03	78.40	14.29	7.28	1	3.20	1.86	0.70
5g	46-26.9	123-59.8	1	0.00	58.47	32.72	8.81	2	3.79	1.98	0.67
6g	46-27.6	124-00.4	tf	0.00	68.83	23.78	7.39	2	3.59	1.63	0.84
7g	46-28.1	124-00.4	1	0.00	55.98	27.34	16.68	2	4.68	2.73	0.73
8g	46-28.6	124-00.4	1	0.00	19.96	56.73	23.31	7	6.18	2.80	0.54
9t	46-29.2	124-01.0	1	0.00	97.34	2.66	0.00	1	2.74	0.25	0.36
9b	(54 cm from top of core)			0.00	82.10	14.52	3.38	1	3.23	1.09	0.74
10g	46-29.8	124-01.0	tf	0.00	95.51	3.36	1.12	1	2.62	0.32	0.10
11g	46-28.6	124-00.8	20	0.00	88.99	8.18	2.83	1	2.69	0.82	0.46
12t	46-27.7	124-00.9	tf	0.00	73.49	20.85	5.66	2	3.44	1.39	0.75
12b	(51 cm from top of core)			0.00	73.11	20.92	5.98	2	3.54	1.57	0.55
13g	46-27.0	124-00.6	15	0.00	73.67	18.04	8.29	2	3.64	1.93	0.80
14g	46-26.5	124-00.5	tf	0.00	79.99	15.14	4.87	1	3.22	1.43	0.74
15g	46-26.1	124-00.7	tf	0.00	78.90	15.46	5.64	1	3.21	1.47	0.74
16t	46-35.0	124-02.1	tf	0.00	65.52	28.45	6.03	2	3.42	1.67	0.67
16b	(15 cm from top of core)			0.00	94.53	5.11	0.36	1	2.47	0.51	0.16
17g	46-36.5	124-02.3	tf	0.00	95.53	3.35	1.12	1	2.51	0.35	0.26
18g	46-35.1	124-01.4	tf	0.00	97.88	1.74	0.39	1	2.58	0.32	0.26
19g	46-33.1	124-01.4	tf	0.54	98.64	0.82	0.00	1	2.32	0.31	0.00
20g	46-31.0	124-00.0	33	0.00	96.57	2.67	0.76	1	2.59	0.28	0.32
21g	46-31.0	124-00.7	15	0.28	97.94	1.79	0.00	1	2.41	0.29	0.01

¹g=grab, t=top of core, m=middle of core, b=bottom of core.

²ft from MLLW, tf=tidal flat.

³Shepard, 1954. (See Fig. 4 for class meaning)

⁴phi notation, Folk and Ward, 1957.

Table 1. (continued)

SAMPLE	LATITUDE	LONGITUDE	DEPTH	SAND-SILT-CLAY RELATIONSHIPS					FOLK AND WARD VALUES		
				GRAVEL	SAND	SILT	CLAY	CLASS	MEAN	DEV	SKEW
				$\%$	$\%$	$\%$	$\%$				
22g	46-33.3	123-58.0	40	0.00	97.07	2.93	0.00	1	2.37	0.31	0.14
23g	46-33.2	123-58.7	20	0.00	98.51	1.49	0.00	1	2.14	0.37	-0.01
24g	46-33.2	123-59.0	33	0.00	98.79	1.21	0.00	1	2.28	0.32	0.15
25g	46-33.2	123-59.4	1	0.07	88.82	7.40	3.70	1	2.53	0.84	0.48
26g	46-34.9	123-58.4	30	0.00	98.56	1.44	0.00	1	2.36	0.28	0.09
27g	46-34.8	123-59.0	6	0.01	98.91	1.08	0.00	1	2.45	0.27	-0.17
28g	46-35.1	123-59.6	25	0.00	99.73	0.27	0.00	1	2.14	0.28	0.07
29g	46-35.1	124-00.4	12	0.00	93.68	4.30	2.02	1	2.71	0.54	0.52
30g	46-36.2	124-01.1	tf	0.00	98.83	1.17	0.00	1	2.37	0.25	-0.25
31g	46-36.3	124-00.5	32	0.00	99.37	0.63	0.00	1	2.38	0.29	-0.39
32g	46-36.5	123-59.8	24	0.00	99.45	0.55	0.00	1	2.31	0.29	-0.28
33g	46-38.4	124-01.4	27	0.00	100.00	0.00	0.00	1	2.22	0.30	0.06
34g	46-38.1	124-01.4	18	0.00	99.73	0.27	0.00	1	2.27	0.30	0.02
35g	46-37.9	123-59.2	14	0.00	100.00	0.00	0.00	1	2.24	0.29	0.09
36g	46-37.6	123-58.6	1	0.00	100.00	0.00	0.00	1	2.34	0.30	-0.01
37g	46-38.4	123-58.3	3	0.00	91.84	6.58	1.58	1	2.76	0.55	0.51
38g	46-36.5	123-58.5	21	0.00	80.82	11.63	7.55	1	3.25	1.52	0.76
39g	46-34.7	123-57.1	1	0.00	81.06	13.02	5.92	1	3.23	1.28	0.76
40g	46-34.0	123-56.5	1	0.00	94.70	5.30	0.00	1	2.62	0.40	0.69
41g	46-31.2	123-58.4	27	0.00	97.65	1.57	0.78	1	2.53	0.25	-0.22
42g	46-29.9	123-58.0	22	0.00	97.08	1.70	1.22	1	2.63	0.22	0.39
43g	46-31.1	123-58.2	tf	0.21	94.24	3.85	1.71	1	2.56	0.50	0.31
44g	46-29.5	124-01.7	tf	0.00	88.32	8.44	3.24	1	2.46	0.88	0.55
45g	46-24.7	124-01.0	tf	0.00	89.54	7.22	3.24	1	2.66	0.81	0.69
46g	46-27.2	124-01.5	tf	0.00	96.39	2.55	1.06	1	2.44	0.31	0.28
47g	46-22.8	123-57.1	tf	0.00	5.02	65.15	29.83	7	6.92	2.33	0.37
48g	46-24.8	123-56.2	tf	44.00	32.79	14.53	8.68	1	0.90	4.14	0.53
49g	46-25.8	123-54.2	tf	0.57	21.47	67.33	10.63	3	5.18	2.38	0.28
50g	46-37.7	123-57.4	tf	0.00	64.50	32.64	2.86	2	3.51	0.86	0.14
51g	46-42.4	123-57.4	tf	0.00	83.28	11.15	5.57	1	2.84	1.52	0.71

Table 1. (continued)

SAMPLE	LATITUDE	LONGITUDE	DEPTH	SAND-SILT-CLAY RELATIONSHIPS					FOLK AND WARD VALUES		
				GRAVEL	SAND	SILT	CLAY	CLASS	MEAN	DEV	SKEW
	<u>N</u>	<u>W</u>		<u>%</u>	<u>%</u>	<u>%</u>	<u>%</u>				
52g	46-42.1	123-58.6	tf	0.00	95.11	3.91	0.98	1	2.56	0.42	0.27
53g	46-43.5	124-04.5	tf	0.00	100.00	0.00	0.00	1	2.44	0.32	-0.16
54g	46-42.9	124-02.2	tf	0.00	99.72	0.28	0.00	1	2.43	0.41	-0.24
55g	46-43.0	124-00.9	tf	0.00	97.15	2.85	0.00	1	2.62	0.40	0.13
56t	46-43.8	123-52.4	tf	0.00	47.89	41.28	10.83	2	4.56	2.13	0.46
56m	(16 cm from top of core)			0.00	7.46	63.09	29.44	7	6.85	2.63	0.29
56b	(27 cm from top of core)			0.00	5.65	61.17	33.19	7	7.26	2.51	0.33
57g	46-38.6	124-02.2	5	0.00	100.00	0.00	0.00	1	2.42	0.26	0.08
58g	46-39.6	124-02.6	12	0.00	100.00	0.00	0.00	1	2.19	0.32	0.02
59g	46-40.0	124-02.3	58	0.47	99.53	0.00	0.00	1	1.97	0.38	0.00
60g	46-41.8	124-01.1	91	0.87	98.53	0.60	0.00	1	2.21	0.30	0.02
61g	46-41.3	124-01.0	15	0.00	100.00	0.00	0.00	1	2.18	0.33	0.07
62g	46-41.8	123-58.4	41	0.00	99.41	0.59	0.00	1	2.33	0.30	-0.10
63g	46-43.2	123-58.4	tf	0.00	90.68	6.02	3.30	1	2.56	0.71	0.33
64g	46-43.4	123-56.1	tf	0.00	98.88	1.12	0.00	1	2.40	0.27	-0.07
65g	46-43.7	123-54.4	12	0.00	97.85	1.17	0.98	1	2.18	0.58	0.10
66g	46-42.8	123-53.8	tf	0.00	66.42	24.71	8.87	2	3.73	1.93	0.83
67g	46-42.2	123-53.2	24	0.00	98.57	1.07	0.36	1	2.62	0.21	0.35
68g	46-41.7	123-52.9	tf	0.00	29.95	56.00	14.05	3	4.93	2.49	0.52
69g	46-41.7	123-55.8	41	0.00	42.20	47.89	9.91	3	4.56	2.15	0.42
70g	46-42.6	123-56.2	6	0.00	89.53	6.33	4.15	1	2.21	1.53	-0.06
71g	46-40.4	123-55.6	tf	0.00	74.02	21.85	4.12	2	3.13	1.41	0.69
72g	46-38.8	123-57.0	10	0.00	80.79	14.96	4.25	1	3.18	1.24	0.69
73g	46-28.0	123-50.4	62	0.07	97.10	1.83	1.00	1	2.57	0.20	0.52
74g	46-26.7	123-56.4	10	0.00	94.47	3.57	1.96	1	2.64	0.42	0.46
75g	46-26.6	123-55.3	24	0.00	87.58	7.26	5.16	1	2.04	1.77	0.34
76g	46-26.6	123-54.7	tf	0.00	32.98	52.69	14.33	3	4.85	2.47	0.46
77g	46-29.2	123-56.7	tf	0.00	20.59	61.46	17.95	3	5.48	2.41	0.54
78g	46-31.2	123-56.2	4	0.00	34.94	51.85	13.21	3	4.77	2.34	0.45

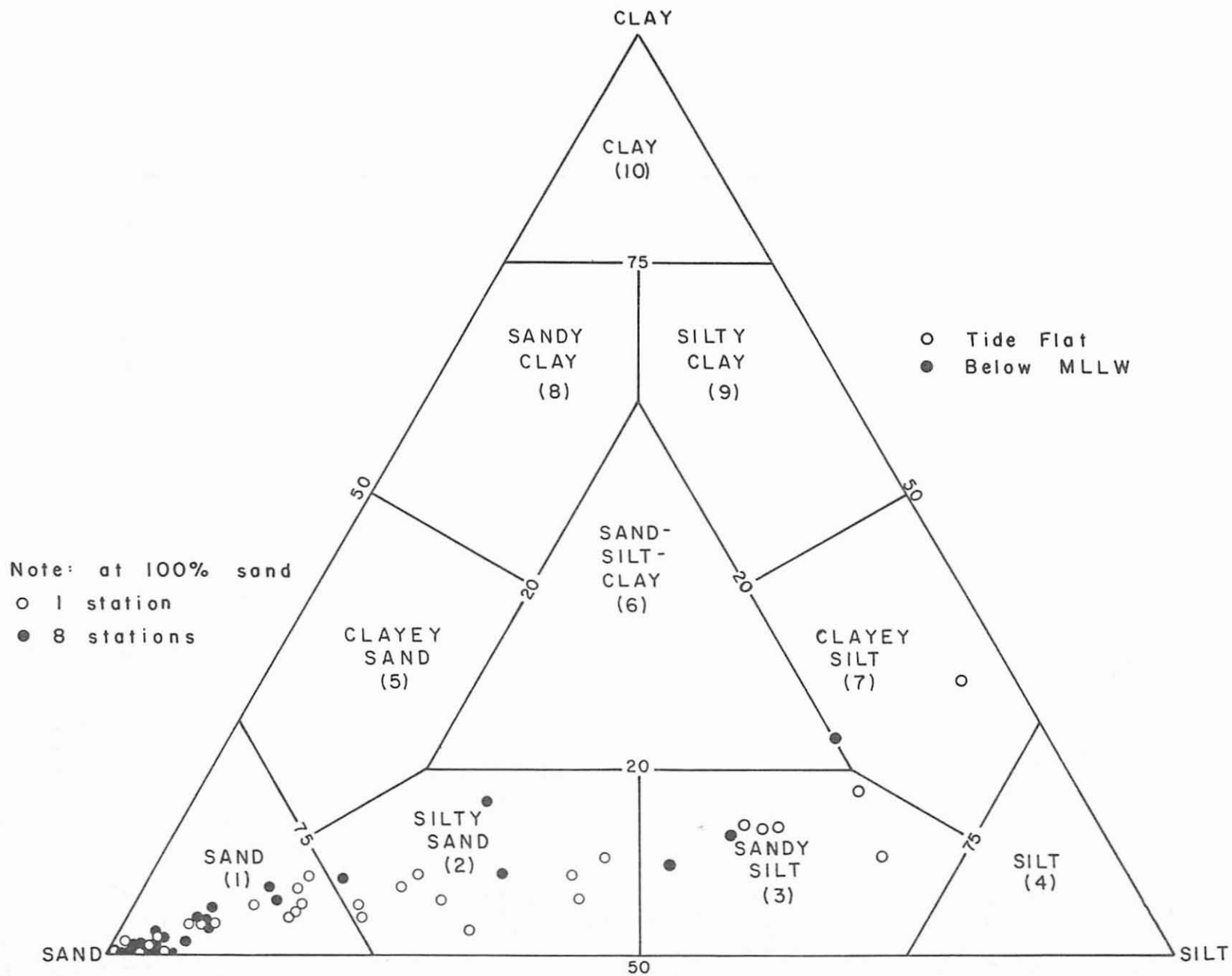


Fig. 4. Sand-silt-clay relationships for Willapa Bay samples.

flat samples and eight samples from depths below MLLW were composed of 100% sand. The sediments on the tidal flats ranged from 100% sand at the bay entrance on Cape Shoalwater (Sample 53) to 5% sand at the south end of the bay near the mouth of the Bear River (Sample 47).

The sediments from 62% of the sampling stations had a mean grain-size in the fine-sand class (3 phi; Fig. 5). Mean grain-size for sediments on the tidal flats exhibited a wide range from fine sand to silt (4 phi to 8 phi), while most of the sediments below MLLW were in the fine-sand class. Along Nahcotta Channel, the mean grain-size increased from Sample 13 northward to Sample 60 near the bay entrance. The mean grain-size generally decreased from the tidal flat samples near the channels and distributaries to the tidal flat samples near the high water line. Station 48, 44% gravel, contained road metal from a nearby highway, causing an unnatural composition.

The mean grain-size of Sample 16 increased with depth in the core. The sediments at the location of this sample, as well as at Samples 17, 18, and 19, contained a 1- to 2-mm layer of silt- and clay-size material on the tidal flat surface, beneath which the material was coarser. The mean grain-size of Sample 3 also increased with depth in the core, but the layering mentioned above was not noted. In Samples 9 and 12, the mean grain-size decreased with depth in the cores; Sample 56, taken in a marshy area, also showed a decrease in mean grain-size with depth in the core.

Standard Deviation: The standard deviation, used as a measure of sediment sorting, increased markedly with a decrease in the mean grain-size (Fig. 6). Due to this relationship and the relationship between mean grain-size and depth of the sample, standard deviation and sample depth were also related. Sediments at the deeper stations tended to exhibit better sorting, with the exceptions of Samples 69, 72, and 75, which were located in channels near the mouths of rivers. As with the mean grain-size, wide ranges of units of standard deviation were found on the tidal flats. The best-sorted sediments were located at the bay entrance, in the depths along Nahcotta Channel, and along Stanley Channel.

The sorting in Samples 3 and 16 improved with depth in the core in conjunction with an increase in mean grain-size. In Samples 9, 12, and 56, the sorting became poorer with depth in the core as the mean grain-size decreased.

Skewness: The negatively skewed sediments (skewness less than -0.10) and the nearly symmetrical sediments (skewness between 0.10 and -0.10) had mean grain-sizes larger than 2.5 phi; sediments with mean grain-sizes finer than 2.5 phi were positively skewed. Approximately 83% of the tidal flat samples and 54% of the samples from below MLLW were positively skewed (skewness greater than 0.10; Fig. 7). Samples exhibiting negative skewness were found on the sand flats at Cape Shoalwater and in the south arm of Willapa Bay along Nahcotta Channel (Samples 30, 31, and 32).

Skewness within the cores showed no trends.

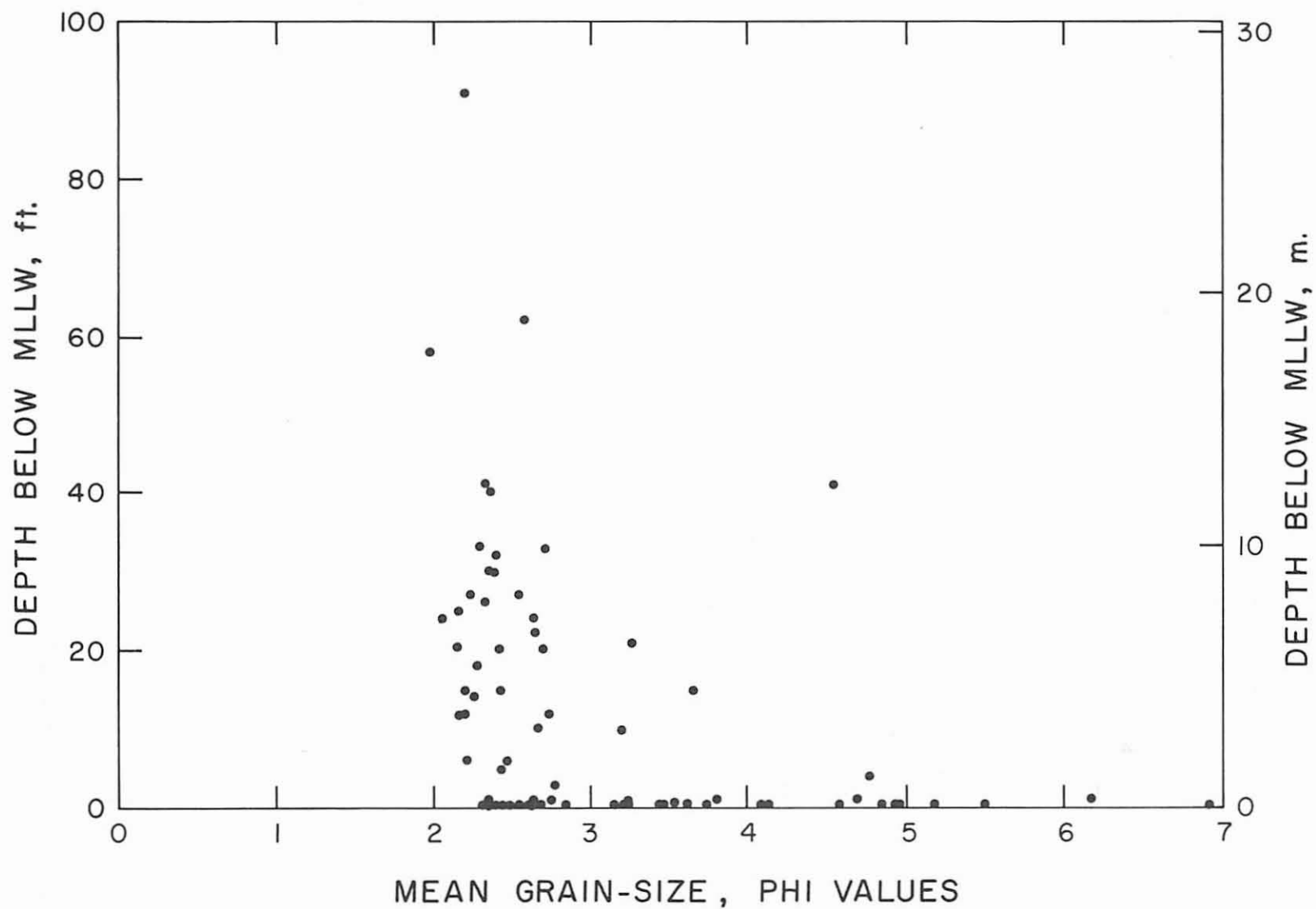


Fig. 5. Mean grain-size as a function of depth.

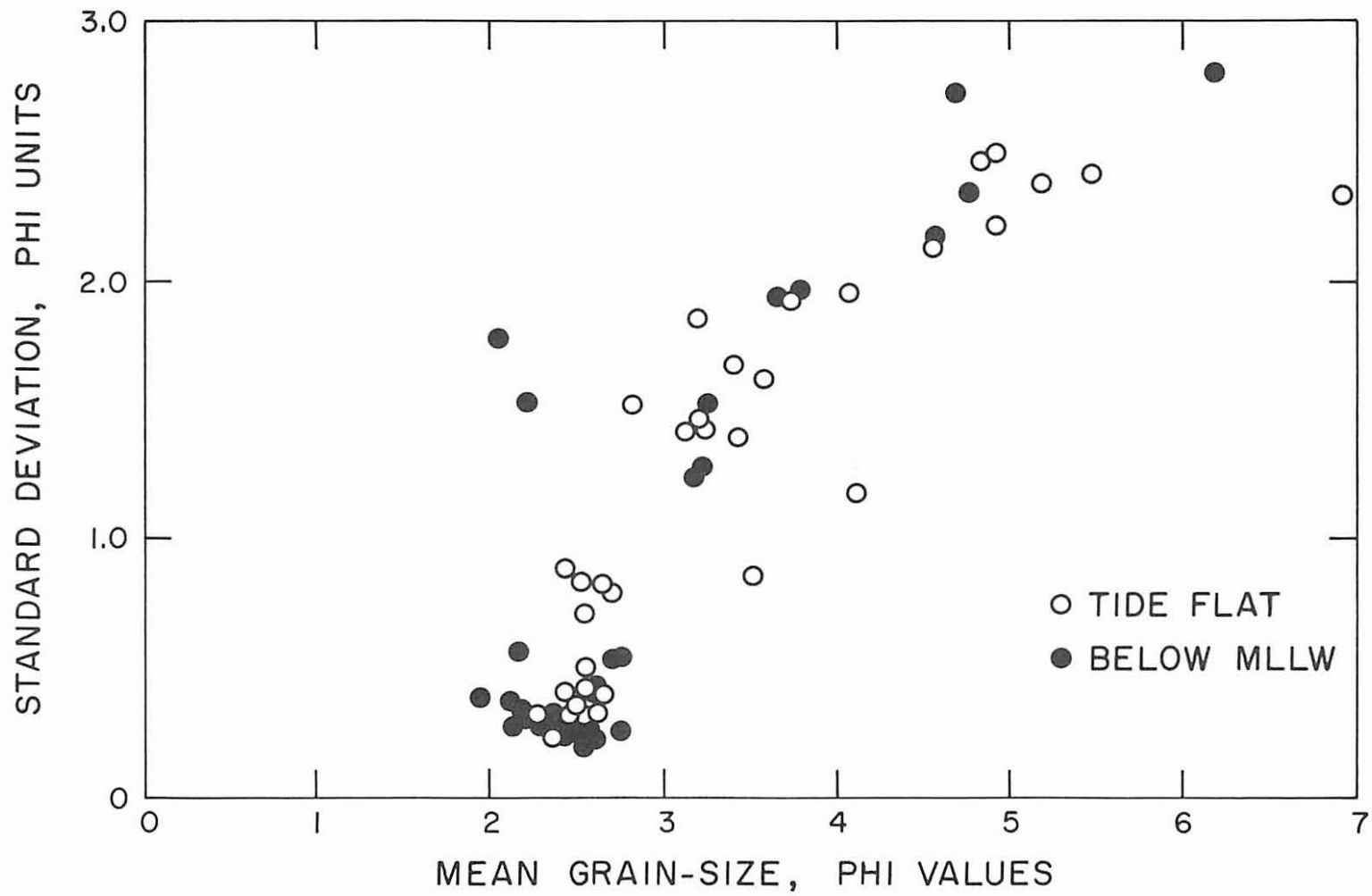


Fig. 6. Standard deviation as a function of mean grain-size.

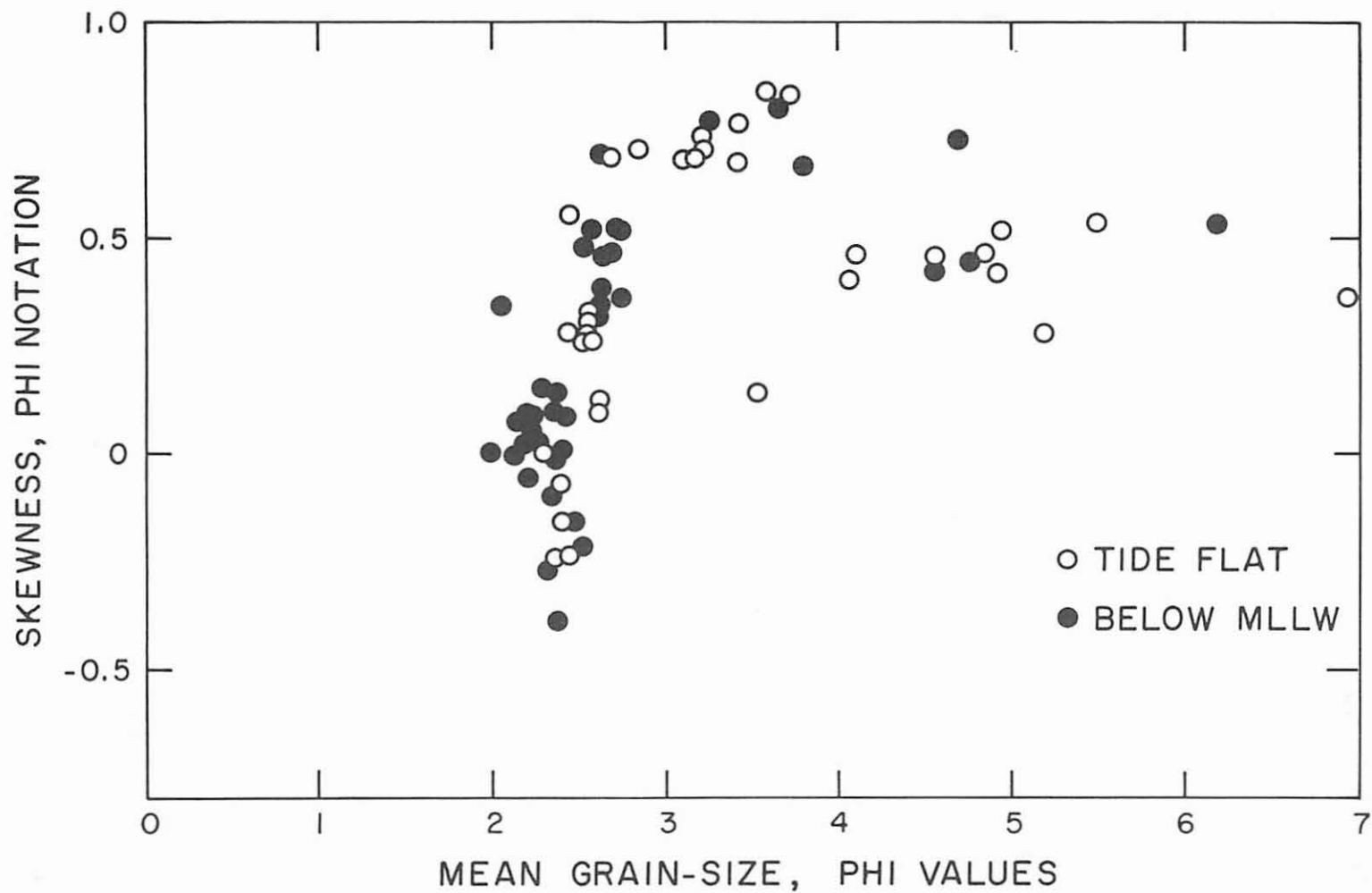


Fig. 7. Skewness as a function of mean grain-size.

Composition of Sediments

Subsamples were ground to finer than 4 phi for analyses of their carbon content (Appendix II). Twelve samples, over the range of carbon content for the Willapa Bay sediments, were analysed for organic nitrogen content (Appendix III). Fractions of each phi size in the sand classes (-1 to 4 phi) of each sample were examined under a microscope for Foraminifera; heavy mineral analyses were made on the 3- and 4-phi size classes of selected samples (Appendix IV).

Carbon: Large fragments of shells were picked from the samples before chemical analyses were conducted. Carbonate-carbon content (percentage of carbon present in the sample as carbonate) ranged from 0 to 1.5% carbon (Table 2). Only 12 samples had measurable amounts of carbonate-carbon, and each contained tests of Foraminifera and Ostracoda with small shell fragments. All but one of these samples had a mean grain-size in the fine- and very fine-sand classes (Fig. 8).

The organic carbon content of the samples was calculated as the difference between the total carbon content and the carbonate-carbon content. Values of 0.1 to 2.5% carbon were found, the higher percentages associated with finer-size tidal flat sediments (Fig. 9). An odor of hydrogen sulfide was noted beneath the thin layer of fine material covering the surface of the tidal flats at Stations 16, 17, 18, and 19. Hydrogen sulfide was also noted in the sediments at Stations 44, 46, 49, and 56.

Only the core from Station 56 showed a marked increase in organic carbon with core depth; 0.7% carbon at the top; 1.2% in the middle of the core; 2.6% at the bottom. This increase in organic carbon with depth in the core is associated with a decrease in mean grain-size.

Table 2 gives the percentages of organic carbon for all the samples containing measurable percentages of carbonate-carbon.

Organic Nitrogen: The organic nitrogen content for 12 samples, representing the range of carbonate-carbon and organic carbon percentages, varied from 0.01 to 0.19% nitrogen (Table 2). The ratios between organic carbon (C) and organic nitrogen (N) were from 2.0 to 15.2. The C/N slope of a least-squares regression line was 12.7; the x-intercept was 0.018% organic nitrogen (Fig. 10). For the tidal flat samples, the C/N slope of a least-squares regression line was 10.4; the x-intercept was -0.039% organic nitrogen. The C/N slope of a least-squares regression line for the samples taken below MLLW was 5.2; the x-intercept was -0.007% organic nitrogen.

Heavy Minerals: Heavy mineral separations were made using bromoform (sp gr 2.85) on the fine-sand (2- to 3-phi) and very fine sand (3- to 4-phi) size classes of some samples and the mineral fractional percentages were determined (Tables 3 and 4; Appendix IV). These size classes were studied as they included the modal size of most of the samples and contained the greatest concentrations of

Table 2. Carbonate-carbon, organic carbon (C), and organic nitrogen (N) contents in Willapa Bay sediments, with C-N ratios.

<u>SAMPLE STATION</u>	<u>PERCENTAGE, BY VOLUME, OF THE TOTAL SAMPLE</u>			<u>C/N</u>
	<u>CARBONATE- CARBON</u>	<u>ORGANIC CARBON (C)</u>	<u>ORGANIC NITROGEN (N)</u>	
3	0.00	1.22	0.08	15.2
9	0.07	0.12	0.04	3.0
16	0.00	1.79	0.13	13.8
18	0.20	0.11		
19	0.08	0.22		
21	0.23	0.19		
25	0.13	0.27	0.06	4.5
29	0.01	0.65	0.04	16.2
35	0.01	0.06	0.03	2.0
47	0.01	2.37	0.19	12.5
50	0.09	0.62		
59	0.14	0.02		
60	0.01	0.07	0.01	7.0
67	0.00	0.19	0.04	4.8
69	0.61	1.15		
71	0.86	0.39		
72	0.08	0.65		
74	1.51	0.51	0.09	5.7
75	0.40	0.76	0.14	5.4
77	0.01	2.05	0.16	12.8

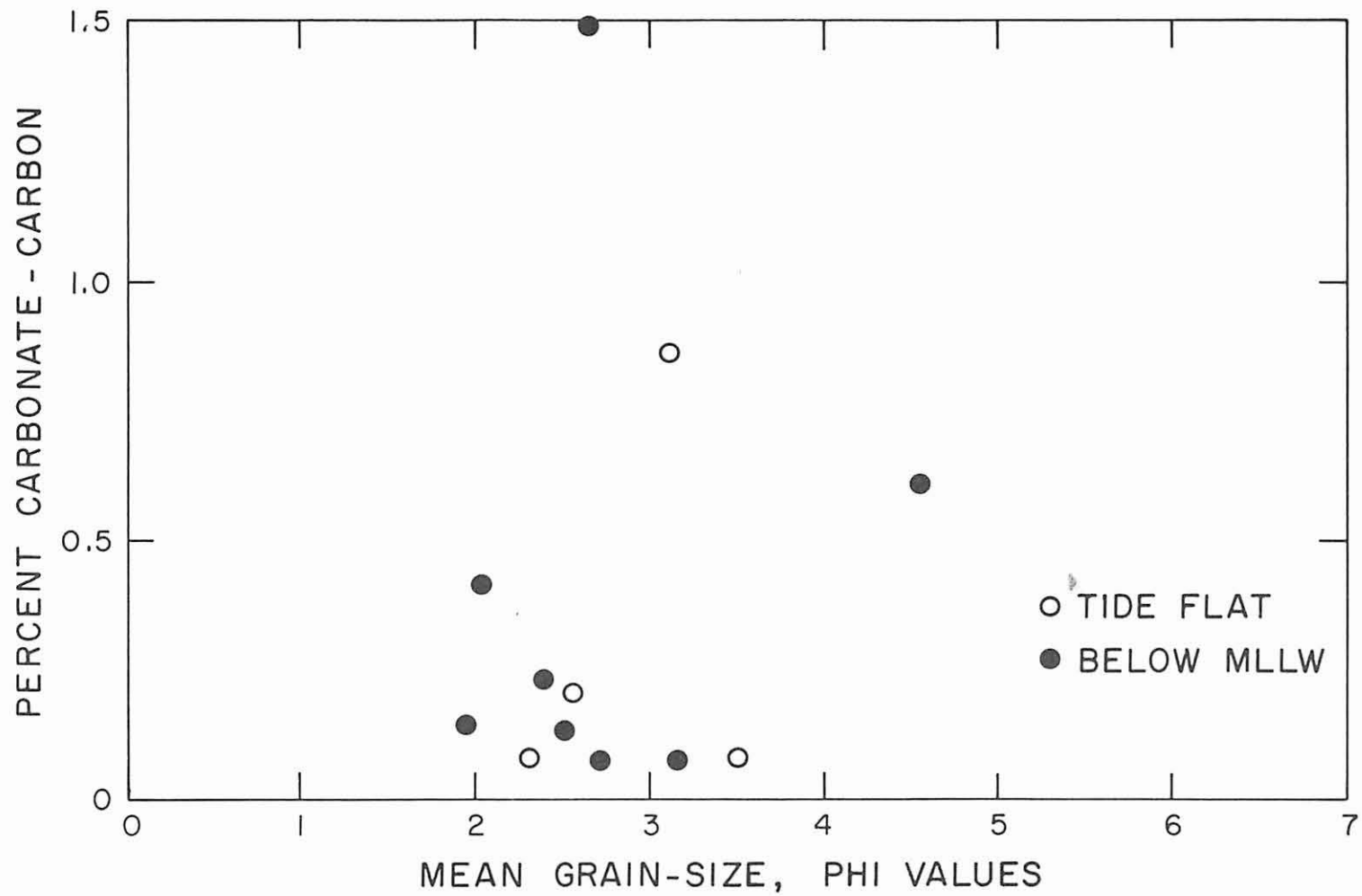


Fig. 8. Percentage carbonate-carbon as a function of mean grain-size.

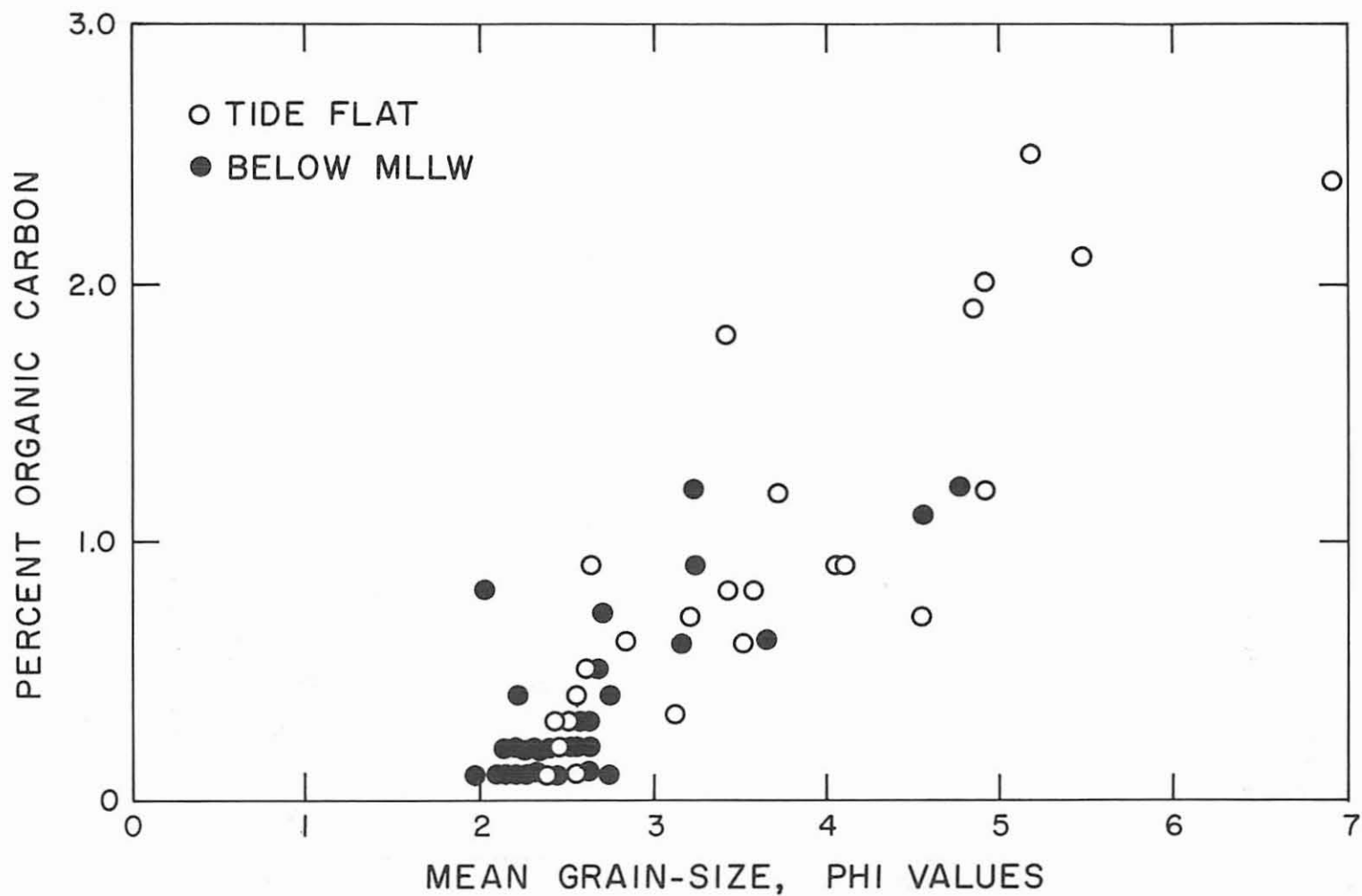


Fig. 9. Percentage organic carbon as a function of mean grain-size.

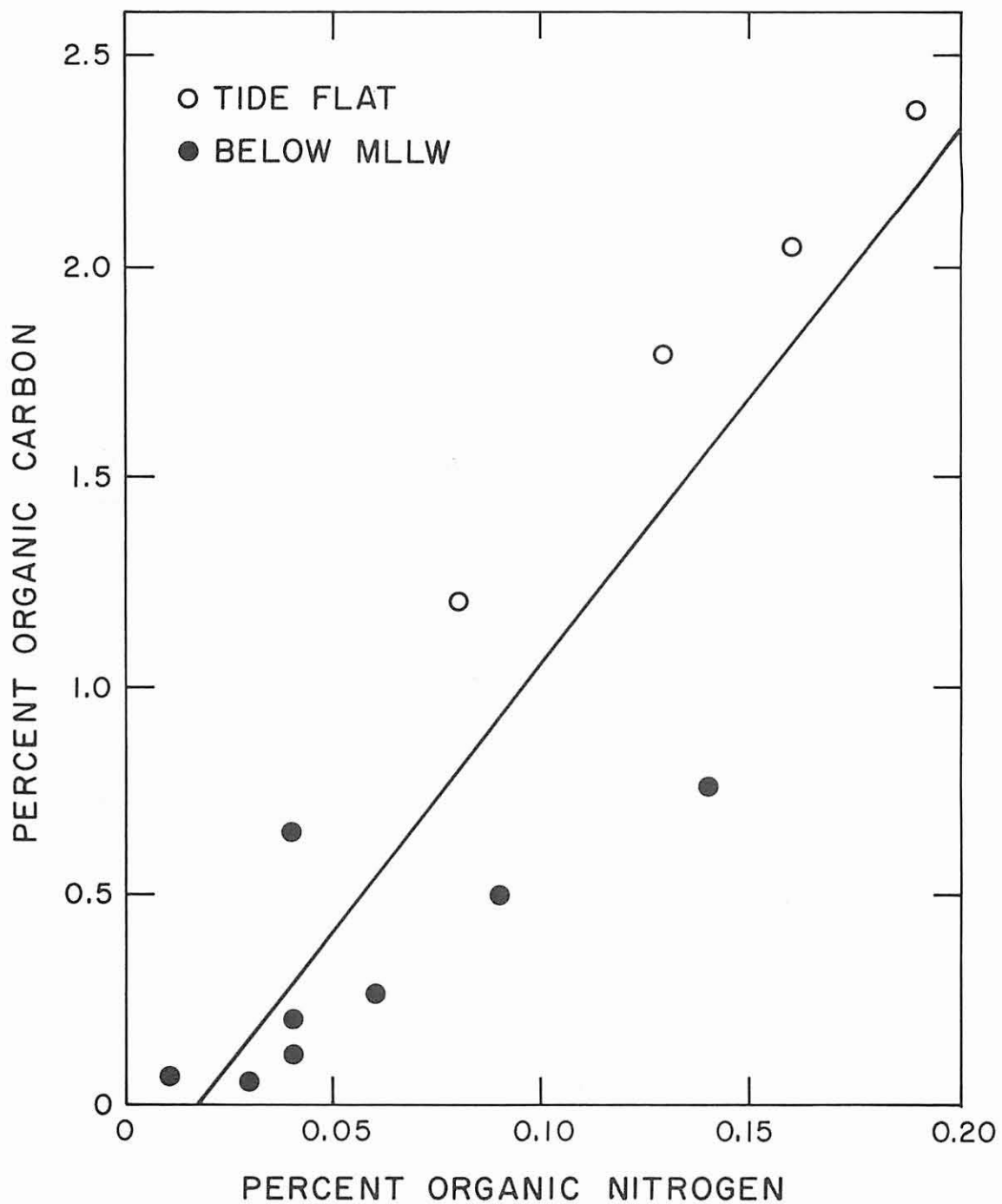


Fig. 10. Percentage organic carbon as a function of percentage organic nitrogen, with the least squares regression line for all the samples.

Table 3. Percentages of heavy and magnetic fractions at selected sample stations for the 3- and 4-phi size classes.

<u>SAMPLE STATION</u>	<u>PERCENTAGE, BY WEIGHT, OF THE TOTAL SIZE CLASS</u>			
	<u>3-PHI</u>		<u>4-PHI</u>	
	<u>HEAVY FRACTION</u>	<u>MAGNETIC FRACTION</u>	<u>HEAVY FRACTION</u>	<u>MAGNETIC FRACTION</u>
6	1.6	0.2	16.2	3.8
9	4.4	0.6	18.1	1.9
18	17.7	2.2	82.8	24.3
20	4.2	0.7	33.7	4.9
22	5.3	0.9	37.3	6.0
26	6.3	1.2	58.2	12.6
27	8.5	1.0	40.1	5.1
28	9.2	0.8	59.1	11.4
29	7.0	1.8	17.9	2.8
32	4.8	0.4	37.7	4.8
34	5.9	0.8	49.0	6.3
39	7.3	0.9	13.0	1.3
40	9.0	0.9	31.0	3.4
57	4.4	1.2	49.7	11.2
58	5.9	1.5	13.9	3.6
59	9.0	2.4	43.4	7.6
60	5.3	0.5	24.4	2.9
61	9.8	3.1	49.4	15.8
62	8.3	0.5	45.6	4.1
67	6.4	0.6	29.0	2.3
69	8.3	0.7	11.7	1.0

Table 4. Composition of the heavy fraction in Willapa Bay for the 3- and 4-phi size classes.

SAMPLE	SIZE CLASS	PERCENTAGE, BY NUMBER, OF THE HEAVY FRACTION ¹												
		ORTHO	CLINO	AMPH	GARN	KYAN	SILL	MUSC	MICA	EPID	ZIRC	SPH	LITH	OPAQ
6	3	5	tr ²	12	tr	tr	tr	3	2	tr			73	4
	4	2	2	16	tr	tr	tr	tr	1				28	49
9	3	4	3	11			tr	1	tr				71	9
	4	22	5	17	3	tr			tr				33	19
18	3	24	5	18	5	tr	tr		tr				36	10
	4	31	6	13	6					tr	tr	tr	11	31
20	3	16	2	10	tr	tr		tr	tr				64	6
	4	31	4	18	3	tr		tr					35	9
22	3	14	4	11	2	tr			tr	tr	tr		59	8
	4	20	5	14	3	tr			tr	tr	tr	tr	42	14
26	3	14	7	12	2	tr			tr	tr			61	2
	4	20	4	9	4				tr	3	1	1	24	33
27	3	16	7	7	tr	tr	tr	tr	tr				59	10
	4	33	3	11	3	tr	tr		3				39	7
28	3	9	4	6	tr	tr	tr	3	5				54	18
	4	8	1	9	tr		tr	5	7	tr			52	17

¹ORTHO=orthopyroxenes, CLINO=clinopyroxenes, AMPH=amphiboles, GARN=garnets, KYAN=kyanite, SILL=sillimanite, MUSC=muscovite, MICA=other micas, EPID=epidote, ZIRC=zircon, SPH=sphene, LITH=lithic fragments, OPAQ=opaque minerals.

²tr=minerals present in amounts less than 0.5% of the heavy fraction.

Table 4. (continued)

SAMPLE	SIZE CLASS	PERCENTAGE, BY NUMBER, OF THE HEAVY FRACTION												
		ORTHO	CLINO	AMPH	GARN	KYAN	SILL	MUSC	MICA	EPID	ZIRC	SPH	LITH	OPAQ
29	3	4	3	11	tr			1	tr				75	5
	4	11	2	12	tr	tr			tr	tr			72	1
32	3	7	4	8	1	tr		tr	tr	tr	tr	tr	76	3
	4	14	6	16	4	tr	tr			5	tr	tr	40	12
34	3	23	2	8	tr		tr	tr	tr	tr			57	7
	4	43	4	17	4	1	tr		tr	tr			18	12
39	3	3	tr	6	tr			2	6	tr			79	3
	4	6	3	5	tr	tr		tr	1	tr	tr		82	1
40	3	12	3	9	tr				tr	tr			68	7
	4	24	4	16	4	tr	tr			tr			39	12
57	3	5	2	8		tr						tr	82	2
	4	17	7	10	3		tr			tr	tr	tr	31	30
58	3	5	tr	2	tr								85	8
	4	7	3	5	tr	tr	tr			1	tr		75	7
59	3	7	3	6		tr				tr			79	4
	4	20	8	10	3		tr			4	tr	tr	46	7
60	3	12	4	14				tr	tr				65	4
	4	31	6	19	4	tr	tr						27	12
61	3	7	2	5	tr		tr	tr		tr			80	5
	4	28	5	17	2	tr			tr			tr	36	10

Table 4. (continued)

<u>SAMPLE</u>	<u>SIZE</u> <u>CLASS</u>	<u>PERCENTAGE, BY NUMBER, OF THE HEAVY FRACTION</u>												
		<u>ORTHO</u>	<u>CLINO</u>	<u>AMPH</u>	<u>GARN</u>	<u>KYAN</u>	<u>SILL</u>	<u>MUSC</u>	<u>MICA</u>	<u>EPID</u>	<u>ZIRC</u>	<u>SPH</u>	<u>LITH</u>	<u>OPAQ</u>
62	3	6	2	4	tr					tr	tr	83	4	
	4	16	11	9	4	tr				4	tr	47	8	
67	3	3	2	7	tr				tr	tr		87	tr	
	4	16	6	18	tr	tr						50	9	
69	3	6	3	13	1	tr		tr	1			69	5	
	4	9	6	14	3	tr		tr	tr		tr	57	10	

heavy minerals. A marked increase in the percentage of heavy minerals was noted with decreasing grain size class. Sample 18 had high concentrations of heavy minerals and magnetic minerals in the very fine-sand size class. There was a general increase in heavy and magnetic minerals from Sample 6 in Nahcotta Channel northward through Samples 9, 20, 22, 26, 32, and 34 to Sample 61 near the bay entrance.

The opaque minerals were mostly magnetite, with a few grains of ilmenite and rutile. The orthopyroxenes were primarily hypersthene; small amounts of enstatite were present. Most of the hypersthene grains contained minute inclusions (Schiller-structure); many of the grains were euhedral. Solution was indicated on the orthopyroxene and clinopyroxene grains by hacksaw terminations (Pettijohn, 1957). The predominant amphiboles were green hornblende and brown basaltic hornblende.

Light Fraction: Although no mineral counts were made of the light fraction (less than 2.85 sp gr) of the samples in Willapa Bay, some interesting features were noted. Most of the samples contained 70 to 90% lithic fragments. The most common light mineral was quartz, as rounded to well-rounded grains. Some frosted grains were present in Samples 17, 18, 19, and 21. Small percentages of unaltered plagioclase feldspar were also in the light fraction.

Only eight samples lacked volcanic pumice. The average refractive index of glass fragments in the pumice was 1.507. Small inclusions of opaque (usually magnetic) minerals were present in the pumice.

Tests of Foraminifera and Radiolaria, shells of Ostracoda, spines of Echinodermata, and pieces of Bryozoa occurred in the light fraction, with diatoms, wood chips, and pieces of eel grass (Zostera marina; Holway, 1934). Small fragments of oyster and clam shells were found in some samples.

Foraminifera: The Foraminifera in the samples from Willapa Bay were identified by Miss Susan C. Cooper, Department of Oceanography, University of Washington (Table 5). F. L. Parker (The Scripps Institution of Oceanography, La Jolla, California; 1953, unpublished note) studied several samples from Willapa Bay and stated "there are typical shallow water forms, salt marsh forms, and some which indicate the presence of less saline water, perhaps near the mouth of a river."

Haplophragmoides hancocki, Tiphotrocha comprimata, Trochammina mascrecens, and Reophax sp 1 are indicative of a marsh environment and decrease in numbers with increasing marine conditions, whereas Jadammina polystoma and Trochammina inflata increase (Parker and Athearn, 1959). Elphidiella and Elphidium are good indicators of a shallow marine environment. Miliammina fusca fluctuates independently of the degree of brackish or marine conditions (Parker and Athearn, 1959). Willapa Bay and Grays Harbor represent the most northerly occurrences of Ammonia beccarii along the Pacific coast of North America (Milliman, 1963; B. J. Enbysk, Department of Oceanography, University of Washington, personal communication). One individual Cyclammina trullissata was found in

Table 5. Locations of Foraminifera species in Willapa Bay.

<u>SPECIES</u>	<u>SAMPLE STATIONS</u>
<u>Ammobaculites</u> sp - - - - -	19, 49, 65, 74, 76.
<u>Ammonia beccarii</u> (Linne) - - -	19, 20, 21, 25, 38, 39, 40, 41, 42, 43, 45, 46, 50, 63, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77.
<u>Buccella frigida</u> (Cushman) - - -	21.
<u>Cyclammina trullissata</u> (Brady) -	75.
<u>Discorbis sanjuanensis</u> Cushman and Todd - - - - -	25, 50, 73.
<u>Eggerella advena</u> (Cushman) - - -	68, 72.
<u>Elphidiella hannai</u> (Cushman and Grant) - - - - -	20, 21, 25, 27, 37, 38, 39, 40, 41, 42, 43, 62, 67, 69, 71, 72, 73.
<u>Elphidium clavatum</u> Cushman - - -	19, 25, 45, 50.
<u>Elphidium frigidum</u> Cushman - - -	19, 21, 25, 43, 50, 71.
<u>Elphidium incertum</u> (Williamson) -	21, 25, 37, 39, 45, 50, 65, 67, 68, 69, 71, 72, 76.
<u>Elphidium orbiculare</u> (Brady) - - -	39, 73.
<u>Elphidium</u> sp 1 - - - - -	25, 46, 71.
<u>Elphidium</u> sp 2 - - - - -	69.
<u>Elphidium subarticum</u> Cushman - -	19, 39, 68.
<u>Elphidium translucens</u> Natland - -	19, 21, 50.
<u>Eponides repandus</u> (Fitchel and Moll) - - - - -	23.
<u>Haplophragmoides hancocki</u> Cushman and McCulloch - - -	47 (?), 73, 76, 77.
<u>Haplophragmoides</u> sp - - - - -	19, 45, 47, 77.
<u>Jadammina polystoma</u> Bartenstein and Brand - - -	50, 66.
<u>Miliammina fusca</u> (Brady) - - -	19, 43, 44, 45, 46, 47, 49, 65, 66, 67, 73, 74, 75, 76, 77, 78.
<u>Quinqueloculina</u> sp - - - - -	19, 21, 50, 71.
<u>Reophax</u> sp 1 (similar to <u>Reophax</u> sp 1 of Parker and Athearn, 1959) - - - -	19, 45, 46, 47, 65, 69, 71, 72, 74, 75, 76, 77.
<u>Tiphotrocha comprimata</u> (Cushman and Bronnimann) - - -	77.
<u>Triloculina</u> sp - - - - -	19, 21, 25, 71.
<u>Trochammina inflata</u> (Montagu) - -	18, 37, 38, 39, 44, 45, 50, 56, 62, 63, 66, 67, 68, 69, 72, 74, 75, 76, 77, 78.
<u>Trochammina mascrecens</u> Brady - -	68, 70, 72, 77.

Sample 75 near the Naselle River and is probably a Tertiary fossil, indicated by its crystalline test. Based on the above observations, the suites of Foraminifera found at each sample station in Willapa Bay may be classified as brackish-water, marine, or mixed marine and brackish-water (Fig. 11). The brackish-water suites of Foraminifera were found in or near the mouths of rivers flowing into Willapa Bay; the marine suites were found on the tidal flats and in the channels and distributaries of the bay away from the rivers. Between these two suites were located samples containing the mixed suite of Foraminifera.

DISCUSSION AND INTERPRETATION

Willapa Bay embraces a wide range of sedimentary environments, as do most coastal plain estuaries. The sources of the sediments and the distribution of their physical and chemical characteristics must be interpreted in order to differentiate these environments.

Sources of Sediments

The four sources of sediment to be evaluated are the rivers flowing into Willapa Bay, the Pacific Ocean and its beaches, the shore of the bay, and the sand and sand dunes of Long Beach Peninsula. The increase of tidal flat area in Willapa Bay from about 43% of the bay in 1950 (U.S. Army Corps of Engineers, personal communication) to about 55% in 1964 indicates the importance of sedimentation.

Rivers: Generally, rivers are the principal source for sediment deposited in an estuary (Stevenson and Emery, 1958). As the river water flows into the estuary and mixes with sea water, the salt content of the fresh water increases, causing a flocculation of suspended colloidal clay-size material (Whitehouse and Jeffrey, 1954). Particles of sand- and silt-size material are deposited near the mouth of a river entering an estuary owing to a decrease in the fluid stress associated with the river current (Inman, 1963). These processes explain the observed sedimentation in the river channels, especially in the Willapa River Channel, which requires dredging to maintain it to a navigable depth and width for ocean vessels, and in Stanley Channel near its confluence with Nahcotta Channel. Flocculated material deposited near the mouths of rivers may be resuspended by bottom currents or may flow by gravity as a "fluid mud" to deeper areas (Krone, 1962). The absence of silt- and clay-size sediment in the well-sorted fine sand in the main channels indicates bottom tidal currents strong enough to prevent deposition. The narrows in Stanley Channel (Sample 73) reaches a depth of 62 ft (19 m) and contains a very well-sorted fine sand indicating a nondepositional area owing to a restriction of the tidal flow. Much of the material that flocculates upon entering Willapa Bay from the rivers is carried along with the resuspended material onto the tidal flats.

An increase in the abundance of heavy minerals in Sample 26 in the Nahcotta Channel compared with the adjacent channel stations (Samples 22 and 32) indicates a contribution of sediment from the Naselle River.

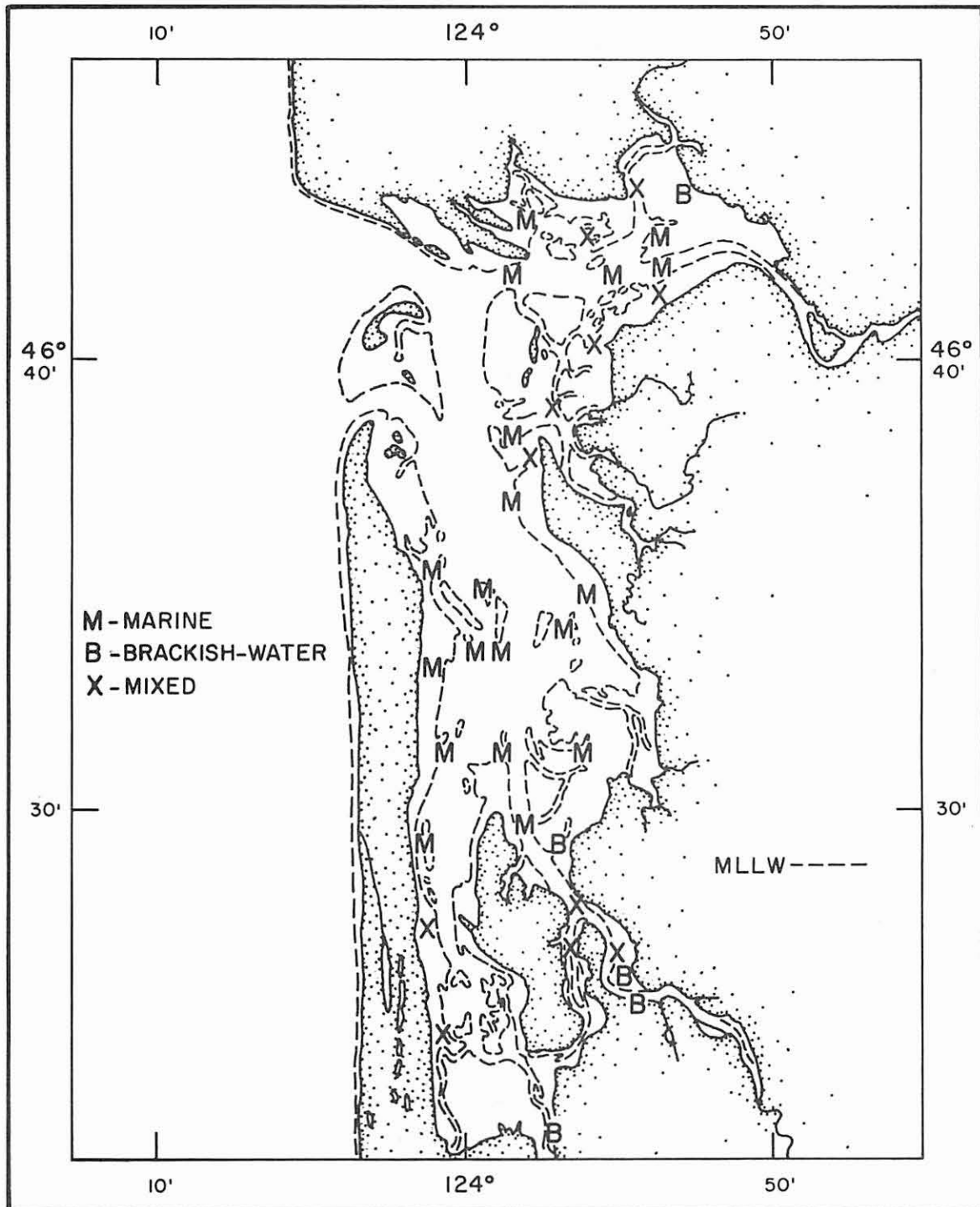


Fig. 11. Distribution of suites of Foraminifera in Willapa Bay.

The Eocene basalts, chiefly tholeiitic pillow lavas, which lie within the Willapa Bay drainage area, are a possible source of hypersthene, clinopyroxenes, amphiboles, and magnetite.

Ocean and Ocean Beaches: Probably the major factor causing the areal increase of the tidal flats in Willapa Bay is the shoaling north and east of Leadbetter Point. The sediment in this area is a well-sorted fine sand, with near zero skewness, little organic matter, and no Foraminifera. According to Inman (1949), this type of sediment is characteristic of beach sands subjected to sorting by longshore currents and wave action. Some of the sediment in this area is carried in from the south by littoral drift along Long Beach Peninsula ocean beach. This shoaling forces the tidal flow through the curved channel at the bay entrance against Cape Shoalwater, causing erosion of the cape (Fig. 3). Waves from the ocean which reform after breaking over the offshore tidal delta increase this erosion. Sediment from this area of erosion is not deposited in the bay entrance channel, but is transported out to the tidal delta or into the bay by strong tidal currents and littoral drift.

The spit extending southeastward into Willapa Bay from Cape Shoalwater and the spit at Toke Point are the result of transport of sediment eroded from the cape, as is the large shoal area of Ellen Sands. Sediment from the cape is also transported out to and deposited on the tidal delta where it comes under the influence of southward littoral drift, as evidenced by the southward migration of the channel through the tidal delta. Wave action on the tidal delta can transport sediment into the shoal area off Leadbetter Point.

Thus, some of the sediment within Willapa Bay is derived from sources north and south of the bay entrance. Much of the bay sediment is derived from Cape Shoalwater, transported into the bay by tidal currents and littoral drift or carried out to the tidal delta by tidal currents, moved southward along the tidal delta by littoral drift, and transported into the shoal areas by wave action. The result is a net influx of sediment into Willapa Bay, much of it being well-sorted fine sand.

Pettijohn (1957) noted that garnet, hornblende (blue-green variety), kyanite, sillimanite, epidote, magnetite, and quartz, all present in Willapa Bay, form a detrital mineral suite characteristic of high-rank metamorphic rocks. Augite, hypersthene, basaltic hornblende, ilmenite, magnetite, and rutile indicate a heavy mineral suite derived from basic igneous rocks. Ballard (1964) stated that the Columbia River was the dominant source for material contributed to the ocean beaches adjacent to Willapa Bay, the hypersthene being a characteristic mineral of the tholeiitic Columbia River basalts and the andesite strato-volcanoes of the Cascade Range (Waters, 1962). The kyanite and sillimanite may be derived from metamorphic rocks of the Idaho batholith in the Columbia River drainage basin. However, much of the sediment in Willapa Bay may be derived from locally reworked Tertiary and Quaternary deposits.

Bay Shore: There is evidence of some erosion of the shore in Willapa Bay. Small stacks near Bay Center and cliffs along the north and east shore of the bay show undercutting by waves. The major factor contributing to the erosion of these features is rainfall and slumping; waves are important only during periods of high tides.

Long Beach Peninsula: Onshore winds carry sand from the spit into the bay through the blowouts observed by Cooper (1958) to exist from the end of the tree line on Long Beach Peninsula to Leadbetter Point. Samples 17, 18, 19, and 21 contained frosted quartz sand grains indicating an eolian origin. Guilcher and King (1961) found that marsh sediments deposited in the lee of sand dunes are often sandy because of winnowing of the dunes by wind. Assuming that wind transport from the spit into Willapa Bay took place during the formation of the spit, the total contribution of sediment from Long Beach Peninsula was important to the development of the tidal flats adjacent to the spit.

Pumice: Deposits of volcanic ash from volcanoes in the Cascade Range of Washington and Oregon are common in many areas of Western Washington. The average index of refraction for the ash from Glacier Peak, Washington, is 1.505 (Rigg and Gould, 1957) and from Mount Mazama, Oregon, is between 1.500 and 1.510 (Powers and Wilcox, 1964). Royce (1964) found layers of ash in cores taken in Willapa Submarine Canyon off Willapa Bay with an average index of refraction of 1.505. The pumice from the Willapa Bay samples, having an average index of refraction of 1.507, may be derived from ocean beach sediments or a reworking of ash deposits within the Willapa Bay drainage area.

Organic Carbon and Organic Nitrogen: Scholl (1963) found that the ratio of organic carbon to organic nitrogen (C/N) was dependent upon the type of organic matter in the sediment. Terrestrial plant debris, which has a higher C/N than marine organisms, causes an increase in the C/N in estuarine sediments over open-ocean shelf sediments. Andersen (1962) found evidence within a fjord that the ratio increased from marine conditions to areas under the influence of fresh water runoff. Similar results were noted by Gucluer (1962). The C/N values range from 8 to 12 for most marine shelf sediments and from 18 to 35 for coastal swamps and peat deposits (Scholl, 1963). The wide variations in C/N in marine sediments are explained by Bader (1954, 1955) to be dependent on the wide variations in the lignin content of marine sediments and the resistance of lignin to decomposition.

Although some C/N values calculated for the sediments in Willapa Bay (Table 2) are probably low owing to questionable organic nitrogen determinations (Appendix III), the samples with C/N exceeding 12 contained wood chips and grass debris, had high organic carbon content, and were associated only with brackish-water Foraminifera. The samples with C/N of 7 or less contained no terrestrial plant debris, had low organic carbon content, and were associated with marine or mixed marine and brackish-water Foraminifera.

There appear to be two types of organic matter in the Willapa Bay samples. One type, associated with the fine-grained tidal flat sediment, had an average C/N of 13.8 (C/N slope from a least-squares regression line of 10.4), and the other, associated with the coarser channel sediments, had an average C/N of 6.1 (C/N slope of 5.2). The actual meaning of the C/N values is still a point of controversy to many marine geologists. The low organic carbon and organic nitrogen percentages found in the channel sediments are caused by a removal of organic matter and fine material by strong bottom currents and more complete oxidation of the organic matter in the permeable sand.

Sediment Distribution

There are two main sedimentary environments in Willapa Bay, the tidal flats and the channels and distributaries. As is to be expected for an estuary, wide variations of sediment properties are found within these two environments.

Sediments in the river channels range from fine sand to silt, with the coarser mean grain-sizes located where the channels are narrow and the currents high. Higher organic carbon content is associated with the finer sediments. The Foraminifera in the river channels, consisting of both marine and brackish-water forms, reflect the mixing of fresh and saline waters. The bar at the confluence of Stanley Channel with Nahcotta Channel and the dredging required in the Willapa River Channel indicate deposition of river-derived sediment.

The sediments in Nahcotta Channel and the bay entrance channel are generally well-sorted fine sands with near zero skewness. They are characterized by low organic carbon content and no macroscopic marine organisms other than a clam found in Sample 26. Inman (1949) showed that sediments with median diameters near the fine-sand class are best sorted; sediments finer or coarser are more poorly sorted. The sediment in the main channels is probably moved back and forth by the tidal currents and fine material deposited during slack water may be removed during a flood or ebb tide. This fine sediment is transported onto the tidal flats and deposited there. The slight decrease in mean grain-size of the channel sediments toward the south in Nahcotta Channel indicates the decrease in bottom current velocities away from the bay entrance. The decrease in the percentage of heavy minerals with this decrease in mean grain-size and current velocities is explained by the hydraulic equivalence between the size of the heavy mineral grains and the size of a quartz grain (of lower specific gravity) with which it is deposited (Rubey, 1933; Rittenhouse, 1943).

Sediments on the tidal flats adjacent to the mouths of the North, Willapa, Naselle, and Bear Rivers are very-poorly-sorted, positively skewed silts containing suites of brackish-water Foraminifera. These sediments have the highest organic carbon content in Willapa Bay and are probably river-derived. The fine sediment in Sample 56 is at least 100 cm in thickness; at least 120 cm of fine sediment occurs at the south end of the bay and near the mouth of the Naselle River. These

tidal flats are the result of the interaction of the river building a delta at its mouth and the tidal currents preventing deposition in the channels. Much of the sediment which would be deposited at the mouth of a river flowing into a nontidal embayment is carried onto the tidal flats bordering the river channel by the flood tide and deposited during slack water. Van Straaten and Kuenen (1957) have shown that deposition generally exceeds erosion on tidal flats because of the "settling-lag effect" of tidal currents.

The tidal flats adjacent to Long Beach Peninsula contain well-sorted fine sand with positive skewness and an overlying layer of silt- and clay-size material. This layer thickens from about 1 cm at Sample 16 to about 150 cm near the south end of the bay. The fine sediment making up this layer is river-derived, carried onto the tidal flats in suspension by flood tides. The fine sand found beneath this layer was part of the normal spit deposition as Long Beach Peninsula developed. As the end of the spit grew to the north, the source of fine sand was cut off and the deposition of silt began. Tidal currents, wave action, biological activity, and agitation by oyster dredges prevent thick layers of fine sediment from being deposited near the bay entrance; this fine material is carried into the bay to be deposited on the tidal flats near the south end, where the sediments were found to be poorly-sorted silt (Samples 1 and 2). Similar processes are taking place inside the spits growing southeastward into Willapa Bay from Cape Shoalwater and Toke Point.

The shoal areas formed north of Leadbetter Point and at Ellen Sands are formed by the deposition of fine sand from the ocean beaches and the erosion of Cape Shoalwater. The sediments on the tidal flat at Cape Shoalwater are well-sorted fine sands with negative skewness, indicating a minor mode slightly coarser than the major one in the fine sand class. The sediment making up the minor mode is probably present on Cape Shoalwater and represents a lag deposit being slightly concentrated as the cape is eroded.

SUGGESTIONS FOR FURTHER RESEARCH

Because of the wide range of environments found in Willapa Bay, many problems must be solved in a general manner until detailed studies are conducted. Some projects that would be useful are listed below.

1. A simultaneous collection of suspended sediment and measurement of current velocities would help clarify the transport patterns in Willapa Bay.

2. A study of "tagged" sediments placed on the sand flat at Cape Shoalwater would show whether the material eroded from the cape is actually added to the shoal area off Leadbetter Point by way of the offshore tidal delta.

3. Detailed analyses of core samples from the marshes may give some clues as to the depositional rates.

4. Petrographic examination of sediments introduced to Willapa Bay from the rivers would give valuable information about the contribution of heavy minerals from this source.

CONCLUSIONS

1. Willapa Bay, a coastal plain estuary, consists of extensive tidal flats cut by distributaries and channels. It is probably one of the few major estuaries along the coastline of the United States not strongly polluted by city and industrial waste disposal.

2. Sediment eroded from Cape Shoalwater, at the entrance to Willapa Bay, is carried out to the offshore tidal delta and into the bay to form shoals and spits. As the cape recedes northward, the entrance channel migrates with it, and a large shoal area has developed between the channel and Leadbetter Point. An important littoral drift to the north is indicated at the bay entrance.

3. The channel through the offshore tidal delta migrates to the south, shoals, reforms to the north and again migrates southward in cycles of 10 to 20 years, indicating an offshore littoral drift to the south.

4. Sediments of the tidal flats in Willapa Bay range from thick deposits of silt- and clay-size material at the south end of the bay and adjacent to the river mouths to eroding sand flats on the north side of the bay entrance. The fine sediment deposition is a result of the interaction of river silting and tidal currents.

5. Nahcotta Channel is constantly being scoured clean of deposited sediment by strong bottom currents. Well-sorted fine sand with low organic carbon content and few macroscopic marine organisms is characteristic of this channel.

6. Channel sedimentation does occur in the Willapa River Channel and in Stanley Channel Near the confluence with Nahcotta Channel. This sediment is generally river-derived.

7. Heavy minerals in Willapa Bay form two suites, one originating from high-rank metamorphic rocks and the other from basic igneous rocks. These minerals are probably derived from the Willapa Bay and Columbia River drainage basins as well as reworked local sediments. At the present time, sediment eroded from Cape Shoalwater is probably the most important source of fine sand to the bay.

8. Two types of organic matter appear to be present in Willapa Bay based on the ratio of organic carbon to organic nitrogen (C/N).

One type, associated with the fine-grained tidal flat sediment, had an average C/N of 13.8; the other type, associated with the coarser channel sediment, had an average C/N of 6.1.

9. Foraminifera in Willapa Bay may be classified in terms of brackish-water, marine, and mixed brackish-water and marine suites. The distribution of these suites of Foraminifera is closely related to the sedimentary environments in the bay.

10. The tidal flat adjacent to Long Beach Peninsula represents a relict of the growing spit; the layer of finer-grained sediment over fine sand represents a deposition of river-derived material subsequent to growth of the spit past the given location.

REFERENCES

- Andersen, N. K. 1962. Recent sediments of Deep Inlet, Alaska. M.S. Thesis. Univ. Washington, Seattle. 152 p.
- Bader, R. G. 1954. Use of factors for converting carbon or nitrogen to total sedimentary organics. *Science* 120(3122):709-710.
- Bader, R. G. 1955. Carbon and nitrogen relations in surface and sub-surface marine sediments. *Geochim. Cosmochim. Acta* 7:205-211.
- Ballard, R. L. 1964. Distribution of beach sediment near the Columbia River. Univ. Washington Dep. Oceanogr. Tech. Rep. 98. 82 p.
- Cameron, W. M., and D. W. Pritchard. 1963. Estuaries. P. 306-324 in M. N. Hill (ed.), *The sea. II. Composition of sea-water, comparative and descriptive oceanography*. Interscience Publishers, New York.
- Collias, E. E., M. R. Rona, D. A. McManus, and J. S. Creager. 1963. Machine processing of geological data. Univ. Washington Dep. Oceanogr. Tech. Rep. 87. 119 p.
- Cooper, W. S. 1958. Coastal sand dunes of Oregon and Washington. *Geol. Soc. Am. Mem.* 72. 169 p.
- Creager, J. S., D. A. McManus, and E. E. Collias. 1962. Electronic data processing in sedimentary size analyses. *J. Sediment. Petrol.* 32:833-839.
- Fenneman, N. M. 1931. *Physiography of Western United States*. McGraw-Hall, New York, 534 p.
- Folk, R. L., and W. C. Ward. 1957. Brazos River bar: a study in the significance of grain size parameters. *J. Sediment. Petrol.* 27:3-26.
- Gucluer, S. M. 1962. Recent sediments in Saanich Inlet, British Columbia. M.S. Thesis. Univ. Washington, Seattle. 119 p.
- Guilcher, A., and C. A. M. King. 1961. Spits, tombolos, and tidal marshes in Connemara and West Kerry, Ireland. *Proc. Roy. Irish Acad.* 61B(17):283-338.
- Holway, T. W. 1934. Some observations on the Pacific oyster *Ostrea gigas* Thunberg and the native oyster *Ostrea lurina* Carpenter in Willapa Bay. M.S. Thesis. Univ. Washington, Seattle. 62 p.
- Inman, D. L. 1949. Sorting of sediments in light of fluid mechanics. *J. Sediment. Petrol.* 19:51-70.

- Inman, D. L. 1963. Sediments: physical properties and mechanics of sedimentation. P. 101-151 in F. P. Shepard, Submarine geology. Harper and Row, New York.
- Krone, R. B. 1962. Flume studies of the transport of sediment in estuarial shoaling processes (final report). Univ. California (Berkeley) Eng. Res. Lab. 110 p.
- Krumbein, W. C. 1934. Size frequency distribution of sediments. J. Sediment. Petrol. 4:65-77.
- Krumbein, W. C., and F. J. Pettijohn. 1938. Manual of sedimentary petrography. Appleton-Century-Crofts, Inc., New York. 549 p.
- McManus, D. A. 1963. A criticism of certain usage of the phi-notation. J. Sediment. Petrol. 33:670-674.
- Milliman, J. D. 1963. Recent marine sediments in Grays Harbor, Washington. M.S. Thesis. Univ. Washington, Seattle. 172 p.
- Parker, F. L., and W. D. Athearn. 1959. Ecology of marsh Foraminifera in Poponesset Bay, Massachusetts. J. Paleontol. 33(2):333-343.
- Pettijohn, F. J. 1957. Sedimentary rocks, second edition. Harper and Brothers, New York. 718 p.
- Powers, H. A., and R. E. Wilcox. 1964. Volcanic ash from Mount Mazama (Crater Lake) and from Glacier Peak. Science 144: 1334-1336.
- Pritchard, D. W. 1952. Estuarine hydrography. Advances Geophys. 1: 243-280.
- Riggs, G. B., and H. R. Gould. 1957. Age of Glacier Peak eruption and chronology of post glacial peat deposits in Washington and surrounding areas. Am. J. Sci. 255:341-363.
- Rittenhouse, G. 1943. The transportation and deposition of heavy minerals. Bull. Geol. Soc. Am. 54:1725-1780.
- Royce, C. F., Jr. 1964. Sediments of Willapa Submarine Canyon. M.S. Thesis. Univ. Washington, Seattle. 87 p.
- Rubey, W. W. 1933. The size-distribution of heavy minerals within a waterlaid sandstone. J. Sediment. Petrol. 3:3-29.
- Scholl, D. W. 1963. Sedimentation in modern coastal swamps, Southwestern Florida. Bull. Am. Assoc. Petrol. Geologists 47(8): 1581-1603.
- Shepard, F. P. 1954. Nomenclature based on sand-silt-clay ratios. J. Sediment. Petrol. 24:151-158.

- Shepard, F. P. 1963. Submarine geology, second edition. Harper and Row, New York. 557 p.
- Snively, P. D., and H. C. Wagner. 1963. Tertiary geologic history of Western Oregon and Washington. Washington Dep. Conserv. Div. Mines Geol. Rep. Invest. 22, 25 p.
- Sternberg, R. W., and J. S. Creager. 1961. Comparative efficiencies of size analysis by hydrometer and pipette methods. J. Sediment. Petrol. 31:96-100.
- Stevenson, R. E., and K. O. Emery. 1958. Marshlands at Newport Bay, California. Allan Hancock Foundation Publ. Occas. Paper 20, 109 p.
- Sverdrup, H. U., M. W. Johnson, and R. H. Fleming. 1942. The oceans, their physics, chemistry, and general biology. Prentice-Hall, Inc, Englewood Cliffs. 1087 p.
- Taylor, G. L. 1933. A centrifuge tube for heavy mineral separations. J. Sediment. Petrol. 3:45-46.
- U.S. Coast and Geodetic Survey. 1959. U.S. Coast pilot 7, Pacific coast, California, Oregon, Washington, and Hawaii. U.S. Government Printing Office, Washington, D.C. 383 p.
- U.S. Coast and Geodetic Survey. 1962. Tide tables, high and low water predictions, 1962, West Coast North and South America including the Hawaiian Islands. U.S. Government Printing Office, Washington, D.C. 224 p.
- U.S. Eighty-third Congress, Second Session. 1954. Willapa River and Harbor, and Naselle River, Washington. House Doc. 425, U.S. Government Printing Office, Washington, D.C. 60 p.
- Van Straaten, L. M. J. U., and P. H. Kuenen. 1957. Accumulation of fine grained sediments in the Dutch Wadden Sea. Geol. Mijnbouw 19:329-354.
- Van Veen, J. 1936. Onderzoekingen in de Hoofden. Landsdrukkerij, The Hague. 252 p.
- Washington State Department of Fisheries. 1951-1962. Physical and chemical data, Willapa Bay. Washington Dep. Fish. Res. Div., Olympia.
- Waters, A. C. 1962. Basalt magma types and their tectonic associations: Pacific Northwest of the United States. P. 158-170 in G. A. MacDonald and H. Kuno (ed.), The crust of the Pacific Basin. Am. Geophys. Union Monogr. 6, Washington, D.C.

Weaver, C. E. 1937. Tertiary stratigraphy of Western Washington and Northwestern Oregon. Univ. Washington Publ. Geol. 4, Seattle. 266 p.

Wentworth, C. K. 1922. A scale of grade and class terms for elastic sediments. J. Geol. 30:377-392.

Whitehouse, U. G., and L. M. Jeffrey. 1954. Flocculation in estuaries. A.M. College Texas Dep. Oceanogr., College Station. 69 p.

APPENDIX I. MECHANICAL ANALYSIS

Grain-size analyses were conducted using the standard procedure of the Sediment Analysis Laboratory, Department of Oceanography, University of Washington.

1. Each grab sample, which had been sealed in a heavy plastic bag in the field, and each core, sealed in the core liners, were stored at a temperature of about 4°C prior to laboratory analysis.
2. The entire grab sample was quartered in the laboratory to obtain a representative sample of about 20 g. The cores were sawed lengthwise into two equal halves and a sample of about 20 g was taken from the top and bottom of the core (Sample 56 was also sampled from the middle). These subsamples were washed with distilled water and dispersed in a peptizing agent (marasperse N).
3. Each dispersed sample was wet-sieved through a 62-micron screen to separate the coarse (sand-size) fraction from the fine (silt- and clay-size) fraction. The fine fraction was collected in a 1000-ml sedimentation cylinder.
4. Each sample was size graded according to the Wentworth (1922) scale using phi notation as described by McManus (1963). The size in phi values is defined as the negative log to the base two of the particle diameter in mm divided by a standard diameter of 1 mm, i.e.:

$$\text{phi} = - \log_2 \frac{(\text{particle diameter in mm})}{(\text{standard diameter of 1 mm})}$$

5. The coarse fraction was washed of peptizing agent, dried in an oven at 95°C to constant weight, and weighed. The sample was then placed in a 0.5 phi-unit progression set of 3-inch standard sieves and shaken on a Ro-tap automatic shaking machine (W.S. Tyler Co., Cleveland, Ohio) for 10 min. The fraction retained on each sieve was weighed to the nearest mg and placed in vials for microscopic analysis.
6. The pan fraction (finer than 4 phi) obtained from the dry sieving was added to the fine fraction obtained by wet sieving in the 1000-ml cylinder. A pipette analysis was performed to determine the 0.5 phi-unit progression size fractions between 4 phi and 11 phi (0.49 microns). Wadell's correction of Stokes' law was applied to determine the settling velocities of the different sized particles (Krumbein and Pettijohn, 1938). Each size-range aliquot was placed in a tared 50-ml beaker, oven dried to constant weight, and weighed to the nearest mg, taking into account the weight of the dried peptizer in the sample.

7. Statistical parameters for describing the size distribution in each sample were calculated using an IBM 709 Computer program (Creager, McManus, and Collias, 1962; Collias et al., 1963). Folk and Ward (1957) statistical parameters were used throughout this report to describe the sediments.

Although the reproducibility of cumulative data from pipette analyses of the fine fraction is only about ± 1.0 phi units at the 50th percentile (Sternberg and Creager, 1961), the size analyses of the Willapa Bay sediments contain less error because most of the samples are well-sorted fine sand.

APPENDIX II. CARBON ANALYSIS

The carbon content of each sample was determined using a Laboratory Equipment Company (LECO) Gas Analyser.

1. A split of each total sample was dried and ground in a small ceramic ball mill to a particle size of approximately 4 phi (62 microns).
2. About 0.5 g of the ground sample was placed in a ceramic crucible with small amounts of tin catalyst and iron accelerator and burned in a dry oxygen atmosphere at about 2000°C.
3. The carbon dioxide evolved as a result of the oxidation of the carbon in the sample (any carbon monoxide formed was oxidized to carbon dioxide in a hot copper oxide column) was collected in a graduated burette over a solution of sulfuric acid in distilled water.
4. The mixture of carbon dioxide and oxygen collected in the burette was pumped through a solution of potassium hydroxide which absorbed the carbon dioxide. Returning the remaining oxygen to the burette permits the determination of the amount of carbon dioxide formed by burning the sample, a measure of the total carbon in the sample.
5. To determine the amount of carbon present in the sample as carbonate, a 2-g fraction of the ground sample was placed in a flask connected with the LECO Gas Analyser burette. Approximately 10 ml of a solution of 10% phosphoric acid and 2% ferrous sulfate (to prevent oxidation of carbon in the sediment) was added to the sample; the mixture was boiled, causing an evolution of carbon dioxide which was collected in the burette for measuring as above. The results were calculated as percentage carbon in the form of carbonate.
6. The organic carbon content of the sample was then calculated as the difference between the total carbon and the carbonate-carbon contents.

Twelve samples of National Bureau of Standards carbon steel (51-b), containing 1.2% carbon, were burned in the LECO furnace to determine the error in the total carbon analysis. The accuracy of this method was found to be 3.3%, with a reproducibility of $\pm 0.04\%$ carbon.

Chemically pure calcium carbonate was used to determine the error of the carbonate-carbon analysis. The method was accurate to 1.8% with a reproducibility of $\pm 0.21\%$ carbonate-carbon.

APPENDIX III. NITROGEN ANALYSIS

The Laboratory Equipment Company (LECO) Nitrogen Analyser was utilized for the determination of organic nitrogen.

1. A 0.2- to 0.4-g fraction of a sample ground to about 4 phi (62 microns) particle size was placed in a nickel crucible with 6.0 g of sodium hydroxide.
2. The sample was fused in a LECO furnace in an argon atmosphere, releasing ammonia gas which was collected in a solution of 0.00551 N hydrochloric acid with methyl red indicator.
3. After the sample was completely fused, the acid solution was back-titrated with a solution of 0.0231 N sodium hydroxide and the organic nitrogen content of the sample was calculated.

R. Couture (University of Washington, Department of Oceanography, personal communication) has determined that the precision for the above analysis for the range of organic nitrogen found in the Willapa Bay samples (0.01 to 0.19% organic nitrogen) is $\pm 0.01\%$ nitrogen. However, the accuracy of this method has not yet been determined. It is apparent from the very low values of the ratio of organic carbon to organic nitrogen (2.0 for Sample 35) that the organic nitrogen percentages are high, probably due to some breakdown of the inorganic nitrogen compounds in the sediment (M. G. Gross, Department of Oceanography, University of Washington, personal communication).

APPENDIX IV. HEAVY MINERAL ANALYSIS

Separation of heavy minerals from selected samples was made using bromoform (tribrom-methane, sp gr 2.85). For these analyses, the 3- and 4-phi size classes were used as they include the modal size of most of the samples and contained the greatest concentrations of heavy minerals. A pycnometer was used to determine the specific gravity of the bromoform.

1. Approximately 2 g of each sample were placed in a separation tube similar to the Taylor centrifuge tube (Taylor, 1933) but with the lower end enlarged, retaining a constriction between the upper and lower end for separation of the light and heavy fractions. These separation tubes were designed by J. T. Whetten (Department of Oceanography, University of Washington).
2. Bromoform was added to the sample in the tube to above the constriction. The sample was then shaken and centrifuged for 10 min.
3. A cork on a glass rod was inserted into the constriction of the tube and the light fraction was poured out into a filter, washed free of bromoform with acetone, dried, and weighed.
4. After removal of the cork from the tube, the heavy fraction was filtered off, washed, dried, and weighed.
5. The magnetic content of each sample was determined by weighing the fraction of the heavy mineral concentrate that could be picked up by a small hand magnet. Some of the grains separated by this method were lithic fragments containing small amounts of magnetic minerals.
6. The mineral concentrates were mounted on glass microscope slides using Lakeside 70 plastic resin (refractive index of 1.54) and 500 to 700 grains were identified and counted from each heavy mineral slide.

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13. ABSTRACT Willapa Bay, a coastal plain estuary, contains extensive tidal flats cut by channels and distributaries. Well-sorted fine sand occurs throughout the bay, with increasing amounts of silt- and clay-size sediment present on the tidal flats near the south end of the bay and adjacent to the mouths of rivers flowing into the bay. The channels are generally scoured of this fine sediment by strong bottom currents. Organic carbon and organic nitrogen contents in- creased with decreasing mean grain-size, and the ratio of carbon to nitrogen revealed two types of organic matter in the bay. At the bay entrance, a littoral drift to the north results in extensive shoaling north of Leadbetter Point and erosion on Cape Shoalwater. A southward migration of the channel through the tidal delta off the bay entrance indicates a littoral drift to the south in this area. Spits and shoals forming inside the bay entrance are a result of a net influx of fine sand into the bay from the eroding cape. The distribution of brackish-water to marine suites of Foraminifera is closely related to the sedimentary environments in the bay. Heavy minerals indicate source areas for the sediment from the Columbia River drainage basin as well as the Willapa Bay drainage basin. Fine sand on the tidal flats east of Long Beach Peninsula is a relict of the growth of the spit.		

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