Chapter 23

HEAVY-MINERAL PROVENANCE IN AN ESTUARINE ENVIRONMENT, WILLAPA BAY, WASHINGTON, USA: PALAEOGEOGRAPHIC IMPLICATIONS AND ESTUARINE EVOLUTION

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ABSTRACT

Modern sediments from representative localities in Willapa Bay, Washington, comprise two principal heavy-mineral suites. One contains approximately equivalent amounts of hornblende, orthopyroxene, and clinopyroxene; this is derived from the Columbia River, which discharges into the Pacific Ocean a short distance south of the bay. The other suite, dominated by clinopyroxene, is restricted to sands of rivers flowing into the bay from the east. The heavy-mineral distributions within the bay suggest that sand discharged from the Columbia River, borne north by longshore transport and carried into the bay by tidal currents, accounts for nearly all of the sand within the interior of Willapa Bay today.

Pleistocene deposits on the east side of the bay contain three heavy-mineral assemblages, two of which are identical to the modern assemblages described above. These assemblages reflect the relative influence of tidal and fluvial processes on the Late Pleistocene deposits (100,000–200,000 BP. Amino acid racemization in Quaternary shell deposits at Willapa Bay, Washington. Geochimica et Cosmochimica Acta 43, 1505–1520). They are also consistent with those processes inferred on the basis of sedimentary structures and stratigraphic relations in about two-thirds of the samples examined. Anomalies can be explained by recycling of sand from older deposits. The persistence of the two heavy-mineral suites suggests that the pattern of estuarine sedimentation in Late Pleistocene deposits closely resembled that of the modern bay.

The third heavy-mineral suite is enriched in epidote and occurs in a few older Pleistocene units. On the north side of the bay, the association of this suite with southwest-directed foresets in cross-bedded gravel indicates derivation from the northeast, perhaps from an area of glacial outwash. The presence of this suite in ancient estuarine sands exposed on the northeast side of the bay suggests that input from this northerly source may have intermittently dominated Willapa Bay deposition in the past.

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1. INTRODUCTION

Results of heavy-mineral studies in modern estuaries help to identify where the greatest amount of interaction between oceanic and river influences takes place and thereby determine the extent of influence of the tidal prism within the estuary. The degree of fluvial influence in estuarine sediment, relative to other input mechanisms, depends on the location within the estuary and the mass and mode of fluvial sediment transport relative to other transport mechanisms (Guilcher, 1967). Streams with limited discharge relative to the tidal prism influence only their immediate areas of discharge within an estuary.

Van Andel (1955) was one of the first to recognize and quantify mineralogical variation in depositional environments of the Rhône River delta. He divided the identified heavy minerals into "marine" and "terrestrial" groups. More recent studies of heavy minerals in estuarine environments have concentrated on variations due to selective sorting (Al-Bakri, 1986) and differing sediment textures where mineralogical differences could not be discerned (Mohan, 1995).

On the West coast of the United States, Kulm and Byrne (1966) used relative abundances of heavy minerals to differentiate among the marine, fluviatile, and marine–fluviatile realms of depositions in Yaquina Bay, Oregon. Scheidegger and Phipps (1976) also identified marine, river and "mixed" sediments in Gray's Harbor, just north of Willapa Bay, based on heavy-mineral content. In similar studies in Tillamook Bay, Oregon (Glenn, 1978) and Alsea Bay, Oregon (Peterson et al., 1982), zones of dominant marine, shoreline, and river influence were identified. Peterson et al. (1984b) extended the earlier study of Alsea Bay by examining relative amounts of hypersthene as an indicator of the presence of beach sand in estuarine deposits as seen in sediment cores. In comparing six estuaries along the Oregon and Washington coasts, Peterson et al. (1984a) found that a normalized ratio of hypersthene to augite was sufficient to determine the relative amounts of beach and river sands in the modern sediments of four of the estuaries.

A few studies have used heavy minerals to interpret sediment-input mechanisms in pre-Pleistocene deposits. Derry (1933) showed that glacial tills and interglacial sediments in the Don Valley, near Toronto, Canada, contained similar heavy minerals, but different relative abundances. Zemstov (1974) deciphered an unfossiliferous succession on interglacial-alluvial, glacial-moraine, and marine Quaternary deposits of the West Siberian plain, using specific heavy-mineral associations.

Terrace deposits exposed around the margins of Willapa Bay, Washington, represent the filling of a succession of ancient estuarine bays that existed at this site during the Pleistocene (Clifton, 1983). In these deposits, faunal assemblages, trace fossils, sedimentary structures, textural characteristics, and geometric considerations provide a basis for developing criteria for identifying depositional facies within an estuary fill (Clifton and Phillips, 1980; Clifton, 1982, 1994; Anima et al., 1989; Clifton et al., 1989; Clifton and Leithold, 1991; Gingras et al., 1999; Clifton and Gingras, 2004). The mineralogy of these sediments is another source of information about the in-filling of this tidal basin (Luepke and Clifton, 1983). The present paper is a summary and update of that initial work.

The distribution of heavy minerals in bay deposits should reflect the proportions of sedimentary input from different sources. For most estuaries, the input is oceanic, through tidal transport, from drainage basins that feed the estuary through fluvial transport, or from sources within the estuary itself through wave or tidal-current erosion of bay cliffs.

2. MODERN BAY SETTING

The Willapa Bay tidal inlet lies 50 km north of the Columbia River on the southwestern coast of Washington (Fig. 1). Long Beach Peninsula, also known as the Willapa Barrier, separates the bay from the open ocean. This sand spit (38 km long by 2.0–3.5 km wide) is the most extensive along the Pacific coast (Smith et al., 1999). Extending from the headland at the mouth of the Columbia River, it is built by sediments from the river as they are swept northward by longshore currents. Several rivers drain directly into the bay from the north, south, and east sides; none of these rivers compare in size to the Columbia (see Table 1). Pleistocene terraces border the bay on the north, south, and east sides. When this study was undertaken, Willapa Bay was described as the last relatively unspoiled large estuary in the United States (Chasan, 1978). Estuaries are natural magnets for human settlement, and more development has occurred since the 1970s, particularly on Long Beach Peninsula. Nevertheless Willapa Bay itself remains relatively undisturbed (Vanderburgh et al., 2003).

Dominant directions of longshore transport along this part of the Washington coast are from south to north. Winds from extra-tropical cyclones approach the coast generally from the west and generate most of the larger waves that reach the coast (Ruggiero et al., 1997). Local winds range from northwest to southwest (Ballard, 1964; Ruggiero et al., 2005). Tides are mixed semi-diurnal and range from 2.5 m at the bay's entrance to 3.1 m at Nachotta on the bay's west side; the size of the tidal prism has been calculated at 0.72 km^3 (Andrews, 1965; Ruggiero et al., 2005).

The rivers that drain the south and east side of Willapa Bay flow through primarily Eocene volcanic terrane (Fig. 1), especially the Crescent Formation (Wagner, 1967a, b; Wells, 1979). Petrographic examinations of rocks of the Crescent Formation show them to contain 25–37% augite (Pease and Hoover, 1957; Wolfe and McKee, 1972). By contrast, the rivers on the north side drain an area covered mostly by Quaternary terraces and the Tertiary Lincoln Creek and Astoria Formations (Gower and Pease, 1965; Wagner, 1967a). A preliminary examination of several units within the terraces there indicates a varied mineralogy similar in many ways to that of the Columbia River (Luepke, 1982a).

Andrews (1965), who identified heavy minerals but did not study their distribution in detail, made the first survey of Willapa Bay sediments. Heavy-mineral studies on the sediments of the Columbia River and beaches adjacent to its mouth have been documented in numerous publications (Hodge, 1934; Ballard, 1964; Kelley and Whetten, 1969; Whetten et al., 1969; Scheidegger et al., 1971; Luepke, 1982b).

3. PLEISTOCENE DEPOSITS

Pleistocene terraces crop out extensively along the northern and eastern margins of the bay and around much of Long Island at the south end of the bay. Many of

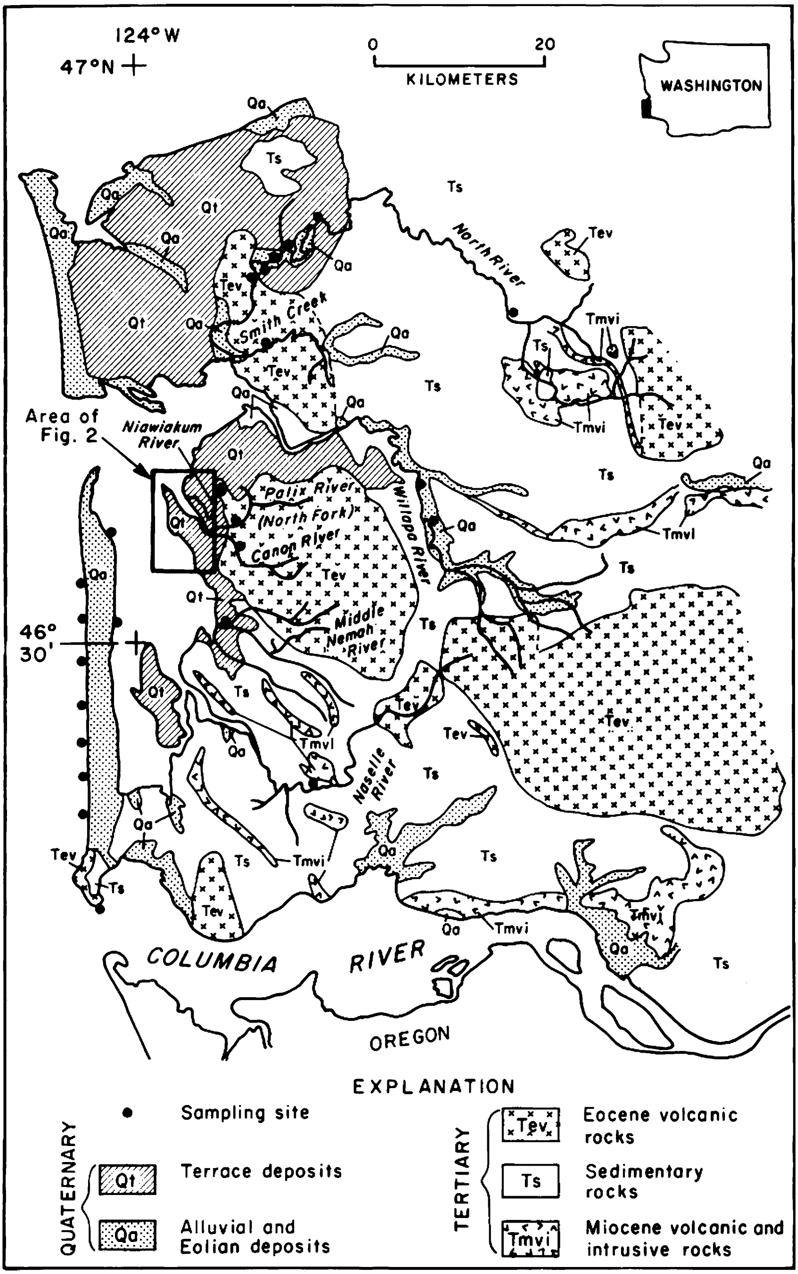

Fig. 1. Geological map showing location of samples collected on beaches and rivers in the Willapa Bay area. Geology modified from Pease and Hoover (1957), Wagner (1967a, b), Wolfe and McKee (1968, 1972), Wells (1979). From Luepke and Clifton (1983) with permission from Elsevier.

Table 1. Comparison of the Columbia River with rivers draining into Willapa Bay, Washington

River	Total length (km)	Drainage area (km^2)	Average annual discharge (m/sec)
Columbia	1931	670,810	5650
North	93	826	27
Willapa	67	668	18
Naselle	45	345	12
Smith Creek	23	174	–
Canon*	15	26	–
Middle Nemah	14	23	3
Palix, North Fork*	12	23	–
Niawiakum	11	10	–

Note: –, No data available.

*Lengths and drainage area measured directly from U.S. Geological Survey quadrangle maps. Other lengths and drainage area complied from Veirs (1969). Average yearly discharges compiled from U.S. Geological Survey (1972, 1974). Columbia River data from Rand McNally (1980).

these deposits contain sedimentary structures and fauna indigenous to the modern bay, and clearly represent transgressive-to-highstand estuary deposits. High-stand terrace surfaces related to these bayfills are evident around the margins of Willapa Bay, although the higher, older surfaces are much dissected and difficult to define. The best-defined, and apparently youngest, terrace surface lies at an elevation of ~13 m and can be traced from Goose Point to Pickernell Creek on the eastern side of the bay (Fig. 2).

Deposits underlying this terrace comprise a variety of intertidal and subtidal deposits (Clifton, 1983). Their ages, based on amino-acid racemization of shells, extend back ~100,000–200,000 years BP (Kvenvolden et al., 1979). The deposits beneath the 13 m terrace have been divided into five stratigraphic units (Fig. 3), four of which formed at substantially different relative positions of sea level (Clifton, 1983). Table 2 summarizes the sediment characteristics, ages, and depositional environments of the five units.

One suite of samples collected from Goose Point in the oldest unit (Unit I) contained diatoms filled with diagenetic pyrite. Two genera, *Camplyodiscus* and *Cosinodiscus*, are present. *Camplyodiscus* dominates the assemblage; it is a benthic diatom that attaches itself to brackish-water plants. *Cosinodiscus* is a marine-shelf to open-ocean planktonic form. Diatoms in Willapa Bay have been described in detail by Hemphill-Haley (1993a, b, 1995). Towards the southern end of the exposures, near Pickernell Creek, Unit I becomes somewhat sandier and contains angular pebbles of basalt, suggesting proximity to local sources.

Unit II represents subtidal deposition (Clifton, 1983). Unit III, which dissects both Units I and II, appears to be a valley fill formed during, or at the end of, a period of lowered sea level (Clifton, 1983). Unit IV is the most extensively exposed of the terrace units and directly underlies most of the 13 m terrace. Bimodally opposed foreset-bedding implies a strong tidal influence during the deposition of this unit. Channels filled to the 13 m terrace level with sandy and muddy sediments locally

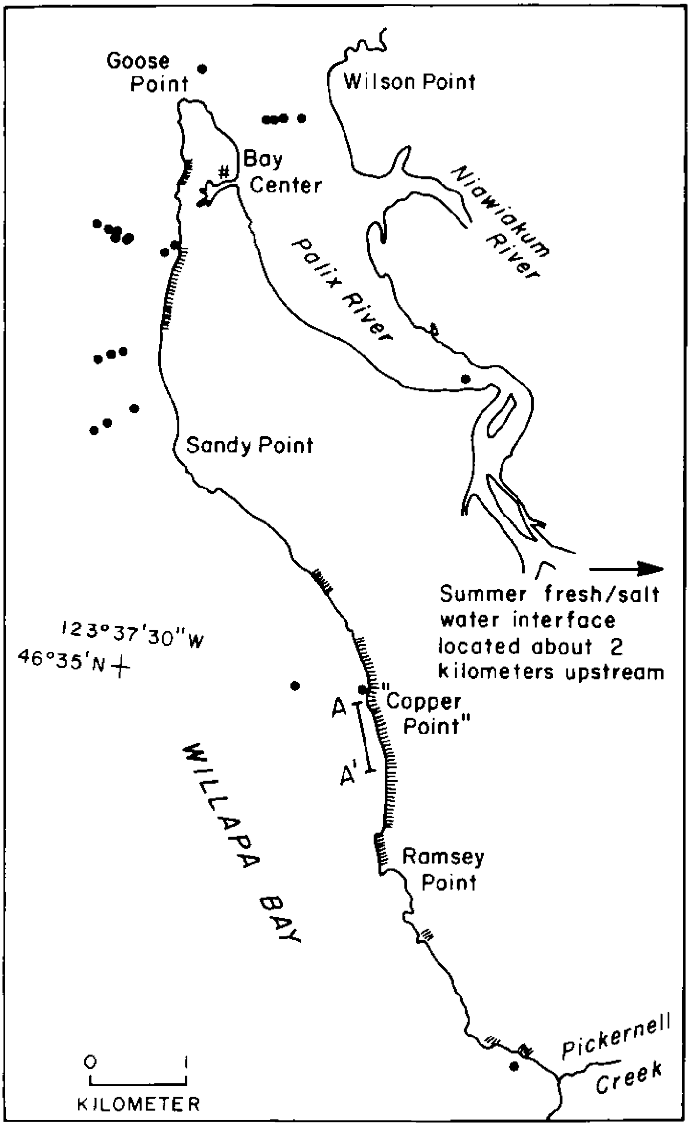

Fig. 2. Enlargement of area in Fig. 1, showing sampling sites on tidal flats and within the lowermost reach of the Palix River. Hachured area shows location of the 13 m terrace from Goose Point to Pickernell Creek. Sea-Cliff section A–A' shown in Fig. 3. From Luepke and Clifton (1983) with permission from Elsevier.

dissect this unit. The Unit V strata generally lack fauna and burrows and are therefore considered to represent a fluvially dominant episode deposited after, but at the same sea-level position as, Unit IV (Clifton, 1983).

Stratigraphic relations among the deposits that underlie the higher, older terraces are less clear. A number of units exist at elevations up to 150 m (Wagner, 1967b);

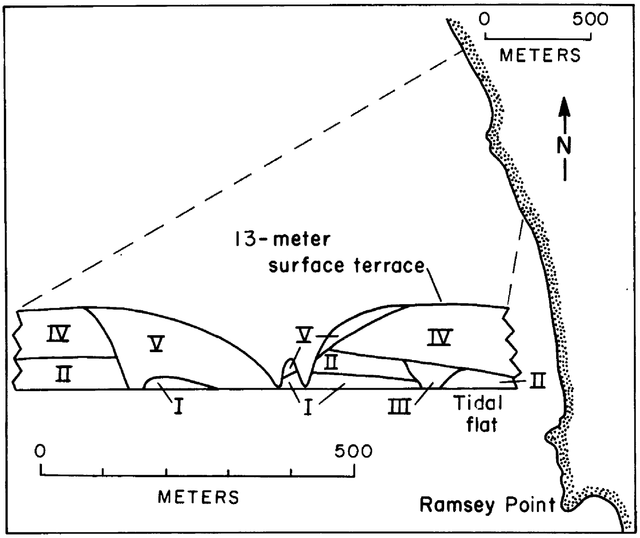

Fig. 3. Schematic diagram of relationships of the five units below the youngest (13 m) Pleistocene terrace, Willapa Bay. See Fig. 2 for location of section A–A'. From Luepke and Clifton (1983) with permission from Elsevier.

Table 2. Summary of information on the Pleistocene terrace units examined in Willapa Bay

Unit	Sediment texture	Age* (years BP)	Depositional environment†	Number of samples point-counted
I	Mud; locally sandy with angular pebbles	200,000	Intertidal and uppermost subtidal	27
II	Cross-bedded and bioturbated sand	200,000	Subtidal	24
III	Mud with root and rhizome structures	Dissects Units I and II	Valley fill	17
IV	Interbedded mud and sand	100,000	Subtidal to intertidal near terrace surface	18
V	Sand and mud, with local gravel and abundant logs and wood clasts	Locally dissects unit IV	Fluvial	12

Note: See Fig. 3 for schematic diagram of stratigraphic relationships.
*Amino-acid racemization dates on shells in unit, from Kvenvolden et al. (1979).
†As identified by Clifton (1983) with permission from Elsevier.

they are slightly deformed and generally less well exposed than the lower terrace units.

4. METHODS

Samples from the five Late Pleistocene units were taken between Goose Point and Pickernell Creek (see Fig. 2). To examine the potential for sediment input, beach samples were collected from both sides of the Long Beach Peninsula and fluvial samples from the following rivers: Middle Nemah, Naselle, Willapa, Palix (North Fork), Canon, Niawiakum, and North rivers, and from Smith Creek (see Fig. 1). Modern tidal-flat samples were confined to flats adjacent to the 13 m Pleistocene bay cliffs (see Fig. 2).

Modern beach samples of 300–500 g were collected in the upper swash zone of the Long Beach Peninsula by scraping the upper surface of the sand to a depth of 2 cm. Tidal-flat samples were similarly collected. River samples were taken in sandy areas near the banks, upstream from the zone of tidal influence. The five samples from the lowermost reaches of the Palix River (Fig. 2) were collected at depths from 1.8 to 5.5 m by SCUBA divers using coring equipment (Luepke and Clifton, 1983).

Only sand-sized material (2.0–0.062 mm) was analysed. Samples were washed with demineralised water, the water decanted to remove silt and clay, and then air-dried. Splits of samples were separated in tetrabromoethane (density = 2.96). The heavy minerals were then sieved and the 3–4 phi (0.125–0.062 mm) fraction microsplit for grain mounts. Lakeside 70 ($n = 1.54$) was used as the mounting medium.

The number of grains counted depended on their abundance and the prevalence of opaque minerals and mineral aggregates (grains containing more than one mineral). The average number of non-opaque grains counted was ~250. For some samples, a total of 300 grains sufficed to provide enough identifiable heavy minerals, but a few samples required a count of up to 600 grains. Total counts as low as 143 grains usually represented samples with very few heavy-mineral grains in the 0.125–0.062 mm fraction. Regardless of how many grains were actually counted, the entire slide was examined, and any mineral species seen but not encountered during the point-count was noted as present. In addition to the heavy-mineral samples point-counted from the five Late Pleistocene units (see Table 2), 18 samples were point-counted from tidal flats, 27 from rivers, 25 from beaches, and 14 from older Pleistocene units. A total of 200 samples were point-counted for the study.

Heavy minerals were counted using the line method. To ensure that all grains would be randomly encountered, half the total number of grains per slide was counted in left-right traverses, and the other half in up-down traverses. Care was taken that the two traverses never overlapped. Though this method gives a number frequency, which biases a sample towards the larger grains, counting a limited size range (Galehouse, 1969, p. 814) minimizes this problem. To check the method's accuracy, the heavy minerals from 16 beach samples were sieved at 1/4 phi (0.25 mm) intervals. Point counts of minerals in the 0.149–0.125 mm and 0.125–0.105 mm size ranges were compared with those in the 0.125–0.062 mm range. No significant differences in mineral frequencies were noted (Luepke and Clifton, 1983).

5. DISTRIBUTION OF HEAVY MINERALS

The heavy-mineral suites in both the modern and Pleistocene deposits in Willapa Bay contain a wide variety of minerals (Luepke, 1982a), attesting to the mineralogical immaturity of the sediments. The same mineral species identified in the Pleistocene terraces also appear in the modern estuary, beach, and river sands. Of the 200 samples point-counted for this study, 52 selected samples are presented in Table 3.

The most common groups are orthopyroxene (mostly hypersthene, with rare enstatite), clinopyroxene (mostly augite and titanaugite, with rare diopside and aegerine-augite), and hornblende (green, blue-green, brown, and basaltic hornblende). These three groups comprise more than 70% of the non-opaque heavy-mineral count. Various percentages of epidote group minerals, garnet, kyanite, sphene, zircon, and rutile occur in nearly all samples. Other minerals identified include apatite, staurolite, sillimanite, chloritoid, tourmaline, and glaucophane.

5.1. Modern Sediments

The percentages of orthopyroxene, clinopyroxene, and hornblende in samples from modern beaches, rivers, and tidal flats were normalized to 100% and plotted on ternary diagrams (Fig. 4). In the discussion to follow, samples that plot near the centre of the ternary diagram are said to have an hornblende-orthopyroxene-clinopyroxene (H–O–C) suite and those near the clinopyroxene end member are said to have a clinopyroxene suite.

Samples from the ocean side of Long Beach Peninsula tend to have approximately equal proportions of the three mineral species in the H–O–C suite, with either hornblende or orthopyroxene being the greatest of the three species (Fig. 4a). This H–O–C heavy-mineral suite resembles that described in samples taken from the Columbia River (Whetten et al., 1969), a clear reflection of the influence of northward longshore transport on the development of the Long Beach Peninsula. Two samples collected at the mouth of the Columbia River plot within the field of the ocean-Beach samples (Fig. 4a).

Samples collected on the tidal flats form a pattern on the ternary diagram (Fig. 4b) very similar to the ocean side beach-sand pattern of Fig. 4a. Two contrasting heavy-mineral assemblages were detected in samples from above the zone of tidal influence in rivers draining directly into Willapa Bay (Fig. 4a). The rivers draining from the north side of the bay (North River and Smith Creek) have a mixed assemblage of the three mineral groups, but much less orthopyroxene than in the Long Beach Peninsula samples. The heavy-mineral suite from rivers draining into the bay from the east, in contrast, is almost totally dominated by clinopyroxene. This reflects the dominance of basalt of the Crescent Formation on the Bay's east side (Wagner, 1967b). However, the samples taken from the east-side Palix River below the interface of fresh and saline water (see Fig. 2) contain the H–O–C suite (Fig. 4b).

5.2. Pleistocene Deposits

Samples from each of the five terrace units were also plotted on ternary diagrams (Fig. 5). The H–O–C suite dominates in all but a few samples from the Pleistocene

Table 3. Non-opaque heavy-mineral composition of selected samples collected in Willapa Bay, Washington

Sample no.	Collection site	OPX	CPX	HBL	EPI	GAR	Sphene	Zircon	Rutile	APA	KYA	STAR	UNK	Other
74Na-1	Naselle River	13.4	58.2	17.9	4.0	1.0	1.0			2.0		0.5	2.0	
74Nem-2	Nemah River	9.0	74.1	11.4	3.5	*	*	0.5			0.5		1.0	
74Wi-3	Willapa River	2.1	91.5	3.5	2.1		*							0.7
77NP-1	North Palix River	6.3	63.8	18.5	8.3	0.4	0.4	*			0.4	0.4	1.6	
77C-2	Canon River	6.8	88.9	1.8	1.8		0.7							
74No-1	North River	14.5	24.8	33.6	18.7	3.8	2.3	0.8	0.4		*	0.4	0.4	0.4
77No-1	North River	19.6	22.0	36.4	16.3	1.4	0.5	1.0	1.0		*	1.0	0.5	0.5
77No-2	North River	16.7	25.4	36.0	17.5	2.2	0.9	*	0.4		0.4			0.4
77S-1	Smith Creek	14.7	16.9	43.3	16.5	3.4	1.1	0.4	0.8	0.4	0.8	0.4	*	1.5
77S-2	Smith Creek	13.8	13.5	34.2	20.7	6.6	4.3	2.6	*	0.7	*	2.0	1.0	0.6
74WGL-51	LBP, bay side	39.4	18.9	14.4	14.4	9.1	0.8	*	1.5	0.8			0.8	
77WGL-53	LBP, bay side	24.6	19.6	36.3	15.9	1.4	0.4	*		*	1.4	0.4		
77WGL-54	LBP, bay side	25.0	16.8	41.4	13.1	0.4				*	1.2	0.4	0.4	1.2
74WGL-56	LBP, ocean side	45.8	22.2	20.4	5.1	3.2	0.9	*		0.9	*	*	0.5	1.0
77WGL-63	LBP, ocean side	26.2	11.5	52.7	9.0		0.4							0.4
77WGL-68	LBP, ocean side	29.9	15.2	44.3	10.2	*	*			*	0.4			*
Q823-12b	Palix R. mouth	20.9	15.0	41.4	15.0	5.1	*	*	0.4		0.4	*	0.4	0.8
Q824-6	Palix R. mouth	23.4	20.9	36.5	13.1	4.1	0.4	0.4		*	0.4		0.8	
Q824-10	Palix R. mouth	30.5	18.9	29.7	11.9	7.0	0.4	*	*	*	0.8	0.4	0.4	
74T1-8	Tidal flat	38.1	23.0	22.9	10.7	2.0	0.4		*	0.8	0.8	*	0.8	0.4
74T3-5	Tidal flat	31.0	23.0	19.4	14.2	7.1	1.3	0.4	*	0.4	1.8	0.9		0.4
74T4-4	Tidal flat	29.2	27.4	22.8	11.9	5.9	1.4	0.9		*	0.5	*		
S801-1	Tidal flat	20.5	37.7	20.5	19.7	0.8		*		0.8	*			*
P114-1	Unit I	16.5	27.8	42.1	9.4	1.9	0.4	*		0.4	*		0.4	1.1
R901-9	Unit I	12.3	51.8	20.9	11.8	1.8	*	*		*	*	0.5		1.0
R902-3	Unit I	5.9	59.2	19.2	13.5	0.8	*	*	0.4		0.8	*	0.4	*
S828-1	Unit I	19.8	16.4	39.2	19.4	3.4	0.4		*	*	0.4			1.1

77WGL-77	Unit I	24.2	13.5	42.5	14.3	2.7	0.4		0.4	0.2	0.4	0.2		1.2
77WGL-11	Unit II	41.7	9.9	33.4	9.1	2.3	1.2		0.4	*	1.2	*	0.4	
77WGL-12	Unit II	33.5	3.4	41.8	14.8	3.4	0.4			0.8	1.5	*	0.4	*
77WGL-47	Unit II	40.1	19.0	23.0	11.9	4.4	0.4	1.2	*	*	*			
P113-12	Unit II	36.0	22.7	15.6	10.0	13.3	0.5	*	0.5	*	0.5	*	0.9	
S825-2	Unit II	45.6	13.3	21.4	11.9	5.8	1.0	*	*		*	0.3		0.6
77WGL-13	Unit III	37.3	20.8	17.3	10.2	12.2	0.8	*			0.4	*	0.8	0.4
77WGL-35	Unit III	44.1	9.3	19.0	14.6	10.5	0.4	*		*	0.8	1.2		
77WGL-43	Unit III	37.4	11.3	27.8	13.5	8.7	0.4	0.4	*	*	*	*	0.4	
P113-6	Unit III	39.7	16.5	28.1	5.8	9.1	*	*		0.4	0.4	*		
R902-1	Unit III	8.1	71.1	13.4	6.9						0.4			
77WGL-9	Unit IV	24.1	37.9	21.4	8.5	4.9	1.3	0.4		*	0.4	*		*
77WGL-15	Unit IV	33.2	9.5	40.3	11.9	2.0	*	0.4		0.8	0.8	0.8		0.4
77WGL-18	Unit IV	26.2	31.3	32.5	7.1	2.0	0.8	*		*	*	*		
77WGL-29	Unit IV	32.8	17.0	26.3	11.2	10.4	0.8		*	*	*	1.2		0.4
S825-3	Unit IV	20.8	47.9	15.8	11.6	1.9	*	0.8		0.4	0.8			*
77WGL-51	Unit V	3.7	83.5	7.0	5.5	*	*	*					0.4	
77WGL-52	Unit V	3.3	89.2	3.0	3.0	0.7	0.4			*			0.4	
P113-5	Unit V	17.6	48.6	20.0	4.8	6.2	0.5	*	0.5	0.5	*	*	1.4	
R901-1	Unit V	4.0	87.6	4.0	2.0	1.5	*	0.5						0.5
U822-2	Unit V	6.6	72.1	6.2	13.6	0.8	0.4	*			*	0.4		
77WGL-80	Older terrace	6.2	3.7	23.0	59.7	4.1	1.2	0.4	*		0.8	0.8		
77WGL-82	Older terrace	17.1	6.0	26.7	43.0	6.0	0.4	0.4	*	0.4	*			
U824-4	Older terrace	7.8	76.4	4.3	11.6	*	*					*		
U827-6	Older terrace	9.3	0.8	35.5	45.6	1.6		0.8	2.0					0.8

Note: Data complied from Luepke (1982a). Key: LBP, Long Beach Peninsula; OPX, orthopyroxene; CPX, clinopyroxene; HBL, hornblende; EPI, epidote group; GAR, garnet; APA, apatite; KYA, kyanite; STA, staurolite; UNK, unknown. Samples beginning with numbers collected by the author; samples beginning with letters collected by H. E. Clifton with permission from Elsevier.

*Mineral is present in sample at <0.1percent.

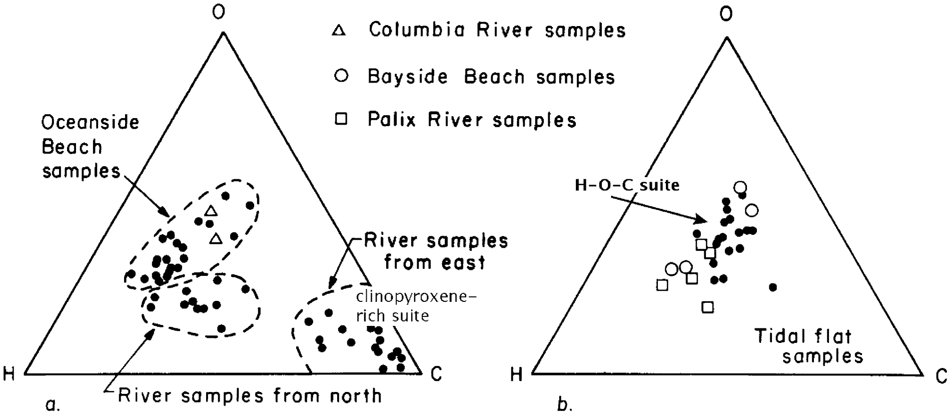

Fig. 4. Normalized distribution of orthopyroxene (O), clinopyroxene (C), and hornblende (H) in modern Willapa Bay sediments. (a) Ocean-side beach and river sands. Note similarity of samples from the Columbia River to ocean-side beach samples. (b) Bayside beach and tidal-flat sands. Note difference of samples at the mouth of the Palix River from other river samples in a. After Luepke and Clifton (1983) with permission from Elsevier.

units. Four samples from Unit II have the lowest clinopyroxene content of all five units (Fig. 5b). Four samples from Unit I and six from Unit V contain more than 60% orthopyroxene (Figs. 5a, e).

Another distinctive heavy-mineral suite appears in some of the terrace deposits older than those of the 13 m terrace. These samples, collected on both the north and east sides of Willapa Bay (Luepke, 1982a), contain a pronounced epidote-rich heavy-mineral suite (40–60% epidote). This heavy-mineral suite is anomalous here because none of the other Pleistocene deposits examined contain so much epidote. Two of the epidotiferous samples from the north side of the bay were taken from a gravely bed in which large-scale cross-bedding dips uniformly towards the southwest, suggesting a source to the north.

Epidote has been found to be susceptible to dissolution in acidic weathering conditions, which may be related to pyrite oxidation (Smale's personal communication with Crampton and Moore, 1990, cited on p. 336). In Unit I, the only unit to contain pyritized diatoms, no correlation exists between epidote percentages and the presence of the diatoms. In all five units the percentage of epidote ranges between 4 and 15%, with two samples from Unit V showing values lower than 4%. Again, no correlation exists between lower percentages of epidote and indications of environmental instability such as grain etching or iron-oxide encrustation, both of which were noted in some samples. It is therefore unlikely that effective acidic weathering conditions influenced the preservation of epidote group minerals in the Late Pleistocene terrace deposits.

6. MODERN INPUT MECHANISMS

Sediment enters Willapa Bay in three primary ways: (1) tidal transport of oceanic sand into the bay; (2) discharge from interior rivers; and (3) erosion of adjacent

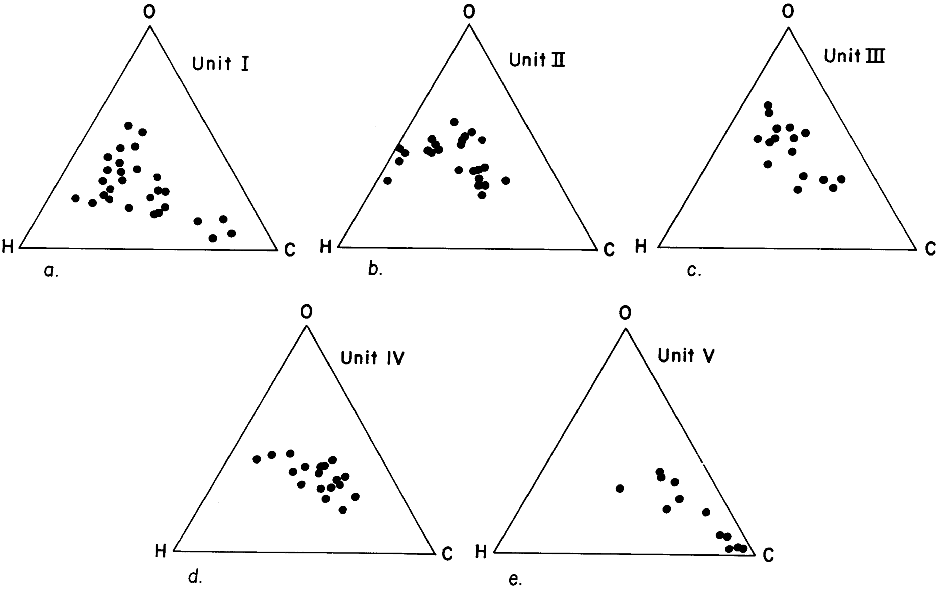

Fig. 5. Normalized distribution of hornblende (H), orthopyroxene (O), and clinopyroxene (C) in sediments of Pleistocene terrace units, Willapa Bay. From Luepke and Clifton (1983). (a) Unit I (oldest). Note the Pickenrell Creek samples near the C point. (b) Unit II. Note the four samples with very low percentages of clinopyroxene. (c) Unit III. (d) Unit IV. (e) Unit V (youngest) with permission from Elsevier.

Pleistocene terraces. The heavy-mineral assemblages do not permit a clear separation of oceanic input from that derived by erosion of the terraces: both would yield the H–O–C suite signature. Moreover, input from rivers draining from the north side of the bay cannot be accurately assessed because of their general similarity to Columbia River sediments.

In contrast, the rivers draining into the bay from the eastern side bear a heavy-mineral suite rich in clinopyroxene that reflects the widespread basaltic rocks in the drainage basins. This distinctive suite is also directly relevant to interpreting the heavy-mineral assemblages of the Pleistocene units examined in detail on the bay's east side.

The dominance of the H–O–C suite in the samples from the lower reaches of the Palix River implies that the clinopyroxene suite is highly restricted within the modern bay sediments. Although the number and distribution of river samples taken below the fresh/salt water interface are limited, the clinopyroxene suite most likely predominates today only above the zone of tidal transport.

7. PALAEOGEOGRAPHIC IMPLICATIONS

7.1. Unit I

The heavy minerals in most samples from Unit I reflect the H–O–C suite (Fig. 5a), which is consistent with the interpretation of this unit as an intertidal to uppermost subtidal depositional environment (Clifton, 1983). A highland area underlain by Miocene and older rocks (Huntting et al., 1961) that ranges in elevation from 50 to over 1000 m separates the Columbia River from the Willapa Bay drainage basin. At the south end of the bay, where the divide is lowest (around 50 m), older Pleistocene terrace deposits show no evidence of a major, north-flowing fluvial system attributable to the Columbia River. Therefore the mineral assemblage probably reflects oceanic sand introduced by tidal transport. The presence of open-ocean diatoms locally within Unit I is also consistent with an oceanic input. Four samples from Unit I, however, plot within the clinopyroxene-rich field of the ternary diagram (Fig. 5a). These particular samples were collected near Pickernell Creek, a location where more abundant sand and basaltic pebbles suggest a stronger fluvial influence.

7.2. *Unit II*

Samples from Unit II also show an H–O–C heavy-mineral suite (Fig. 5b). Four samples contain the lowest clinopyroxene content of all five units. The reasons for this are not clear. Kittleman (1972, p. 173) noted a decrease in brown clinopyroxene with increasing age and weathering of sediments in the Wildcat Canyon Archaeological Site on the Columbia River. Intrastratal dissolution, where documented, has been found to affect the heavy-mineral suite of a sandstone far more than a corresponding shale, because the greater porosity of sandstone allows corrosive fluid circulation and the possibility of chemical attack (Blatt and Sutherland, 1969; Morton and Hallsworth, 2007, this volume). Unit II contains significant amounts of sand, and its porosity may have permitted intrastratal dissolution to occur. However, optical examination of the grains has shown no significant difference in the degree of grain etching present in this unit as compared with the other units in modern sediments.

7.3. *Unit III*

Unit III is a muddy channel-fill that has no evidence of tidal influence, although the samples show only the H–O–C suite (Fig. 5c). It is likely that the heavy-mineral suite reflects sediments eroded from the units (I and II) into which these ancient channels cut.

7.4. *Unit IV*

Samples from Unit IV contain an H–O–C suite (Fig. 5d), consistent with a stratigraphic interpretation as a tidally influenced estuarine fill.

7.5. *Unit V*

Unit V has been interpreted as a fluvially dominant unit with a suggestion of tidal influence. The heavy minerals of this unit support this interpretation, because about half of the samples contain the clinopyroxene-rich suite characteristic of the fluvially dominated sediments in this area (Fig. 5e). However, it is not clear whether samples characterized by an H–O–C suite reflect tidal influence or derivation from older sediments, because Unit V cuts both Units II and IV, which contain an H–O–C heavy-mineral suite.

7.6. Older Pleistocene Deposits

The epidote-dominated heavy-mineral suite found in samples from two older Pleistocene units was at the time of its discovery somewhat enigmatic (Luepke and Clifton, 1983). This suite seems to be altogether absent from sediments in the modern Bay as well as from the Late Pleistocene deposits studied, suggesting that its source was available only intermittently during the Pleistocene. The apparent northerly derivation of this suite present in deposits on the Bay's north side suggests that it may have come from an area covered by glacial outwash. Significant epidote-bearing rocks are now known to be meta-sedimentary rocks in the Olympic Mountains in northwest Washington (C.D. Peterson, personal communication, 2003). The occurrence of the epidote-rich suite in estuarine sediments on the Bay's east side (Wilson Point, Fig. 2) indicates that during the time of their deposition, fluxes carrying abundant epidote may have dominated the central part of the estuary, similarly to that of the modern H–O–C suite.

A complete palaeogeographic reconstruction of Willapa Bay during the Pleistocene is beyond the scope of this study. However this heavy-mineral study suggests a possible outside sediment source and a different palaeotransport direction not obvious from the examination of modern sediments alone.

8. CONCLUSIONS

Pleistocene terrace deposits, exposed on the east side of Willapa Bay, comprise five units that contain three distinctive heavy-mineral suites, two of which are present in adjacent modern bay sediments. One is similar to the Columbia River suite and the other to the clinopyroxene-rich assemblage in sediments from rivers that currently drain into the east side of the estuary. The Columbia River suite, defined as H–O–C suite, is the most common in Late Pleistocene sediments, being present in samples from all five terrace units. It is, however, unlikely that the Columbia River ever discharged directly into this site of the bay. The H–O–C suite is interpreted to be the result of tidal currents carrying oceanic sand from discharges of the Columbia River, or from local erosion of older deposits in which this suite predominates. This interpretation is based on the distribution of the H–O–C suite in modern bay sediment. The clinopyroxene suite is particularly valuable for confirming the influence of fluvial influx in the Pleistocene sediments. The presence of this suite in Unit I, where it is restricted to the southernmost exposures, is consistent with textural changes and the occurrence of basaltic clasts at the same locality. This distribution aids reconstruction of the shape of the Bay at the time Unit I was deposited.

Unit III, although interpreted sedimentologically as a fluvial unit lacking evidence of tidal influence, nevertheless contains an H–O–C suite and is therefore re-interpreted as a channel-fill deposit. The dominance of the H–O–C suite here can readily be attributed to reworking of sands from Units I and II, into which the channels are incised. The predominance of the H–O–C suite in Units II and IV is consistent with their interpretation as the result of deposition in large, tide-dominated bays that resemble the modern Bay in geometry and size of tidal prism. Unit I presents an interpretive problem. It is composed of more uniformly muddy sediments than either Unit II or IV. Evidence for tidal transport is cryptic, even though these deposits, from other criteria, clearly lay within the zone of tidal influence. However, the predominance of the H–O–C suite suggests that tidal transport was an important factor in the deposition of this unit, inasmuch as local sources for the H–O–C suite cannot clearly be identified. The clinopyroxene suite, dominating Unit V, supports the interpretation of fluvial activity based on other evidence, and suggests that tidal transport had little influence on sedimentation in this unit.

The presence of a different heavy-mineral suite, dominated by epidote, in some Pleistocene deposits older than the 13 m terrace, suggests that in earlier periods of deposition, the input mechanisms differed radically from those of the present day. The identification of epidote-bearing rocks in the Olympic Mountains far to the north of Willapa Bay confirms a potential source and direction of transport for these sediments. Other than the heavy mineralogy, there are few if any indications that sediment input within an ancient bay came predominantly from an external source such as glacial outwash.

No significant differences in the degree of grain etching have been noted in the Pleistocene sediments as compared to the modern ones. This indicates that, in general, intrastratal dissolution did not materially affect the heavy-mineral suites within the youngest Pleistocene sediments. In Willapa Bay, where sediment sources have not changed over the studied time-span, heavy-mineral analysis is a useful tool that, when integrated with stratigraphy and sedimentary structures, adds an extra—sometimes critical—dimension to the interpretation of ancient depositional environments.

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